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THE DEVELOPMENT OF A METHOD OF ESTIMATING AND FORECASTING WINDS AT 10,000 FEET OVER THE NORTH ATLANTIC

BY

H. H. LAMB, B.A.

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THE DEVELOPMENT OF A METHOD OF ESTIMATING AND FORECASTING WINDS AT 10,000 FEET OVER THE NORTH ATLANTIC*

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H. H. LAMB, B.A.

Forecasts of winds aloft are of great importance for indicating to the pilot of a long-distance aircraft the most advantageous flying level for any particular flight and to the airway company the conditions determining the probable duration of the flight, required petrol load and consequent passenger-carrying capacity. For civil trans-Atlantic flights forecasts of wind at the surface and at three levels aloft are usually asked for. The commonest heights specified to date have been 2,000, 5,000 and 10,000 feet.

Winds at 2,000 feet have been satisfactorily forecast from the isobars on the forecast sea-level pressure chart for a fixed time in mid-flight, on the assumption of geostrophic conditions. From the first experimental trans-Atlantic flights in 1937 until 1941, when a regular passenger service was in full operation, winds at the higher flying levels were derived from this low-level wind, assuming a normal change with height given by statistical figures of the behaviour of various winds, based on an analysis of 10 years' results of pilot balloon ascents made by ships' officers of the German merchant navy on the North Atlantic trade routes. Adjustment would then be made in the light of the qualitative idea of the thermal wind vector, obtained from the general temperature gradients suggested by the air mass analysis of the current surface charts. This process is not satisfactory on theoretical grounds. Purely qualitative estimates are obviously not enough. On the other hand quantitative reckoning of the thermal wind vector has not been found practicable, even over land where meteorological ascents are fairly numerous; for the precise formula is awkward to work with, and simpler approximate forms suited to practical use are only obtained by neglecting terms whose magnitude is often too great to be neglected, and the results are correspondingly untrustworthy.

The lack of a regular supply of reports of direct observations of upper winds over the ocean was the great difficulty even in peace time. Pilot balloon observations have been made from ships at sea from time to time, and by 1939 the first stationary ships specially appointed for weather observations had made their appearance. The network of such observations is likely always to be sparse, however, and balloon observations are limited to occasions of good weather. The problem, therefore, is to find a sufficiently good, indirect method of arriving at the required wind, at the same time making full use of any direct evidence available.

A possible approach to a solution of the problem is given by computation of pressures aloft: if this can be done with sufficient accuracy, it is possible to draw isobaric charts for levels in the free air. Wind at the level of the chart may then be obtained directly, by assuming geostrophic conditions and using a geostrophic scale appropriate to the mean density at the level in question. This assumption cannot be precisely true so long as there are any vertical air displacements, but it may be expected to come within the limits of accuracy of the computation and to give results scarcely less satisfactory than at 2,000 feet.

By 1941 the problem had become much more serious owing to the complete cessation of data from ships in the greater part of the oceanic area involved and the great increase of traffic on the trans-Atlantic air route. It became imperative, therefore, to adopt some reasonably probable method of arriving at a coherent picture of the pattern of wind-flow in the free air over the ocean by whatever indirect approaches were available. It was felt that any such picture, if it could be derived, would at least serve to clarify the forecaster's ideas and give him some definite basis for his forecasts.

The method described below was, therefore, developed in the Irish Meteorological Service, and since June 1941, charts of wind and pressure at 10,000 feet over an area extending from the Rocky Mountains to western Europe have been constructed twice daily and used in forecasting winds aloft.†

The fact that serious errors in flight times (2 hours or more in an average flight time of 15 hours) have now been virtually eliminated by this means and that this improved position has been maintained despite a further curtailment of data in December 1941, suggests that the method does, in fact, give a reasonably reliable representation of the isobaric field at 10,000 feet. In these circumstances a detailed description of the technique employed may be of interest.

The 10,000-foot level has been chosen for various reasons. It is well in the middle of the height range with which we are at present concerned; so that figures for lower levels may be obtained by interpolation between this and the 2,000-foot wind, and figures for levels up to about 15,000 feet may be got by extrapolation. Moreover, it is convenient that 3,000 metres are nearly 10,000 feet, and data reported for either level will be appropriate to the 10,000-foot chart. Finally, the method makes use of certain rules of thumb about lapse rates of

*Received on 13th November, 1942; originally issued as Technical Note No. 4 of the Meteorological Service on 14th January, 1943; now published as Geophysical Publication, Vol III, No. 3.

†The construction of 10,000-ft. charts was discontinued in October, 1946 when the 700 mb. chart was introduced as a routine.

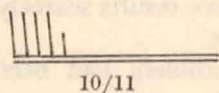
temperature which could scarcely be carried to much greater heights. So far as is known, these rules of thumb are a distinctive feature of the Irish technique, in contrast with the methods of other services, where no allowance for variations of lapse rate is generally made.

Data.

The following categories of data are plotted on the 10,000-foot chart:—

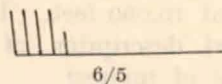
1. Pilot balloon winds at 10,000 feet.
2. Nephoscope observations on medium cloud.
3. Pressures at 10,000 feet.

Pilot balloon observations at 10,000 feet within two hours of the time of the chart are plotted in black according to the following model:—



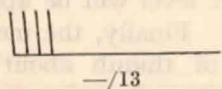
A dot represents the position of the observing station and a double arrow the direction of the observed wind. The wind strength is shown to the nearest 5 mph., by one whole stroke for each 10 mph., and a half stroke for 5 mph. The figures shown as the numerator of a fraction give the height of the observation in thousands of feet above sea-level, whilst the denominator gives the time to the nearest hour G.M.T. Thus the example shown above represents a wind of 45 mph. from 270°, observed at 10,000 feet at 11h. G.M.T.

Some use can often be made of balloon observations which are not at the precise height and time. At stations where observations for the correct time and height are not available, we therefore plot the observations for the nearest height and time, so long as these are within 5,000 feet and within twelve hours of the appropriate height and time. These winds are plotted according to a like model, except that the wind direction is shown by a single arrow. (By this reminder correspondingly less weight is given to these observations in the analysis):—



The example represents a wind of 45 mph. from 270°, observed at 6,000 feet at 05h. G.M.T.

Medium cloud nephoscope observations are plotted *in red*, exactly as on surface charts.* The time of the observation is added as the denominator of a fraction, whose numerator (height) must be represented by a dash.



*Experiments are also being made at the present time (1942) in plotting C_M and mapping on the 10,000 ft. chart the extent of the medium cloud sheets.

†Bull. Amer. Met. Soc., January, 1941.

The example represents a C_M Neph of 40 mph. from 270°, observed at 13h. G.M.T.

High cloud nephoscope observations are not plotted on the 10,000-foot chart.

Pressures are obtained by computation from the M.S.L. pressure and the mean temperature of the air-column between sea-level and 10,000 feet. Mean temperatures T_m are obtained from upper air soundings wherever these are available; elsewhere by estimate. This is the crux of all methods of obtaining winds at high levels indirectly by deduction, and will be dealt with more fully later. The figures obtained for pressure at 10,000 feet are plotted boldly in red, to the nearest half millibar: for convenience the temperature values used are also shown.

Derivation of pressure values at 10,000 feet.

The method of reckoning pressures at 10,000 feet must be quick as well as accurate.

Fundamentally we use the integrated form of the pressure-height formula:

$$\log p_0 - \log p = \frac{gz}{RT_m}$$

where p_0 is the pressure at sea level
 p is the pressure at height z
 T_m is the mean temperature of the air column in °A.

Taking the constants to have the following values:

$$g = 9.80 \text{ metres per sec.}^2 \text{ with sufficient accuracy for all latitudes,}$$

$$z = 3,048 \text{ metres (10,000 feet),}$$

$$R = 287.0 \text{ in metre-second units,}$$

and at the same time converting to common logarithms, we get:

$$\log_{10} p_0 - \log_{10} p = \frac{45.1957}{T_m}$$

Originally this equation was applied in practice by means of computation scales very similar to the slide rule described by Fulks and Dightman.† A slide rule was constructed, but it was found more expeditious to make use of fixed scales on which the lengths were measured off with dividers. Later, however, this method too was replaced by an even quicker device due to Mr. C. J. Gillman of the Irish Meteorological Service. This is the computing diagram shown in Figure 1. The diagram in actual use measures 11 by 10 inches and, covering a range from 940 to 1,050 mbs. for sea-level pressure and from -20 to +80°F for mean air-column temperature, is sufficient for all practical purposes. To obtain the pressure at 10,000 feet from given values of p_0 and T_m is only a matter of seconds.

The point which requires care and discretion, and takes time, is the selection of the appropriate T_m values.

Mean Temperature of the Air Column T_m

Different methods are used to get T_m according to whether upper air soundings are available or not.

At stations where ascents have been made within twelve hours of the time of the 10,000-foot chart, always provided that no change of air mass has occurred in the meantime, the temperature of the equivalent isothermal atmosphere is taken. This is obtained from the ascent curve by the equal-area method, an adjustment being made in the lowest levels for the screen temperature reported at the time of the chart. When using a diagram on which temperature is plotted against pressure for this purpose, it is necessary to have a rough idea of the pressure corresponding to 10,000 feet; this may be had from the following table, giving the difference $p_o - p$, between sea-level pressure and pressure at 10,000 feet, to the nearest 10 millibars for widely different pressures and temperatures.

TABLE I.

($p_o - p$) mbs. *First Approximation Table.*

T_m	°F	+ 50	+ 5	— 40
		°C	+ 10	— 15
p_o				
1050		320	350	380
1000	310	330	360
950	290	320	340

These figures make it possible to judge the temperature of the equivalent isothermal atmosphere to the nearest degree Fahrenheit or half degree Centigrade, from which the pressure at 10,000 feet may be reckoned to the nearest half millibar or so. Occasional errors arising from erroneous instrument readings will be apparent when T_m and p are compared with the values at neighbouring stations, obtained either by the same process or by estimate. Faulty surface pressures are known at once from the analysis of the surface chart and are avoided in making the computations.

Where no results of meteorological ascents are available, T_m is estimated from representative values of surface temperature T_o . Representative values of T_o , corresponding to adiabatic lapse rates, are given particularly

- (i) by ships
- (ii) by coastal stations with onshore breezes,
- (iii) by stations where big cumulus or cumulonimbus clouds are reported,

- (iv) by stations where stratocumulus, stratus or fractonimbus clouds are suspected to have considerable vertical development, especially with precipitation falling or in cyclonic situations.

Reference may be made within reason to earlier and later charts in order to find a representative surface temperature value for any station. Stations where ground inversions or subsidence inversions are evident must be rejected for estimation purposes.

A list is kept of key points on coasts and islands for which estimates of T_m are always attempted, if at all possible, in order to give a good network. Careful checking over of this list will ensure that no unnecessary gaps are left in the network by oversight. (The recurrent ground inversions over the Newfoundland region, particularly with easterly winds in spring and summer, associated with advection of warm air over the cold coastal waters, present a difficulty; the inversion may, however, be broken up locally in the afternoon to give a convection sky and representative surface temperatures at one or two isolated stations towards the leeward coast). Full use is made of any available ship reports.

From a representative surface temperature value T_o , the mean temperature of the air column T_m from sea-level to 10,000 feet is obtained by the following rules of thumb:—

1. *Saturated Adiabatic Lapse Rate throughout* e.g., with rain or drizzle falling, and ceiling very low.

$$T_m = (T_o - 13) \text{ } ^\circ\text{F.}$$

2. *Dry Adiabatic Lapse Rate throughout* e.g., in cases of strong heating from underneath, principally on afternoons in the warm season over continents and in the tropics, and with small cloud amounts.

$$T_m = (T_o - 27) \text{ } ^\circ\text{F.}$$

North of 40°N cases of dry adiabatic lapse rate through a height of more than 5,000 feet are very rare.

3. *Dry Adiabatic Lapse Rate to the Base of the Cloud in the ground turbulence layer, Saturated Adiabatic Lapse Rate above that height.* These are the conditions most commonly holding with all types of low cloud, between the ground and the level of the top of the cloud. The following is, therefore, the rule most frequently used for obtaining T_m .

$$T_m = (T_o - 13 - 1.4 h) \text{ } ^\circ\text{F}$$

where h is the height of the base of the low cloud in thousands of feet, taken to the nearest thousand feet below cloud-level.

At ships and stations where no report of cloud-height is given, a figure of 2,000 feet is assumed in most cases north of 40°N latitude, 3,000 feet for places south of this latitude. A lowering of 1,000 feet below these figures is generally allowed, when precipitation is falling.

Superadiabatic lapse rates sometimes occur. In strong outbreaks of Arctic air over the British Isles and neighbouring waters of Gulf Stream origin the saturated adiabatic lapse rate is frequently exceeded throughout the layers in which cumulonimbus clouds are present. The dry adiabatic lapse rate may be exceeded below the cloud-base in Arctic outbreaks and also in the afternoons in very warm weather over land. Estimates must then be adjusted in the light of the lapse rates and T_m values revealed by neighbouring ascents, which should be used as a guide in all cases.

Fronts are allowed for in the following manner. At surface stations within the colder air mass near a front, T_m is first estimated as before from a representative value of T_o ; then, if the distribution of altocumulus or lower frontal cloud, indicates the presence of the warmer air mass in the upper part of the 10,000-foot air-column, a certain number of degrees are added to T_m for this. The correction depends on the mean difference between the temperatures of the two air masses at the same level, and on the vertical extent of the portion of the 10,000-foot air-column which is occupied by the warmer air mass, the latter figure being obtained from the distance of the station from the front on the sea-level chart and an assumed slope. We assume a mean slope of 1 in 200 for warm fronts, 1 in 75 for cold fronts; and the mean temperature differences between the air masses are taken as follows:

TABLE II.
Airmass Temperature Differences.

	W. Europe and Atlantic Ocean	North America
Warm Front	8°F	16°F
Cold Front	6°F	18°F

These figures give us the following numerical rules for correcting T_m , as first obtained from T_o in the cold air.

TABLE III.
 T_m Corrections.

	W. Europe and Atlantic Ocean	North America
	°F	°F
Warm Front	+ (8 - 2x)	+ (16 - 4x)
Cold Front	+ (6 - 4x)	+ (18 - 12x)

x is the horizontal distance of the station from the front at sea-level in hundreds of miles. For unusually sharp fronts the corrections may be increased up to double these figures.

Weak fronts and old occlusions are not taken into account.

Construction and analysis of the 10,000-foot chart.

Over the area with which we are concerned between the Rocky Mountains and the seaboard of western Europe about forty good pressure values at 10,000 feet can generally be obtained by the estimation process. On days when many meteorological ascents are available, fewer estimations will be required. It is found possible to draw the map from a well-scattered network of some forty to fifty points, which include some estimation points over the sea. In peace-time when ships' reports are received from widely-scattered points over the ocean the network of pressure values at 10,000 feet should be much improved. In present circumstances the T_o values used for the estimations at sea are taken from the characteristic surface temperatures in the different air masses, entered on the surface chart by the analyst.

The possibility of drawing the 10,000-foot map from so few points is due to its simpler character as compared with the sea-level chart, a fact that is amply witnessed by the smooth flow of wind at 10,000 feet shown by pilot balloon observations whenever these are available. On the 10,000-foot chart the smaller and less important complexities of the surface chart are eliminated. Topographical deformations of the field of flow (lee-troughs, etc.), and thermal depressions of purely local and transitory existence due to diurnal heating usually disappear; secondary cold fronts do not reach up to 10,000 feet as a rule, and therefore do not appear; and old occlusions and other weak fronts, which no longer correspond to any noteworthy veer of wind and are of little dynamic importance, are conventionally dropped in the construction of the 10,000-foot chart. This greater simplicity of the high-level chart is a virtue, since it focusses the analyst's attention on the more dynamically important features of the situation.

It has been found generally most convenient to place the fronts first in relation to their positions on the surface chart, before attempting to draw the isobars at 10,000 feet. Failing other evidence, warm fronts, and warm occlusions (if they are still occlusions at 10,000 feet), are placed about 400 miles ahead of the sea-level positions; whilst cold fronts, and cold occlusions, are placed about 150 miles behind the sea-level positions. These distances are increased in low latitudes, where even the major fronts often fail to reach up to 10,000 feet due to flattening out of the cold-air tongues.

It is clear that the warm sectors of depressions are more extensive at 10,000 feet than at the ground. The centres of low pressure associated with the tips of the warm sectors are correspondingly displaced towards the north or north-west of their sea-level positions, in the case of normally orientated frontal systems. Once the depression is fully occluded, however, its axis has become more nearly vertical or may even have an abnormal inclination.

Isobars are drawn at the same interval as on the surface charts of the same scale. In practice a spacing of 4 mbs. is used in the Irish Meteorological Service.

Geostrophic scale for use on 10,000-foot Charts.

It is necessary to construct a special geostrophic scale for the mean density at 10,000 feet.

The geostrophic equation gives us :

$$V = \frac{dp}{dn} \cdot \frac{1}{2\varrho \omega \sin \varphi}$$

where V is the wind velocity,

$\frac{dp}{dn}$,, pressure gradient,

ϱ ,, density,

ω ,, Earth's angular velocity of rotation,

and φ ,, latitude.

If we consider any particular latitude, and if $\frac{dp}{dn}$ be the same at 10,000 feet as at sea-level, then the ratio of the geostrophic wind at 10,000 feet to the geostrophic wind taken from the sea-level isobars is :

$$\frac{V_{10,000}}{V_0} = \frac{\varrho_0}{\varrho_{10,000}}$$

Taking -2°C and 697 mbs., or a density of 0.895 kgs/m³, as the standard conditions at 10,000 feet for construction of the scale, we find that the geostrophic wind at 10,000 feet is about 30 per cent. stronger than the geostrophic wind at 2,000 feet for the same pressure gradient (isobar-spacing).

This geostrophic scale may be used in constructing the chart, as well as for obtaining geostrophic wind velocities from the completed chart. It is useful in drawing the map over regions where pressure values are few (owing to difficulties of estimation for instance) but where at the same time pilot balloon reports are plentiful. This is liable to occur in subsidence regions, but a careful watch must be kept in such cases for departures of reported winds from geostrophic value, wherever the vertical motions are pronounced.

Practical applications of the 10,000-foot Chart.

The uses for which the 10,000-foot chart is designed may be summarized as follows :—

- (i) estimation of existing wind at 10,000 feet, by use of the geostrophic scale,
- (ii) forecasting wind at 10,000 feet, by means of a forecast chart, and
- (iii) derivation of estimates of wind at other levels, by interpolation between sea-level chart and 10,000-foot chart, or by extrapolation up to 15,000 feet.

The construction of the forecast chart, referred to under (ii), involves the principle of continuity. A forecast chart for the 10,000-foot level might be arrived at by marking the depression and anti-cyclone tracks on the actual 10,000-foot charts, and extrapolating into the future on the basis of their known history. Moreover, this need not be any merely formal extrapolation, but rather a reasoned prognosis of the future state and position of the pressure systems; the fact that the high-level pressure field is free from many of the complexities of the surface map and that the major features which do appear usually present a steady and regular development makes the prognosis comparatively easy. In practice, however, the 10,000-foot forecast* chart is constructed from the forecast chart for sea-level in exactly the same way as the actual 10,000-foot charts are obtained from the corresponding surface charts, and the result is checked against the series of actual 10,000-foot charts to see that it is consistent with them and presents a reasonable extrapolation.

Further possible applications of the 10,000-foot Chart.

Quite apart from the uses for which these charts are expressly designed, it appears that observed departures of apparently trustworthy pilot balloon winds from geostrophic value may lead to conclusions about the dynamic changes of pressure occurring, cyclogenesis and so on. Departures of wind from geostrophic value at this height in the free air are not due to friction, but are associated with net gain or loss of mass of air in different parts of the map; the redistribution of mass is accompanied by changes of pressure and by vertical displacements of the air.

If we are to use the high-level chart to make deductions about the dynamical changes taking place, it will be useful to consider the cases of departure from geostrophic conditions from the theoretical point of view.

Consider first departures of wind direction. Directional convergence means inflow of wind across the isobars towards the higher pressure at points of anti-cyclonic curvature, resulting in accumulation of air, rising pressure and perhaps ultimately anticyclogenesis. Outflow of air across the isobars, on the other hand, would tend to even out the pressure distribution.

Directional divergence occurs at points of cyclonic curvature with outflow of air across the isobars away from the lower pressure. The trough must then deepen, the pressure gradients are increased and perhaps ultimately cyclogenesis results from this process. Inflow of air across the isobars in the direction of the trough would tend to even out the pressure differences.

*The term "Forecast chart" here means a chart showing the pressure distribution at some specified period ahead (normally about 12 hrs.) as forecast from the current chart.

The angles of deviation between isobaric and true wind direction are in most cases small, and scarcely vitiate forecasts of wind direction based on the geostrophic assumption.

Consider now departures of wind velocity. We shall consider these departures in isolation from any departure of direction. This is not strictly true, for, as we shall see, gain or loss of air from the various pressure systems is always involved and therefore, of necessity, some deviation of wind direction from the line of the isobars, but the angles of deviation are small. We consider, therefore, that the pressure gradient force B , the geostrophic or Coriolis force G , and the centrifugal force C act approximately at right angles to the isobars, although strictly G and C act at right angles to the streamlines of flow.

In the case of cyclonic curvature the gradient wind equation states the conditions for equilibrium as follows:—

$$-\frac{1}{\rho} \frac{dp}{dn} = 2\omega V \sin \varphi + \frac{V^2}{r}$$

where r is the radius of path curvature, and the other symbols have the same meanings as before. The pressure-gradient term is opposed by both geostrophic and centrifugal terms. The latter both involve V ; and if the velocity V is greater than the equilibrium value, $C + G$ will be too great for balance with B . Loss of air from the region of already low pressure (in fact directional divergence!) must result. It is to be noticed that the equilibrium value of V is really less than the geostrophic value with cyclonic curvature, owing to the effect of the V^2/r term. If V is less than the equilibrium value, B will be too strong for balance with $C + G$, and inflow towards the lower pressure with weakening of the pressure gradient will result.

For anticyclonic curvature the gradient wind equation takes the form:—

$$-\frac{1}{\rho} \frac{dp}{dn} = 2\omega V \sin \varphi - \frac{V^2}{r}$$

Here the geostrophic term opposes the effects of pressure gradient and centrifugal force. The terms involving V act against one another, and the consequences are not as clear as in the case of cyclonic curvature. However, it is clear that, as V increases above the equilibrium value the V^2/r term must eventually take charge. This suggests that winds above gradient strength would be associated with weakening of the high pressure system, whilst winds below gradient strength would be accompanied by directional convergence and strengthening of the pressure gradient. With anticyclonic curvature the equilibrium value of V is actually greater than the geostrophic value, owing to the effect of the V^2/r term.

We may now draw up a series of rules for diagnosis of actual cases:—

1. Cyclogenesis—directional divergence (outflow) in the trough—overstrength winds.
2. Anticyclogenesis—directional convergence (inflow) in the wedge of high pressure—possibly no pronounced departure of wind velocity.

3. The pressure field tends to become uniform under the reverse conditions.
4. If the wind has its equilibrium value in any particular region, but is generally above (below) gradient strength in the neighbouring region to windward, pressure must rise (fall) between these two regions. This rule is self-evident, and applies even to a situation with straight isobars.
5. If the wind has its equilibrium value in any particular region, but is generally above (below) gradient strength in the neighbouring region to leeward, pressure must fall (rise) between these two regions.

Over the Atlantic Ocean in present circumstances there is not much opportunity of using the 10,000-foot charts for such deductions. These considerations, however, explain why wind velocity may depart by some 10 mph. from geostrophic value with gradients for 40 mph. when the pressure systems are in a state of active development, giving the most serious failures of forecast to which this method is liable.

Conclusion.

The upper air observations available to the Irish Meteorological Service at the present time are insufficient to permit of a direct check* of the accuracy of this method of constructing 10,000-foot charts, but the technique appears to have justified itself as a workable method of forecasting upper winds, which suggests that the charts thus derived must have some real relation to fact.†

*Some of the original experimental charts drawn in May 1941 are given in an Appendix to illustrate the technique; in this Appendix some comparisons have been made between observed winds and geostrophic winds obtained from the charts.

†Added 7th December, 1943.—Since this Note was written a Technical Memorandum of the Meteorological Office, Air Ministry (S.D.T.M. No. 62 of 11th August, 1943) by T. H. Martin, has been received; this memorandum gives the results of a check, against actual observations, of the accuracy of the contour charts of the 750 and 500mb. surfaces which have been constructed in the Meteorological Office, since January 1943, using a method introduced there by Pettersen. As Pettersen's method of constructing these charts is basically the same as that used in constructing the 10,000-ft. chart (estimations based upon representative surface observations and an adiabatic lapse rate), Martin's demonstration of the relatively close agreement between observed values and the values computed by Pettersen's method may be regarded as definitely confirming also the accuracy of the method, described in the foregoing Note, of constructing the 10,000-ft. chart.

Martin's results further suggest that the use, in the 10,000-ft. technique, of the dry adiabatic lapse rate, for the very lowest layer of the atmosphere, in certain circumstances, instead of the saturated adiabatic lapse rate employed in Pettersen's method, gives a somewhat greater accuracy.

Martin finds that the mean errors in the height of the 750mb surface come to about +30 feet and that they are not appreciably larger in the case of the 500mb surface. This positive height error indicates that the actual lapse rate was slightly greater than that assumed while the second result indicates that this error arises in the lowest part of the air column. It appears logical, therefore, to attribute the error to the assumption of a saturated adiabatic lapse rate for a layer where the dry adiabatic might be more appropriate.

If, to test this hypothesis, we take $p_0 = 1010$ mb, $T_0 = 50^\circ\text{F}$, and a cloud base of 2,000-ft. as a typical example of N. Atlantic and British Isles conditions, we find $T_m = 37^\circ\text{F}$ and $p_{10,000} = 692$ mb, on Pettersen's assumption of a saturated lapse rate, and $T_m = 34^\circ\text{F}$ and $p_{10,000} = 690.5$ mb, assuming a dry adiabatic lapse rate up to the cloud base. The +30-ft. error found by Martin is of the same order and in the same sense as this difference of 1.5 mb. This suggests that the errors found by Martin in the height of the 750 mb. and 500 mb. surfaces might be further reduced by introducing into the method of computation the assumption specified in Rule 3 (p. 3) of the present Note.

APPENDIX

Illustrative Series of 10,000-ft. Charts : May 12/16th, 1941.

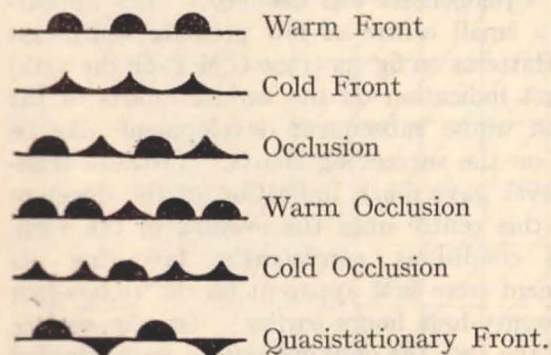
Figures 2 to 6 reproduce the 10,000-foot charts for the North Atlantic and North American region for 1300 GMT. on the 12th to 16th May, 1941. Figures 2a to 6a show the corresponding M.S.L. Charts.

The data used in construction of the 10,000-foot charts consisted of pilot balloon observations from the United Kingdom, Ireland, Newfoundland, Canada, U.S.A., Spain and Portugal and the Spanish and Portuguese possessions ; also upper air temperature observations from the following places :—

Mildenhall, Suffolk, England.	Oklahoma, Okla. Washington, D.C.
Aldergrove, N. Ireland.	Lakehurst, N.J.
Miami, Florida.	St. Louis, Mo.
Charleston, S.C.	Buffalo, N.Y.
Atlanta, Ga.	St. Joliet, (Chicago, Ill.).
Pensacola, Florida.	Portland, Me.
Brownsville, Tex.	Minneapolis, Minn.
San Antonio, Tex.	Sault Ste. Marie, Mich.
Nashville, Tenn.	Bismarck, No. Dakota

and from a U.S. Coastguard vessel stationed about 39° N. 46° W. in the Atlantic Ocean. In addition pressures at 10,000 feet were deduced from assumed representative surface air temperatures and lapse rates at points scattered over the entire chart.

Isobars have been drawn at 4-mb. intervals, with the exception of lightly-drawn and clearly-numbered intermediate isobars entered to show centres of low and high pressure on figures 3 and 4. Fronts are shown according to the following notation :—



Dots have been used to indicate uncertain fronts, or frontal positions fixed on insufficient evidence.

It is necessary to remember that fronts shown at 10,000 feet conventionally represent the intersection with the 10,000-foot plane of the upper surface of what is often a deep transition layer ; the line of the front on the 10,000-foot chart thus marks off the boundary between the warm air mass and a transition belt which may have a horizontal extent of the order of hundreds of miles. Sharp fronts,

sharp frontal wind shifts and sharp angles in the isobars will be correspondingly rare at 10,000 feet. Also since air movements in the vertical plane are taking place on a broader scale than on the earth's surface (which necessarily limits them), the gradient wind component across a front at 10,000 feet can seldom be taken as a measure of its rate of advance.

One of the most striking characteristics of the 10,000-foot chart series (figs 2 to 6) is the disappearance of the centres of high pressure shown over Northern Canada and Greenland on the surface charts (figs. 2a to 6a). The high pressure at low levels is associated with the great density of cold air near the surface. Some of the centres of low pressure over the United States also fail to reach up to 10,000 feet. High temperatures and low densities are associated with a comparatively slow rate of fall of pressure with height. The net results of these effects is that the charts for 10,000 feet over the North American Continent present a much simpler picture than the corresponding surface charts. Moreover the steady eastward advance of the meridional frontal systems throughout their entire length is easier to understand by reference to the 10,000-foot charts than to the surface charts.

The axis of a low pressure system leans towards the side where the coldest air masses are found. Over the eastern North Atlantic and the European seaboard this means a normal tendency to lean towards the north-west, but over the American Continent the axis of a depression is liable for the same reason to lean far towards the north or north-east.

The axis of a high pressure system leans towards the side where the warmest air masses are found. This normally means an inclination towards the south-west or south. The surface temperature contrast from land to sea in the tropics and consequential heating of the air over the land, however, produces a persistent tendency to high pressure aloft over the Sahara. The chart series (2a to 6a) shows the subtropical high pressure system over the Atlantic displaced somewhat to the south of its normal position. The 10,000-foot charts (figs. 2 to 6) show the high pressure belt still further south. Over the coast of Africa the change from N.E. trade winds at the surface to S.W. countertrades at 10,000 feet can be clearly seen.

Two notable features of the period covered by these charts were the oceanic anticyclone in latitude 50°N and the depression near the Azores. That both these features appear also on the 10,000-foot charts is a symptom of their persistence ; events of a transitory nature seldom show much development in depth. The unusual Azores Low is so well developed at 10,000 feet that it must extend to much greater heights, and one suspects

that it may have been induced from aloft. No frontal analysis of this depression appears possible but it is noteworthy that the centre deepened as the cold air supply intensified on the 15th and 16th bringing in air of maritime arctic origin.

To follow successfully the developments over the Atlantic deduced pressures at 10,000 feet for Madeira, the Canary Islands, the Azores, Bermuda and American ships on the trade route to the West Indies are essential. Further north we must use estimated pressures based on characteristic surface temperature and air mass lapse rate values for points over the sea, paying particular attention to available surface observations from Iceland, Greenland, Resolution Island and the Canadian arctic regions.

Turning now to points of detail, we shall discover some interesting verifications of the validity of the method and of the chart series shown in the figures.

Figures 2, 3 and 4 show a strong gradient for south-westerly winds at 10,000 feet over the United States just east of the Rockies. Winds of 30 to 40 mph. and over are indicated, though no pilot balloon observations are available to provide a check. The situation as regards forecasting is thus similar to that which arises over the ocean. The entire series of 10,000-foot charts is consistent in showing this belt of strong south-westerly winds, becoming eventually rather more westerly, advancing eastwards across the United States. The first verification from direct observations came on the 15th (fig. 5) where winds of 30 to 40 mph. from directions between 240° and 260° are shown by the balloons at all stations in this current. Next day (fig. 6) the directions are from 250° to 290° and speeds of 50 mph. appear.

Over the Atlantic Ocean the occasional balloon observations from the one available ship in 39°N 46°W agree well with the pattern of the isobars. Further east the same may be said of the observations available from Madeira, Spain and the British Isles. Winds for 7,000 feet and over have been plotted on figs. 2 to 6 to eke out the network of observations where readings as high as 10,000 feet are lacking.

Finally, it will be worth while to examine fig. 3; the 10,000-foot chart for 13th May, 1941, in some detail; for this chart was drawn deliberately from the estimated pressure values alone, the balloon observations being entered later. The agreement between the expected and observed wind values is gratifying, and reveals in a striking manner both the successes and the known limitations of the method. The following table illustrates the comparison between expected and observed wind

values at 10,000 feet for eight fairly distributed stations on fig. 3.

STATION	Geostrophic Wind	Observed Wind
Barcelona, Spain ...	350° 15 mph.	330° 10 mph.
Kupuskasing, Ontario ...	350° 30 mph.	350° 30 mph.
Caribou, Maine ...	220° 25 mph.	220° 15 mph.
Buffalo, N.Y. ...	340° 10 mph.	350° 10 mph.
New Haven, Connecticut ...	270° 12 mph.	250° 20 mph.
Indianapolis, Ind. ...	350° 25 mph.	360° 15 mph.
Little Rock, Arkansas ...	350° 20 mph.	350° 25 mph.
Jacksonville, Florida ...	270° 30 mph.	280° 40 mph.

The most notable departures from expected values occurred in Florida. There several stations consistently reported winds 10 mph. or rather more above geostrophic strength, with a slight tendency to blow outward across the isobars away from the trough over the south-eastern States. Elsewhere the departures of the observations from expected wind values are more haphazard, and the balloons from neighbouring stations do not agree in this respect amongst themselves.

The overstrength winds over Florida and Georgia, transporting air away from the trough over the south-eastern section of the U.S.A., were a feature also of the preceding day's chart (fig 2). The geostrophic wind at 10,000 feet over Jacksonville, Florida was then 280° 20 mph. although the observed wind was 290° 30 mph. The evidence of observed winds and pressures computed from observed upper air temperature values are sufficiently convincing that in this region on the 12th and 13th May, 1941, the wind flow at 10,000 feet really did depart from the geostrophic balance in the sense noted. Cyclogenesis was deduced. The appearance of a small centre of low pressure south-east of Cape Hatteras on fig. 3a (1300 G.M.T. on the 13th) is the first indication on the surface charts of the depression whose subsequent development may be followed on the succeeding charts. Pressure tendencies never gave much indication of the development of this centre until the evening of the 13th, although conditions consistently favouring its development were first apparent on the 10,000-foot charts twenty-four hours earlier. On the surface charts of the 12th the only indications were afforded by a detailed study of the ships' observations on the trade route from United States east coast ports to the Caribbean; erratic wind directions given by the light breezes observed showed some tendency to the development of anticlockwise circulations, and excessive extents of medium cloud overhead were observed.

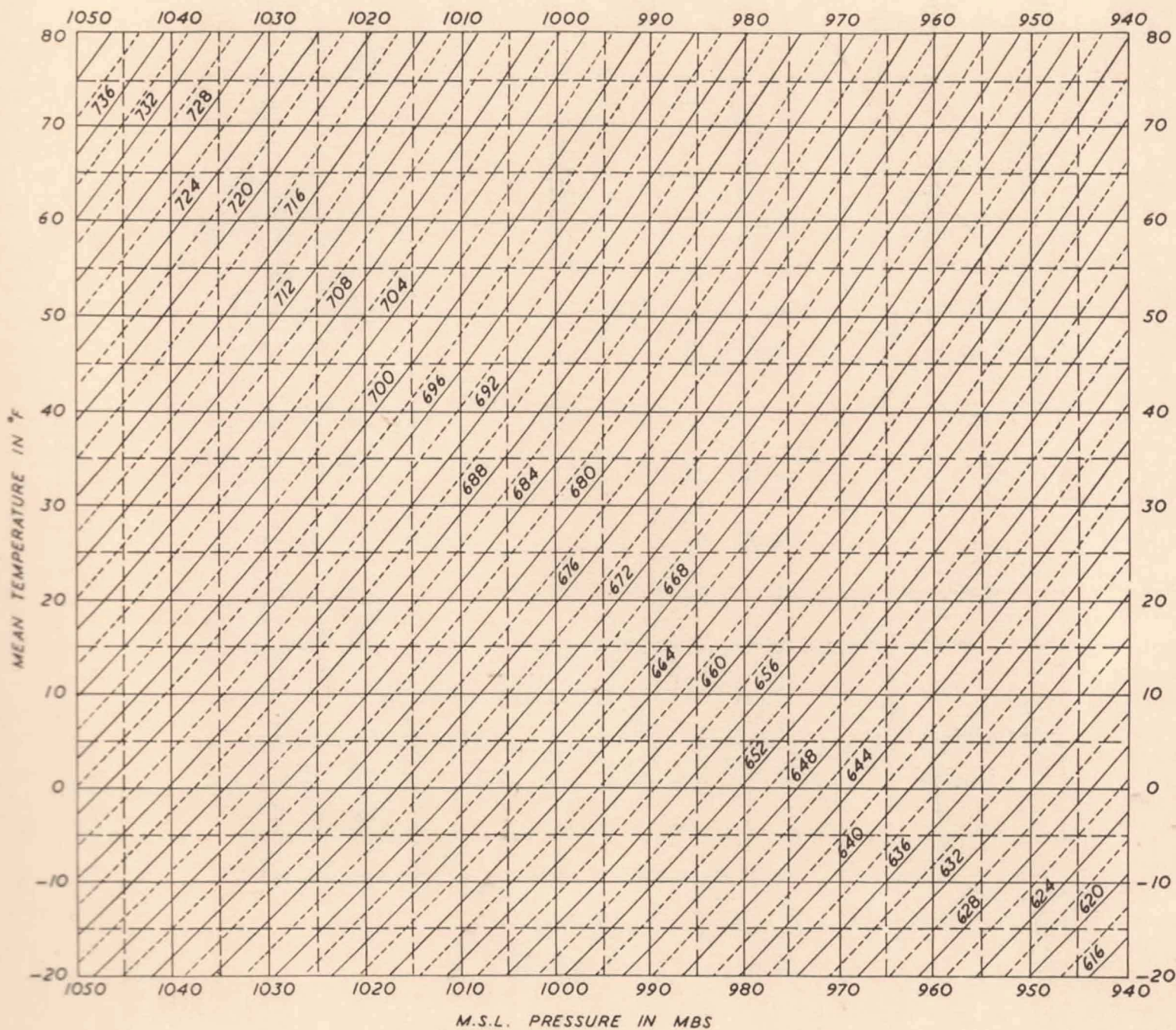


FIG. 1. DIAGRAM FOR OBTAINING ATMOSPHERIC PRESSURE AT 10,000 FT.

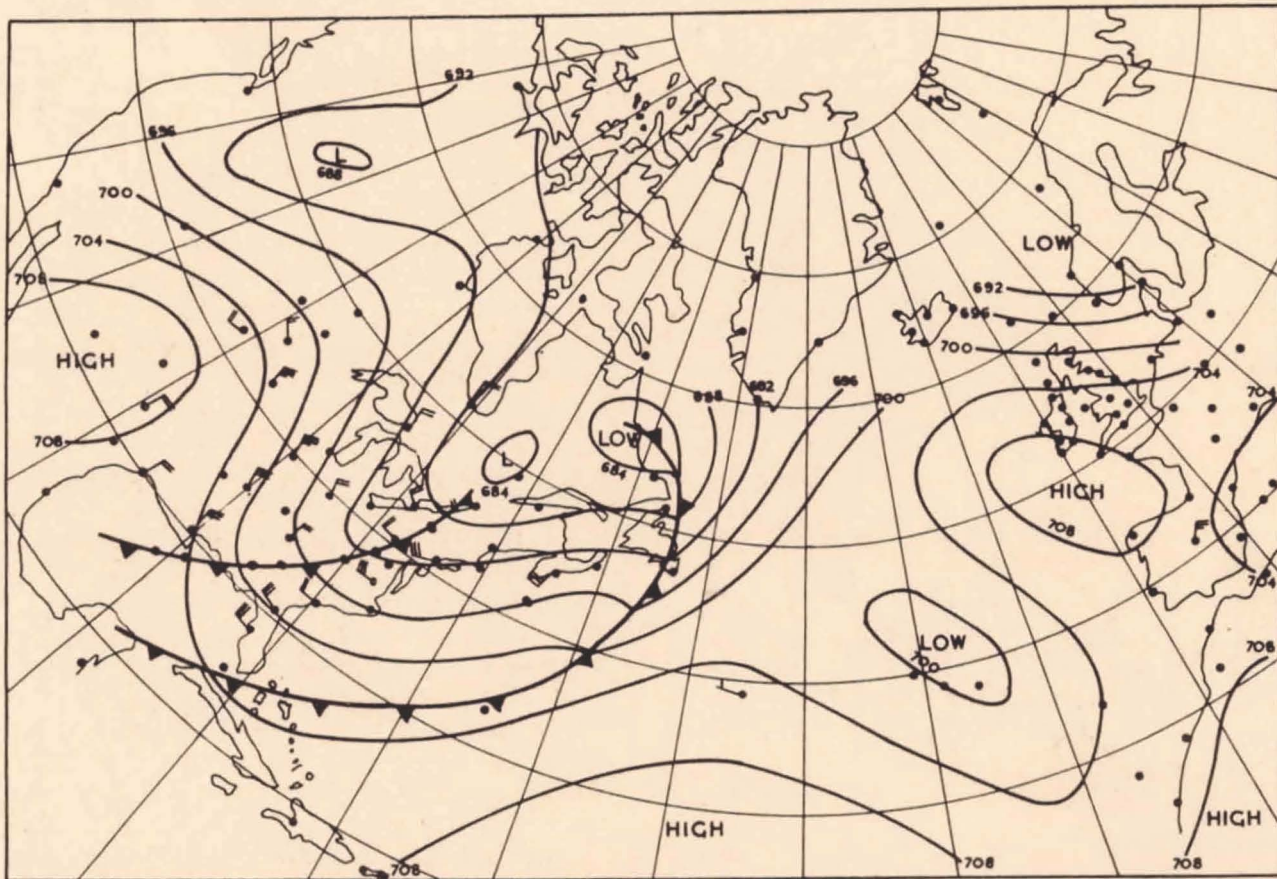


Fig. 2. 10000 ft. chart - 1300 G.M.T. Monday 12th May 1941

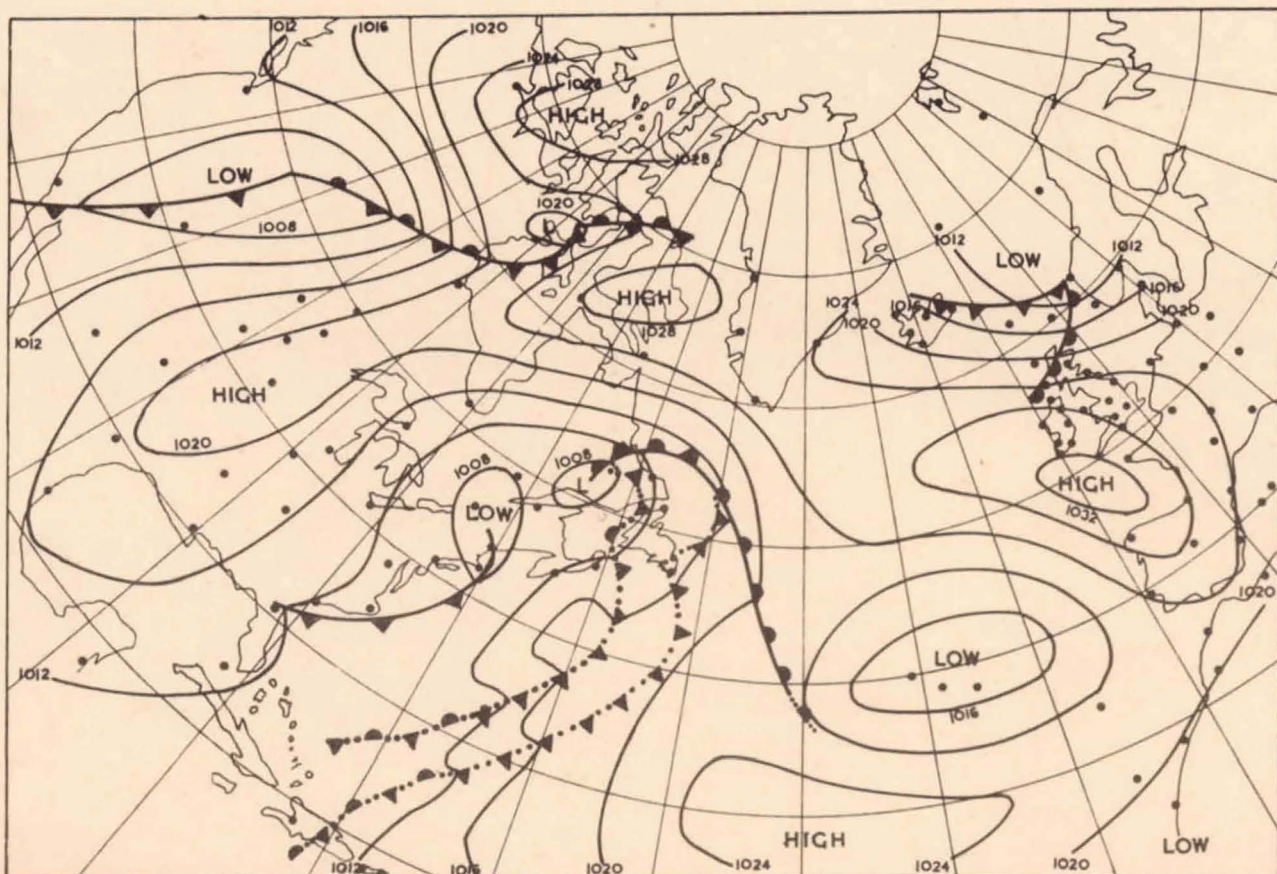


Fig. 2a. Mean Sea Level chart - 1300 G.M.T. Monday 12th May 1941

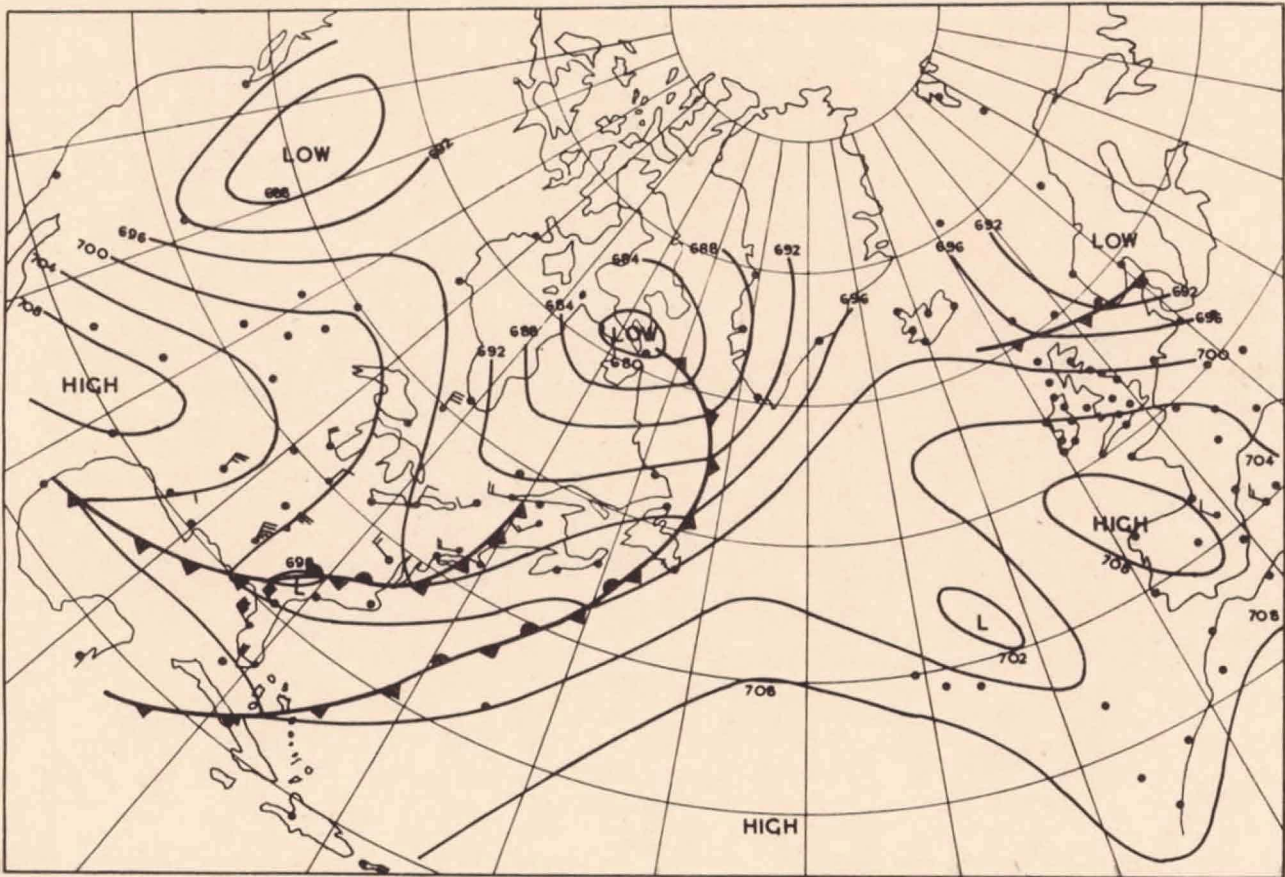


Fig. 3. 10000 ft. chart - 1300 G.M.T. Tuesday 13th May 1941

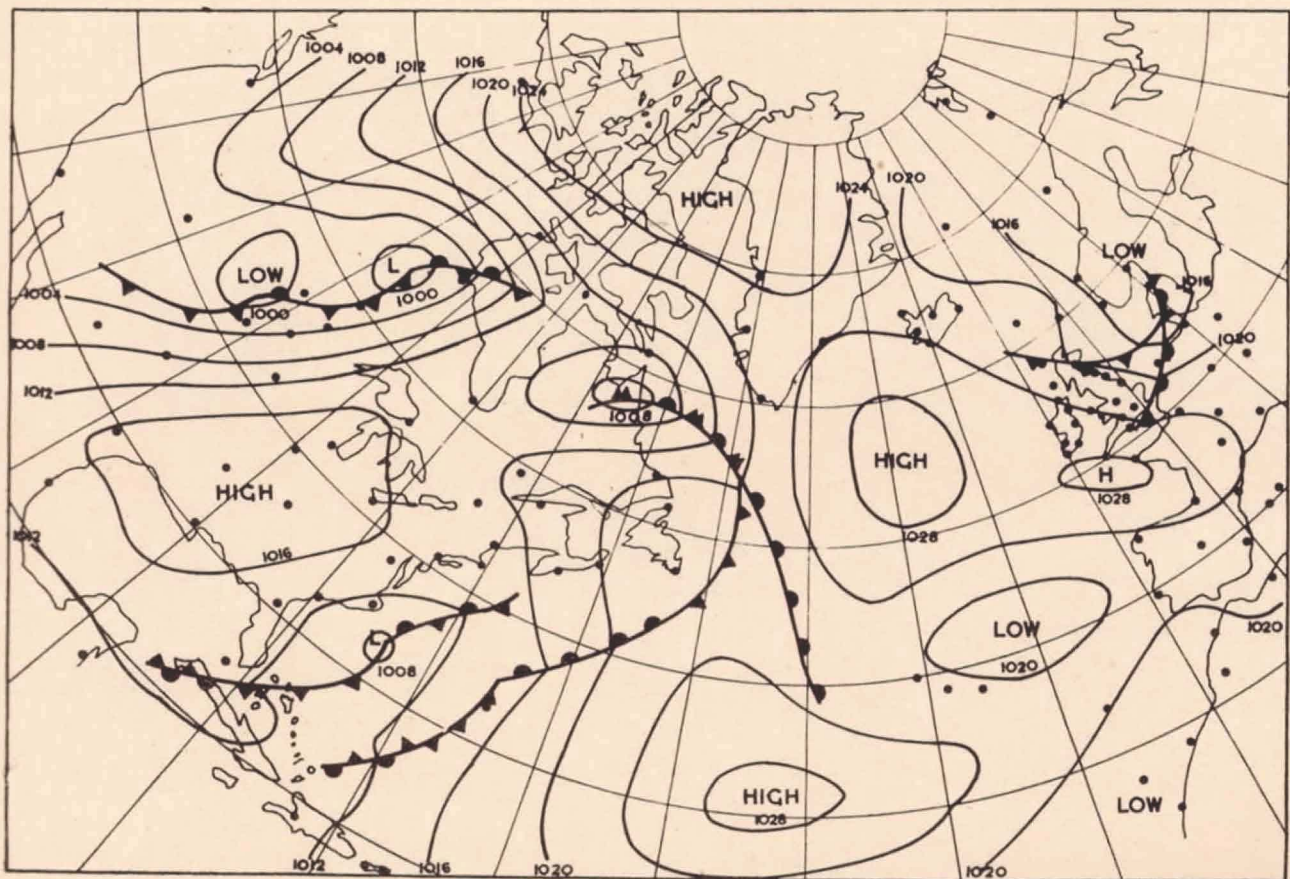


Fig. 3a. Mean Sea Level chart - 1300 G.M.T. Tuesday 13th May 1941.

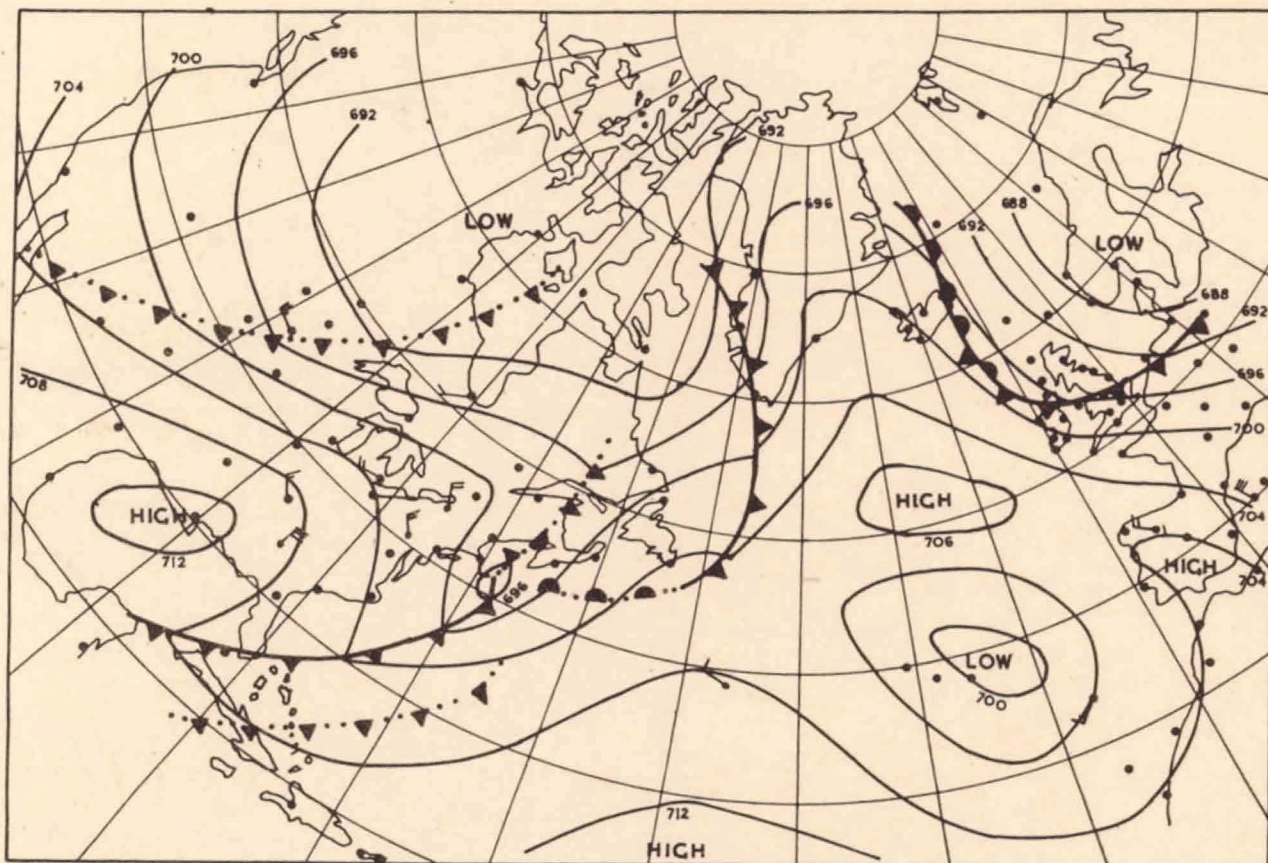


Fig. 4. 10,000 ft. chart - 1300 G.M.T. Wednesday 14th May 1941.

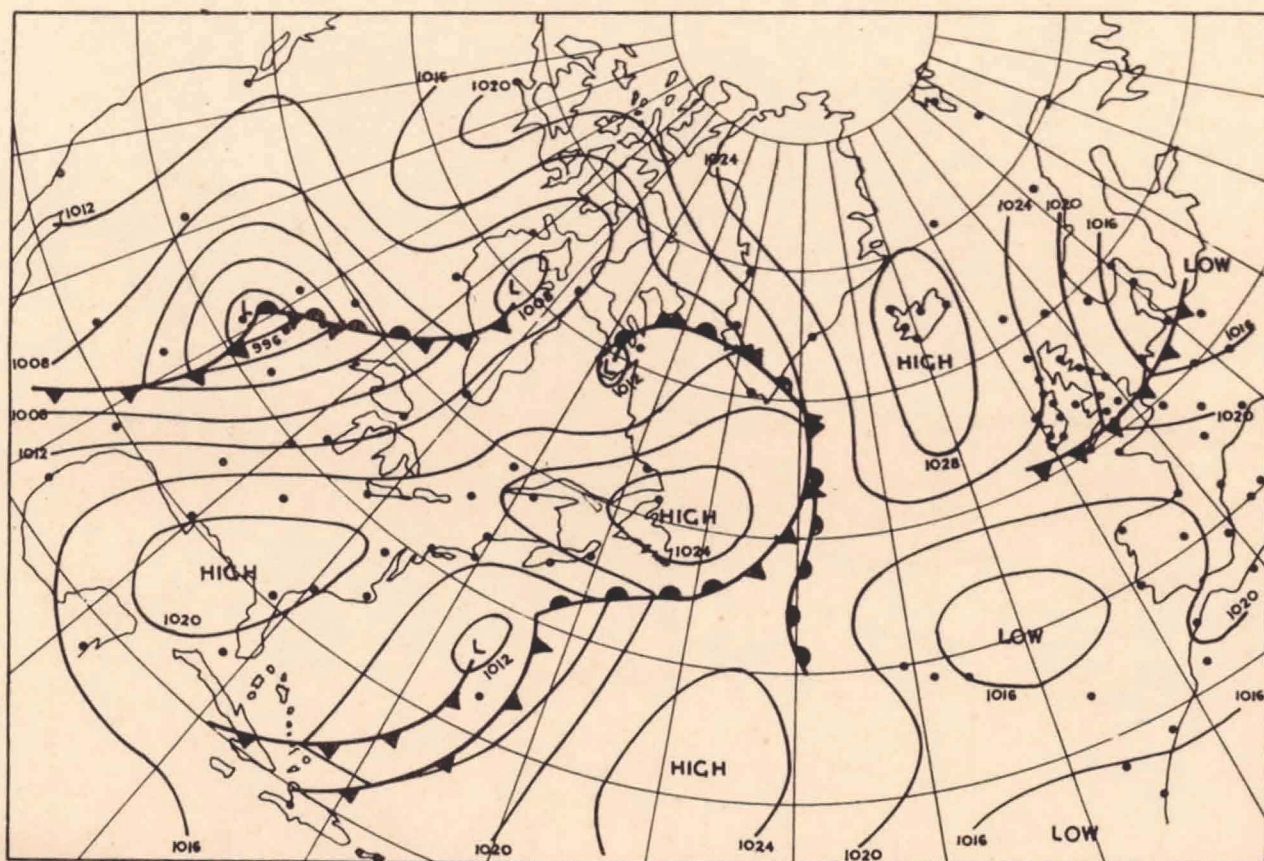


Fig. 4a. Mean Sea Level chart - 1300 G.M.T. Wednesday 14th May 1941.

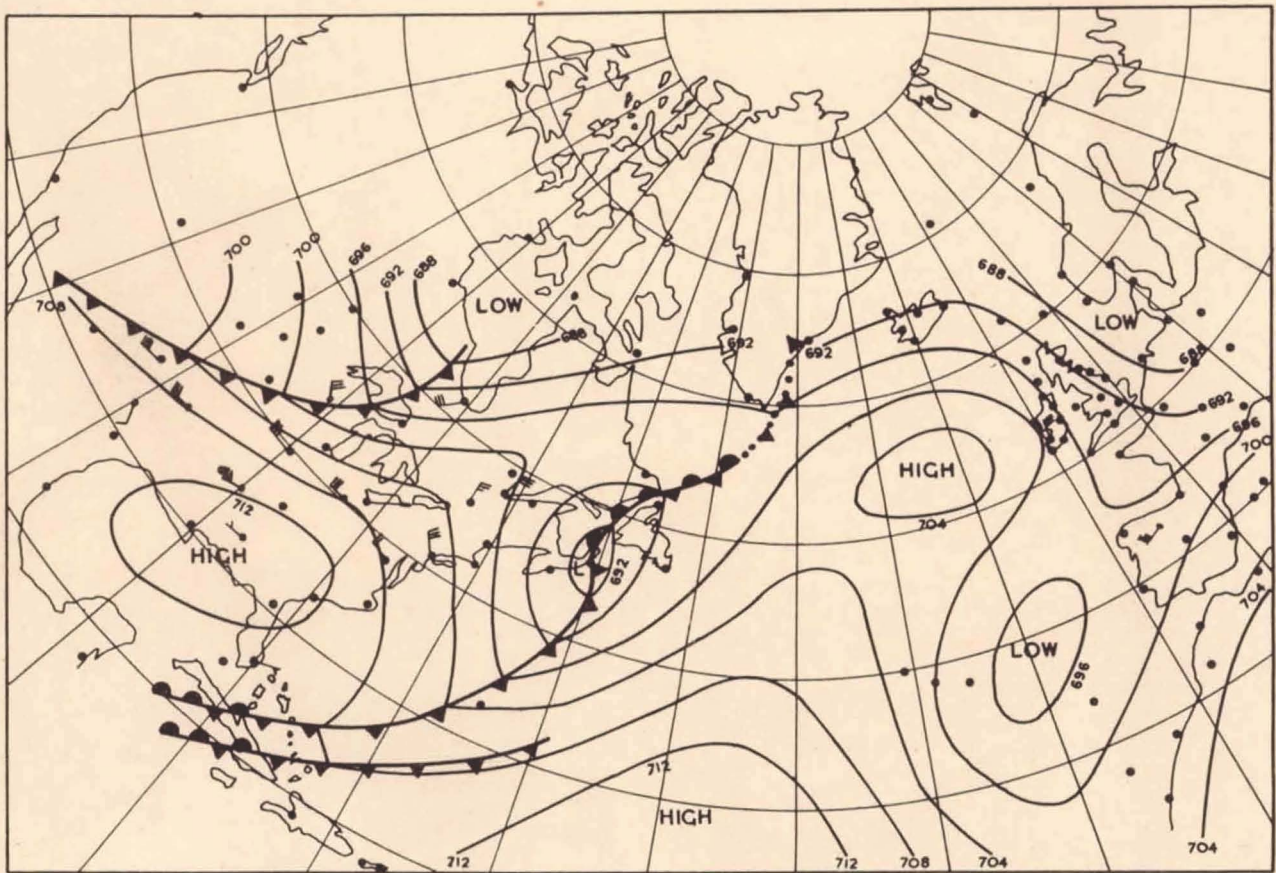


Fig. 5. 10000 ft chart - 1300 G.M.T. Thursday 15th May 1941.

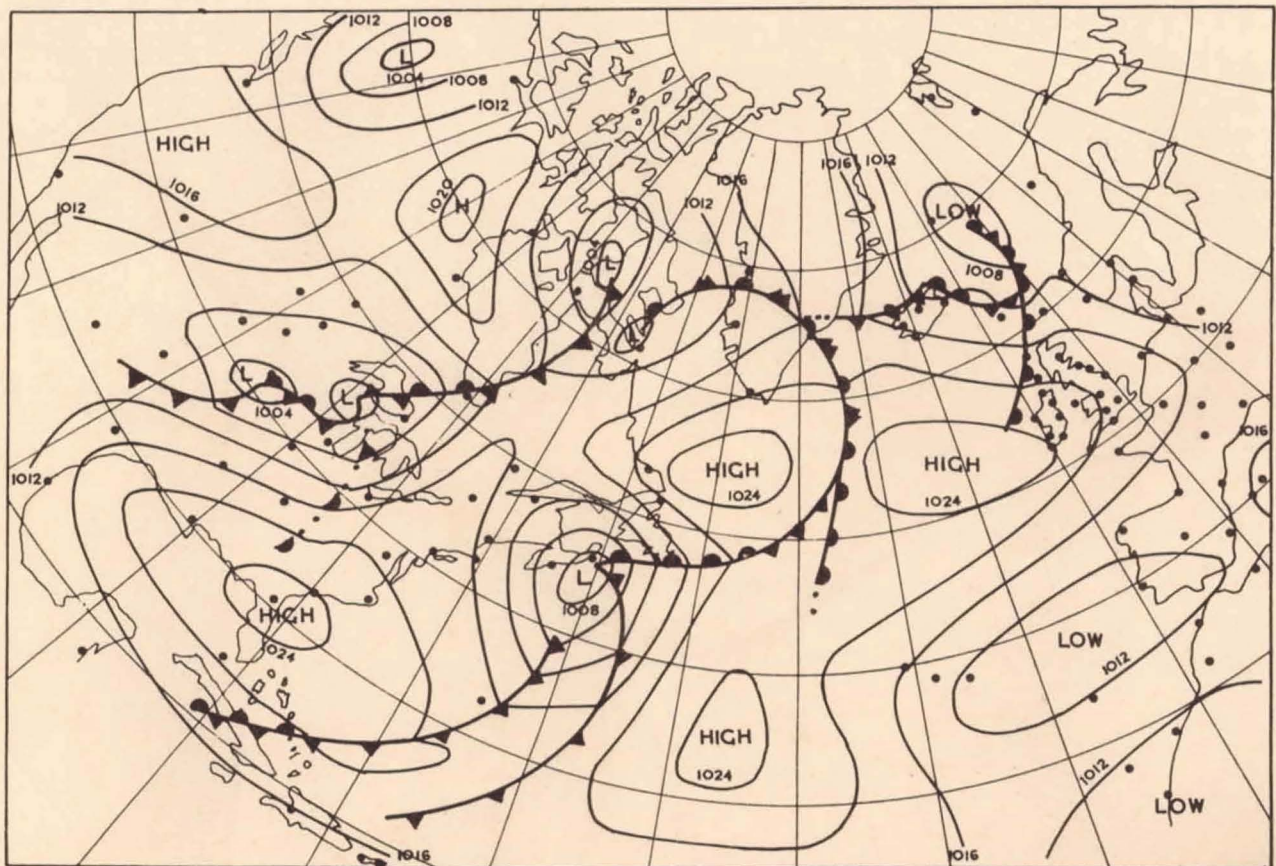


Fig. 5a. Mean Sea Level chart - 1300 G.M.T. Thursday 15th May 1941

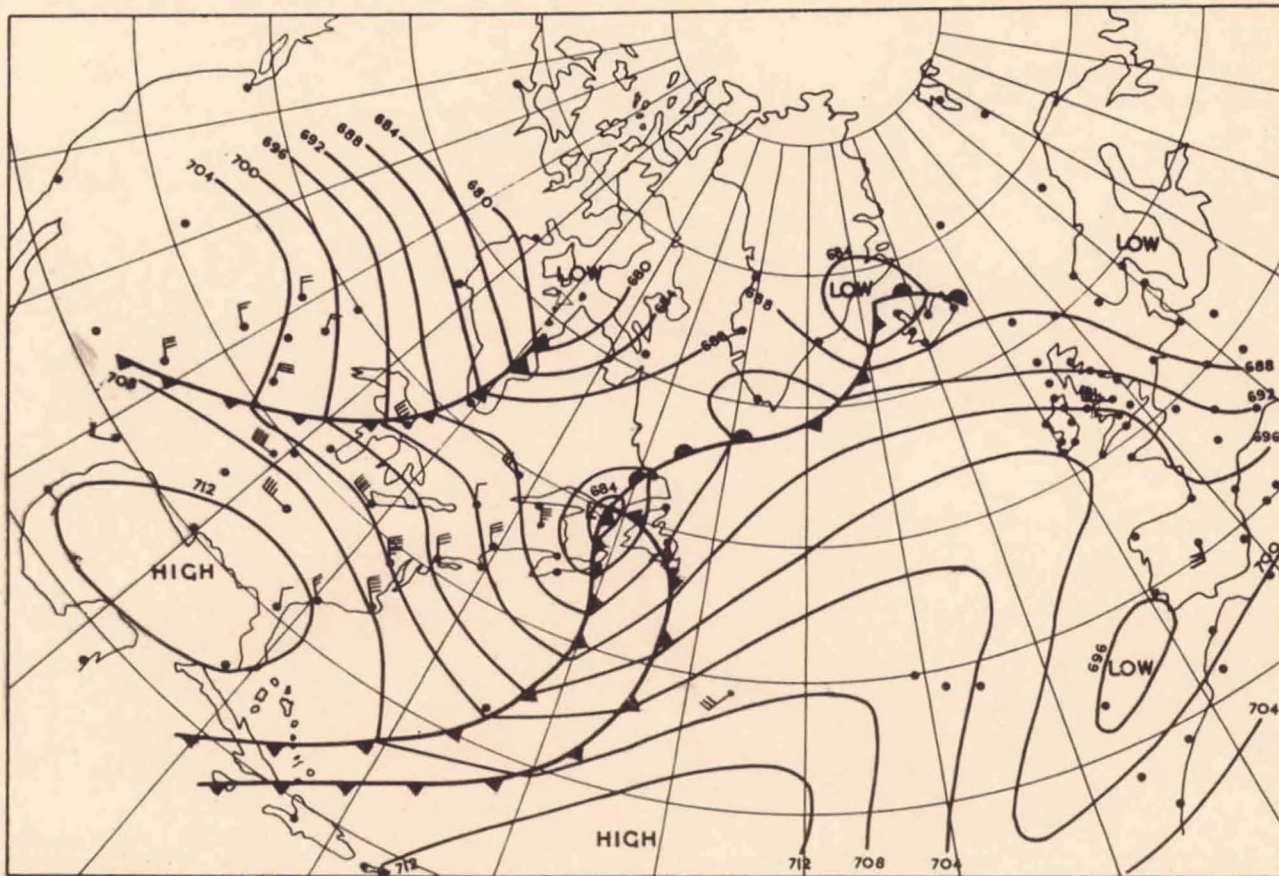


Fig. 6 10,000 ft. chart - 1300 G.M.T. Friday 16th May 1941

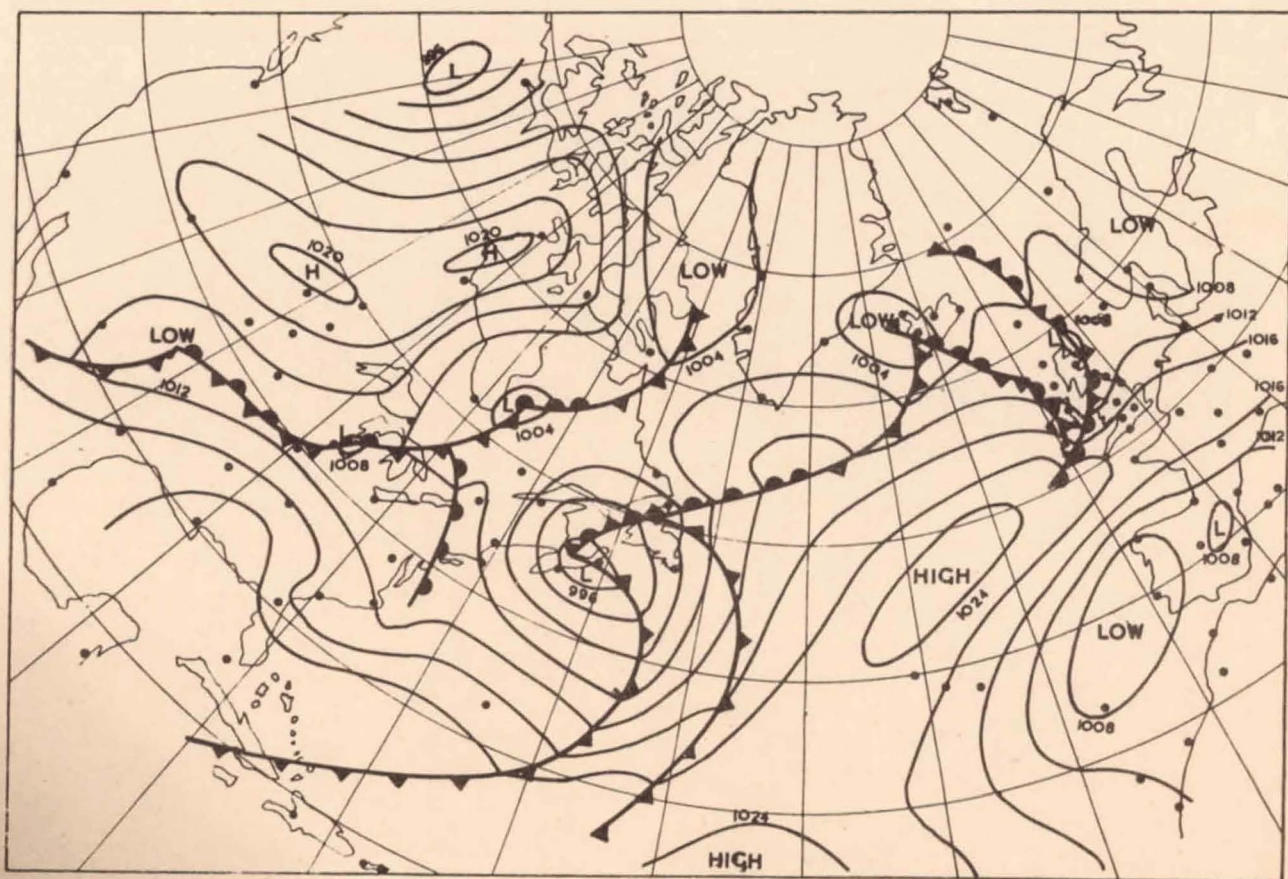


Fig. 6a Mean Sea Level chart - 1300 G.M.T. Friday 16th May 1941.

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