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by

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"SYNOPTIC PROPERTIES OF FRONTAL SURFACES"

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Introduction .

The tremendous impact of frontal analysis techniques on weather forecasting will be denied by no one. There has, nevertheless, been a growing tendency to feel that such techniques have already been exploited to the full, to the partial exclusion of more recent developments and techniques such as the long-wave theory, the jet stream, and thickness and differential analysis. However, a swing of the pendulum to the other extreme would be equally undesirable. Indeed, a critical appraisal of the results obtainable from a complete three-dimensional frontal analysis reveals that such an analysis can contribute greatly to these newer techniques. In this paper, the value of a complete frontal analysis and the underlying significance of the frontal concept will first be discussed, followed by a review of the physical and mathematical properties of frontal surfaces on which the various possible applications of frontal techniques are founded.

Significance of Frontal Analysis

1. In general it may be said that the frontal concept provides a physical basis for forecasting through its entities which are capable of prognostication on non-kinematic grounds. Thus, both physical and mathematical aids are available as direct and indirect results of frontal theory.

2. More specifically, the frontal theory provides a highly flexible model of the structure, motion, and development of both pressure and weather systems. This makes possible the co-ordination and integration of upper air data into a consistent picture of the atmosphere and clarifies the close relationship that exists between pressure systems on the one hand and weather systems on the other.

3. The existence of fronts appears to be a fundamental property of the large-scale operation of the atmosphere. For example, the isolation of cold domes and warm pockets and the transformation of air masses are required in order to balance the latitudinal gradient of net surface radiative flux. Furthermore, the concentration of baroclinicity and the jet stream maximum associated with the polar front arise in a manner very imperfectly understood but still of obvious dynamic importance.

4. Frontal analysis provides both physical and mathematical aids for semi-mechanical techniques of analysis of upper level charts. This applies both to current and prognostic charts when prepared by either ab initio or differential means. Such analyses are especially important near fronts where gradients of temperature and contour height are large and where their second order space derivatives are also large. It may be noted that accurate chart analyses are particularly vital for dynamic computations in such regions. Examples are Sutcliffe's thermal vorticity development theorem

and my own dynamic instability criteria, both of which find their chief application in frontal regions where they are rather critical with respect to the construction of chart isopleths.

5. The motion and development of fronts and frontal waves are directly linked to the problem of pressure changes. This arises in the first place by reason of the concentration of horizontal temperature and density advection in regions of frontal surfaces. This relationship is especially valuable when differential analysis techniques are being used to co-ordinate surface and upper level prognostic charts. The behaviour of fronts is further linked to pressure pattern development because of the interrelation between frontal wave development and cyclogenesis. A complete three-dimensional frontal analysis is particularly useful in those cases when frontal waves commence at intermediate tropospheric levels rather than at the surface. One further fact to note in this connection is the presence of surface pressure troughs at the positions of upper cold and upper warm fronts. Clearly, the motions of these upper fronts may be forecast more readily from upper air data than the motions of the surface troughs from surface data.

6. From a study of the structure of incipient frontal waves there may be deduced clues for changes in the long-wave pattern aloft, especially in the development of a new trough to shorten the existing wave length. The region of such changes will be reflected in a region of maximum wave development since the polar front is linked, through its associated thermal pattern, with pressure changes aloft. Moreover, a consideration of frontal development aloft provides a basis for forecasting the cut-off and possible later re-assimilation of cold domes and their attendant cold lows, which exert a strong steering influence on nascent cyclones at lower levels. Studies such as these therefore indicate regions where the long-wave pattern is being stabilized through the formation of cut-off cold lows and warm highs, as well as those regions in which a blocking mechanism is being initiated.

7. A complete frontal analysis assists greatly in locating the jet stream, either approximately through the 550 mb position of the polar front or more directly through the assistance offered in differential analysis to 300 mb in such regions. Aids to the forecasting of the motion and development of jet streams are also available since the motion of the 550 mb front can be evaluated independently. In addition, an estimate can be made of any significant change of frontal slope, which is linked through the baroclinic field to the magnitude of the jet stream maximum. This is especially valuable in regions where cold domes may be cut off, to the north of which a new jet stream may then appear.

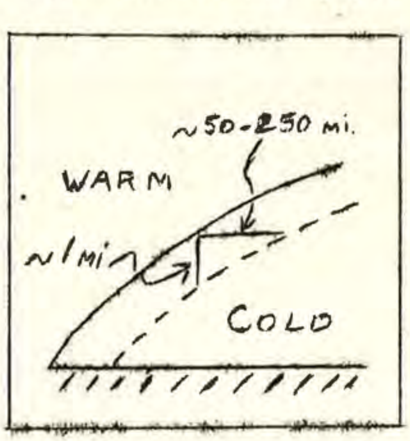
8. Finally, frontal contour charts themselves may be utilized for the computation of vertical motions immediately above and below all frontal surfaces, embracing the regions of greatest weather interest. The

same technique leads to a consistency check between forecast values of wind speeds and frontal speeds and the qualitative assessment of vertical motions.

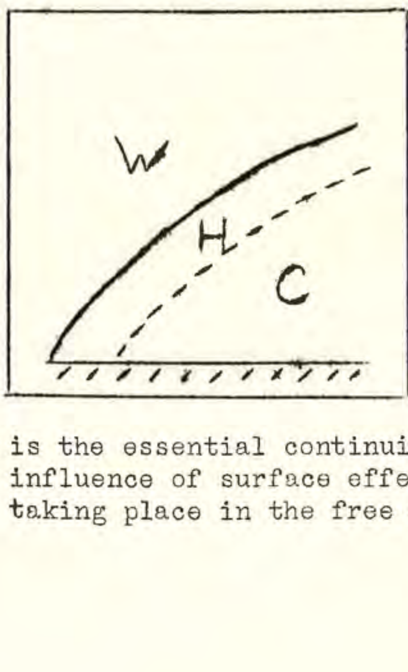
In order to make full use of these valuable concepts and in order to effect a complete three-dimensional frontal analysis from all available data, it is necessary to know in some detail the physical and mathematical properties of frontal surfaces.

Fundamental Properties of Frontal Surfaces

1. A frontal surface is a sloping three-dimensional zone of maximum baroclinicity (horizontal rate of change of temperature), separating two air masses of much lesser baroclinicity. This zone has dimensions of the order of 100 mb (~1 mi.) in depth and 50-250 mi. in width. This zone is relatively stable to all mixing processes--in the vertical because of the very stable lapse rate and in the horizontal because the effects of stable lapse rate, cyclonic horizontal shear and cyclonic curvature exceed the destabilizing influence of the strong vertical wind shear. Thus the term frequently applied to this zone--mixing zone--is definitely a misnomer, suggesting continual weakening instead of the maintenance observed. This zone is also frequently termed a transition zone.

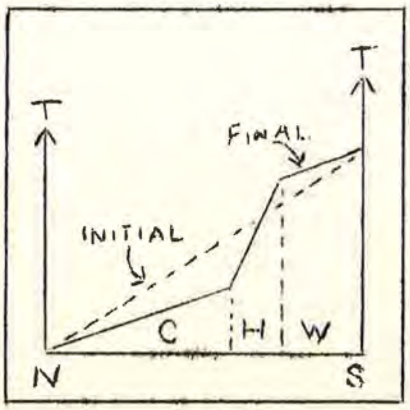


Physically speaking, this term is not appropriate since appreciable modification will seldom be taking place. Mathematically speaking, the term suggests gradation of properties such as is actually observed. This gradation is the chief property of the zone and since the zone represents an intensely baroclinic state, the most appropriate name for the zone would seem to be 'hyperbaroclinic (H) zone'. The term 'frontal zone' is best reserved for the case of a broad baroclinic zone without sharp boundaries such as is occasionally observed during the transition of a cold air mass to a warm one, or vice versa, immediately prior to the re-institution of a normal frontal surface in a new location.

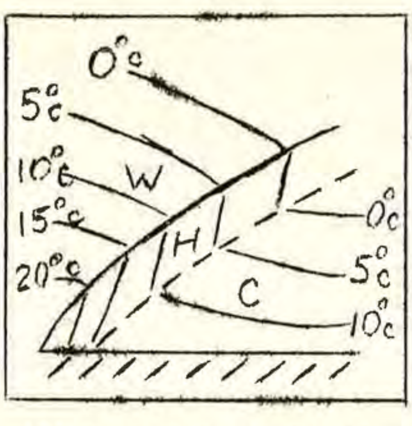


2. Another fact of great importance is the essential continuity in space and time of frontal surfaces above the influence of surface effects, despite the mixing processes which must be taking place in the free atmosphere. Actually, it appears that these mixing

processes are effective chiefly in the separate air masses themselves, weakening the temperature gradients in the air masses and strengthening the horizontal temperature gradients in the zone of weak mixing power --the hyperbaroclinic zone. This explanation is remarkably similar to the one proposed by Rossby for the existence of the jet stream, which is intimately linked to the frontal model through the hydrostatic and thermal wind equations, as Palmén has demonstrated.



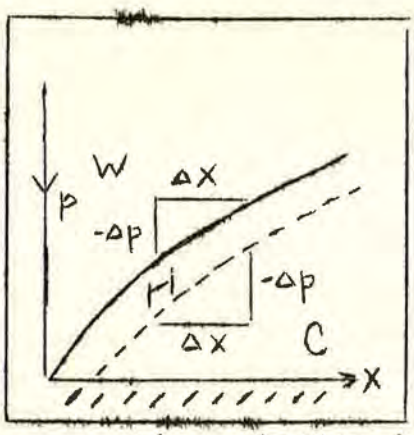
3. At each boundary surface there is a two-dimensional first order temperature discontinuity, i.e., a zeroth order discontinuity of temperature gradient along any direction in any vertical plane through which the frontal surface has a non-zero slope. This mathematical property may be thought of as a necessary and sufficient condition for the existence of a frontal surface, when combined with the requirement that the zone be essentially continuous in space and time.



4. As a direct consequence of this first order temperature discontinuity it may simply be deduced that there will be (a) A zeroth order discontinuity in the orientation of isotherms; (b) A second order discontinuity in the pressure or contour height; (c) A first order discontinuity in pressure or contour height gradients, i.e., in the geostrophic wind direction and speed; (d) A zeroth order discontinuity in isobar or contour curvature. The full implication of these results will be outlined shortly.

5. The isobaric slope of a frontal surface, using pressure as the vertical co-ordinate, may be defined as:

$$m_p = -\frac{\Delta P}{\Delta X}$$



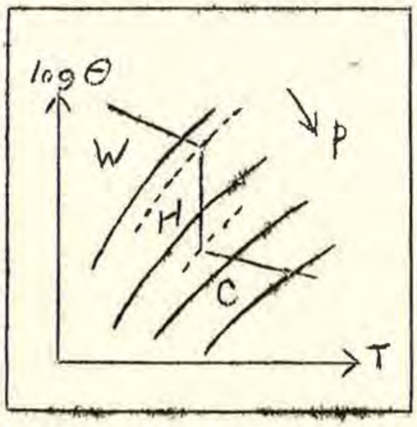
defining the X axis as being at right angles to the front at any level, and directed from the warm air to the cold. Using the concept of a first order temperature discontinuity, there follows:

$$m_p = \frac{\beta'_H - \beta'_W}{\gamma'_W - \gamma'_H} = \frac{\Delta\beta'}{\Delta\gamma'},$$

where $\beta' = -(\partial T/\partial x)_p$ and $\gamma' = \partial T/\partial p$, all quantities being normally positive except γ'_H for a temperature inversion in that zone. $\Delta\beta'$

and $\Delta\gamma'$ are the corresponding discontinuities in the temperature gradients themselves.

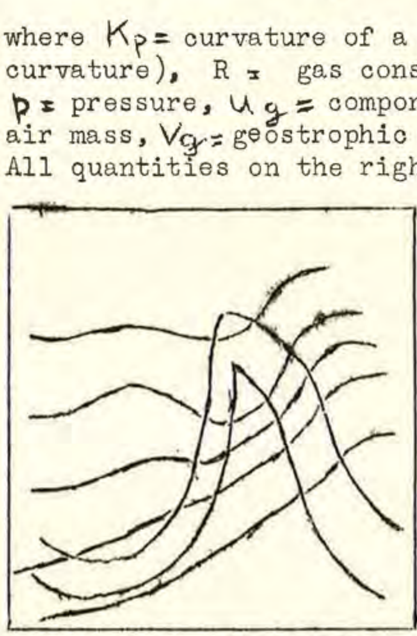
It may be seen that for a steep front (e.g. a normal cold front) $\Delta\beta'$ will be relatively large and $\Delta\gamma'$ will be relatively small. For a shallow front (e.g. a normal warm front) $\Delta\beta'$ will be relatively small and $\Delta\gamma'$ relatively large. On a tephigram the lapse-rate discontinuity, $\Delta\gamma'$, can be seen directly; thus the tephigram analysis of a warm front will generally be simpler than that of a cold front. On a wind hodograph the discontinuity in vertical wind shear, proportional to $\Delta\beta'$ because of the thermal wind relation, can be seen directly; thus the hodograph analysis of a cold front will often be simpler than that of a warm front. The significant fact that emerges is that, for the purposes of a complete three-dimensional frontal analysis, tephigram and hodograph analyses are valuable complementary tools. Furthermore, frontolysis cannot be assumed to have taken place unless both vertical and horizontal discontinuities have become weak, as revealed by tephigram and hodograph analyses.



6. From the basic postulate of a first order temperature discontinuity there may be derived the following equation for the discontinuity in contour (or isobar) curvature at a front:

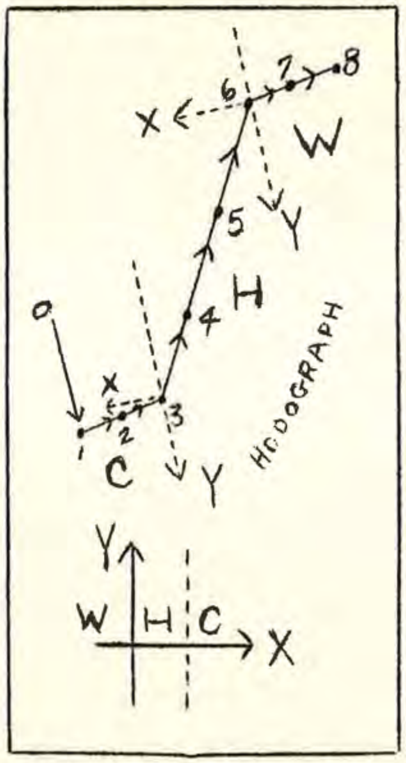
$$K_{p_H} - K_{p_W} = \frac{m_p R u_g^2}{\ell_p V_g^3} (\beta_H' - \beta_W')$$

where K_p = curvature of a contour line ($= 1/R_p$ where R_p = radius of curvature), R = gas constant for air, ℓ = coriolis parameter ($2\Omega \sin\phi$), p = pressure, u_g = component of geostrophic wind directed toward the cold air mass, V_g = geostrophic wind speed ($m_p = -\Delta p/\Delta x$, $\beta_H' - \beta_W' = \Delta\beta'$ as before). All quantities on the right will be positive so that, since K_p is positive for cyclonic curvature and negative for anti-cyclonic curvature, it follows that the contours will have greater cyclonic curvature in the hyperbaroclinic zone than in the warm or cold air masses proper. To this requirement must be added the proviso that the orientation of the contours is not discontinuous at the two frontal boundaries.



Now: $m_p\Delta\beta'$ is large for a steep (e.g., cold) front and small for a shallow (e.g., warm) front. Thus cold fronts in the lower levels will exhibit a very large discontinuity in curvature, the theoretical U-type trough being almost indistinguishable from a conventional V-type trough. Conversely, shallow warm fronts in the surface layers may exhibit virtually no curvature discontinuity, as is the case with southerly winds in both the warm and cold air masses. In general, a cold front will be found in advance of a relatively sharp and narrow U-trough; whereas a warm front will be found to the rear of a relatively weak and broad trough, and at times the hyperbaroclinic zone curvature may be actually anticyclonic, with stronger anticyclonic curvature in the separate air masses.

7. From the quasi-homogeneous air mass concept it is clear that the temperature gradient along a front at any level will be small; this quantity will also be continuous across the front. The temperature gradient normal to the front will frequently be relatively large in the warm and cold air masses, especially so close to the front, and very large in the hyperbaroclinic zone. From these statements, making use of the thermal wind equations, it may be deduced that:



(a) The thermal wind in the warm and cold air masses will often be approximately parallel to the front and will be of a moderate magnitude above and below the frontal surfaces if the air masses are definitely baroclinic.
(b) The thermal wind in the hyperbaroclinic zone will be even more closely parallel to the frontal orientation and will be notably stronger than the thermal winds for layers above and below.
(c) The vertical shear of the wind component perpendicular to the front will be continuous. From this fact, the orientation of a front may be deduced from a hodograph.
(d) The vertical shear of the wind component parallel to the front will be discontinuous and from this discontinuity $\Delta\beta'$ may be computed, using the relation:

$$\frac{\partial v_{gH}}{\partial p} - \frac{\partial v_{gW}}{\partial p} = \frac{R}{\ell p}\left(\beta'_H - \beta'_W\right)$$

For comparable values of $\Delta\beta'$, this shear discontinuity will be greater at low latitudes than at high latitudes.

8. It follows that a single-station analysis of a simultaneous rawinsonde ascent will reveal:

(a) Pressure (or height) levels of both boundary surfaces from tephigram and hodograph plots.
(b) $\Delta\delta'$ for both boundary surfaces from the tephigram plot.
(c) Orientation of both boundary surfaces from the hodograph plot.
(d) $\Delta\beta'$ for both boundary surfaces from the hodograph plot.
(e) m_p for both boundary surfaces from values of $\Delta\gamma'$ and $\Delta\beta'$.

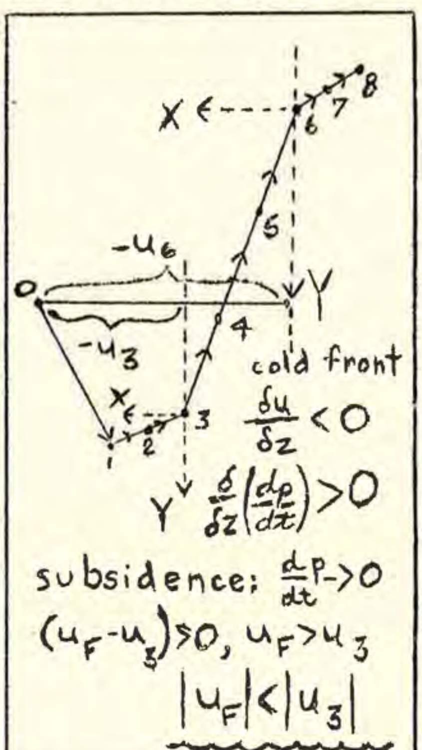
Computations of frontal slope may well be advantageous in oceanic areas, or areas only sparsely covered by upper air data. Elsewhere it will be sufficient to abstract the levels and orientations of frontal surfaces, and obtain frontal slopes if required from the isopleths on the final frontal contour chart.

9. The frontal hyperbaroclinic zone is quasi-substantial in nature, i.e., it is composed of essentially the same air particles at different times. This is an assumption, which is certainly justifiable as a first approximation at least. As a result of this postulate, it follows that the vertical motion, defined with respect to pressure as the vertical co-ordinate, is given as:

$$\frac{dp}{dt} = m_p \left(u_F - u\right)$$

where u_F is the frontal speed, normal to the front, and is positive for a warm front and negative for a cold front.

10. It will be apparent that no independent forces act to move a frontal surface, so that its motion is completely determined by the horizontal and vertical velocities of air at the frontal surfaces. In other words, u_F is the dependent variable in the above equation and cannot be considered as an independent variable. The vertical velocity is determined solely by the integrated divergence or convergence up to the level in question, i.e., in the cold air below the frontal surface. "Overrunning" is thus a physical state, but not a physical process.



11. The slope, speed, and orientation of the upper and lower hyperbaroclinic zone boundary surfaces are nearly identical, as would be expected unless excessive horizontal divergence or convergence exists. As a result, the chief variations in the vertical through the zone are those of u and dp/dt, permitting valuable qualitative deductions from a single wind sounding through a frontal surface.

It is known that dp/dt generally increases numerically with height up to the level of non-divergence (about 600 mb, on the average), in the absence of significant orographic effects. Thus if a front is below 600 mb, $|(u_F - u)|$ at the lower surface is less than $|u_F - u|$ at the upper surface. Moreover:

$$\frac{\delta}{\delta z}\left(\frac{dp}{dt}\right) \simeq -m_p \frac{\delta u}{\delta z} \simeq \frac{dp}{dt} \times \text{variable positive parameter.}$$

Thus the sign of the vertical motion can be assessed and a rough correction could be applied to u at the lower level in order to obtain the speed of the front.

If actual values of the vertical velocities are desired, it is necessary to evaluate m_p and u_F from frontal contour charts.