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CYCLONIC AND ANTICYCLONIC DEVELOPMENT

By R. C. SUTCLIFFE, Ph.D.

[Manuscript received April 21, 1939]

SUMMARY

Development of pressure systems involves horizontal divergence (positive or negative) approximately balanced by divergence of opposite sign in the upper troposphere, the total divergence integrated vertically and represented by the rate of change of surface pressure being a relatively small residual. It follows that a criterion for development is that there should be a significant difference between the lower and upper fields of divergence. Divergence is determined by the field of geostrophic departure or acceleration and it is shown that the difference between lower and upper divergence consists of two parts due respectively to shearing and to the development of thermal gradients. Rules concerning the distribution of surface divergence and convergence in different pressure and temperature distributions are inferred and a method of approaching the problem of forecasting on a three-dimensional basis is put forward.

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1. INTRODUCTION

With the present and expected growth in the volume of current aerological data placed in the hands of the forecasting services the practical possibility of attacking the general problem of development on a systematic three-dimensional basis is rapidly approaching. While some progress has already been made elsewhere, notably in Germany and America, the lack of adequate information has so far precluded similar work for the British Isles. The present purpose is to present a novel line of inquiry of a purely dynamical nature and to show that it has practical possibilities for forecasting.

2. THE GENERAL PROBLEM

On the basis of his classical correlation coefficients for variables in the free atmosphere W. H. Dines (1914 and 1925) observed that if some agency could be introduced to account for divergence of air above the developing depression and convergence above the anticyclone, within the upper troposphere, the observed statistical facts would have an explanation " satisfactory and complete in all respects." This pronouncement has been overshadowed in recent work by the success of the frontal and air mass conceptions, which has been achieved in spite of the inadequacy of dynamical theory, and it has been left largely to German workers to apply Dines' suggestion to the practical problem. Scherhag (1934) originated what is now known as his " divergence theory " and arrived at the proposition that " divergent upper winds must produce in general a fall of pressure if they are not compensated by a strong convergence below." His ideas have given rise to a considerable literature where strong claims to their practical value have been put forward (see for example Rodewald (1938)) although they have met with some criticism (see Baur and Philipps (1936)) and the present writer has so far been unable to accept his criterion for upper divergence which appears to be simply fanning of the upper isobars. If, however, the term divergence is used in its ordinary mathematical sense Scherhag's discussion is most important as re-emphasizing the dynamical aspects of the problem and we would go even further and give full weight to Dines' insight with the proposition: " divergence in the upper troposphere is both necessary and sufficient for cyclonic development, convergence for anticyclonic development."

In addition to Dines' decisive statistical evidence there is other powerful support both theoretical and observational.

One of the most important features of the development of a pressure system is divergence or convergence in the lower troposphere closely connected with the isallobaric field (Brunt and Douglas (1929)). Brunt (1939) estimates that in a developing anticyclone, with only weak isallobaric gradients, the divergence accounts for subsidence at the rate of about 1 km. per day. This if uncompensated would cause the general pressure to fall by some 100 mb. per day. Apart from being of the wrong sign this is altogether of greater magnitude than the observed rate of change of pressure. In the developing depression isallobaric gradients are much larger and the low-level accumulation of air would if uncompensated by divergence above lead to considerably larger pressure changes. It follows then that development involves convergence at different levels and that the total effect as represented by the rate of change of hydrostatic pressure at the surface is a relatively small residual. Neither the lower nor the upper member of the dynamical system can exist without the other and if a field of divergence (or convergence) can be recognised in the upper atmosphere the associated lower convergence (or divergence) completing the scheme of cyclonic (or anticyclonic) development must occur automatically.

The meaning of the loose term " upper atmosphere " may be narrowed to the " upper troposphere." This is almost *a priori* obvious since the lower troposphere is occupied by the lower member of the field of divergence and the large mass concentration can hardly be balanced by motion in the tenuous air of the stratosphere. Observation definitely proves that the tropopause marks an effective limit to vertical motion and so confines the greater part of the whole mass divergences to the troposphere. Some writers may still propose to explain the low pressure of the depression by the advection of a warm and " light " stratosphere ignoring the vital fact that mere changes of density are of small account compared with the much larger dynamic effects. Incidentally, although the stratosphere of the depression is as a rule warm it is not " light " for the weight of the stratospheric air is given by the pressure at the tropopause which in the depression is considerably above the normal. A depression generally has a heavy stratosphere and again to quote Dines (1922) " it is the mass of air which is important; its temperature is quite immaterial." In what proportions this additional mass in the stratosphere is due to advection and to convergence is not decided, but in any case it can hardly have much control upon the large amounts of divergence and convergence which take place below. It is, however, likely that if divergence occurs primarily in the upper troposphere it would involve convergence both above and below. There might well be convergence of velocity at a higher level of similar magnitude to that near the surface and whether observed ozone concentrations may be accounted for in this way is a question upon which the author would welcome opinion.

The practical problem is to diagnose divergence or convergence in the upper troposphere and the following method is put forward.

3. THE INVESTIGATION OF UPPER CONVERGENCE AND DIVERGENCE

As was stressed in a previous paper (Sutcliffe, 1938) a geostrophic wind system has no divergence and the divergence is given by the field of geostrophic departure, or, ignoring turbulence, by the field of acceleration. The problem then is to investigate the acceleration in the free atmosphere. The geostrophic departure is proportional to the acceleration and directed at right angles to it, to the left in the northern hemisphere.

Divergence of course depends on the horizontal derivatives of the geostrophic departure, but the general nature of the field of divergence will normally be given by inspection of the field of departure.

Let V be the vector wind at any height and V_0 be the " surface wind " taken above the frictional layer. V_s is defined by the vector equation

$$V = V_0 + V_s$$

and will be called the shear.

Then

$$\frac{dV}{dt} = \frac{dV_0}{dt} + \frac{dV_s}{dt}$$

where

$$\frac{d}{dt} \equiv \frac{\partial}{\partial t} + V \,.\, \nabla \equiv \frac{\partial}{\partial t} + V_0 \,.\, \nabla + V_s \,.\, \nabla$$

substituting

$$\begin{aligned} \frac{dV}{dt} &= \frac{\partial V_0}{\partial t} + V_0 \,.\, \nabla V_0 + V_s \,.\, \nabla V_0 + \frac{dV_s}{dt} \\ &= \left(\frac{dV}{dt}\right)_0 + V_s \,.\, \nabla V_0 + \frac{dV_s}{dt}. \qquad . \quad . \quad . \quad . \qquad (1) \end{aligned}$$

where $(dV/dt)_0$ is the surface acceleration.

Now, in accordance with section 2, development consists of upper and lower divergences of opposite sign and it follows from equation (1) that the divergence represented by the acceleration terms $V_s \,.\, \nabla V_0$ and dV_s/dt, which vanish at the surface and increase with height, must in the upper troposphere overbalance that represented by the surface effect $(dV/dt)_0$. If the field of $(V_s \,.\, \nabla V_0 + dV_s/dt)$ indicates upper divergence there must of necessity be lower convergence represented by $(dV/dt)_0$ and cyclogenesis. Upper convergence shown by the same terms similarly implies lower divergence and anticyclonic development. It is sufficient, therefore, to consider the field of $V_s \nabla V_0 + dV_s/dt$ alone. In other words it is proposed to investigate the difference between the upper and lower fields of divergence rather than either one considered alone. This is the essentially novel feature of the analysis.

$V_s . \nabla V_0$ represents the effect of the upper wind shearing over the surface wind and will be called the shearing term. In quasi-geostrophic motion V_s is the thermal wind and dV_s/dt will be called the thermal development term.

Equation (1) is not an artificial mathematical resolution of the upper acceleration but expresses the physical fact that in general where there is shearing of the upper wind over the lower or where the temperature gradients are changing it is dynamically impossible for the motion to be balanced at both levels, that is dV/dt and $(dV/dt)_0$ cannot vanish simultaneously; there must be development either above or below, and the further interaction between the two levels required by continuity and the hydrostatic transmission of pressure leads to either cyclonic or anticyclonic development.

It may be noted in passing that the normal reversal of thermal gradients in the stratosphere should cause V_s to decrease with height and the divergence defined by $V_s . \nabla V_0 + dV_s/dt$ should decrease possibly leaving at greater heights an effect determined mainly by $(dV/dt)_0$ and therefore of the same sign as that at the surface. This would involve considerable high level convergence and subsidence in the stratosphere of the depression, the reverse over the developing anticyclone, as suggested on general grounds in section 2.

4. METHOD OF APPLICATION TO GENERAL PROBLEMS

The practical application of the ideas to particular occasions is left for later investigation but to demonstrate the possibilities certain general problems will be considered. The process of reasoning is quite straightforward and very rapid once the general ideas are grasped.

(*a*) Estimate the direction of the upper acceleration component $V_s . \nabla V_0$ or dV_s/dt as the case may be, where its magnitude is pronounced.

(*b*) Estimate the direction of the corresponding upper geostrophic departure—at right angles and to the left of the acceleration vector.

(*c*) From the general distribution of these departures locate the regions of upper convergence or divergence.

(*d*) Assume that these indicate anticyclonic or cyclonic development with the accompanying divergence or convergence respectively at low levels.

5. THE EFFECT OF SHEARING—THE TERM $V_s . \nabla V_0$.

Case 1.—*Shearing across a surface trough of low pressure.*

(*a*) *Upper winds over-running the surface winds.*—This is the common case since troughs usually extend from colder to warmer regions.

Taking V_s perpendicular to the trough line, $V_s . \nabla V_0$ is directed along the trough line towards the low pressure. The corresponding component of geostrophic departure therefore is perpendicular to the trough and opposes V_s. This implies upper divergence ahead of the trough and upper convergence behind, that is surface convergence ahead and divergence behind.

Now it is certainly true that most troughs whether of cold or warm front variety or non-frontal do give evidence of surface convergence ahead—forward shearing supplies the explanation.

(*b*) *Upper winds lagging behind the surface wind.*—Cases of opposing shear are surprisingly rare and would be worth special investigation. They should tend to show surface convergence behind the trough and divergence ahead.

(*a*) and (*b*) may be combined in the rule that lower convergence at a trough should tend to occur on the side towards which the thermal wind is directed.

Case 2.—Shearing across a wedge of high pressure.

In this case it is shown directly that low-level divergence at a wedge should tend to occur on the side towards which the thermal wind is directed—a very well-known feature of wedges over the British Isles.

It will be noted that in general there is a tendency for cyclonic development near a trough and for anticyclonic development near a ridge, on the side towards which the thermal wind is directed. In other words, both trough and ridge will tend to move by development in this direction—the control which high level winds appear to have on the travel of surface pressure features is well known.

Case 3.—Shearing along a trough.

In this case $V_s . \nabla V_0$ becomes significant when the pressure gradient along the surface trough line varies.

(*a*) *Warm front type of trough.*—The upper shear is then outwards from the low pressure. It is easy to show that over a part of the trough which has a minimum of gradient the upper geostrophic departures associated with $V_s . \nabla V_0$ converge, there must be low level divergence in sympathy.

Similarly, a rapidly moving part of the trough tends to be one of surface convergence and cyclogenesis. This deduction agrees with the fact, not otherwise easily explained, that secondaries on warm fronts form where the front is moving comparatively rapidly and bulging towards the cold air.

(*b*) *Cold front type of trough.*—Here the opposite holds. A portion of a cold frontal trough which is moving relatively slowly tends to suffer convergence and cyclogenesis—where it is moving relatively rapidly it tends to suffer divergence. The failure of cold front rain where the cold front is moving rapidly and bulging forward has long been recognized.

6. THE EFFECT OF THERMAL DEVELOPMENT—THE TERM dV_s/dt

In general the rate at which the thermal wind is changing may be difficult to estimate but there are certain cases in which the nature of the change is obvious.

Case 4.—Local heating.

Over an area subject to heating there is an increasing thermal wind in the upper air of anticyclonic direction. The corresponding geostrophic departure is outwards from the area giving upper divergence. The corresponding low-level convergence completes the process of cyclonic development. This problem is perhaps equally well interpreted on simple isallobaric grounds but is usefully introduced here to show that our process of reasoning arrives at the same result. Apart from direct heating latent heat liberated by condensation may have the same effect and the mechanism by which general vertical instability may produce a cyclonic depression is perhaps so explained. It is suggested that it is not the kinetic energy of instability represented by area on an aerological diagram which is converted by some obscure mechanism into circulatory motion but that the liberated thermal energy has the same effect as local heating. The probability that upward motion, by introducing a significant factor $w\,(\partial/\partial z)\,V_s$ into $(d/dt)\,V_s$, may result in dynamical instability and general deepening of a simple thermal depression has been dealt with elsewhere (Durst and Sutcliffe, 1938).

In addition to heating, either by radiation or condensation, thermal development may take place by distortion of the isotherms accompanying the field of motion.

Case 5.—A current of warm air moving rapidly towards a region of relatively cold and stagnant air—say a warm frontal zone approaching an anticyclone.

Here the crowding of the isotherms gives a component $(d/dt)\,V_s$ directed along the isotherms with the colder side to the left. The corresponding geostrophic departure is directed from warm towards cold giving in the upper air convergence towards the colder side, divergence on the warmer side, and requiring as a necessary accompaniment, low-level divergence on the colder side and convergence on the warmer side. Although this scheme does not give the finer points of warm front structure it brings out the essential feature—surface divergence in advance and convergence behind the zone of transition. It likewise affords a simple intelligible explanation of the fact that a warm front becomes very active if it is " obstructed " by a cold anticyclone or a slowly moving ridge—in this case a depression occludes rapidly—whereas if the cold air is running away freely in advance causing no crowding of the isotherms the transitions from cold to warm air may occur with little disturbance.

Case 6.—Temperature increasing up-wind.

In this case there will tend to be surface convergence where the wind speed normal to the isotherms is relatively large, divergence where it is relatively small. Thus with a normal temperature gradient southerly winds which increase southwards indicate the approach of a cyclonic disturbance whereas southerly winds which decrease southwards indicate the approach of anticyclonic conditions.

Case 7.—Temperature decreasing up-wind.

Here the opposite tendency appears. There will tend to be surface convergence where the wind speed normal to the isotherms is relatively weak, divergence where it is relatively strong. Thus in a polar current a local weakening of the gradient is a sign of cyclonic development. As another example, a cold outbreak approaching a warm anticyclone implies surface convergence and cyclogenesis ahead, surface divergence and anticyclogenesis behind, and the warm anticyclone tends to collapse as pressure builds up in the cold air.*

7. CONCLUSION

It has been shown that the method of analysis leads directly to certain rules many of which are already known on empirical grounds and it is claimed that a case has been made out for applying the same ideas to routine forecasting when observational data permit. The most promising line is to plot out for some convenient level of the upper troposphere the thermal wind distribution V_s—the relative pressure profile as plotted in Germany achieves this. By studying the terms $V_s . \nabla V_0$ and $d/dt\, V_s$, presumably an approachable problem at any rate in well defined cases, the possibility of explaining and ultimately anticipating developments will be decided.

The general problem will be complex; in particular it will be necessary to bear in mind the possible importance of convergence and divergence, vertical motion and thermodynamical processes in determining the thermal development but there is scope for extensive research before the limitations or possibilities will be decided.

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* The increase or decrease of temperature gradients by distortion of the isotherms may be regarded as covered by the generalised terms "frontogenesis" and "frontolysis," but, in considering the three-dimensional dynamical development, it is preferable to avoid these terms which, it is felt, are more properly restricted to the special problem of the development and degeneration of surface discontinuities.