

This suggests that the basic idea underlying the notion of a cutoff could in principle be more precisely defined in terms of IPV distributions. As far as we can see, such a definition would be entirely consistent with the traditional synoptic view of the essential phenomenon, taking other evidence into account such as wind and temperature fields (cf. Fig. 15) together with observational case studies of the time development of the cutting-off process. For instance section 10.1 of Palmén and Newton (1969, p. 274) describes the birth of a large cutoff cyclone from the cold "polar-source region", with which, at a certain stage of development, "it is still united by an 'umbilical cord' in the form of a shear line". From the information presented it appears that the stage of development referred to is fundamentally similar to that shown in our Fig. 5 for 23 September 1982, even though the orientation, geographical location, and other details are different.

Palmén and Newton describe the polar-source region as 'tropospheric' (*loc. cit.*, and top of p. 284). However, it has become increasingly clear, both from examples like that of Fig. 5 and from the theoretical principles reviewed in this paper, that this concept requires modification if one is interested in questions of dynamical cause and effect. For dynamical purposes an important part of the polar-source region is Kleinschmidt's lower-stratospheric reservoir of high-PV air. At least in cases like that of Fig. 5, the observed development appears to be largely controlled by long-range, quasi-isentropic advection of high-PV air from the lower-stratospheric reservoir. The word 'controlled' is used deliberately here, its use being justified by the invertibility principle. Whereas low temperature advection, for instance, may well appear important from a purely diagnostic point of view in, say, the middle troposphere ahead of the moving IPV anomaly, it can be argued that in terms of cause and effect its importance is actually secondary, in such cases, by comparison with that of IPV advection at higher altitudes. This is because much of the coldness of the free atmosphere beneath the IPV anomaly is attributable to the induced temperature field of the anomaly. As such, it *cannot be advected anywhere* unless

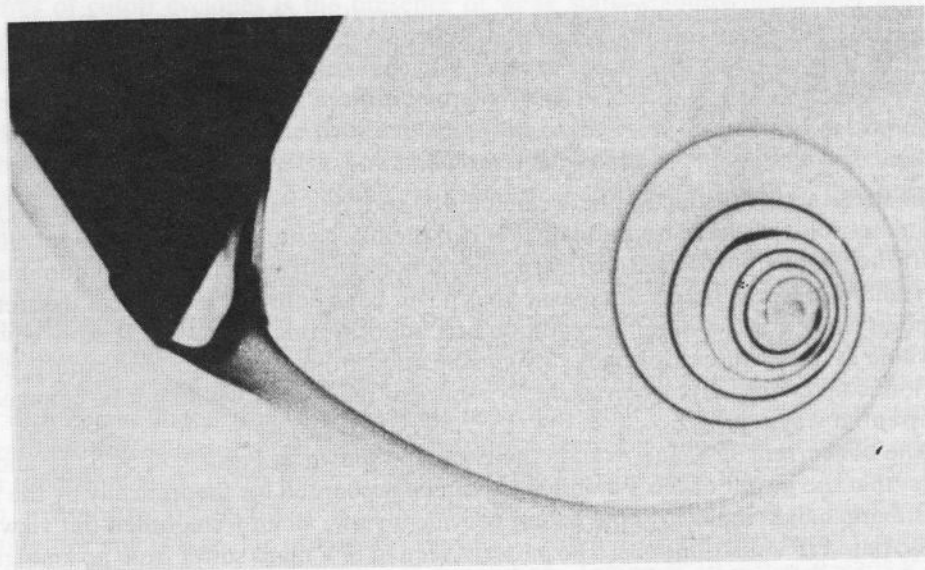


Figure 22. A standard fluid-dynamical experiment showing barotropic vortex rollup visualized by dye injection (Pullin and Perry 1980). A piston, not shown, drives water from left to right with almost constant speed normal to the axis of a wedge of  $30^\circ$  semi-vertex angle; the wedge acts as a source both of dye and of vorticity.

the anomaly is itself moving in the direction concerned. The point made in section 4 about the compensating effects of vertical motion is relevant here. Temperature advection near the ground is, of course, an entirely different matter, a fact which is related to the constraining effect of the earth's surface upon large-scale vertical motion and which has already been illustrated in several ways in section 5.

The phenomenon of cutting off exemplified in Figs. 5 and 11 appears to have counterparts in classical aerodynamics. Figure 22 shows what appears to be an aerodynamical (barotropic) counterpart to the 24 September panel in Fig. 5, as far as the cutoff cyclone and its presumed 'umbilical cord' are concerned. The figure, taken from a paper by Pullin and Perry (1980), represents a laboratory photograph using the dye method of flow visualization; the dye roughly marks high vorticity values (although the vorticity diffuses faster than the dye). The spatial resolution is, of course, far greater than that of Fig. 5, and the 'umbilical cord' shows up clearly. This type of flow is known to be accurately described by the barotropic vorticity equation, with a diffusive term included.

Features common to the aerodynamical and meteorological cases are the existence of a source of cyclonic (potential) vorticity fluid on the left, advection of cyclonic (potential) vorticity fluid from left to right, and a tendency for the furthest part of the (potential) vorticity distribution to *wind itself up* (a concept justifiable in terms of the concept of 'induced velocity field') into a compact, nearly axisymmetric vortex. Aerodynamicists use the term 'vortex rollup' to describe the phenomenon, and it has been extensively studied; see, e.g., p. 590 of the textbook by Batchelor (1967), and for more detail the review by Saffman and Baker (1979). The main difference between the two cases lies in the nature of the source region, which in the laboratory case is the boundary layer on a solid, wedge-shaped obstacle, seen at the left of the photograph, but in the meteorological case is Kleinschmidt's stratospheric reservoir of high-PV air. Also, in the atmospheric case there may well be much less spiral fine-structure in the IPV distribution than Fig. 22 might suggest, because of the different initial conditions. (And even if such structure were initially present—as was suggested in section 2(d) for another case—it would tend to be destroyed by small-scale quasi-barotropic shear instabilities.)

## 9. CONCLUDING REMARKS

Perhaps the central point we have tried to bring out in this paper is the way in which the IPV concept succinctly encapsulates all the balanced dynamics usually described in terms of advection, divergence and vertical motion. IPV thinking gives direct insight, for example, into the circumstances in which the effects of advection and vertical motion tend to cancel each other; recall again the thought-experiment described in section 4. Especially for quasi-conservative processes involving rapid advection of upper air synoptic-scale features (sections 2(c), 6(e)), IPV thinking has considerable potential for furthering our understanding of the behaviour of real weather systems. Moreover, the invertibility principle suggests that the IPV concept should remain useful even in the presence of moist or dry diabatic heating or cooling (sections 6(e), 7), along with other non-conservative effects such as friction and gravity-wave drag. As was pointed out in section 4 the crucial advantage of IPV maps over, say, isobaric absolute vorticity maps, is the conceptual separation they offer between the effects of advection on the one hand, and the effects of vertical motion on the other.

The use of coarse-grain IPV maps together with surface  $\theta$  maps should lead not only

