# THE USE OF POTENTIAL VORTICITY AND LOW-LEVEL TEMPERATURE/MOISTURE TO UNDERSTAND EXTRATROPICAL CYCLOGENESIS

Michael McIntyre
Department of Applied Mathematics and Theoretical Physics
Silver St, Cambridge CB3 9EW, U.K.

## 7. THE SIMPLEST KIND OF CYCLOGENESIS, THE "VACUUM-CLEANER" EFFECT, AND AN INTERESTING CASE OF A FAILED FORECAST

The simplest conceivable kind of cyclogenesis occurs when an single upper-air IPV (IPT), or surface PT, anomaly is advected into the region of interest, from some other location where its surroundings make it less "anomalous". The invertibility principle, as applied to isolated anomalies like those in §5, tells us that the arrival of a single such anomaly has to be accompanied by the arrival of its induced wind, vorticity and static-stability structure -- for example, in the case of an upper-air anomaly and no low-level anomaly, by a structure like that shown in Fig. 5. Bleck (1974, Fig. 2) gives a three-dimensional graphical depiction of this process, following Kleinschmidt. In the real atmosphere one has to add a frictional boundary layer, but its effects are seldom drastic enough to change the basic picture, especially if we are dealing with rapid upper-air advection.

Fig. 10 shows some coarse-grain IPV maps from operational analyses, taken from HMR, in a real case giving a fairly clear example of essentially this kind of cyclogenesis (20-25 September 1982). Low-level PT anomalies seemed to be relatively unimportant in this case. An upper-air anomaly, consisting of high-PV stratospheric air, was advected from near Hudson Strait across the Atlantic towards Europe, and appeared to roll itself up into a large cutoff cyclone (at 18°W on 24 Sept.) having a structure like that of Fig. 5. The resulting surface cyclone is prominently visible near the centre of the top left panel of Fig. 11, the ECMWF surface analysis for

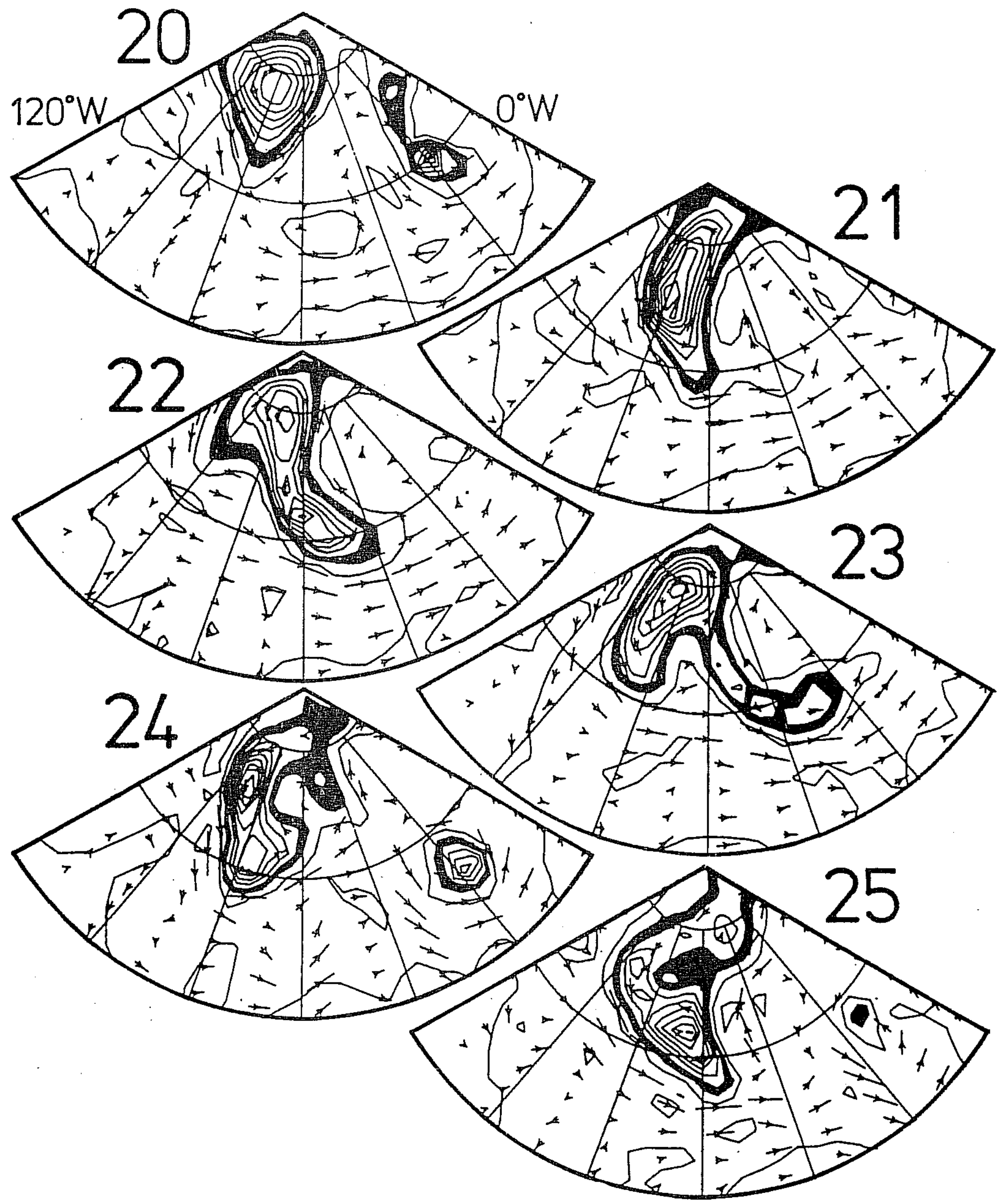



Fig. 10 300 K isentropic maps of PV for 20-25 September 1982, from ECMWF operational analyses. Latitude circles are 40°N, 60°N and 80°N; Greenwich meridian on the right, 120W on the left. Contour interval is 0.5 PVU, with 1.5 to 2 PVU blacked in, locating the tropopause. Wind arrows on the 300 K surface are scaled such that an arrow drawn northward from 40°N to 60°N would indicate a speed of 100 m $s^{-1}$.

24 September 1982.

The vertical motion field has to fit in with these events. Consider an air parcel in the lower troposphere ahead of the cyclone -- imagine it, say, near 800mb at the edge of Fig. 5 -- and suppose that it subsequently gets caught up in the advancing cyclone. If diabatic and frictional contributions are negligible, the parcel must clearly ascend, since it has to ride some way up the relevant isentrope as it enters the cyclone. The

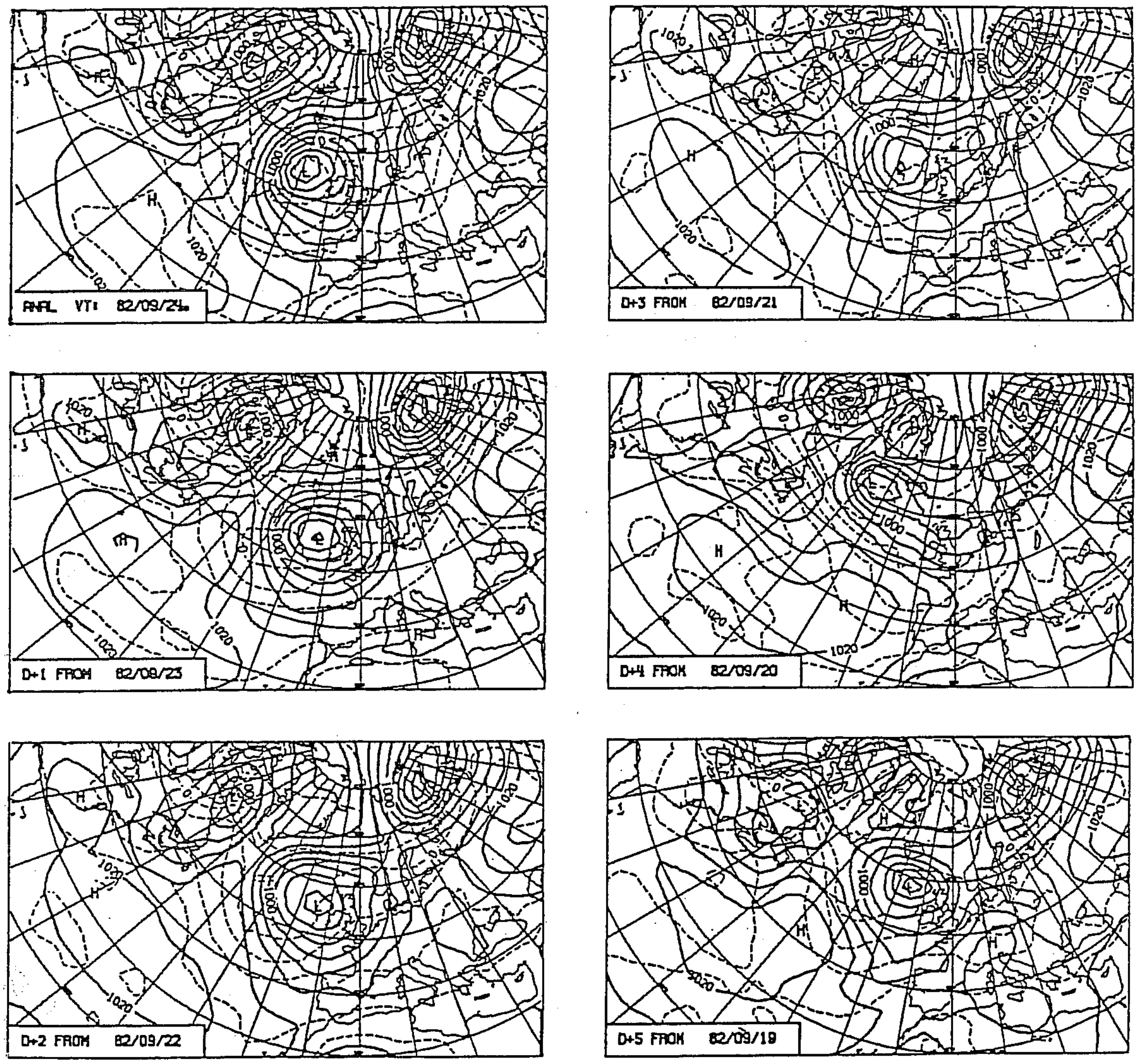



Fig. 11 ECMWF sea-level pressure (solid contours) and 850mb temperature (dashed contours) analysis for 24 September 1982 (top left), and five forecasts for that day from 23, 22, 21, 20 and 19 September. Contour intervals 5 mb and 5 K.

uphill slope of the isentrope is a qualitatively robust part of the structure induced by the moving upper anomaly; any other shape compatible with the IPV distributions would be impossibly far out of balance -- the apparent "action at a distance" again, cf. §2. The same ascent stretches vortex lines below the upper anomaly, and spins up the lower part of the cyclone.

In summary, other contributions aside (see HMR, appendix), it is as if a cyclonic upper anomaly, advancing relative to the atmosphere below it, is "acting on the underlying layers of the atmosphere somewhat like a rather broad, very gentle 'vacuum cleaner', sucking air upwards towards its leading portion" (HMR §4),

in just such a way as to give rise (so to speak) to the vorticity and temperature anomalies that comprise the induced flow structure in those underlying layers. The vertical-motion signature produced by this "vacuum-cleaner effect" is well known in synoptic meteorology. It is the basic reason why cloud and precipitation tend to form more or less on the advancing side of a cyclone; some case studies are cited in HMR §4. The strength of the effect is evidently related to the IPV anomaly strength and to the speed of upper-air advection relative to the lower layers. Among "other contributions", there may be some degree of reinforcement from frictional convergence and from the propensity of the northward induced wind field ahead of the cyclone to ride up the large-scale poleward slope of an isentrope (e.g. HMR eq. A11). Much stronger reinforcement, in many cases, will come from latent-heat release.

The "vacuum-cleaner effect" just described is, of course, nothing other than what is sometimes called the quasigeostrophic "forcing" of vertical ascent and surface-cyclone development by an advancing cyclonic structure, another of whose characteristics is positive upper-air vorticity advection. Despite the terminology the effect is not dependent, of course, on the quasigeostrophic approximations. In principle it can be computed much more accurately.

Fig. 10 suggests something interesting about the ECMWF operational forecasts shown in the remaining panels of Fig. 11. It can be seen that the east-Atlantic surface cyclone discussed above was reasonably well forecast from 1, 2, 3 and 5 days before 24 September, whereas the 4-day forecast was much worse (middle right panel). The initial condition for the 4-day forecast corresponds to the top left IPV map in Fig. 10. We may hypothesize that a slight error in, say, the length of the left-hand "trough" or cyclonic feature in that map could easily have been made in the analysis, and could easily have accounted for the bad forecast. It seems obvious that such an error could critically affect the precise amount of high-PV air subsequently advected from the polar stratosphere, to form the IPV anomaly that induced the cutoff cyclone. It would be of great interest to run suitable transplant experiments (e.g. Hollingsworth et al. 1985, §5d), concentrating on the region surrounding the tip of the IPV trough, in order to test this hypothesis.

## 8. SIMPLE REINFORCEMENT (THE ORR EFFECT)

The next simplest kind of cyclogenesis may occur when an upper-air anomaly like that of Fig. 5 is advected over a surface anomaly like that of Fig. 6. Even if nothing happens to strengthen the PV or PT amplitudes of the anomalies themselves, their induced fields will tend to constructively interfere, i.e. to reinforce. The fields are strictly additive only in the quasigeostrophic approximation, for which the inversion operator is linear; but the idea of reinforcement is qualitatively valid under realistic conditions (Thorpe 1986). The reinforcement can be significant if the two anomalies are not too far apart vertically, in comparison with the relevant Rossby height

$$H \sim f_e L/N \,. \tag{8.1}$$

Here L is a horizontal scale, N is another measure of static stability, the buoyancy or Brunt-Väisälä frequency, and $f_e$ is an effective local Coriolis parameter, of the order of the geometric mean of the local absolute vorticity and twice the local angular velocity. (In cyclones like that of Fig. 5, $f_e$ may be quite a bit bigger than f itself.) The Rossby height gives the vertical scale H of structures induced by isolated PV or PT anomalies, in terms of their horizontal scale L. H is relevant also, therefore, to the effectiveness at the earth's surface of the simplest kind of cyclogenesis described in the previous section. The estimate (8.1) assumes that H is not much greater than the atmosphere's density scale height (HMR §3 gives more general estimates).

Simple reinforcement between the induced fields, as the given upper and lower IPV or PT anomalies come into phase, is enough in itself to cause eddy energy to increase, in addition to strengthening surface winds and deepening surface pressure. This eddy energy growth, and the associated nonzero energy conversions, do not mean that instability is involved. Instability, in the classical sense of Charney, Eady and their successors, involves growth in the amplitudes of the IPV or surface PT anomalies themselves, as well as in all other variables. The theoretical concept that corresponds most closely to simple reinforcement of the fields due to given IPV or PT anomalies is a different one, sometimes referred to as the

"Orr effect". It has recently been studied by Brian Farrell using linearized, quasigeostrophic theory, in the work cited in §3 of Brian Hoskins' first lecture in this volume. Simple reinforcement, as distinct from instability, can clearly be an important factor in real cases of cyclogenesis.

## 9. INSTABILITY AND PHASE LOCKING

The distinguishing feature of classical instability is, as already stated, amplification of the IPV or surface PT anomalies themselves. The way this happens in classical instability scenarios involves an interesting phase-locking mechanism, which also appears to be involved, in a less clear-cut form, in some cases of real cyclogenesis, as we shall see. The phase-locking mechanism is itself a consequence of the Rossby-wave phase propagation mechanism described in §2 and Fig. 1.

Fig. 12, taken from HMR, shows the simplest kind of anomaly pattern that

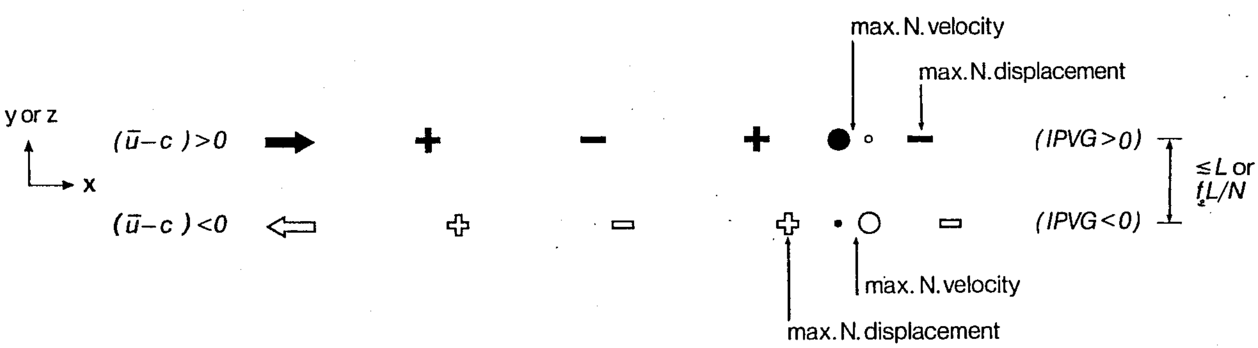



Fig. 12 Pattern of IPV anomalies typical of the simplest barotropic and baroclinic instabilities on a zonal shear, the sense of the shear being indicated by the broad arrows at the left. The frame of reference has been chosen to move with the wave pattern. The basic IPV gradients (IPVG) are positive at the top and negative at the bottom of the picture. The solid black dots indicate (for the right-hand-most half wavelength) the location of a maximum in the northward velocity induced by the upper IPV pattern alone. The open dots indicate the same thing for the lower IPV pattern. The transverse dimension is northward (y) in the case of the barotropic instability, and upward (z) in the case of the baroclinic instability. Intermediate, "mixed" instability cases also exist, to which precisely the same kind of pattern is relevant when viewed in tilted coordinates. For the fastest growing instabilities, the phase shift between the two IPV patterns is usually larger than that shown.

exhibits phase-locking and PV amplification. It represents either a baroclinic instability wave of the general sort first studied by Eady (in which case it may be compared to Fig. 3 of Brian Hoskins' first lecture), or a barotropic instability wave of the type already encountered in Fig. 3e. The two halves of Fig. 12 can be thought of as comprising a pair of counterpropagating Rossby waves, one above the other in the case of baroclinic instability, or side by side in the case of barotropic instability.

They are "counterpropagating" in two senses. The first is that their intrinsic phase speeds (i.e. relative to the basic flow) are opposite to each other, the top one being towards the left, and the bottom one towards the right. This is because two opposite-signed basic IPV gradients are involved (or the equivalent surface PT gradients), marked "IPVG > 0" and "IPVG < 0" in Fig. 12. The second sense of "counterpropagating" is that both propagate against the local basic flow (which therefore has to be a shear flow in the sense shown by the broad arrows on the left of Fig. 12, consistent with the standard integral theorems on necessary conditions for instability).

In the situation shown in Fig. 12, it is not hard to see that the induced velocity field of each Rossby wave partially reinforces that of the other (see caption). The effect of each wave is therefore to increase the magnitude of the other's intrinsic phase speed. In other words, each Rossby wave is actually helping the other to propagate against the basic flow, faster than it would do so by itself. Notice what would happen if, for example, the two waves were to drift further out of phase, the top one to the left and the bottom one to the right. Intrinsic phase speeds would drop in magnitude, and the basic flow would win against the phase propagation and bring them back. If they were to drift further into phase, phase propagation would be enhanced and would win against the basic flow, again bringing them back into the phase relationship shown. This is the phase-locking mechanism. It depends of course upon the waves being close enough to affect each other; in the baroclinic case this means within a Rossby height (8.1) of one another.

It can now be seen that, as shown toward the right in Fig. 12, one result of the phase-shifted, phase-locked configuration is that the velocity in each layer is <u>less</u> than a quarter wavelength out of phase with the displacement. This plus simple kinematics implies growth, of both the velocities and the displacements, and therefore growth of the IPV anomalies. It should be noted in addition that there are phase-locked configurations that arise for longer wavelengths, which gives stronger Rossby phase propagation [recall the scale effect, e.g. eq. (2.4)] and hence a larger phase shift. With a sufficiently large phase shift, the two waves begin to slow down each other's intrinsic phase speed, rather than speeding it up. But a little reflection shows that phase-locking still takes place. In fact, the fastest-growing normal modes usually have these larger phase shifts. Further discussion may be found in HMR §6, including a very careful discussion of the instability and phase-locking mechanisms together with some information on how they operate in less simple configurations.

Fig. 12 gives only the linearized picture, valid only for small sideways displacement-slopes like those sketched in Fig. 1. PV thinking, together with recent developments in the theory of wave-activity conservation relations (Haynes 1988, McIntyre and Shepherd 1987 & refs.), and cross-fertilization from studies of stratospheric breaking-Rossby-wave scenarios like that motivating Figs. 2-4, have taken us a good deal further. These developments have given tremendous insight into the qualitative way in which a baroclinic instability on a realistic tropospheric jet goes strongly nonlinear, involving low-level saturation followed (in the zonal wave-6 case) by substantial vertical Rossby group propagation, and Rossby wave breaking usually on the equatorward side of the jet rather like the case in Figs. 2-4 above (see also §2.2 of Brian Hoskins' lecture, and a forthcoming paper by Hoskins, McIntyre and Thorncroft, 1988). Processes of this latter kind, whether excited by nonlinear baroclinic instability or in other ways, seem to provide the essential clue to the "perplexing problem" of the large-scale angular momentum transport flagged by Lorenz (1967, pp. 85, 150) in his classic monograph on the general circulation; recall point 4 of §3 above.

## 10. MORE ABOUT REAL CYCLOGENESIS

A cyclonic IPV anomaly embedded in a typical westerly upper-air flow induces a structure whose upper-air part is the "short wave" or "short-wave trough" familiar to synopticians. (A very clear example appears in Figs.

14a,15a below (500 mb forecast geopotential height maps for 19 and 20 February 1979). In a very interesting recent study, Mattocks and Bleck (1986) have shown that such structures can indeed be obtained by embedding an IPV anomaly into a realistic upper-air westerly flow and then inverting. (They used a geostrophic inversion in isentropic coordinates). These structures, then, are what many of the upper-air advection scenarios discussed in §§7-9 look like on a conventional upper-air chart. What do our theoretical ideas lead us to expect, as regards their cyclogenetic effect? The answers certainly depend, at least, on four factors that have been brought out in the more idealized contexts of §§7-9:

1. IPV anomaly strength (best succinct depiction is on an IPT map),

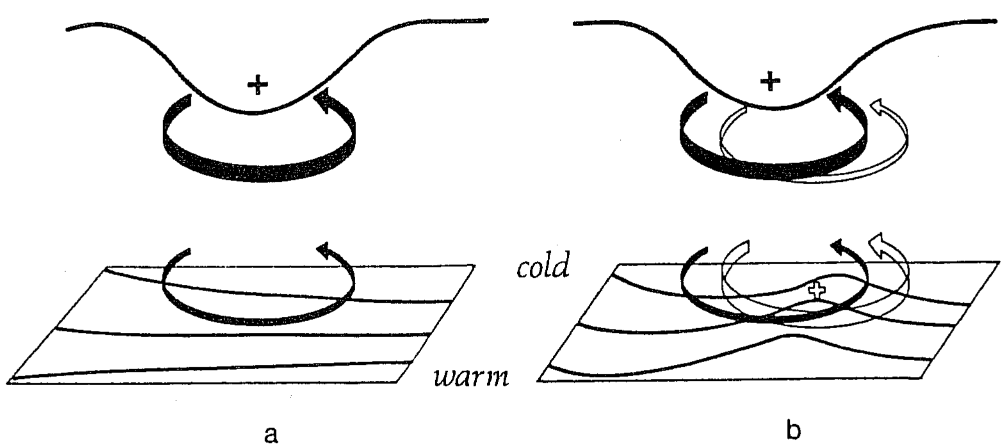



Fig. 13 A schematic picture of cyclogenesis associated with the arrival of an upper-air IPV anomaly over a low-level baroclinic region. In (a) the upper-air cyclonic IPV anomaly, indicated by a solid plus sign and associated with the low tropopause shown, has just arrived over a region of significant low-level baroclinicity. The circulation induced by the anomaly is indicated by solid arrows, and potential-temperature contours are shown on the ground. The low-level circulation is shown above the ground for clarity. The advection by this circulation leads to a warm temperature anomaly somewhat ahead of the upper IPV anomaly as indicated in (b), and marked with an open plus sign. This warm anomaly induces the cyclonic circulation indicated by the open arrows in (b). If the equatorward motion at upper levels advects high PV polar lower-stratospheric air, and the poleward motion advects low PV sub-tropical upper-tropospheric air, then the action of the upper-level circulation induced by the surface potential-temperature anomaly will, in effect, reinforce the upper-air IPV anomaly and slow down its eastward progression. (To this extent the situation is similar to the small-amplitude instability situation represented by Fig. 12.)

2. Rossby height in relation to altitude of anomaly above the surface,

3. strength of low-level anomalies (which will depend inter alia on low-level warm advection), and

4. the extent to which phase-locking and mutual amplification of surface and upper-air anomalies is significant.

(We shall see very shortly that the factors 2-4 are all profoundly affected by latent heat, which is why the latter is not listed as an independent factor.)

In connection with 4, it is important to realize that a partial, temporary phase-locking, which would not qualify as a strict normal mode instability like that in Fig. 12, may still be highly significant to a forecaster interested in the precise degree of surface cyclogenesis. In this sense, I feel that the ideas and insights of instability theory have a much wider qualitative significance than one might think from the comparative rarity, in the real atmosphere, of clearly documented examples of normal-mode exponential growth from small amplitude like the case of Fig. 3e above (which was rare in the model stratosphere), or its baroclinic equivalent, which some synopticians call "Petterssen type A" cyclogenesis, arguably rarer than Petterssen believed (L. Uccellini, personal communication), although Dick Reed (personal communication) claims to have one such example (See also Reed and Albright (1986)).

How do we bring these ideas together in a slightly more realistic-looking synoptic context? A standard cyclogenetic situation is shown schematically in Fig. 13, again taken from HMR. Following HMR let us suppose that, as in the simplest case of cyclogenesis in §7, a short-wave or cyclonic upper-air IPV anomaly arrives over a pre-existing low-level baroclinic region, as suggested in Fig. 13a. Thermal advection by the induced low-level circulation will tend to create a warm low-level anomaly ahead of the upper IPV anomaly (Fig. 13b), enhancing the effects of any low-level warm advection already present. This warm surface anomaly will induce, as in Fig. 6, its own cyclonic circulation. At low levels this circulation will add to the circulation induced from upper levels (Figs. 5 or 13a), giving an intense low-level cyclone whose centre is a little ahead of the advancing upper-level IPV anomaly. While the low-level anomaly remains ahead of the upper-level anomaly there may be feedback to upper levels, tending to phase-lock the two anomalies and cause them to intensify together -- like a small portion of Fig. 12, the small-amplitude normal-mode instability situation. In particular, the upward extension of the circulation induced by the low-level warm anomaly will tend to intensify the upper-level IPV anomaly by advecting high-PV air equatorwards, on the left of the picture, and, because this advection is strongest just behind the upper-level IPV anomaly, will also tend, to a varying extent, depending in particular on factor 2 above, to slow down its advance.

We next consider how all this might be affected by moisture.

## 11. THE EFFECTS OF MOISTURE, INCLUDING EXPLOSIVE CYCLOGENESIS

The key point is, of course, point 2 above, regarding the Rossby height. Larger $H$ means tighter vertical coupling, tighter phase locking, and more mutual amplification. How can $H$ get larger? According to (8.1), by reducing $N$; moreover, if $N$ is reduced sufficiently, one can have large values of $H$ with much smaller values of $L$, implying much faster development on much smaller spatial scales. Finally, the vacuum-cleaner effect is exactly what is needed to initiate lifting and make a transition to saturated ascent -- which is very like reducing $N$ in just the way envisaged.

In short, a strong upper anomaly arriving over a warm, moist layer is a bit like what Fred Sanders might call a detonator arriving over a layer of high explosive, but what I should like to call a vacuum cleaner arriving over a small hole in a carpet. The vacuum cleaner is suddenly free to pull air upwards over some small area where saturated ascent has commenced, releasing the air parcels from the constraining effect of the dry static stability that is reflected in the relatively small value of $H/L$ in dry cases like Fig. 5. This seems to give a feel for the suddeness, and perhaps also the fickleness and forecast uncertainty -- will the upward suction be enough, or the air moist enough, to get some air parcels over the saturation threshold? Once some break through, the vertical coupling tightens and the whole thing can run away with the characteristic suddeness that must make life very difficult for forecasters on occasion.

One can use a numerical model to test the prediction that moist ascent should promote phase-locking and explosive mutual amplification. Louis Uccellini (personal communication) has told me of such an experiment in his group at NASA-Goddard, although I haven't seen the results. Figs. 14-16 show the results of another such experiment, by Simmons and Miller (1988, this volume), for the celebrated Presidents' Day Storm of 19 February 1979, by now a much-studied classic case of explosive cyclogenesis. Synoptic studies (e.g. Bosart 1981, Uccellini et al. 1984, 85) give an impression of strong phase-locking and mutual amplification; and this impression is supported by Figs. 14 and 15, which are 24-hour and 48-hour stages of a forecast initialized for 12 GMT on 18 February, using the Betts-Miller moist convective adjustment parametrization in the ECMWF T106 operational model. This forecast captures a large part of the observed situation on both the 19th and 20th. The upper and lower disturbances appear to be closely coupled together, and show a phase lag on the 19th like those depicted in Figs. 12 and 13, characteristic of anomaly amplification.

So what happens if we take away the latent heating? If the foregoing ideas are correct, there should then be far less amplification, and the upper anomaly, in particular, should be weaker and should move eastwards faster than in Figs. 14 and 15. Fig. 16 shows that this is just what happens. It shows a 48-hour forecast that is the same in every respect except that latent heating was ignored throughout.

Addendum: It seems likely that the small but intense cyclone that devastated parts of southeast England in the early hours of 16 October last year, was a case of much the same type of explosive cyclogenesis. Storms of this type and intensity are comparatively rare in the east Atlantic region: indeed the 16 October storm has been described as a "500-year freak". Hoskins and Berrisford (1988) present upper-air IPT maps and other diagnostics that do indeed show what seem to be freak conditions, from 12 GMT on 14 October onward, having an unusual potential for explosive cyclogenesis. In significant respects, conditions resembled the commoner western-Atlantic explosive conditions, but were in some ways more extreme.

## 12. POSTSCRIPT: A VISION OF THE FUTURE

I want to share a dream about future weather forecasting operations, something that Glenn Shutts and I indulged in briefly during a conversation some time ago -- with apologies to L.F. Richardson.

The year is 2010. The international demand for good one-week weather

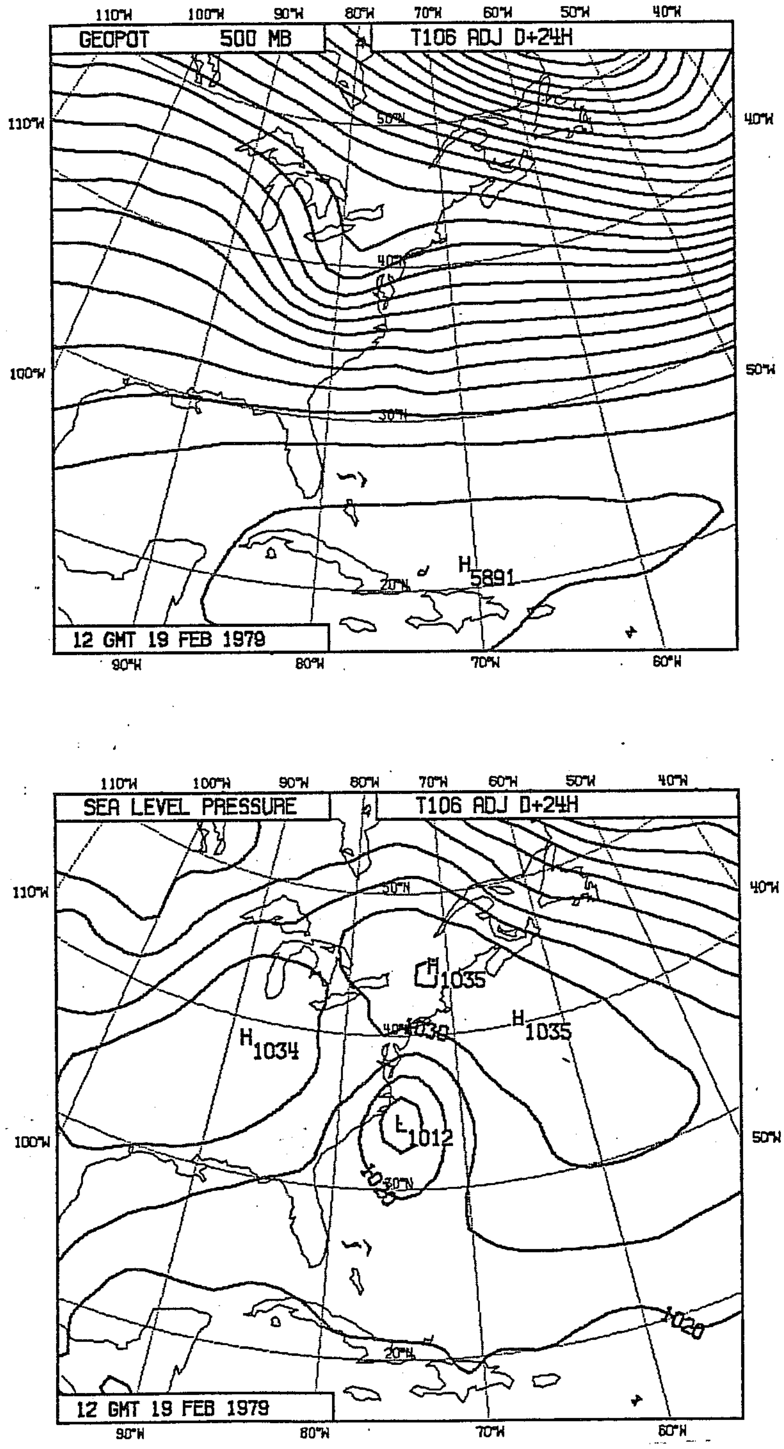



Fig. 14 1-day forecast of the Presidents' Day Storm using the Betts-Miller moist adjustment scheme in the ECMWF T106 operational model.

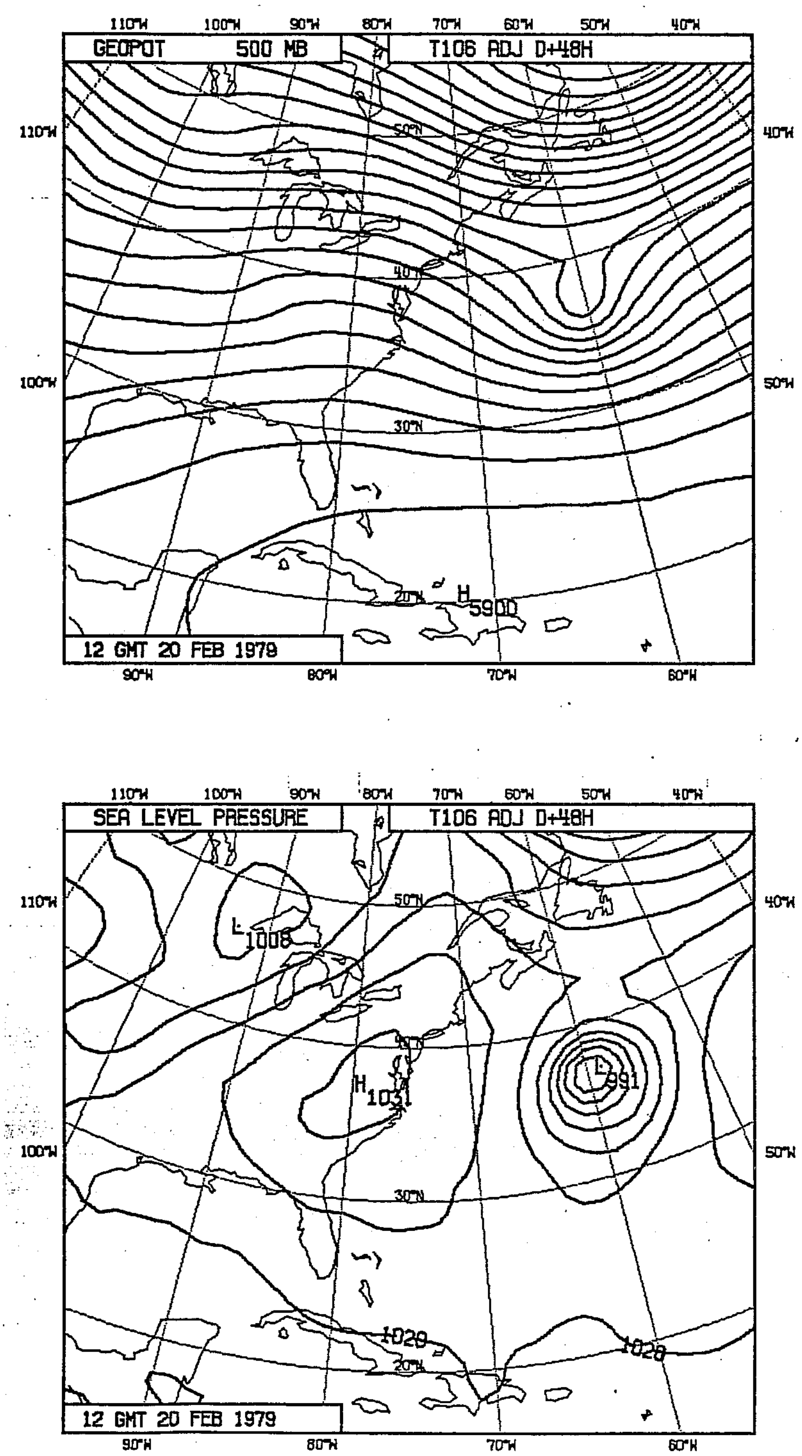
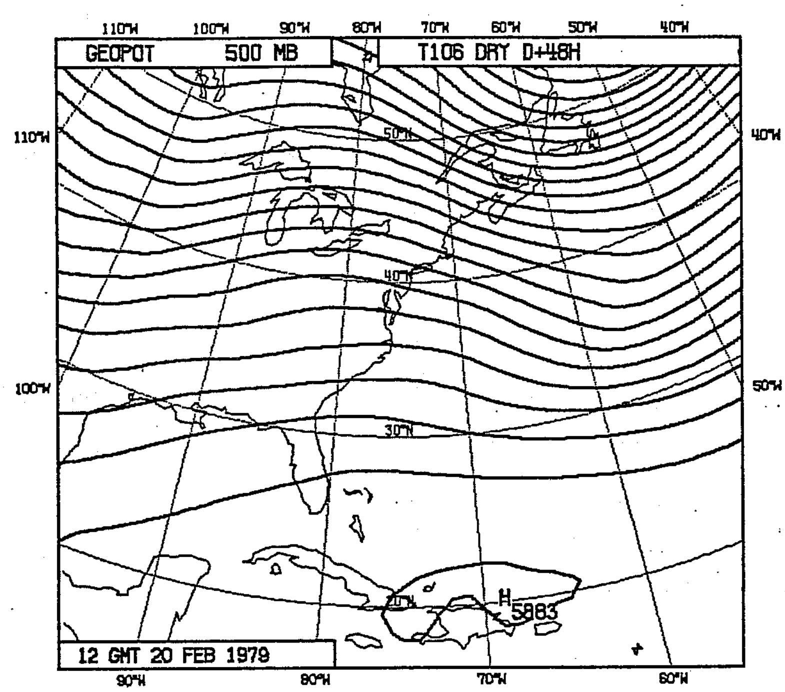



Fig. 15 Second day of the same forecast of the Presidents' Day Storm as in Fig. 14.



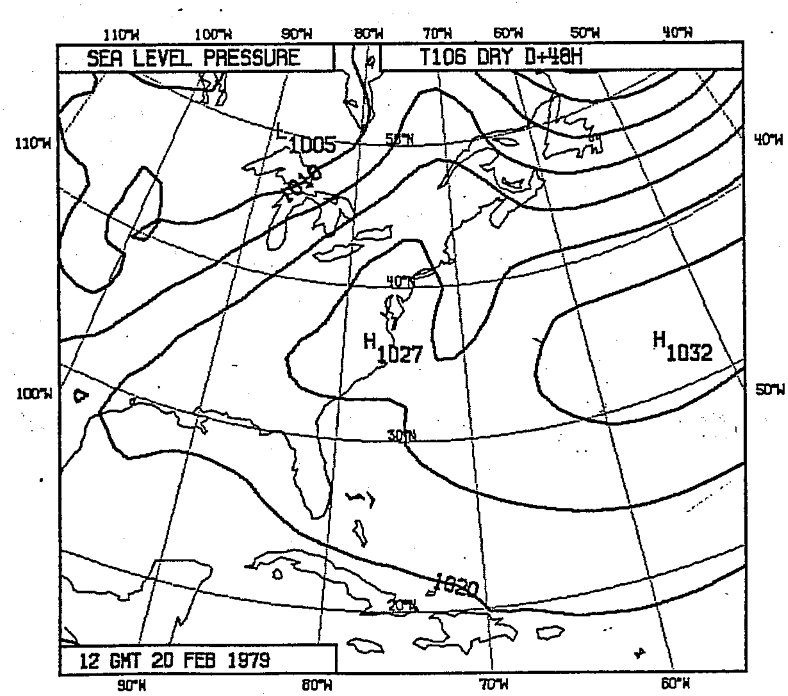




Fig. 16 Same as Fig. 15 but with no latent heating. See Simmons and Miller (1988, this volume).

predictions has led to the establishment of an enormously enhanced observing network, and to a concentration of supercomputing resources at the two new International Forecasting Centres at Tsukuba and Bracknell-Reading. An added incentive has been the recent and unexpected acceleration of the greenhouse warming accompanied by an increase in the frequency and severity of moisture-related weather phenomena, coinciding unfortunately with further population growth in low-lying coastal areas. The way had already been prepared for the release of resources by the introduction into public weather bulletins, late in the 20th century, of well-explained, semiquantitative estimates of forecast uncertainty. It was widely believed that these briefings had been the single most important influence towards building public confidence in the scientific respectability of weather forecasting, helped of course by improvements in actual forecasting skill, and the serious use of graphical presentation techniques.

The observing network is of course largely automated by now, much of it being based on remote sensing from space, but data assimilation and forecasting procedures have quite deliberately not been fully automated. Artificial intelligence systems are still far from being competitive with the human brain in certain respects -- particularly the visual system of a gifted individual who has had the full childhood educational and games experience, and who has been given the incentive of a highly respected professional status after surviving rigorous training and selection procedures.

The data and forecasting quality control systems at Tsukuba and Bracknell-Reading are among the many twenty-first-century information technological systems in which the efficiency of man-machine interaction has been fully developed. The basic mode of operation is, of course, the visual inspection and manipulation of thermodynamical and dynamical fields -- not only to inform the forecasters about the evolution of the system's model atmosphere (and in particular to show up the locations of glitches at data assimilation times), but also to facilitate interactive repairs to the model fields. Techniques such as maximum-entropy image-processing and variable-speed animation have of course long been taken for granted, as has the succinctness, near-completeness, and high visibility with which advected quantities like PV/PT and moisture convey dynamical and thermodynamical information, with their good localization of the effects of bad data on the analyzed fields.

Quite often a forecaster carries out the repairs directly on the PV/PT and moisture fields, for instance painting-in missing sharp edges or shear lines whose likely presence in an upper-air IPT distribution might be a good guess from experience, using an animated version of a display like Fig. 4. An efficient inversion algorithm runs in the background, and feeds a short-term hindcasting model whose output is convolved with the appropriate weighting functions; a system of audio signals informs the forecaster whether, and in what way, he or she is reducing or increasing the stress between the 4D analysis and the observational constraints. The latter include satellite brightness temperatures, and information on advected quantities such as water vapour, cloud, ozone and other trace chemicals. There is also a warning signal if the limitations of the balance concept are approached, and an ability to diagnose any spontaneous emission of inertio-gravity waves that results, and assess the consequences for mesoscale developments.

Even in the year 2010 there are still fairly severe limitations on the size of the ensemble of initial conditions that can be used to help assess forecast uncertainty. So although a basic ensemble is always run, for which the initial conditions are varied objectively, there is also provision for half a dozen or so special forecast runs, based on the forecasters' subjective assessment of the most sensitive locations for varying the initial conditions, such as the region near 80°W, 60°N at the top left of Fig. 10 above. This is regarded as one of the most important parts of the duty forecaster's responsibility.

Forecasters are provided with good incentives to develop their subjective skills. For instance, one member of the ensemble of forecast runs always takes the first objective analysis as initial condition, and after verification the system logs the improvement in skill, if any, that has resulted from the "repair" work that initialized the main run. This added to the forecaster's personal score and thence bonus payment. Another high-scoring event is finding initial conditions for a special forecast run that proves to have an unusually high rate of divergence from the main run, for a given rms initial difference. The urge to develop personal skill and become an internationally famous "ace forecaster" is intense, even though only a select few earn that status, and is just one small but significant part of the drama that has contributed to the new prestige and glamour of the atmospheric sciences.

---


## Acknowledgements

I am particularly grateful to Warwick Norton for kindly allowing me to quote his unpublished results (Figs. 7-9), and to ECMWF, Tony Hollingsworth, and Adrian Simmons for allowing me to reproduce Figs. 11 and 14-16. Brian Hoskins and Ian James generously supplied the original code for, and gave help with, the Reading models. Many colleagues have shared their knowledge, ideas, historical recollections, and unpublished work including Rainer Bleck, Lance Bosart, Keith Browning, Mike Cullen, Ed Danielsen, David Dritschel, Franco Einaudi, Arnt Eliassen, Kerry Emanuel, Peter Haynes, Tony Hollingsworth, Brian Hoskins, Ian James, Martin Juckes, Steve Koch, Dan Keyser, Geoff Monk, Warwick Norton, Tim Palmer, Ray Pierrehumbert, Dick Reed, Prashant Sardeshmukh, Ted Shepherd, Glenn Shutts, Adrian Simmons, Alan Thorpe, Adrian Tuck, Louis Uccellini, and Martin Young. Work at Cambridge was supported in part by the Meteorological Office, NERC, the Nuffield Foundation, SERC, the ULCC Computing Centre, and the US Office of Naval Research.


## References


Arnol'd, V.I., 1966: On an a priori estimate in the theory of hydrodynamical stability. Izv.Vyssh.Uchebn.Zaved.Matematika 54, no.5, 3-5. (English transl.: Amer.Math.Soc.Transl., Series 2 79, 267-269 (1969).)

Bleck, R., 1974: Short range prediction in isentropic coordinates with filtered and unfiltered numerical models. Mon. Wea. Rev., 102, 813-829.

Bleck, R. and Mattocks, C., 1984: A preliminary analysis of the role of potential vorticity in Alpine lee cyclogenesis. Beitr. Phys. Atmos., 57, 357-368.

Bleck & Mattocks 1986: Misquote for Mattocks and Bleck 1986 (q.v.)

Bosart, L.F., 1981: The President's Day snowstorm of 18-19 February 1979: a subsynoptic-scale event. Mon. Wea. Rev., 109, 225-242.

Charney, J.G., 1948: On the scale of atmospheric motions. Geofysiske Publ. 17 (2), 3-17.

Crighton, D.G., 1975: Basic principles of aerodynamic noise generation. Prog. Aerospace Sci., 16., 31-96.

Crighton, D.G., 1981: Acoustics as a branch of fluid mechanics. J. Fluid Mech., 106, 261-298.

Eliassen, A., 1980: Balanced motion of a stratified, rotating fluid induced by bottom topography. Tellus, 32, 537-547.

Haynes, P.H. and McIntyre, M.E. 1987a: On the representation of Rossby-wave critical layers and wave breaking in zonally truncated models. J. Atmos. Sci. 44, 2359-2382.

Haynes, P.H. and McIntyre, M.E. 1987b: On the evolution of vorticity and potential vorticity in the presence of diabatic heating and frictional or other forces. J. Atmos. Sci. 44, 828-841.

Hollingsworth, A., Lorenc, A.C., Tracton, M.S., Arpe, K., Cats, G., Uppala, S., Kållberg, P., 1985: The response of numerical weather prediction systems to FGGE level IIb data. Part I: Analyses. Quart. J. Roy. Meteorol. Soc., 111, 1-66.

Hoskins, B.J. and Berrisford, P., 1988: A potential-vorticity perspective of the storm of 15-16 October 1987. Weather, to appear (March 1988 issue).

Hoskins, B.J., McIntyre, M.E. and Robertson, A.W. 1985: On the use and significance of isentropic potential-vorticity maps. Quart. J. Roy. Meteorol. Soc. 111, 877-946. Also 113, 402-404.

Hoskins, B.J., McIntyre, M.E., and Thorncroft, C., 1988: On the role of nonlinear radiation, wave propagation and wave breaking in the life cycles of baroclinic instabilities. J. Atmos. Sci., to be submitted

Juckes, M.N. and McIntyre, M.E., 1987: A high resolution, one-layer model of breaking planetary waves in the stratosphere. Nature, 328, 590-596.

Kleinschmidt, E., 1950a: Über Aufbau und Entstehung von Zyklonen (1. Teil) Met. Runds., 3, 1-6.

Kleinschmidt, E., 1950b: Über Aufbau und Entstehung von Zyklonen (2. Teil) Met. Runds., 3, 54-61.

Kleinschmidt, E., 1951: Über Aufbau und Entstehung von Zyklonen (3. Teil) Met. Runds., 4, 89-96.

Lighthill, M.J., 1978: Waves in Fluids. Cambridge University Press, 504 pp.

Lorenz, E.N., 1967: The Nature and Theory of the General Circulation of the Atmosphere. Geneva: World Meteor. Org., 161 pp.

Lorenz, E.N. and Krishnamurthy, V., 1987:: On the nonexistence of a slow manifold. J. Atmos. Sci., 44, 2940-2950.

Mattocks, C. and Bleck, R., 1986: Jet streak dynamics and geostrophic adjustment processes during the initial stages of lee cyclogenesis. Mon. Wea. Rev., 114, 2033-2056.

McIntyre, M.E. and Palmer, T., 1984: The "surf zone" in the stratosphere. J. Atm. Terr. Phys., 46, 825-849.

McIntyre, M.E. and Palmer, T.N. 1985: A note on the general concept of wave breaking for Rossby and gravity waves. Pure Appl.Geophys. 123, 964-975.

McIntyre, M.E. and Shepherd, T.G., 1987: An exact local conservation theorem for finite-amplitude disturbances to nonparallel shear flows, with remarks on Hamiltonian structure and on Arnol'd's stability theorems. J. Fluid Mech. 181, 527-565.

Palmén, E. and Newton, C., 1969: Atmospheric circulation systems. Academic Press, 603pp.

Reed, R.J. and Albright, M.D., 1986: A case study of explosive cyclogenesis in the eastern Pacific. Mon. Wea. Rev., 114, 2297-2319.

Sanders, F. and Gyakum, J.R., 1980: Synoptic-dynamic climatology of the 'bomb'. Mon. Wea. Rev., 108, 1589-1606.

Simmons, A.J. and Miller, M., 1988: The prediction of extratropical weather systems — some sensitivity studies. ECMWF Seminar, "The Nature and Prediction of Extratropical Weather Systems", held 7-11 Sept., 1987. (This volume.)

Thorpe, A.J. 1985: Diagnosis of balanced vortex structure using potential vorticity. J. Atmos. Sci., 42, 397-406.

Thorpe A.J., 1986: Synoptic scale disturbances with circular symmetry. Mon. Wea. Rev. 114, 1384-1389.

Thorpe, A.J. and Emanuel, K.A., 1985: Frontogenesis in the presence of small stability to slantwise convection. J. Atmos. Sci. 42, 1809-1824.

Truesdell, C., 1951: Proof that Ertel's vorticity theorem holds in average for any medium suffering no tangential acceleration on the boundary. Geofisica pura e applicata (PAGEOPH) 19, 167-169.

Uccellini, L.W., Kocin, P.J., Petersen, R.A., Wash, C.H. and Brill, K.F., 1984: The Presidents' Day cyclone of 18-19 February 1979: synoptic overview and analysis of the subtropical jet streak influencing the pre-cyclogenetic period. Mon. Wea. Rev., 112, 31-55.

Uccellini, L.W., Keyser, D., Brill, K.F., and Wash, C.H., 1985: The Presidents' Day cyclone of 18-19 February 1979: Influence of upstream trough amplification and associated tropopause folding on rapid cyclogenesis. Mon. Wea. Rev., 113, 962-988.

Vautard, R. and Legras, B., 1986: Invariant manifolds, quasi-geostrophy and initialization. J. Atmos. Sci., 43, 565-584.

Warn, T. and Ménard, R., 1986: Nonlinear balance and gravity-inertial wave saturation in a simple atmospheric model. Tellus, 38A, 285-294.