SYNOPTIC-DYNAMIC DIAGNOSIS OF MEDIUM RANGE WEATHER FORECAST SYSTEMS

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1. INTRODUCTION

The objective of the monitoring of a NWP operational system is to detect deficiencies in the analysis and forecast system. This is done from a) verification statistics, b) diagnostic studies and c) synoptic monitoring of the forecasts. For the problems associated with verification and diagnostics, see contributions by Simmons and Klinker in this volume. In this article the emphasis will be on the synoptic-dynamic monitoring of forecasts, in particular to trace the causes of bad forecasts with respect to errors in the initial conditions. The results of such investigations might reveal problems in the observational network, the quality control or the analysis system.

2. INVESTIGATIONS INTO FORECAST FAILURES

Errors in the initial conditions are caused by a combination of deficiencies in the observations, the analysis system and the model. Identifying erroneous observations which have been used might reveal loopholes in the quality control system. Observations may not only be wrong, they can be unrepresentative for the scales described by the resolution of the model. Even correct and representative observations can introduce errors due to the way the analysis system spreads out the information. Finally, systematic rejections of correct and representative observations might be due to systematic errors in the model.

3. THREE STEPS IN ERROR TRACKING

The investigation of a bad forecast is made in three steps to answer *when* did the error enter into the analysis, *where* did it happen and *what* caused the error?

3.1 *WHEN* DID THE ERROR ENTER INTO THE ANALYSIS?

It might seem obvious that an inspection of the operational verification scores would tell which forecasts are bad and thus when the decisive error entered into the analysis. However, great caution must be exercised already at this stage, since the ECMWF operational verification statistics refer to forecasts starting from 12 UTC analyses. Any error could of course have entered during any previous analysis cycle (in the ECMWF system at 18, 00 and 06 UTC) and then not be rectified by later data.

Secondly, using regional (in contrast to hemispheric) verification statistics one must be aware that the effects of an analysis error takes time to enter the verification area. The date of a particularly bad forecast might therefore not necessarily be the time when the decisive error entered into the analyses. It is therefore worthwhile to compare verification scores for Europe, with verifications for the Northern Hemisphere and even upstream areas, like the North Atlantic, North America. Ultimately, the exact timing of an analysiserror can best be established by running forecasts from previous analyses.

3.2 *WHERE* DID THE ERROR ENTER INTO THE ANALYSIS?

Different methods, empirical as well as objective, are used to trace the geographical origin of forecast errors: forecast error maps, sensitivity analyses and the ensemble prediction perturbations.

3.2.1 ERROR MAPS

Error maps of the geopotential fields, overlaying the forecast under investigation, are normally computed for 12 hour intervals up to +120 h or +144 h, sometimes +168h. The level chosen for the tracking is mostly 500 hPa, but sometimes 1000 hPa or 250 hPa are used.

A sequence of error maps normally shows how the initial errors move downstream together with the synoptic system where they originated. At first the errors amplify, but after a couple of days stagnate or even weaken. By then new errors with opposite signs have started to develop downstream, ahead of the initial errors. These secondary or downstream errors amplify, stagnate and receded during the following days, while generating new errors of opposite sign downstream, and so on like a "domino effect". After about six days into the forecast a longitudinally elongated wave train of errors with alternating signs have developed streching almost around half of the hemisphere. The largest amplitudes of the errors are in the eastern part. This means paradoxically that the weather system which contained the initial error has been less affected than the systems downstream (which might have been correctly analysed). With increasing forecast time the error patterns gradually become complex when errors from different sources start to interact in a non-linear way (fig.1).

The error tracking is conducted by following the main wave train of errors back in the forecast. The tracing focuses on the most amplified part of the wave train, the maximum "error energy", not on individual errors. In the atmosphere, as in other physical systems, the transmission of energy is not by the phase speed of waves but their "group velocity", which is normally different; slower than the phase speed for water waves, faster for large-scale atmospheric waves in the westerlies (fig.2). Although for most applications in physics the group velocity is derived from an dispersive wave equation, from a physical point of view the group velocity is a more fundamental entity than the phase velocity (Phillips, 1998, p.1104). (For an overview of the development of the concept of group velocity in dynamic and synoptic meteorology, see Appendix.)

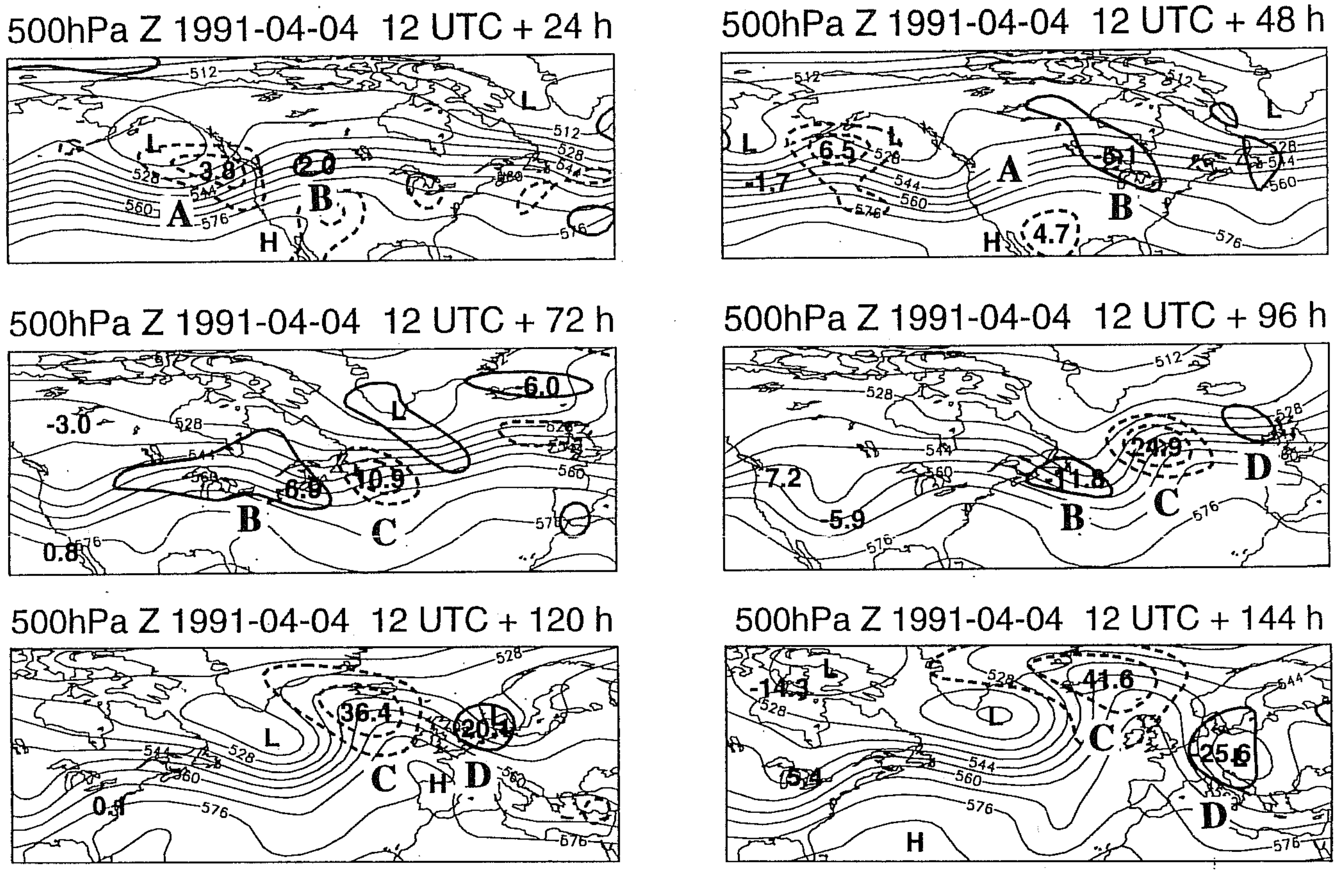

Fig. 1: The forecast 500 hPa flow (thin lines) and errors (thick dashed lines positive, thick full lines negative errors) from 4 April 1991. A TEMPSHIP west of Vancouver had been wrongly decoded and caused a 20-30 gpm positive analysis error (denoted **A**). Early in the forecast a new downstream negative error **B** is created. While it moves eastward, a third generation positive error **C** is developing over the west Atlantic, followed later by a negative error **D** over the British Isles. By then errors **A** and **B** have faded away.

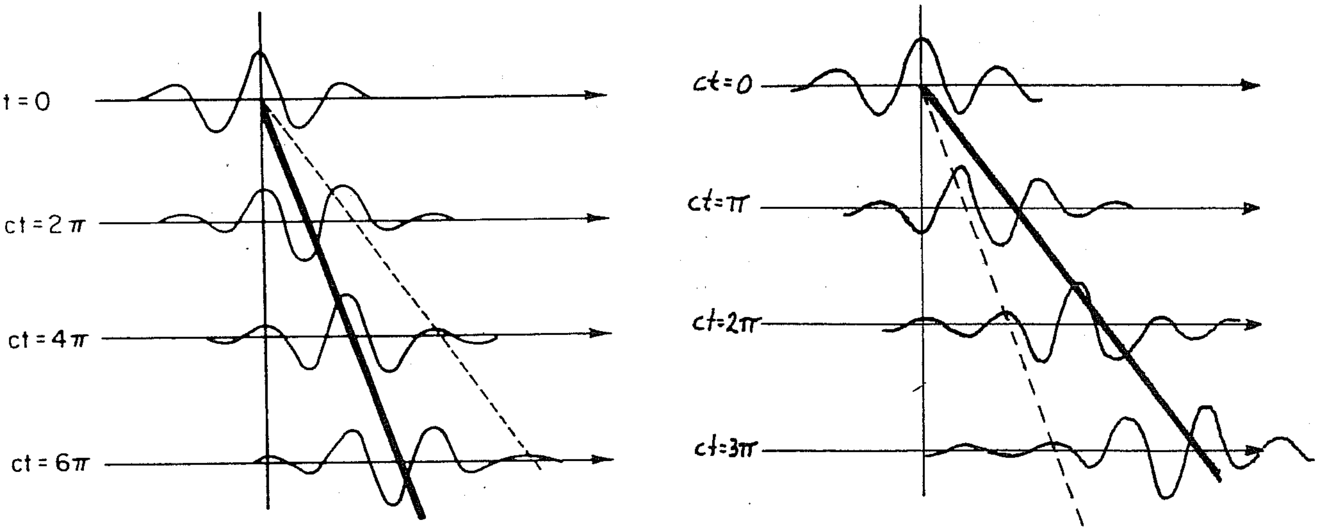

Fig. 2: A schematic illustration of different forms of group velocity: a) for a wave with phase speeds higher than the group velocity, for example gravity waves on water surfaces (after Holton, 1972,1979,1992); b) for a wave for which the phase speed is less than the group velocity, for example for an atmospheric large-scale planetary ("Rossby") wave. In the former case waves are dampened as they move out from the area of maximal amplitude, in the latter case downstream waves are amplified and new waves created, while the initial weaken.

3.2.2 THE SPREAD OF INFLUENCE IN THE EXTRA-TROPICAL ATMOSPHERE

The most likely areas for errors to amplify rapidly, are baroclinic zones and developing cyclones. They provide the most efficient mechanism for the spread of influence in the mid-latitude upper-tropospheric westerlies. The speed of this transport is roughly 30 m/s, which corresponds to 30°/day at 45° latitude, in summertime slightly slower. On the Southern Hemisphere the typical velocity is 40°/day due to the predominant zonal flow and low frequency of blocked patterns.

The fast speed of the influence means that a three day forecast for Europe is mostly dependent on the initial conditions over the whole N Atlantic, a five day forecast on the initial conditions over North America, and a seven day forecast on the initial conditions over the North Pacific (fig.3). On an individual error map, this appears as an initial error which will move slowly downstream while it generates a wave train with increasing longitudinal extension (fig.4).

A physical-dynamical model of the propagation of energy is schematically outlined in fig. 6 in the Appendix. As the kinetic energy is released into the upper tropospheric flow it is rapidly transported downstream. Arriving in the next system it will either interact directly with a new development or through an intermediate stage by conversion to available potential energy. This downstream baroclinic system will, during its development, transport part of its released energy into the next system downstream. This will continue as long as the dynamic conditions downstream are favourable for further developments ("downstream development"). If the conditions are not favourable, the downstream transport will come to an end.

3.2.3 SENSITIVITIES

The indications from the error tracking are compared with sensitivity analysis calculations (see Klinker et al, 1998). Using the adjoint formulation of the ECMWF model (in T63 resolution) changes in the analyzed temperature and wind field are calculated which would minimize the +48 h forecast errors. These perturbations are, due to the variational approach, small and located in dynamically sensitive areas, which might not necessarily be the exact location of the real errors.

3.2.4 EPS PERTURBATIONS

The main locations of the perturbations calculated by the Ensemble Prediction System (EPS) also help to determine where the atmosphere is sensitive to *possible* errors. These perturbations are therefore *a priori* sensitivities in contrast to the *posteriori* sensitivities mentioned in 3.2.3, since they do not depend on the outcome of any forecast. It is also possible to study those EPS members which have successfully deviated from the bad non-perturbed (control) forecast. The locations of the perturbations of these members might provide indication of the real analysis errors. But as with the sensitivities, also the EPS perturbations might not, due to the variational approach, necessarily be on the exact location of the real errors.

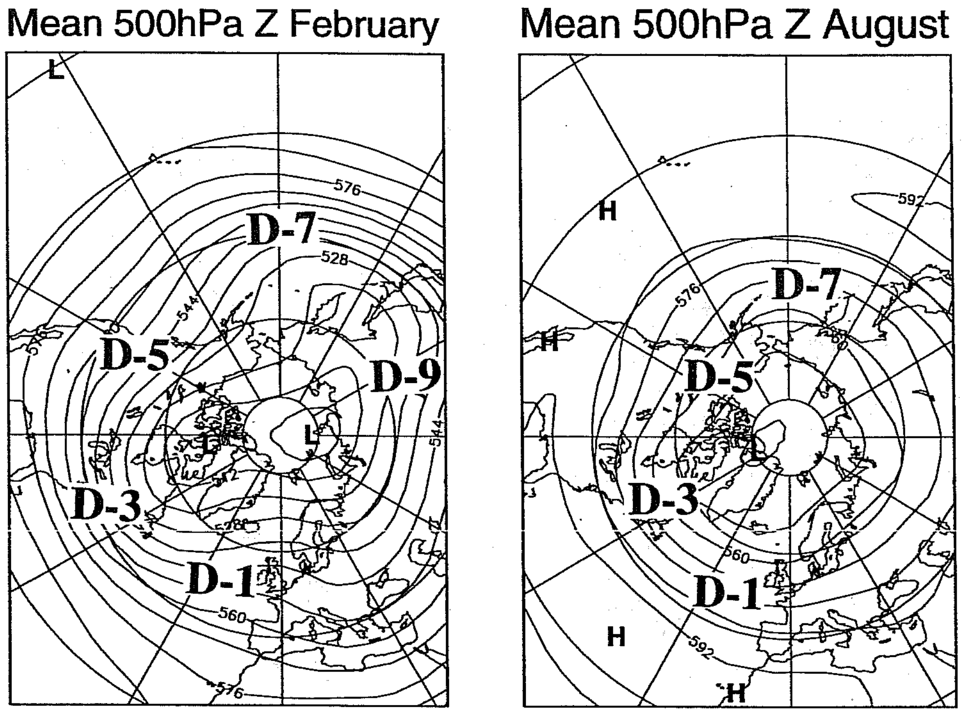

Fig. 3: The areas in the NH where analysis errors D-N days back in time will have an effect on the forecasts over Europe at D+0. a) during winter the zonal flow is stronger and passes over the dense network over the US; b) summertime when the US is covered by a subtropical ridge, the main flow is slower and passes over Alaska, Canada and Greenland with their coarse network of observing stations.

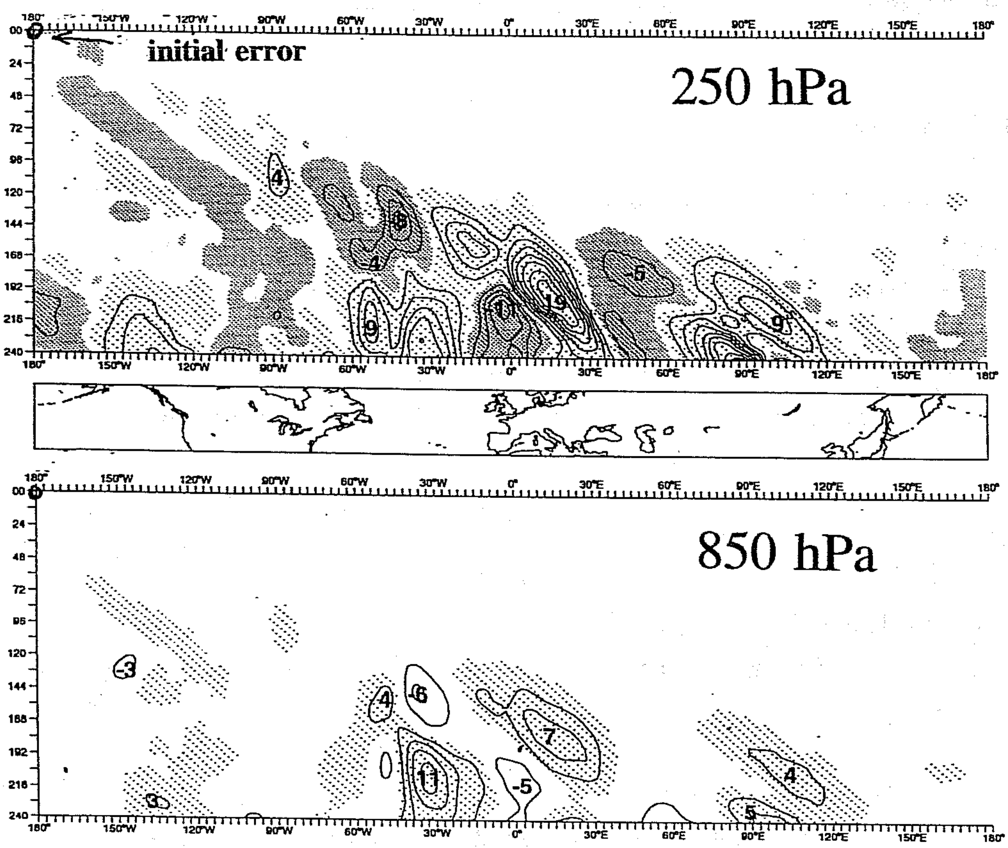

Fig. 4: A forecast time-longitude diagram of the difference in geopotential between two forecasts starting from 20 September 1994 12 UT with identical analyses, except in a few gridpoints at the Date Line, where an aircraft report in one analysis had been entered twice, in the other been rejected. The differences in the forecast started to be felt over Europe after 120 hours, although the main differences entered 1-2 days later. The difference on the +168 h forecast were profound with a storm over N Europe in one forecast, a weak low in the other.

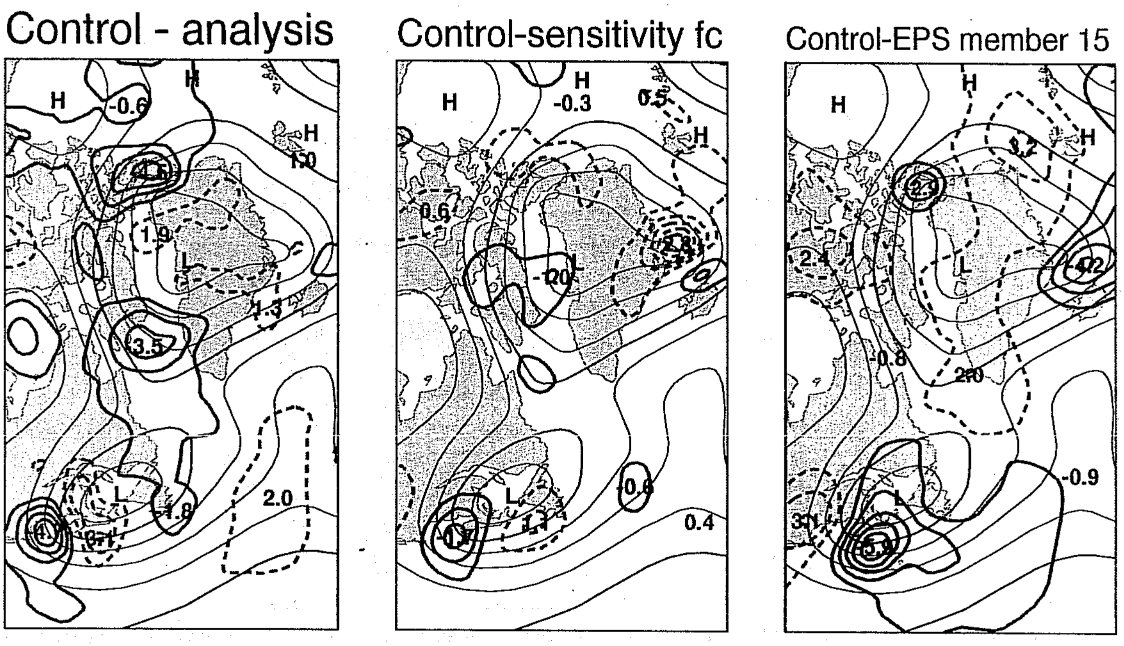

Fig. 5: a) The 12 h 500 hPa forecast error from the 13 May 12 UT ECMWF forecast; b) the difference between the ECMWF forecast and the forecast whose analysis has been modified by the sensitivity perturbations; c) the difference between the ECMWF forecast and the best member (nr 15) from the 50 member EPS ensemble.

3.2.5 INCREMENT CHARTS

The results from error tracking, the sensitivities and EPS perturbations are compared with the analysis increments (analysis-background field). In particular in situations when a good forecast has been followed by a poor one, the increments can provide important information about the time and place of significant analysis changes. The RMS of the increments over 5-7 days provide indications of regions with potential analysis difficulties, either due to a poor first guess or erroneous data. Spatial time means of AN-FG increments provide indications of used stations with marked biases.

3.2 DIFFERENCE TRACKING

The most favourable condition for error tracking is when a clearly poor forecast has been preceded by a generally good forecast. In the same way as with error tracking, computing the differences between consecutive forecasts, the origin of any forecast "inconsistency" can be traced back. Sensitivity calculations, which estimate how the previous day's analysis should have been modified to make its +48 h forecast as similar as possible to +24 h forecast one day later, also provide useful guidance, as do the EPS perturbations. Tracking can also be performed by using the forecast difference with other models, like the UK Met Office, NCEP or DWD models.

The most difficult situation arises when none of the previous forecasts were near to being correct. In such a case the right signal might never have been in the forecast system, due to a lack of data. The monitoring task is then to find out if any observation or observations had wrongly been rejected or not sufficiently considered. This can happen when ships or buoys report extreme conditions close to tropical storms, in the absence of high resolution surface wind observations from satellites like SSMI or SCAT/QSCAT.

3.3 *WHAT* DATA AFFECTED THE ANALYSIS?

When the approximate time and area of origin of the analysis problem has been determined, the ECMWF data base provides records and statistics of the available observations in the area. If it is found that one or several observations are wrong in a way that could have been identified in real-time, modifications of the quality control are made accordingly. If the observational errors turn out to be systematic, a blacklisting is made of the station(s). To establish systematic errors, statistics of differences to the background field or similarity with nearby platforms are computed.

The cause and effect relation between increments and observations is not always trivial. Although increments caused by wind and pressure/temperature observations have different signatures, exceptions from the rules are frequent. Through the geostrophic coupling strong pressure/temperature increments can be caused by pure wind observations; strong wind increments can be caused by pressure/temperature observations.

A erroneous observation, that would normally have been rejected or ignored, can sometimes be accepted and appear to have created a strong increment. A re-analysis with the observation left out will then not change anything. In such cases it is the influences from neighbouring (correct) stations, which have been spread out in a way that makes the analysis accept the erroneous observation.

4. EXPERIMENTAL RE-RUNS

Error tracking can only provide a well-founded hypotheses of the cause of a particular forecast failure. The best confirmation is a re-run of the forecast with changed initial conditions, analysis system or model properties. Unfortunately the outcome of such experiments is not always trivial to interpret. *Forecast changes after modifications of the data supply, the analysis system or the model properties, might therefore not necessarily be a direct consequence of the these modifications.*

1. Blacklisting or unblacklisting certain observations or observation types will not only change the analysis directly, but also indirectly since other observations than those under investigation might be treated differently. Some might even be rejected or have a previous rejection overturned in the quality control. If the re-analysis extends over more than one cycle, the background field will also change and affect subsequent quality controls.

2. Due to the global spectral fit, any local change of the analysis will have global effects. Although

normally very small, they might affect the quality control. There are documented cases when the global effects of a removal of a SHIP in the Atlantic changed the analysis and then the background field over Japan in a way that then led to a rejection of a (bad) radio sonde and a highly improved forecast over the North Pacific!

3. There are cases when the influence of an upper-tropospheric aircraft report in a dynamically stable area can influence the analysis in a lower-tropospheric unstable area through the influence of the vertical structure functions, and there initiate a significant forecast change.

5. OUTLOOK

The experience summarized here is based on several years of monitoring of the ECMWF model, but should also be relevant for other global and limited area models. The operational introduction at the ECMWF of the Four Dimensional Analysis system (4DVAR) in November 1997 significantly improved the forecast quality, but has also made the error tracking procedure more complicated. Analysis increments no longer have a local interpretation and can be brought about by "downstream development" during the six hour window. The 4DVAR can also spread analysis increments more strongly vertically than previous systems.

Although the 4DVAR has some ability to identify erroneous or irrepresentative observations, it frequently fails to do so. Once erroneous observations are accepted the 4DVAR tries to give them a dynamical interpretation which, if wrong, can be very harmful to the forecast. This makes a proper quality control of the observations and operational monitoring of analyses and forecasts even more necessary.

6. SUMMARY

Synoptic-dynamic monitoring of NWP forecasts is a necessary complement to the usual statistical verifications and diagnostics, in particular in cases of unusually poor forecasts. Experience shows that investigating forecast failures

- almost always manages to identify the region(s) where the error(s) originated
- in many cases manages to identify the observations involved
- sometimes manages to identify the observation which caused the bad forecast
- surprisingly often identifies *other* systematic errors, unrelated to the particular bad forecast

Monitoring the NWP system provides a platform where the modellers and the forecasters can meet in a common interest. The results of the investigations can be conveyed to the forecasters at training courses; feedback from the forecasters can take place during common meetings where the model performance is discussed.

Appendix I: Downstream development - an historical bibliography

The understanding how atmospheric systems interact over distances grew out in the 1930's from both theoretical considerations and synoptic observations. The unification of theory and practice occurred, when this process was interpreted as a transport of kinetic energy during the constraint of geostrophic adjustment processes.

From work on the large scale behaviour of atmospheric motion, Rossby and collaborators (1939) derived the well-known dispersive wave formula (Platzman, 1968). Rossby (1945) found that the group velocity of these "Rossby waves" yielded values much in excess of the phase speed, indicating that the wave energy travelled faster than the wave and could lead to generation of new waves downstream. Rossby (1949b) suggested that the initial development occurs through a baroclinic process, in which potential energy is converted into kinetic energy. Platzman (1949) suggested that the purely barotropic component of the upper tropospheric large-scale circulations may perform an important function as "perpetual catalytic agents" by operating as channels through which local concentrations of atmospheric energy are permitted to travel in advance of the parent disturbance and activate latent supplies of energy successively in different longitudes. Further analyses with respect to the design of NWP systems were made by Charney (1949, 1951 a,b), Charney and Eliassen (1949) and, as a confirmation of the importance of group velocity, the first automatic weather forecast by Charney et al (1950). For an overview of the concept of energy dispersion, in particular with respect to NWP models, see Phillips (1990).

Observational evidence for an energy propagation was supplied by synoptic studies of strong cyclogeneses on the Gulf of Alaska and their rapid downstream influences over North America and the North Atlantic (Namias, 1944; Namias and Clapp, 1944; University of Chicago, 1947; Cressman, 1948, 1949). Before WWII Danish and Norwegian forecasters had noted that soon after a deep cyclogenesis occurred over the western part of the Atlantic, there was a tendency for strong anticyclones to form over Ireland (Evjen, 1936). Guided by this synoptic rule and led by Rossby's theories Hovmöller (1949, see also Hovmöller's contribution in Rossby, 1949 b) developed his famous time-longitude diagram of daily 500 hPa geopotential heights between 30 and 55 N where group velocities could be were measured. The speed of this transport was found to be almost is roughly 30°/day at 45° latitude (about 30 m/s) which agrees well with the theoretical calculations of the "group velocity" of dispersive Rossby waves as well as the mean velocity of the upper tropospheric flow. Building upon Rossby's previous work on geostrophic adjustment theory, Yeh (1949) and Gambo (1951) investigated the dispersion mechanism in more detail.

In the beginning of the 1950's it was widely recognized that kinetic energy released in baroclinic disturbances, was propagated by the upper tropospheric flow, most importantly the jet-streams (McIntyre, 1951). This provided a link to synoptic assessements. Riehl et al (1952) showed that group velocity and downstream development were useful in real-time forecasting. They also noted that the group velocity formula was more suitable for synoptic application than the Rossby wave formula for phase velocity, partly because of its more constant value. Further synoptic studies by Parry and Roe (1952), Carlin (1952, 1953), Austin et al (1953), Winston (1955), Hughes et al (1955) and to some extent Reiter (1958) made use the concept of energy dispersion in the mid-latitude baroclinic zonal westerlies. See also Reed and Sanders (1953), Smith and Forsdyke (1953), Smith (1955) and Miles (1959) who studied downstream development but gave it different interpretations.

Although Rossby regarded the concept of group velocity as a definite break with the classical theories of Margules and Bjerknes, proponents of the "Bergen School" seem to have been appreciative of the new concept (T. Bergeron, personal communications 1972-74, Petterssen, 1956, p.364). In their major *oeuvre* one can read:

> "The energy in a train of waves is being propagated, not with their phase speed, which is less than the wind speed, but with the group velocity, which is greater. Attention is centred, in this new line of attack, not on the propagation of matter, for instance in the form of outbreaks of cold and warm air, but on the propagation of waves and atmospheric states, and thus energy, through matter."(Godske, et al, 1959, p.625, see also p.725 and p.781).

However, for unknown reasons the group velocity approach faded away in the literature during the second half of the 1950's and the 1960's, except in Charney (1966) in a discussion on the planning of a global observation experiment. Hoskins, Simmons and Andrews (1977) have suggested that the lack of further real development in the theory was probably due to the discovery of the baroclinic instability process which put theoretical emphasis on local conversion of energy rather than propagation from another region.

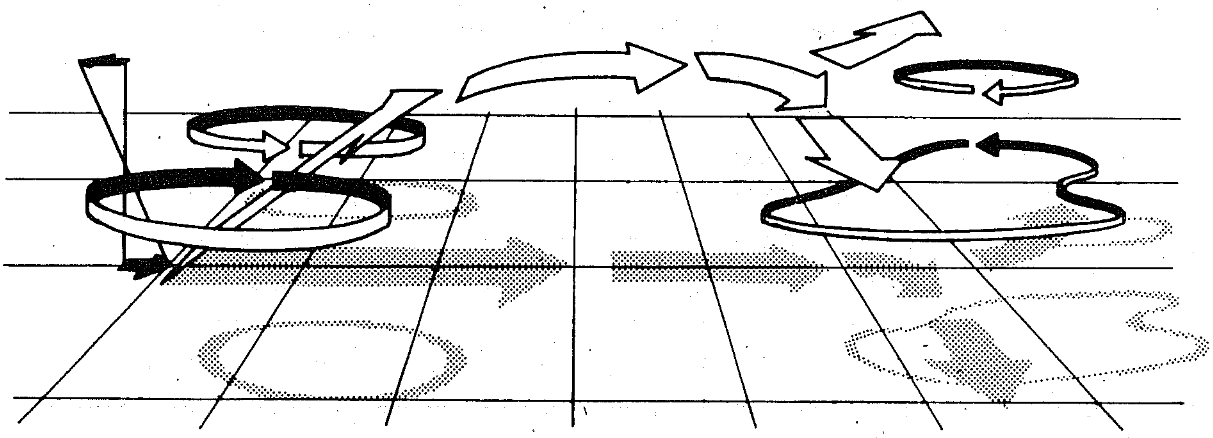

Fig. 6: A schematic diagram by Hoskins et al (1983) of the three-dimensional distribution of the activity in the storm tracks. Eddy activity originates at low levels at the start of the track and propagates upwards and eastward, where the eddies strengthen the wind but weaken the vertical wind shear. Towards the end of the storm track eddy activity propagates mainly horizontally in the upper troposphere, with a stronger meridional component.

The group velocity concept saw a revival in the 1970's first by Miyakoda et al (1971) who used Hovmöller diagrams to confirm that the major wave packets propagated at group velocity of about 30 longitude degrees per day. They also noted that the production of this wave energy and its propagation are the most dominant factors in the evolution of weather, and therefore are the most important items in extended-range prediction. Later Hoskins, Simmons and Andrews (1977) showed how a stationary source of vorticity which could give rise to a succession of downstream trough and ridges. Simmons and Hoskins (1979) found by model simulations and analyses that a local distribution of vorticity moves downstream and amplifies, and gives rise to a succession of downstream troughs and ridges. Because the major trigger of baroclinic instability is provided not by random small-amplitude perturbations, but by large-amplitude disturbances at some distance, they saw evidence for the longer term predictability of large-scale atmospheric motion.

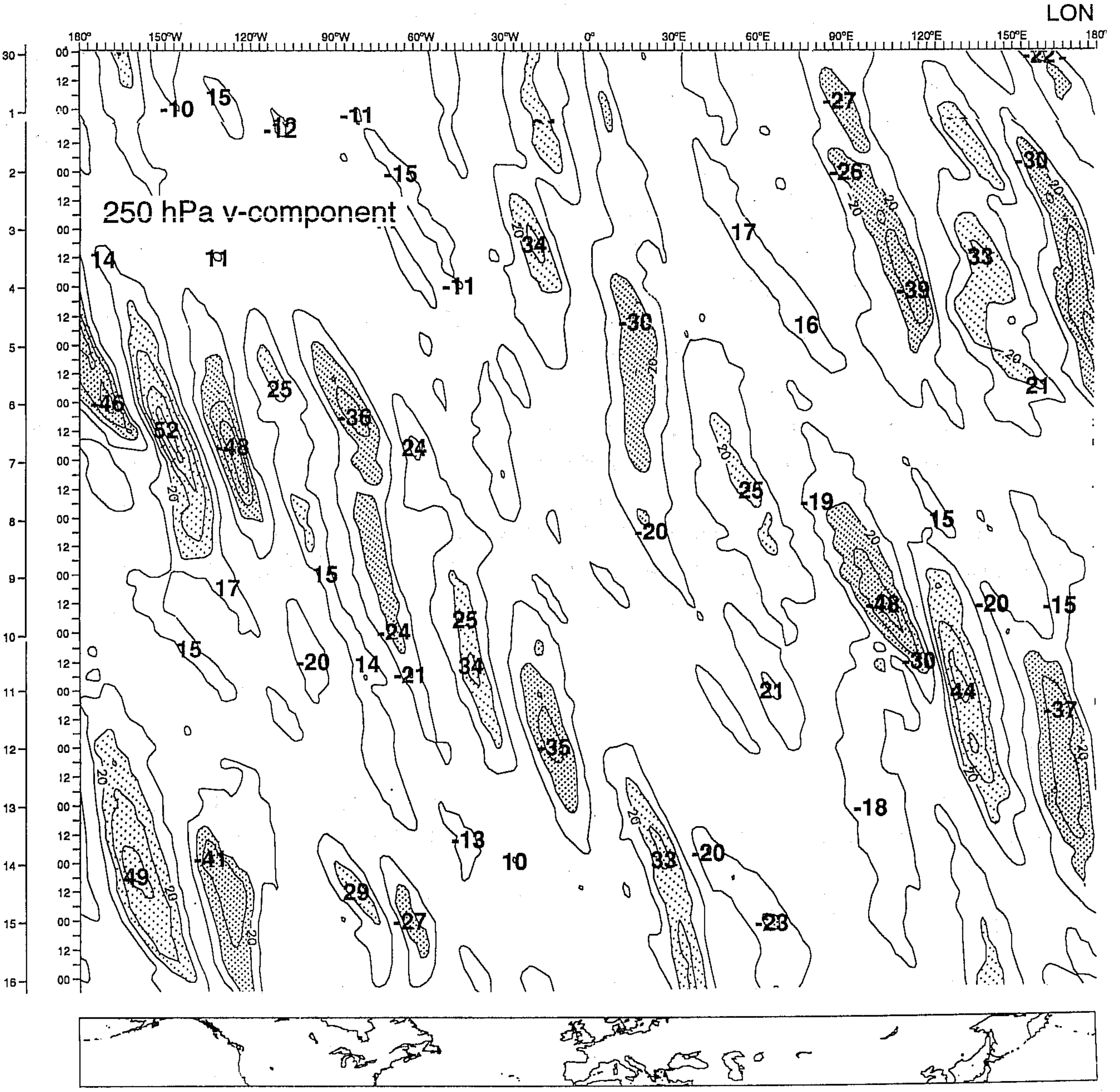

Fig.7 The meridional component of the 250 hPa wind averaged over the latitude band 60-35 N (see cylindircal map at the bottom) plotted in a time-longitude, so called "Hovmöller diagram", from 30 April to 16 May 1995. This type of display provides a clear indication of the rapid downstream spread of successive amplifications. Whereas the individual troughs and ridges move with a phase speed of about 10°/day, the downstream amplifications progresses 2-3 times faster. There are two striking incidents with downstream development: one starting on 30 April over E Asia and terminating on 16 May over W Asia, the second started on 3 May over the Atlantic and reached North America two weeks later.

Hollingsworth et al (1980) found several episodes of downstream energy propagating during the latter half of February 1976, and Joung and Hitchman (1982) studied the upstream conditions precluding cold outbreaks over East Asia as defined by cold front passages over Korea. Fraedrich and Lutz (1987) made a climatological study of the speed of the downstream development on the Southern Hemisphere, and found it to be as much as 40°/day consistent with the predominant zonal flow and low frequency of blocked patterns (see also van Loon, 1965).

After a short lapse the group velocity has seen a revival during the 1990's thanks to the works by Isodoro Orlanski and his co-workers. Orlanski had been on sabbatical in Buenos Aires in 1987 which coincided with the time of the Antarctic Ozone Campaign. Analysing a deep storm which was believed to have contributed to the production of an ozone "mini-hole" over the Palmer Peninsula, they noticed that the cyclone system had a curious precursor upstream, in the middle of the Pacific Ocean. When analysing the energetics of the simulation at high time resolution Orlanski and his group found to their surprise that the storm they were interested in was growing at the expense of a decaying system upstream (Orlanski, personal communication 1996). This resulted in a series of ground breaking papers (Orlanski and Katzfey, 1991; Orlanski and Chang, 1993; Orlanski and Sheldon, 1993, 1995; Chang, 1993; Chang and Orlanski, 1993, 1994; see also Lee and Held, 1993).

The traditional analysis of group velocity sees it as the propagation of patterns resulting from interference between two simple harmonic superimposed waves. Although Rossby (1945) regarded this as "a recourse to artificially introduced interference patterns", this has become much of a standard. The papers which have emerged from Orlanski's investigations often provide a physical interpretation which links organically to other studies of the energetics of the atmosphere and the dynamics of jetstreams (see for example Uccelini and Johnson, 1979).

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