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Convection and its parametrization recent progress

M. Tiedtke and M.J. Miller

Research Department

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1. INTRODUCTION

A fundamental component of the Centre's forecast model physics is the convective parametrization scheme, and the development and testing of new more comprehensive schemes has been a major aspect of the research work in the past few years. This paper aims to review this. Following a discussion of recent observational and modelling developments in general, two schemes are described which have been developed and tested in global forecasts. These schemes are:

(i) a generalized adjustment scheme based on the observational fact that the thermal state in convective situations is strongly controlled by cumulus convection, and hence reference lapse rates can be defined towards which temperature and humidity can be relaxed,

(ii) a massflux scheme which follows closely diagnostic studies showing that large-scale cumulus convective heating and moistening can be expressed in terms of cumulus induced circulations.

In the second part of the paper, verification of the schemes in global forecasts is discussed in terms of tropical and extra-tropical skill and maintenance of the mean flow, and outstanding problems and prospects considered.

1.1 The problem

The fundamental importance of diabatic heating by cumulonimbus clouds has long been recognized, not only in the maintenance of the tropical energy budget and mean flow but also as the primary energy source for tropical disturbances. Accurate modelling of the dynamics of the atmospheric general circulation depends crucially on our ability to represent the interactions between the large-scale circulations and the major convective heat sources, and the study and understanding of these is central to the medium and extended-range forecasting problem. The moisture and cloud fields associated with the convection likewise modulate the radiative sources and sinks and as models and radiation schemes improve there is increasing evidence of important feedbacks etc. on timescales much shorter than previously studied.

The role of deep convection in the extra-tropics is less well documented historically but has been a major research area in the last decade. A variety of convectively dominated phenomena have been identified which contain complex partitioning of convective and stratiform rain-producing structures. Many observational and theoretical studies have shown that convective precipitation is an important component of most baroclinic systems either as 'upright' convective ascent or 'slantwise' ascent in zones of strong vertical and/or horizontal shears.

Another area of active and relevant research is in the problem of the interaction of the tropics and extra-tropics; investigations of the relationships between modulations in space and time of tropical convective activity and low-frequency extra-tropical variability emphasises the need for better parametrizations and ultimately a more unified coupling between the various physical parametrization schemes.

The moisture supply into the regions of deep convection is determined by subtle interrelations between surface fluxes, vertical redistribution by turbulence and shallow convection and the entrainment of dry, subsiding air into the boundary layer. Therefore the problems of convective parametrization and the verification of the resulting fluxes etc. are fundamentally complex and progress is necessarily slow and difficult. This is particularly true in the context of medium-range (global) forecasting which combines both the requirements of synoptic detail and the longer timescale 'climate' balances.

The wealth of convective organization at all latitudes is now well-documented. In the extra-tropics convection in strong baroclinic flow or strongly diurnally controlled convective activity over the continents pose considerable doubts as to the possibility of representing these convective transports with the same parametric forms as, say, tropical ocean convection or squall lines and cloud clusters.

With these difficulties and complexities it is perhaps not too surprising that convective parametrization research requires access to an NWP model or a GCM and can only be done in a limited number of research centres. Of recent note are the convection schemes developed by Geleyn (1985) and Bougeault (1985). They have compared their schemes under different synoptic situations and also at different resolutions in limited-area and hemispheric models. Much has been learnt about the performance of the schemes under extra-tropical conditions but the studies have necessarily not addressed problems related to tropical systems and the maintenance of the large-scale flow. Elsewhere parametrization work seems to have mostly concentrated on studies of cyclogenesis and convective complexes (ECMWF Seminar 1987). These sensitivity experiments produce a wide range of responses to different schemes and varying parameters, but a lack of direct verification of convective fluxes often devalues these studies in a more general context.

1.2 May 1985 parametrization changes

In the context of this paper it is pertinent to briefly review the significant changes in the convection parametrizations made in May 1985 (Tiedtke et al. 1985, Tiedtke et al. 1988). The introduction of a shallow convection scheme increased the moisture flux out of the subtropical boundary layer, increasing the surface evaporation, and hence the moisture source for deep convection. This increased moisture source together with a reduced moistening parameter in the Kuo scheme produced greater rainfall amounts and the increased convective heating changed the tropical temperature bias from a systematic cooling to a warming. These changes resulted in improved ITCZs, a more intense Hadley circulation and more intense and realistic subtropical highs: The resulting reduction in model systematic errors particularly in the tropics and sub-tropics was marked and an overall improvement in forecast skill was seen at all latitudes.

1.3 Outstanding tropical errors

Despite the significant improvements referred to above and several other model and analysis changes which have further improved the extra-tropical forecast skill and reduced the models systematic errors (Arpe, 1988) there are still major shortcomings especially in the maintenance of the tropical mean flow and the forecasting of tropical transient eddies. There is an easterly wind error in the tropics which is most prominent in Northern Hemisphere winter (Fig. 1) and summer, with smaller (still easterly) errors in spring/autumn. This error extends through much of the upper troposphere with a large latitudinal extent (Fig. 2). Likewise the forecasts fail to maintain the strength and locations of the large-scale divergent circulations as shown in Fig. 3. As will be shown later, these mean errors are sensitive to the representation of convection.

The May 1985 physics changes strongly magnified the existence of a 'spin-up' problem in the tropical forecasts, whereby the convective precipitation is excessive during the first three days of the forecast and then regains a reasonable balance but with too dry and warm a tropical troposphere. Illari (1987) reviewed the sensitivity of the spin-up to analysis and convection changes.

The present operational tropical forecasts do not deepen and/or maintain transient eddies well; this has not been intensively studied but may be related to the above spin-up problems.

1.4 Extra-tropical forecasts

As discussed above, the presence of strong wind shear, mid-level cloud bases and 'slantwise' instability, complicate the convective parametrization problem in extra-tropical latitudes. The new schemes described in the next section allow mid-level convection and have been extended to include slantwise convection but only in a preliminary research context. The importance of convective momentum transports in strong wind shear is appreciated (Miller and Moncrieff, 1984) but has not yet lead to a practical scheme.

As will be seen, improving convection schemes has a systematic benefit to forecast quality and occasionally very marked sensitivity as described in Simmons and Miller (1988) and later in Section 3.5.

The impact of tropical convection on the extra-tropical flow is difficult to assess but 'relaxation-type' experiments and experiments in which modifications to parametrization schemes are made only in the tropics do indicate sensitivity at least for certain flow regimes.

1.5 Cloud/radiation interactions

While acknowledging the fundamental role of the radiative forcing and the more subtle cloud-radiation processes, this paper will necessarily omit discussion of this wider subject.

The following sections discuss the basis of two new convection schemes developed at the Centre which attempt to (i) represent more comprehensively the convective processes described above and (ii) alleviate some of the outstanding deficiencies.

It is planned to replace the existing deep and shallow convection schemes in the near future.

2. PARAMETRIZATION OF CUMULUS CONVECTION

2.1 General aspects

Parametrization of cumulus convection in large-scale model implies the interaction of the synoptic flow, individual clouds and possible organization in meso-scale cloud complexes with well developed circulations. Although there seems to be sufficient evidence from observational and numerical studies that cumulus convection is basically parametrizable in spite of the existence of meso-scale organization, large uncertainties exist as to the appropriate closure assumptions and modelling of cloud fields; presently applied closures basically fall into one of two categories (Arakawa and Chen, 1987):

(i) Specification of convective warming and moistening to maintain equilibrium states

This type of closure implies that convection exerts a strong influence on the large-scale flow such that under convective situations the thermal structures rapidly approach certain equilibrium states. This type of closure is applied in simple adjustment schemes such as the moist adiabatic adjustment scheme (Manabe et al., 1965) and the generalized adjustment scheme (Betts, 1986) but also in the highly sophisticated Arakawa-Schubert scheme (Arakawa and Schubert, 1974).

(ii) Coupling of convective heating and moistening to advective (and boundary layer) processes

Here the assumption is that penetrative convection occurs in response to large-scale processes in particular the low level large-scale moisture convergence as for example in the Kuo scheme (Kuo, 1965 and 1974) which is widely used in large-scale models.

Both closures seem to be supported by observational data and it is presently not possible to give preference for one against the other. Nor is it even clear whether these distinct closures are sufficient to describe properly the range of convective phenomena requiring parametrization.

In addition to the uncertainty about the basic closure there is little agreement among modellers as to whether and to what degree the cloud fields should be modelled. Those who advocate the use of adjustment schemes generally argue that the convective cloud fields and their associated circulations cannot be inferred with sufficient accuracy from the large-scale flow and therefore are best bypassed. On the other hand the representation of cumulus cloud fields and their associated circulations in the context of the so-called massflux-schemes appears justified on the basis of observational studies which show that realistic profiles of convective heating and moistening can be derived using very simple cumulus cloud models representing 1-dimensional entraining plumes.

In view of these large uncertainties the Centre has developed convection schemes of these various types and tested them in global models, and during recent years a number of convection schemes were assessed (S. SAC(83)8).

We found that none of these schemes has significant advantages over the operationally used Kuo-scheme and consequently the only change to the operational model in May 1985 consisted of a modification to the Kuo-scheme together with the introduction of a new scheme for shallow convection (Tiedtke et al. 1985).

Although these changes lead to significant improvements in the Centre's forecasts and analyses in various aspects (Tiedtke et al., 1988), there still exist large deficiencies in the simulated flow as shown earlier which in all likelihood are connected to cumulus parametrization and so there remains a strong motivation for further studies in cumulus parametrization. Since the changes in May 1985 we have concentrated on the development of only two schemes, that is

(1) the generalized adjustment scheme
(2) a massflux scheme in connection with a moisture convergence closure.

The closures and physical concepts of the two schemes are fundamentally different and, in view of the given uncertainty in cumulus parametrization, it seemed desirable to retain this flexibility.

The basic features of the two schemes may be summarized as follows.

2.2 Generalized adjustment scheme

The scheme is based on the observational evidence that in convective situations there exists a quasi-equilibrium between the cloud fields and the large-scale forcing Betts (1986). This implies the existence of characteristic temperature and moisture profiles which can be observed and used as the basis for adjustment schemes for shallow (non-precipitating), deep and middle-level convection. Given suitable profiles the large-scale temperature and moisture fields can then be simply adjusted as

$$\left(\frac{\partial \bar{T}}{\partial t}\right)_{cu} = \frac{T_{ref} - \bar{T}}{t} \qquad (1)$$

$$\left(\frac{\partial \bar{q}}{\partial t}\right)_{cu} = \frac{q_{ref} - \bar{q}}{t} \qquad (2)$$

In our scheme the lapse rates of the reference profiles of temperature T_{ref} and moisture q_{ref} are defined from observational data in the tropics (Betts, 1986) and are applied over the whole globe. An important feature of the reference temperature profiles is that for situations of penetrative convection in accordance with observed tropical soundings the lower troposphere is conditionally unstable whereas the higher levels are stable. The scheme is therefore much more realistic than the moist adiabatic adjustment scheme where the reference profile is that of a moist adiabat. The reference moisture profile is defined assuming typical degrees of subsaturation. For the case of shallow convection the reference lapse rates are those of a mixing line through the air below cloud base and the air above the level of non-buoyancy.

The relaxation time is a disposable parameter which has been determined from 1-dimensional experiments using special observational data sets (Betts and Miller, 1986) which were used to test thoroughly both deep and shallow schemes. An important aspect which is central to the adjustment philosophy is that the difficulties in representing the wide range of cloud and subcloudscale processes are effectively bypassed. Nevertheless, the scheme relies heavily on observational data to provide realistic reference profiles and relaxation times under various conditions. Particular difficulties arise for the boundary layer. Due to the strong interaction of the boundary layer flow and the convective-scale flow, the definition of reference profiles in the boundary layer and in particular the relaxation time-scale is of crucial importance and the scheme's treatment of the boundary layer interaction has been modified during the last year in order to remove undesirable features in the simulated large-scale flow. The modification consists of defining a reference profile for the subcloud layer and computing a local adjustment time from the local moisture budget such as to either maintain the subcloud moisture content and equivalent potential temperature values or to allow systematically higher ones. The present scheme, with only one reference lapse rate for penetrative convective situations, plus one for midlevel convection may be considered a preliminary version. However, given sufficient observational data and sufficient experimentation the scheme can be refined to perform optimally for various convective regimes and at various model resolutions.

2.3 <u>Massflux-scheme</u>

The scheme is very different from the adjustment scheme as the interaction between the large-scale flow and the cumulus cloud fields are explicitly modelled. The scheme is described in detail in Tiedtke (1988) and is therefore only briefly summarized here.

Clouds are represented as a bulk model following earlier studies by Yanai et al (1973 and 1976) who prior to the introduction of spectral cloud ensembles in diagnostic studies applied a bulk model and obtained realistic contributions from convection to the large-scale budgets of heat and moisture.

The large-scale budget equations are in the usual notation (s = dry static energy):

$$\frac{\partial \bar{s}}{\partial t} + \bar{v}.\nabla\bar{s} + \bar{w}\frac{\partial \bar{s}}{\partial z} = -\frac{1}{\bar{\rho}}\frac{\partial}{\partial z}(\bar{\rho}\,\overline{w's'}) + L(\bar{c}-\bar{e}) + \overline{Q_R} \quad (3)$$

$$\frac{\partial \bar{q}}{\partial t} + \bar{v}.\nabla\bar{q} + \bar{w}\frac{\partial \bar{q}}{\partial z} = -\frac{1}{\bar{\rho}}\frac{\partial}{\partial z}(\bar{\rho}\,\overline{w'q'}) - (\bar{c}-\bar{e}) \quad (4)$$

where the cumulus transports are given as

$$(\bar{\rho}\,\overline{w's'}) = (M_u s_u + M_d s_d - (M_u + M_d)\,\bar{s}) \quad (5)$$

$$(\bar{\rho}\,\overline{w'q'}) = (M_u q_u + M_d q_d - (M_u + M_d)\,\bar{q}) \quad (6)$$

(M_u/M_d = updraft/downdraft massflux, index u/d refers to updrafts/downdrafts).

The conceptual idea of the cumulus clouds is that adopted in many diagnostic studies. Cumulus clouds are assumed to be embedded in the large-scale environment, share the same cloud base but extend to various heights. They are defined by updraft and downdraft mass fluxes and by their thermal properties as dry static energy s, moisture q and cloud water content ℓ. They are modelled as one-dimensional entraining plumes and the bulk of the clouds are assumed to be in a steady state. Then the equations for the bulk of updrafts are

$$\frac{\partial M_u}{\partial z} = E_u - D_u$$

$$\frac{\partial (M_u s_u)}{\partial z} = E_u\,\bar{s} - D_u\,s_u + L\,\bar{\rho}\,c_u \quad (7)$$

$$\frac{\partial(M_u q_u)}{\partial z} = E_u \bar{q} - D_u q_u - \bar{\rho} c_u$$

$$\frac{\partial(M_u \ell)}{\partial z} = \qquad - D_u \ell + \bar{\rho} c_u - \bar{\rho} G_p$$

(E_u/D_u = entrainment/detrainment rates,

c_u = condensation rate in updrafts,

Gp = generation of precipitation water).

Downdrafts are considered to be associated with convective precipitation from the updrafts and originate from cloud air influenced by the injection of environmental air. The equations for the bulk of downdrafts are the same as for the updrafts except now describe a saturated descent hence

$$\frac{\partial M_d}{\partial z} = E_d - D_d$$

$$\frac{\partial(M_d s_d)}{\partial z} = E_d \bar{s} - D_d s_d + L \bar{\rho} e_d \qquad (8)$$

$$\frac{\partial(M_d q_d)}{\partial z} = E_d \bar{q} - D_d q_d - \bar{\rho} e_d$$

(e_d = evaporation rate of convective precipitation to maintain saturated descent).

The scheme represents 3 types of convection, i.e. penetrative convection in connection with large-scale convergent flow, shallow convection in suppressed conditions associated with tradewind cumuli and mid-level convection associated with potentially unstable air above the boundary layer and large-scale ascent. The closure assumptions for determining the bulk cloud massflux are essentially of the moisture convergence type: penetrative convection and mid-level convection are maintained by large-scale moisture convergence via dynamical entrainment of environmental air through cloud base and cloud edges and shallow convection is maintained by supply of moisture through the cloud bases in response to surface evaporation. In addition there is turbulent entrainment/detrainment depending on cloud size in accordance with observational data.

The intensity of downdrafts is assumed to be directly proportional to those of the updrafts following observational studies (Johnson, 1976 and 1980).

The scheme is attractive as it has a clear physical concept of the interaction of cumulus cloud fields and the large-scale flow, and observational data studies support the use of a simple bulk cloud model. However, the closure assumptions are less certain as little guidance is obtainable from observational studies. In particular it remains questionable whether the closure assumptions presently used hold under the various synoptic situations encountered in a global forecast model. This is an area for future development.

Parametrization of cumulus momentum transport is very uncertain and therefore is often neglected in large-scale models. A simple scheme where cumulus effects are expressed in terms of convective massfluxes has been proposed by Schneider and Lindzen (1976). This approach which for tropical cloud clusters is supported by a comprehensive data study (Lee, 1984) has been adopted in the massflux scheme and has been found to be beneficial in reducing the errors in the mean tropical flow (see below).

Before applying the scheme in global forecasts it was extensively tested using single column data sets from tropical field experiments (GATE, Marshall Island, ATEX, BOMEX) and from SESAME-79 for extratropical organized convection. The verifications show that the fields of convective heating and drying are realistically reproduced (Tiedtke, 1988). As an example we show in Fig. 4 the convective massflux for the two tropical data sets of penetrative convection (Atlantic, GATE and Pacific, Marshall Islands) which clearly shows that the scheme is able to reproduce the different profiles of convective updrafts over the tropical Atlantic and tropical Pacific. This is significant for large-scale models as the vertical profiles of convective heating and large-scale ascent strongly depend on the profiles of convective updrafts.

3. RESULTS

3.1 Experimentation

Here we summarize the results from the experimentation with the two convection schemes. The adjustment scheme has been comprehensively tested and has been run on 35 initial dates during the last two years; 24 forecasts are from re-assimilated analyses. In addition extended integrations (T63, 30 days) were made from two summer and two winter dates. The massflux scheme in its present version has been available since August 1987 and tested on 28 initial dates and also in extended integrations. Both schemes were also tested in the data assimilation suite for short periods during the Australian Monsoon Experiment (AMEX, Jan/Feb 1987) where the data coverage in the convectively active area north of Australia was enhanced.

3.2 Convective forcing and time-mean tropical flow

The primary aim of convection parametrization is to produce realistic profiles of convective heating. Unfortunately adequate data to verify these profiles are not available and therefore convection is often assessed in terms of zonal means of the time averaged heating. The zonal mean values obtained from the three convection schemes (i.e. operational scheme and the two new schemes) show distinctly different profiles (Fig. 5a-c). The heating in the tropics from the operational Kuo-scheme appears rather small at higher levels over the sea (Fig. 5a, top/left) as compared to the two new schemes (Fig. 5b and 5c, notice the different plotting intervals). The adjustment scheme (Fig. 5b) produces some cooling above the zero buoyancy level of penetrative clouds particularly over the tropical oceans, this being absent in the other two schemes.

The effect of convective heating on the large-scale flow is most pronounced in the divergent part and consequently it is there that we see the largest impact from the two new schemes. In agreement with the stronger heating extending over a deeper layer we find that the divergent flow at higher levels is much stronger in the integrations with the two new schemes (Fig. 6). In particular we notice that the collapse of the circulation over the Indonesian area and West Pacific which is typical for the operational model disappears and there is now better agreement with the analysed divergent flow.

However, the impact on the rotational flow is much smaller leaving the errors in the zonal wind in winter for example rather unaffected by cumulus parametrization (Fig. 7). However, the error seems to be more sensitive to momentum forcing by cumulus convection as we infer from the extended summer integrations where the massflux scheme was run a) with momentum transports and

b) without momentum transports. When momentum transport is included the wind errors are much reduced most noticeably over the western Atlantic, South America and Pacific (Fig. 8). The effect of momentum forcing is seen to be in broad agreement with the findings of Heckley and Gill (1984) who found with a linear model that the length scale of the response flow from a heat source largely depends on the friction on the flow. It would therefore appear that the strong erroneous easterly flow in the experiments without friction reflect the undamped response flow from the heat sources in particular over the Indonesian area and Indian Ocean. When cumulus friction is included the flow appears to be effectively damped and does not extend beyond the Atlantic as is observed.

3.3 Tropical analyses and forecasts

It is well known that the convection scheme used in the assimilating model influences the analysis of both the mass and wind fields, particularly in the tropics. The two new schemes produce a warmer tropical troposphere (by 0.5°K in the zonal mean) and differences in the zonal mean wind of the order of 0.5m/sec. The divergent wind which strongly depends on cumulus parametrization as already discussed in section 3.2 above is markedly intensified as can be seen in the velocity potential at 200 mb (Fig. 9). Tropical forecasts typically lose skill after a few days because of errors in the analyses and rapid error growth during the early stages in the forecasts. The impact of cumulus parametrization on the analysis and forecast of tropical cyclones was studied in the region of North Australia and equatorward during a period of the Australian Monsoon Experiment (AMEX, Jan/Feb. 1987) by evaluating the operational and research convection schemes behaviour in analyses and short-range forecasts in this area. The data assimilation suite was rerun with the two convection scheme and forecasts run from these reanalyses.

As might be expected the forecasts of tropical disturbances including cyclones/hurricanes are highly sensitive to the convection scheme. There were several tropical cyclones during the AMEX period and one was located in the Gulf of Carpentaria at 12Z on 10/2/87 (Fig. 10) which is used here to demonstrate the impact of convection parametrization on analyses and forecasts. The analyses and 24/48 hour forecasts verifying on the same date are shown in Figs. 11 and 12. Apart from a wind maximum at 850 mb the operational analysis hardly shows the cyclone and the forecasts show a very weak feature, as discussed in section 1.3. The adjustment analysis shows the cyclone well-located and with a stronger wind maximum. The 24 hour forecast verifies well and develops the system a little further, it is however weaker and further east in the two-day forecast. The three-day forecasts (not shown) with either convection scheme do not represent the cyclone well at all, possibly as the cyclone was a relatively small feature compared to most major cyclones/hurricanes.

The massflux scheme was also tested in a 3-day assimilation again during AMEX. Its performance is found to be between the operational scheme and the adjustment scheme giving somewhat more intense cyclones than the operational scheme but weaker than with the adjustment.

3.4 Spin-up problem

The assimilation experiments during the AMEX period were also used to study the impact of the various convection schemes on the spin-up problem (see Illari, 1987 for a general discussion of the problem). Fig. 13 shows the spin-up in forecasts based on initial data assimilated with the same convective scheme as in the forecasts. The results confirm the earlier finding that the convection scheme has a dramatic effect on the behaviour of the spin-up. The operational convection scheme shows the typical spin-up/spin-down of convective heating during the first two days whereas the adjustment scheme produces an initial imbalance followed by a rapid adjustment. The massflux scheme seems to produce well balanced initial states as there is no indication of a spin-up in the global mean heating rate.

As convective heating is significant for the development of tropical cyclones the spin-up might affect the treatment of cyclones in data assimilation and during the early stages of the forecasts.

3.5 Extra-tropical forecasts

The sensitivity of extra-tropical forecasts to the representation of convection is the subject of considerable research with limited-area models examining explosive cyclogenesis for example (ECMWF Seminar 1987), but much less is understood in the medium-range context. The diabatic forcing from convection influences synoptic systems directly through deep convection at fronts and through mid-level and slantwise convection, however more subtle is the extra-tropical response to tropical convection. Extensive medium-range forecast experimentation summarized by ensembles of objective scores show a mean improvement in extra-tropical forecast skill for the two new schemes (Fig. 14a-b). However, for practical reasons, only in a few cases has it been possible to highlight both the direct and the indirect response by modifications to the convection scheme at different latitude belts. These cases indicate that in the medium-range both types of response are important and can on occasion contribute equally to forecast skill in the medium-range. The overall behaviour is evident in the spread of the forecast quality in terms of the scatter of the anomaly correlation for the predicted height fields (Fig. 15a-b). These show that the forecast quality diverges with forecast time and reaches values of as little as 20% by day 6.

In a number of forecasts the skill scores are deteriorated by changing convection schemes. In view of the results of predictability and forecast 'spread' studies this should not be too surprising, since as forecasts lose skill in locating the low-frequency long-wave pattern, which in turn defines the storm tracks, improving diabatic forcing of baroclinic eddies does not necessarily gain forecast skill but the reverse. Fig. 16 and 17 show two cases where convection parametrization did significantly improve the medium range forecasts in the northern hemisphere. Large improvements (indicated by a circle in the scatter diagram in Fig. 14) are obtained in forecasts from the 17 January 1988 over Europe and the Eastern Atlantic at day 2 and day 8 (Fig. 16) which originate from differences in developing cyclones over the Atlantic in the early stages of the forecasts.

In the summer case (11 June 1986) major differences are obtained in response to changes in the development of a short-wave trough over the Eastern USA during the first two days which then influences the European sector in the medium range.

Concluding remarks

We have reviewed the work on convection parametrization at ECMWF during recent years. It confirms the fundamental point that although much progress has been made mainly through diagnostic data studies in the understanding of convective organization and its interaction with the large-scale flow, the advance in cumulus parametrization has been slow and must still be considered a partly unsolved problem. This impacts on the Centre's research programme as the evolution of the large-scale flow depends strongly on cumulus convection; particularly in the tropics even at short timescales, and in the extra-tropics mainly in the medium- and extended-range but occasionally also at shorter timescales.

We have presented the recent development of two schemes which have been shown to give improvements in some aspects of the simulated flow, but further improvements in convective parametrization are still needed to reduce the large tropical wind errors, and increase the skill of the tropical short range forecasts and extratropical medium range forecasts.

We feel there is still a major requirement for more data-studies designed to provide guidance for formulating closure assumptions for various synoptic conditions.

Other areas where such studies are also needed are for cumulus momentum transport, convection in strong shear and slantwise convection. Although parametrization has started in these areas there are many uncertainties in the assumptions made without support from data.

An important area which has not been addressed in this paper is the interaction of cumulus convection with other processes such as those of the boundary layer and radiation. We are aware that a deficiency in the present model formulation is the inconsistent way clouds are defined for radiation calculation and the cloud parametrization in the model. Consequently a project has been started where the convective cloud fields are explicitly predicted in the framework of the massflux scheme.

It may seem that an over-emphasis has been put on outstanding errors and problems rather than on progress, however we stress that considerable effort has been spent on understanding what these problems are, and in the development of two new schemes which improve on our current operational ones. We have attempted to highlight advances and difficulties and stress the basic need for further observational programmes and more ideas and input from the meteorological community.

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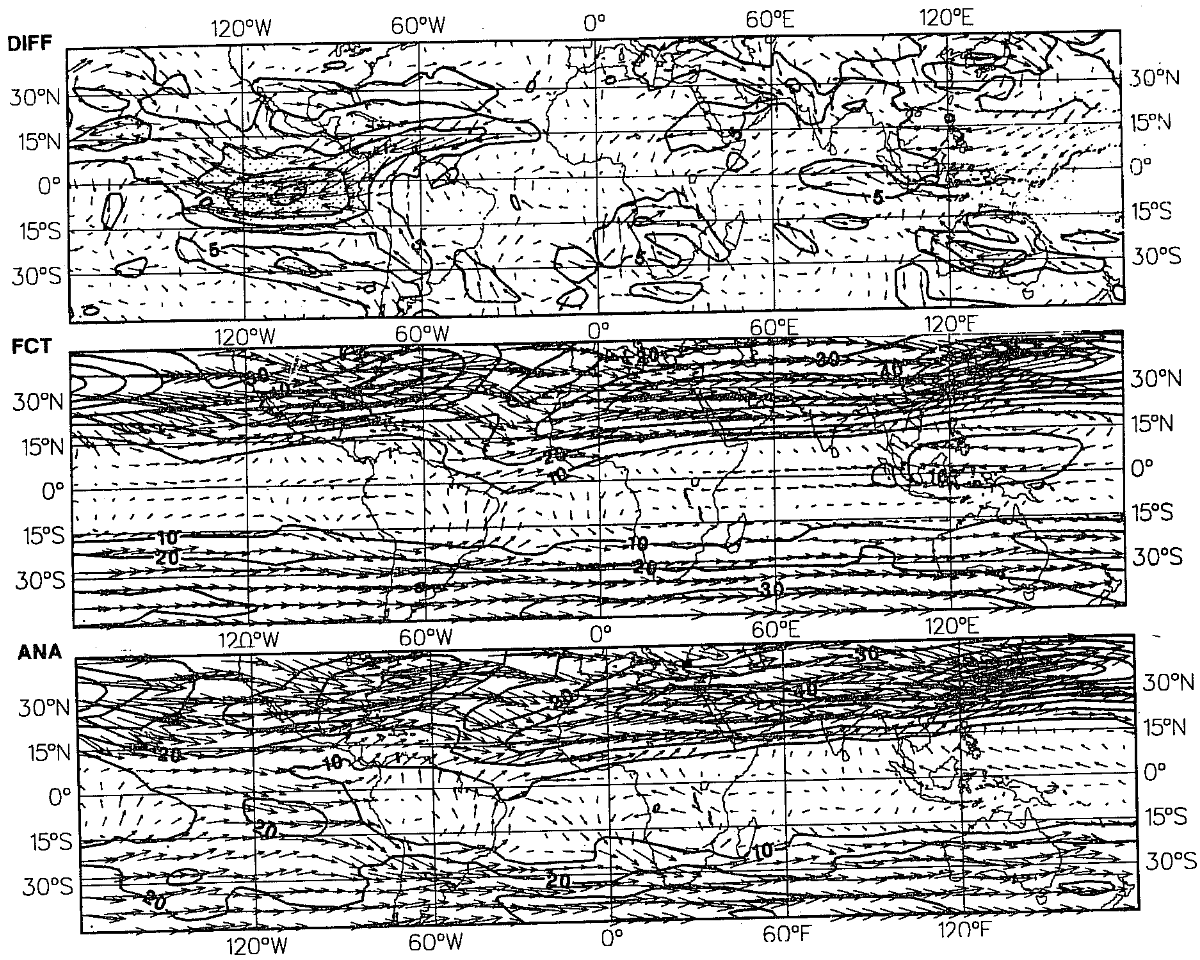


Fig. 1 Mean tropical flow and forecast error (top) at 200 mb for the ensembles of all analyses and 10 day forecasts during 1 December 1987 to 29 February 1988.

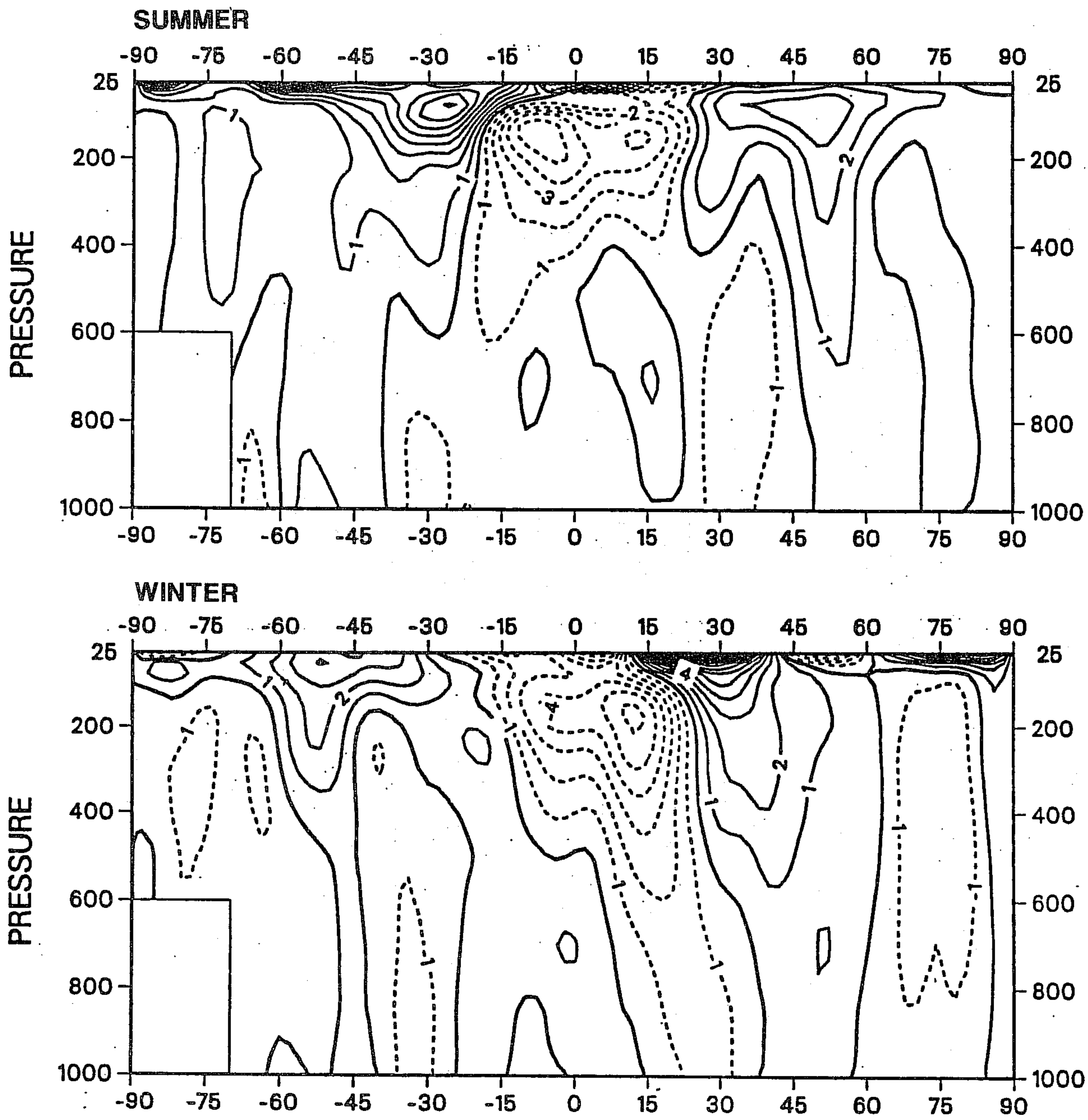


Fig. 2 Zonal mean error of zonal wind for the ensembles of all 10 day forecasts
top: 1 June - 31 August 1987,
bottom: 1 December 1987 - 29 February 1988.

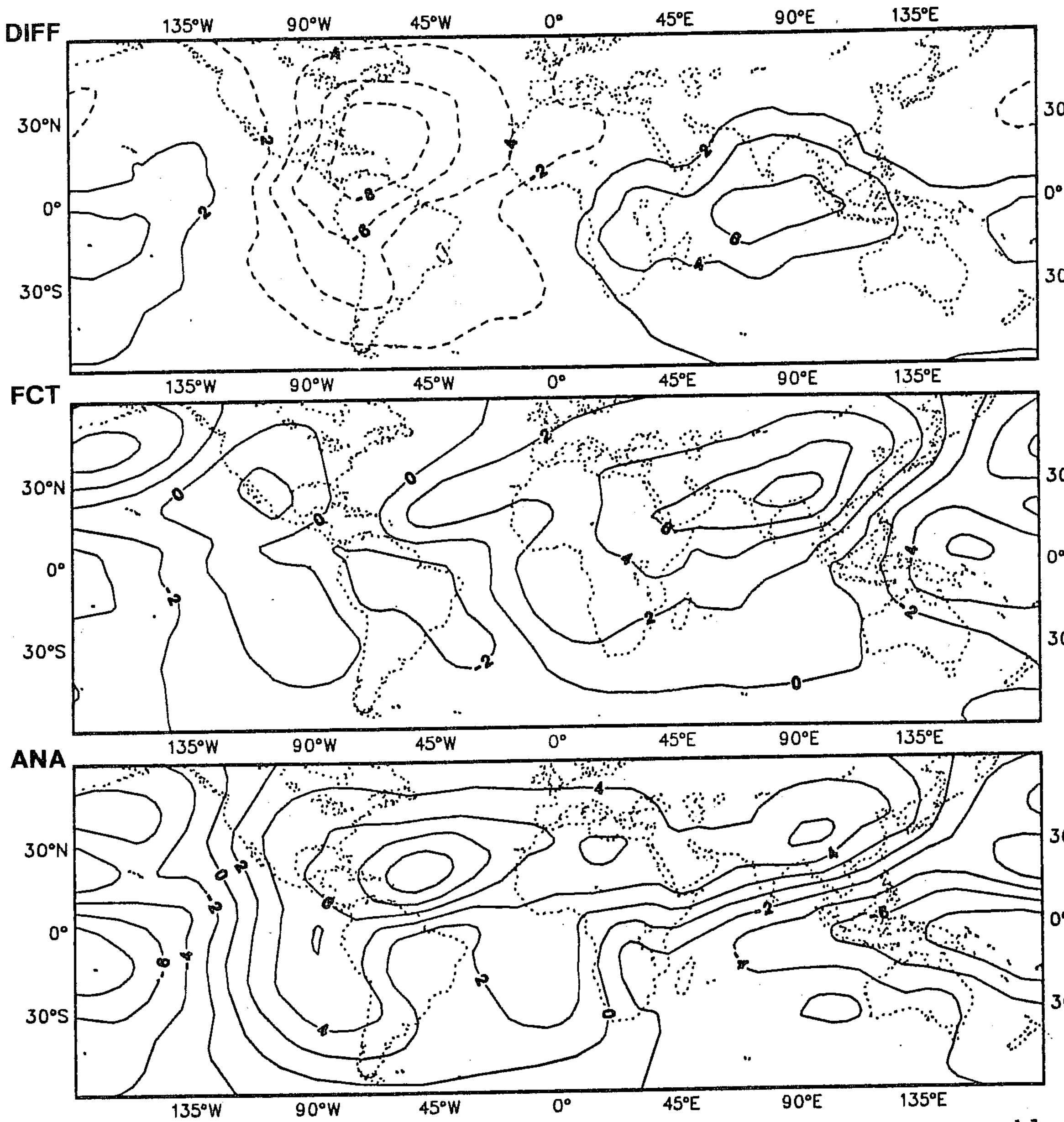


Fig. 3 Mean velocity potential ($10^6 m^2/sec$) at 200 mb for the ensembles of all analyses and 10 day forecasts during 1 December 1987 to 29 February 1988.

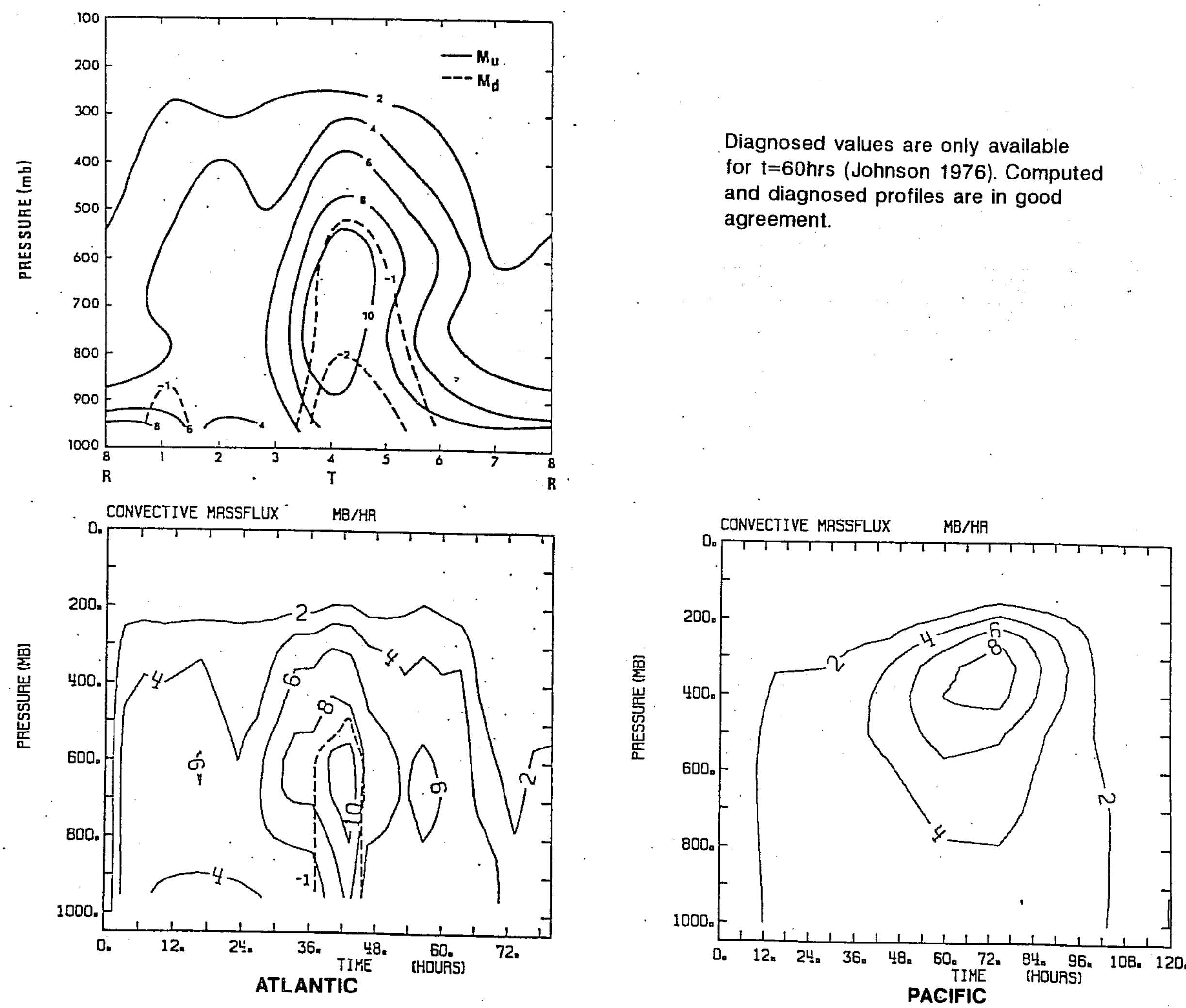


Fig. 4 Time-height cross-section of convective massflux for easterly wave composite over Atlantic and Pacific. Diagnosed values for Atlantic (top) are from Johnson (1980).

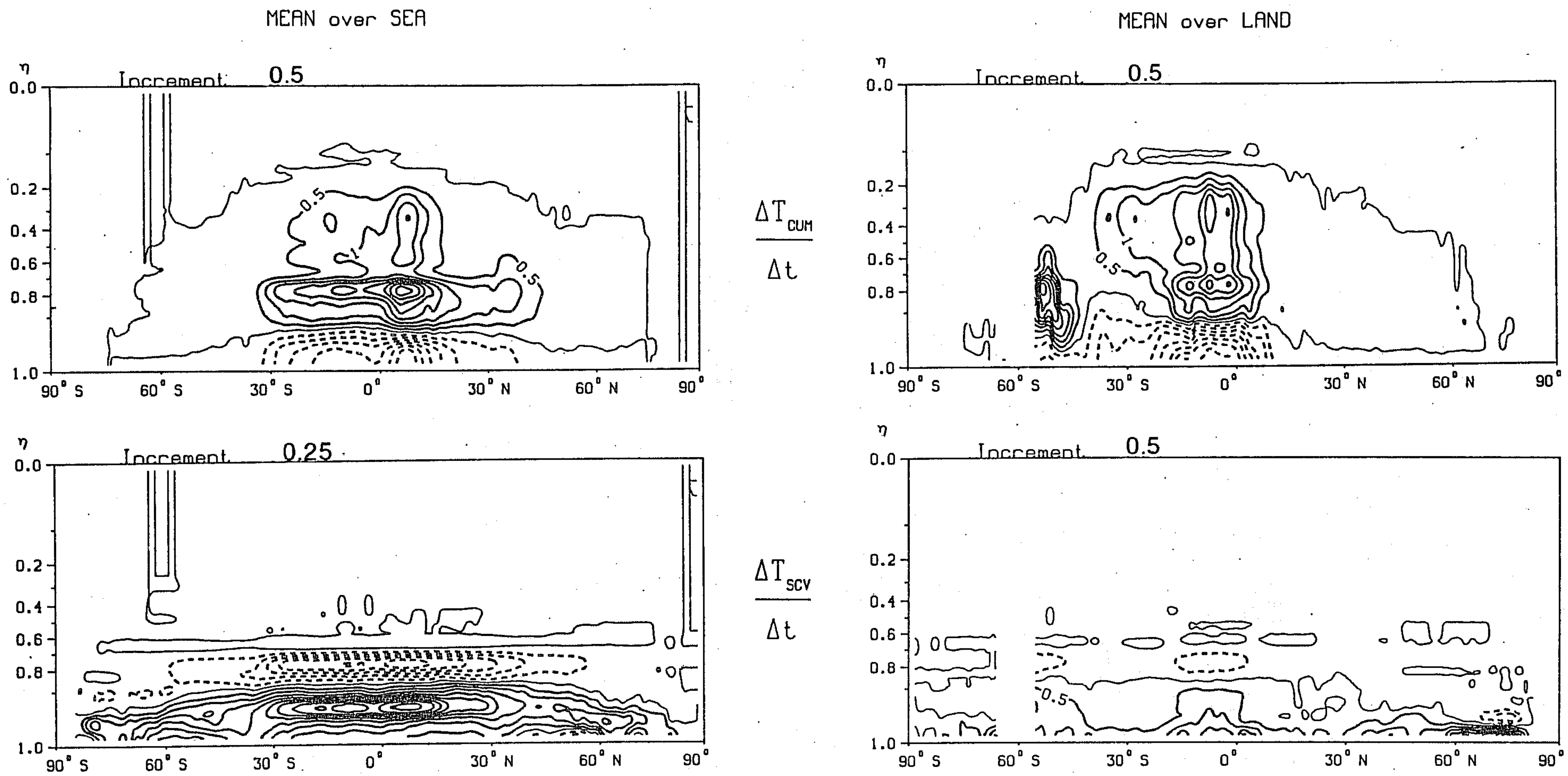


Fig. 5a Latitude-height dependent convective heating: Operational scheme (Kuo and SCV): 30 day mean convective heating (K/day) zonally averaged over all sea points (left) and over all land points (right) due to penetrative convection (top) and shallow convection (bottom) for 30 day T63 integration (H3M) from 17.1.88,12Z.

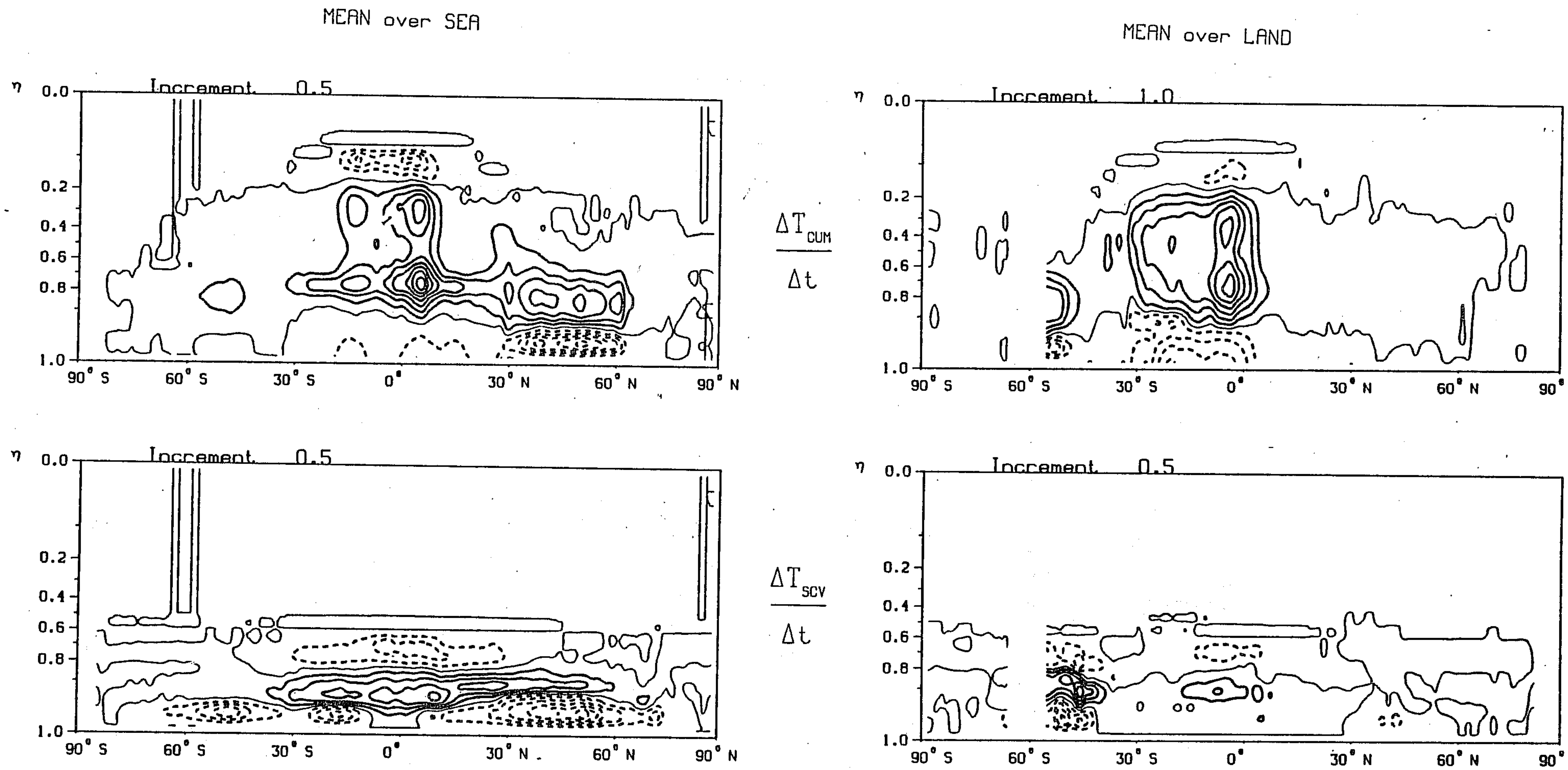


Fig. 5b As Fig. 5a, but for 30 day integration with adjustment scheme (HRP).

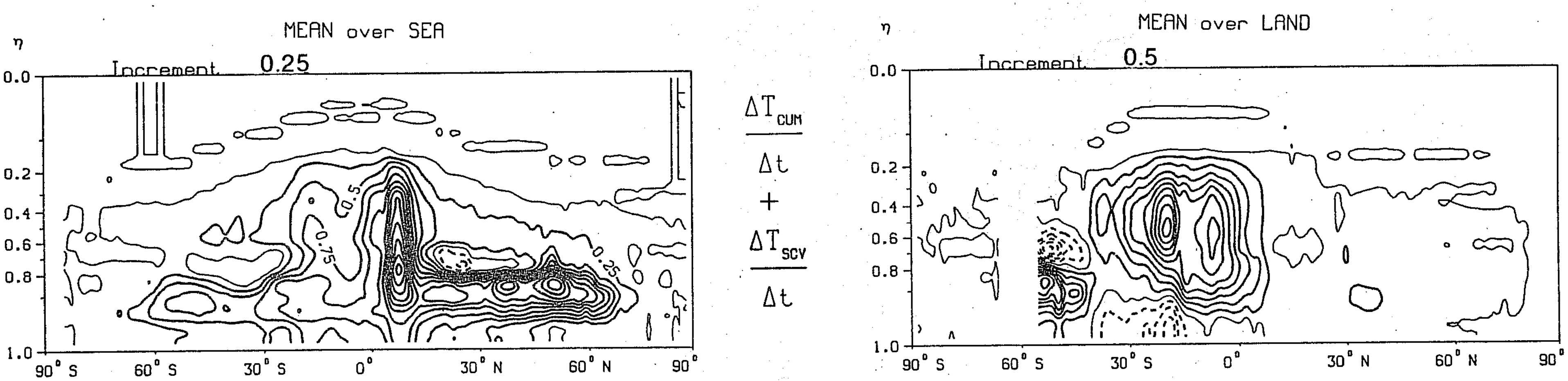


Fig. 5c As Fig. 5a, but net convective heating for 30 day integration with massflux-scheme (HIV).

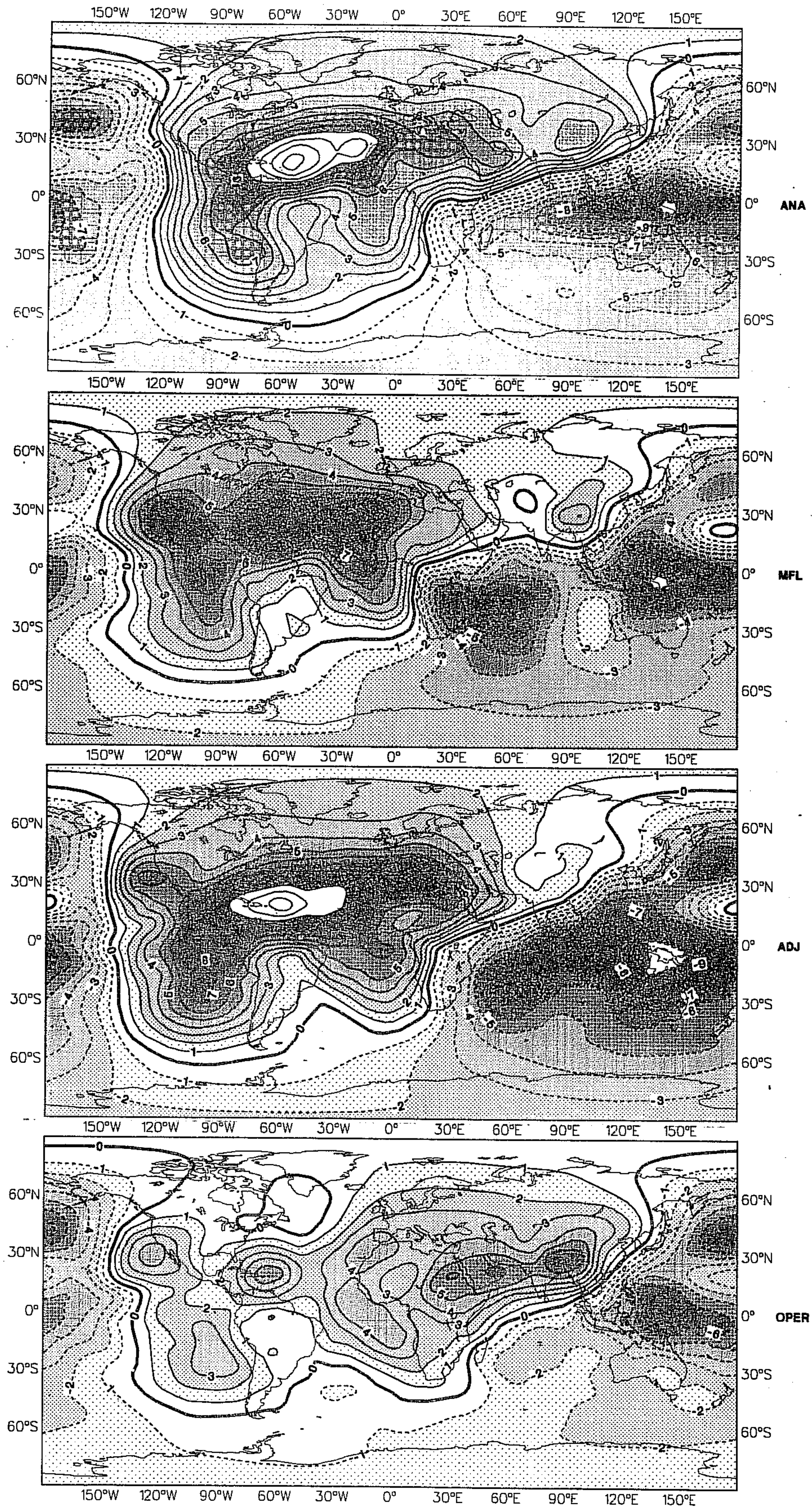


Fig. 6 30 day mean velocity potential ($10^6 m^2/sec$) at 200 mb for the integrations from 17.1.88,12Z with the operational scheme (H3M), the adjustment scheme (HRP) and the massflux scheme (HIV) plus analysed field.

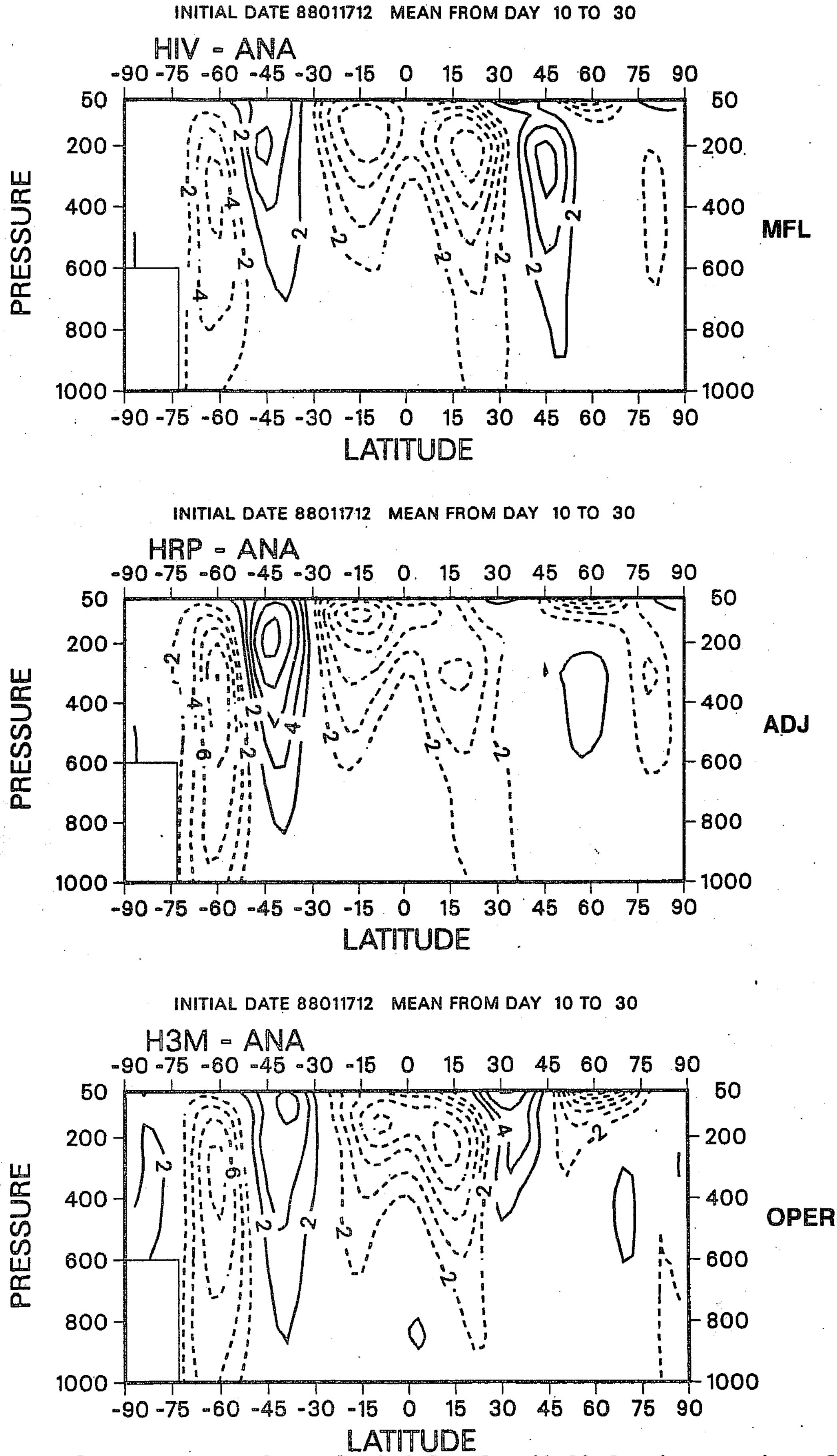


Fig. 7 Zonal mean error of zonal wind for day 10-30 for integrations from 17.1.88 with operational scheme, adjustment scheme and massflux-scheme.

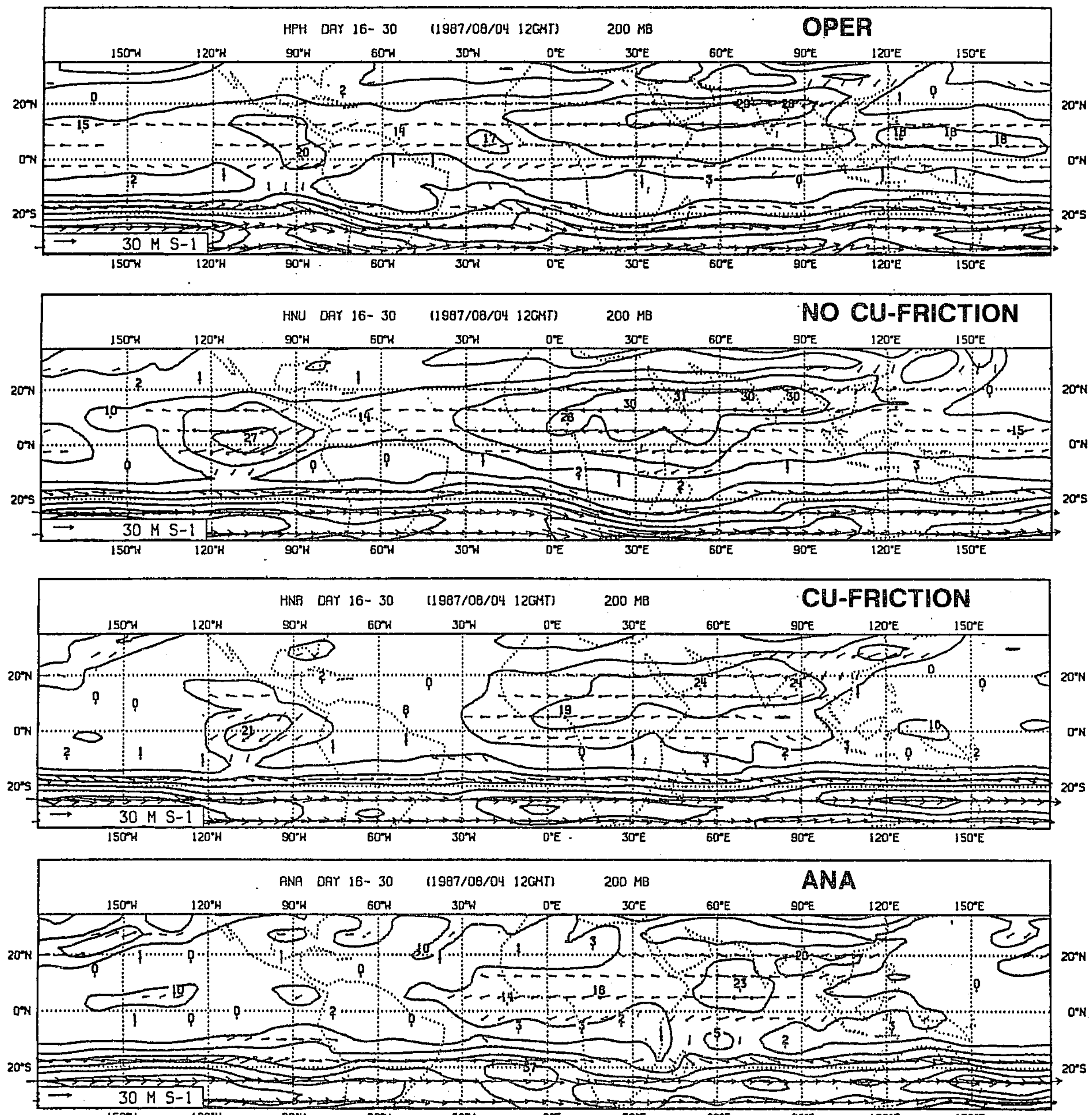


Fig. 8 (16-30) day mean tropical flow at 200 mb for T63 integrations from 17.1.88,12Z with operational model, massflux scheme without cumulus friction and with cumulus friction plus analysed mean flow for same period.

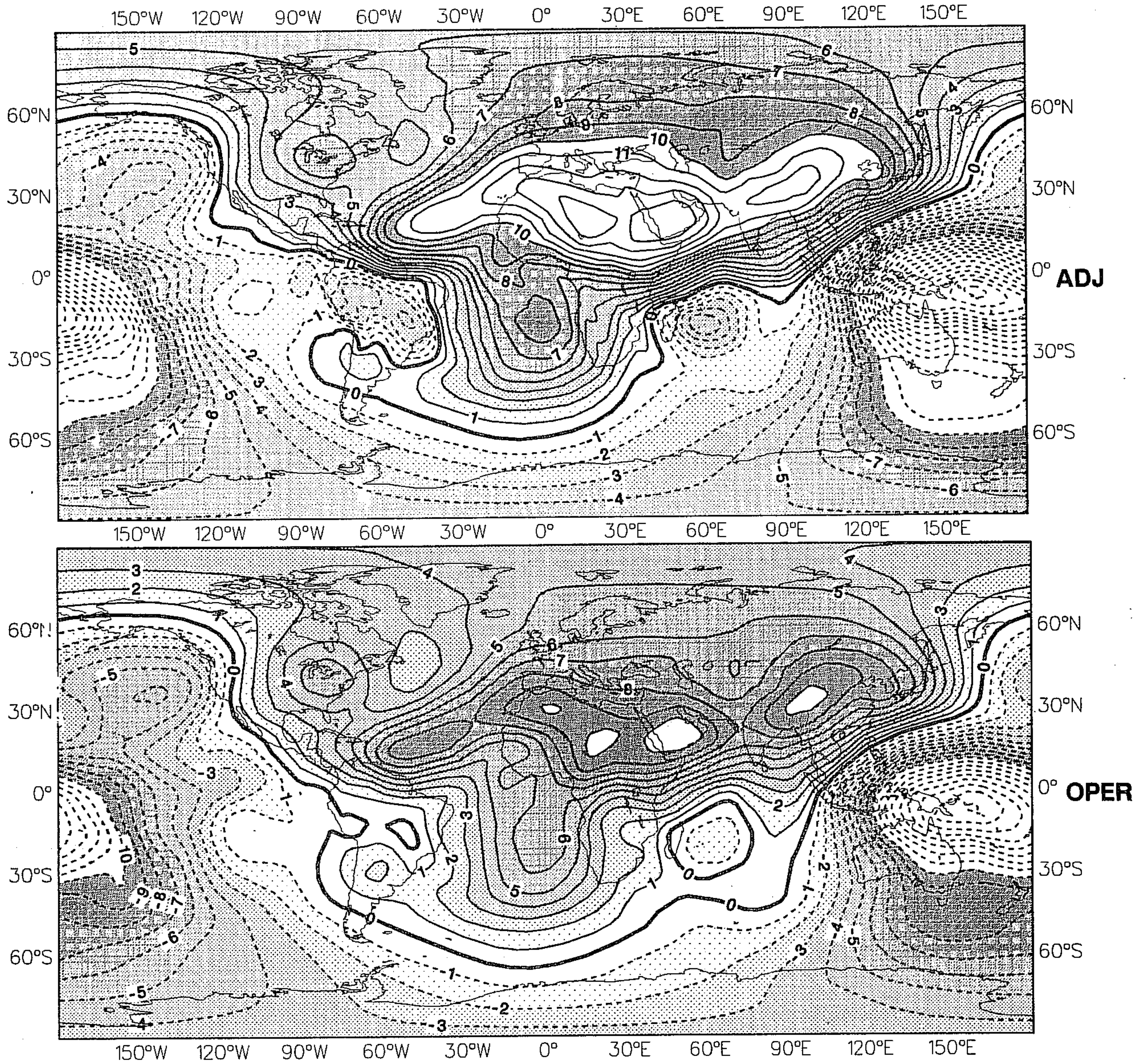
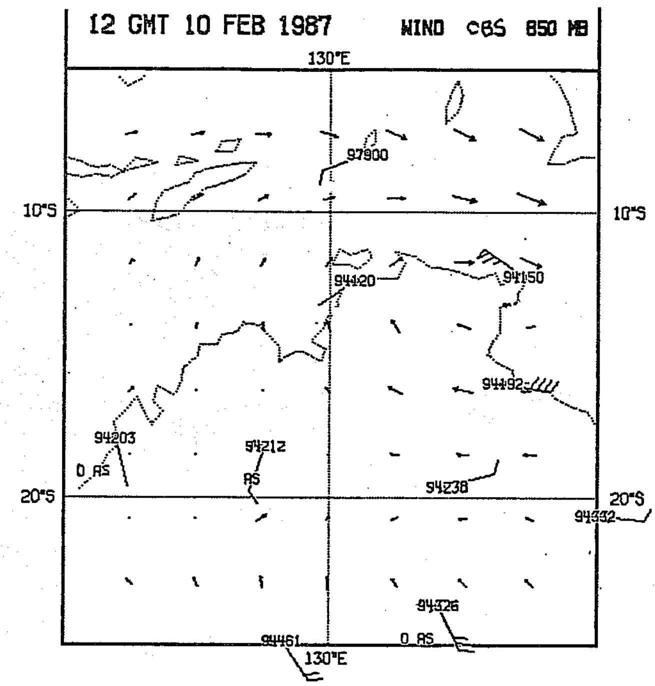
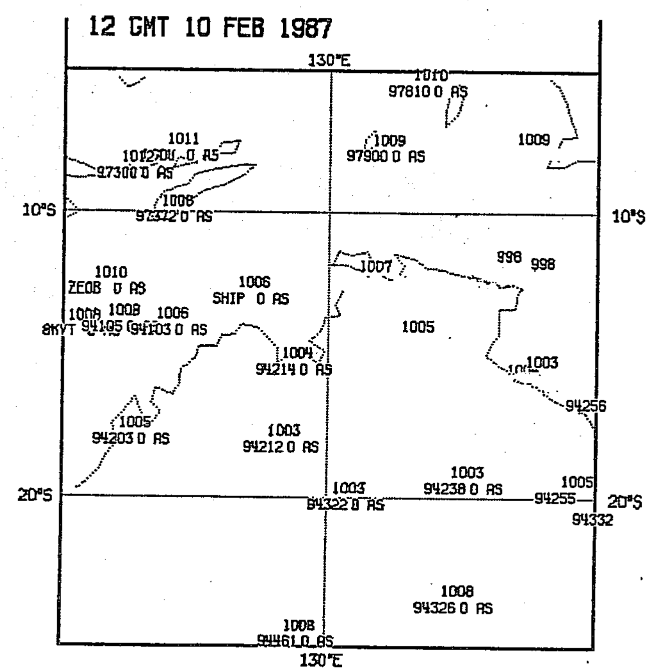


Fig. 9 Analysed 200 mb velocity potential ($10^6 m^2/s$) averaged for period 4.2.87,12Z to 16.2.87,12Z. Top: data assimilation with adjustment scheme, bottom: operational data assimilation.



850mb WIND OBS



SURFACE PRESSURE OBS

Fig. 10 Wind and pressure observations locating cyclone near 14°S, 137E.

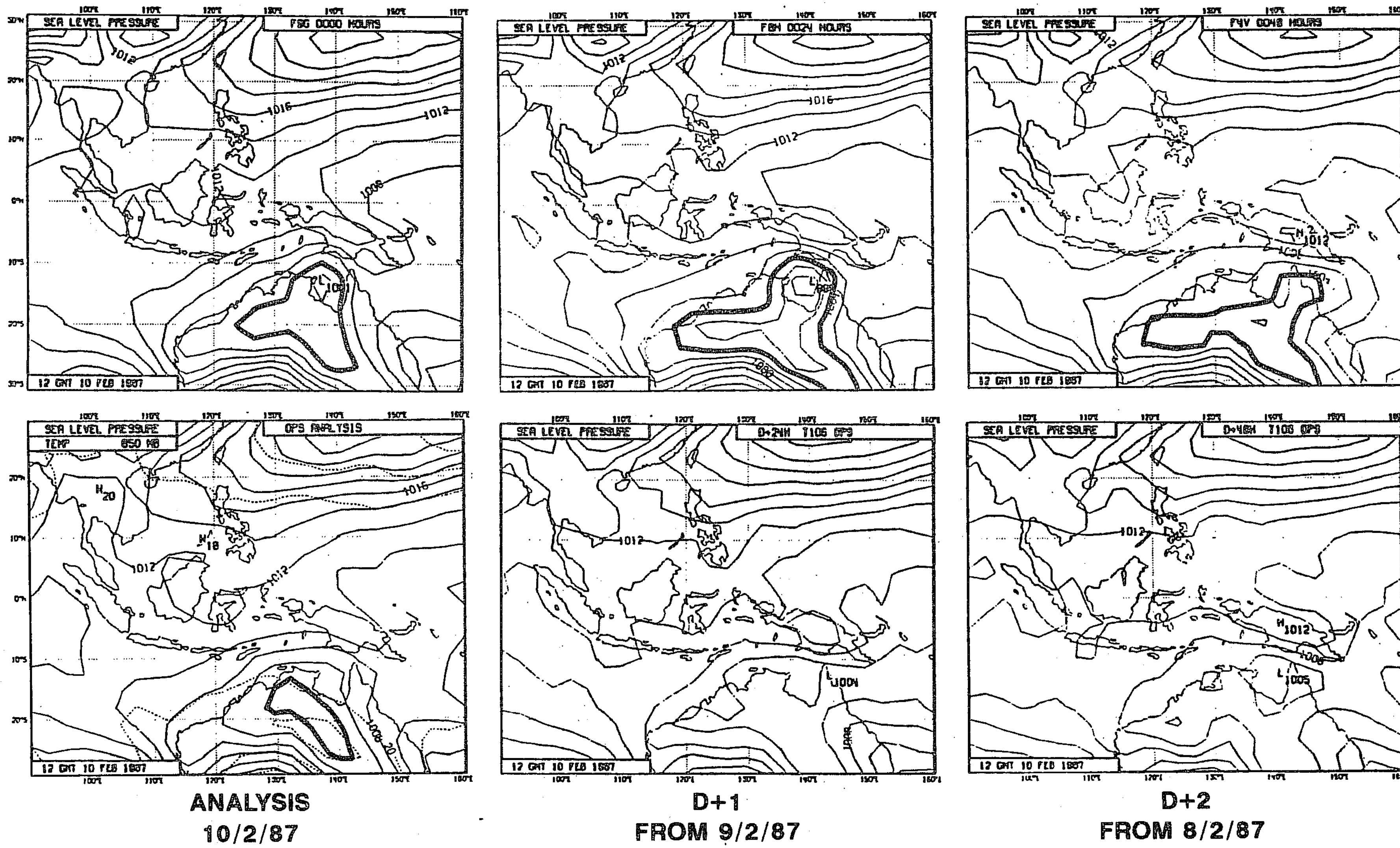


Fig. 11 Top row: adjustment analyses and forecasts - surface pressure
Lower row: operational analyses and forecasts - surface pressure

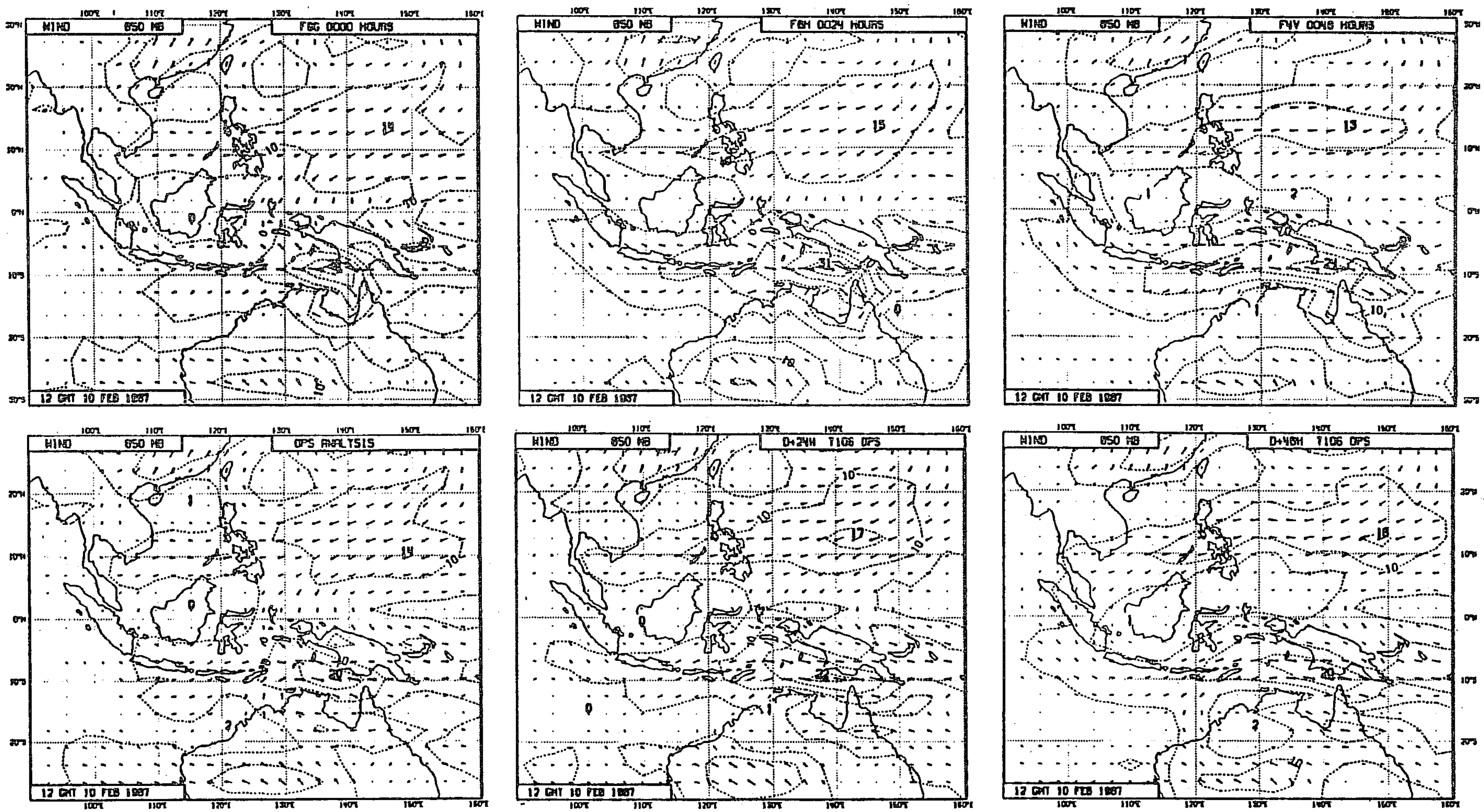


Fig. 12 As Fig. 11 but for 850 mb winds.

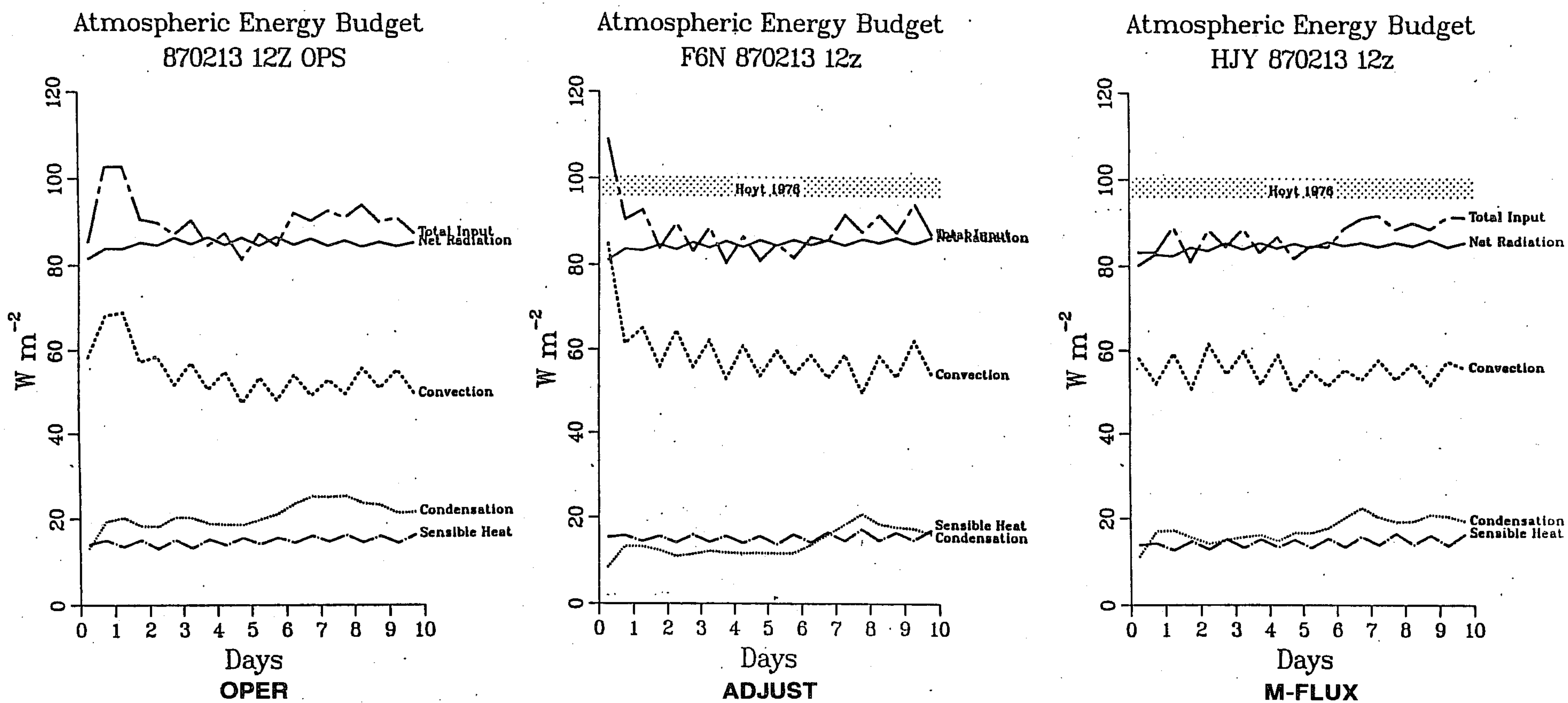
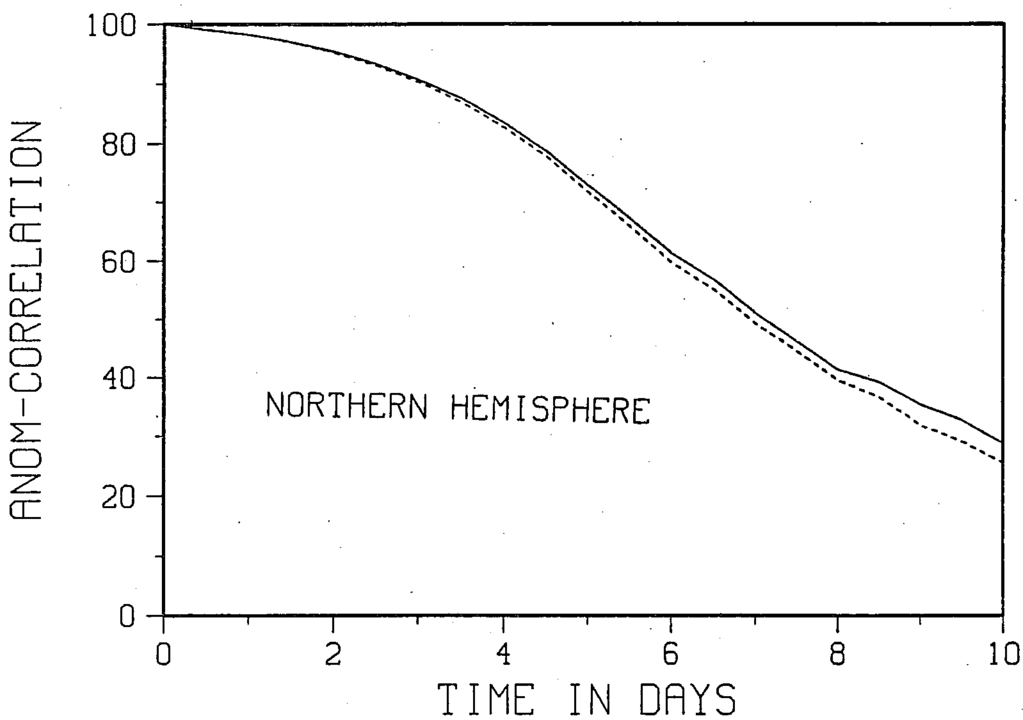


Fig. 13 Time evolution of diabatic heating due to radiation, cumulus convection, large-scale condensation and turbulent heat flux for whole globe for operational forecast and forecasts with adjustment scheme and massflux scheme (initial date 13.2.87,12Z).

ANOMALY CORRELATION (%) Z 1000-200 HPA



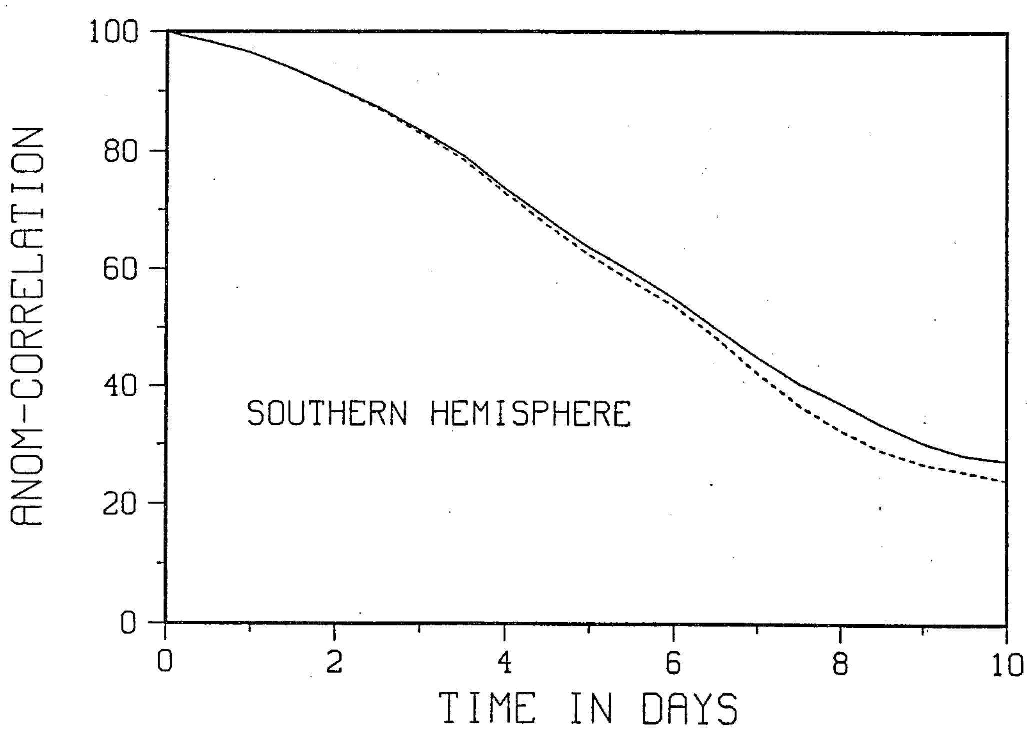


Fig. 14a Massflux-scheme: mean anomaly correlations of 1000-200 mb heights in the extratropical northern and southern hemisphere for 28 forecasts with massflux-scheme (solid line) and control forecasts with operational physics (dashed line).

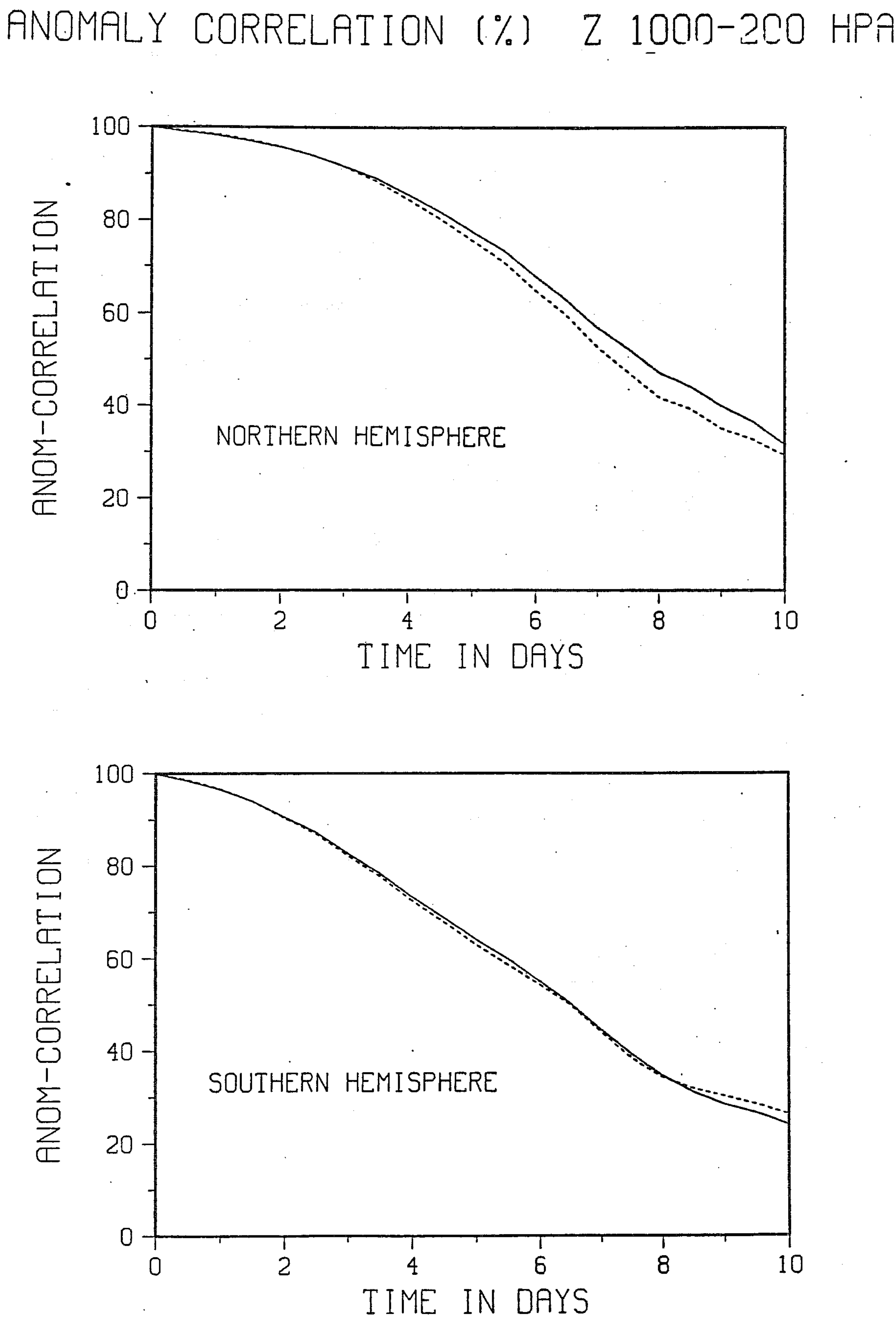


Fig. 14b As Fig. 14a but for 25 forecasts with adjustment scheme (solid line) and control forecasts with operational scheme (dashed line).

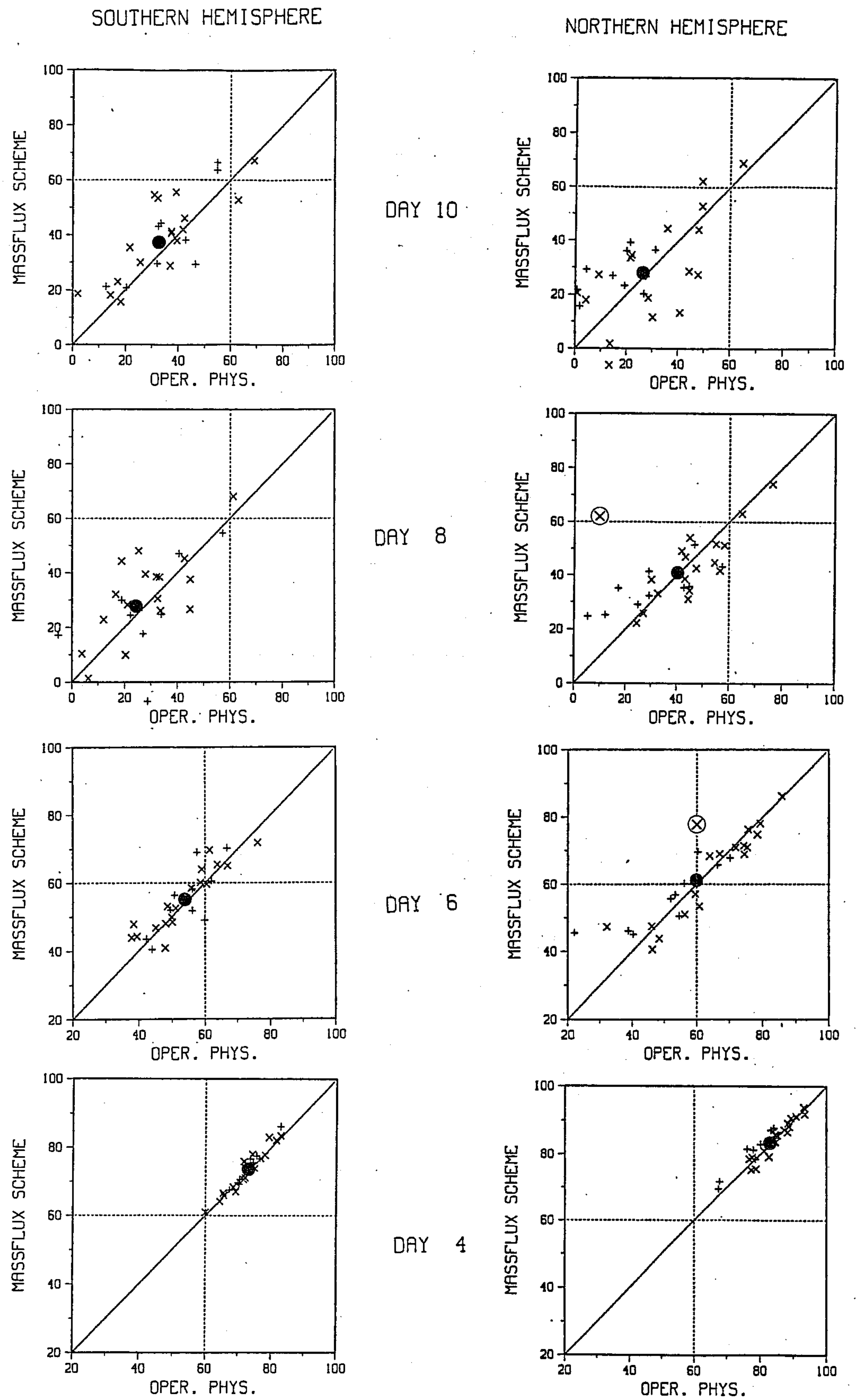


Fig. 15a Massflux-scheme: scatter diagrams of anomaly correlation of (1000-200) mb heights in extratropical Northern Hemisphere (right) and Southern Hemisphere (left). Summer cases are represented by + signs, winter cases by x signs and the mean by a thick dot. Case with circle refers to forecast from 17.1.88, 12Z shown in Fig. 16.

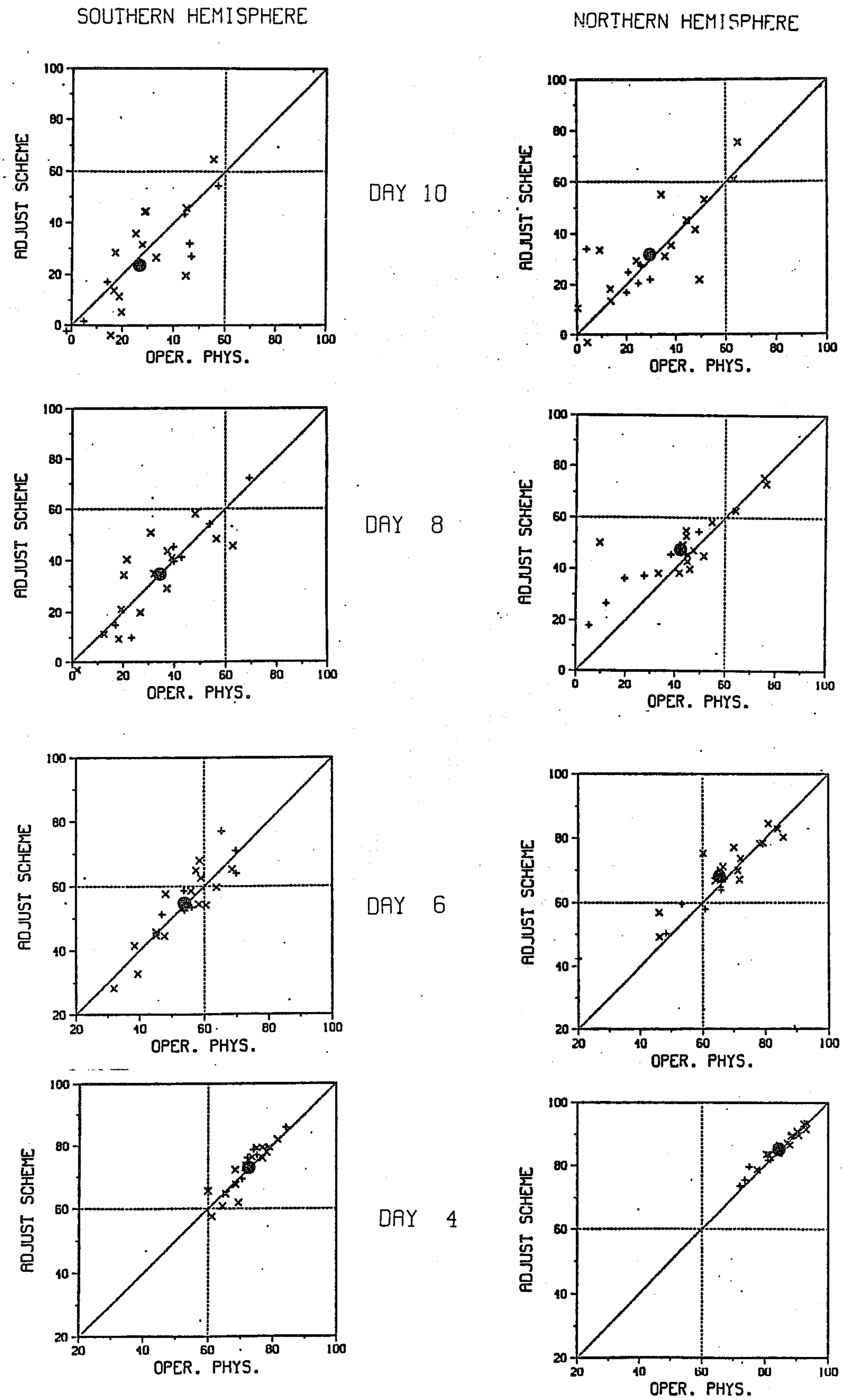


Fig. 15b As Fig. 15a but for 25 adjustment forecasts and control forecasts.

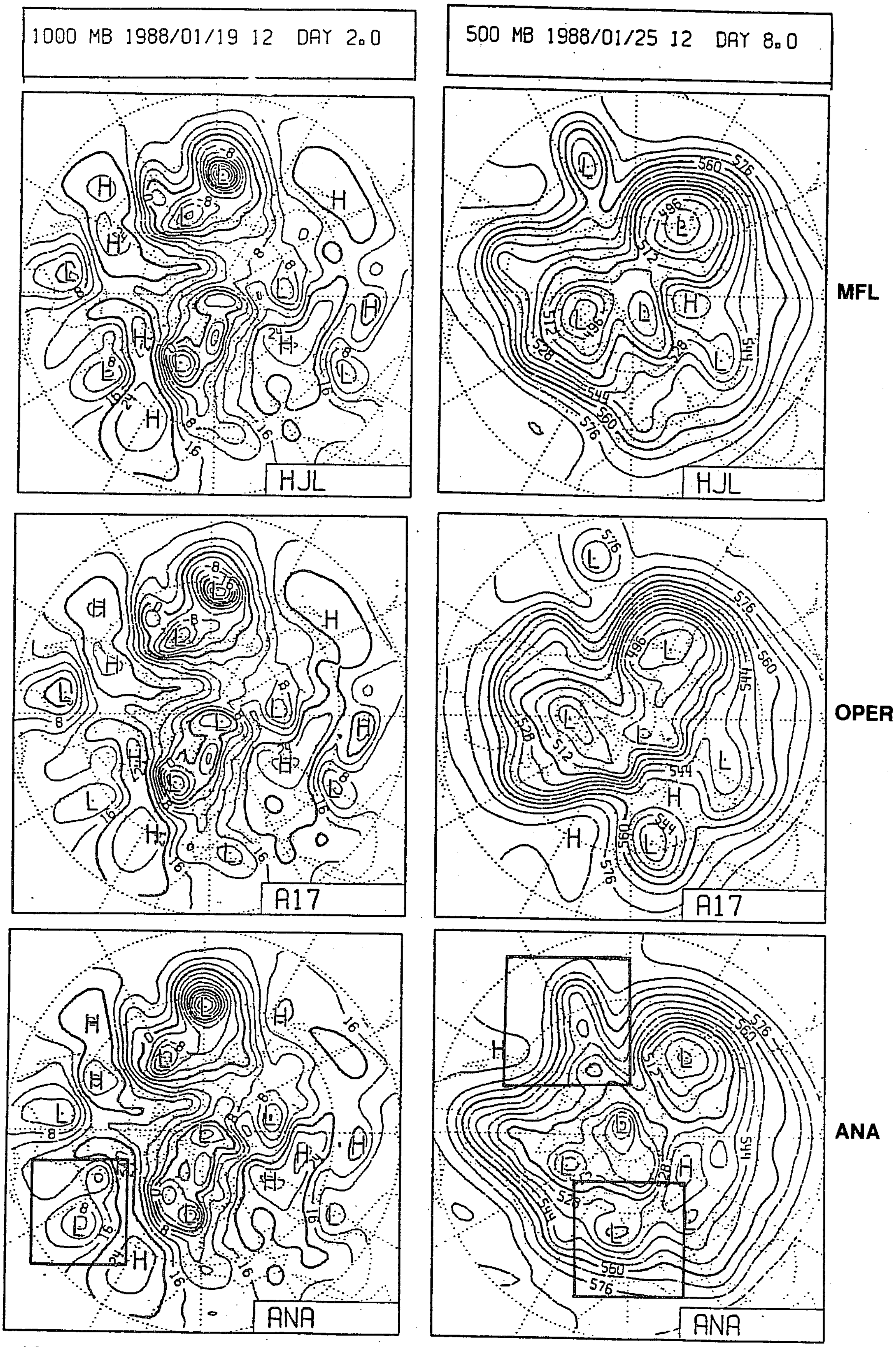


Fig. 16 Analysed and predicted height-fields at day 2 (left) and day 8 (right) for forecasts from 17.1.88,12Z. Marked areas are those with largest forecast differences.

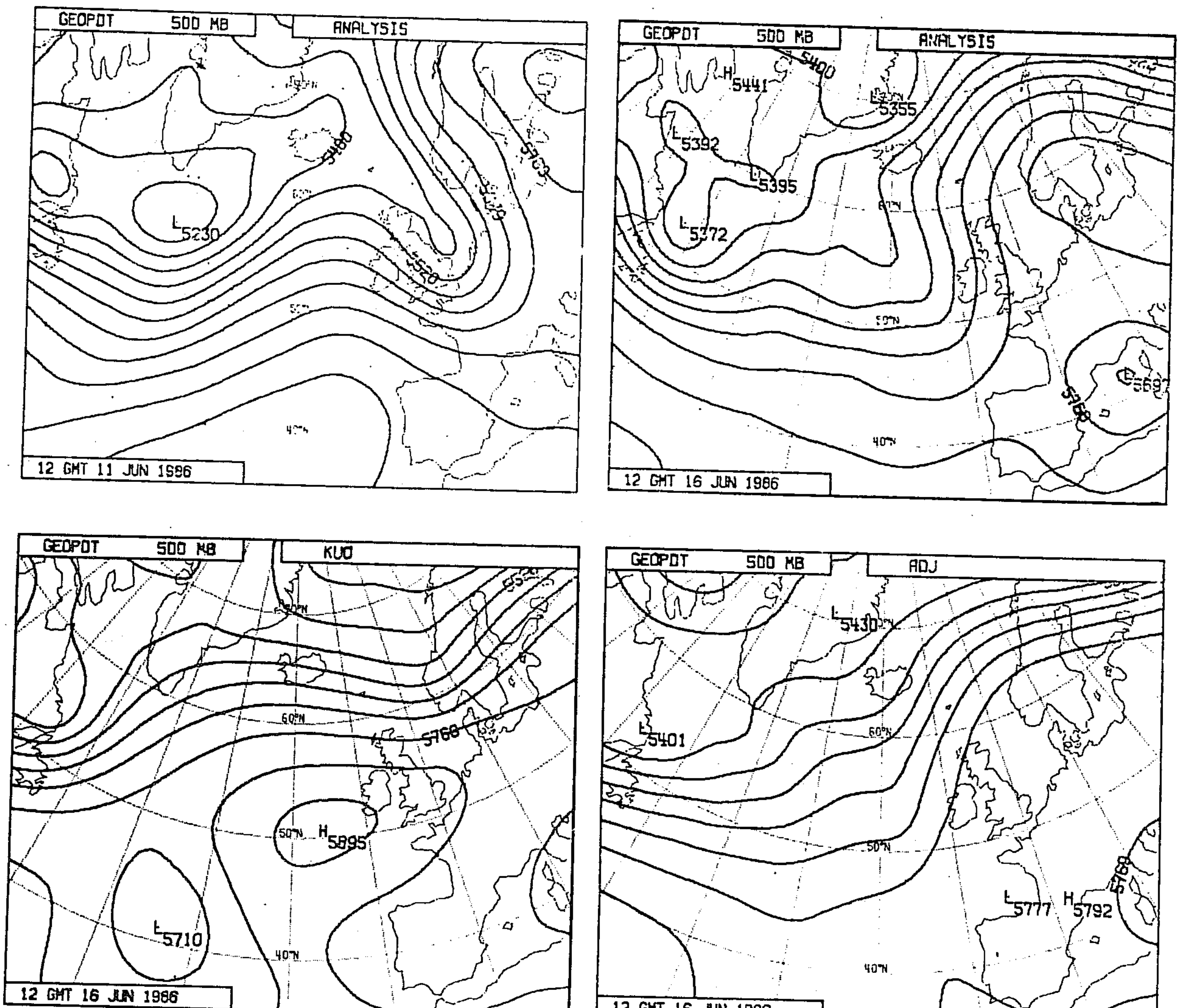


Fig. 17 500 hPa height analyses and forecasts (contour interval 60 m) for day 5 starting from 12Z, 11 June 1986, using the Kuo convection scheme and the adjustment scheme.