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Development of the operational parameterization scheme

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Abstract

A revised physical parameterization was introduced operationally in May 1985 in addition to the increased horizontal resolution. The revisions include modifications to the parameterization of deep convection, the introduction of a new scheme for shallow cumulus convection as well and a new cloud scheme.

This paper discusses the effects of these modifications on the simulated large-scale flow and illustrates their impact on the forecast quality of an ensemble of forecast experiments. The changes affect primarily the diabatic forcing in the tropics and therefore initially influence the tropical flow. The response of the extratropical flow occurs later in the forecast and affects the quality of the second half of the 10 day forecasts. In summary the revisions results in the following changes:

Tropics and subtropics

(a) intensification of the tropical diabatic heat sources through an intensified hydrological cycle by enhanced moisture supply in the subtropics;

(b) removal of the model's tendency to cool the tropical and subtropical troposphere;

(c) improved forecasts of the tropical flow beyond day 2 resulting from a reduction of systematic errors;

Extratropics

(a) strengthening of subtropical anticyclones which became realistic;

(b) intensified baroclinic energy conversions and stronger large-scale disturbances in winter hemispheres as a result of an increased production of zonal available potential energy by tropical diabatic heating;

(c) On average, with the T63 model, the forecasts are improved beyond day 6; in some forecasts the improvement is apparent at day 3; the improvements are larger and occur much earlier in the forecasts with the high resolution T106 model than with the T63 model.

CONTENTS

1. INTRODUCTION

Diagnosis of the ECMWF forecasts have revealed that some of the forecast errors are systematic, and there is evidence that removal of these systematic errors would lead to a significant improvement of the medium range forecasts. It has been argued that to a large extent these errors result from erroneous diabatic forcing. In particular the large errors encountered in the tropics and subtropics suggest serious deficiencies in the diabatic forcing. There is concern that these tropical errors may be the source of some of the mid-latitude forecast errors and a continuous effort is being made at ECMWF to:

(a) diagnose and verify the diabatic forcing in the model;

(b) study its effect on the large-scale flow;

(c) improve the parameterization of the diabatic processes in the model.

Much of the recent diagnostic work has been presented at ECMWF workshops:

- radiation - Geleyn (1980) and Slingo et al. (1985)
- boundary layer processes - Louis et al. (1981) and Tiedtke (1981)
- cumulus convection - Tiedtke (1981, 1983)
- net diabatic effects - Savijärvi (1980).

These studies revealed deficiencies in the formulation of some of the processes and have already lead to modifications of our parameterization scheme on several occasions:

Spring 1980: adjustment of disposable parameters in the boundary layer scheme

Spring 1984: introduction of the diurnal cycle together with an improved representation of soil processes

Winter 1984: reformulation of the long wave radiation scheme.

There are still large deficiencies in the model's thermal forcing in the tropics, which have not been corrected; these lead to:

(a) insufficient diabatic heating by cumulus convection in the tropics and this results in the tropical troposphere being too cold;

(b) erroneous differential heating, being too strong in some areas (Indonesia) and too weak in others (Atlantic ITCZ and Northern Brazil), which may contribute to some of the systematic errors in the tropical circulation.

In order to overcome these deficiencies the parameterization of penetrative cumulus convection and cloud-radiation interaction was reformulated and the turbulent transport of moisture and sensible heat by shallow cumulus convection was included. The revised scheme has been tested extensively and compared against the operational scheme. It significantly improved medium-range forecasts and was introduced into operations together with the high resolution T106 model on 1 May 1985. This paper gives a description of the parameterization changes and presents results from the forecast experiments performed with the new scheme.

2. PARAMETERIZATION CHANGES

The parameterization scheme of the operational model was changed on 1 May 1985 in three main areas:

(a) penetrative cumulus convection;

(b) turbulent transport of moisture and sensible heat by shallow cumulus convection;

(c) cloud cover formulation for radiation calculation.

The overall effect of the first two changes is to produce a more realistic hydrological cycle, which was too weak previously, and results in stronger tropical heat sources. The third change was introduced in order to obtain more realistic cloud fields for the radiation calculation.

In addition to these modifications, minor changes were made to the parameterization of condensation processes.

In this section the individual changes and their effect on the flow are described. The combined effect of all the changes is discussed later.

2.1 Penetrative cumulus convection

Penetrative cumulus convection is parameterized by a Kuo-type scheme, in which cumulus convective heating and moistening is related to the local (i.e. grid-scale) moisture supply due to large-scale convergence and surface evaporation.

Two modifications have been made to the Kuo scheme. Firstly, the cloud base is redefined as the condensation level for surface air (lowest model level) rather than that for air with the mean characteristics of the well mixed layer. This change enhances the occurrence of cumulus convection which was previously underestimated, and gives a more realistic response, by the convection, to the diurnal cycle in surface heating over the continents. The second important change involves the moistening parameter β, which determines the partitioning between convective heating and moistening. In the previous scheme β was assumed to depend linearly on the saturation deficit averaged over the entire cloud layer:

$$\beta = 1 - \frac{\int_{p_{top}}^{p_{base}} RH\, dp}{p_{base} - p_{top}}$$

where RH is the relative humidity. This formulation tended to overestimate the moistening and underestimate the heating by latent heat release. This deficiency was particularly noticeable in a simulation of intense cumulus convection during GATE (using the composite data for Phase III, Thompson et al., 1979). The simulation was much improved when β was replaced by β^3, which has a stronger dependency on the environmental saturation deficit and provided less moistening and more heating and as a result a more realistic thermal state. Although large uncertainties remain about the correct value of the moistening parameter in different convective situations, it was decided to use the parameter β^3 in all experiments.

The net effect of the two changes is to produce a much improved vertical structure in convective situations. An example of this is given in Fig. 1, which shows a typical ascent over West Africa. With the original Kuo scheme, there is a tendency for the atmosphere to be too cold and too moist, whereas with the modified scheme the upper troposphere is considerably warmer and drier due mainly to the redefined moistening parameter.

2.2 Shallow cumulus convection

Shallow cumulus convection is generally not parameterized in large-scale models for two main reasons. Firstly, the effects of shallow convection on the large-scale flow is not well understood and its importance for the large-scale flow has probably been underestimated. Secondly, the vertical resolution of large-scale models is generally too coarse to resolve the cloud layer associated with shallow convection; the ECMWF vertical grid spacing probably being just near the critical resolution.

Shallow convection affects directly the local thermal state since it ensures that water vapour is accumulated in a cloud layer at the top of the well mixed boundary layer. This is most pronounced in the trades and has been confirmed by observational studies during BOMEX[1] (Rasmusson et al. 1973) and during ATEX[2] (Augstein et al. 1973). Beyond this local effect there is a

1 BOMEX = Barbados Oceanographic and Meteorological Experiment, 1969
2 ATEX = Atlantic Trade Winds Experiments, 1969

large effect on the global hydrological cycle and therefore on the diabatic forcing of the large-scale flow, i.e. by:

(a) enhancing the moisture supply from the subtropical oceans;

(b) enhancing the moisture transport into the tropical area through the trades;

which in turn leads to

(c) larger diabatic heating through latent heat release.

The diagnosis of the Centre's forecasts shows deficiencies in all these areas which could be attributed to the lack of shallow convection over the subtropical oceans. In response to these findings a shallow convection scheme has been developed, in which the turbulent transports of sensible heat and moisture are represented by vertical diffusion within moist convectively unstable layers, through cloud base and the level of non-buoyancy. A full description of the scheme is given in Tiedtke (1983) but is briefly summarized here.

The effects of non-precipitating cumulus convection on the large-scale heat and moisture budget can be described by the turbulent fluxes of sensible heat, moisture and condensation processes:

$$\left(\frac{\partial \bar{s}}{\partial t}\right)_{cu} = -\frac{1}{\bar{\rho}}\frac{\partial}{\partial z}(\bar{\rho}\ \overline{w's'}) + L(C-E)$$

$$\left(\frac{\partial \bar{q}}{\partial t}\right)_{cu} = -\frac{1}{\bar{\rho}}\frac{\partial}{\partial z}(\bar{\rho}\ \overline{w'q'}) - (C-E)$$

where $\bar{s} = c_p\bar{T} + gz$ is the dry static energy, C and E are the condensation- and evaporation- rate, respectively. For non-precipitating cumulus convection the time change and advection of liquid cloud water ℓ by the large-scale flow are typically small and consequently the balance is between the turbulent transport of liquid cloud water and the result of the condensation-evaporation process

$$C-E = \frac{1}{\bar{\rho}}\frac{\partial}{\partial z}(\bar{\rho}\ \overline{w'\ell'})$$

Thus, the effect of shallow cumulus convection can be described by the turbulent fluxes of sensible heat, moisture and liquid cloud water.

In the present version of the scheme the turbulent transports of liquid cloud water are ignored and the turbulent fluxes of heat and moisture are parameterized by means of the mixing length theory

$$\left(\frac{\partial \bar{s}}{\partial t}\right)_{cu} = \frac{1}{\bar{\rho}} \frac{\partial}{\partial z} \left(\bar{\rho}\ K \frac{\partial \bar{s}}{\partial z}\right)$$

$$\left(\frac{\partial \bar{q}}{\partial t}\right)_{cu} = \frac{1}{\bar{\rho}} \frac{\partial}{\partial z} \left(\bar{\rho}\ K \frac{\partial \bar{q}}{\partial z}\right)$$

The diffusion coefficients are assumed to be constant throughout the cloud layer and a value has been chosen so that the scheme gives the best reproduction of ATEX and BOMEX data.

$$K = \begin{cases} 10\ m^2/sec & \text{in cloud layer} \\ 0 & \text{elsewhere.} \end{cases}$$

The scheme effectively transports moisture from the cloud free part of the boundary layer into a cloud layer above. This is most pronounced in the trades, where shallow convection counteracts the drying and warming effect of the large-scale subsidence. A typical ascent in the trade winds (Fig. 2) shows that with shallow convection the well mixed boundary layer is capped by a conditionally unstable cloud layer with a realistic moisture content slightly below saturation extending over a few model levels. This has to be compared with a shallow totally saturated boundary layer in the control run.

2.3 New cloud scheme

The interaction of clouds with radiation may have a large influence on the forcing of the atmosphere's flow and is considered to be important for medium-range and longer forecasts. The main prerequisite for this computation is the specification of realistic cloud amounts and cloud properties from the model variables. In the previous operational scheme no distinction was made between different cloud types and the total cloud cover was universally specified from the relative humidity. Recent assessment of this scheme (Slingo and Ritter, 1985) indicates reasonable skill in predicting clouds associated with extratropical disturbances. However, it has defects in the representation of convective and boundary layer clouds.

A new cloud scheme has recently been developed (Slingo, 1985) which rectifies some of the deficiencies. It is again based on a diagnostic approach, using empirical relationships between cloud cover and model variables to represent the probability of occurrence of cloudiness. The scheme allows for four cloud types: convective clouds and three layer clouds - high, middle and low level (see Fig. 3).

Convective cloud cover C^c is determined from the precipitation rate P given by the model's convection scheme (see Table 1).

$$C^c = a + b \ln P$$

Table 1. Relationship between convective cloud clover and precipitation rate (P)

C^c	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8
P(mm day^{-1})	.14	.31	.70	1.6	3.4	7.7	17	38	85

For high clouds the scheme distinguishes between two types of cirrus, that associated with outflow from deep convection and that associated with frontal disturbances. Anvil cirrus is assumed to occur when there is very deep and intense convective activity, i.e. extending above 400 mb and exceeding 40% cloud cover (i.e. 3.4 mm/day). The cloud cover is then taken to be

$$C = 2.0\ (C^c - 0.3)$$

Extratropical and frontal cirrus are determined from a function of relative humidity RH which is similar to that used in the previous operational scheme

$$C = \begin{cases} \left(\frac{RH - 0.8}{0.2}\right)^2, & \text{if } RH > 0.8 \\ 0 & \text{elsewhere.} \end{cases}$$

The same relationship is used to describe middle layer clouds predominantly associated again with frontal systems.

Low clouds are particularly difficult to predict because they are so dependent on the structure of the model's boundary layer and their interaction with the radiation field. Two types are considered. The first class of clouds are associated with extratropical fronts and tropical disturbances and are characterised by generally moist air and large-scale ascent. These are parameterized using the same relative humidity criterion as above with an additional constraint from the vertical velocity. The second class of low level clouds are strongly linked to the boundary layer and are invariably associated with low level inversions in temperature and humidity, e.g. the tradewind inversion. The cloud cover is determined from the intensity of the inversion and the relative humidity under the inversion.

The scheme has been tested on a variety of cases and cloud maps compared with satellite data and climatological information. It appears to give realistic cloud distributions and has its largest impact on the tropical and subtropical cloudiness. The low level cloudiness is markedly increased over the subtropics (for example, see Fig. 4) and the transition from the dense frontal clouds of the extratropics to the broken convective regimes of the tropics is evident. Cirrus-clouds connected to the penetrative convection appear also realistic in space.

The representation of the diurnal cycle in cloudiness is also much improved with the new scheme. Over the tropical continents the cloudiness increases during the daytime and decreases again in the evening when convection ceases. Thus, the undesirable variation in cloudiness over the summer continents noted with the previous scheme appears to be rectified (see Fig. 4 - South America at night and Africa during the day).

The impact of the new cloud scheme on a 10-day forecast is not very large, certainly not as large as that due to the changes in the convection parameterization . This is partly because radiative time-scales themselves are large and partly because the previous scheme was already successful at representing extratropical frontal clouds. However, the scheme gives a modest but consistent improvement in skill.

2.4 Evaporation of large-scale precipitation and melting of snow

The parameterization of both processes, previously based on the Kessler scheme (Kessler, 1969), is simplified. Evaporation of large-scale rain is in accordance with observations, assumed to effectively moisten the subcloud layer, that is rain evaporates at the maximum possible rate so that a layer must first be saturated before rain/snow reaches the next level below.
The procedure for melting snow is based on the observational data summarised by Mason (1971). The total snow melts within a thin layer just below freezing level. These simplifications to the parameterization of evaporation and melting appear justified in view of the large uncertainties about the assumptions made previously, in particular those for the melting process, and they don't affect substantially the characteristics of the forecast.

3. NUMERICAL EXPERIMENTS

The revised parameterization scheme was tested in a series of 10-day forecasts and in extended integrations using the T42 resolution model (see Table 2). The forecasts are compared with those from the operational scheme used until 1 May 1985. The 10-day integrations include:

- 13 pairs of T63 forecasts

and

- 8 pairs of T106 forecasts

The initial data are those of operational forecasts spread evenly over the seasons during 1983 to 1985, as well as one additional case during FGGE (11 June 1979). The latter was chosen because it includes the monsoon onset and proved to be a very good test case for the study of the effects of cumulus convection.

Table 2. List of forecast experiments and their code numbers

Initial Date	T63		T106		T42 (0-60)d	
	Exp.	Control	Exp.	Control	Exp.	Control
15.5.83	BHU	W69	BM6	BM5		
15.7.83	BCA	W55	BN6	BN5		
15.10.83	BFE	W75	-	-		
15.1.84	BFD	W58	BNK	BPF		
15.3.84	BHI	Y17	-	-		
15.7.84	BKH	BKG	-	-		
15.8.84	BKJ	BKI	BM4	BLV		
15.12.84	BIE	oper	BLT	BLN		
20.12.84	BIF	oper	-	-		
15.1.85	BM8	oper	BMC	BLU		
11.6.79 (FGGE)	BHH	X31	-	-		
15.2.85	BSW	oper	BRK	CØL		
15.3.85	BUO	oper	BTY	C2A		
17.1.84	-	-	-	-	BBU,BFU	B6A

4. RESULTS OF FORECAST EXPERIMENTS

The parameterization changes primarily affect the tropical and subtropical flow. Their effect on the extratropical flow is less pronounced and results, to a large extent, from a response to changes in the tropical diabatic heating. Therefore, we discuss first the tropical and subtropical flow and then the extratropical flow.

4.1 Tropics and subtropics

The response of the flow to parameterization changes is very similar in all experiments and results from a reduction of the systematic errors in the large-scale diabatic heating, i.e.

(a) an overall increase of the hydrological cycle and in consequence the diabatic heating,

(b) changes in the geographical distribution of the tropical heat sources in response to increased moisture supply in the trades.

In view of the similar response in all experiments we show the effect on the large-scale flow for only one case (11 June 1979), but demonstrate its effect on forecast quality for all cases by means of verification results from an ensemble of forecasts.

4.1.1 Thermal state and hydrological cycle

The modifications of the hydrological cycle are a result of the interaction between the new shallow convection and the modified deep convection scheme. Shallow convection effectively transports moisture from the lower part of the boundary layer into a cloud layer; this process is most pronounced in the trades. The total moist layer (sub-cloud plus cloud layer) is considerably deeper (50-100 mb) and therefore contains a higher amount of moisture which is advected into the ITCZ.

The moisture balance for the trades must therefore be maintained by a larger moisture supply through evaporation from the oceans. In fact the increase exceeds 50 W/m^2 (equivalent to almost 2 mm/day of precipitable water) over large areas and reaches nearly 1 mm/day in the zonal averages over the subtropics (Fig. 5). This additional moisture supply is significant for the penetrative cumulus convection in the tropics as illustrated by the total precipitation. Compared to the operational model considerably higher precipitation rates (see Fig. 5) occur along the ITCZ downstream of the trades (Atlantic and North Brazil, Central Pacific, Indian Ocean) and smaller rates over Indonesia. The differences exceed 5 mm/day in some areas. As precipitation is difficult to verify, the climate estimate for June by Jaeger is added in Fig. 6. The comparison shows that the precipitation rates obtained with the new physics are much closer to the climate distribution. Further, the overall precipitation is increased, as is evident from the zonal mean values (Figs. 5). As a consequence of this overall larger diabatic heating the model's tendency to generate a too cold tropical and subtropical troposphere is removed as is apparent from the zonal mean temperatures (Fig. 7a); instead the model is now a little too warm. The changes to the hydrological cycle and the thermal state are qualitatively confirmed by all experiments performed so far.

4.1.2 Tropical flow

Assessment of the tropical flow shows that the improvement in the diabatic heating leads to significant improvements in the simulation of the tropical flow. This is particularly evident in the time-mean flow. The 5-10 day mean flow at 850 mb (Fig. 8a), for the forecast from 11 June 1979, shows stronger tradewinds particularly over the Atlantic and the absence of the spurious westerly flow over Africa, which is a typical feature of control forecasts. The reduction of the westerly flow over Africa as compared to operational forecasts is presumably connected to the strengthening of the heat sources over the Atlantic and South America. Similar large improvements are found in the flow of the upper troposphere. The change towards a more realistic mean flow arises from a reduction of the systematic errors in response to the more realistic distribution of the diabatic heat sources. Assessment of the tropical flow shows further that the response to the altered diabatic heating becomes established between day 2 and day 4 in the forecast since there is little evidence of a response of day 2 but sufficient at day 4 with improvements against the control forecast as in the 5-10 day mean, i.e. stronger tradewinds and a weaker westerly flow over Africa.
The time-evolution of the response of the flow to changes in the diabatic forcing is also clearly reflected in the scores for the wind field, particularly the long waves and the zonal mean wind. They confirm again that the response of the large-scale flow to the changes in parameterization occurs

between day 2 and day 4 and has almost reached its final level at day 4.

Assessment of the tropical flow for other cases confirms the above results. In every forecast is the tropical flow improved, the improvements being noticeable in most cases between day 2 and day 4 with respect to the long waves and on average 1 day earlier for the zonally averaged flow. This is also reflected in the ensemble verification for wind (Fig. 9).

Assessing the T106 forecast reveals that the improvements are independent of the horizontal resolution of the forecast model and are much larger than by only increasing the resolution as is evident from the comparison of T106 and T63 with the control physics (Fig. 9).

The improvement of the tropical flow is clearly seen in every forecast and results mainly from a reduction of systematic errors. The effect of the parameterization changes on the transient eddies like tropical cyclones, tropical storms, etc., has only been studied for some cases and is therefore less clear. However, the cases considered so far indicate that the diabatic forcing with the new physics produces more realistic development. The revised physics led for example to a better forecast of the monsoon onset over India during FGGE in the forecast from 11 June 1979. This has been confirmed by Mohanty et al (1985) who studied the onset in detail in a series of forecasts using various combinations of parameterization schemes.

4.2 Extratropics

The impact of the parameterization changes on the extratropical flow is less pronounced than in the tropics, but is still evident in all forecasts. However, whereas changes in the tropical flow led to better forecasts in all cases, this is not the case for the extratropics and an ensemble of T63 forecasts was necessary to ascertain its overall positive nature. It is also not clear whether the large deterioration of the forecasts noted in two of the 13 cases is due purely to an erroneous forcing introduced by the physics changes or to other model deficiencies or to poor initial data. Apart from the forecast skill itself the response of extratropical flow to the parameterization changes is very similar and apparent in all forecasts. Assessment of the forecasts reveals that the extratropics change largely in response to the tropical diabatic forcing through:

(a) the strengthening of the Hadley circulation which affects the subtropical anticyclones being stronger and more realistic and

(b) an intensification of the baroclinic energy conversions particularly in the winter hemispheres via an increased diabatic generation of zonal available potential energy.

4.2.1 Zonal mean flow

Again we base the discussion on the results from the forecast from the FGGE case, 11 June 1979.

The largest impact of the parameterization changes is on the thermal state. The extratropics which are generally too cold in operational forecasts particularly in the winter hemisphere are now less cold by 0.5-1.0K (Fig. 7a). The extratropical zonally averaged zonal wind is only affected slightly by the paramterization changes (Fig. 7b), whereas the subtropical jets are stronger by up to 4 m/sec thereby affecting baroclinic development.

4.2.2 Extratropical flow

Objective verification of single forecasts shows that the parameterization changes may have a rather nonuniform effect on forecast quality. The reason for the diversity of the impact is unclear. Besides the possibility of an erroneous diabatic forcing by the revised parameterization scheme poor initial data, erroneous developments in the early stages of the forecasts and unrealistic feedbacks of cumulus convection with other processes may contribute equally to a more rapid degradation of the forecasts in some cases. Therefore, rather than try to examine single cases we concentrate on the systematic changes which are common to all forecasts. The most striking feature is the strengthening of the anticyclones; this can, for example, be seen in the 6-day forecasts from 11 June 1979 (Figs. 10). This strengthening brings the anticyclones, in the majority of cases, closer to reality.

Closely related to the strengthening of the anticyclones is a similar strengthening of the large-scale downward motion. In fact, additional anticyclonic vorticity is likely to be produced in connection with the stronger vertical motion ($\frac{\partial\zeta}{\partial t} \sim (f+\zeta)\,\frac{\partial\omega}{\partial p}$) which has resulted from the stronger tropical heat sources. The strengthening of the vertical motion is apparent over large areas of anticyclonic flow and appears also in the zonally averaged values in the winter hemispheres.

Another, although less systematic difference to the control forecasts, is the tendency for stronger cyclones as indicated by the more intense energy cycle and larger eddy kinetic energy as shown below. This feature should, however, be confirmed by a statistical assessment of forecasts separately for all seasons.

4.2.3 Energy cycle

The results of the energy cycle are summarised in Fig. 11, again for the FGGE case, 11 June 1979.

The largest impact of the physics changes are found in the winter hemisphere. There is an increase in the generation of zonal available potential energy, due to tropical diabatic heating, of 30% which in turn is accompanied by an increase in the baroclinic conversions of 15 to 20%. It should be noted that the diabatic generation/dissipation of eddy available potential energy is only slightly affected by the parameterization changes. As a result of the intensified baroclinic conversions the eddy kinetic energy is also increased. The existence of a more intense energy cycle and stronger disturbances could eventually cause a deterioration of forecast quality in cases of erroneous developments. However, objective verification show improved forecasts for all the winter cases considered so far.

The assessment of the energy cycle suggests that the extratropical flow in the winter hemisphere is strongly affected by the changes in the tropical diabatic forcing.

4.2.4 Objective verification

Objective verification indicates that the parameterization changes are not uniform in their effect on forecast quality. Out of the 13 T63 performed, 2 forecasts were significantly worse beyond day 5, 3 forecasts significantly better and 7 forecasts only slightly improved. The overall impact as judged from the ensemble of the 13 T63 cases (Fig. 12a) therefore appears rather small up to day 6 but increases thereafter to a significantly positive level.

The objective verification of the high resolution forecasts indicates further that the positive impact of the parameterization changes becomes larger in the high resolution model as is evident from the ensemble verification (Fig.12b). The improvements are larger and occur earlier in the T106 forecasts than with T63; for T106 they are significant at day 4. The large improvements are particularly noticeable in the medium to long waves, i.e. mainly baroclinic eddies.

These results show that only the combination of

(a) increased resolution and

(b) improved diabatic forcing

substantially improves the forecasts.

5. RELATIVE IMPORTANCE OF THE PHYSICS CHANGES

The relative importance of the changes has only been studied in a few cases. A detailed study (Mohanty et al. 1985) for the 11 June 1979 (covering the monsoon onset) shows that all modifications contribute to the improvement of the simulated large-scale tropical flow, but that the introduction of the effects of shallow convection has the largest impact. However, this result may not be totally conclusive due to the model's spin-up problem in convective heating. Since it is of considerable scientific interest to understand the importance of shallow cumulus convection for the maintenance of the tropical heat sources and the associated circulation, extended integrations were performed:

(a) with shallow convection;

and

(b) without shallow convection.

Assessment of the global heating rates for the various processes (Table 3) shows that

Table 3 Global mean diabatic heating rates (W/m^2) due to radiation (Rad) surface sensible heat flux (F_s) and precipitation (P) between 0 and 30 days for experiments (T42).
B6a (control), BBU (mod.physics), BBU (mod.physics, but without shallow convection SCV).

	Control (B6A)	mod.physics (BBU)	mod.Kuo, without SCV (BFU)	Climate (Oort)
Rad	-74	-78	-78	-102
F_s	15(?)	11(?)	15(?)	20
P	59	76	66	82

shallow convection plays a significant role in the atmospheric heat budget. From the comparison with the integration where shallow convection is ignored (BFU), it follows that the total precipitation is increased by 15%. The increase occurs mainly in the tropics as a result of the additional moisture supply over the subtropics. An evaluation of the geographical distribution of precipitation reveals again larger precipitation rates along the ITCZ downstream of the trades over the Atlantic and Indian Ocean, and less over Indonesia which brings the values closer to reality (i.e. climate estimated by Jaeger).

6. EFFECT OF PHYSICS CHANGES ON DATA ASSIMILATION

The revised parameterization scheme was tested in a 3 day assimilation experiment starting from 12Z, 8 June 1979.

The effect of parameterization changes on the analysed flow is via the first guess fields of moisture, temperature and wind. As expected, the largest impact was on the moisture and temperature in the tropical belt. The negative temperature bias of the first guess in the tropical troposphere is slightly reduced. Recently a reanalysis of a longer period for FGGE with the revised scheme showed, however, a larger improvement.

The largest differences are to be found in the analysed moisture distribution. This is because the first guess moisture field receives a much larger weight than other variables (poor moisture data coverage). The moisture content is reduced in the boundary layer by as much as 2 g/kg in the tropics and increased above the boundary layer. The relative humidity over the tropical and subtropical oceans now appear to be more realistic, exceeding 90% only in a few areas (see for example Fig. 13). As a result of the redistribution of the moisture field, it is expected that this will change the initial meridional moisture transport in a subsequent forecast, in particular towards the tropics by the mean meridional flow.

The reanalysis was followed by a forecast experiment (a 10 day T63 integration) starting from the reanalysed fields. The comparison of this forecast with the control forecast starting from the original analysis showed only small differences until the end of the forecast period.

We therefore conclude that the physics changes are beneficial to the data assimilation, since they reduce the temperature bias of the first guess and produces more realistic first guess moisture fields. The effects on the following forecasts may be small.

7. EXPERIENCE WITH THE REVISED PARAMETERIZATION SCHEME IN OPERATIONAL FORECASTS SINCE MAY 1985

The set of experiments described above provides a realistic test of the parameterization changes since only the parameterization scheme was altered. Further results from the quasi-operational parallel run carried out in April 1985 and the operational forecasts with the new model since 1 May 1985 cannot be equally conclusive about the impact of the physics changes as other parts of the model were also changed. However, the forecasts seem to confirm the results discussed above in many respects, we find that:

(a) Precipitation is largely increased in the tropics and in consequence the model's tendency to generate a troposphere which is too cold is removed;

(b) The large-scale tropical and subtropical flow is improved as systematic errors are reduced;

(c) Subjective assessment of operational forecasts in May and June 1985 indicates that the development of tropical cyclones is now more realistic;

(d) The subtropical anticyclones are more intense and therefore more realistic;

(e) The forecast quality seem to be improved in the northern hemisphere.

These results show again that the new model differs from the previous version in several important aspects. However, there are areas which need further examination, for example, the interaction of the forecast model with the data assimilation and in this context the "spin up" problem. Another important area is the re-examination of the model's systematic errors by studying ensemble forecasts and extended integrations.

In addition to the positive impact the parameterization changes have on the large-scale flow, two specific problems connected to the parameterization scheme were identified by the users in the Member States during the first months of operational forecastings, these were:

(a) the occurrence of spurious rain during periods of weak convective activity;

and

(b) the model's tendency to predict surface temperatures over the continents during the day which are too cold.

The occurrence of spurious convective rain in the model is associated with the simplified treatment of the condensation process. The present scheme does not consider the cloud phase, but instead it is assumed that the total condensed water is immediately released as precipitation. This assumption is in contradiction to observational data summarized by Mason (1971). Mason's summary shows that maritime cumulus clouds only precipitate when they are sufficiently deep, say 1000-1500 m, while continental cumulus clouds may even exceed a vertical extent, from base to top, of 4000 m and more before precipitation is released. A temporary modification has been made in July 1985 to prevent precipitation from shallow cumulus clouds but there is need for further research on the treatment of precipitation processes.

The occurrence of cold surface temperatures over the continents is related to the very difficult problem of parameterizing surface processes. Surface temperature evolving during the day depends largely on how the surface net radiative flux is partitioned into sensible and latent heat. The existence of surface temperatures which are too cold indicates that too much radiation is consumed in evaporating soil water and too little is used for heating. An adequate representation of the retention of water by vegetation would presumably correct this defect. This is a matter of further research but a short term modification has been implemented, which cuts surface evaporation over land by a factor up to 2 depending on surface temperature.

References

Augstein, E., H. Riehl, F. Ostapoff and V. Wagner, 1973: Mass and Energy Transports in an Undisturbed Atlantic Tradewind Flow. Mon.Wea.Rev., 101, 101-111.

Geleyn, J.-F., 1980: Some diagnostics of the cloud radiation interaction in ECMWF forecasting model. ECMWF Workshop on Radiation and Cloud-Radiation Interaction in Numerical Modelling, 15-17 Oct. 1980, pp.135-162.

Holland, J.J. and E.M. Rasmusson, 1973: Measurements of the atmospheric mass, energy and momentum budgets over a 500 km square of tropical oceans. Mon.Wea.Rev., 23, No.6, pp.694-711.

Jaeger, L., 1976: Monatskarten des Niederschlages für die ganze Erde. Ber.Dtsch. Wetterd., Offenbach/Main, No.139, Vol.19, 38pp.

Kessler, E., 1969: On the distribution and continuity of water substance in atmospheric circulations. Met.Monogr., 10, 1-84.

Louis, J.-F., M.Tiedtke and J.F. Geleyn, 1981: A short history of the PBL parameterization at ECMWF. ECMWF Workshop on Planetary Boundary Layer Parameterization, 25-27 Nov. 1981, pp.59-80.

Mason, B.J., 1971: The physics of clouds - 2nd ed. Clarendon Press, Oxford, pp.245.

Mohanty, U.C., J. Slingo and M. Tiedtke, 1985: Evaluation of the prediction of the tropical circulation with modified parameterization schemes. ECMWF Tech.Report to be published.

Savijärvi, H., 1980: Energy budget calculations and diabatic effects for limited areas computed from ECMWF analyses and forecasts. ECMWF Workshop on Diagnostics of Diabatic Processes, 23-25 April 1980, pp.115-134.

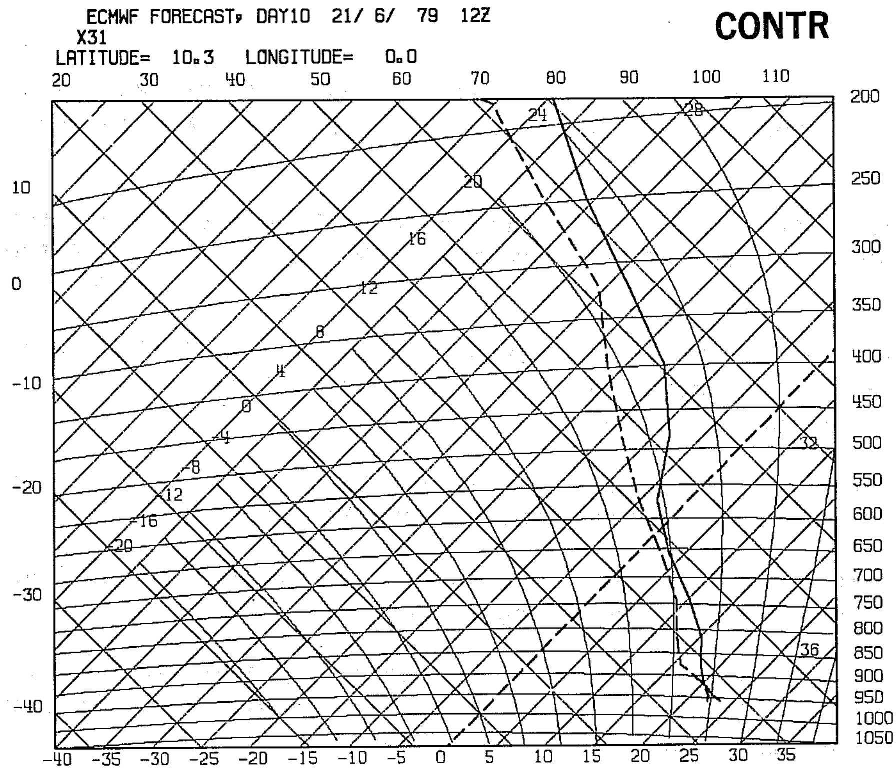
Slingo, J. and B. Ritter, 1985: Cloud prediction in the ECMWF model. ECMWF Tech.Rep.No.46, 46pp.

Slingo, J., 1985: Cloud cover experimentation with the ECMWF model: ECMWF Workshop on the Parameterization of Cloud Cover. ECMWF, 26-28 Nov.1984.

Thompson, R.M. Jr., S.W. Payne, E.E. Recker and R.J. Reed, 1979: Structure and properties of synoptic scale wave disturbances in the intertropical convergence zone of the Eastern Atlantic. J.Atmos.Sci., 36, 53-72.

Tiedtke, M., 1981: Assessment of the PBL flow in the EC-model. ECMWF Workshop on Planetary Boundary Layer Parameterization, 25-27 Nov. 1981, pp.155-192.

Tiedtke, M., 1983: The sensitivity of the time-mean large-scale flow to cumulus convection in the ECMWF model. ECMWF Workshop on Convection in Large-Scale Numerical Models. 28 Nov.-1 Dec. 1983, pp.297-316.



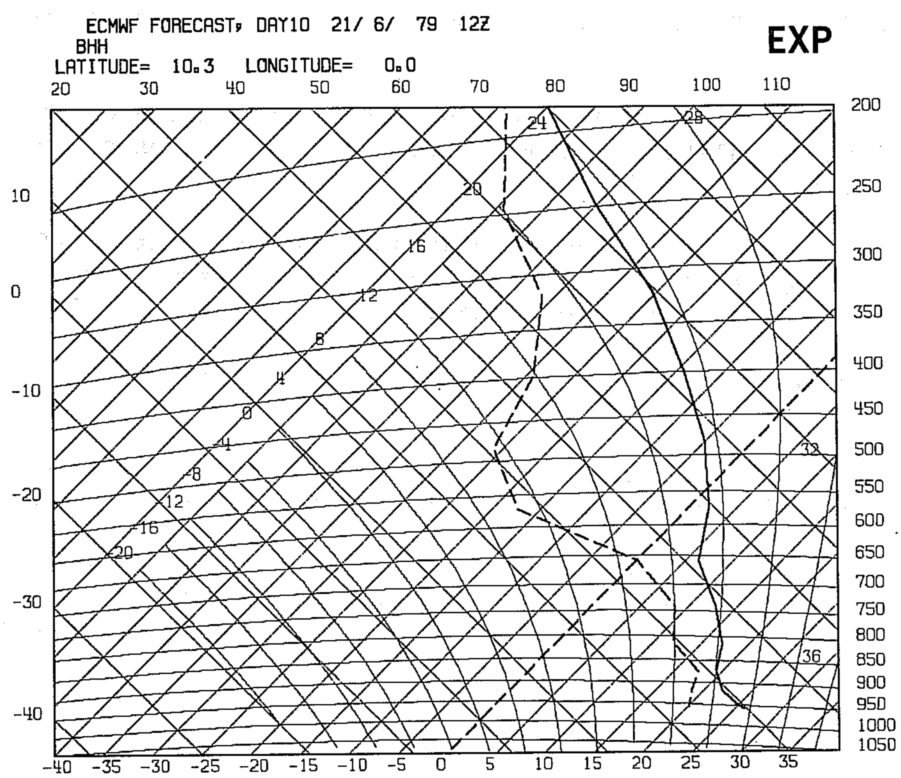


Fig. 1 Vertical distribution of temperature and dew point at day 10 at gridpoint (10.3°N, 0°E) for a forecast from 11 June 1979. Top: control (CONTR); bottom: new physics (EXP)

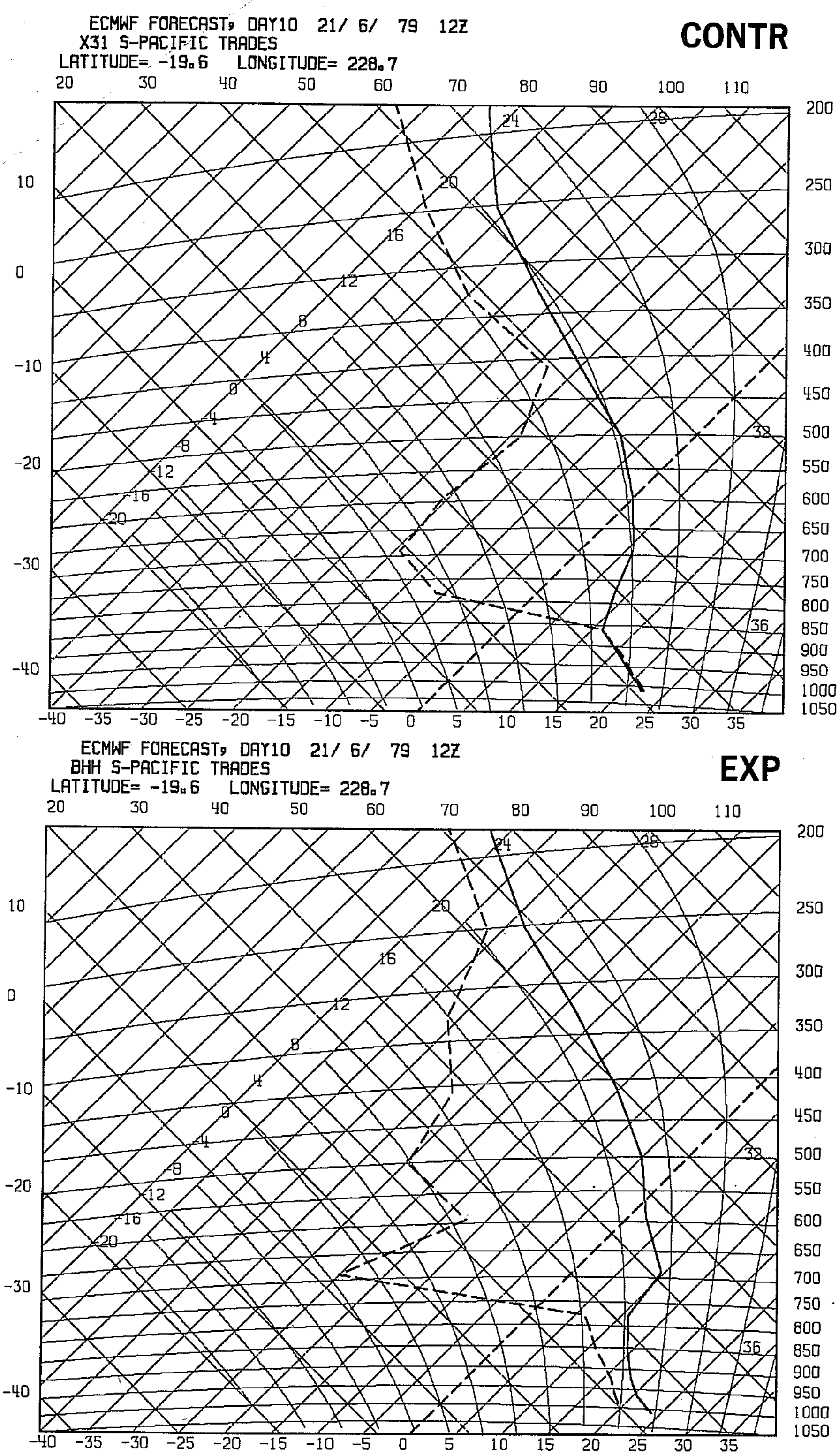


Fig. 2 Vertical distribution of temperature and dew point at day 10 at gridpoint (19.3°S, 228.7°E) for a forecast from 11 June 1979. Top: control (CONTR); bottom: new physics (EXP)

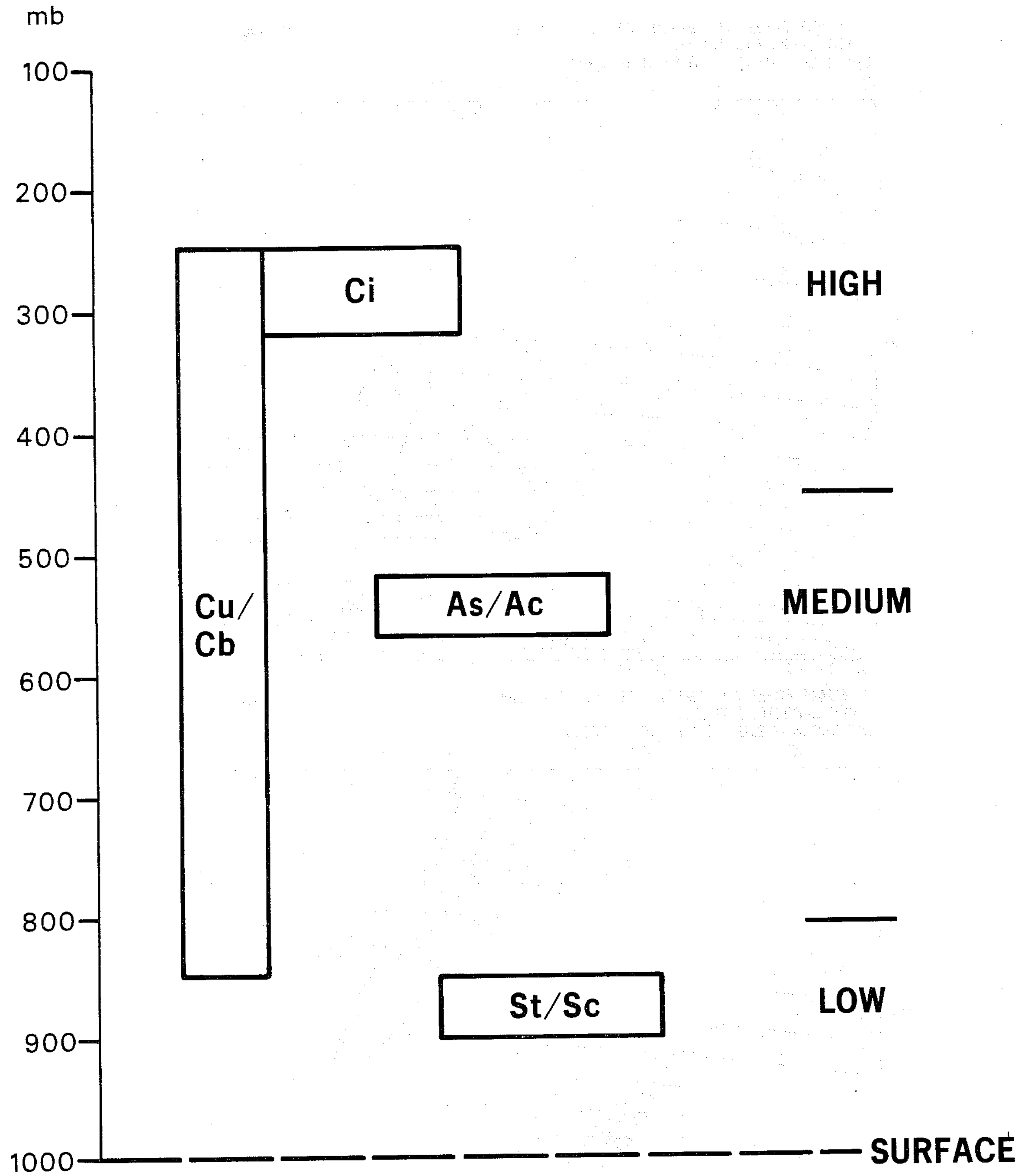


Fig. 3 Schematic representation of the vertical distribution and division into high, middle and low clouds for the new cloud prediction scheme.

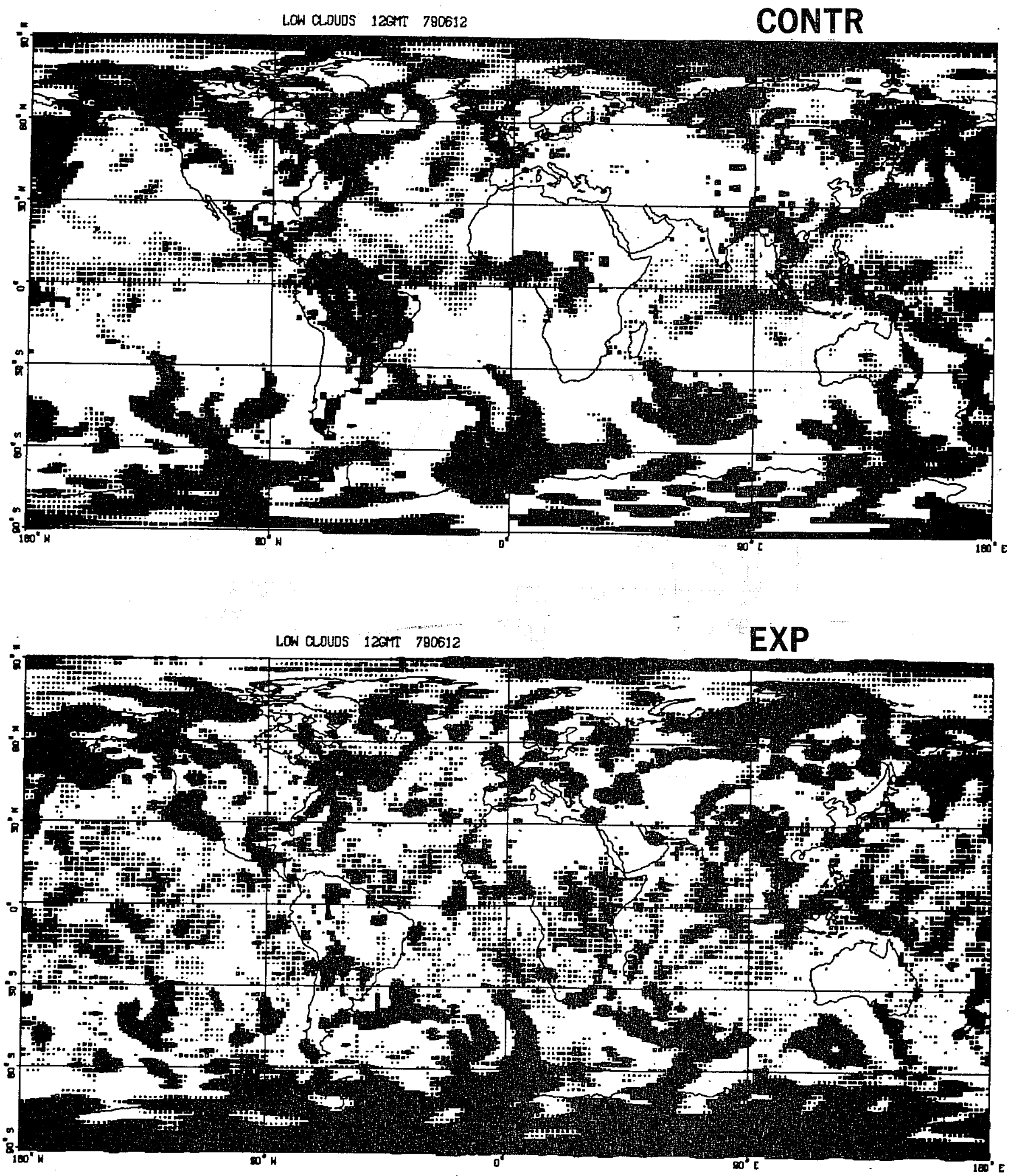
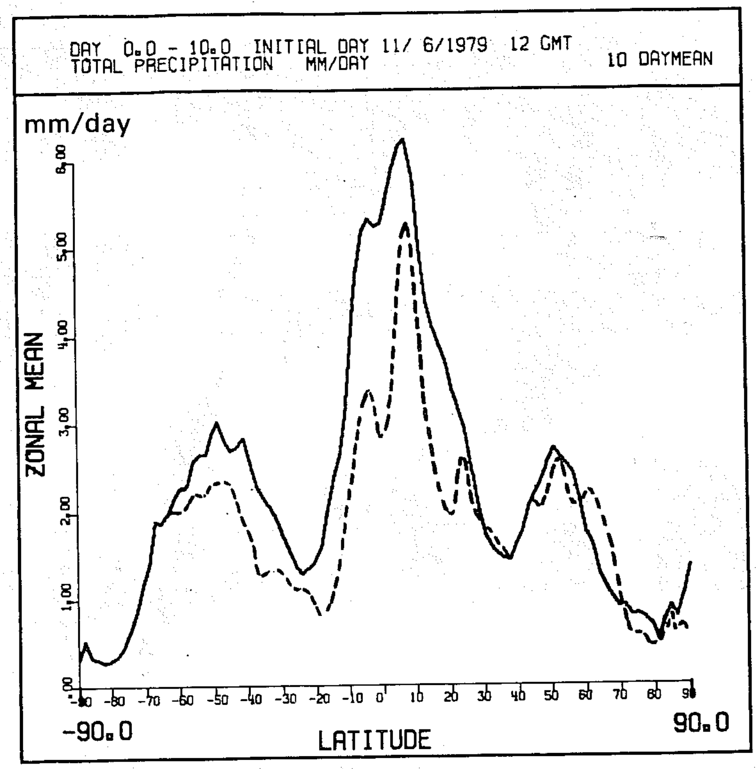


Fig. 4 Low level clouds (stratiform plus cumuliform for the new scheme) diagnosed from day 1 of the forecast from 11 June 1979. Top: control (CONTR); bottom: new physics (EXP)



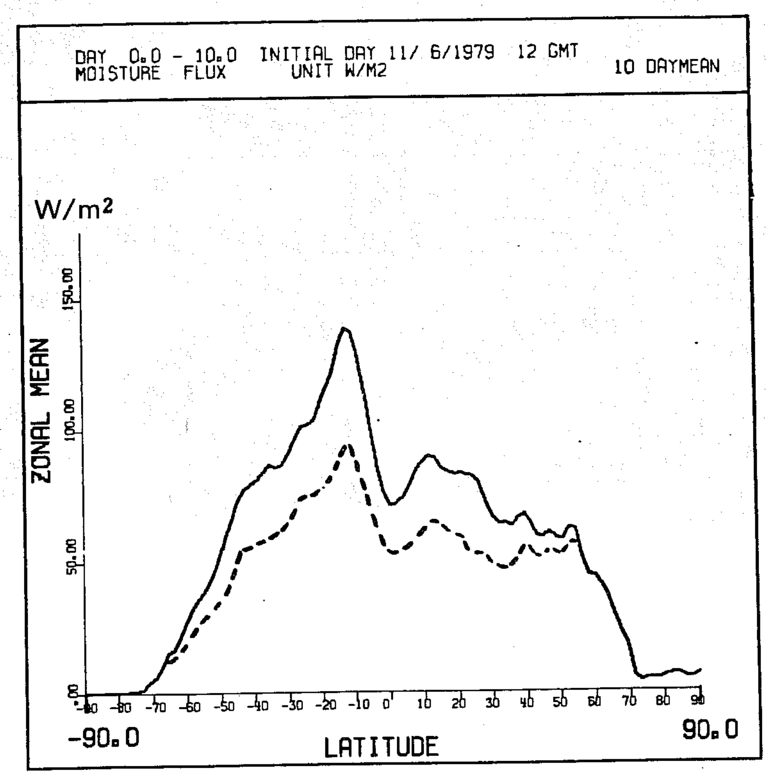


Fig. 5 Latitudinal distribution of 10-day means of zonally averaged precipitation and surface moisture fluxes for experiment (solid line) and control (dashed line) starting 11 June 1979.

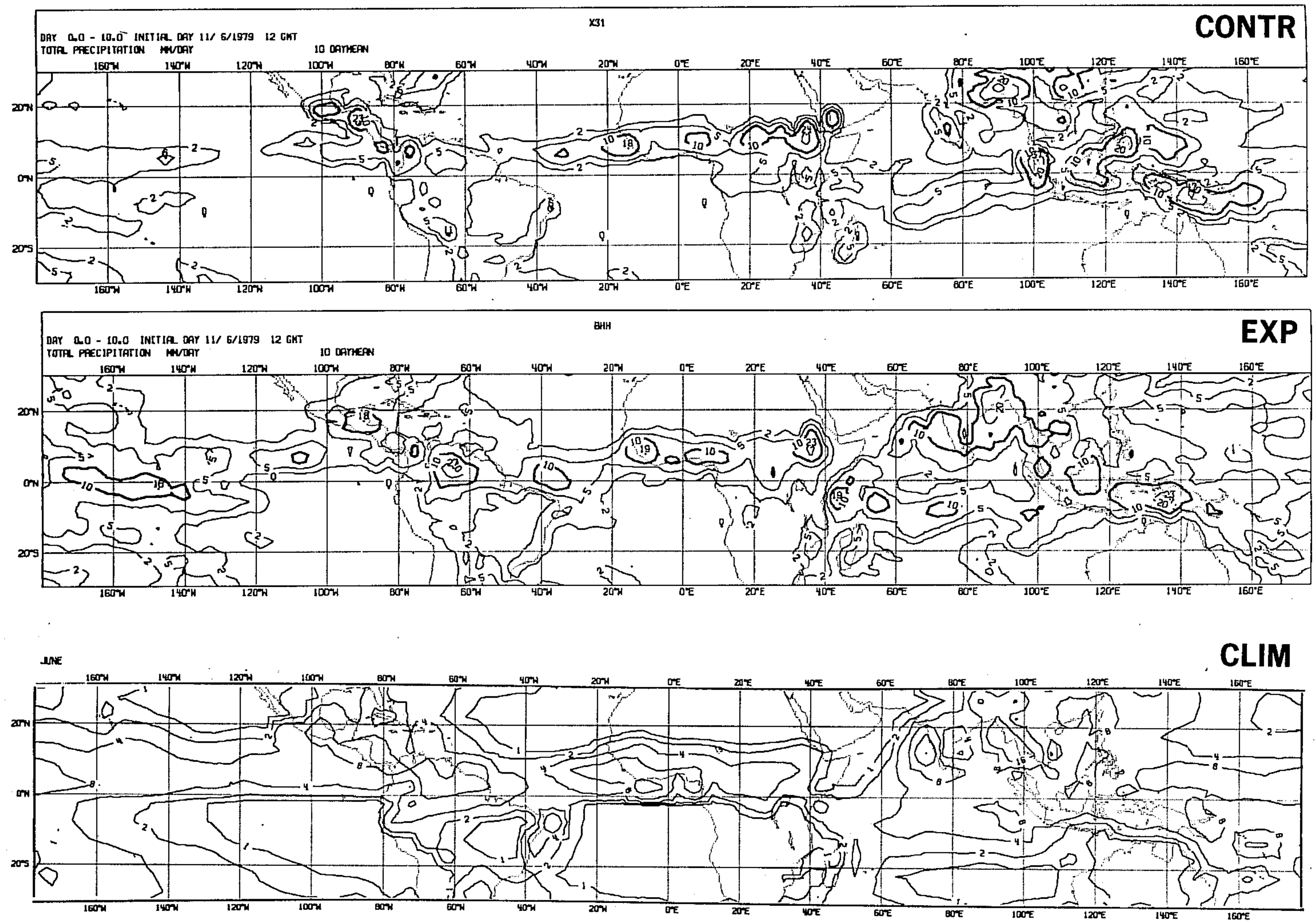


Fig. 6 10 day mean total precipitation rate (mm/day) from experiments starting 11 June 1979.
Top: control (CONTR); middle: new physics (EXP); bottom: Jaeger's climate values for June.

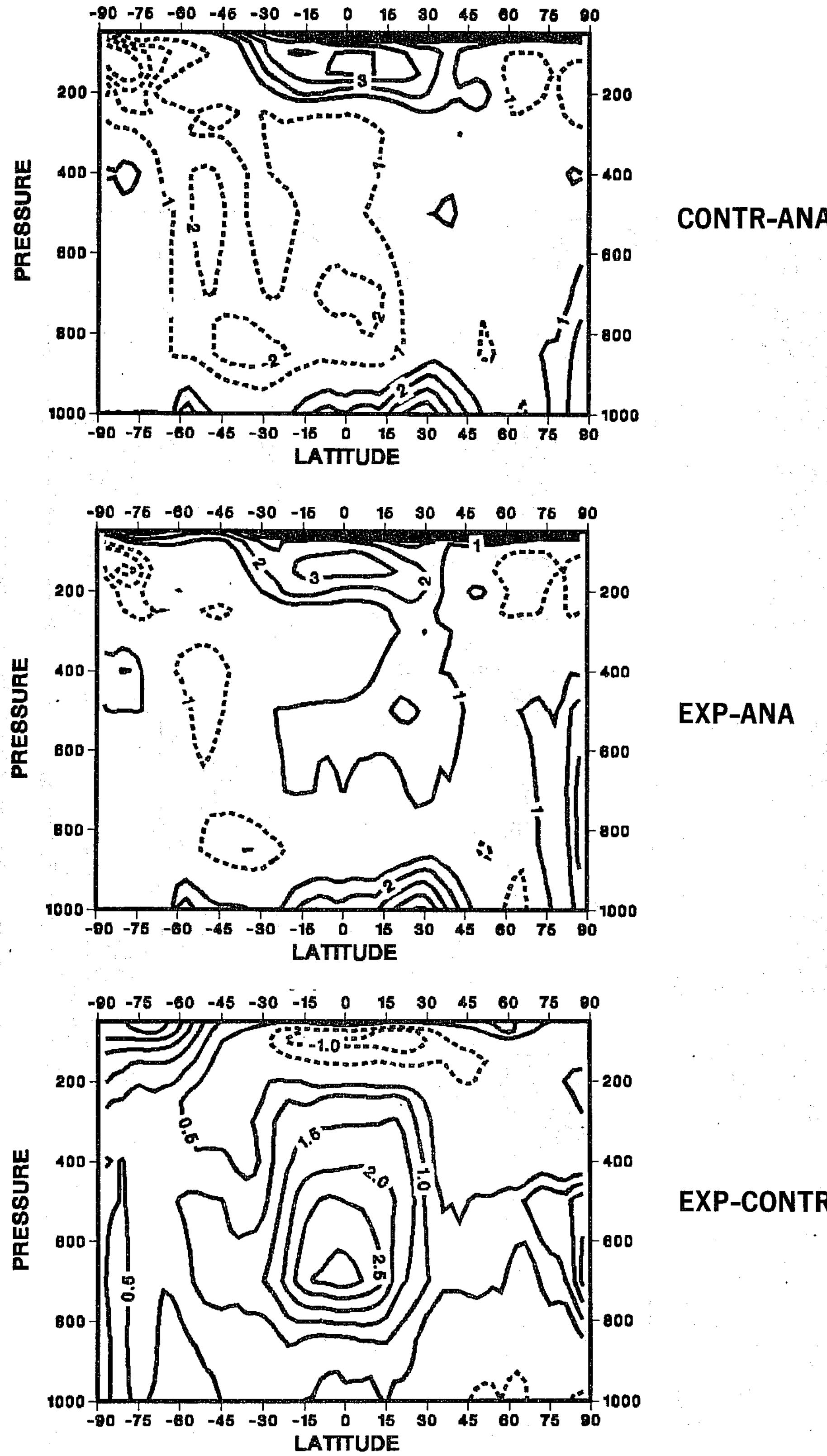


Fig. 7a Height latitude distribution of the 10 day mean zonally averaged temperature deviations for forecasts from 11 June 1979.
Top: control minus analysis (CONTR-ANA); middle: new physics minus analysis (EXP-ANA); bottom: new physics minus control (EXP-CONTR).

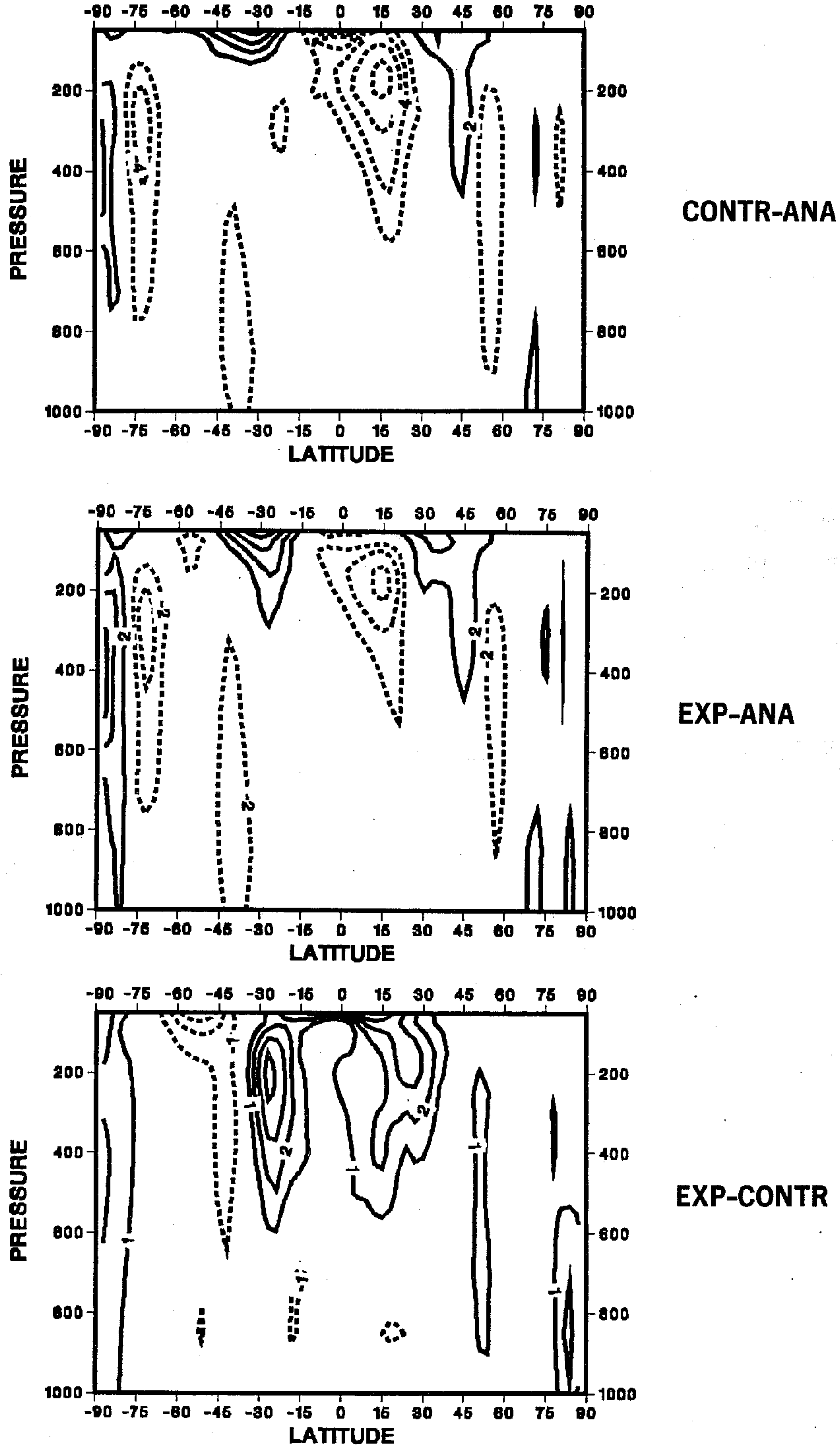


Fig. 7b As Fig. 7a, but for zonal wind (m/s)

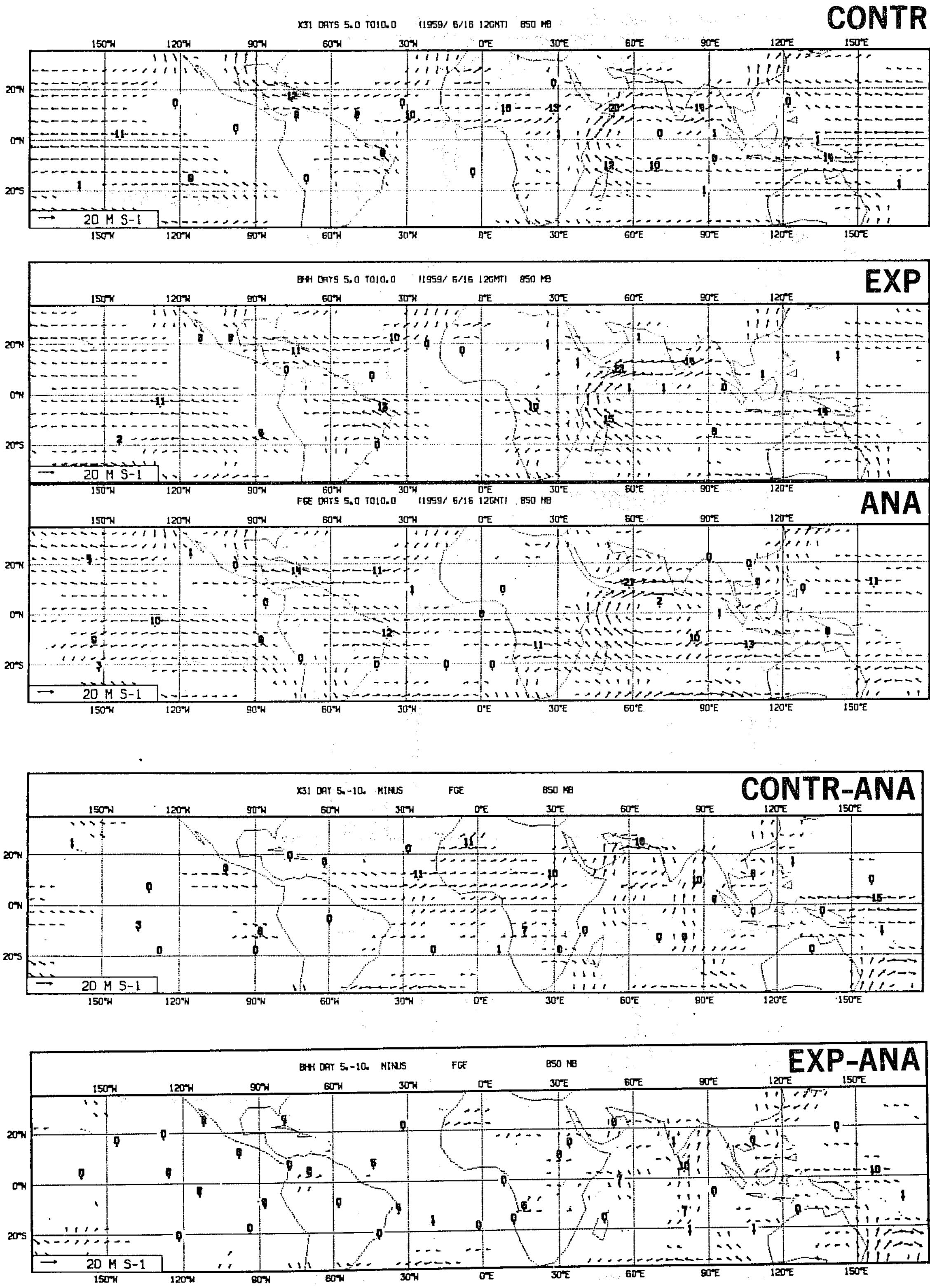


Fig. 8 5-10 day mean tropical flow at 850 mb and deviations from observed flow for control (CONTR) and new physics (EXP)

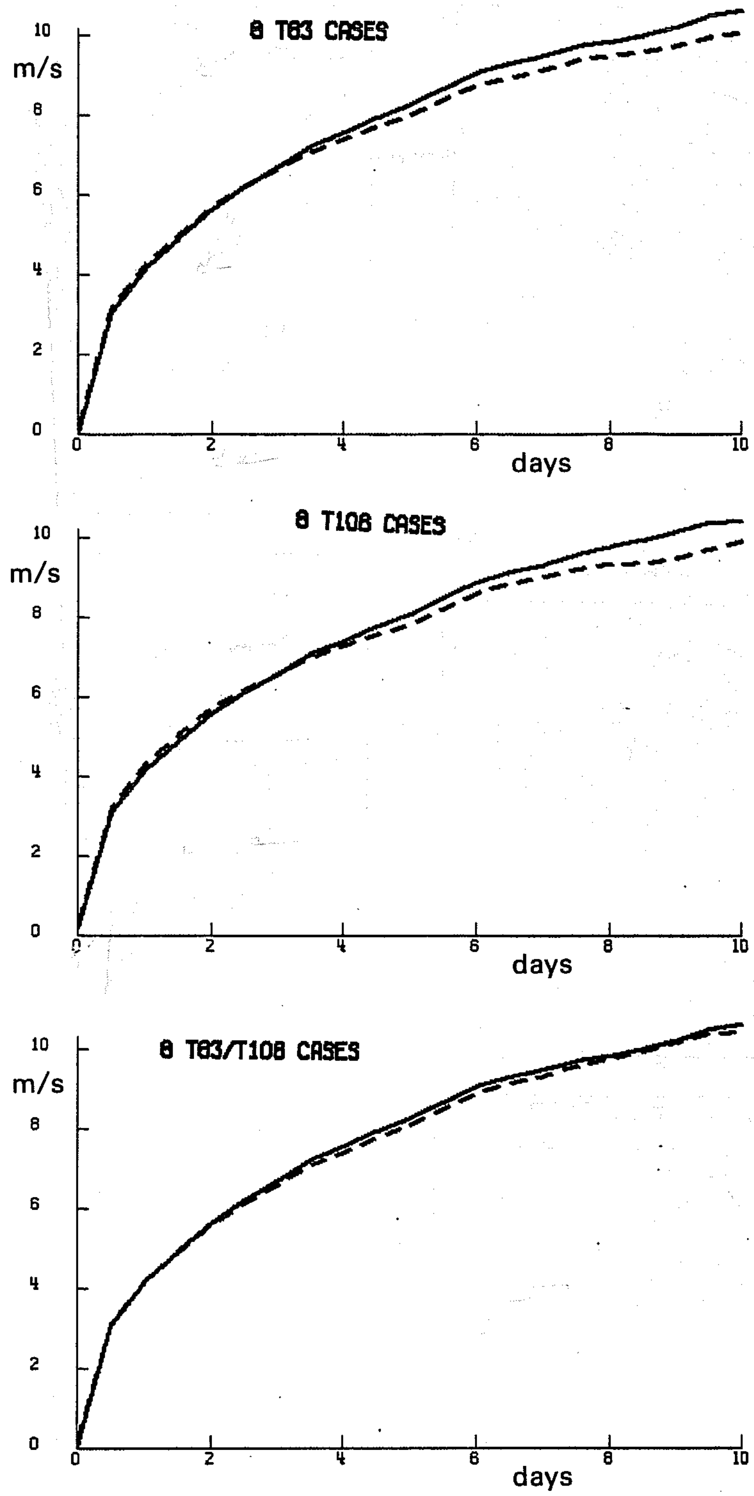


Fig. 9 Ensemble verification (8 cases) of the tropics in the rms wind error (1000-200 mb; 30°S-30°N)
Top: T63 exp. (dashed), T63 control (full); middle: T106 exp (dashed) T106 control (full); bottom: T106 control (dashed), T63 control (full)

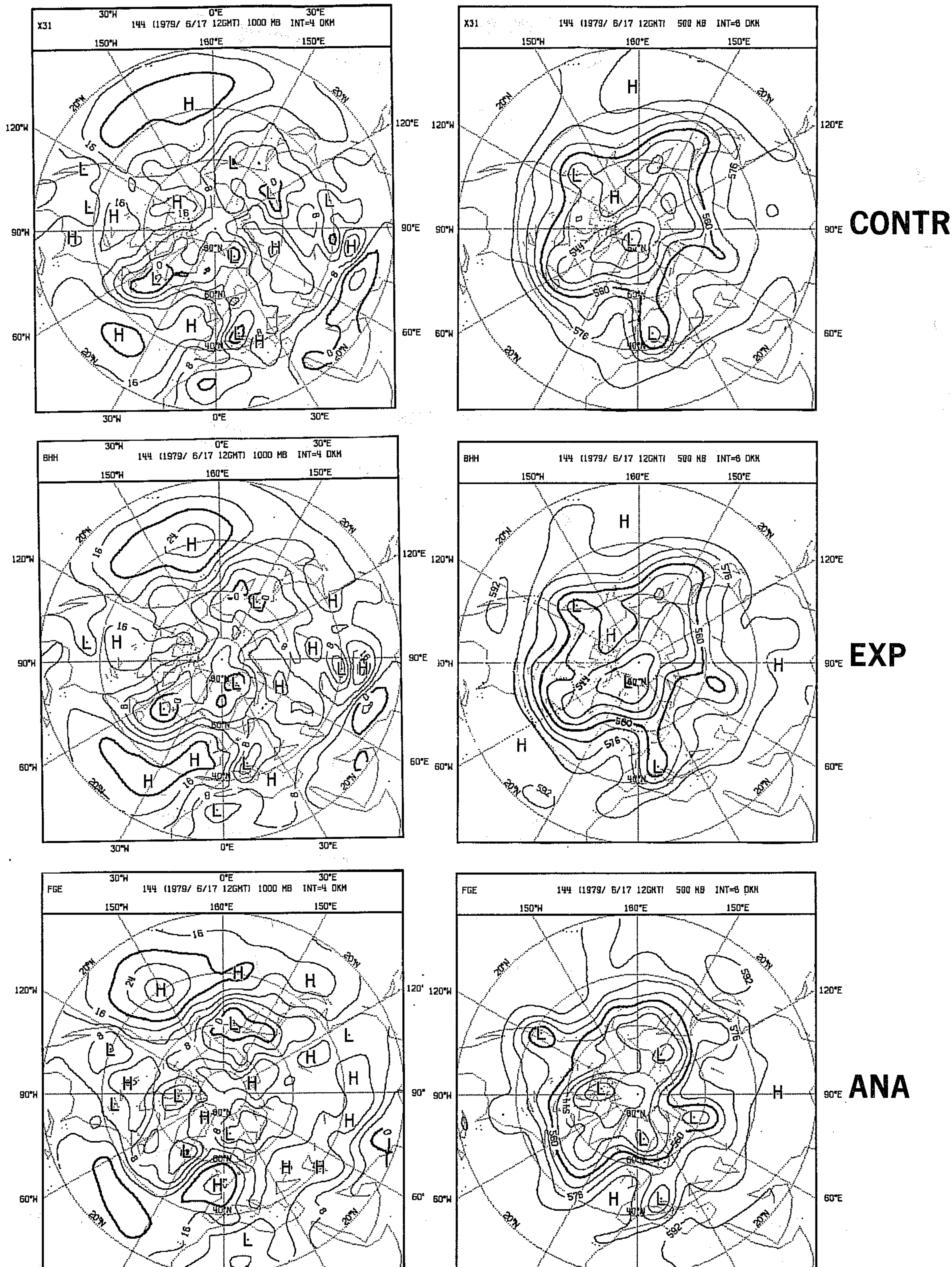


Fig. 10 Analysed and predicted 1000 mb and 500 mb height fields at day 6 of the forecasts from 11 June 1979.
Top: control (CONTR); middle: experiment (EXP);
bottom: analysis (ANA)

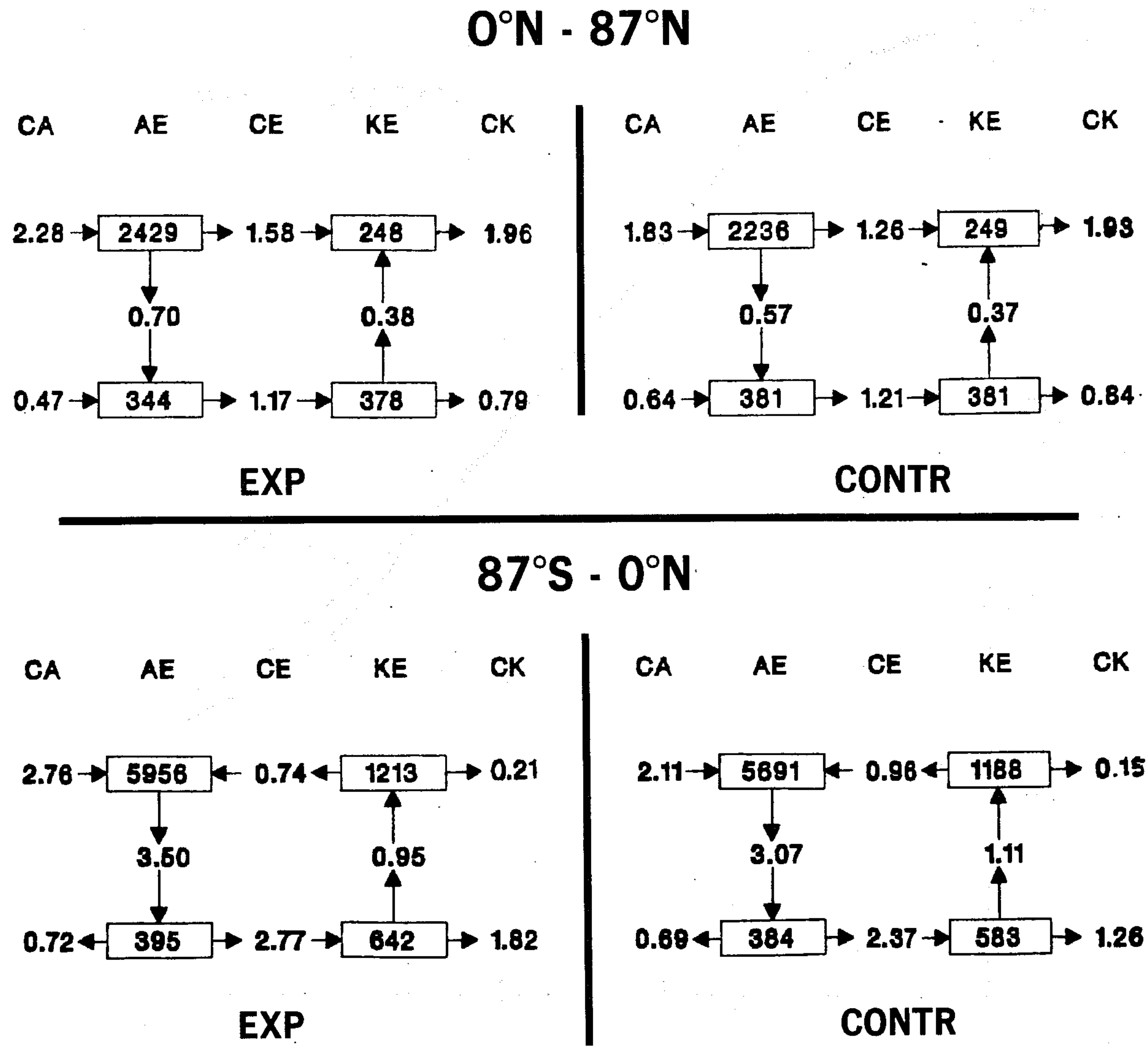


Fig. 11 Energy cycle for northern and southern hemisphere for the control (CONTR) and the physics experiment (EXP) from 11 June 1979.

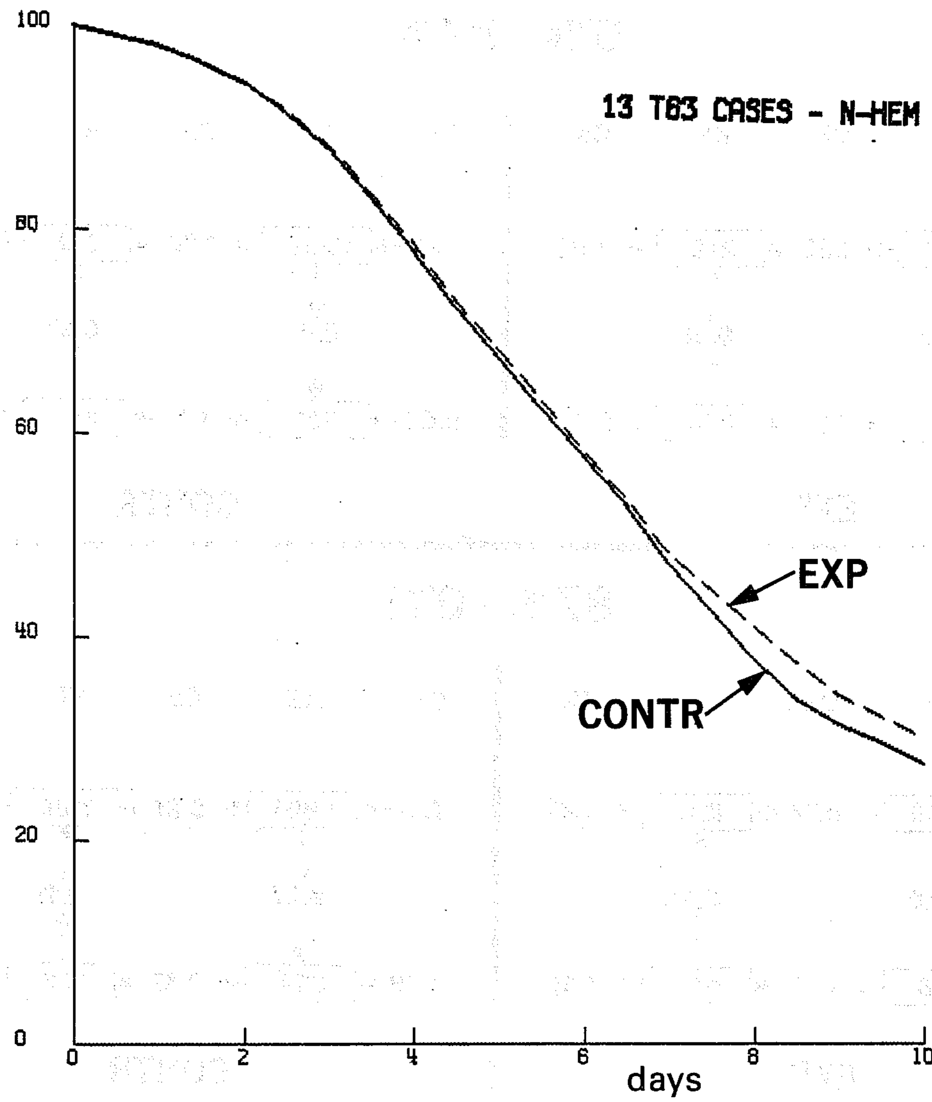


Fig. 12a Ensemble verification (13 cases) of the northern hemisphere using the anomaly correlation of height (1000-200 mb, 20-90°N). Control (full), experiment (dashed).

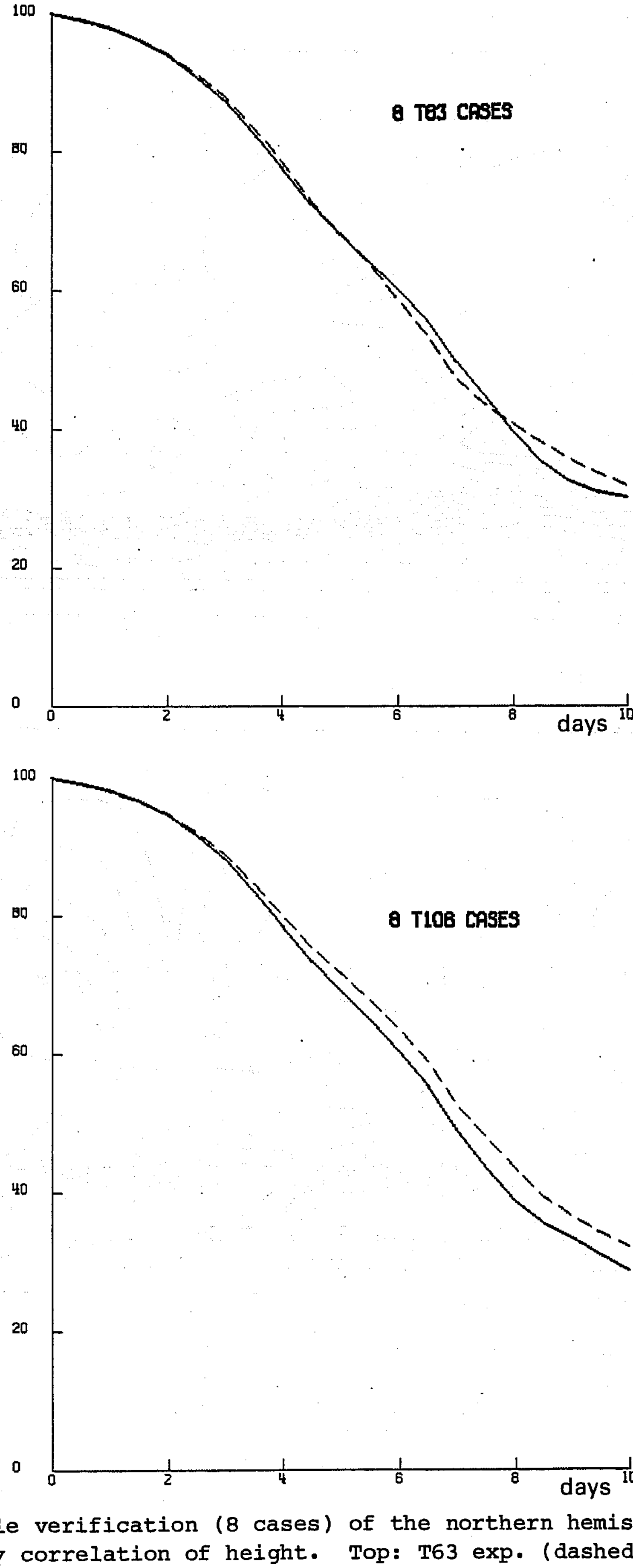


Fig. 12b Ensemble verification (8 cases) of the northern hemisphere using the anomaly correlation of height. Top: T63 exp. (dashed), T63 control (full); bottom: T106 exp. (dashed), T106 control (full).

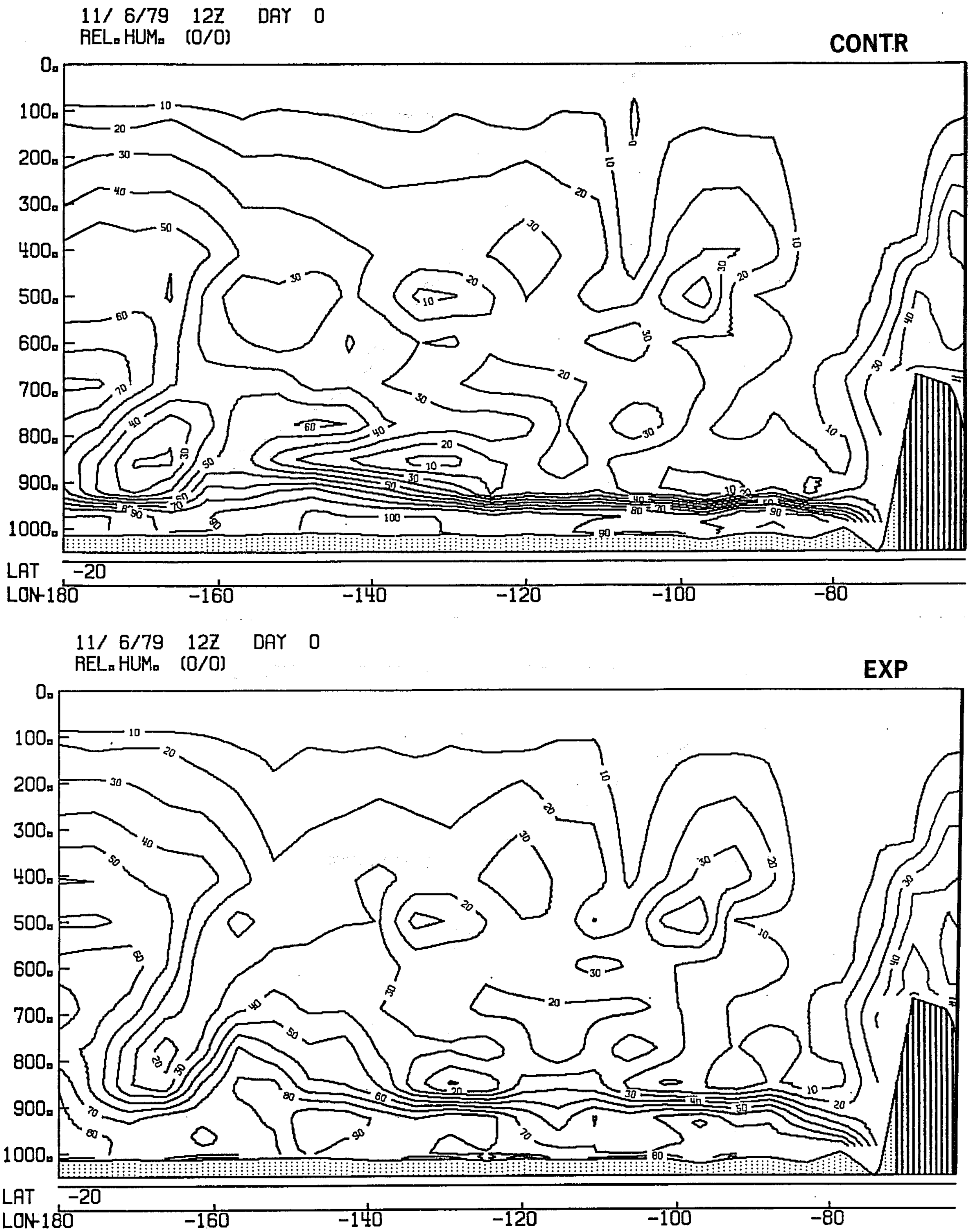


Fig.13 Zonal cross-section of relative humidity for trades under strong subsidence after 3 days of assimilation.
Top: control (CONTR) assimilation; bottom: assimilation with new physics (EXP)