TECHNICAL MEMORANDUM

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The "spin up" problem

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Subject: "Spin-up" problem

1. INTRODUCTION

An important problem in numerical forecast models is the specification of well balanced initial conditions. In the case of purely adiabatic processes constraints on mass and wind fields must be preserved to avoid the generation of gravity modes during the forecast. When diabatic processes are included the balance is more complex involving the thermal as well as dynamical state of the model. Imbalances in the initial thermodynamic state results in a mutual adjustment of the model fields as they approach a dynamical and physical balance. This initial adjustment phase, which can be as long as three days in the tropics, is commonly referred to as the "spin-up". In Bengtsson (1981), the spin-up process was called the "adjustment problem of the second kind": the process by which the observations and the dynamical/physical structure of model fields come into balance. This should be distinguished from the classical problem of geostrophic adjustment, which considers exclusively the dynamical adjustment between the mass and wind fields. The demands placed on a data assimilation scheme by the need to define an initial state in which all fields are in balance, are both stringent and very subtle. A requirement of an analysis/initialization scheme is that in addition to mass and wind fields it should provide consistent fields of derived quantities. These derived quantities are required by the various parameterisation schemes. For instance, the KUO-convection scheme demands precise specification of the initial moisture convergence together with the matching thermodynamic stabilities. In the absence of a three-dimensional high quality data coverage, assimilation schemes are likely to upset some of these internal balances, leading to a spin-up.

A better understanding of the model "spin-up" and the imbalance typical of the initial state may give insights into deficiencies in the data, in the analysis technique and the initialisation. Since the spin-up is also a function of the dynamics and the physical parameterization, it may also provide insights into possible model deficiencies.

Finally, a better understanding of the behaviour of the model in its initial adjustment phase will also help us to understand its subsequent time evolution and how the model approaches climatology.

In this study the spin-up will be discussed from two perspectives:

- globally - concentrating in particular on the model's hydrological budget

and

- locally - monitoring the development of the tropical circulation and in particular the ITCZ during the forecast.

Section 2 presents examples of the forecast fields most sensitive to the spin-up, particularly those contributing to the hydrological budget.

Section 3 considers the sensitivity of the spin-up to the initialization, the use of data and the model physics, concentrating in particular on the choice of convection scheme.

Local aspects of the spin-up are studied in Section 4 in the context of the development of the ITCZ.

2. SYMPTOMS OF THE MODEL "SPIN-UP"

The adjustment during the spin-up manifests itself in various aspects of the forecast fields. It is particularly evident in quantities such as vertical velocity, humidity and rainfall.

Fig 1, shows how the spin-up appears in the vertical velocity; very small vertical velocities are present at the beginning of the forecast but they soon grow to reach a maximum at around 36 hours, with a fully developed divergent circulation.

Fig 2 shows the spatial variance of vertical velocity, ω, as a function of forecast time. It reaches a maximum at 36 hours in the forecast. The model needs about 3 days before a balance is reached and the tropical ω-variance falls back to its climatological values.

Fig 3 plots the mean specific humidity as a function of forecast time. The drying is very intense in the first few days, indicating a large imbalance between precipitation and evaporation. This is clearly displayed in the global hydrological budget, Fig 4a, which provides a good global measure of the spin-up. Precipitation exceeds evaporation in the first few days with a maximum in precipitation between 24 and 36 hours. An equilibrium is reached only after 3 days. A separation between large scale and convective heating (Fig 4b) shows that the spin-up is mainly a tropical problem. This is in fact confirmed by Fig 5, the hydrological budget over the tropical band from 15°N to 15°S, which shows an excess of precipitation over evaporation in the first 3 days. Closer study of the geographical distribution of excess precipitation in the tropics shows, Fig 6, that it is not confined to one specific area; it rains excessively over the major convective regions, particularly Indonesia, the Indian Ocean and Southern America. In the first few days the convective rain tends to be too widely spread and does not exhibit the typical banded structure of the tropical forecast. Only after 3 days does the rainfall pattern show a more organized structure.

In this paper we shall discuss the spin-up problem of the present operational model. Although the basic nature of the spin-up appears to have hardly changed over the years there are some noticeable differences from earlier versions of the forecast model (Fig 7). In the previous model (T63 and original parametrization) the hydrological cycle was much too weak initially and quickly spun up to its balanced state (Fig 7a). In the present model (T106 with modified physics) the hydrological cycle, despite starting at a higher but more realistic level, still spins up as before but falls later to reach a balance by day 3 (Fig 7c). The introduction of a stronger horizontal diffusion into the previous model in March 1984 had little effect on the spin-up other than lengthening the spin-up time from 2 to 5 days (Fig 7b).

In the following the hydrological budget will be used as a measure of the sensitivity of the spin-up to changes in the initial state and the model formulation.

3. SENSITIVITY EXPERIMENTS

A series of sensitivity experiments have been carried out to test how the "spin-up" problem is affected by

a) initialization
b) use of data
c) model physics

a) sensitivity to initialization

It has been argued in the past (Bengtsson, 1981, Heckley, 1982) that the initialization may largely contribute to the spin-up. As discussed in Wergen (1987), the initialization procedure used at ECMWF is a diabatic normal mode initialization. The inclusion of diabatic effects has improved the representation of the divergent part of the circulation. To check the impact of the initialization on the model spin-up, two forecasts are compared, one from an initialized and the other from an uninitialized analysis. Fig 8 shows the convective rain accumulated between 00 and 12 hours into the forecast over Indonesia. As pointed out in Wergen (1987), there is very little difference between the initialized and uninitialized forecasts.

To investigate further the impact of the initialization on the model spin-up, a 3 days forecast with initialization every six hours was carried out. Again the impact of the initialization was found to be negligible. Although an initialization is performed every six hours, after 3 days (Fig 9) the model is able to reach an hydrological balance. Therefore these experiments indicate that the initialization is not responsible for the spin-up.

b) sensitivity to data types

To investigate which types of data contribute most to the spin-up, sensitivity experiments have been carried out consisting of 3 days of data assimilation employing various data types, followed by a 5-day forecast.

In this section sensitivity of the spin-up to data types will be discussed from a global point of view as revealed by the hydrological budget. Local effects of data will be addressed in Section 4.

Using the global hydrological budget as our indicator of the spin-up, most sensitivity was found to the use of moisture data. Fig 10 shows the hydrological budget both in the HUM forecast (from assimilation with humidity data) and NOHUM forecast (from assimilation without humidity data). Clearly the magnitude of the imbalance between precipitation and evaporation has decreased in the NOHUM experiment; the maximum rainfall between 24-36hours decreased from 3.4 mm/day in the CONTROL to around 3.2 mm/day in the NOHUM assimilation. Furthermore a closer hydrological balance is reached by day 4. Such a sensitivity to moisture data is not surprising in view of the strong dependence of the KUO-scheme on moisture convergence.

Some sensitivity was found when surface data are excluded, the largest body of observations in the Tropics, whilst less sensitivity was found to the use of satellite temperatures and satellite winds.

A further radical test to assess the impact of the data was also carried out,uin which a three day forecast is used as a first-guess for a one day assimilation. The subsequent three day forecast can be examined for evidence of the spin-up. In this way it is ensured that evaporation and precipitation are balanced at the start of the assimilation. However, after the insertion of data, the hydrological budget again reveals an imbalance characteristic of the spin-up. This shows that only a few assimilation cycles are required to destroy the hydrological balance typical of a 3-day forecast. In interpreting these results, however, it is important to remember that by day 3 the tropical forecast errors have become so large that inconsistencies between data and forecast fields must be expected, which may contribute to the subsequent spin-up.

To summarize, our experiments have shown some sensitivity to the use of data types in the analysis, particularly moisture data, but they have failed to attribute the "spin-up" problem to the use of one specific data type. Further studies are needed to find out which aspects of the data assimilation (i.e. manner in which data are used, interaction between different data types) is responsible for the inconsistency between analysis and model fields.

So far, we have only addressed sensitivity to data in the context of the present model with the Kuo-scheme. In the next section it will be shown that the spin-up and in particular the adjustment time-scale depends on the choice of convective parametrisation scheme. This seems to indicate that the spin-up is not related to a unique data type but that various types may be responsible depending on which convection scheme is used.

c) sensitivity to convection schemes

Several experiments have been carried out to study the effect of convective parameterization on the hydrological budget. In addition to the KUO-scheme presently employed operationally, the "adjustment scheme" (Betts and Miller, 1986) and a Massflux scheme (being developed at ECMWF) have been investigated.

As mentioned previously the operational version of the KUO-scheme develops rather widespread convective rain particularly between 24-36 hours. A KUO-scheme, modified to ameliorate this problem, has been tested, in which the β-parameter has been adjusted so that precipitation cannot occur below a critical relative humidity of 50%. This modified scheme shows a marked improvement in the hydrological budget, especially when it is also employed in the data assimilation phase (Fig 11). The amplitude of the spin-up has markedly decreased, although now the rainfall amounts are slightly below climatological values. This experiment suggests that the characteristic spin-up behaviour of the operational version of the model is due to an imbalance between the thermodynamical state typical of the assimilation phase and that typical of the forecast, which is a function of the convection scheme.

The form of the spin-up curve is very sensitive to the convection scheme in use. For example, when the "adjustment scheme" is used, the model tends to adjust on a much shorter time-scale, but more vigorously; Fig 12 shows a hydrological budget typical of an "adjustment" forecast. It tends to give excessive rainfall in the first 12-hours, but adjusts quickly to a balance. Although the time scale is much shorter than in the operational KUO, there is still evidence of an adjustment process. On the other hand, the geographical distribution of initial rainfall from an adjustment forecast shows a more organised structure, with the typical banded structure of the tropical rainfall.

Other more complex convection schemes such as the new Massflux scheme, behave differently again (Fig 13). The excess of precipitation in the first few days is no longer present and a balance is reached rather quickly. On the other hand, in the later stages of the forecast, the model precipitation tends to be too low with respect to climatology.

In summary, then, the "spin-up" as seen in the hydrological budget is very sensitive to the type of convection scheme used. This suggests that a vigorous spin-up may be due to an inconsistency between the thermodynamic structure as defined by the data/analysis and the thermodynamic structure typical of the forecast determined largely by the convection scheme.

Further studies are planned to isolate the types of data and the manner in which they are used in the analysis, leading to this inconsistency.

4. DEVELOPMENT OF THE ITCZ

Although the spin-up is clearly seen in the global hydrological cycle, rainfall maps shows that the spin-up problem is worse in certain geographical areas than in others. The ITCZ over the Pacific and Atlantic are particularly sensitive areas. In the first 12 hours of a forecast there is very little convective rain over the ITCZ. However by day 1 the convective precipitation has markedly increased and a clear banded structure develops associated with the ITCZ. The same behaviour is found in uninitialized forecasts, showing that the initialization is unlikely to be responsible for the initial lack of convective activity. To investigate this further, the following NODATA experiment has been carried out: 3 days of assimilation without data but performing the initialization every six hours. In the NODATA experiment the ITCZ is clearly defined and the amount of convective rain in the first 12-hours of the forecast is much larger than in the CONTROL forecast. Thus it appears that the initialization does not play the major role in destroying the convective activity in the tropical ITCZ. Rather, if at the end of the NODATA assimilation data are inserted again, only 2 analysis cycles are required to severely inhibit the convective activity over the Pacific ITCZ. It must be concluded, therefore, that it is the use of data in the analysis rather than the initialization, which is causing the weakening. Studies have been carried out to enquire into the impact of various data types on the development of the ITCZ.

Very little sensitivity is found to satellite winds whereas the exclusion of satellite temperature results in a large response with markedly enhanced convective rain over the ITCZ (Fig 14). This suggests that the use of satellite derived temperatures may be responsible for the low convective activity over the ITCZ in the first day of the forecast. Fig 15 shows a T-ϕ diagram over the Pacific ITCZ for the SATEM analysis (from assimilation with satellite temperature data). It is clear from the profile that the bouyant air parcels come to rest at around 700 mb, where there is a marked inversion. This inversion is typical of analysis profiles in the area and explains the small convective activity in the SATEM experiment. In contrast, Fig 16, a T-ϕ diagram from the NOSATEM analysis (assimilation without satellite temperature data), shows that now, without satellite data, the sharp inversion at the top of the boundary layer is almost absent. Inspection of SATEM reports, however, do not show any inversion, but rather a temperature profile which smoothly decreases with height; see Fig 17, a SATEM report near the point considered in Figs 15, 16. It appears, therefore, that it is not the data themselves which are responsible for the inversion, but rather it is the manner in which they are used by the analysis. Indeed inspection of the relative weights given to the observations and the first-guess in the tropics shows that the analysis is very little affected by the data in the boundary layer; only above 700 mb does the data start to have an impact. It is this rather abrupt change in the weighting of model and data that may be responsible for the sharp inversion in the analysis and hence to the suppression of convective rain.

Investigations are presently underway into improved methods of exploiting satellite derived temperature profiles taking into account the fact that they only crudely resolve the thermal structure of the tropical boundary layer.

5. SUMMARY AND CONCLUSIONS

The spin-up phase of the numerical forecast, in which model fields adjust towards a dynamical and physical balance, has been described and investigated. The spin-up is evident in various model fields, but especially vertical velocity, moisture and precipitation. A particularly sensitive indicator of the spin-up is the global hydrological cycle which shows an excess of precipitation in the first 3 days of the forecast.

Sensitivity experiments have shown that the hydrological cycle is insensitive to the initialization procedure, shows rather more sensitivity to use of various data types in the analysis, especially moisture data, but is most sensitive of all to the convective parameterization scheme. Each convective scheme has its own characteristic signature in the spin-up. The time-scale over which a hydrological balance is eventually reached is a function of the parameterization scheme used (and its tuning). The studies performed so far indicate that the spin-up is not primarily of dynamical origin but rather is a consequence of an incompatability between the thermodynamic state of the model, as determined by the convection schemes, and the thermodynamic state of the analysis, as given by the data.

Sensitivity to various data types is most evident locally, especially over data sparse areas such as the Pacific and Atlantic ITCZ, where satellite data are extensively used. In one case the lack of convective activity over the ITCZ in the first few hours of integration can be traced back to a sharp inversion at the top of the boundary layer which suppresses convective activity. The manner in which tropical satellite temperature profiles are used in the analysis may artificially generate an inversion, which caps and suppresses subsequent convective activity. Further studies are underway to investigate improved methods of using satellite data in the tropical boundary layer.

Our study has described some of the major aspects of this complex problem in which, in the early stages of the forecast, the model fields adjust to the shock associated with the imbalance in the initial state. It is evident that the evolution of the model in the first few days of the forecast will affect its subsequent development. An important aspect of the spin-up problem for further study is its role in conditioning the subsequent development of the forecast and, in particular, its approach to climatology.

To summarize our main conclusions, the spin-up is:

1) insensitive to the initialization procedure

2) sensitive to the use of data in the analysis, in particular to moisture data (globally) and to satellite temperature data (locally - ITCZ)

3) sensitive to the convective parametrization scheme

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Heckley, W, 1982: Adjustment in the Tropics. ECMWF Workshop proceedings on "Current problems in data assimilation", 8-10 November 1982, 299-342.

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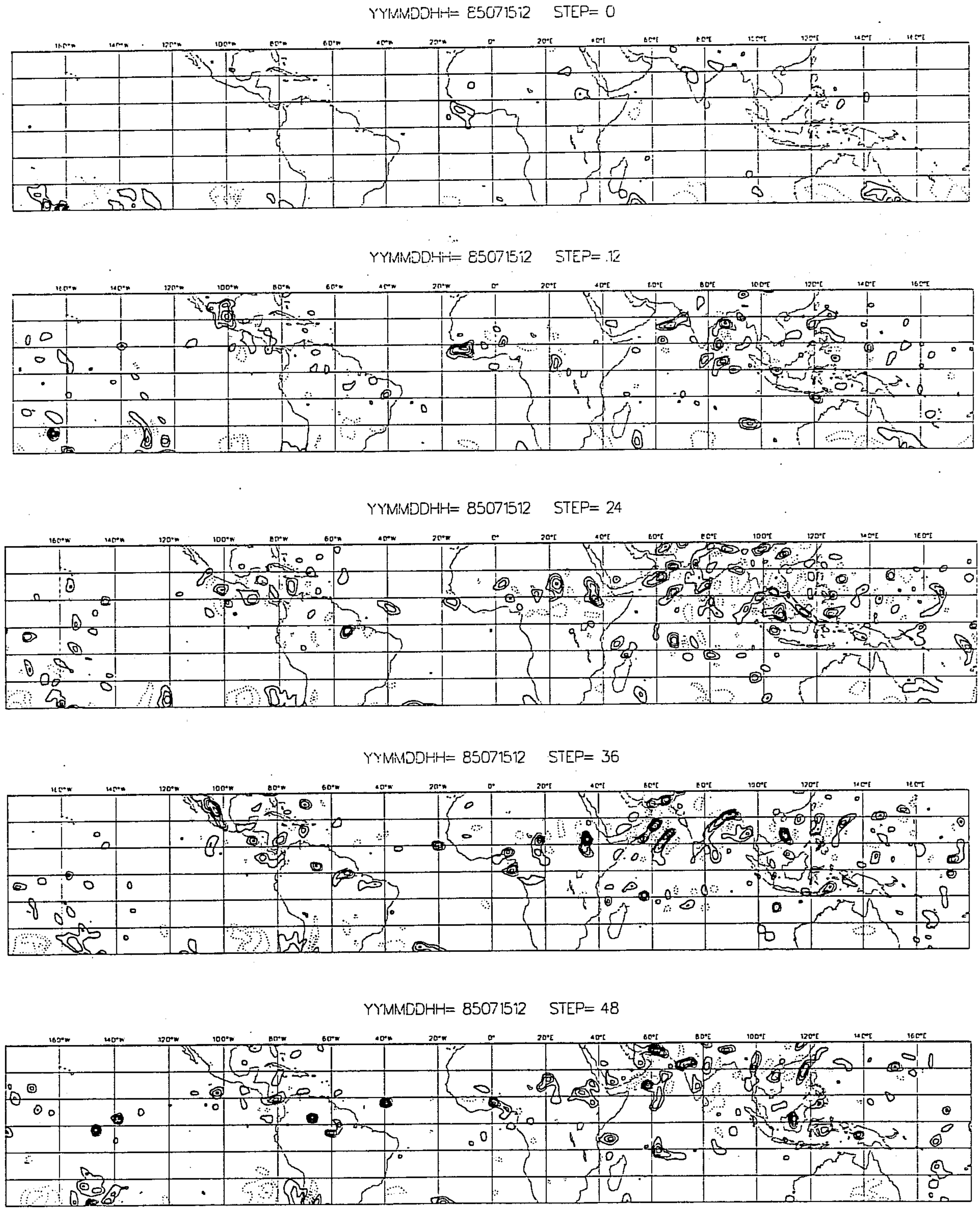


Fig. 1 A sequence of vertical velocity at 500 mb and between 30°N and 30°S during a forecast (0-48 hours). A solid line indicates rising motion.

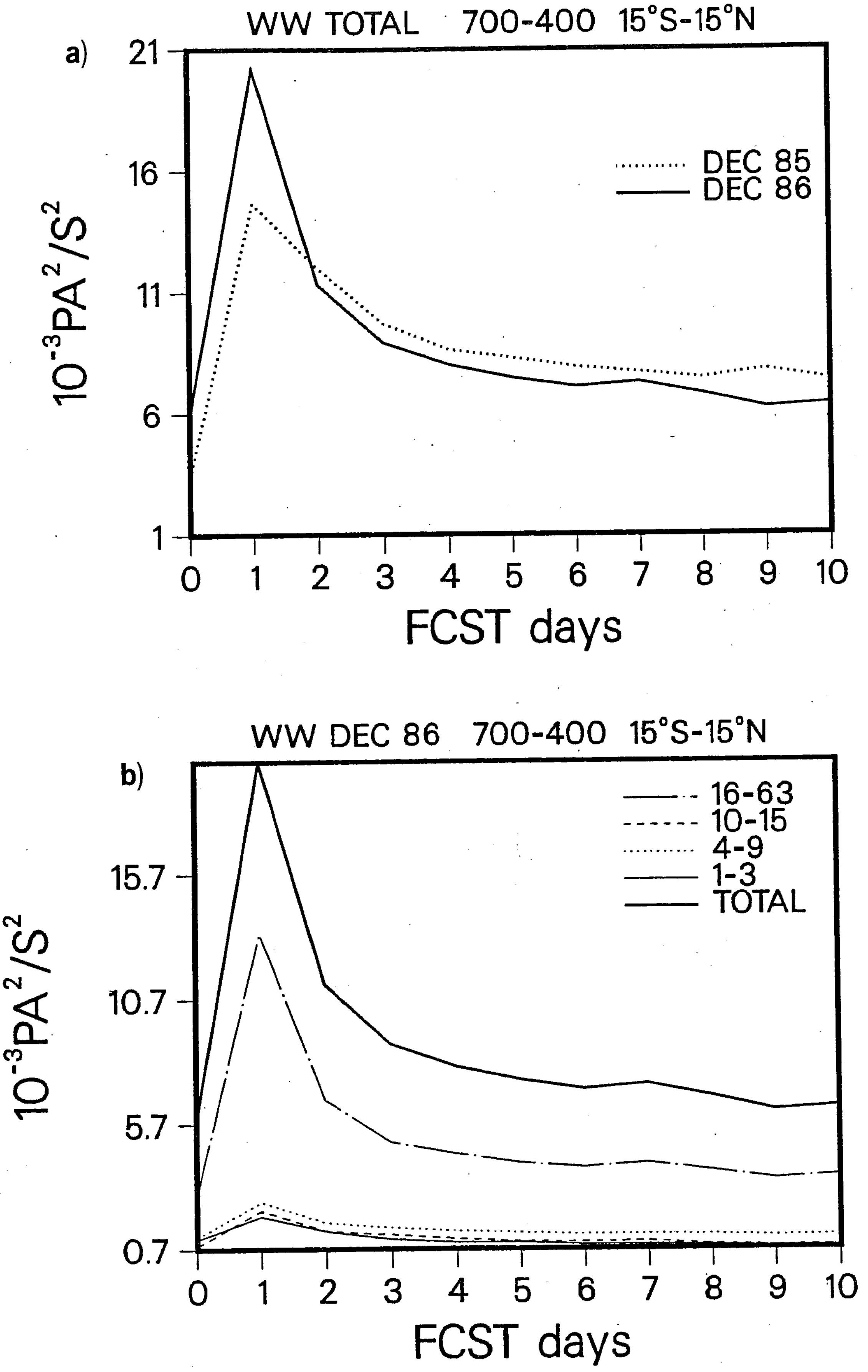


Fig. 2 The area averaed ω-variance ($10^{-3}PA^2/S^{-2}$) as a function of forecast time over the Tropics, 15°N to 15°S, between 700 and 400 mb.

a) total

b) by wave number

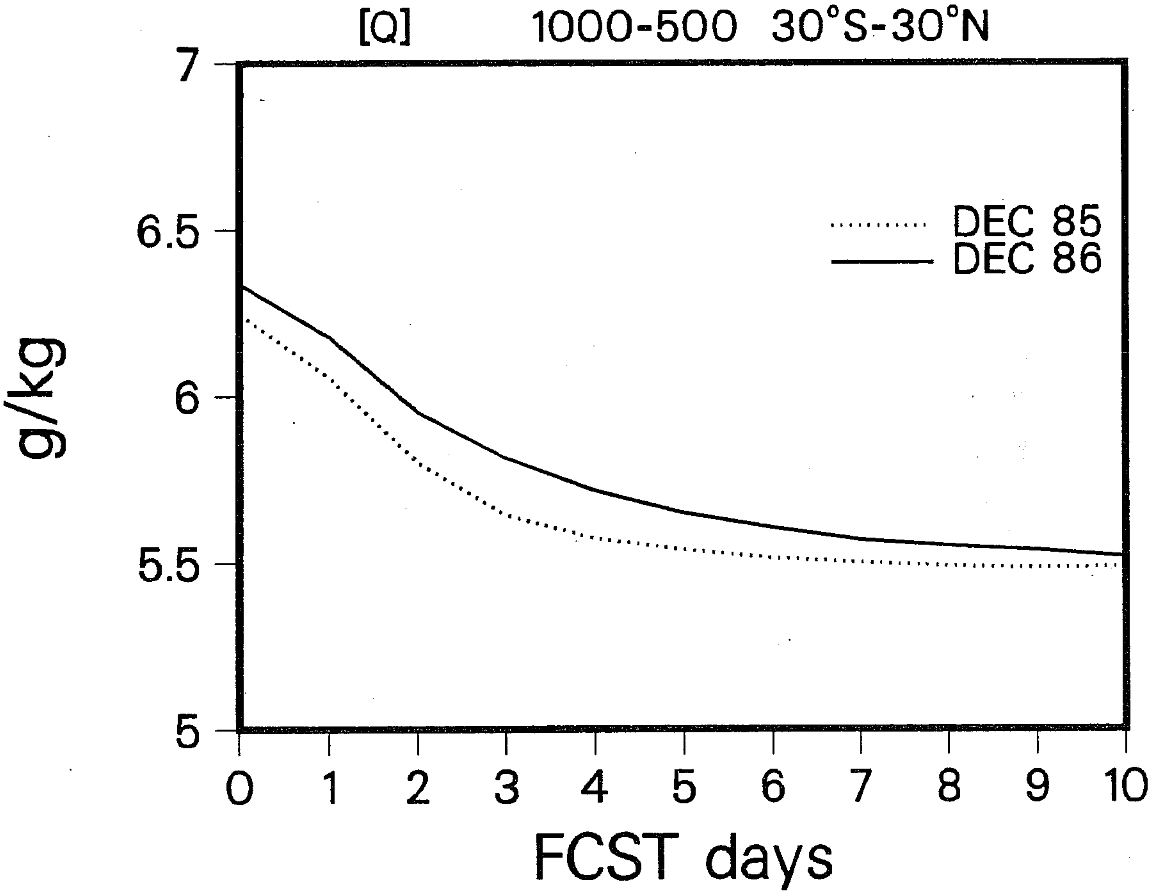


Fig. 3 The area averaged specific humidity as a function of forecast time over 30°S to 30°N and between 1000 and 500 mb.

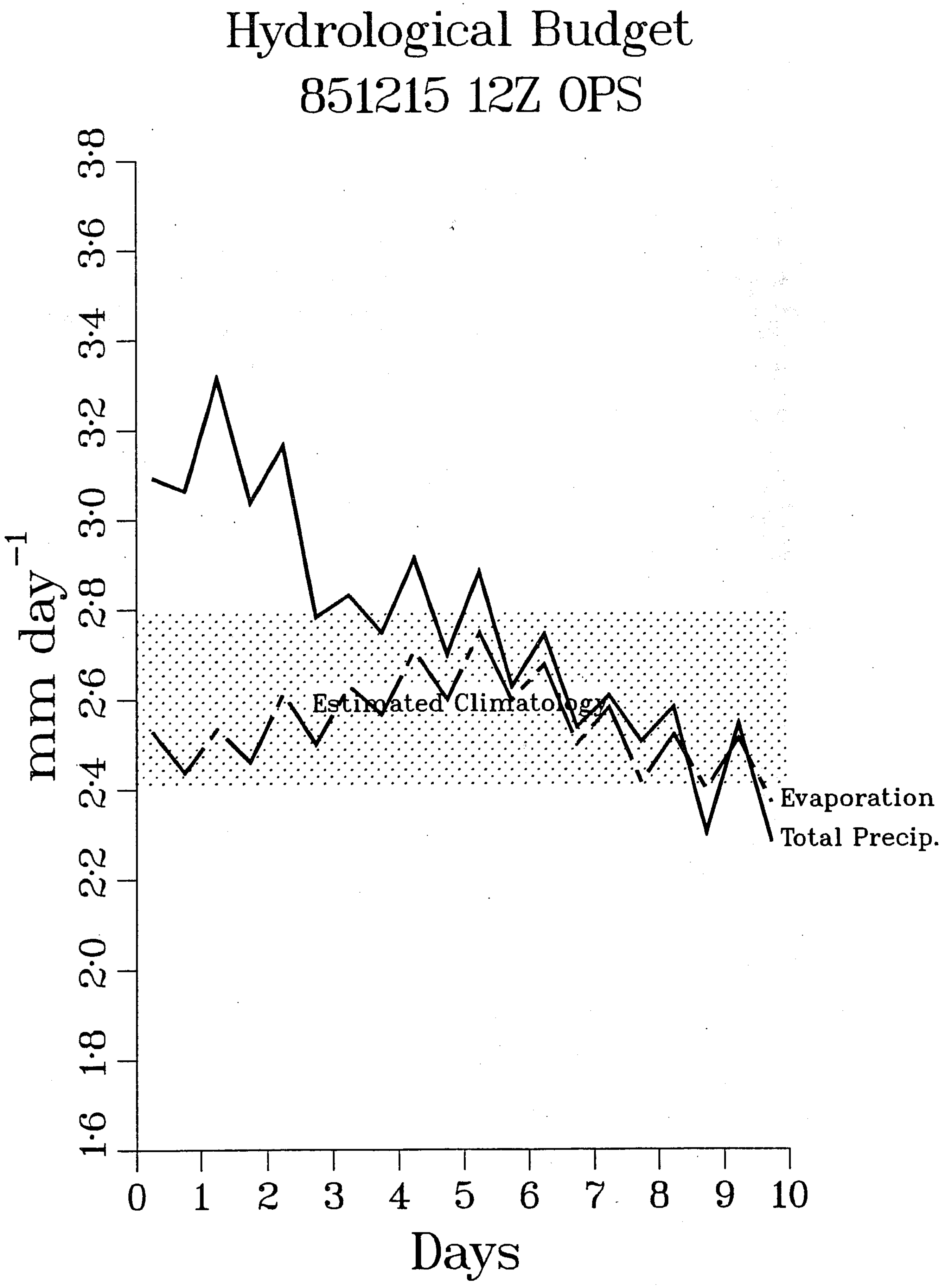


Fig. 4 a) A typical hydrological budget obtained from a forecast from 12 GMT, 15.12.85.

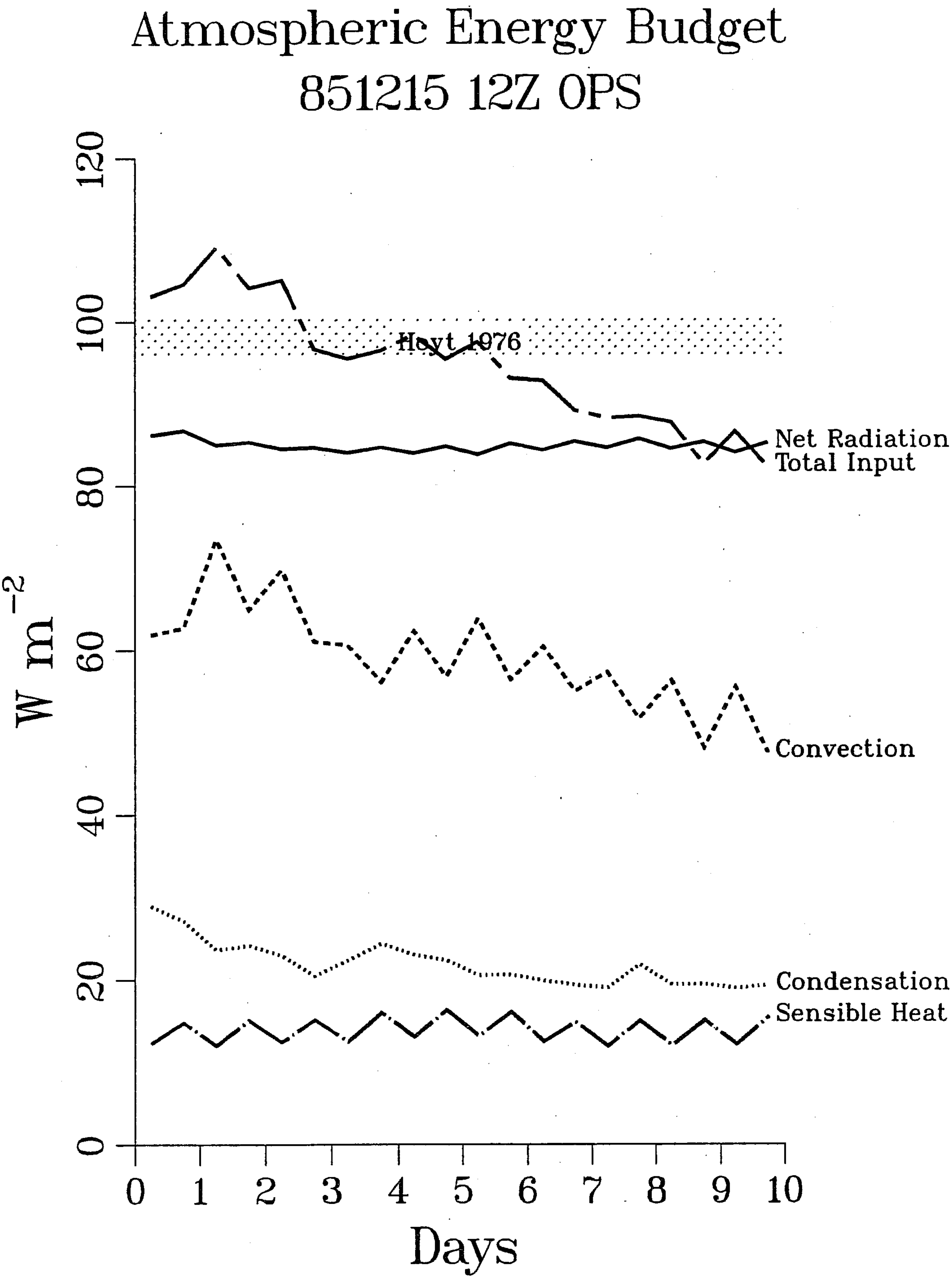


Fig. 4 b) The atmospheric energy budget from the same forecast

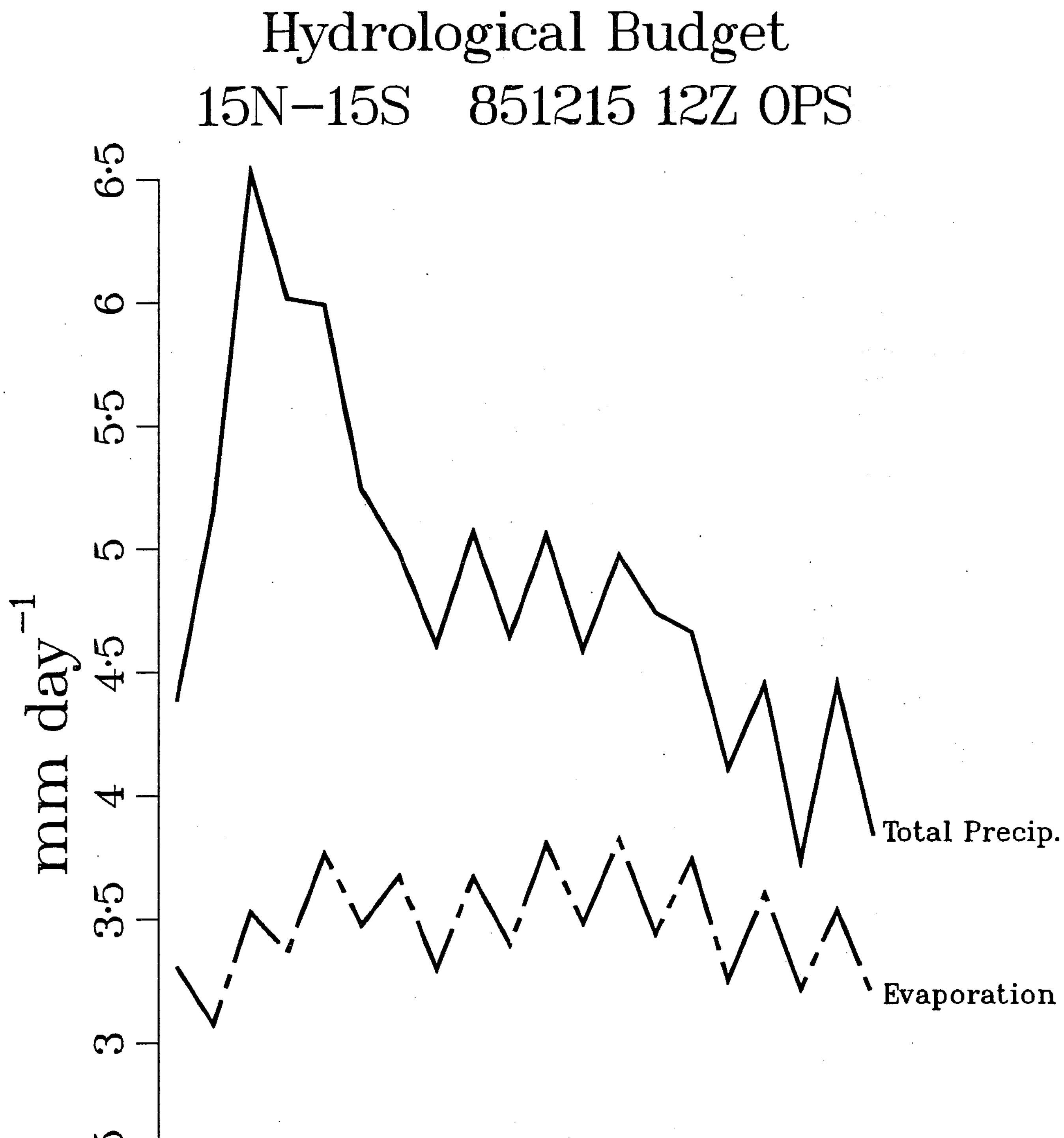
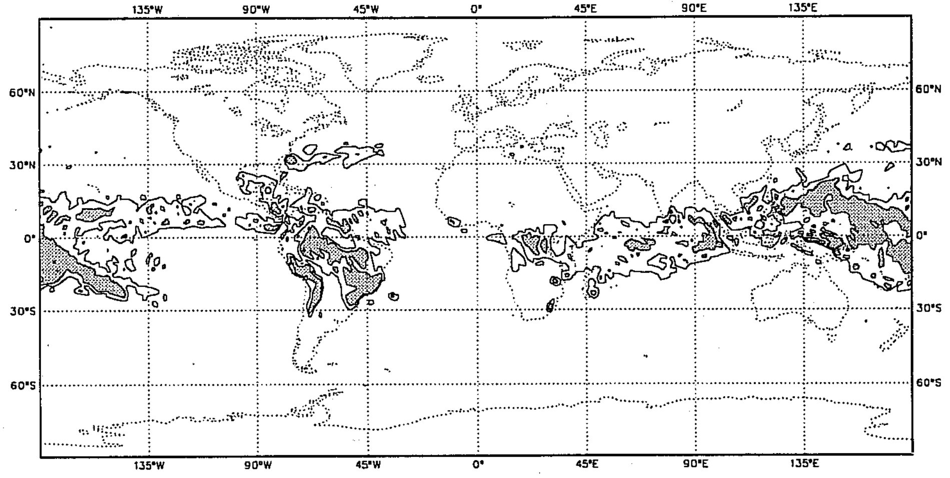
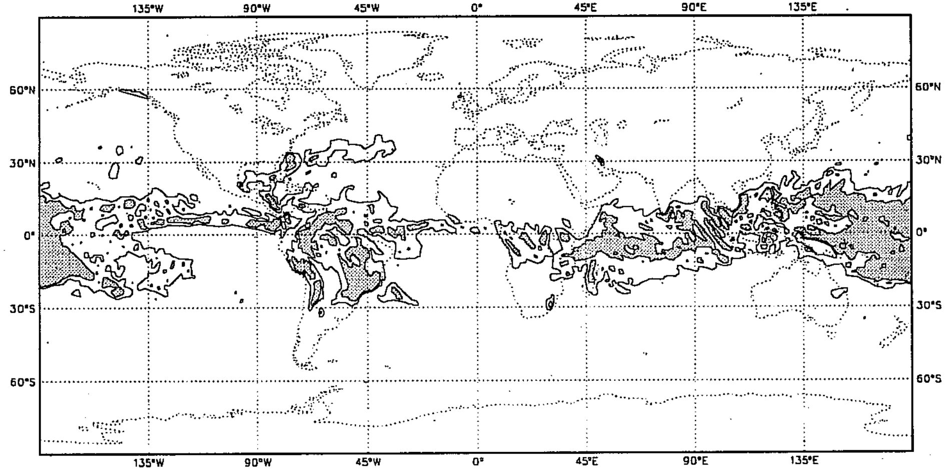


Fig. 5 The precipitation and evaporation budget over the Tropics (15°N to 15°S) for the same forecast as in Fig. 4.

a) CONVC.RAIN CONT. 5.,10.,20mm/DAY
INITIAL DATE 861130 12GMT FCST–day 0.50
AREAS WITH MORE THAN 10. mm/DAY ARE SHADED



b) DIFFERENCE BETWEEN DAY 1.50 AND DAY 1.00



c) DIFFERENCE BETWEEN DAY 4.00 AND DAY 3.00

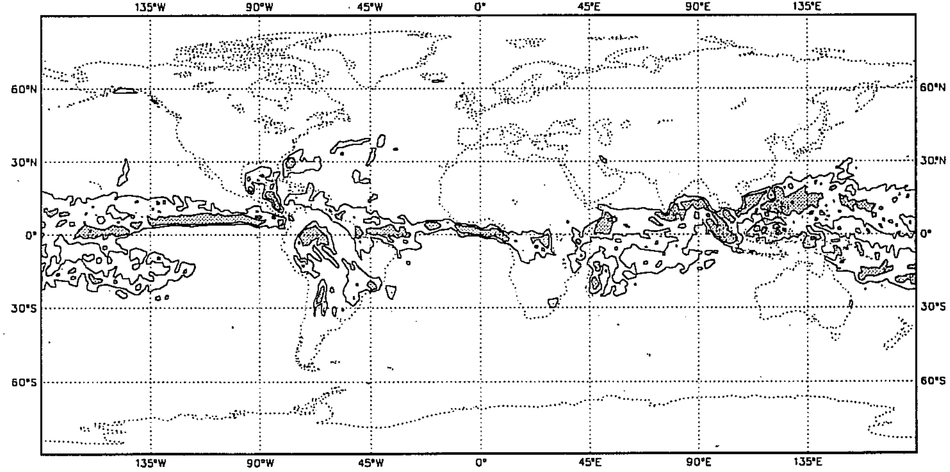


Fig 6 Monthly mean 12-hour accumulated convective precipitation at different forecast times a) 12 hours, b) 36-24 hours, c) 120-96 hours). (areas with more than 10 mm/day are shaded)

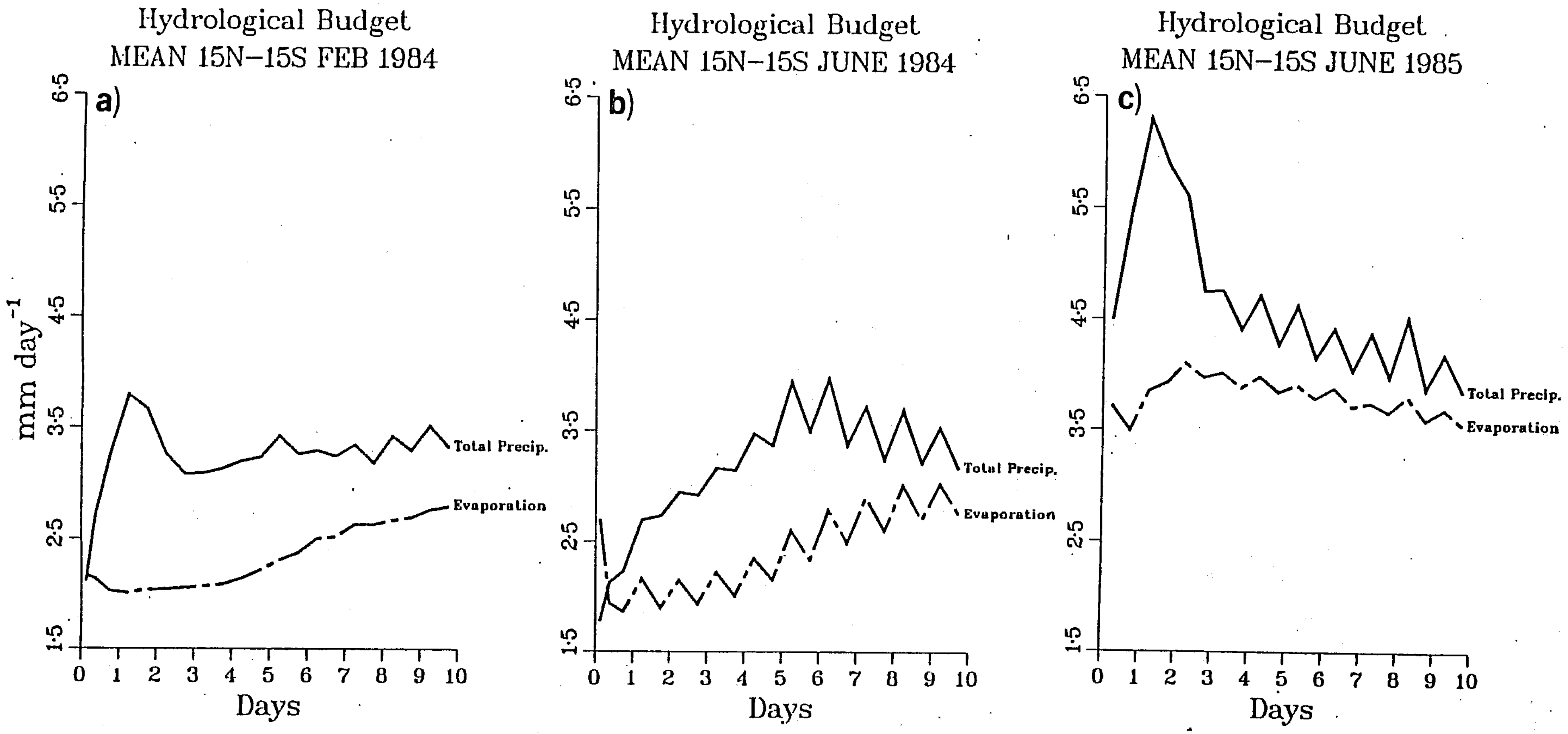


Fig 7 Precipitation and evaporation budgets (mm/day) in the Tropics (15°N to 15°S) a) February 1984 - T63 old physics, b) June 1984 - T63 old physics and enhanced horizontal diffusion, c) June 1985 - T106 new physics and reduced horizontal diffusion (from Brankovic, 1986)

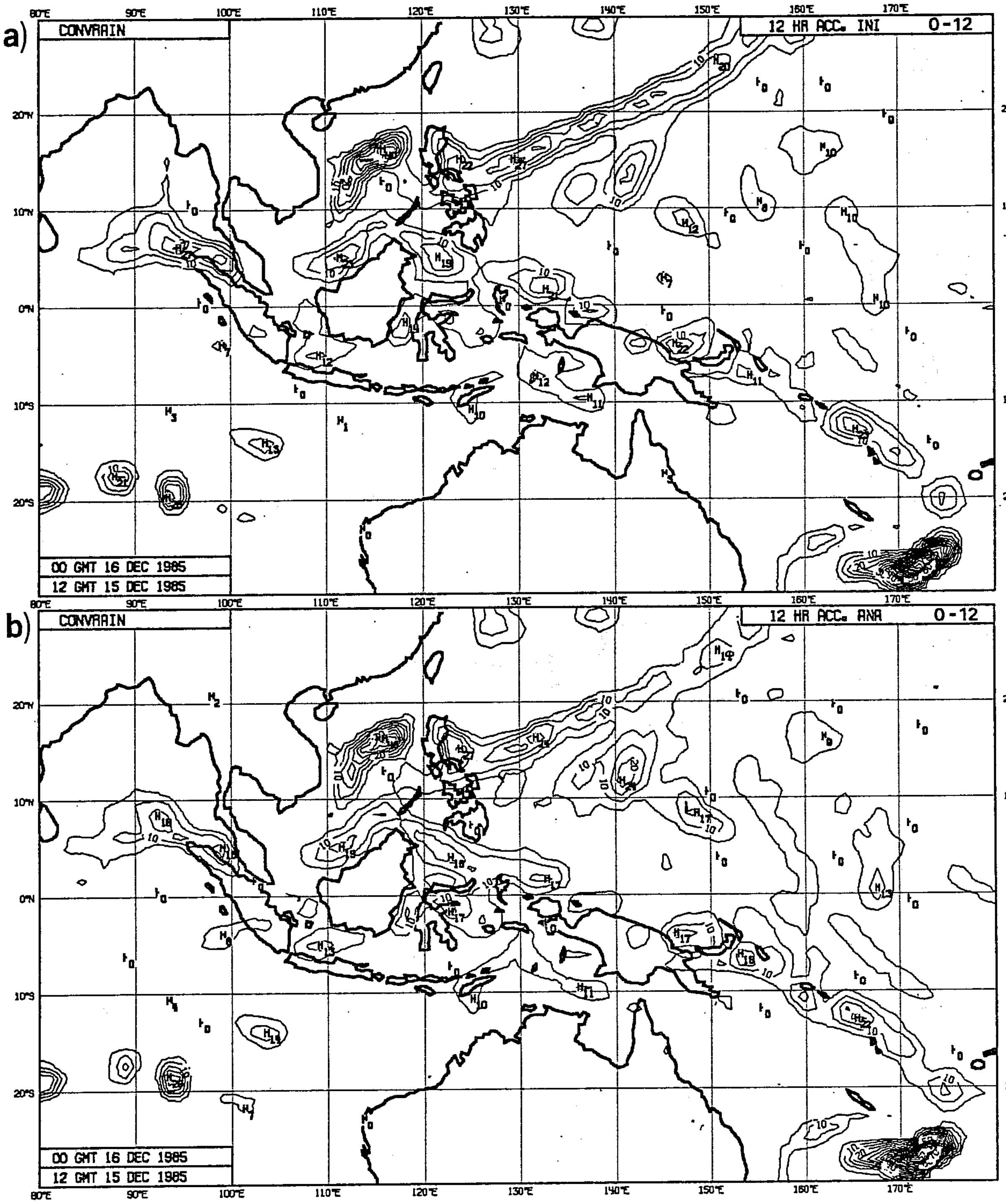


Fig. 8 The 12-hour accumulated convective precipitation for a forecast from 12GMT on 15.12.85 in

a) an initialized forecast

b) an unitialised forecast

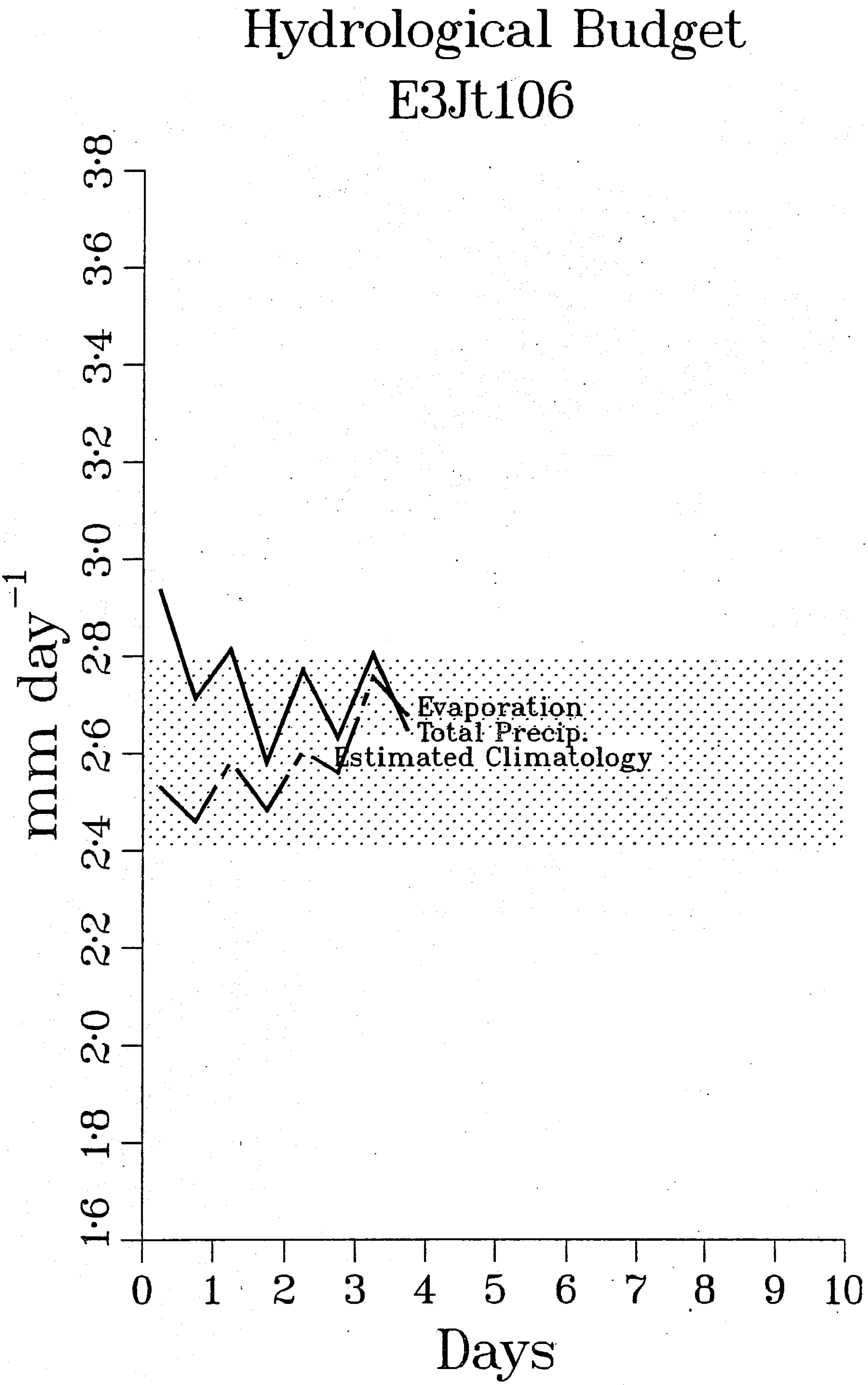


Fig 9 The hydrological budget for a forecast from 12 GMT on 16.12.85 after a 3 days forecast with initialisation every six hours.

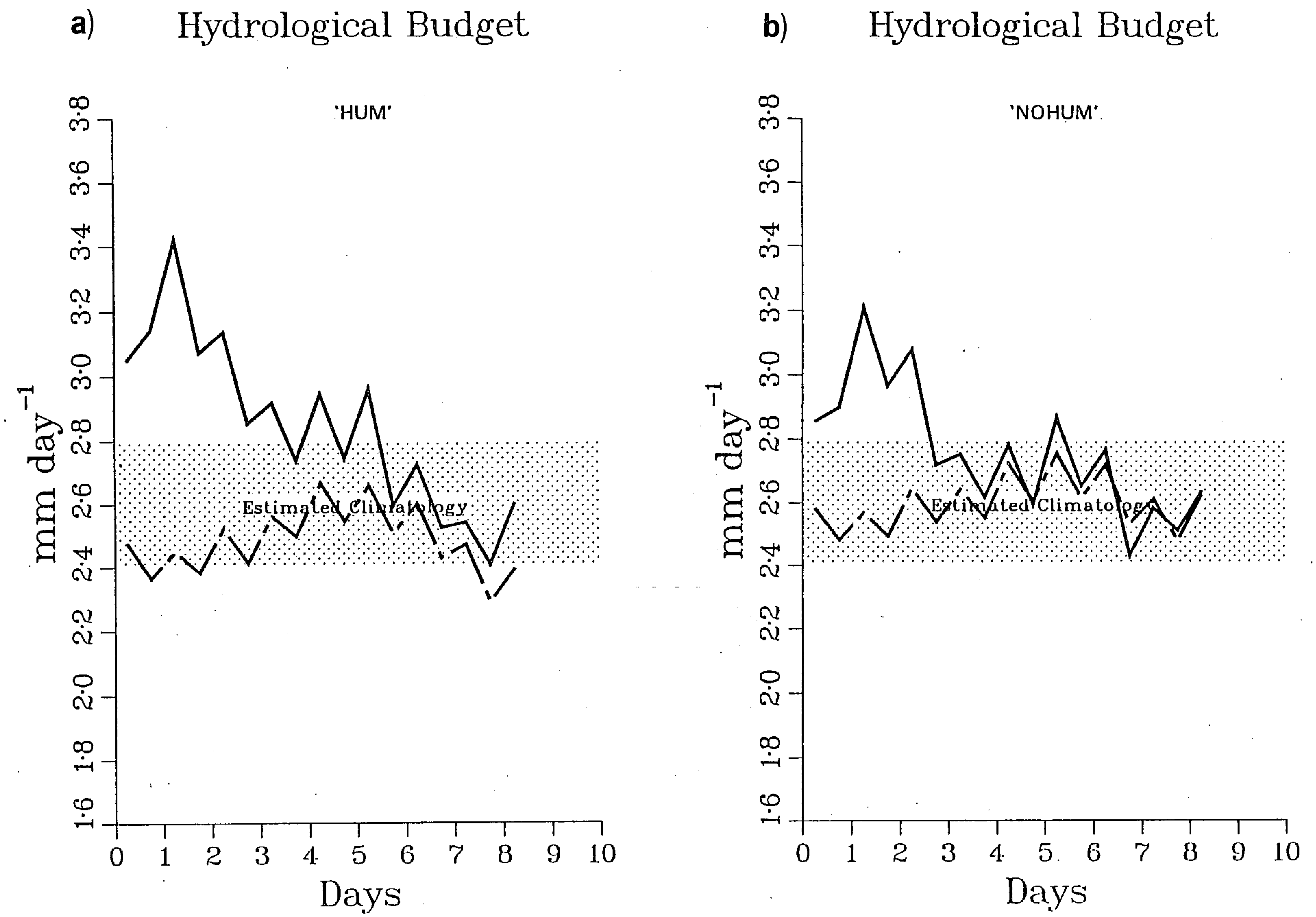


Fig 10 The hydrological budget for a forecast from 12GMT on 15.12.85 for
a) the HUM assimilation
b) the NOHUM assimilation

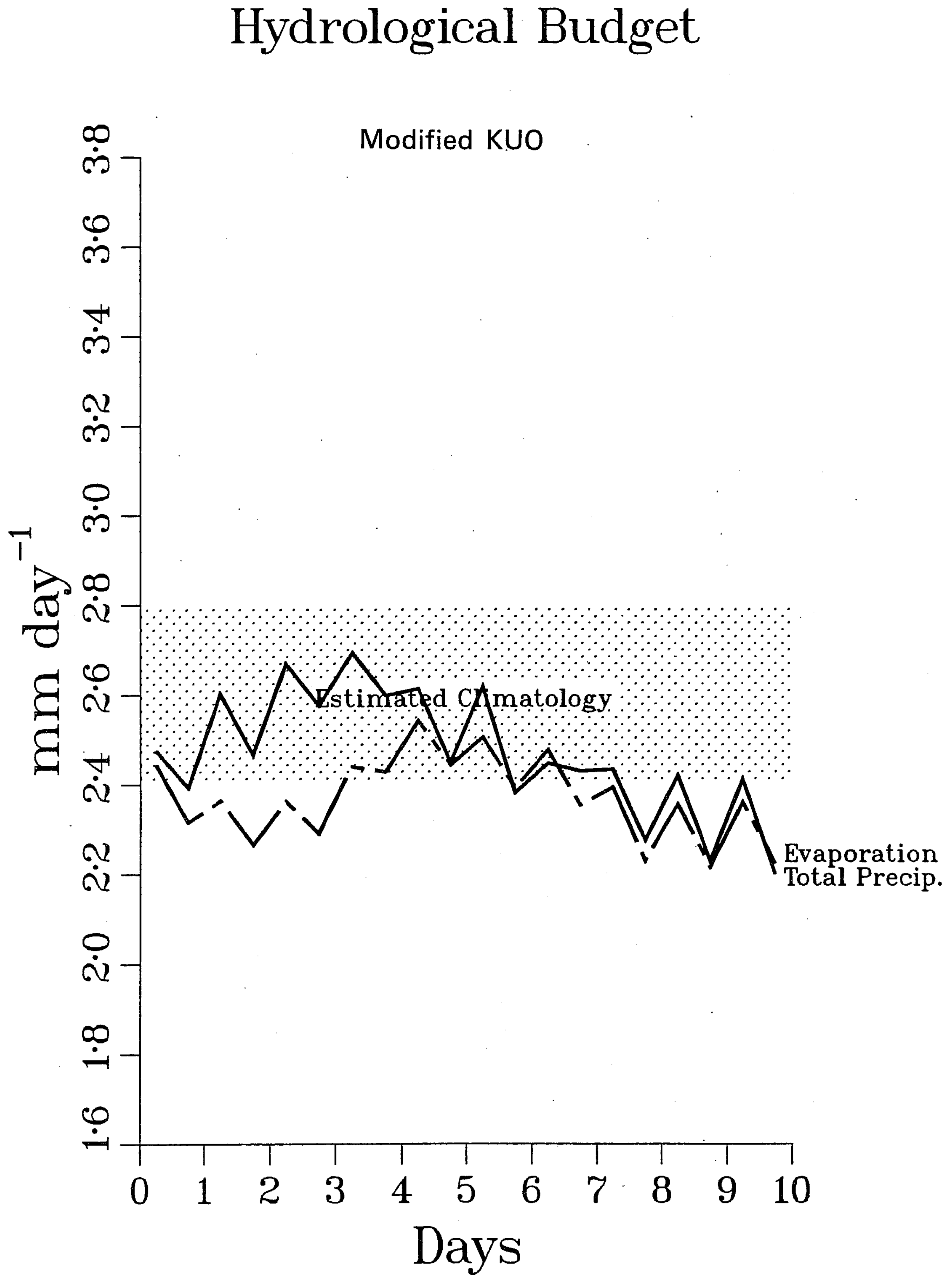


Fig 11 The hydrological budget for a forecast from 12GMT on 15.12.85 using a modified version of the operational KUO-scheme.

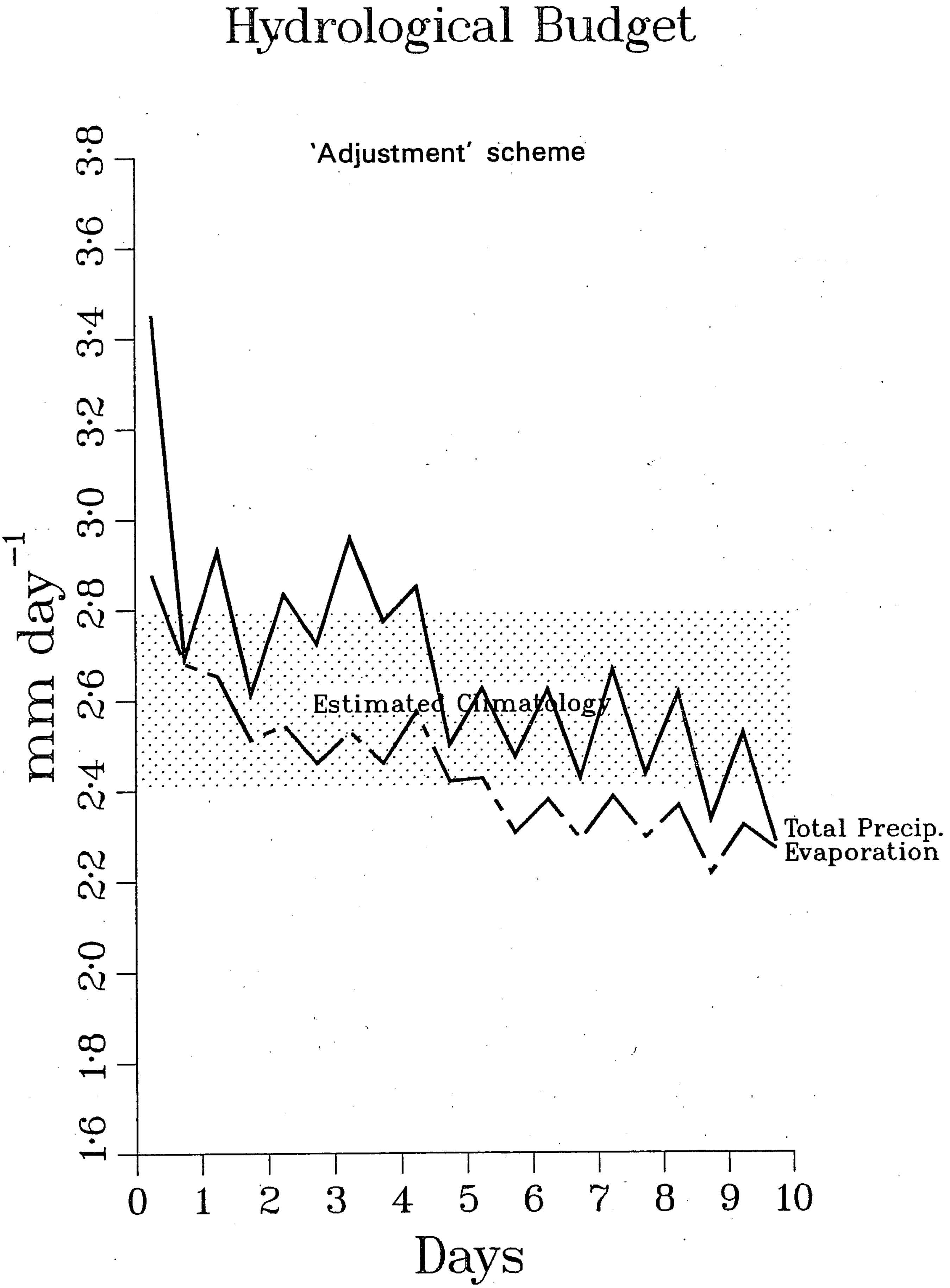


Fig 12 The hydrological budget for a forecast from 12 GMT on 15.12.86 using the "adjustment" convection scheme

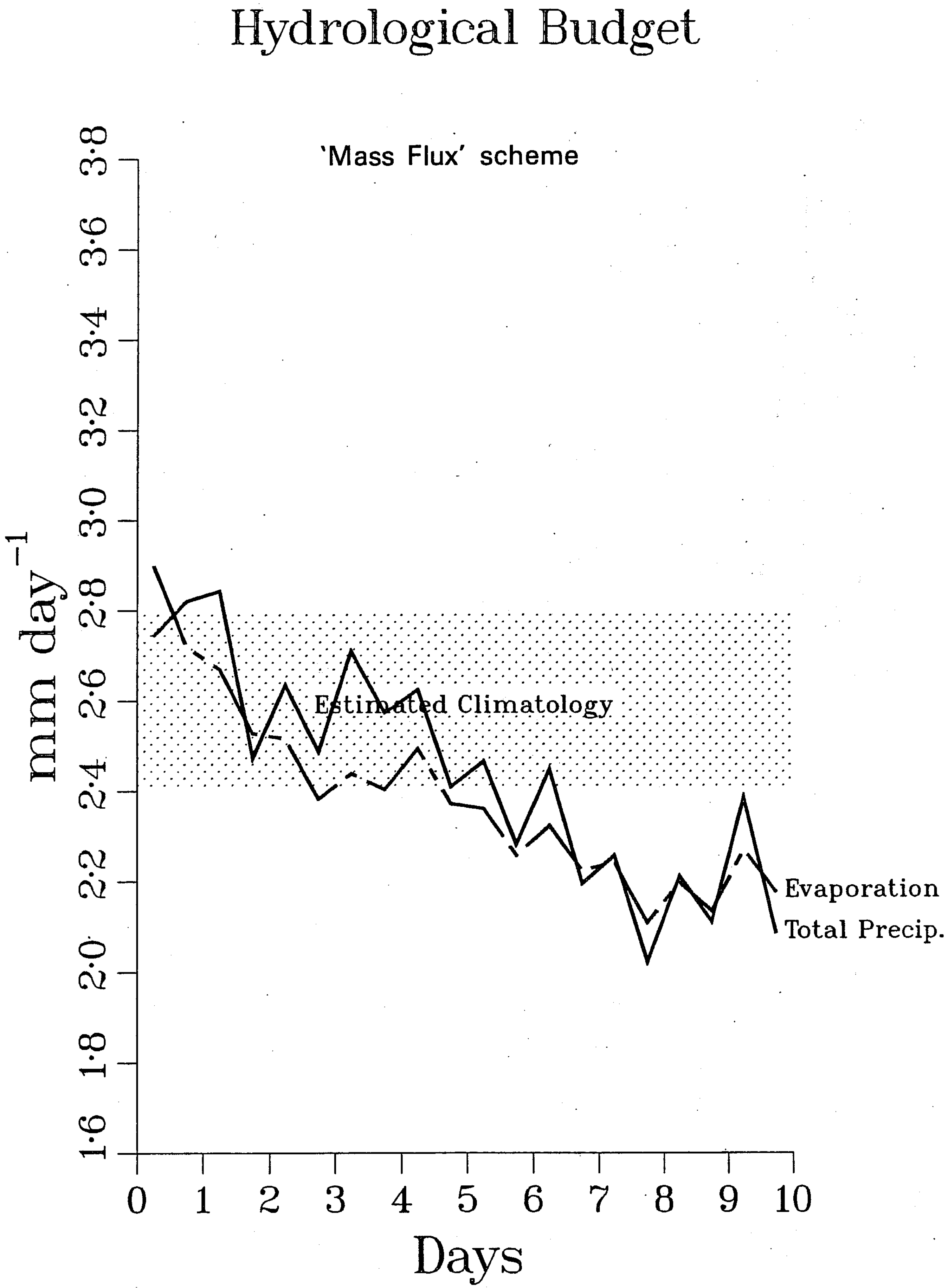
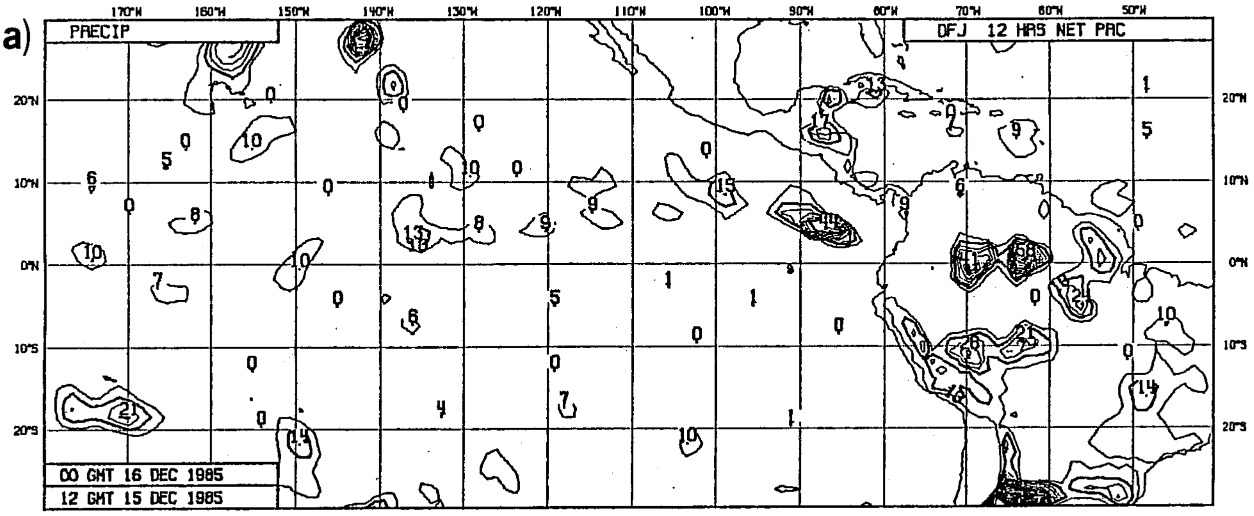


Fig 13 As in Fig 12 but for the "mass flux" convection scheme

'SATEM'

a)



'NOSATEM'

b)

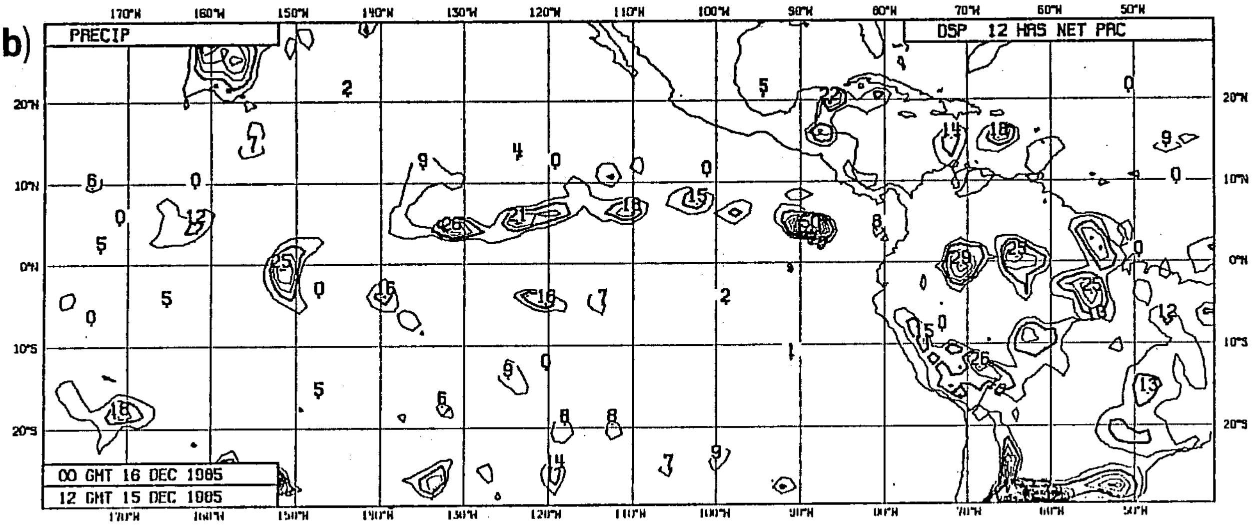


Fig 14 The 12-hour accumulated convective rain over the Pacific ITCZ for the forecast from 12GMT on 15.12.85 for

a) the SATEM assimilation

b) the NOSATEM assimilation

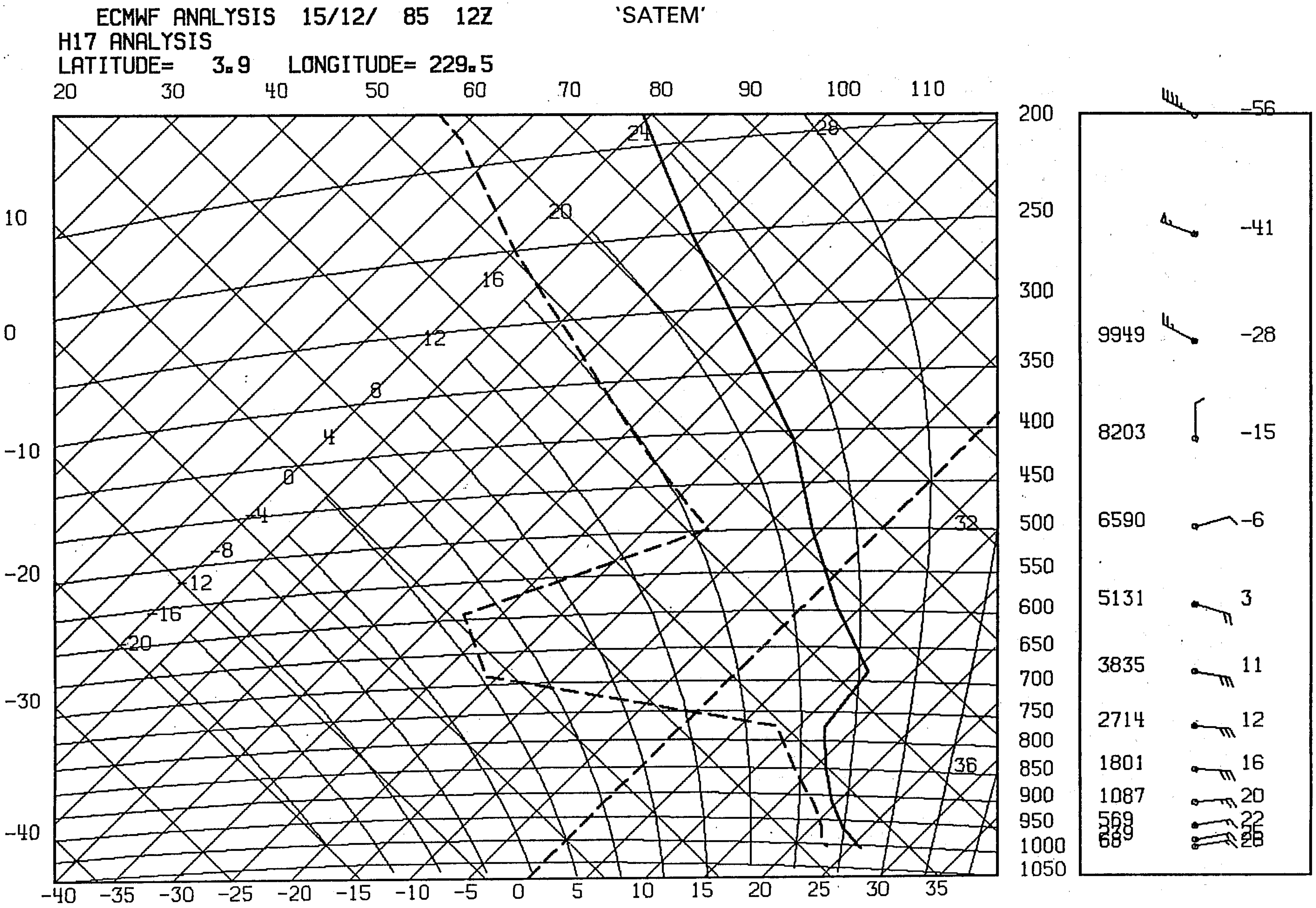


Fig 15 A T-ϕ diagram over the Pacific ITCZ from the SATEM analysis of Fig 14.

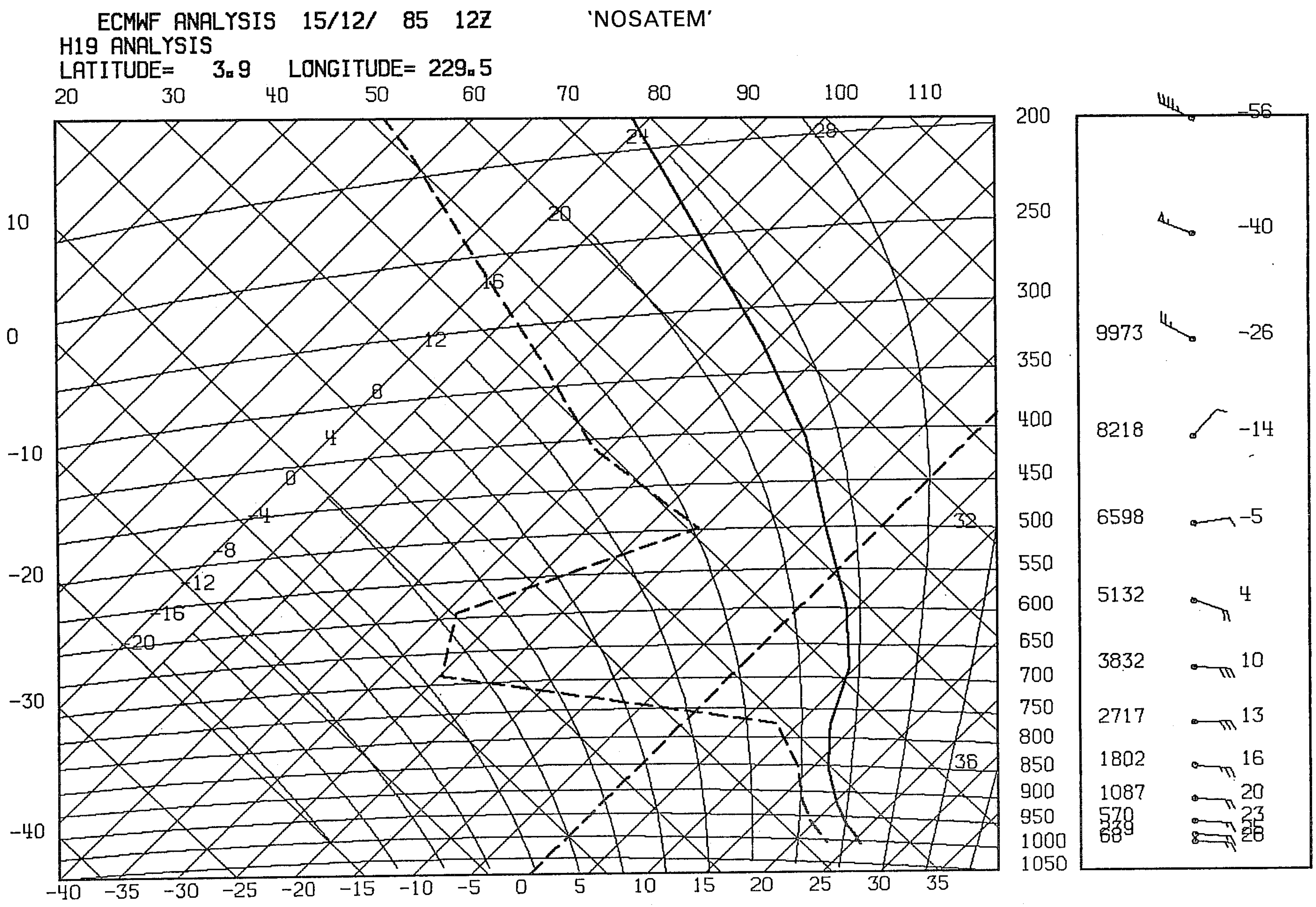


Fig 16 As in Fig 15 but for the NOSATEM analysis

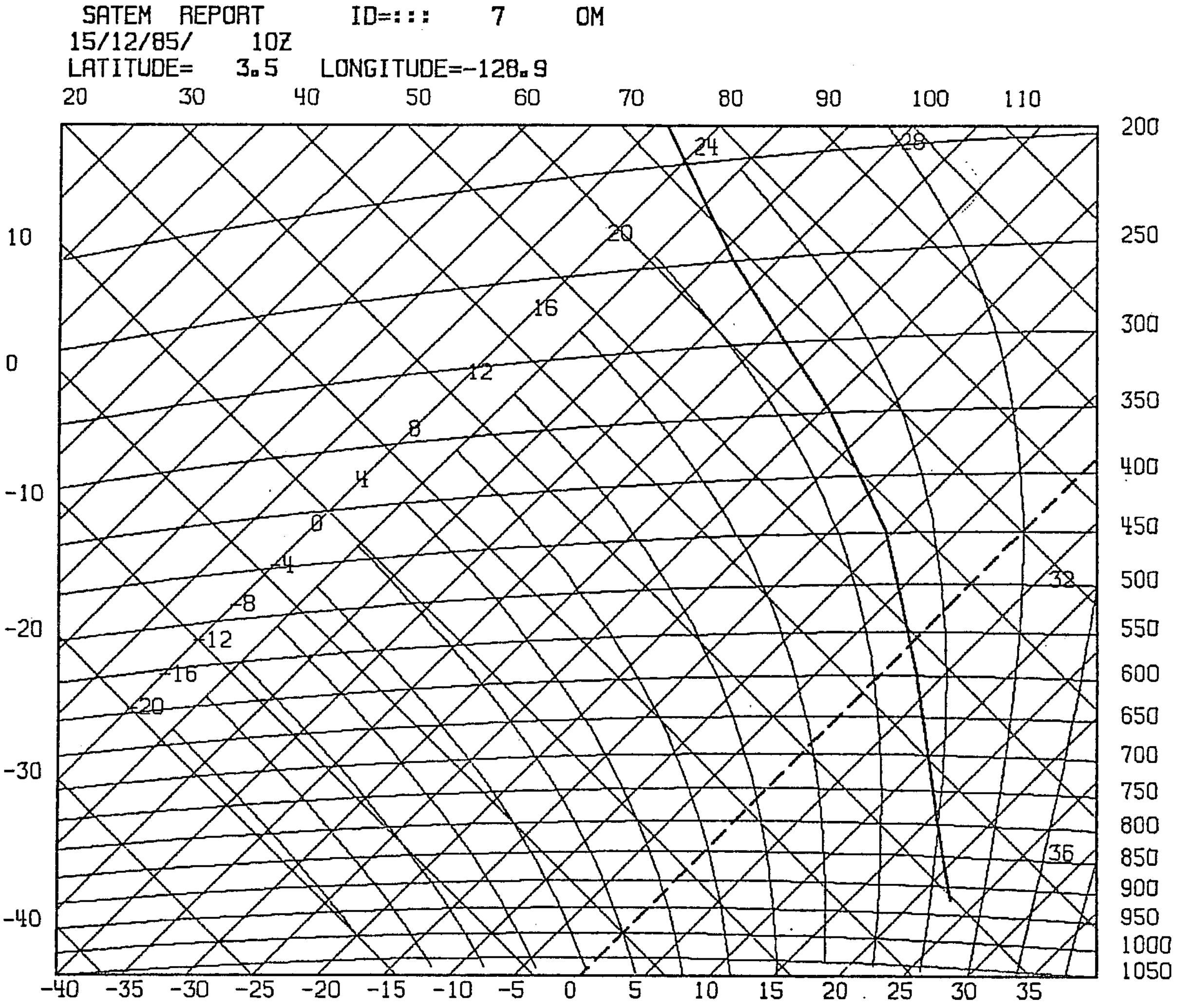


Fig 17 An example of a SATEM report over the Pacific ITCZ