A SHORT HISTORY OF THE OPERATIONAL PBL - PARAMETERIZATION AT ECMWF

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1. INTRODUCTION

The parameterization of the vertical fluxes of sensible heat, latent heat and momentum which are generated by turbulent exchange is one of the most important steps in the design of a physical "package" for a global model. The chosen solution must be valid for the whole earth (even at the equator), it must give good results over land and over sea and, from the numerical point of view, it must be stable, give smooth results and interact harmoniously with the other parts of the "package". When the present operational scheme at ECMWF was designed during 1977, the ideas of Busch (1976) were simplified and some new concepts were introduced, this leading to the method described by Louis (1979). Let us recall here briefly its main characteristics: - drag coefficient formulation at the surface and exchange coefficient formulation throughout the atmosphere; - consistent transition between the two abovementioned formulations; - coefficients depending analytically on the static stability and on the roughness length/mixing length.

This choice of parameterization scheme was made to try and obey the conditions described above. However, twice since the beginning of operational forecasts, we modified the expressions of the analytical formulae or the coefficients in order to improve the results of the global model as well as to be more consistent with some experimental evidence. The operational changes occurred in January 1980 and December 1981.

We shall try in this paper to briefly describe these changes, to justify them and to show why we believe they have improved the quality of the global model.

2. THE ORIGINAL MODEL

It has been extensively described by Louis (1979) and we shall here only recall the main points, without any attempt to justify the minor changes between our first operational version (presented here) and the one described in the paper. For the drag coefficient we shall use C_h and C_m, the subscript h and m referring respectively to latent and sensible heat and to momentum. For the exchange coefficients similarly we have K_h and K_m. z is the height of the model's lowest layer, z_o the roughness length and ℓ the mixing length.

a) Stable case

$$C_m = a_m^2 \left(\frac{1}{1 + b_m R_i}\right)^2 \tag{1}$$

$$C_h = a_h^2 \left(\frac{1}{1 + b_h R_i}\right)^2 \tag{2}$$

b) Unstable case

$$C_m = a_m^2 \left(1 - \frac{2 b_m R_i}{1+2 a_m^2 b_m c_m \sqrt{\frac{z+z_o}{z_o}} |R_i|}\right) \tag{3}$$

$$C_h = a_h^2 \left(1 - \frac{2 b_h R_i}{1+2 a_h^2 b_h c_h \sqrt{\frac{z+z_o}{z_o}} |R_i|}\right) \tag{4}$$

R_i is the bulk Richardson number between heights 0 and z.

$$R_i = \frac{g}{\theta} \frac{\partial\theta/\partial z}{|\partial \underline{v}/\partial z|^2} \tag{5}$$

and we have

$$a_{m/h} = \frac{\kappa_{m/h}}{\ell n\left(\frac{z+z_o}{z_o}\right)} \qquad (6)$$

κ being the von Karman constant.

The values used were

$\kappa_m = 0.35 \qquad \kappa_h = 0.41$

$b_m = 4.7 \qquad b_h = b_m$

$c_m = 7.4 \qquad c_h = 5.3$

For the exchange coefficients one can formally write

$$K_{m/h} = \ell^2_{m/h} \left|\frac{\partial v}{\partial z}\right| f(R_i) \qquad (7)$$

where

$$\ell_{m/h} = \frac{\kappa_{m/h}\, z}{1 + \frac{\kappa_m z}{\lambda}} \qquad (8)$$

λ being the asymptotic mixing length that was chosen to be 300 m after some tuning in the global model. The functions $f(R_i)$ are the same as the ones used for C/a^2 in (1), (2), (3) and (4) whereby for (3) and (4) $a^2 \sqrt{\frac{z+z_o}{z_o}}$ is replaced by

$$\frac{\ell^2}{\Delta z^{3/2}\, z^{1/2}} \left[\left(\frac{z + \Delta z}{z}\right)^{1/3} - 1\right]^{3/2}$$

The number of "free" parameters of the system was at that time 6 and the choice of their values (apart from λ) was guided by the measurements of Businger et al (1971). From now on this system will be referred as (I).

3. THE FIRST SET OF MODIFICATIONS

In day to day diagnostic of the global operational model it soon became apparent that our system was suffering from a lack of boundary layer dissipation. At the same time papers by Wieringa (1980) and Pruitt, Morgan and Lourence (1973) indicated that the distinction between two von Karman constants κ_m and κ_h was probably wrong.

System (II) was then created differing only from (I) in so far as $\kappa_m = \kappa_h = \kappa = 0.40$.

At the same time our doubt about the validity of the Businger's results was extended to the function $f(R_i)$ and we decided to simplify our system and to recompute its "free" parameters. The most important point of this modification was that the slope of $f(R_i)$ around the zero value (neutral case) should be bigger for heat than for momentum . The experimental results were close enough to Pandolfo's (1966) idea that $z/L \approx R_i$ for $R_i \to 0$ (L being the Monin-Obukov length) for us to decide that accordingly the ratio of the slopes should be 1.5. At the same time we noticed that the value of c_m is of little importance in the system (the free convection case for which c_h and c_m are representative requires a small wind shear and thus produces small momentum fluxes, whatever value c_m might have). Since furthermore c_m / c_h was of the order of 1.5 we decided, for reason of computer time saving, to have the same denominator in both the $f(R_i)$ expressions for the unstable case. System (III) was therefore created with the folllowing characteristics:

a) Stable case

$$c_m = a^2 \left(\frac{1}{1 + 2\ b\ R_i}\right) \tag{1a}$$

$$c_h = a^2 \left(\frac{1}{1 + 3\ b\ R_i}\right) \tag{2a}$$

b) Unstable case

$$c_m = a^2 \left(1 - \frac{2\ b\ R_i}{1+3\ a^2\ b\ c \sqrt{\frac{z+z_o}{z_o}}\ |R_i|}\right) \tag{3a}$$

$$c_h = a^2 \left(1 - \frac{3\ b\ R_i}{1+3\ a^2\ b\ c \sqrt{\frac{z+z_o}{z_o}}\ |R_i|}\right) \tag{4a}$$

Plus

$$a = \frac{\kappa}{\ell n\ (\frac{z+z_o}{z_o})} \tag{6a}$$

$$\ell = \frac{\kappa}{1 + \frac{\kappa z}{\lambda}} \tag{8a}$$

with the following values: $\kappa = 0.4$, $b = 5$, $c = 5$, $\lambda = 300$ m.

The system had only 4 degrees of freedom left.

Before operational implementation the changes (I) → (II) and (II) → (III) were extensively tested in a serial of 10 day forecasts and in longer integrations performed with the spectral model of ECMWF with a triangular truncation at wavenumber 40 (T40). Figures 1 and 3 show, for these integrations, averaged values of the 1000 mb and 500 mb fields over the second part of 50 day integrations as compared to the relevant averaged values of the observed fields (analysed by DWD). The progress from (I) to (II) and from (II) to (III) in diminishing the exaggerated depth of the Icelandic and Aleutians lows at 1000 mb and in the associated better simulation of trough and ridges at 500 mb is obvious. In Figures 2 and 4 where differences between the experiments and the climatological field is plotted this progress can be qualitatively estimated as a 40% reduction of the original systematic error. This result was supported by the improvement of objective scores in the 10 day forecasts made with the same changes.

4. THE SECOND SET OF MODIFICATIONS

Since the rest of the global model had undergone some modifications between January 1980 and December 1981 we will speak at the end of this paragraph of an experiment (IV) whereby the PBL parameterization was identical to the one in (III). So, for our description of the scheme, (III) $\equiv$ (IV).

Girard (pers.comm.) pointed out that (2a) had a big disadvantage against (2) For very stable situations ($R_i \to +\infty$) the sensible heat flux $-K_h \cdot \partial\theta/\partial z$ was not disappearing but on the contrary went asymptotically towards the value $\lambda^2 \left|\frac{\partial \bar{v}}{\partial z}\right|^3 \frac{\theta}{g}$ in the stratospheric regions with wind shear. Thus an artificial stratospheric cooling was generated by the model on the basis of an erroneous formulation. Investigation of (1a) and (2a) indicated that the problem was even worse. If, with (1) and (2), the stratospheric problem did not exist, our scheme had never had a critical Richardson flux number. To explain this latter point let us recall that there are theoretical reasons, supported by observational evidence, that forbid the Richardson flux number $R_{i,f} = R_i \cdot \frac{K_h}{K_m}$ to take values bigger than a critical limit when $R_i \to +\infty$. However this was

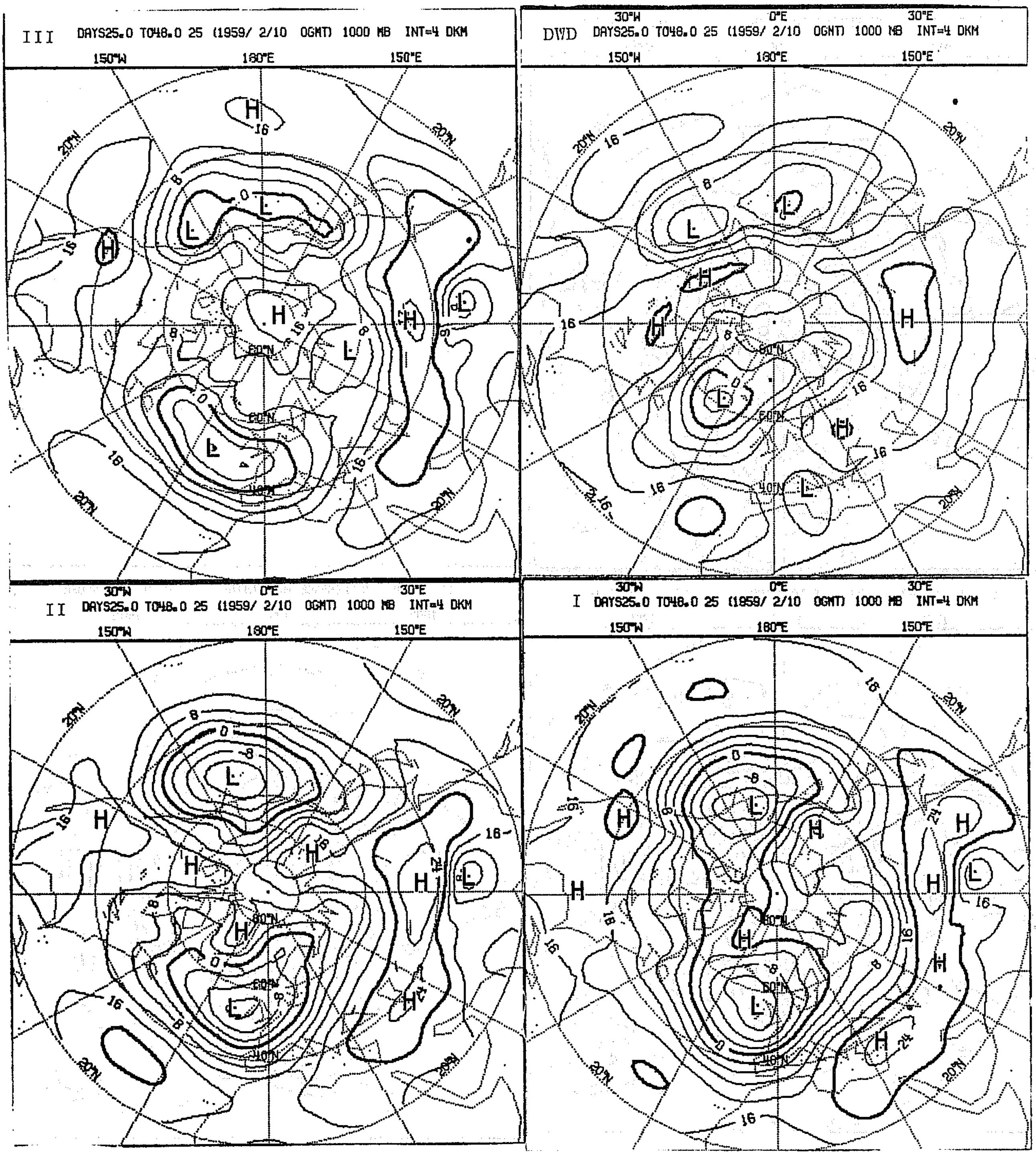

Figure 1 1000mb heights in experiments (I), (II) and (III) averaged between days 25 and 48 compared to DWD analysis.

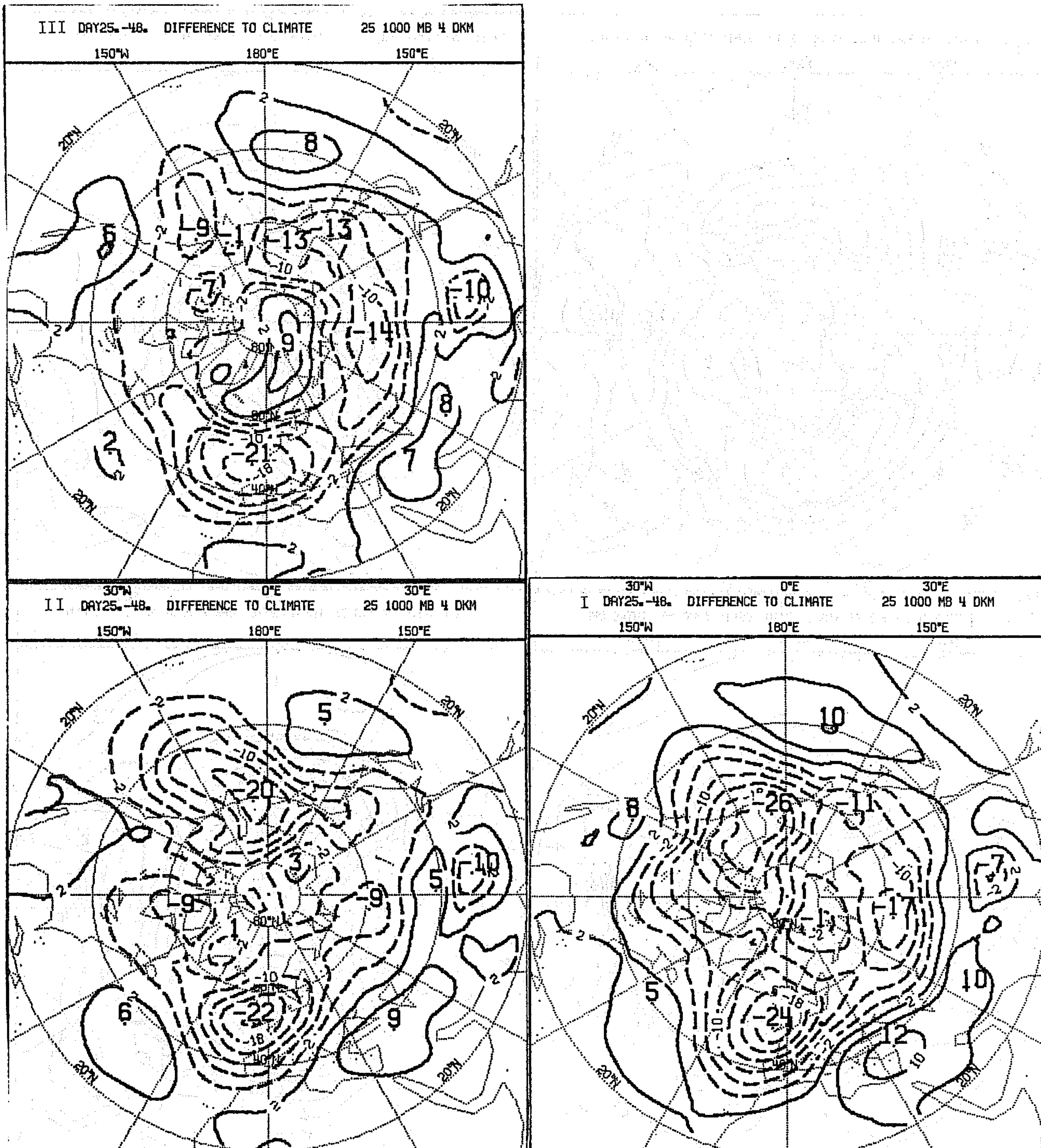

Figure 2 1000 mb heights. Difference to climate in experiments (I) (II) and (III) averaged between days 25 and 48.

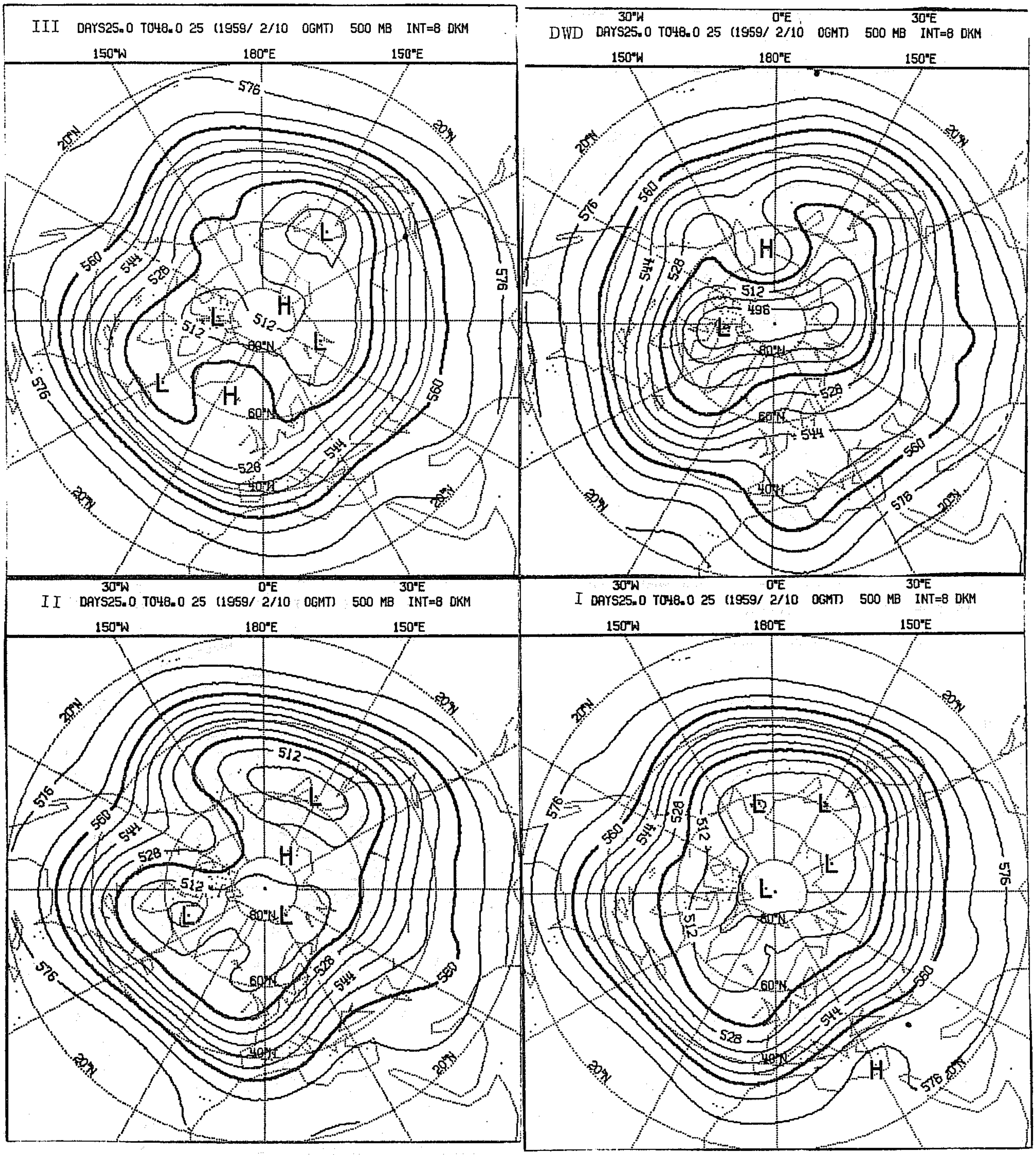

Figure 3 500 mb heights in experiments (I) (II) and (III) averaged between days 25 and 48 compared to DWD analysis.

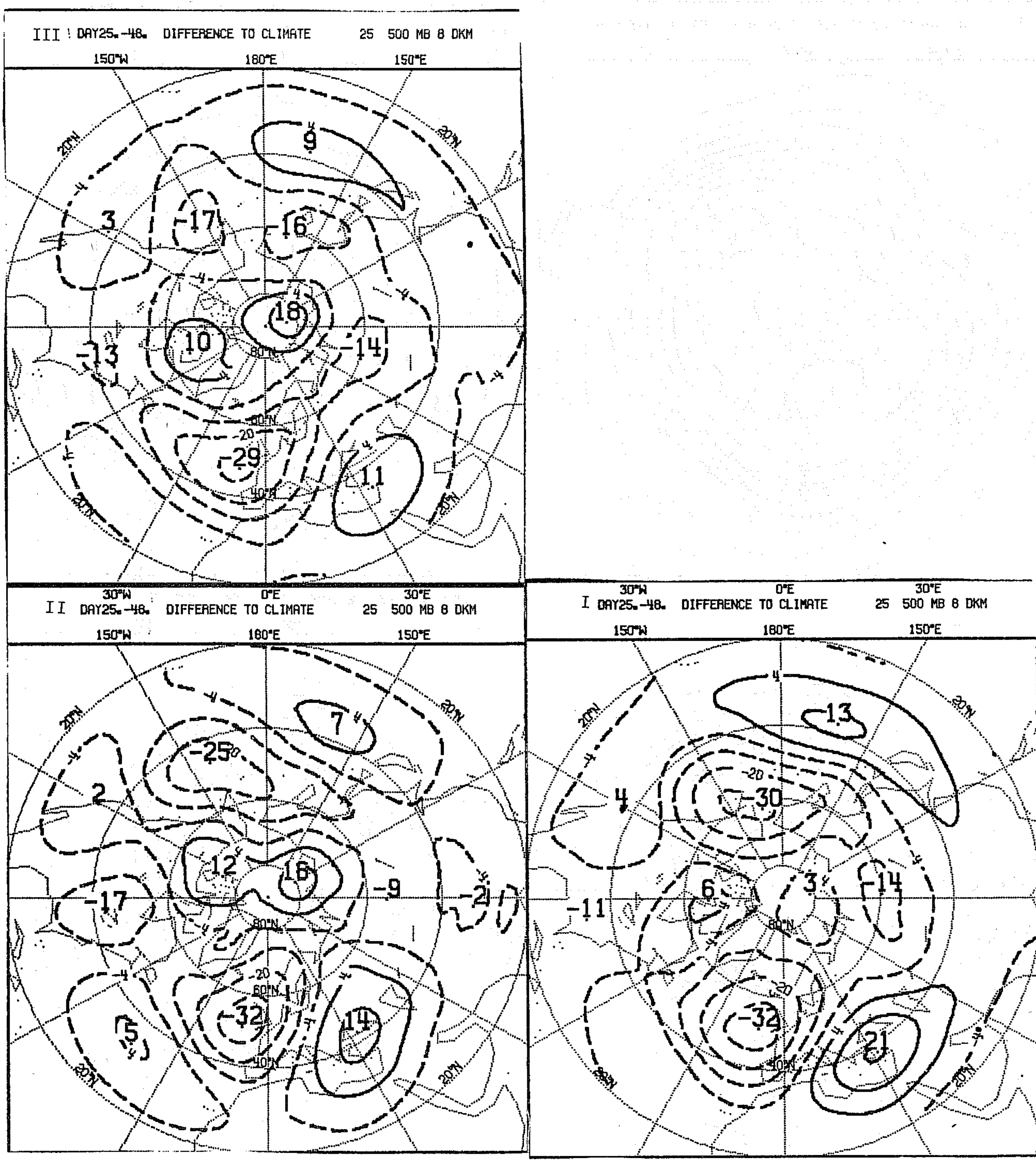

Figure 4 500 mb heights. Difference to climate in experiments (I) (II) and (III) averaged between days 25 and 48.

never the case in our system:

in (I) $\frac{K_h}{K_m} \to 1$ for $R_i \to +\infty$

in (IV) $\frac{K_h}{K_m} \to \frac{2}{3}$ for $R_i \to +\infty$

There was very little theoretical or experimental evidence to guide us in the choice of a new formulation for equations (1) and (2). According to Monin and Yaglom (1979) we decided to follow the quite complicated arguments of Ellison (1957) that can be summarised, for our purpose, by two equations. The well known KEYPS equation and the one added by Ellison

$$\frac{K_h}{K_m} = \frac{1 - R_{i,f}/R_{i,fc}}{(1 - R_{i,f})^2} \tag{9}$$

Integration of these two equations for the case $R_i \to +\infty$ leads, after lengthy computations that we shall not reproduce here, to the following results

$$K_m \sim R_i^{-\frac{1}{2}} \quad , \quad K_h \sim R_i^{-3/2} \tag{10}$$

In order to save computer time it was decided to use the following formulation for the stable case

$$c_m = a^2 \left(\frac{1}{1 + 2\, b\, R_i / \sqrt{1 + d\, R_i}} \right) \qquad (1b)$$

$$c_h = a^2 \left(\frac{1}{1 + 3\, b\, R_i \cdot \sqrt{1 + d\, R_i}} \right) \qquad (2b)$$

where d was chosen as 5, giving a value of the critical Richardson flux number

$$R_{i,fc} = \frac{2}{3\, d} = 0.13$$

quite close to the little observational evidence available. Replacement in (IV) of (1a) and (2a) by (1b) and (2b) gave us system (V).

The results for the boundary layer and for the stratosphere showed the expected improvement but on the other hand some deficiencies appeared in the global model's behaviour near the tropospheric part of the jet. The increase in the exchange coefficient for momentum and the decrease in the coefficient for heat in these regions of slight stability leads to a strong weakening of the jet in the model integrations. To try and keep the benefits of (V) without having these problems it was decided to have two asymptotic mixing lengths, one for the momentum exchange λ_m and one for the heat exchange λ_h. A new tuning of these values gave best results for

$$\lambda_m = 150 \text{ m} \quad \text{and} \quad \lambda_h = 450 \text{ m}$$

And so was system (VI) created, differing from (V) only by these two values.

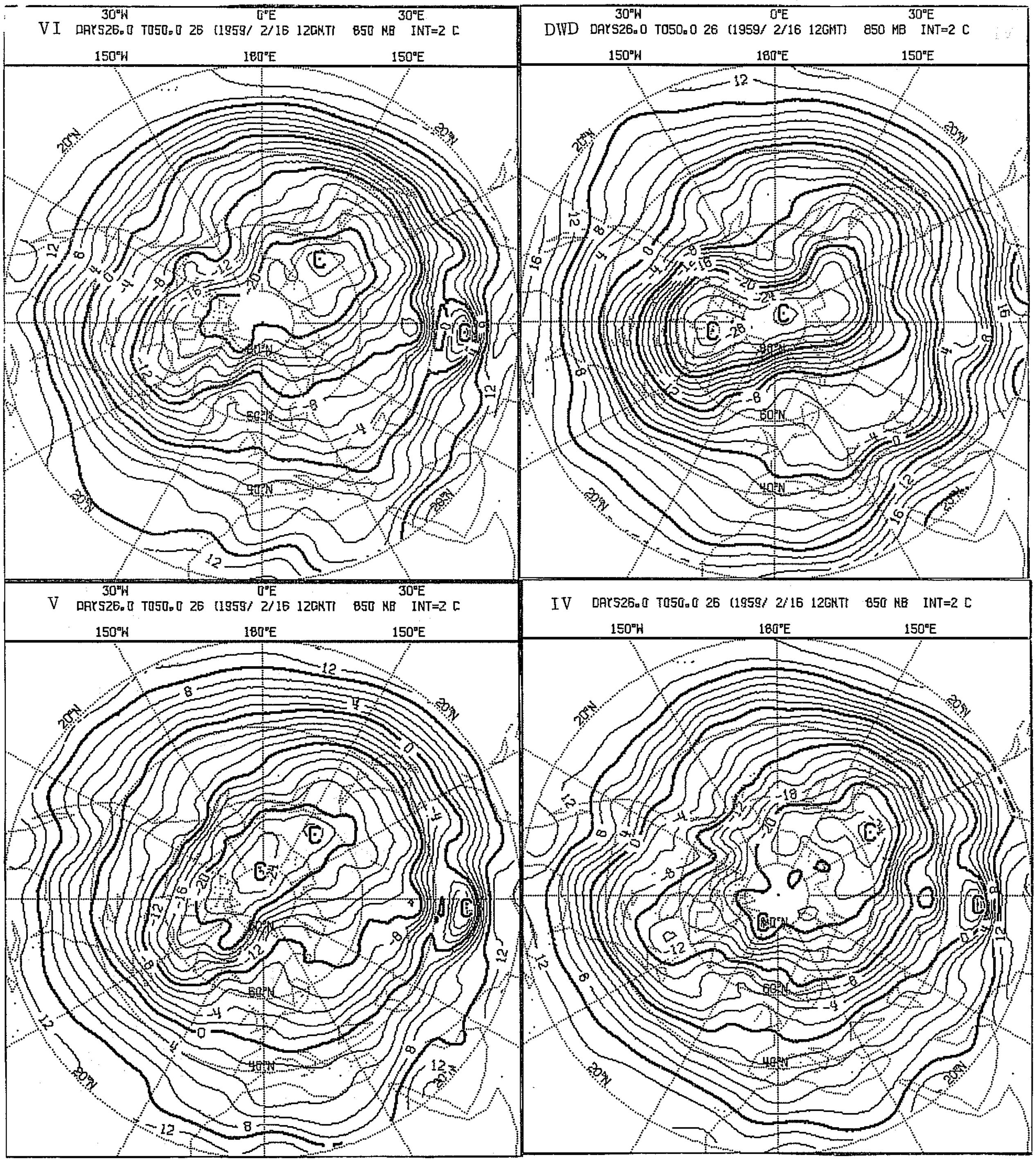

Figure 5 850 mb temperatures in experiments (IV) (V) and (VI) averaged between days 26 and 50 compared to DWD analysis

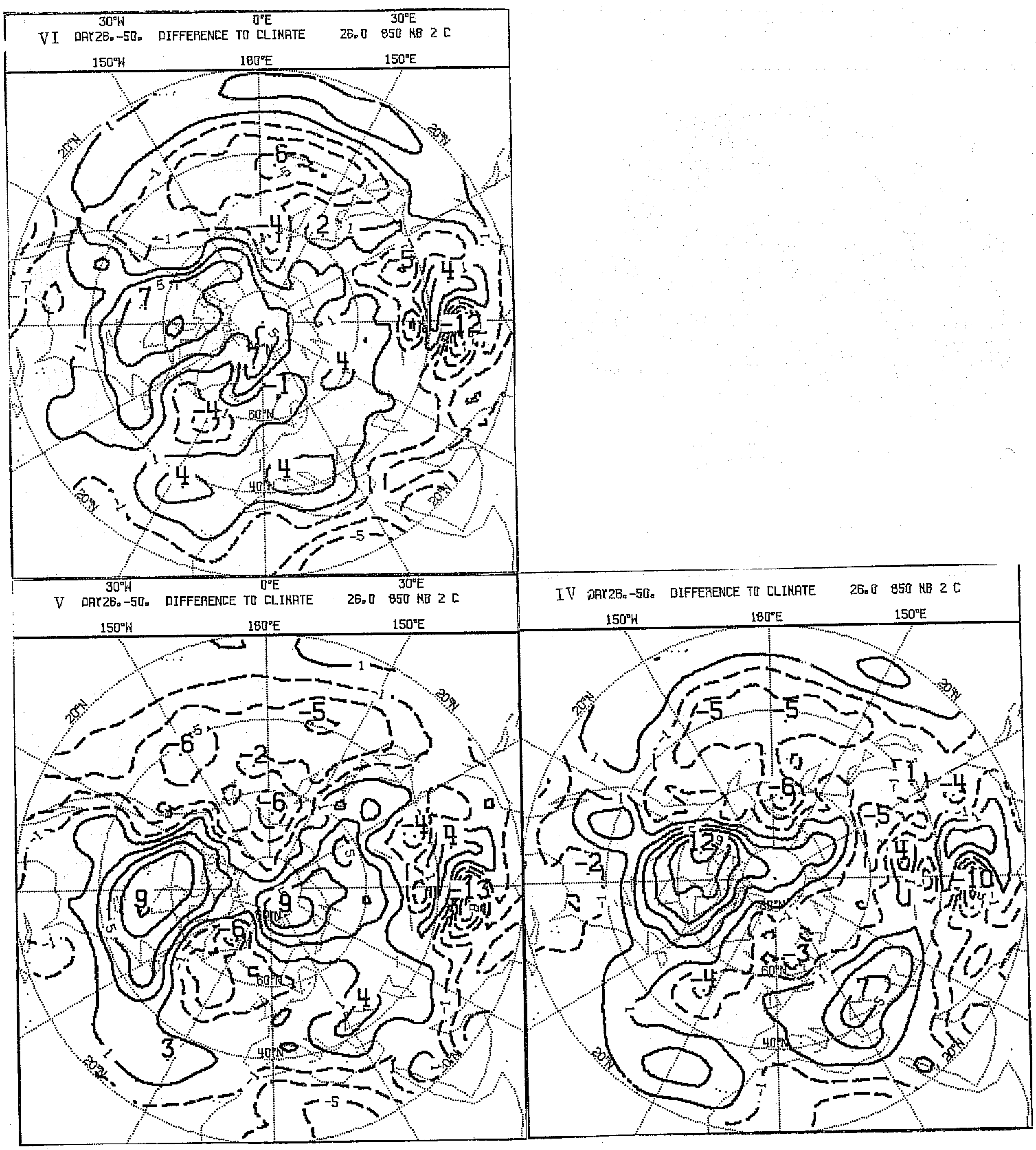

Figure 6 850 mb temperatures. Difference to climate in experiments (IV) (V) and (VI) averaged between days 26 and 50

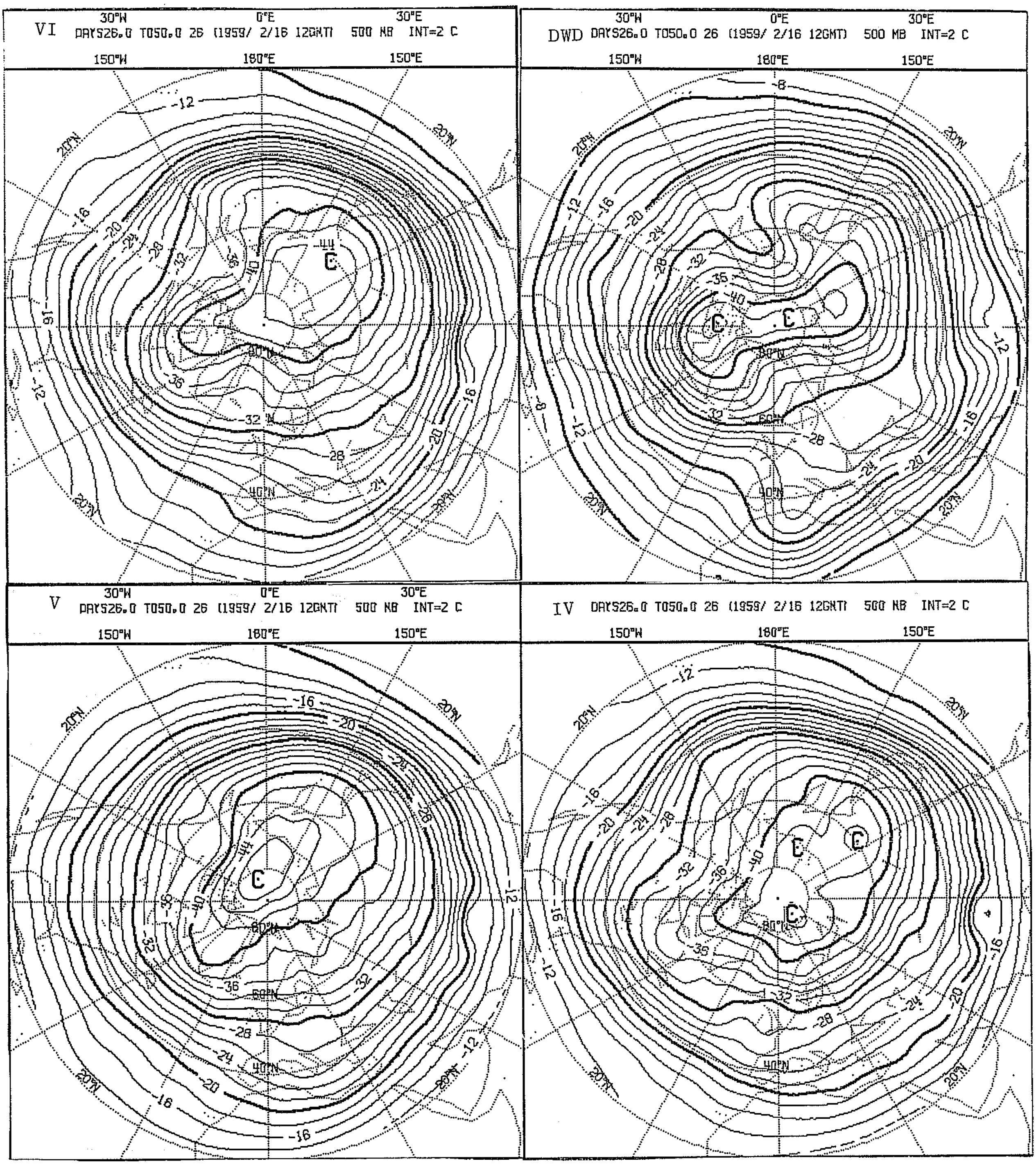

Figure 7 500 mb temperatures in experiments (IV) (V) and (VI) averaged between days 26 and 50 compared to DWD analysis

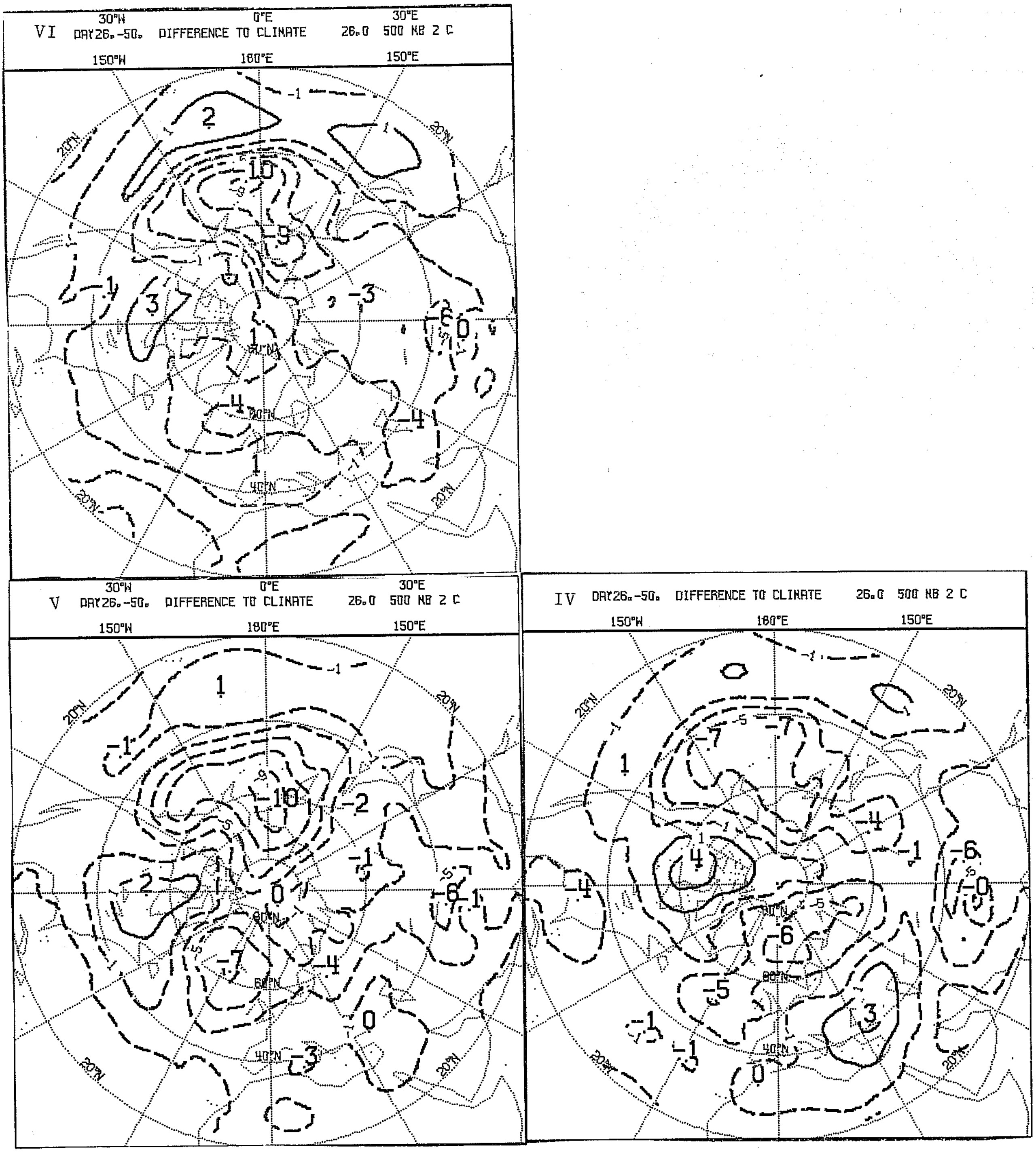

Figure 8 500 mb temperatures. Difference to climate in experiments (IV)(V) and (VI) averaged between days 26 and 50.

Figures 5,6,7 and 8 are similar to 1,2,3 and 4 but for the fact that we now show the 850 mb and 500 mb temperature fields rather than the 1000 mb and 500 mb height fields. Also notice the change in the initial date (21/01/79 instead of 16/1/79) of the integrations. Here again the reduction of the systematic errors in the anomaly over the continental masses at 850 mb and in the Atlantic-European dipole at 500 mb are obvious when going from (IV) to (VI). Unfortunately there is also a slight increase in the anomalies over the Pacific, so that the benefit from these changes can be expected to be smaller than the one from (I) to (III). This is confirmed by only a very small positive impact in objective scores for the 10 day forecasts made with the same modifications. The problems associated with (V) are quite apparent in 500 mb.

Now our system has again 6 "free" parameters κ, b, c, d, λ_m and λ_h but one could easily spare one of these. Indeed what our tuning of λ_m and λ_h has shown us is that, if a value of $R_{i,fc}$ of around 0.13 is good for the boundary layer, it is detrimental for the free atmosphere, and that our new value of

$$\frac{2}{3d}\left(\frac{\lambda_h}{\lambda_m}\right)^2 = 1.2 \qquad \text{for } z \to \infty$$

is preferable. But there are simple arguments to show that for a laminar flow the $R_{i,fc}$ of the free atmosphere should be 1 (production by shear = destruction by buoyancy for the asymptotic case). Therefore one could impose

$$\lambda_h = \lambda_m \sqrt{\frac{3d}{2}}$$

and bring back our number of parameters to 5. We shall probably do this at some time in the future. However it must be clear that λ_m is the only one of

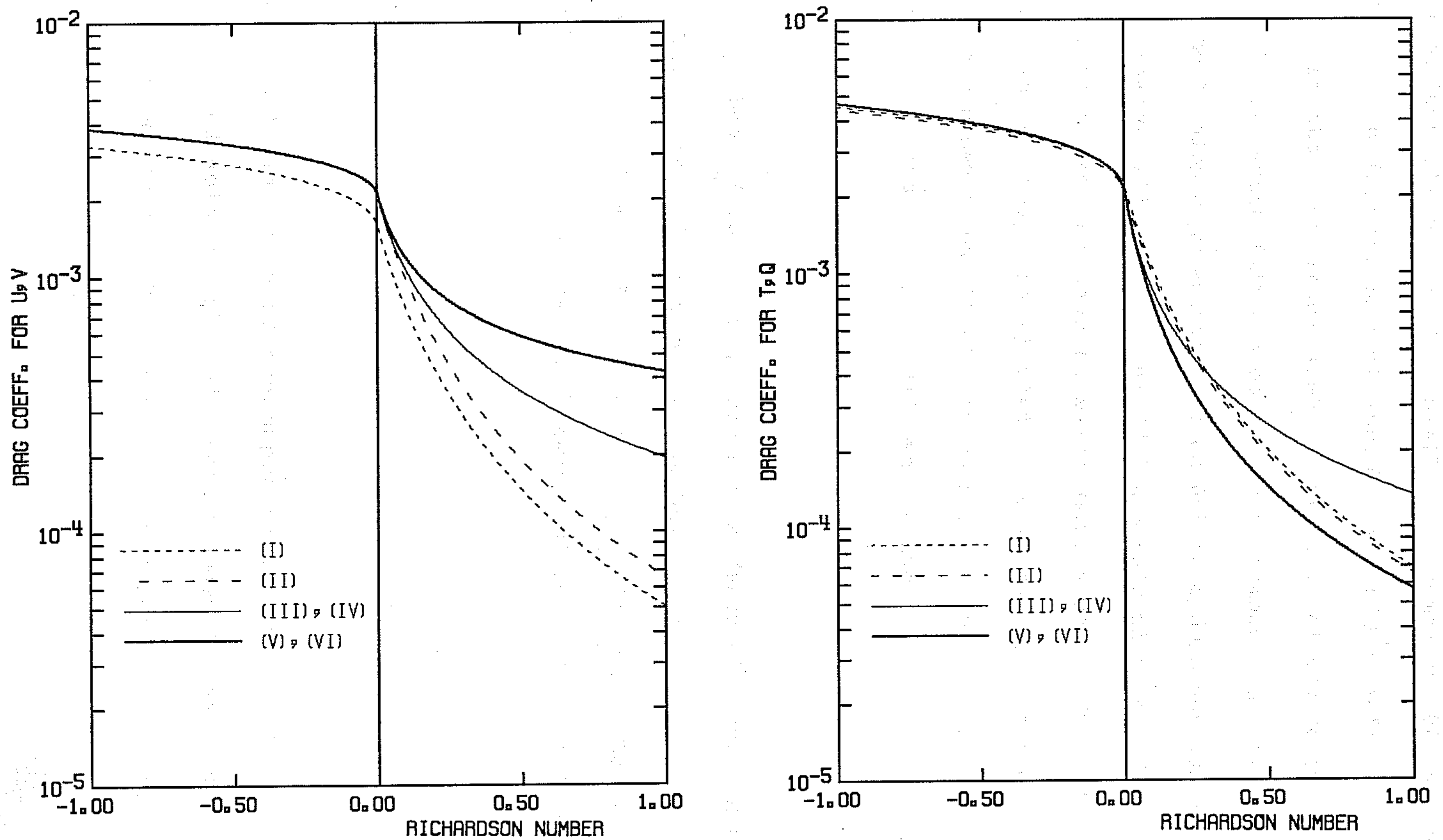

Fig. 9 Plots of the different formulations of the drag coefficients for momentum (left) and for heat and moisture (right), with $z/z_o = 5500$

$a = \frac{\kappa}{\ln(z/z_o)}$		STABLE		UNSTABLE		Asym. Mixing Length $\ell = \kappa z/(1+\kappa_m z/\lambda)$
MOMENTUM	(I)	$a^2 \left(\frac{1}{1 + b R_i}\right)^2$ $\kappa=0.35$ $b=4.7$	(I)	$a^2 \left(1 - \frac{2b R_i}{1+2ba^2 c\sqrt{\frac{z}{z_o}\|R_i\|}}\right)$ $c=7.4$	(I)	$\lambda=300$ m
	(II)	— $\kappa=0.40$ —	(II)	—	(II)	—
	(III) (IV)	$a^2 \left(\frac{1}{1 + 2b R_i}\right)$ $b=5$	(III) (IV)	— $c=7.5$	(III) (IV)	—
	(V)	$a^2 \left(\frac{1}{1 + 2b R_i/\sqrt{1 + d R_i}}\right)$ $d=5$	(V)	—	(V)	—
	(VI)	—	(VI)	—	(VI)	$\lambda=150$ m
HEAT SENSIBLE + LATENT	(I)	$a^2 \left(\frac{1}{1 + b R_i}\right)^2$ $\kappa=0.41$ $b=4.7$	(I)	$a^2 \left(1 - \frac{2b R_i}{1+2ba^2 c\sqrt{\frac{z}{z_o}\|R_i\|}}\right)$ $c=5.3$	(I)	$\lambda=300$ m
	(II)	— $\kappa=0.40$ —	(II)	—	(II)	—
	(III) (IV)	$a^2 \left(\frac{1}{1 + 3b R_i}\right)$ — $b=5$	(III) (IV)	$a^2 \left(1 - \frac{3b R_i}{1+3ba^2 c\sqrt{\frac{z}{z_o}\|R_i\|}}\right)$ $c=5$	(III) (IV)	—
	(V)	$a^2 \left(\frac{1}{1 + 3b R_i \sqrt{1 + dR_i}}\right)$ $d=5$	(V)	—	(V)	—
	(VI)	—	(VI)	—	(VI)	$\lambda=450$ m

these, whose value is so uncertain that we can make a meaningful tuning of it, if it becomes necessary, owing to changes in other parts of the global model.

5. SUMMARY

We have shown how two changes of the $f(R_i)$ formulae in our PBL parameterization have increased the quality of the system both from the theoretical and from the practical point of view, without touching to the basic principles of the scheme. As a recapitulation Table 1 presents the changes in the formulation and in the values of the "free" parameters and Figures 9 the different plots of C versus R_i for a given value of $z/z_o = 5500$.

One can notice that apart from the change (I) to (II) for momentum very little has been modified in the unstable case and that, for the stable case (I) and (IV) are still very similar for heat but totally different for momentum.

Simplifying to the extreme one could say that the main effect of all our modifications has been an increase in the momentum drag especially for stable situations in the boundary layer, which had to be tempered in the free atmosphere.

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