Parameterization of Cumulus Convection

Cloud mass flux distribution within cloud clusters derived from GATE data

by

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1. Introduction

The parameterization of cumulus convection has two aspects:

a.) the generation of cumulus clouds

b.) the effects of the cumulus clouds on the large-scale field

There is of course an interaction of both, thus we cannot always separate the aspects as clearly as we have done above. For most of the models, however, we do not need to know which cloud type and how many clouds are generated the heating and moistening of their environment is of interest. But including radiation into the models the knowledge of the amount and type of clouds is nescessary. I am not aware of any parameterization method which gives the amount and type of clouds. Some models work with a statistical relationship between the humidity at certain levels and the cloud amount (see Sundqvist, 1977 and Slingo, this Volume).
The answer to the question whether cloud development is possible at a certain model grid point is given e.g. by the adjustment method (Manabe et al. 1965), the CISK-method (Charney and Eliassen, 1964; Ooyama, 1964), and Eliassen, 1964; Ooyama, 1964), and the Kuo-scheme (Kuo, 1969). All these methods include also the calcu-

lation of the cloud effects. Recently developed parameterization schemes assume the existence of clouds and describe their interactions with the large-scale field e.g. Arakawa and Schubert (1974) for thermodynamic parameters and Fraedrich (1973 and 1974) for thermodynamic and dynamic parameters. In this paper we shall deal only with the effects of the clouds.

2. Interaction of a cloud ensemble and its environment

In general we do not have a single cloud but a cloud ensemble to study its interaction with the large scale environment. The problem of the parameterization of cumulus convection can be solved only if we understand the physical process of the interaction. It can be described in mathematical form by the following equation:

$$Q_1 - Q_2 - Q_R = \frac{\partial \bar{h}}{\partial t} + \overline{\nabla h \cdot V} + \frac{\partial \bar{h}\bar{\omega}}{\partial p} = - \frac{\partial \overline{h'\omega'}}{\partial p} \qquad (1)$$

$h = c_p \cdot T + gz + Lq$, moist-static energy

Q_1 = apparent heat source (sensible heat)

Q_2 = apparent heat source (latent heat)

Q_R = heating rate due to radiation

The left hand side of equ. (1) contains only large-scale parameters, the right hand side describes the integral effect of the convective clouds. This part can be expanded as follows:

$$\frac{\partial \overline{h'\omega'}}{\partial p} = \frac{\partial}{\partial p} \sum_i \left\{ M_{ci} (h_{ci} - \bar{h}) \right\} \qquad (2)$$

or
$$\frac{\partial \overline{h'\omega'}}{\partial p} = \delta (\hat{h}_c - \bar{h}) - M_c \frac{\partial \bar{h}}{\partial p} \qquad (3)$$

The summation is taken over all clouds which form the ensemble.

M_{ci} = mass flux of i-th cloud
h_{ci} = moist-static energy of the i-th cloud updraft
δ = total detrainment at the cloud top height
$\hat{h}_c$ = moist-static energy at the cloud top height
M_C = total cloud mass flux

Equ. (2) and (3) can be expanded by the introduction of the downdraft effects.

These equations show clearly the importance of the cloud mass flux for the interaction process. The cloud mass flux is the missing link for a simple solution of the parameterization problem as shown by Arakawa and Schubert (1974).

3. Determination of the cloud mass flux

Equ. (1) was applied to tropical cloud ensembles by several groups. The cloud distribution and/or certain cloud types were specified and the cloud mass flux derived together with its effects, the environmental heating and moistening.

Yanai, Esbensen and Chu (1973) specified the cloud type, none interacting clouds which entrain environmental air from the cloud base to the cloud top level but detrain only at the top height level, and used averaged equations. Thus they determined the total cloud mass flux and the total effect of the environmental heating and moistening.

Ogura and Cho (1973) used the same cloud model as Yanai et al. but considered also the cloud population, each cloud is characterized by its entrainment factosλ. They derived an integral equation the solution of which gives the cloud mass flux distribution. This method with some modifications was used by others and for other tropical regions (Nitta 1975, Cho and Ogrura 1974). The main result of all these studies is: the cloud mass flux distribution at the cloud base level shows a bimodal structure, the shallow cumuli and the deep cumuloniumbi contribute most to the mass flux and there is a minimum for clouds reaching only middle levels.

Johnson (1976), Nitta (1977) and Johnson (1978) introduced the downdraft effects into equ (2) and showed that the cloud mass flux maximum for the shallow cumuli is drastically reduced if the downdraft effects are considered.

All these studies the cloud mass flux is indirectly determined given the apparent heat sources, the rariation heating, and the vertical temperature and humidity structure of the environment. We used the direct observations of the cloud parameters within tropical disturbances to calculate the mass flux (Breuch and Ruprecht, 1977).

The cloud mass flux for all clouds with top heights between the level z and z + Δz is given by equ (4):

$$m = N \rho \sigma w \qquad (4)$$

$N \Delta z$ = number of clouds with top height between z and $z + \Delta z$

ρ = density of the updraft air

σ = fractional horizontal area of the updraft

w = updraft velocity

The total cloud mass flux M_C is then the integral over all clouds

$$M_C = \int_0^{\infty} m dz$$

Here the clouds of the ensemble are characterized by their top height z. Applying the simple, one dimensional balance model for entraining clouds the top height, entrainment factor, updraft radius and therefore updraft area are all proportional to each other. We specify the clouds by two assumptions, the entrainment factor is constant from cloud base to cloud top thus the updraft radius is also constant with height, and the cloud do detrain at each level and the detrainment equals the entrainment thus the cloud mass flux of a single cloud is constant with height.

The top height of a cloud with the entrainment factor λ is given at that level z where the following balance is valid (Arakawa and Schubert, 1974):

$$h_c(z,\lambda)-\hat{h}_e^*(z) = 0 \qquad (5)$$

$\hat{h}_e^*$ = saturated moist-static energy of the environment plus the virtual temperatur excess and plus the liquid water content at the cloud top; it can be calculated with the temperatur and humidity profiles of the environment.

We use the well-known relationship to determine the updraft radius r:

$$\lambda = \frac{2\alpha}{r} \qquad \alpha = 0.1 \qquad (6)$$

With (6) we get horizontal fractional area:

$$\sigma = \frac{\pi r^2}{\pi R^2} = \frac{4\alpha^2}{R^2} \lambda^{-2}$$

R = Radius of the reference area (we used the radar observation area with R = 100 km).

4. Observation of the cloud parameters

In the previous section those parameters were derived which are needed for the direct calculation of the cloud mass flux and which can be observed. These are the cloud distribution, the cloud top heights, and properties of the environment.

During Gate (GARP Atlantic Tropical Experiment) direct observations within tropical cloud clusters were accomplished. The cloud distribution was derived from the radar observations on board of the German research vessel "Planet" (Fig. 1). The cases of Sept. 3. and 5. are extremes. In the late afternoon of Sept. 3 very small, apparently randomly distributed echos were observed; in the early morning of Sept. 5 an intensive shower line crossed the ship with large, organized echos.

During recent symposia arguments arose whether the cloud distributions can be described by analytical functions. Lopez (1976) proposed a log-normal distribution. As can be seen from Fig. 1 an exponential function fits the observed cloud distribution well as least for deep clouds. The number of the shallow clouds are highly underestimated by radar thus we hesitate to describe this part of the obsered distribution by any analytical function. For the deep cumulonimbi the difference between the log-normal and the exponential distribution is very small thus one cannot decide which fits the observations best. As will be seen later, the main result of the cloud mass flux distribution is not changed whether we use the observed cloud population or the exponential form.

The relationship between the cloud top height z and the entrainment factor λ was derived with the radiosonde data from the "Planet".

Fig. 2 and 3 show the vertical profiles of $\hat{h}_e^*$ and $h_c(\lambda)$ for the radiosonde ascents of Sept. 3.74 18 GMT and Sept. 5.74 06 GMT, respectively. Applying equ. (5) to these diagrams the top height is given at that level where the $\hat{h}_e^*$ - and h_c-curves intersect. The results are portrayed in Fig. 4. For every radiosonde ascent one curve exists in the z-λ-diagram, that means the z-λ- relationship is uniquely determined by the thermal and moisture stratifaction of the cloud environment.

It is not possible to describe the curves of Fig 4 by an exponential function as it looks like. Both curves show a similar behaviour, the z-λ relationship is different for the shallow clouds and for deep clouds. This finding has a strong effect on the cloud mass flux distribution that will be discussed later.

In order to determine the cloud mass flux at cloud base two parameters are not yet specified according to equ. (4), the density ρ and the vertical velocity w. We assume the cloud base is equal to the lifting condensation level thus ρ can be derived from the radiosonde ascents and it is constant for all clouds.

We have no direct observations of w. Emmit (1978) derived from tethered ballon measurements during GATE cloud base values of about 1-2 m/s; Levine et al. (1973) found for cumulus congestus over Barbados by trackingballoons values between 1.5 and 4 m/s. An estimation of w by the hydrological balance was done for the 5 th of Sept. and gave w= 1 m/s, constant for all clouds.

5. Cloud mass flux distribution

The cloud mass flux distribution at cloud base was calculated with the above discussed parameters and it is shown in Fig. 5 and 6. For both data sets we find the same structure, the distribution is bimodal. This is in agreement with previous studies of Ogura and Cho (1973), Cho and Ogrura (1974), Nitta (1975) and Johnson (1978).

The first maximum is, however, shifted more to deeper clouds compared to the results of the above cited authors. A minimum is apparent in both cases for clouds which reach the middle levels. We tried to understand the reason for these less effictive clouds. The distribution of clouds is not directly related to the bimodal structure that means there is no bimodal structure of the cloud population. We used the exponential functions shown in Fig. 1 for the cloud distribution and calculated the cloud mass flux; the results are given in Fig. 5 and 6 by the crosses. It is evident even with the monotonously decreasing number of the clouds the bimodal structure appears. Although the number of shallow clouds is much greater for the exponential than for the observed distribution the cloud mass flux for these clouds is very small. This finding agrees with the results of Johnson (1976 + 1978) and Nitta (1977), that the very large mass flux determined indirectly is not realistic and is drasticly reduced if downdrafts are included.

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Fig. 1: Mean frequency distribution of radar echo top heights.

Fig. 2: Vertical profiles of the saturated moist static energy of the environment and of the clouds for different entrainment factors for the rawinsonde ascend on Sept. 3, 1974, 18 GMT.

Fig. 3: Same as Fig. 2 but rawinsonde ascend Sept. 5, 1974, 06 GMT

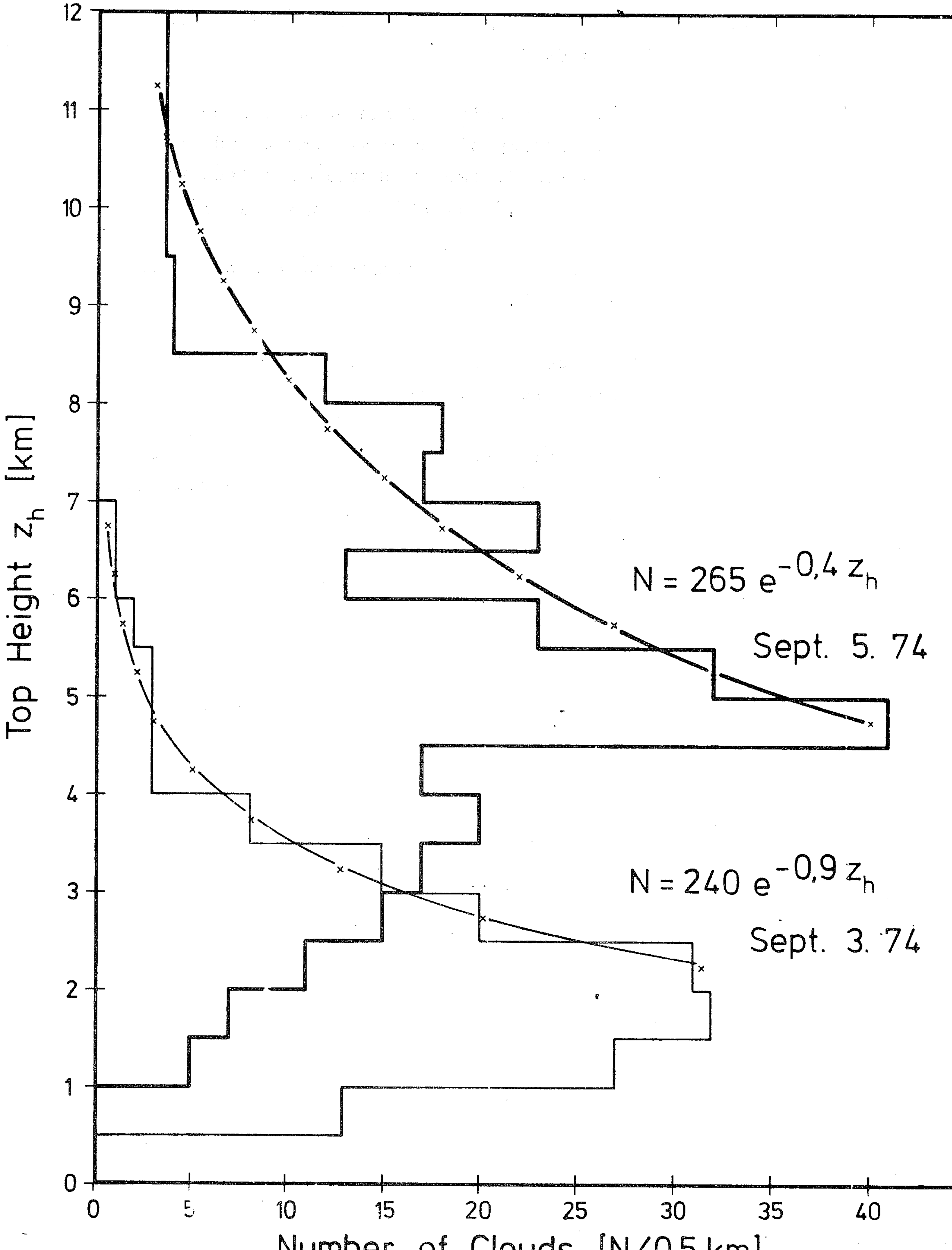
Fig. 4: Cloud top height versus entrainment factor (derived from Fig. 2+3).

Fig. 5: Cloud mass flux distribution on Sept. 3.1974 x = mass flux for the exponential cloud distribution of Fig. 1.

Fig. 6: Same as Fig. 5 but for Sept. 5 1974.

Fig. 7: Cloud top height versus logarithm of entrainment factor; Minimum = minimum of the cloud mass flux distributions (Fig. 5+6).

GATE
Mean Cloud Distribution
Sept. 3.+5. 1974



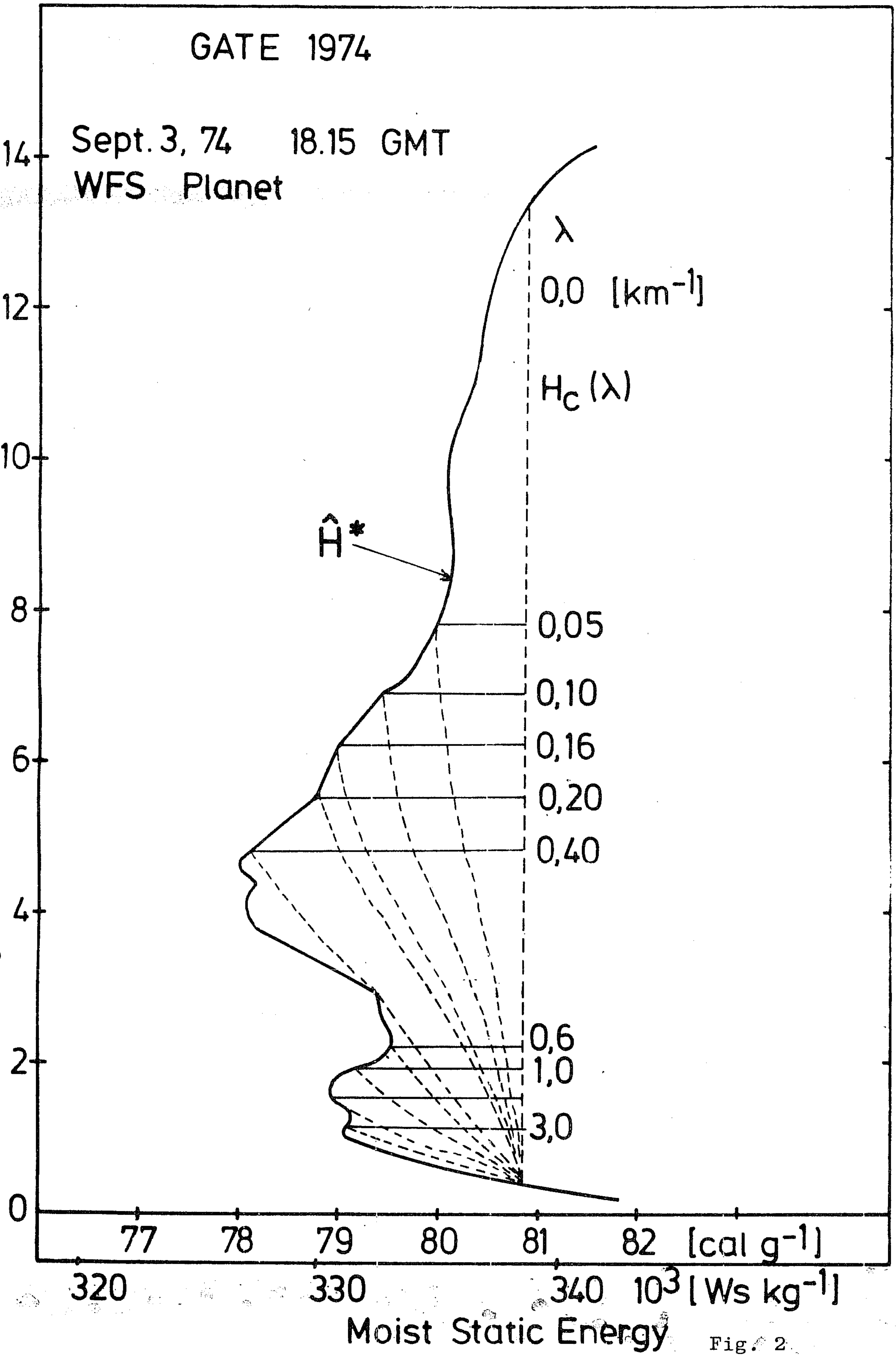

GATE 1974
Sept. 3, 74 18.15 GMT
WFS Planet
λ
0,0 [km^{-1}]
$H_c(\lambda)$
$\hat{H}^*$
0,05
0,10
0,16
0,20
0,40
0,6
1,0
3,0
14
12
10
8
6
4
2
0
77
78
79
80
81
82
[cal g^{-1}]
320
330
340
10^3 [Ws kg^{-1}]
Moist Static Energy

Fig. 2

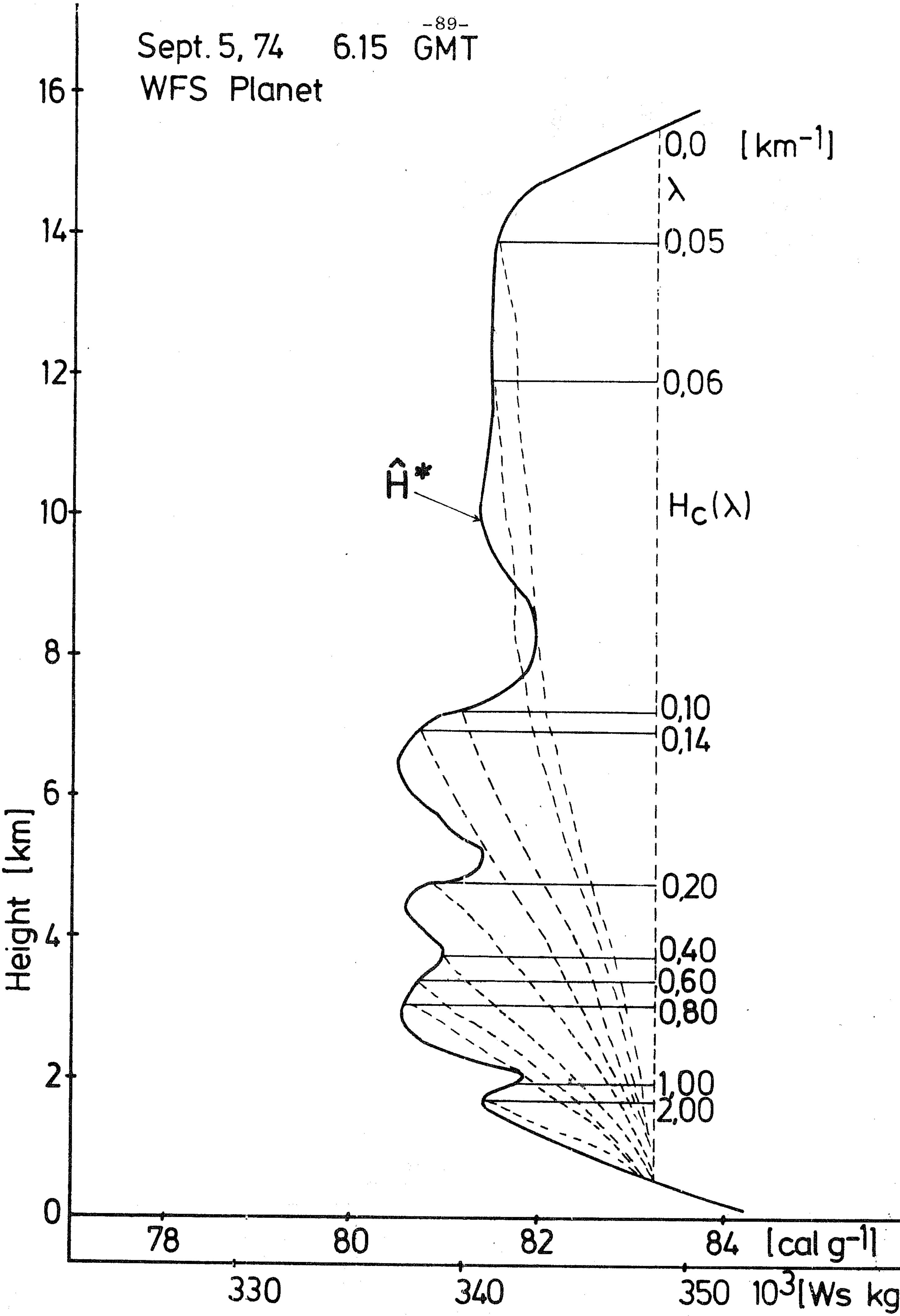

Sept. 5, 74 6.15 GMT
WFS Planet
Height [km]
0
2
4
6
8
10
12
14
16
$\hat{H}^*$
$H_c(\lambda)$
λ
0,0 [km^{-1}]
0,05
0,06
0,10
0,14
0,20
0,40
0,60
0,80
1,00
2,00
78
80
82
84 [cal g^{-1}]
330
340
350 10^3[Ws kg
Moist Static Energy

Fig.

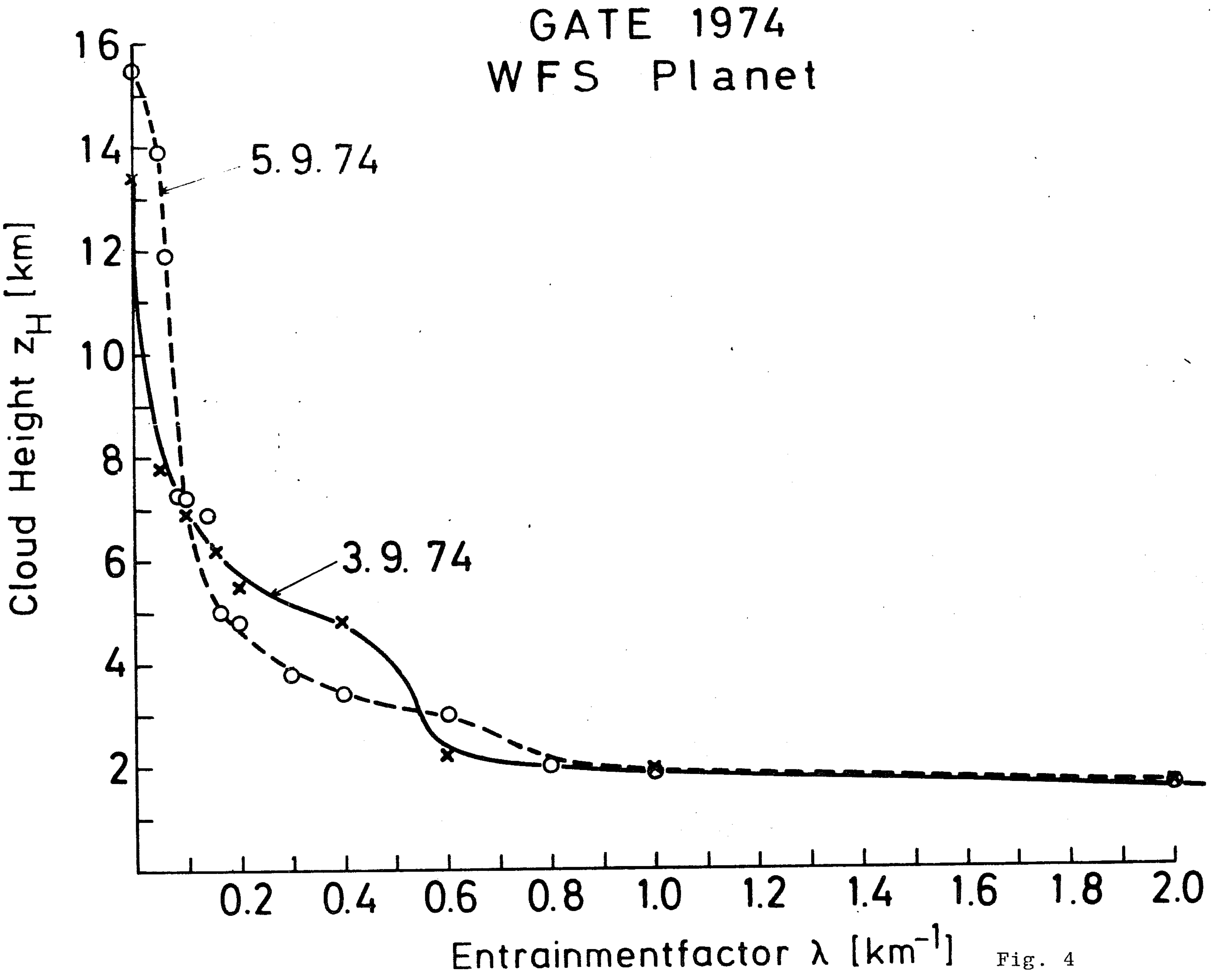

GATE 1974
WFS Planet
5.9.74
3.9.74
Cloud Height z_H [km]
16
14
12
10
8
6
4
2
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
Entrainmentfactor λ [km^{-1}]

Fig. 4

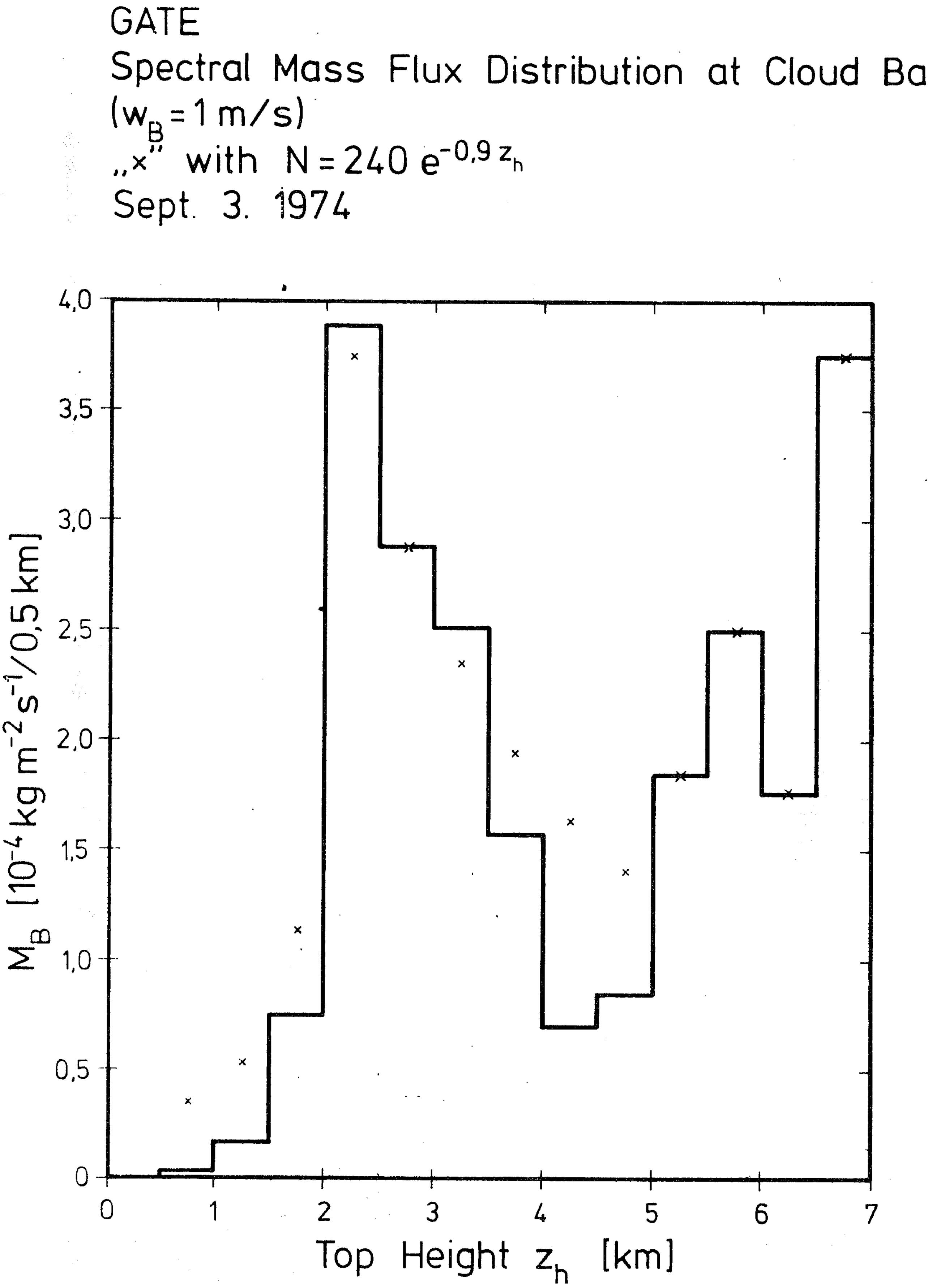

GATE
Spectral Mass Flux Distribution at Cloud Ba
($w_B = 1$ m/s)
„x" with $N = 240\, e^{-0,9\, z_h}$
Sept. 3. 1974
M_B [10^{-4} kg m^{-2} s^{-1}/0,5 km]
4,0
3,5
3,0
2,5
2,0
1,5
1,0
0,5
0
0
1
2
3
4
5
6
7
Top Height z_h [km]

Fig. 5

GATE
Spectral Mass Flux Distribution at Cloud Base ($w_B = 1\,m/s$)
Sept. 5. 1974

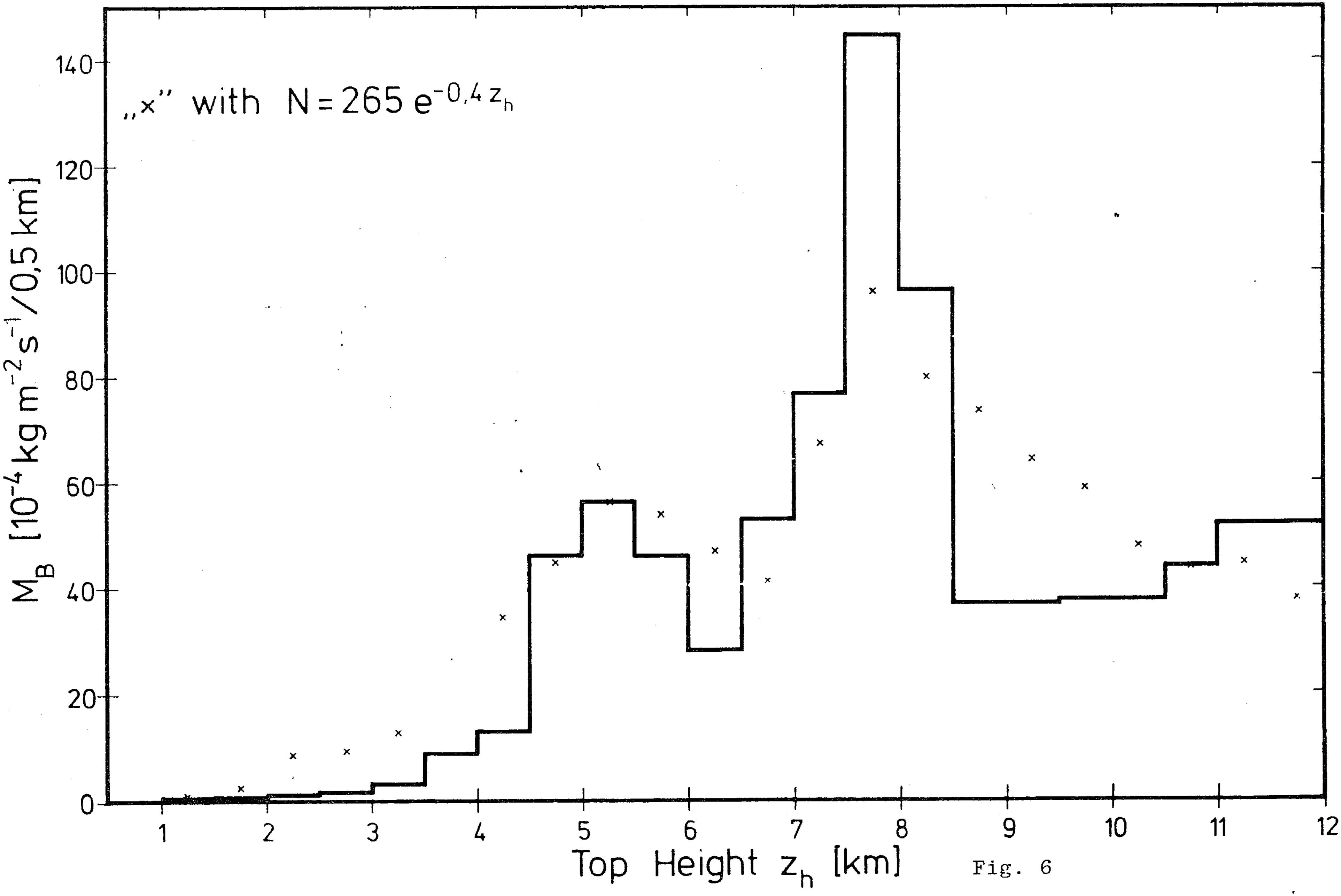
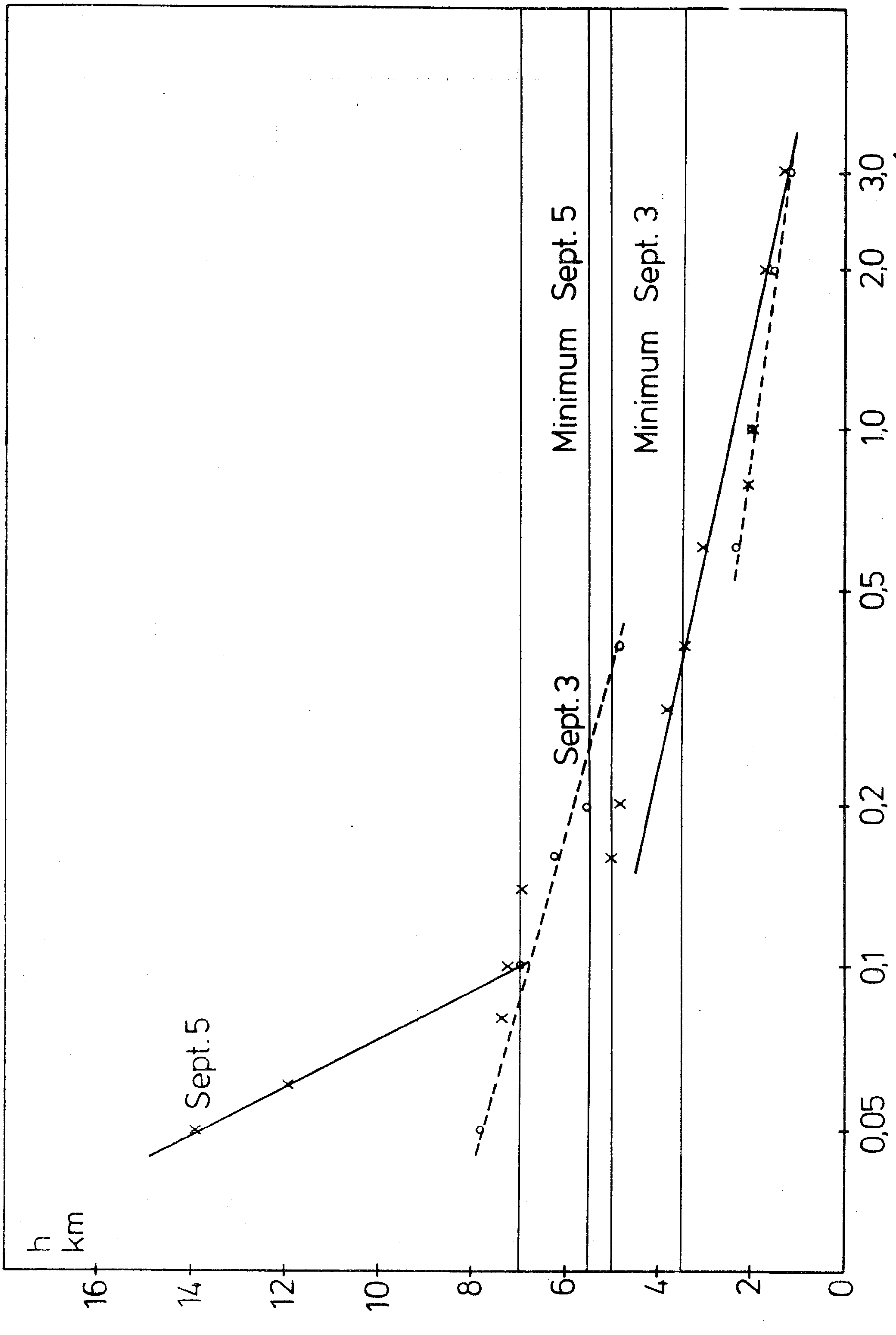


Fig. 6


h
km
16
14
12
10
8
6
4
2
0
0,05
0,1
0,2
0,5
1,0
2,0
3,0
Sept. 5
Sept. 3
Minimum Sept. 5
Minimum Sept. 3