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Heat and moisture fluxes and related structure parameters in the unstable atmospheric surface layer over short vegetations

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1. Introduction

In the past years efforts have been made to relate turbulence characteristics of the atmospheric surface layer to the propagation of electromagnetical radiation. Some of these studies emphasize the aspects of degradation of a beam of radiation due to atmospheric turbulence from the point of view of military and civilian applications of certain wavelengths of radiation (e.g., McMillan et al., 1983; Herben, 1982), while other studies focus on the application of radiation propagation to meteorological research, in particular to the measurement of sensible and latent heat flux, stress and wind (e.q. Wyngaard et al., 1978; Kohsiek, 1982; Hill, 1982; Ting-i Wang et al., 1981).
In the present study attention is focussed on the relations between sensible and latent heat flux and the structure parameters of temperature and moisture. Our interest is that these structure parameters may be inferred from optical scintillation measurements and consequently the heat fluxes could be determined in an optical way. In a paper by Kohsiek (1982) observations of structure parameters and their relations to the heat fluxes have been discussed. It was found there that the results obtained by the author did not always conform to earlier results reported by Wyngaard and LeMone, 1980. Since than, we obtained new data for several vegetated terrains in the Netherlands, on which data will be reported in the following.

2. Theory

We briefly summarize results reported by Wyngaard and Le Mone (1980) for the unstable surface layer:

$$\frac{C_T^2 \, z^{2/3}}{T_*^2} = f_1 \, (z/L) \, , \tag{1}$$

$$\frac{C_{TQ} \, z^{2/3}}{T_*^2 \, Q_*} = f_2 \, (z/L) \, , \tag{2}$$

$$\frac{C_Q^2 \, z^{2/3}}{Q_*^2} = f_3 \, (z/L) \, , \tag{3}$$

where C_T^2 is the structure parameter of temperature, C_Q^2 the one of humidity and C_{TQ} the temperature-humidity structure parameter. T_* is the temperature scaling parameter defined by $T_* = - \langle w'T' \rangle / u_*$, where w' is the fluctuation of the vertical wind, T' the temperature fluctuation and u_* the friction velocity. Similarly, the humidity scaling parameter is defined by $Q_* = - \langle w'Q' \rangle / u_*$ where Q' is the fluctuating specific humidity in g kg^{-1}. The functions f_1, f_2 and f_3 are universal functions of the stability parameter z/L; the Monin Obukhov length L is defined by

$$L = - u_*^3 \, T/kg(Q_o + 0.00061 \, TE_o),$$

where $Q_o = \langle w'T' \rangle$, $E_o = \langle w'Q' \rangle$ (units g $kg^{-1} m \, s^{-1}$), T is the temperature in K and z is the height above the surface. Following Wyngaard and Izumi (1971),

$$f_1 \, (z/L) = 4.9 \, [1 - 7(z/L)]^{-2/3}. \qquad (5)$$

In the free-convection limit ($-z/L \longrightarrow \infty$), $f_1(z/L)$ behaves as

$$f_1(z/L) = 1.34 \, (-z/L)^{-2/3}. \qquad (6)$$

Fairall et al. (1980) found $f_3 = 0.82 \, f_1$; Kohsiek (1982) reports $f_3 = 0.84 \, f_1$ and $f_2 = 0.69 \, f_1$. We write more generally:

$$f_\chi(z/L) = c_\chi \, 4.9 \, [1-7(z/L)]^{-2/3}, \qquad (7)$$

where χ stands for temperature, humidity or temperature-humidity. Eq.(7) will be used below to summarize the results found on different locations.

3. Locations

In the years 1985 and 1986 micrometeorological measurements were carried out on three locations in the Netherlands with different vegetation characteristics. These measurements were organized in the scope of a program that aimed to measure the dry deposition of several polluting gases in the atmosphere on different terrains (Duyzer and Bosveld, 1987). As a by-product, also observations of structure parameters were obtained.

We give some details on the three locations:

i Cabauw (measuring periods 26 April - 9 May 1985 and 18 July - 7 August 1986). Measurements were done near the 200 m meteorological tower of the KNMI. The vegetation is grass with a length varying between 0.1 m and 0.2 m and the surface roughness length is about 0.03 m. The surroundings of the measuring location is rather homogeneous, with the exception of an easterly sector where upwind obstacles (low trees) are found. The Bowen ration mostly varied between 0.3 and 1.

ii Fochtelooërveen (measuring period 18 May - 3 June 1985) This terrain is one of the largest peat moors in the Netherlands and has an area of over 10 km^2. It is covered with a vegetation of heathers, grasses and mosses. Characteristic of this kind of terrain is the humid, spongy soil covered by a loose layer of dead material which very effectively prevents evaporation from the soil. We were surprized by observing Bowen ratios of 2 or more as a rule, while getting wet boots in walking through the terrain. Observations were generally carried out under good fetch conditions with virtually no change of terrain characteristics for 1 km or more. The roughness lenght is 0.05 m.

iii Groote Heide, Leende (measuring period 4 April - 1 May 1986). The Groote Heide (literally, Large Heath) is found in the south of the Netherlands near the town of Leende. Like almost all heaths in the Netherlands, also this one is going through a process where heather gradually is replaced by various kinds of grasses. Here, the process is in an early stage, so heather is still dominant. The upwind terrain was fairly homogeneous for some wind directions, but scattered trees or wet depressions in the terrain were found at other directions. The fetch length was typically 1 km and the roughness length 0.02 m. Bowen ratios were much larger than one as a rule.

4. Instrumentation and data processing

For the purpose of this study the turbulence package that sensed the fast fluctuations of wind, temperature and humidity is of direct relevance. The package (Fig.1) is made up of a sonic anemometer (Kaijo Denki model TR61-A) a Lyman-alpha hygrometer (ERC) and a fine wire platinum temperature sensor (Kohsiek, 1987). At Cabauw, the package was placed at a height of 5.0 m (1985) and 6.5 m (1986), and at the Fochtelooërveen and the Groote Heide it was 11.5 m above the surface. Heat flux, moisture flux, wind stress and structure parameters were calculated on-line by a MINC minicomputer. For the calculation of the structure parameters a time-delay technique was used which involved taking "bursts" of 4 samples of the temperature and the humidity with time intervals between the successive samples varying from 0.04 to 0.08 s, while the time interval between two bursts was about one second. By means of Taylor's hypothesis the three time intervals between the first sample and the three successive ones were converted into spatial intervals, and structure parameters were calculated. This technique has found to be quite reliable (Kohsiek, 1982). All observations were averaged over 10 minutes, from which quantities half-hour averages were constructed later on. Also the three structure parameters generated by the three time intervals were averaged.

5. Results and discussion

In Figs.2-10 the dimensionless structure parameters are presented as functions of the stability parameter -z/L. The drawn lines in the figures represent Eq.(7), where the constant c_χ has been eye-fitted for each case apart. Values of c_χ are summarized in Table 1. Data of C_T^2 and C_{TQ} are lacking for Cabauw, 1985 and data on C_{TQ} are missing for Cabauw, 1986. In the latter case the temperature fluctuations were measured by the sonic anemometer instead of the cold platinum wire as for the other cases. Inspecting Figs.2-10 it is seen that Eq.(7) not always fits well to the data. Especially the data of the dimensionless temperature structure parameter ($C_T^2 z^{2/3} / T_*^2$) tend to maintain their free convection behaviour (that is, propertional to $(-z/L)^{-2/3}$) down to smaller values of $|-z/L|$ than Eq.(7) permits. The two other structure parameters,

C_Q^2 and C_{TQ}, follow Eq.(7) closer, although they too do not level off as fast as Eq.(7) predicts for small values of $|-z/L|$. It is worth noting here that structure parameters observed by Kohsiek (1982) on Table Mountain (near Boulder, Colorado, U.S.A.) follow free convection scaling down to $-z/L \approx 0.02$. Apparently the near neutral behaviour of the present data is in between the situation found on Table Mountain and the one found with the Kansas experiments, on which Eq.(7) has been based.
As a consequence of the often poor fit of Eq.(7) to the data, the values of c_χ in Table 1 should be regarded with reserve. We tried an alternative fit to the data, namely free convection behaviour for $-z/L > 0.1$, and the values of c_χ following from this fit are substantially lower (10-20%) than the values of Table 1.
A matter of practical importance is, how well the fluxes of heat and moisture can be calculated from the structure parameters C_T^2 and C_Q^2 by using free convection scaling only. This method is attractive because it does not require knowledge of the Monin Obukhov length L. The first question is whether or not a free convective regime is present. Figs.2-10 are less suitable to answer this question because the two variables share a common quantity, u_*^2. A relation of the form
$(C_\chi^2 z^{2/3}) / \chi_*^2 \sim (-z/L)^{-2/3}$ then does not nessecarily test for the existance of a free convection regime. A more meaningful procedure is the regression analysis of e.g. 4/3 log Q_0 versus log C_T^2. Such a regression was performed on the C_T^2 data with $-z/L > 0.25$. Fig. 11 shows the result for Fochtelooërveen. The slope of the regression line is 0.93 ±0.04, which is not significantly different from 1. The other two cases (Cabauw 1986 and Groote Heide) showed similar results. Thus, free convection is indeed established here. For the case of free convection, Kohsiek (1982) found

$$Q_0 = \beta' (C_T^2)^{3/4}, \tag{8}$$

$$E_0 = 1.09\ \beta' (C_T^2)^{1/4} (C_Q^2)^{1/2}, \tag{9}$$

where

$$\beta' = 0.55\ z \left(\frac{g}{T}\right)^{1/2}. \tag{10}$$

His value of β' is 16% larger than the value following from the Kansas experiments. From Eqs.(8) and (9) follow a relation for the Bowen ratio $(c_p/L_v)\ (Q_o/E_o)$, where c_p is the specific heat capacity of air (in J kg^{-1} K^{-1}) and L_v the latent heat of vaporization of water (in J/g):

$$\frac{c_p}{L_v}\frac{Q_o}{E_o} = 0.407 \times 0.92 \left(\frac{C_T{}^2}{C_Q{}^2}\right)^{\frac{1}{2}} = 0.37 \left(\frac{C_T{}^2}{C_Q{}^2}\right)^{\frac{1}{2}} \qquad (11)$$

Figs.12-20 present the performances of Eqs.(8)-(11) and Table 2 summarizes statistical result. On the average, the fluxes estimated by Eqs.(8) and (9) are 20% too low, whereas the Bowen ratio is predicted correctly by Eq.(11). The underestimation of the heat and vapour fluxes by Eqs.(8) and (9) may seen contradictory to the reasonable agreement found for the present values of c_χ with the ones of Table Mountain, as expressed by Table 1. The explanation is that the values data of c_χ result from fitting Eq.(7) to the data, which generally results in a positive bias at larger values of -z/L. There, the fluxes are large and hence put relatively much weight in the regression procedure resulting in the values mentioned in Table 2. In spite of the rather crude calculation of the fluxes on the basis of free convection scaling of structure parameters, the result are acceptable and we think that little is to be gained by adding a stability factor as long as the behaviour of the structure parameters at small values of -z/L is still uncertain.

An alternative way to calculate the water vapour flux is by using the structure parameters C_{TQ} and $C_Q{}^2$ instead of $C_T{}^2$ and $C_Q{}^2$. We preferred to use $C_Q{}^2$ because we have more data for $C_Q{}^2$ than for C_{TQ}, which reflects the experience that C_{TQ} is more difficult to measure than $C_Q{}^2$. For the two situations in which we obtained data of C_{TQ} (Fochteloërveen and Groote Heide), Figs.21 and 22 present $C_{TQ}/(C_T{}^2\ C_Q{}^2)^{\frac{1}{2}}$ as function of -z/L. The normalized values are equivalent to inertial subrange correlations coefficiënts. It is seen that they generally vary between 0.6 and 0.8, and do not depend on -z/L. This conforms to earlier observations (Kohsiek, 1982).

6. Conclusion

This report presents data of the structure parameters $C_T{}^2$, C_{TQ} and $C_Q{}^2$ for three locations in the Netherlands with different vegetation characteristics. The locations were: Cabauw (grassland), Fochtelooërveen (peat moor) and Groote Heide near Leende (heather). Dimensionless structure parameters are presented as function of the stability parameter z/L and compared with an expression of Wyngaard and Izumi, 1971. It is found that the present data often follow free convection scaling down to lower vaules of -z/L than predicted by Wyngaard and Izumi. In the limit of free convection, our data of $C_T{}^2$ are a factor of 0.7-0.75 times Wyngaard and Izumi's expression. The present data of $C_T{}^2$, C_{TQ} and $C_Q{}^2$ are also lower than the ones summarized by Kohsiek, 1982. As a result, the fluxes of heat and water vapour derived from the present structure parameters, using the free convection expressions of Kohsiek (1982) are about 20% too low, but the Bowen ratio is predicted correctly. For a better understanding of the cause of these discrepancies one should turn to the budget equations for temperature- and humidity variance. Then, independent information on the energy dissipation is needed (for instance, from inertial subrange spectral measurements, or dissipation measure-ments), which information lacks in the present data set. It is recommended that in future experiments of this kind a measurement of the structure parameter of vertical wind velocity is included, from which quantity the energy dissipation can be calculated straightforwardly.

Table 1. Values of c_χ (Eq.7). TM = Table Mountain (Kohsiek, 1982); C85 = Cabauw 1985; C86 = Cabauw 1986; Fo = Fochteloërveen; GH = Groote Heide.

	TM	C85	C86	Fo	GH
C_T^2	0.83	---	0.78	0.85	0.82
C_{TQ}	0.57	---	----	0.62	0.47
C_Q^2	0.72	0.82	0.71	0.84	0.59

Table 2. Values of the slopes of regression lines forced through the origin in Figs.12-20 and their errors. Case (a) relates to the sensible heat flux, (b) to the latent heat flux and (c) to the Bowen ratio. C86 = Cabauw 1986; Fo = Fochtelooërveen; GH = Groote Heide. Av = average of the 3 cases.

	C86	Fo	GH	Av
(a)	0.75 ± 0.02	0.86 ± 0.01	0.82 ± 0.02	0.81 ± 0.06
(b)	0.74 ± 0.01	0.95 ± 0.02	0.70 ± 0.02	0.80 ± 0.13
(c)	1.11 ± 0.04	0.87 ± 0.01	0.99 ± 0.02	0.99 ± 0.12

7. References

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List of Figures

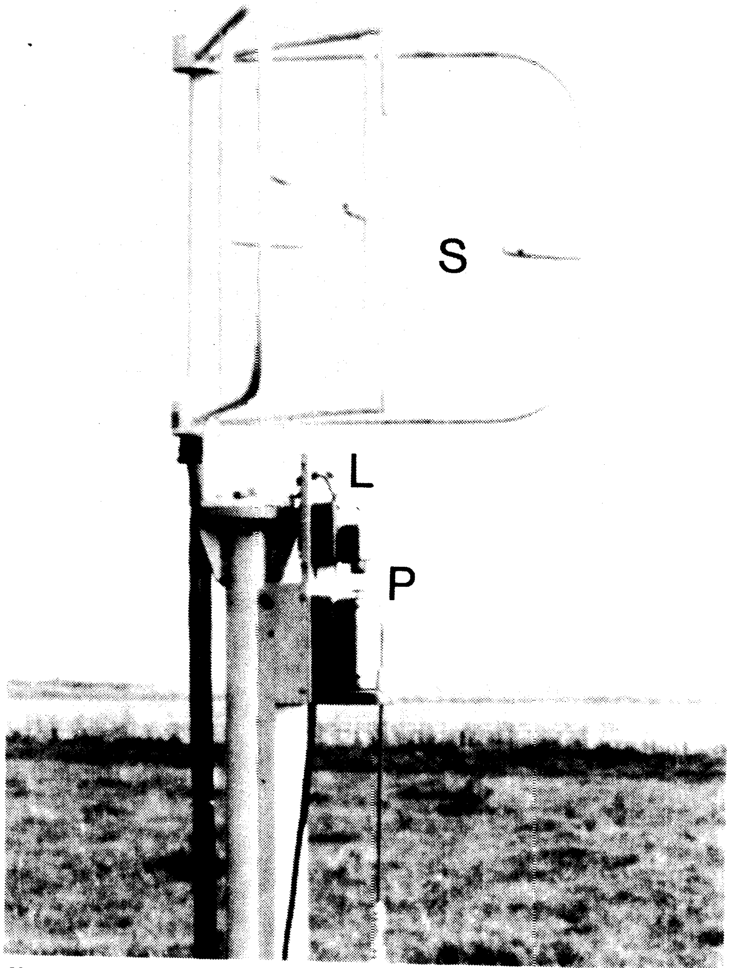
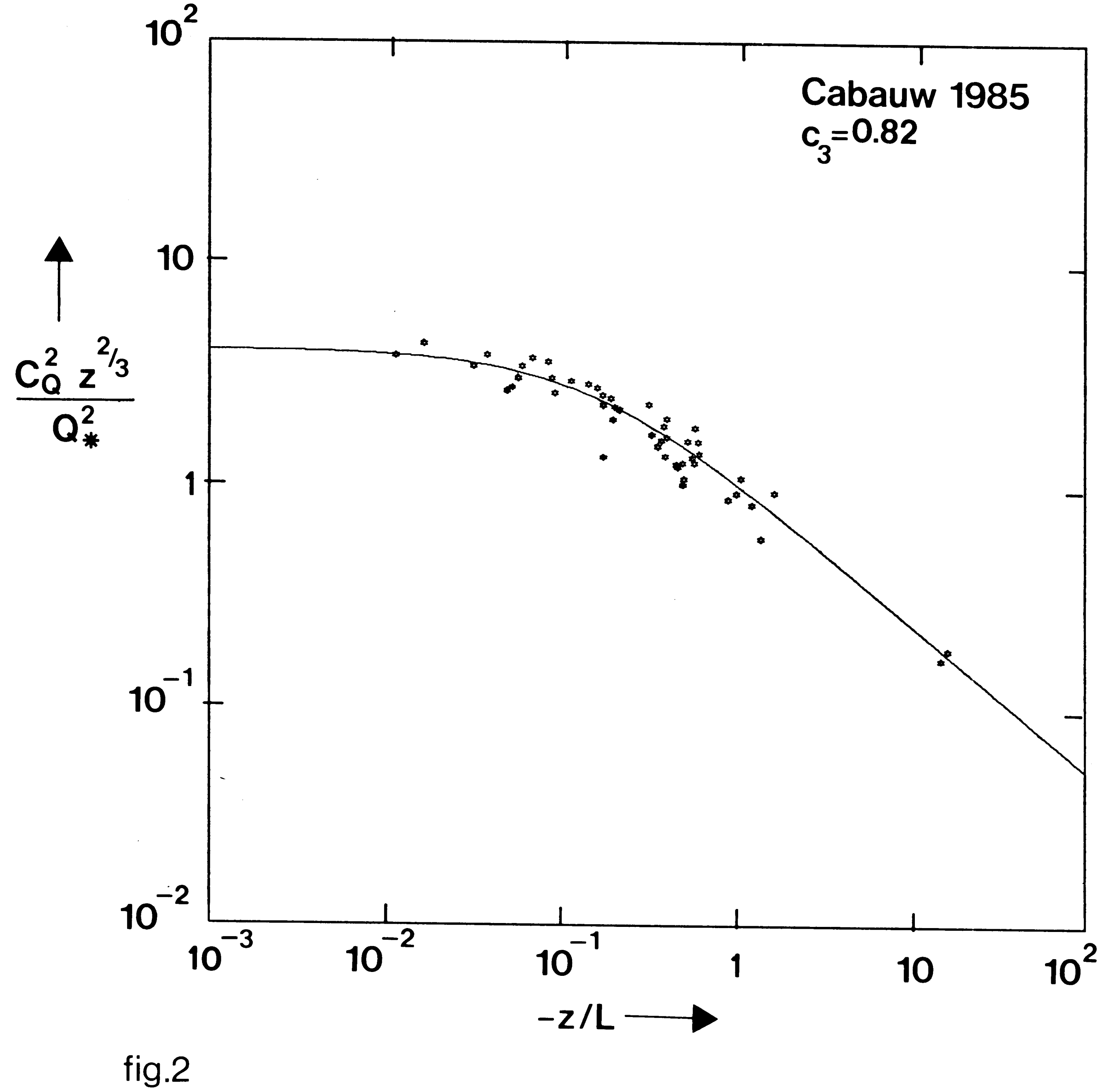
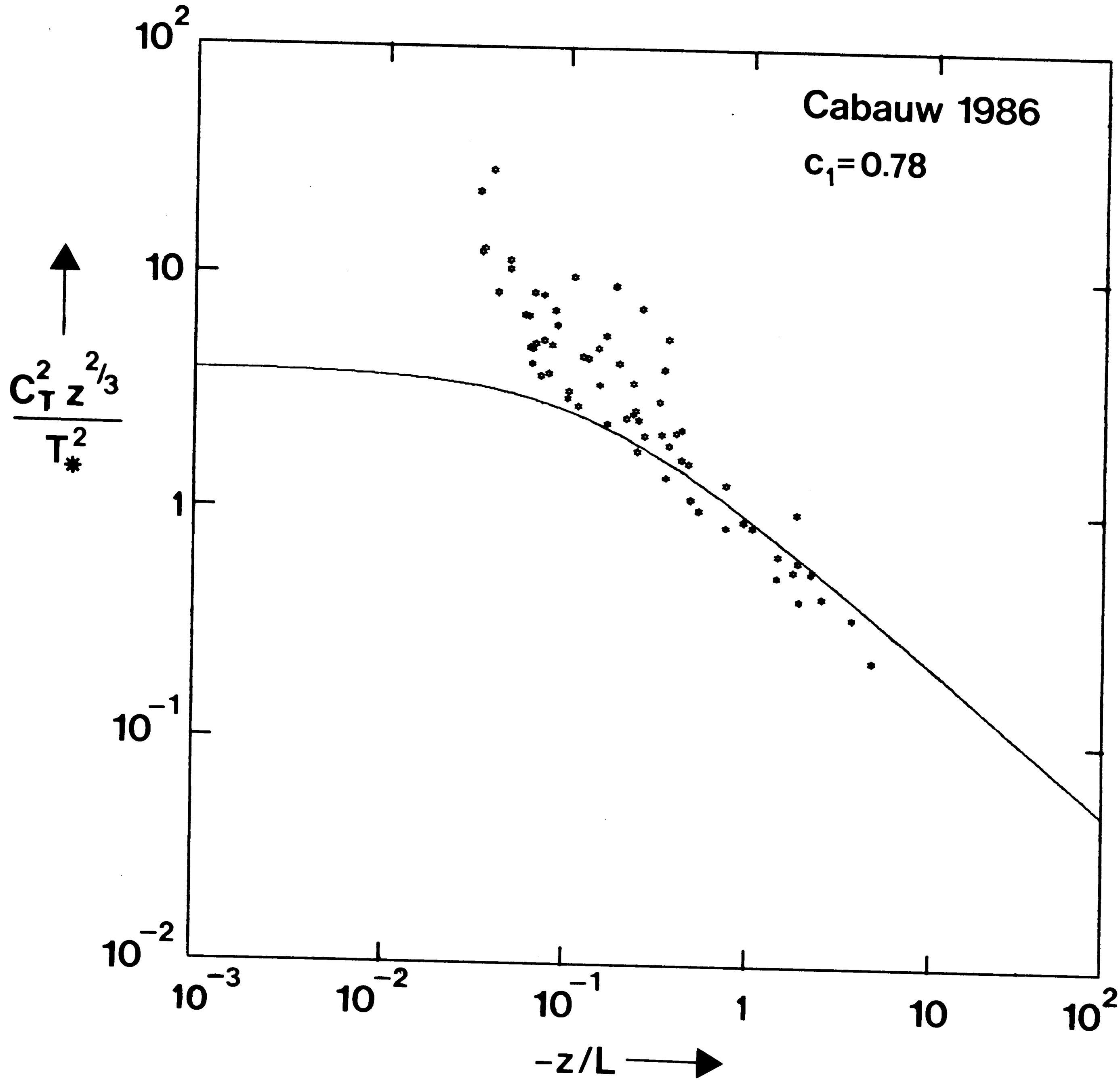


fig: 1



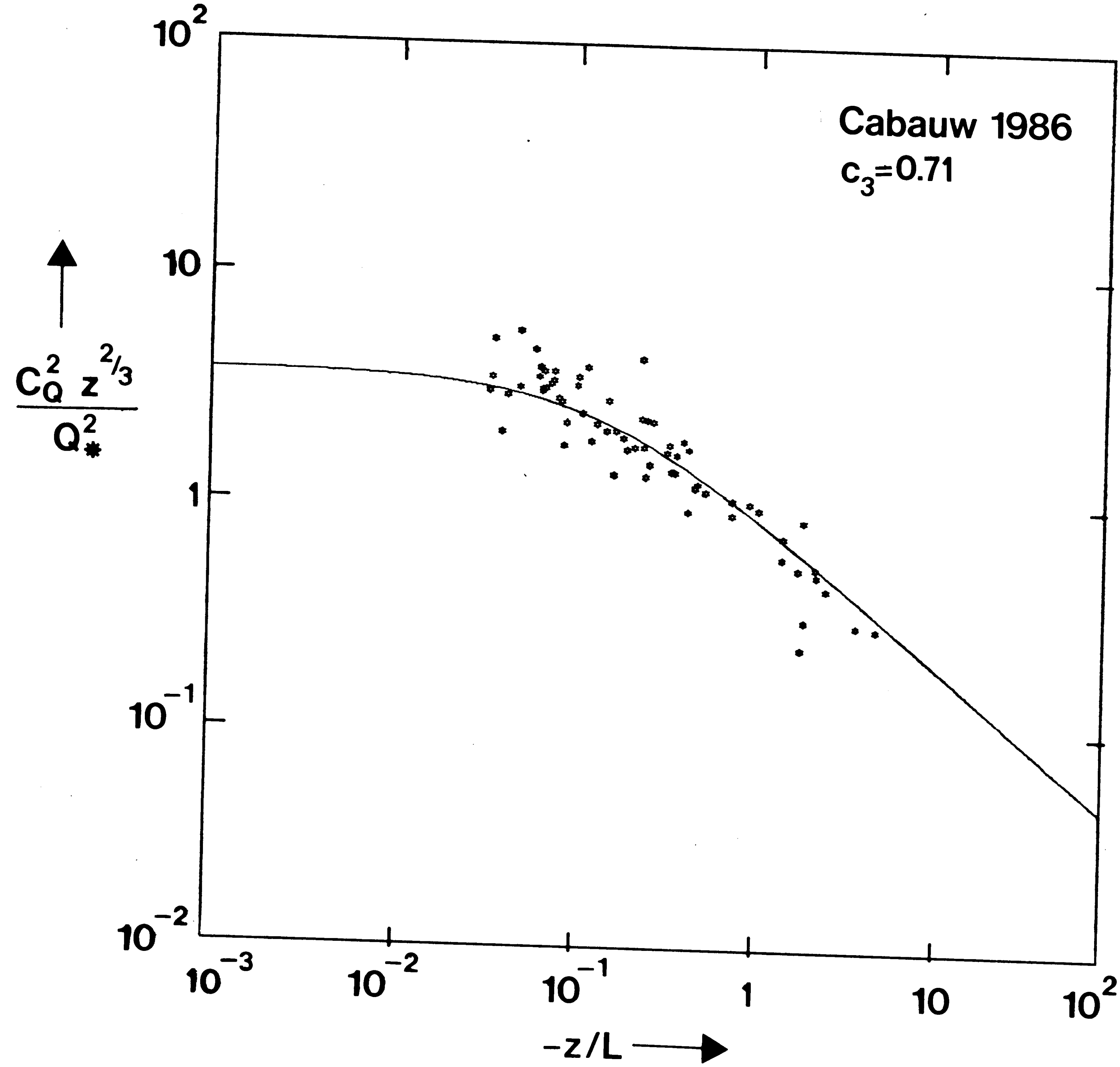
Cabauw 1985
$c_3 = 0.82$
$\frac{C_Q^2 z^{2/3}}{Q_*^2}$
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-2}
10^{-1}
1
10
10^2
$-z/L$

fig.2



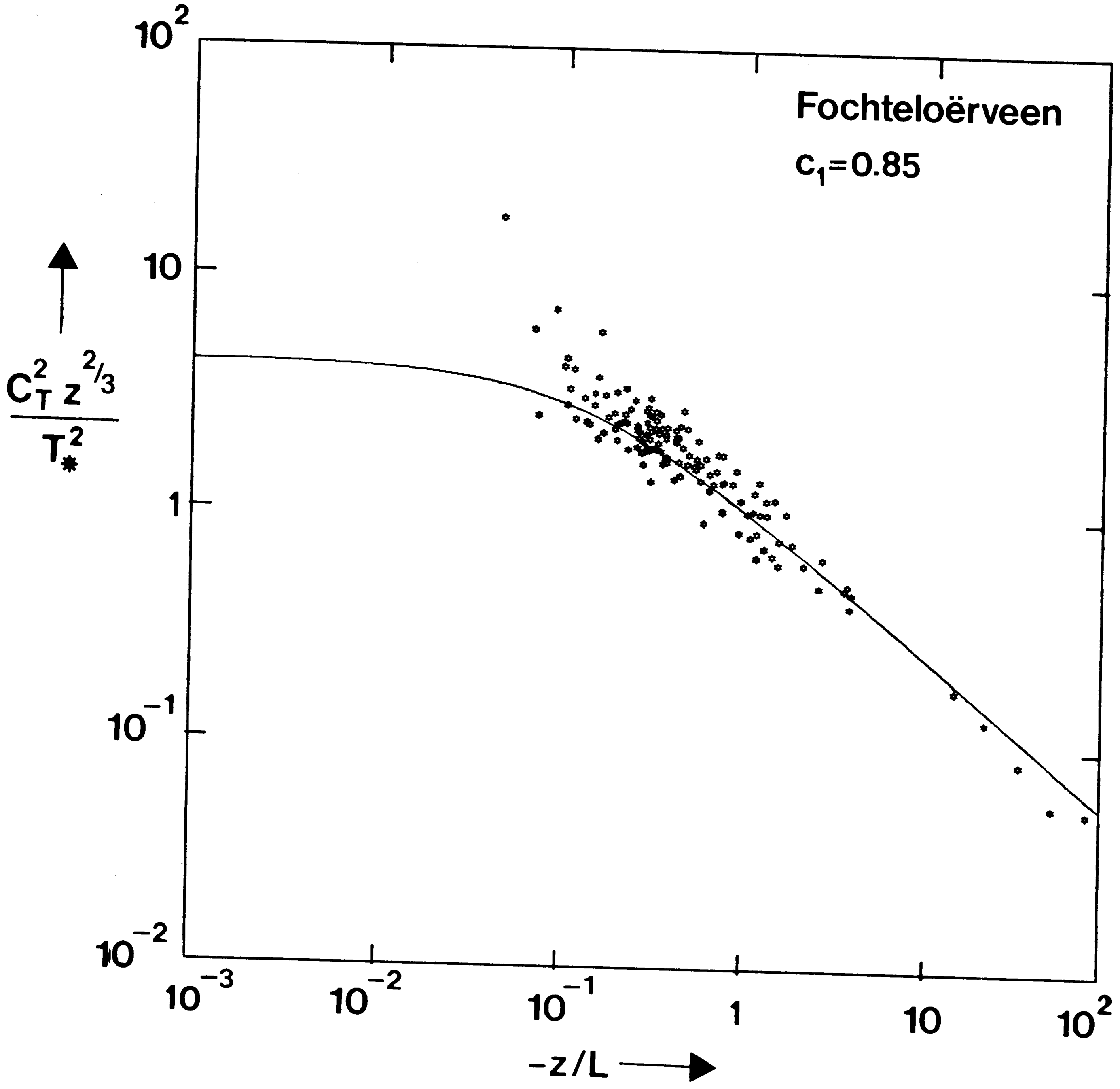
Cabauw 1986
$c_1 = 0.78$
$\frac{C_T^2 z^{2/3}}{T_*^2}$
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-2}
10^{-1}
1
10
10^2
$-z/L$

fig.3



Cabauw 1986
c3=0.71
10^2
10
1
10^-1
10^-2
C_Q^2 z^2/3 / Q_*^2
10^-3
10^-2
10^-1
1
10
10^2
-z/L

fig.4



Fochteloërveen
c_1=0.85
$\frac{C_T^2 z^{2/3}}{T_*^2}$
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-2}
10^{-1}
1
10
10^2
-z/L

fig.5

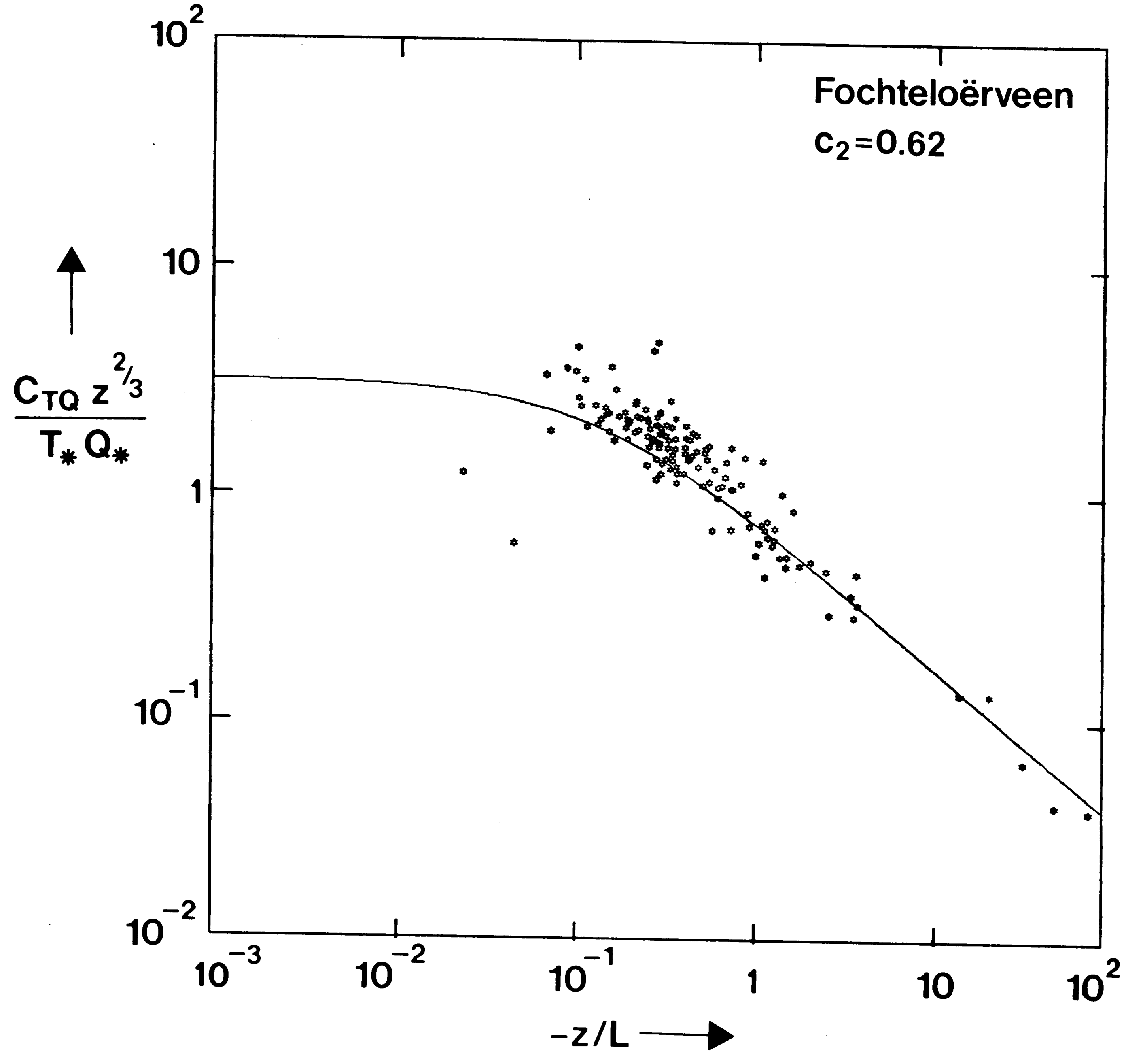

Fochteloërveen
$c_2=0.62$
10^2
10
1
10^{-1}
10^{-2}
$\frac{C_{TQ}\, z^{2/3}}{T_* Q_*}$
10^{-3}
10^{-2}
10^{-1}
1
10
10^2
$-z/L$

fig.6

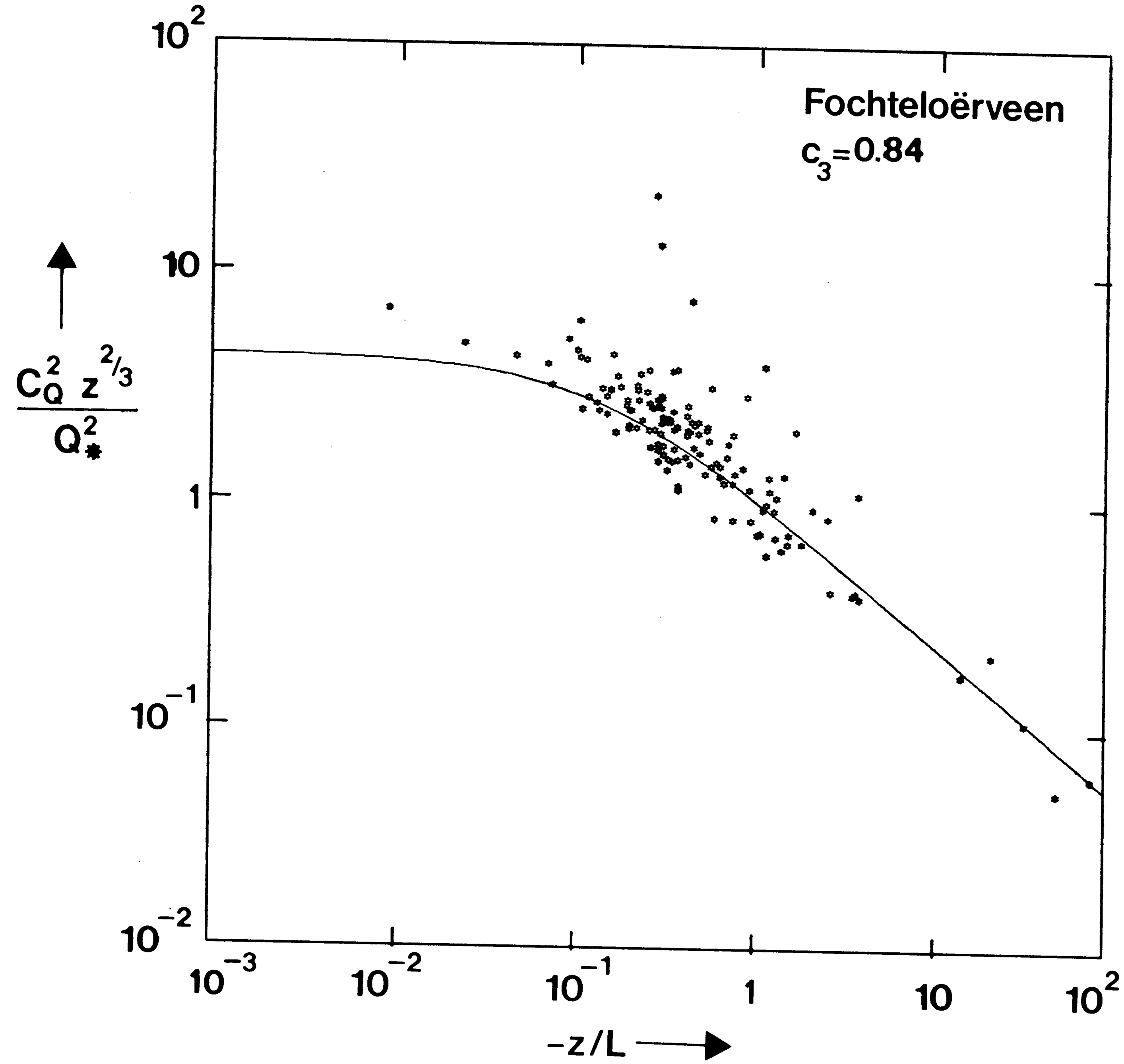

Fochteloërveen
c_3=0.84
$\frac{C_Q^2 z^{2/3}}{Q_*^2}$
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-2}
10^{-1}
1
10
10^2
-z/L

fig.7

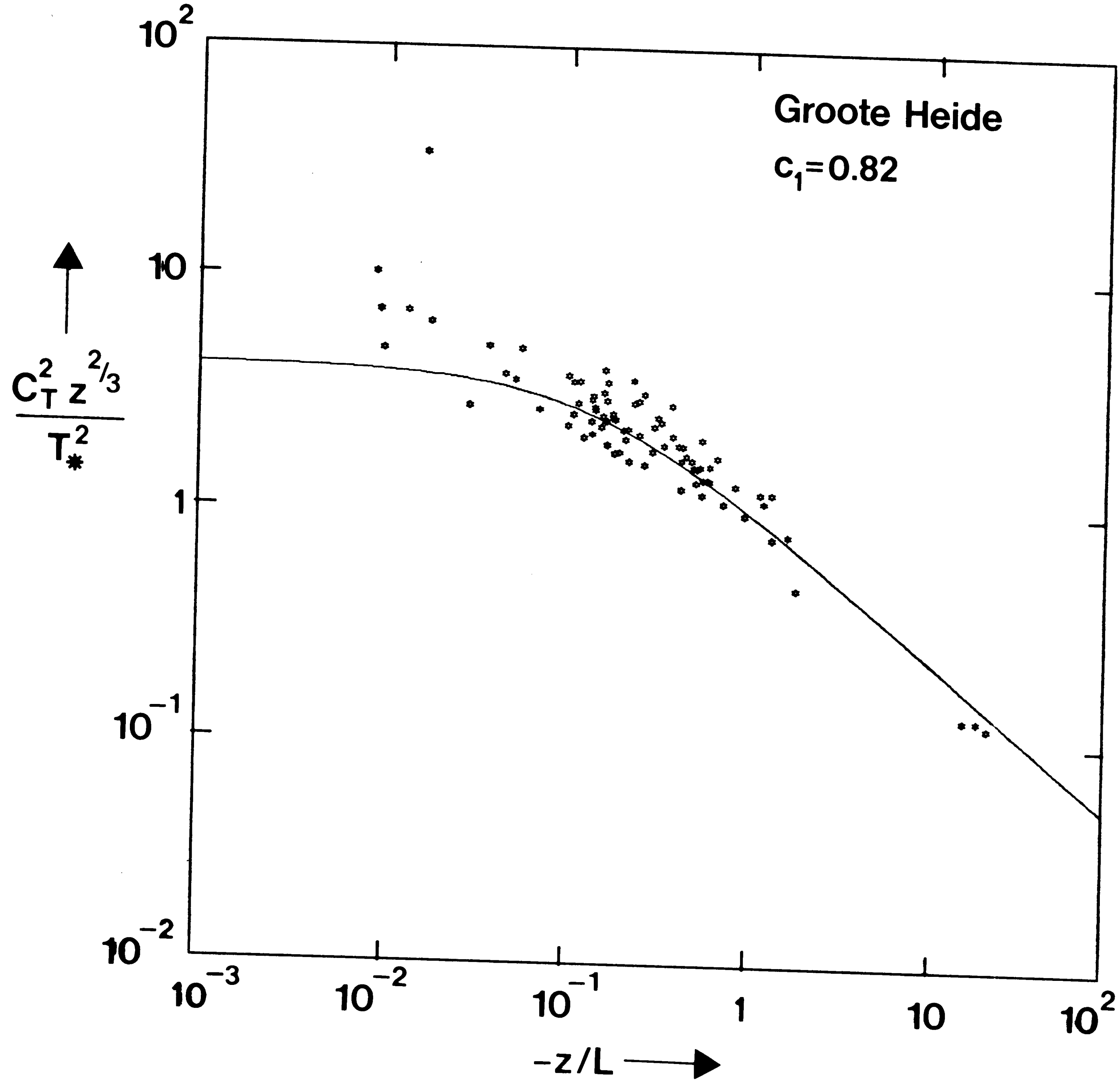

Groote Heide
c1=0.82
$\frac{C_T^2 z^{2/3}}{T_*^2}$
-z/L
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-2}
10^{-1}
1
10
10^2

fig.8

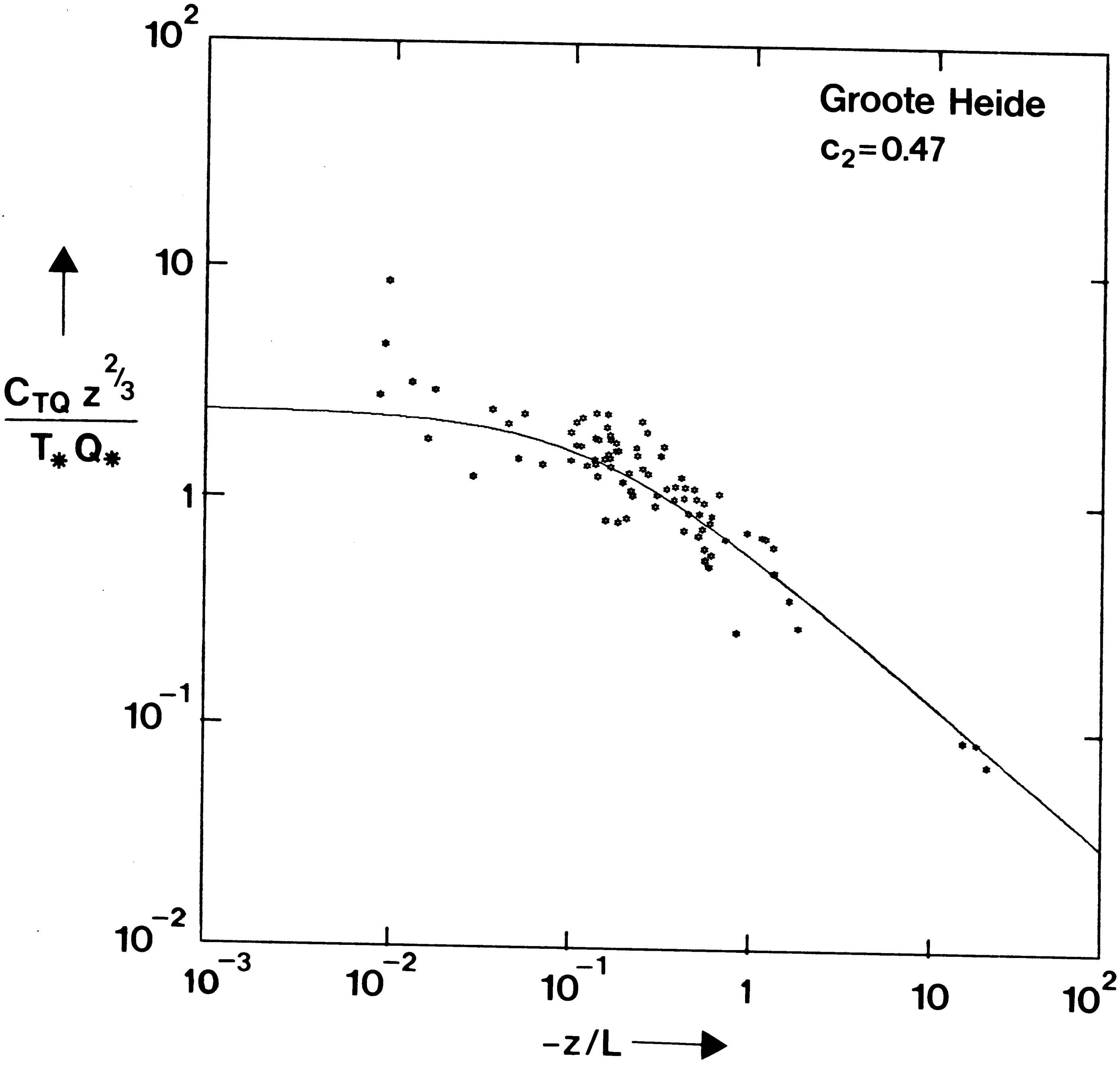
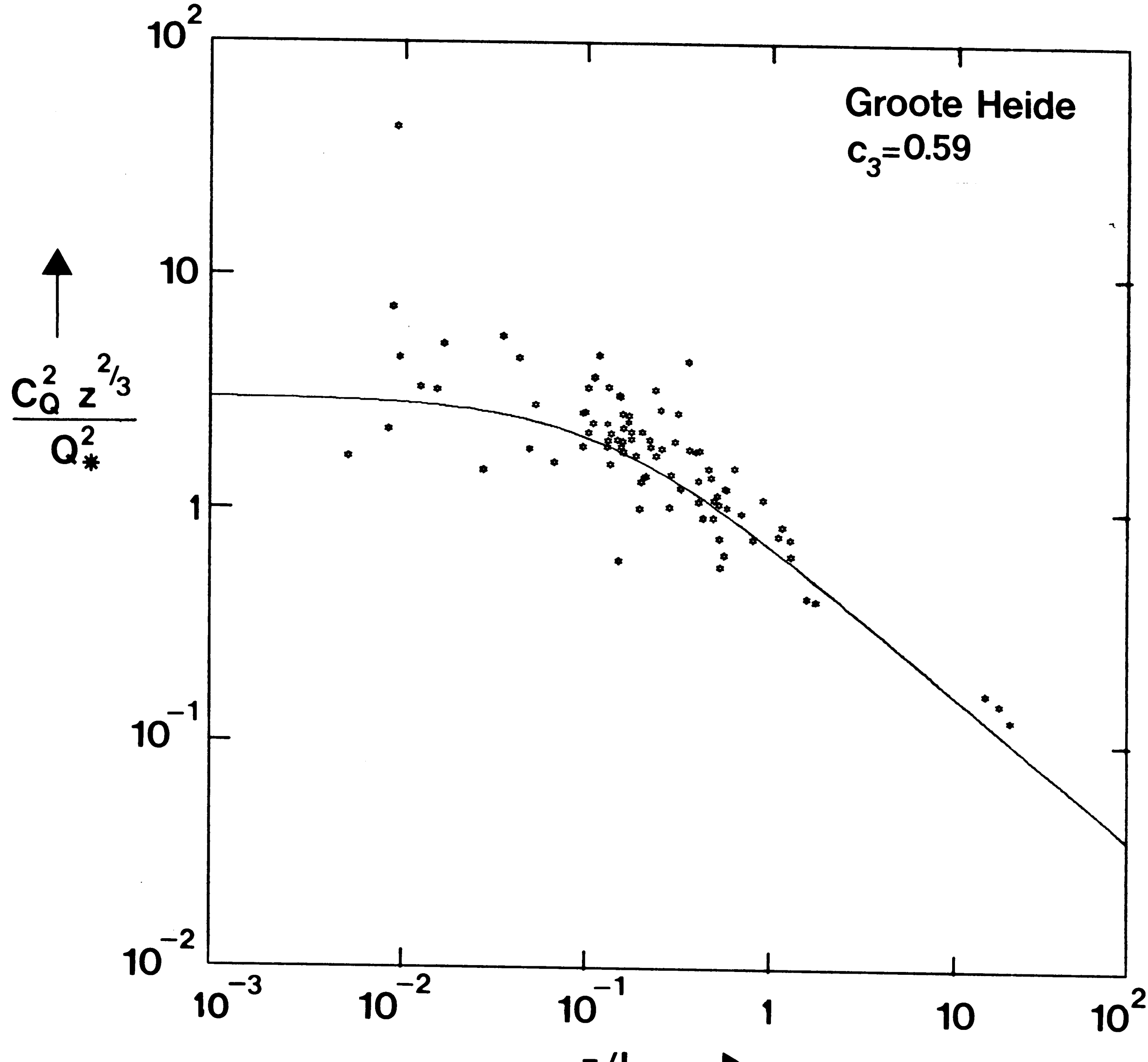

Groote Heide
c_2=0.47
$\frac{C_{TQ}\,z^{2/3}}{T_* Q_*}$
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-2}
10^{-1}
1
10
10^2
$-z/L$

fig.9



Groote Heide
$c_3=0.59$
$\frac{C_Q^2 z^{2/3}}{Q_*^2}$
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-2}
10^{-1}
1
10
10^2
$-z/L$

fig.10

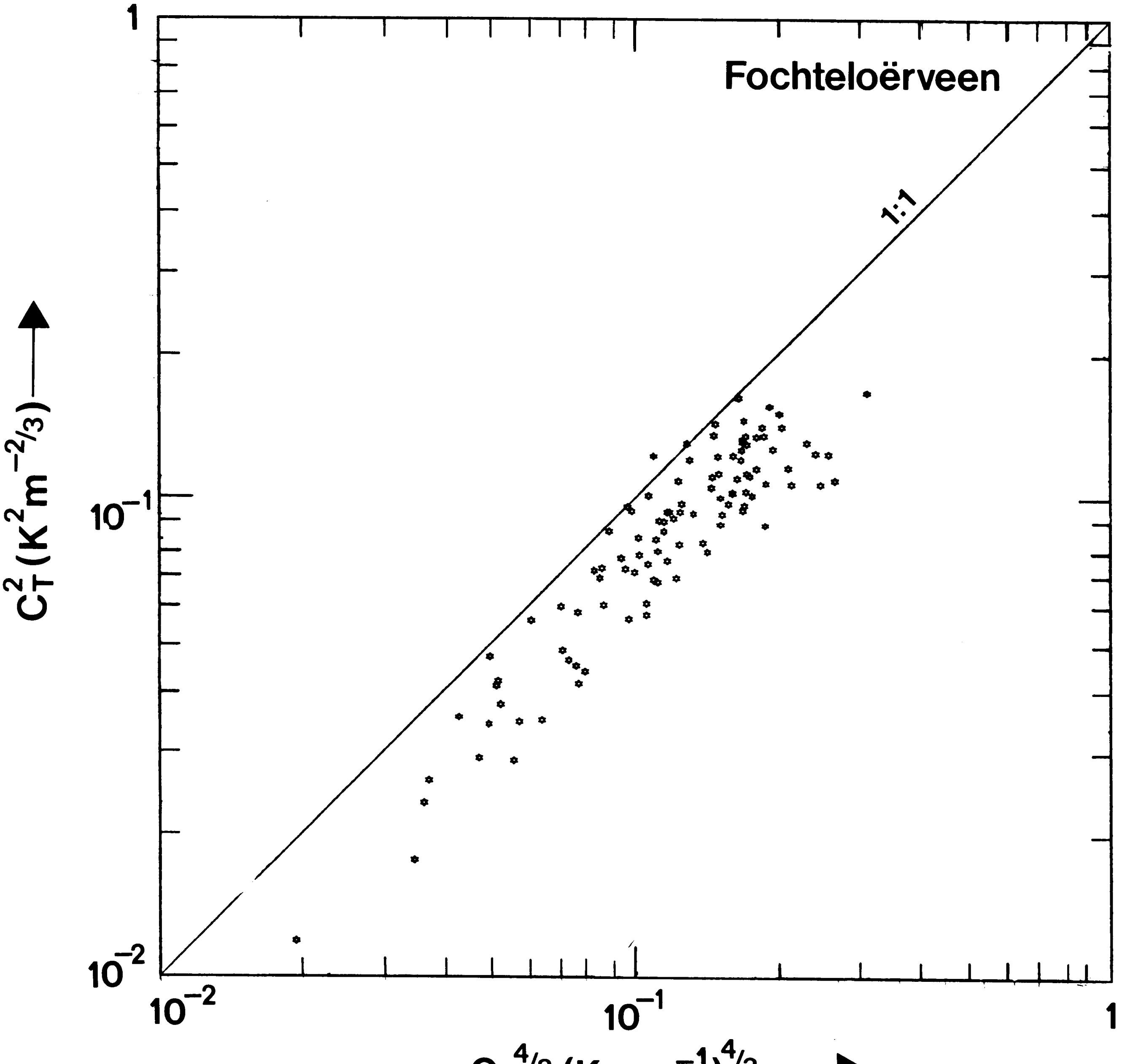


fig.11

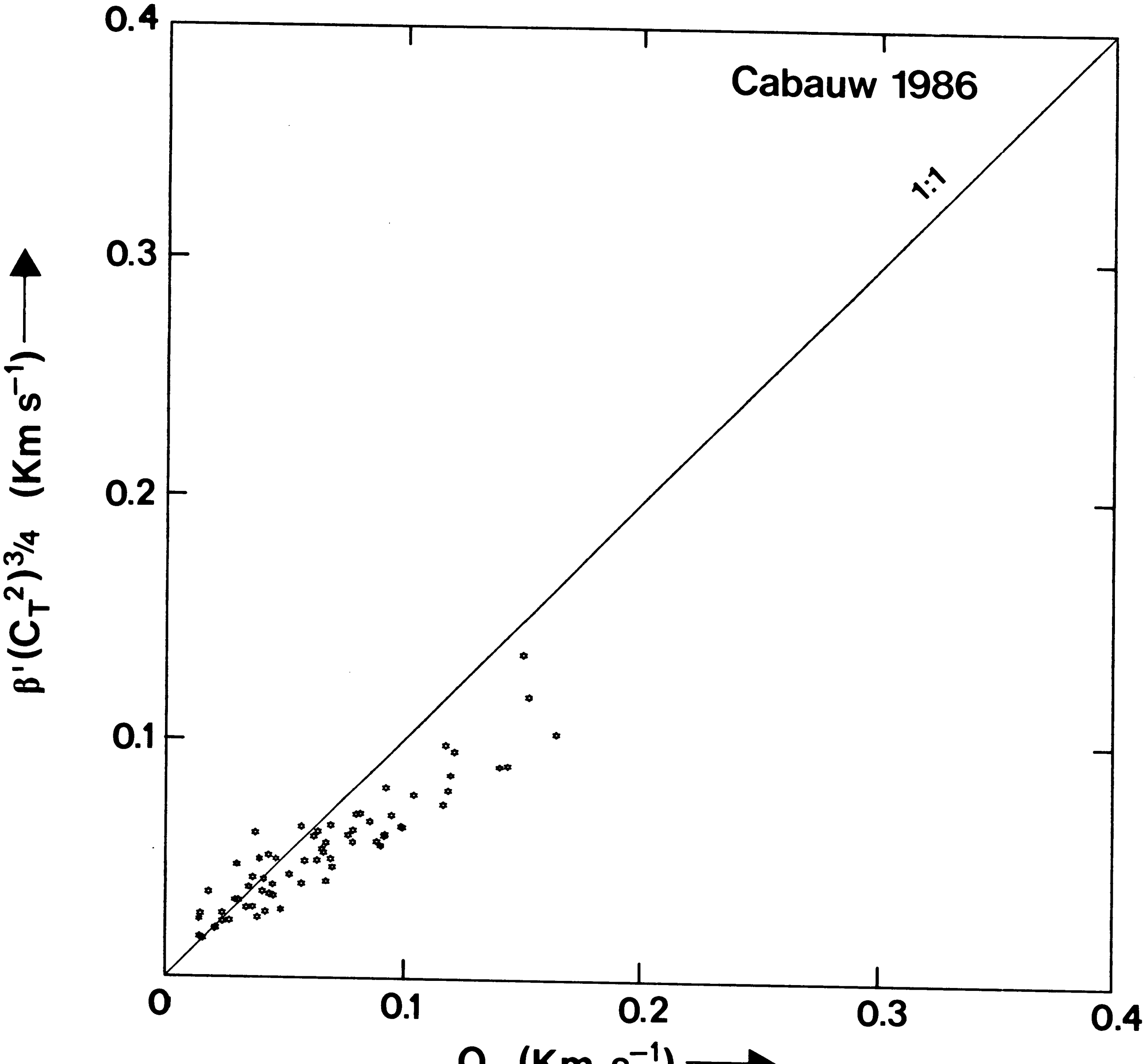


fig.12

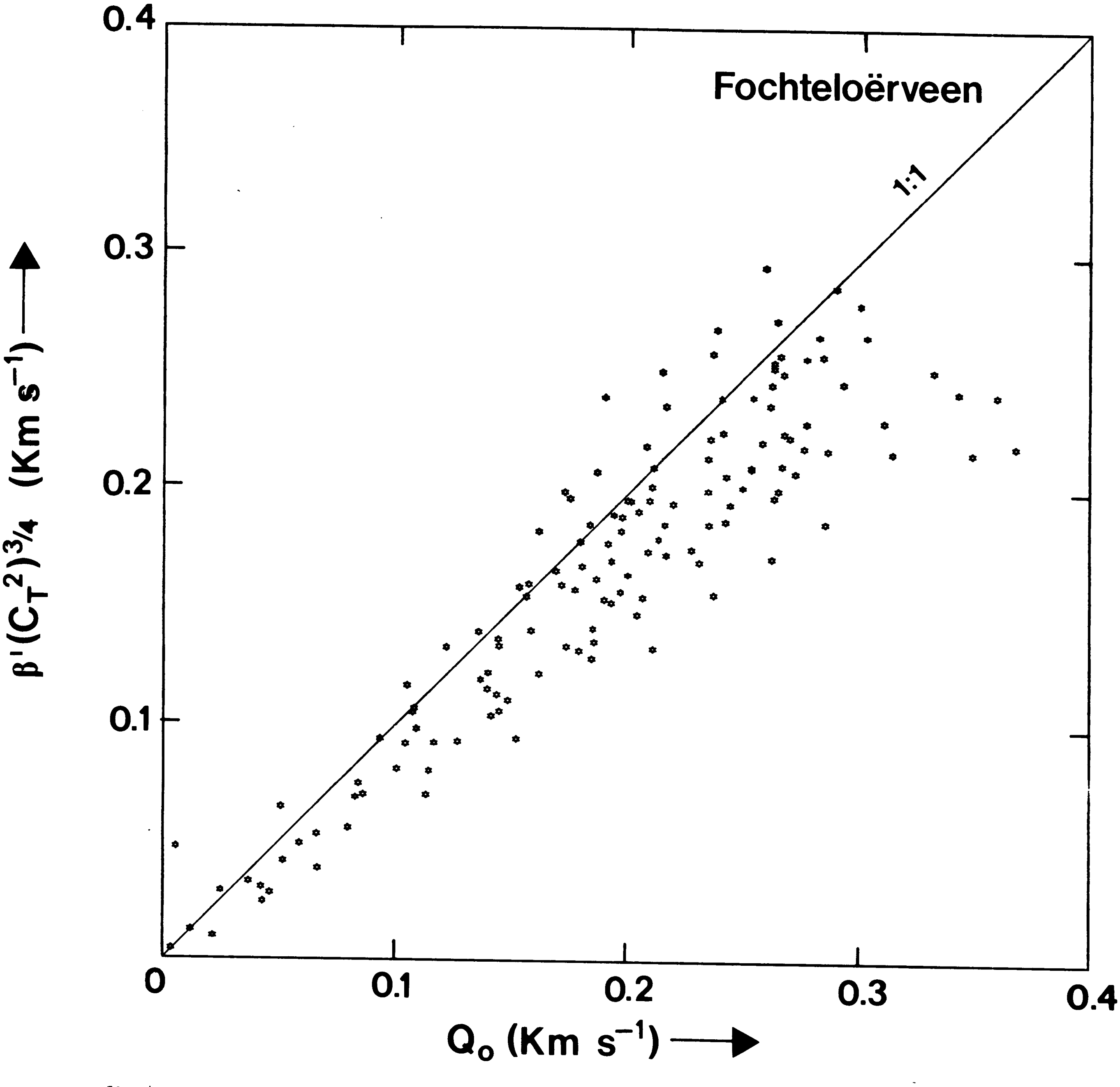

Fochteloërveen
1:1
0.4
0.3
0.2
0.1
0
0.1
0.2
0.3
0.4
$\beta'(C_T^2)^{3/4}$ (Km s^{-1})
Q_o (Km s^{-1})

fig.13

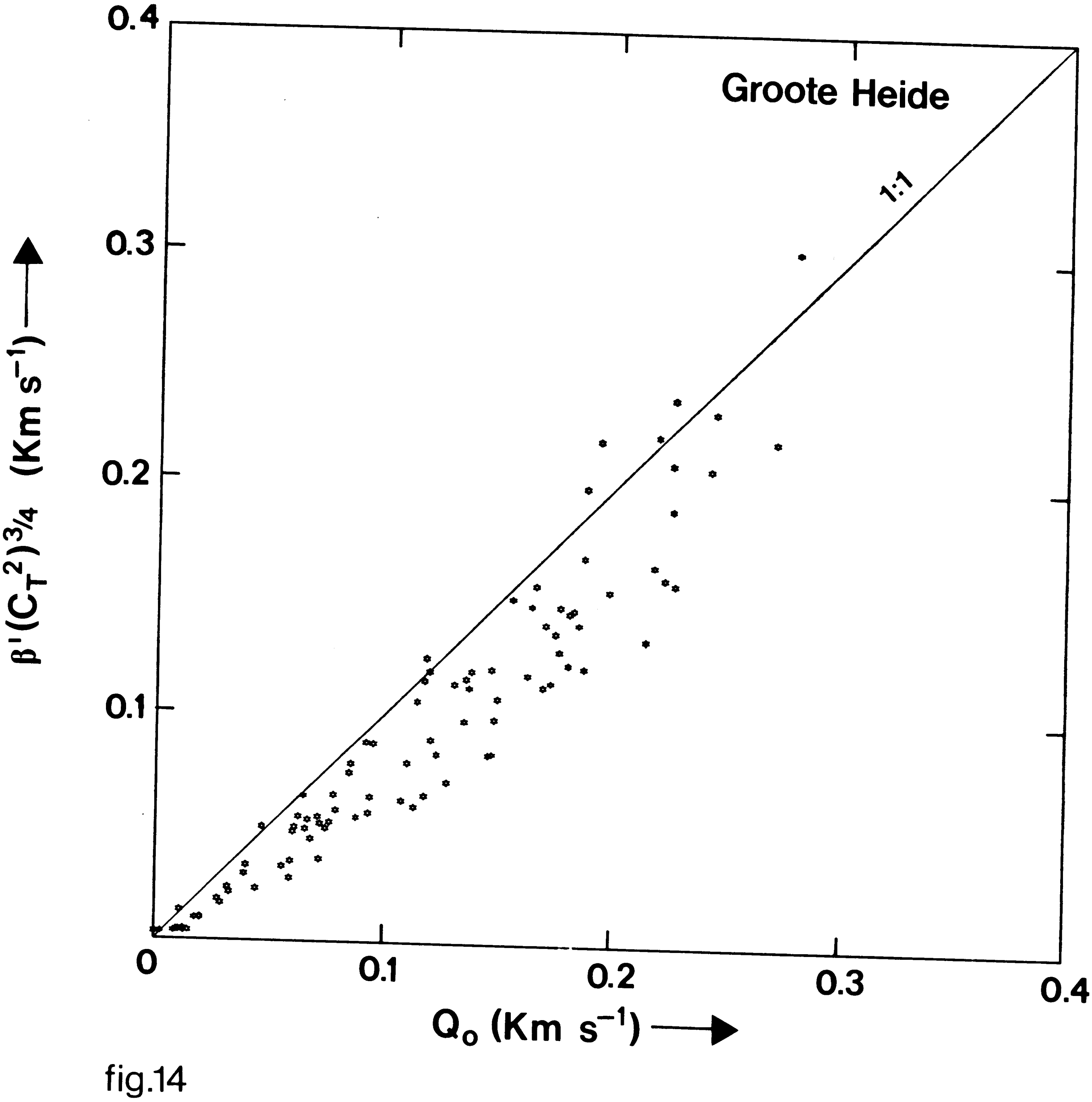
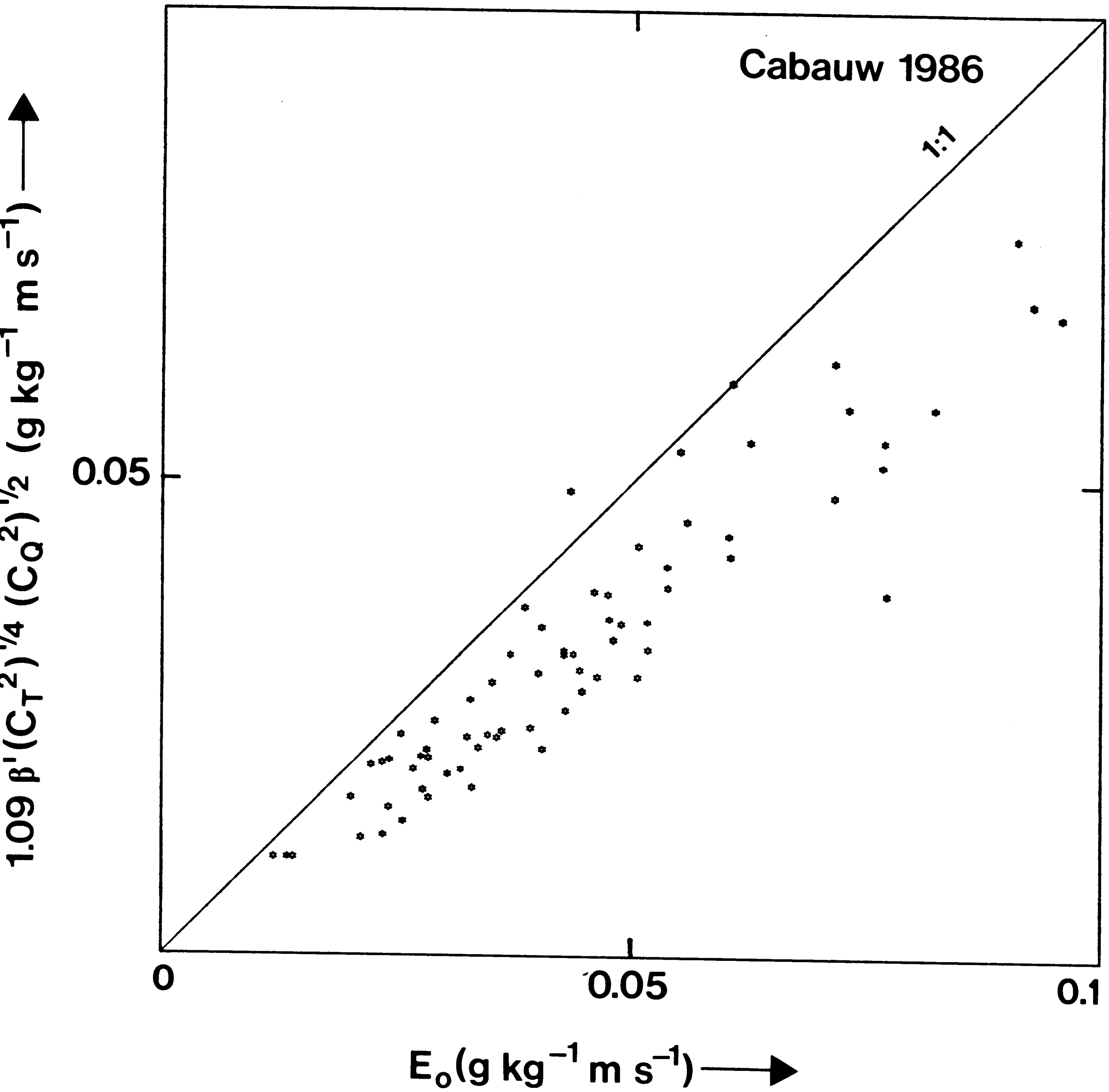
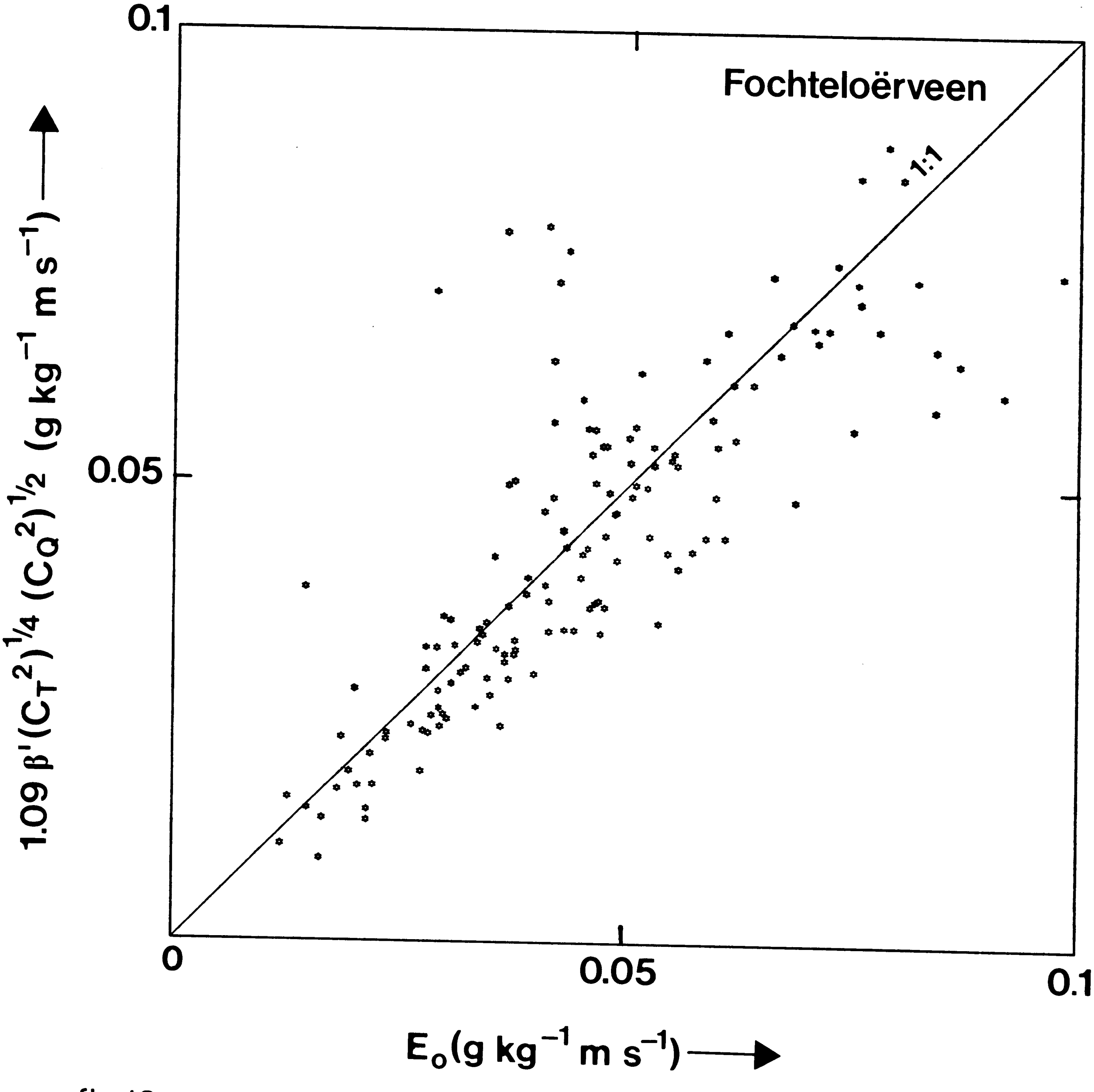


fig.14



Cabauw 1986
1:1
0.05
0
0.05
0.1
$1.09\,\beta'(C_T^{\,2})^{1/4}(C_Q^{\,2})^{1/2}$ (g kg^{-1} m s^{-1})
E_o(g kg^{-1} m s^{-1})

fig.15



0.1
Fochteloërveen
1:1
0.05
0
0.05
0.1
$1.09\,\beta'(C_T^2)^{1/4}(C_Q^2)^{1/2}$ (g kg^{-1} m s^{-1})
E_o(g kg^{-1} m s^{-1})

fig.16

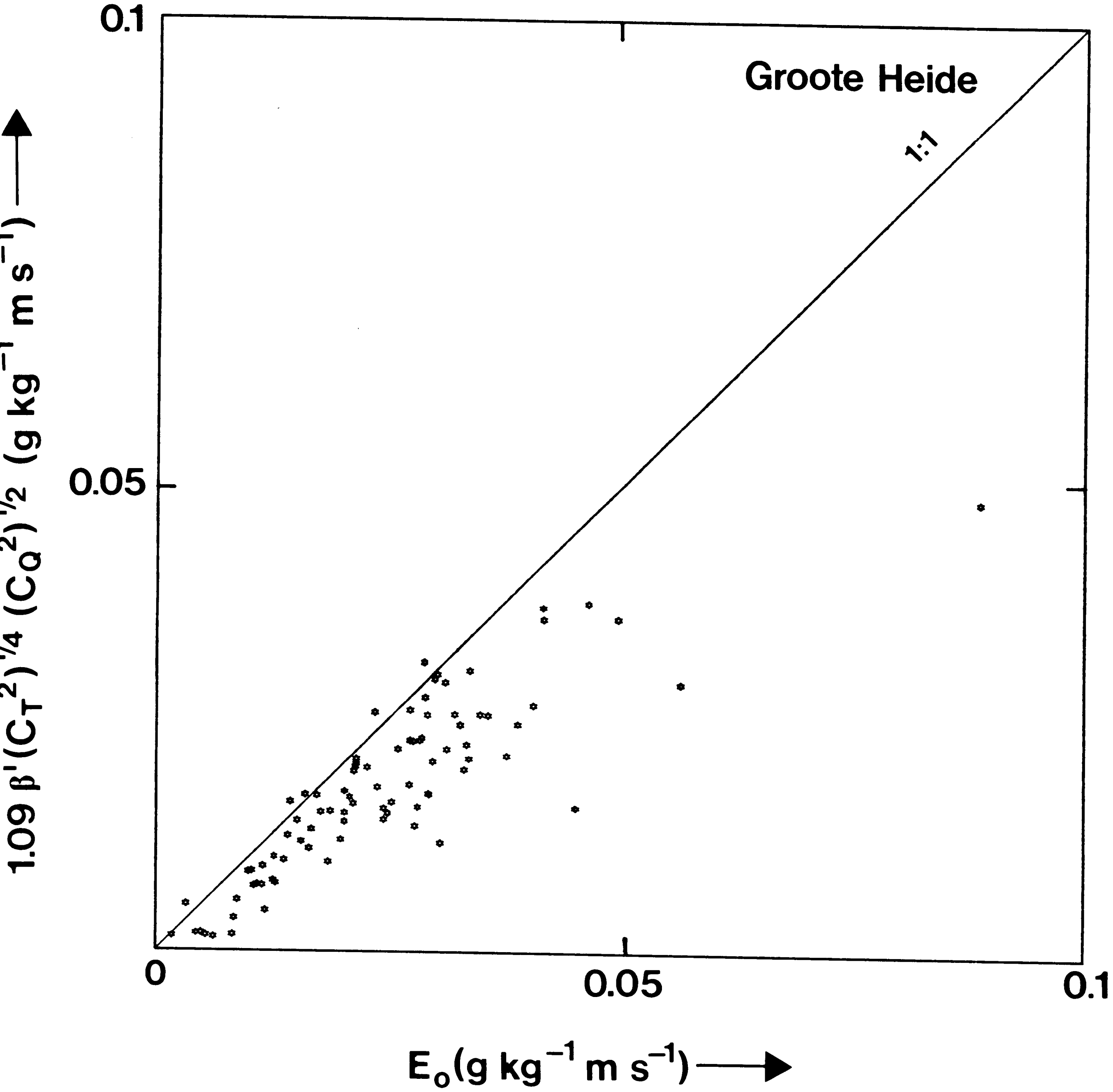

Groote Heide
1:1
0.1
0.05
0
0.05
0.1
$1.09\,\beta'(C_T^2)^{1/4}(C_Q^2)^{1/2}$ (g kg^{-1} m s^{-1})
E_o(g kg^{-1} m s^{-1})

fig.17

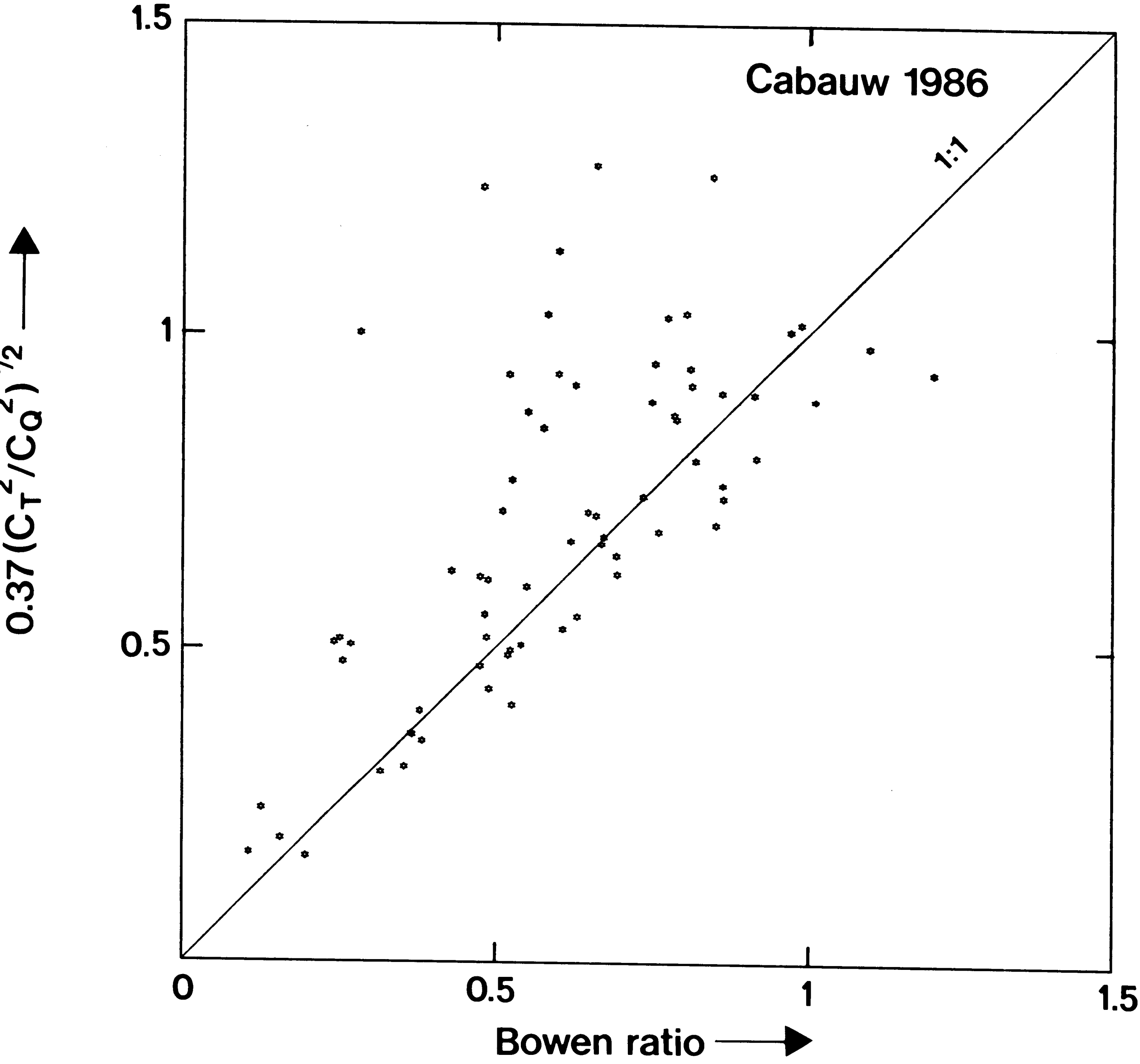


fig.18

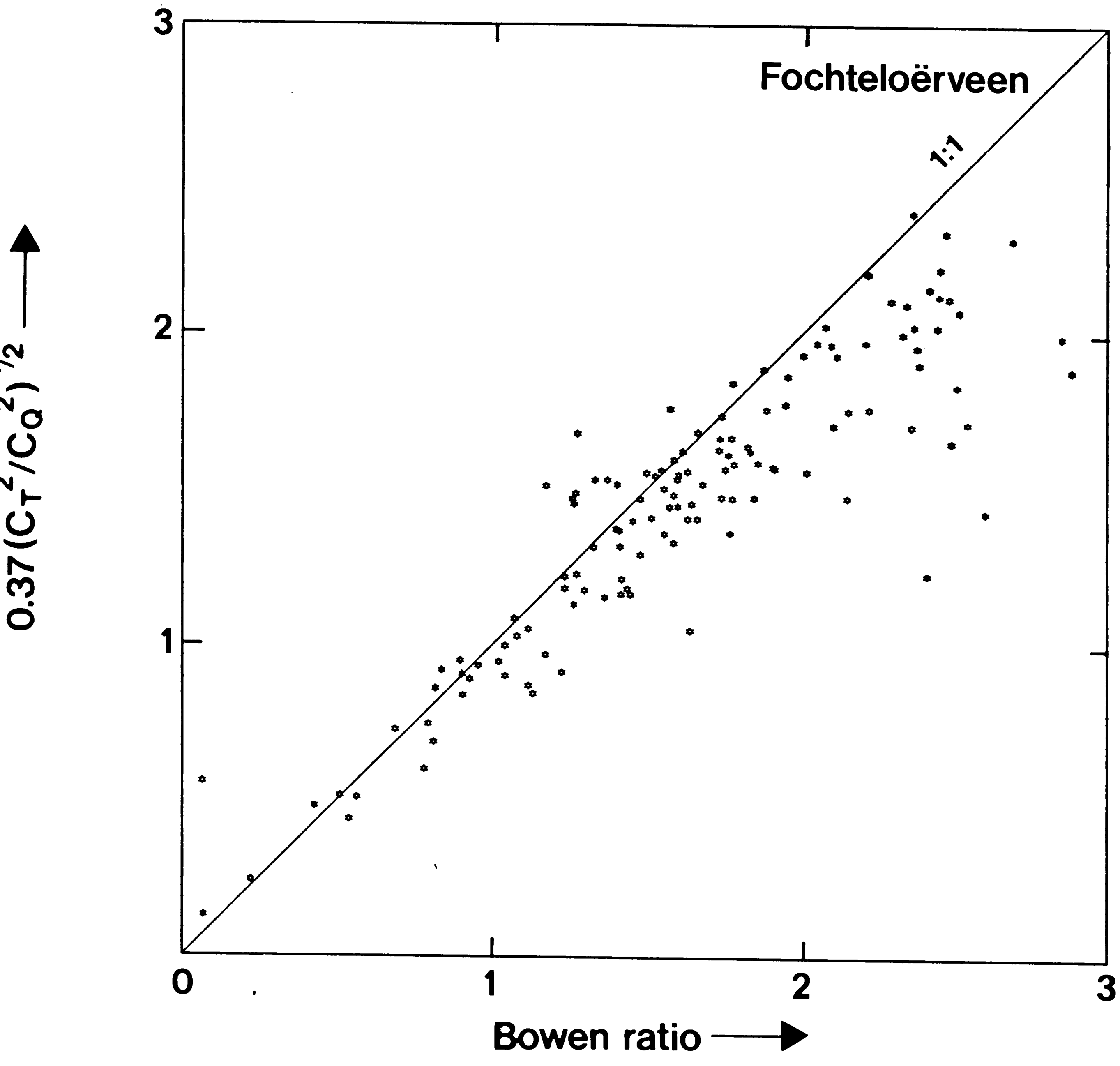


fig.19

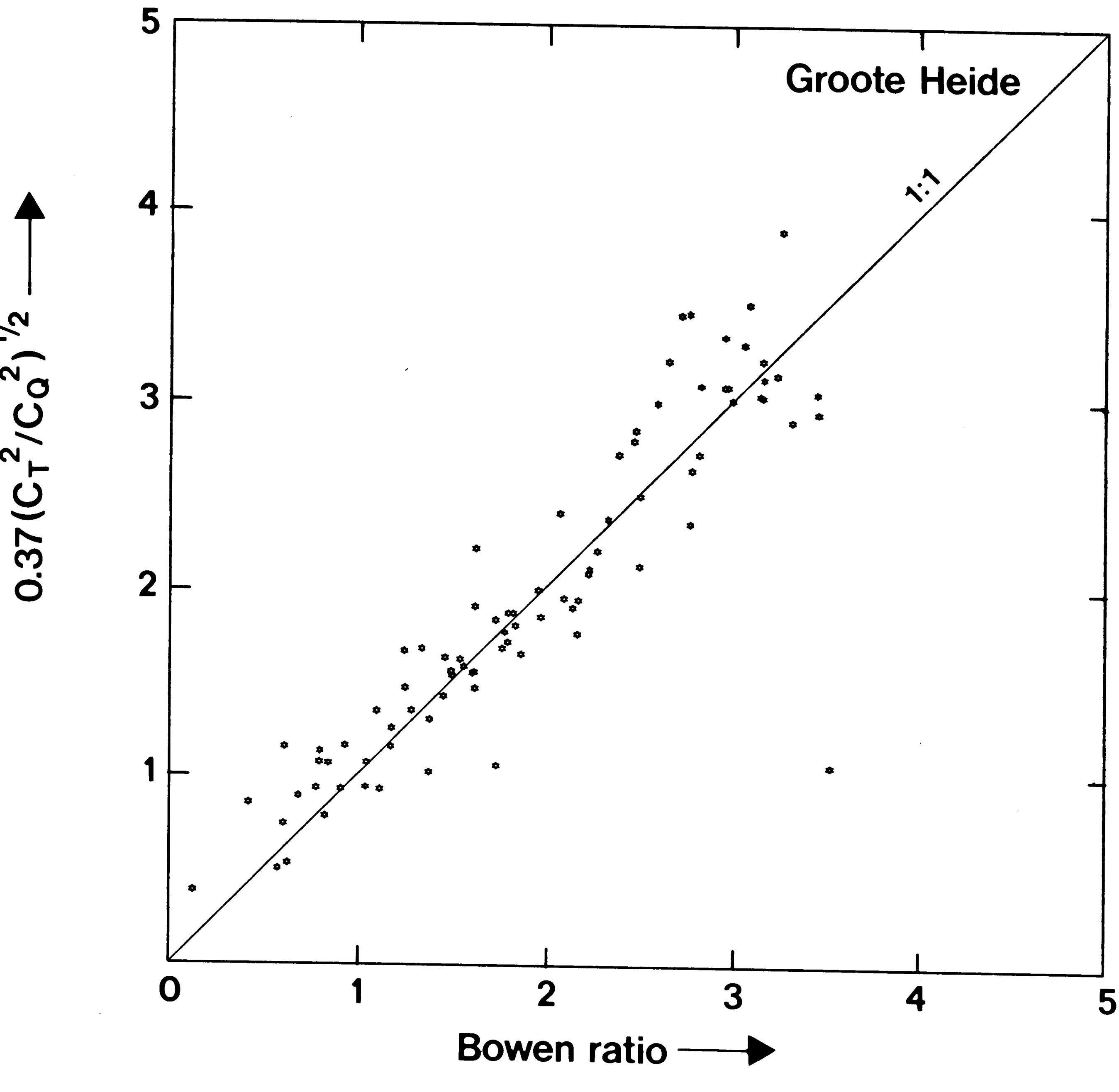
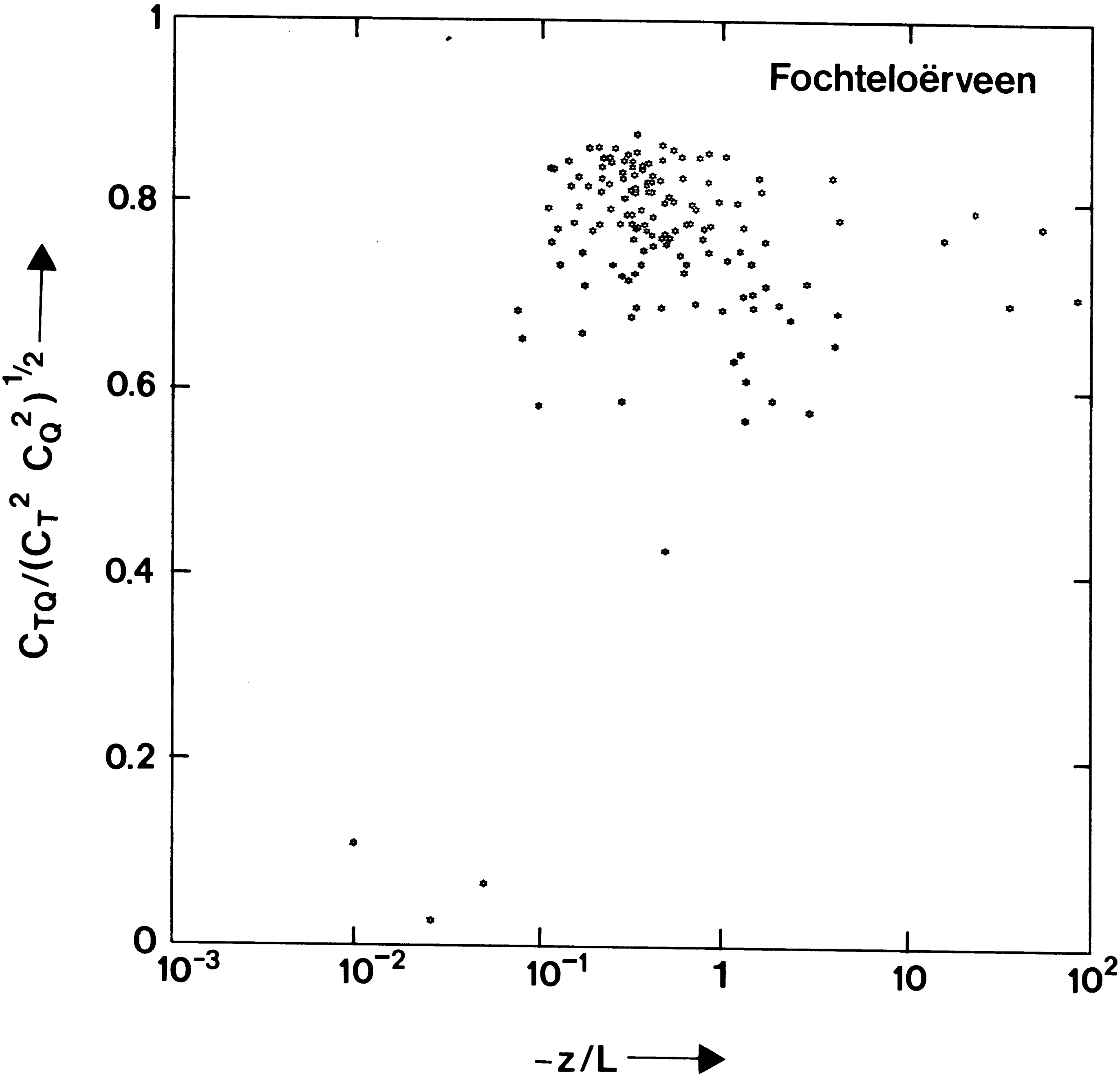


fig.20



Fochteloërveen
1
0.8
0.6
0.4
0.2
0
$C_{TQ}/(C_T^2\ C_Q^2)^{1/2}$
10^{-3}
10^{-2}
10^{-1}
1
10
10^2
-z/L

fig.21

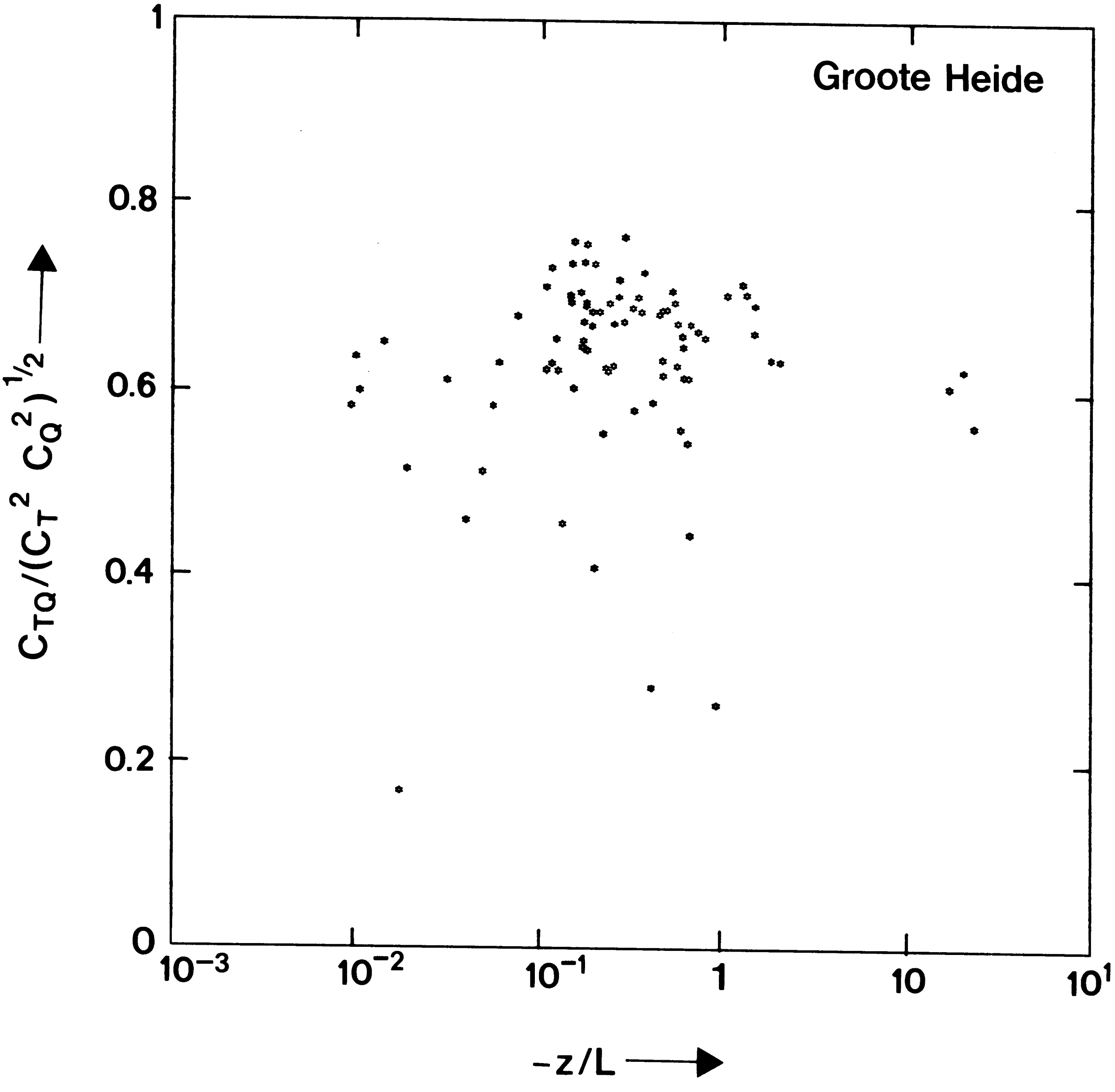


fig.22