A DIAGNOSTIC STUDY OF THE CLOSURE ASSUMPTION IN THE ARAKAWA-SCHUBERT CUMULUS PARAMETERISATION USING GATE DATA

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1. INTRODUCTION

There are several ways of parameterising the effects of unresolvable cloud processes on the evolution of the variables in numerical prediction models. For some purposes it is inadequate to derive equations to explicitly describe the influence of small-scale motions, only their net statistical effects are required. Either a well-established relationship or a hypothesis is then necessary to close the set of additional equations describing the processes in terms of the large-scale variables.

In the Arakawa-Schubert parameterisation scheme for cumulus convection (Arakawa and Schubert, 1974), clouds have explicitly been incorporated in the conceptual model on which the scheme is based. An ensemble of clouds of various heights is assumed to cover a fraction of the large-scale area considered. Each type of cloud has certain properties which it exchanges with its environment and other cloud types through mechanisms like lateral entrainment, and detrainment of cloud air and liquid water at the cloud top. One of the unknowns in the set of equations is the cloud mass flux $M_c(\lambda)$ for the various cloud types.

In order to establish a relationship between $M_c(\lambda)$ and the large-scale fields, a closure has to be applied. It is assumed that a balance exists between the generation of moist convective instability by the large-scale processes and its destruction due to the stabilising effects of clouds as subsidence in the environment of clouds dries and warms the atmosphere. This can be simply expressed by $dA(\lambda)/dt=0$, where $A(\lambda)$ is the cloud work function defined by Arakawa and Schubert (1974). It can be considered as a measure of kinetic energy generation per unit cloud base mass flux for each cloud type. Over the time scale of the large-scale flow, the generation of kinetic energy by the large-scale forcing balances dissipation in the clouds which itself is independent of the large-scale. Essentially, this is an assumption on parameterisability. If the assumption is valid, a quasi-equilibrium exists between the large-scale forcing and the cumulus scale processes; the scheme can then be solved for $M_c(\lambda)$.

Once a parameterisation scheme has been devised, its performance has to be assessed. There are two ways to do this:

(a) The scheme can be coded and implemented into the parameterisation package of a numerical forecasting model. Results of integrations incorporating this scheme at certain time steps can then be compared with observations and/or output from runs with other different parameterisation schemes. Such tests have been done at GFDL (Miyakoda and Sirutis, 1977) and at ECMWF.

(b) The diagnostic test approach can be used. In this some aspects of a parameterisation scheme can be tested separately from the forecasting model, provided there are observations that give the necessary input information and the results of the diagnostic computations can be checked against observations. This provides an easy way of gaining confidence in a scheme without requiring too much computational effort, and it can be done before implementation of the scheme into a full prediction model where feedback mechanisms are likely to obscure the picture.

In this study the second approach is used.

2. DATA

In the diagnostic study that is reported here, the closure assumption in the Arakawa-Schubert scheme has been chosen as the special feature of the parameterisation scheme that ought to be tested before implementing the scheme into a model. GATE data have been used in order to learn more about the behaviour of the cloud work function. The data consists of rawinsonde observations from all the ships in the area (Fig. 1) at 3-hourly intervals for a period of about ten days (Phase III) with a vertical resolution of 5 mb. The evolution of the synoptic situation is shown in Fig. 2 where RADAR rainfall measurements and mean meridional wind indicate the passage of troughs and ridges in the easterly waves. Several typical cloud cluster situations over the Atlantic can be distinguished.

The data was analysed to give profiles of temperature T and specific humidity q at the centre of the triangle in Fig. 1 in order to get values representative for the large-scale. The area covered by the triangle is almost equivalent to the size of a typical grid-box in a numerical model.

3. CALCULATION OF THE CLOUD WORK FUNCTION $A(\lambda)$

The cloud work function was calculated from the thermodynamic profiles for each observation time. Each time 63 different cloud types classified by their entrainment rate λ were considered (Fig. 3). Cloud height is a function of entrainment and can therefore be chosen as the independent variable as well. Fig. 4 shows $A(p_D)$ for a few selected observation times. $A(\lambda)$ and $A(p_D)$ are well behaved functions. The values that were obtained for the period of ten days were embedded in an envelope of maximum and minimum values for each individual cloud type, even though the synoptic situation varied considerably.

Choosing a particular cloud type, a time series gives a first impression of the time changes of the cloud work function (Fig. 5 shows the local time derivatives). From this and further tests it should be possible to judge whether $dA(\lambda)/dt$ is negligible or whether significant changes occur. Extremely low values for all types of clouds are associated with clear regions in the ridges of easterly waves (Fig. 5). In this situation mass fluxes for almost all λ are close to zero and the closure cannot be applied. Another time when marked changes occur is after the passage of the maximum of rainfall from a cloud cluster. Stabilisation effects then rapidly reduce the instability (see Fig. 5, Julian day 248).

Are those changes significant? In order to verify the closure assumption, Arakawa and Schubert proposed to compare the time derivative of A with the large-scale forcing F_c at the same observation time. For a data set from the Marshall Islands (Arakawa and Schubert, 1974), several climatological data sets (Lord and Arakawa, 1980) and semi-prognostic tests (Lord, 1982) it was established that $F_c \gg dA(\lambda)/dt$, which supports the closure assumption. Results from the individual observations during GATE (Konig, 1982) agree with this notion (Fig. 6).

4. SENSITIVITY TESTS AND ERROR ESTIMATES

What are the factors that influence the behaviour of the cloud work function? Sensitivity tests can show whether it is a coincidence that $A(\lambda)$ varies only in a well-defined range or whether a more systematic influence is induced by changes of the thermodynamic structure in the boundary layer or cloud layer.

The cloud work function might also be sensitive to errors in the T and q fields from which it is calculated. This would make it difficult to judge a then meaningless quantity like $dA(\lambda)/dt$.

If either the temperature or moisture profile is changed artificially and the other one is kept the same, the resulting values of A are rather different. In the simple case of warming or cooling the cloud layer as a whole by a certain amount (a percentage of T in degrees K at each level) a strong sensitivity of A towards temperature changes becomes evident (Figs. 7 and 8). There is less sensitivity towards changes in the moisture profiles. A similarly strong sensitivity is shown in Fig. 9, where the surface conditions have been manipulated. As the cloud base is estimated from the surface values as the lifting condensation level, it becomes evident that T and q near the surface ought to be carefully evaluated. This also sheds some doubt on fixing the cloud base level at a certain model level in a low resolution model.

From these diagrams it can also be easily judged what influence the presence of errors in the data would have. If an estimate of observation errors or errors in the analysis of a forecast model is given, the likely behaviour of the cloud work function can be extracted and it can be judged to what degree of accuracy it can be calculated. If the functions on which the parameterisation is based cannot be calculated properly, parameterisability might even be lost. Error bars in Fig. 5 indicate the accuracy that could be achieved in the calculation of $A(\lambda)$ based on estimates of the errors in the thermodynamic profiles of GATE.

If such preliminary diagnostic checks support statements like the closure assumption $dA(\lambda)/dt=0$ by indicating that for certain purposes the observed

$dA(\lambda)/dt$ is sufficiently small and only depends on the cloud type for various synoptic conditions, a generalisation can be made which enables values of $A(\lambda)$ to be taken from a table of normal values.

The drastic changes obtained in the sensitivity tests did not actually occur during the time sequence that was studied. In order to compare the warming or cooling and drying or moistening of the cloud layer, mean differences between observation times over the whole cloud layer were calculated. These tendencies and their corresponding impact on the cloud work function of a special cloud type for all individual observation times are plotted in Fig. 10. This way of comparing is strongly simplified, because it smears out changes over all layers in the vertical. The values shown here are nevertheless in line with statistical studies of cloud cluster situations in the tropics (Ruprecht and Gray, 1976). They report that differences in the temperature profiles are usually quite small over most of the cloud layer. The maximum of differences between clear regions and cloud clusters is less than 1°C and less than the inter-variability in either a cloud cluster or clear region.

During GATE temperature changes and moisture changes seem to occur in such a way that increases of temperature and moisture happen at the same time so that the relative humidity is kept constant. The solid line in Fig. 10 indicates combined changes derived from the sensitivity tests that would be necessary to keep $A(\lambda)$ constant in time. The weak positive correlation in the scatter diagram supports the hypothesis by Arakawa and Schubert (1974) that assumes a coupling between the temperature and moisture changes so that $A(\lambda)$ remains constant and does not climb to any of the large values that appeared in the sensitivity studies and time changes occur only in a limited range.

5. CONCLUSIONS

This cheap and easy diagnostic test of the behaviour of the cloud work function is restricted to a limited data set from the tropics. The results from individual radiosonde observations presented here are in line with those obtained from climatological data (Lord, 1980). Comparison of the observed time changes of $A(\lambda)$ with the large-scale forcing F_C which was suggested as a first verification of the closure assumption shows that the closure is valid for this special case as well. Time changes of $A(\lambda)$ can be trusted to be small enough for a successful application of the scheme as a coupling exists between the changes of the temperature and moisture fields that keeps the relative humidity constant.

In the environment of a large-scale forecasting model, the scheme would also be applied to convection in mid-latitudes. Similar diagnostic studies might be undertaken for a variety of data sets in order to establish the applicability of the scheme in a wider range of situations.

References

Arakawa, A. and W.H. Schubert, 1974: Interaction of a cumulus cloud ensemble with the large-scale environment. Part I J.Atmos.Sci., 31, 674-701.

König, W., 1982: Anwendung der Parametrisierung der Cumuluskonvektion von Arakawa und Schubert zur Bestimmung der Wolkenmassenflüsse. Diplomarbeit, available from University of Cologne.

Lord, S.J. and A. Arakawa, 1980: Interaction of a cumulus cloud ensemble with the large-scale environment. Part III: Semi-prognostic test of the Arakawa-Scubert cumulus parameterization. J.Atmos.Sci., 39, 88-103.

Miyakoda, K. and J. Sirutis, 1977: Comparative integration of global models with various parameterized processes of subgrid-scale vertical transports: Description of the parameterizations. Contr.to Atmos.Physics, 50, 445-487.

Ruprecht, E., 1982: An investigation of tropical cloud clusters over the GATE area. Part I: The environmental fields of the cloud ensembles within the cloud clusters. Contr. to Atmos.Physics, 55, 51-78.

Ruprecht, E. and W.M. Gray, 1976: Analysis of satellite-observed tropical cloud clusters II Thermal, moisture and precipitation fields. Tellus, 28, 414-425.

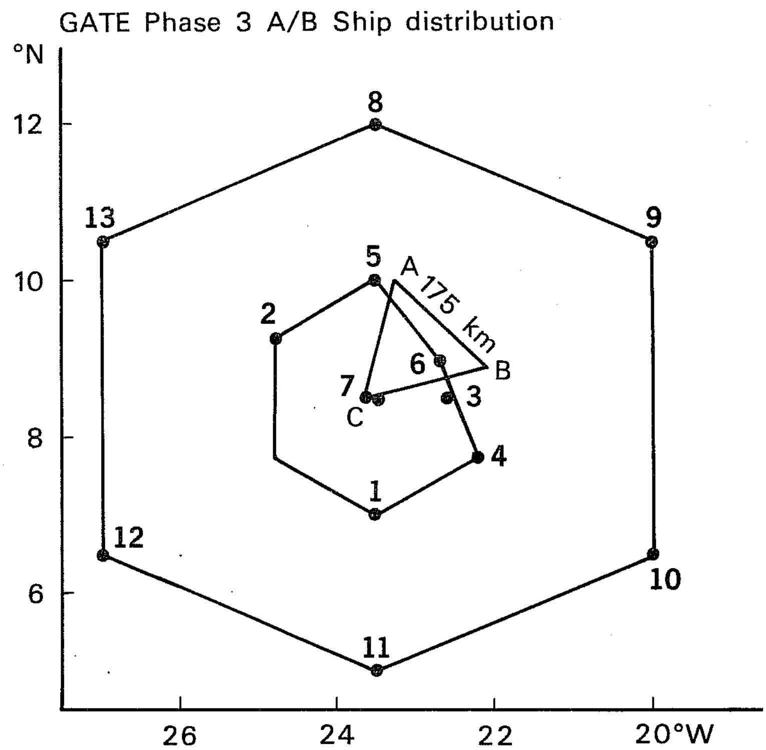

Fig. 1 Distribution of the A/B-scale ships during Phase III of GATE and position of the triangle (ABC) used for the analysis (from Ruprecht, 1982).

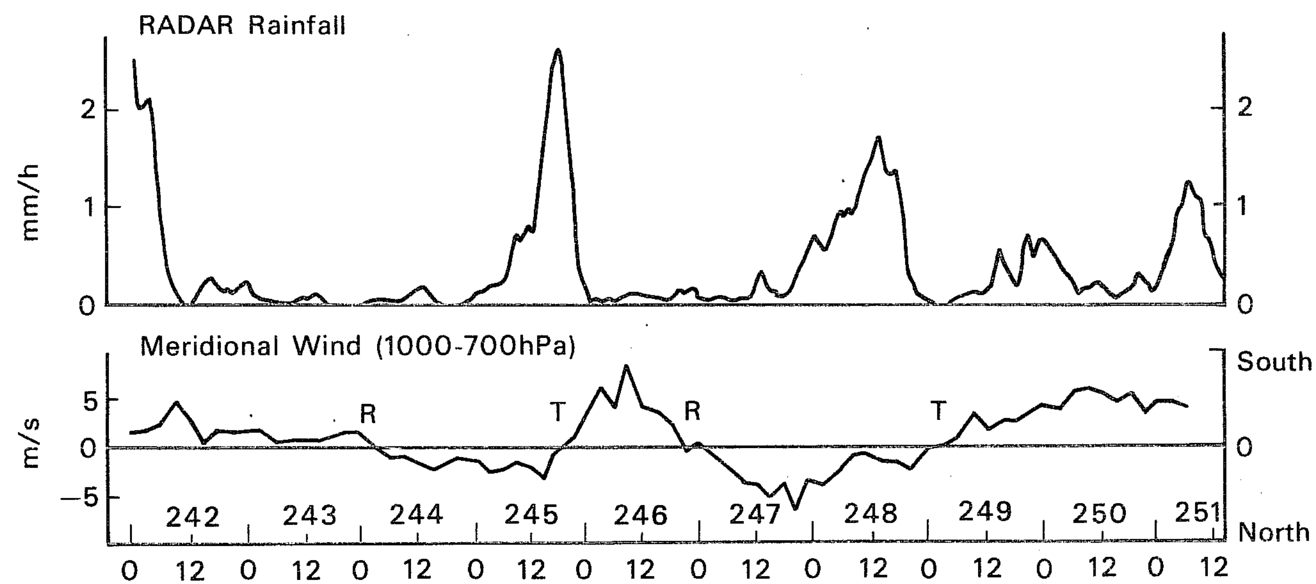

Fig. 2 Time series of mean meridional winds and radar rainfall at 900 mb. R(T) = ridge (trough) of a wave disturbance (from Ruprecht, 1982).

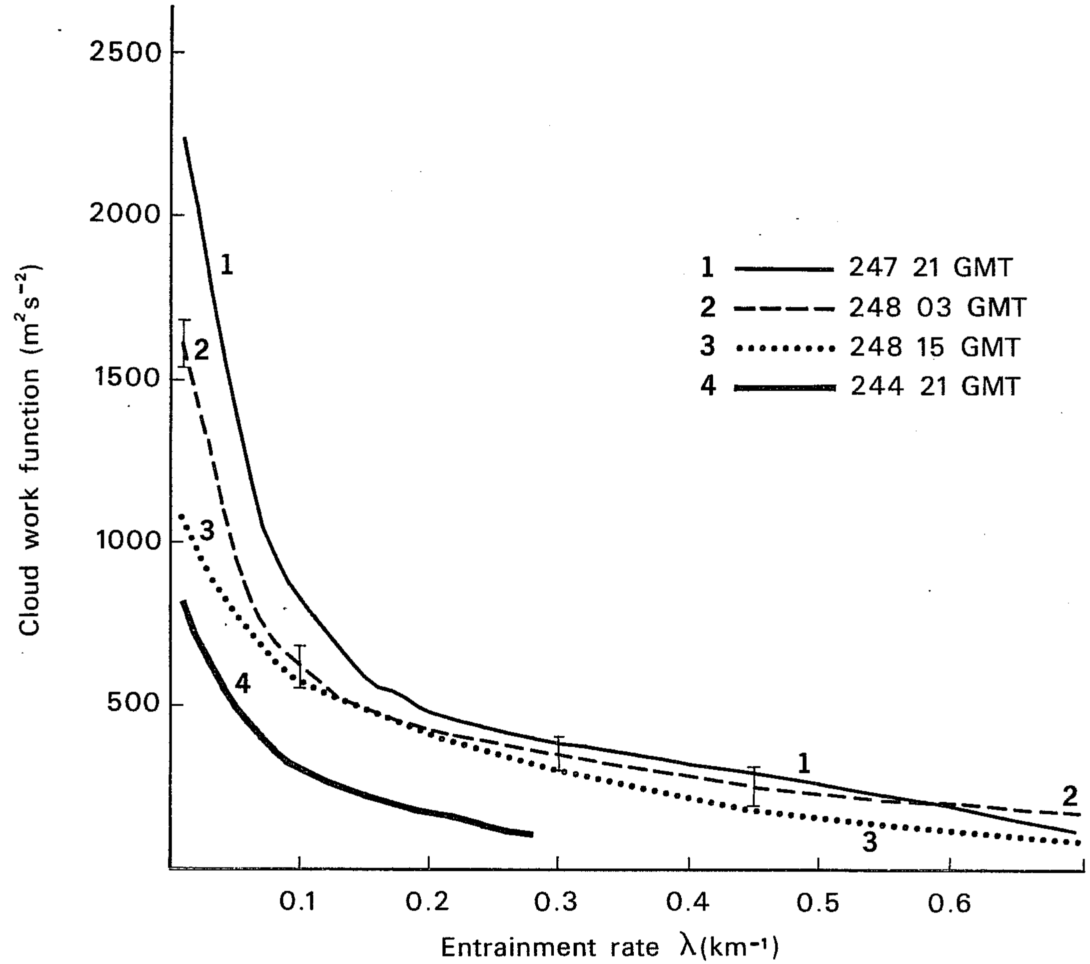

Fig. 3 Cloud work function as a function of the entrainment rate λ for four observation times.

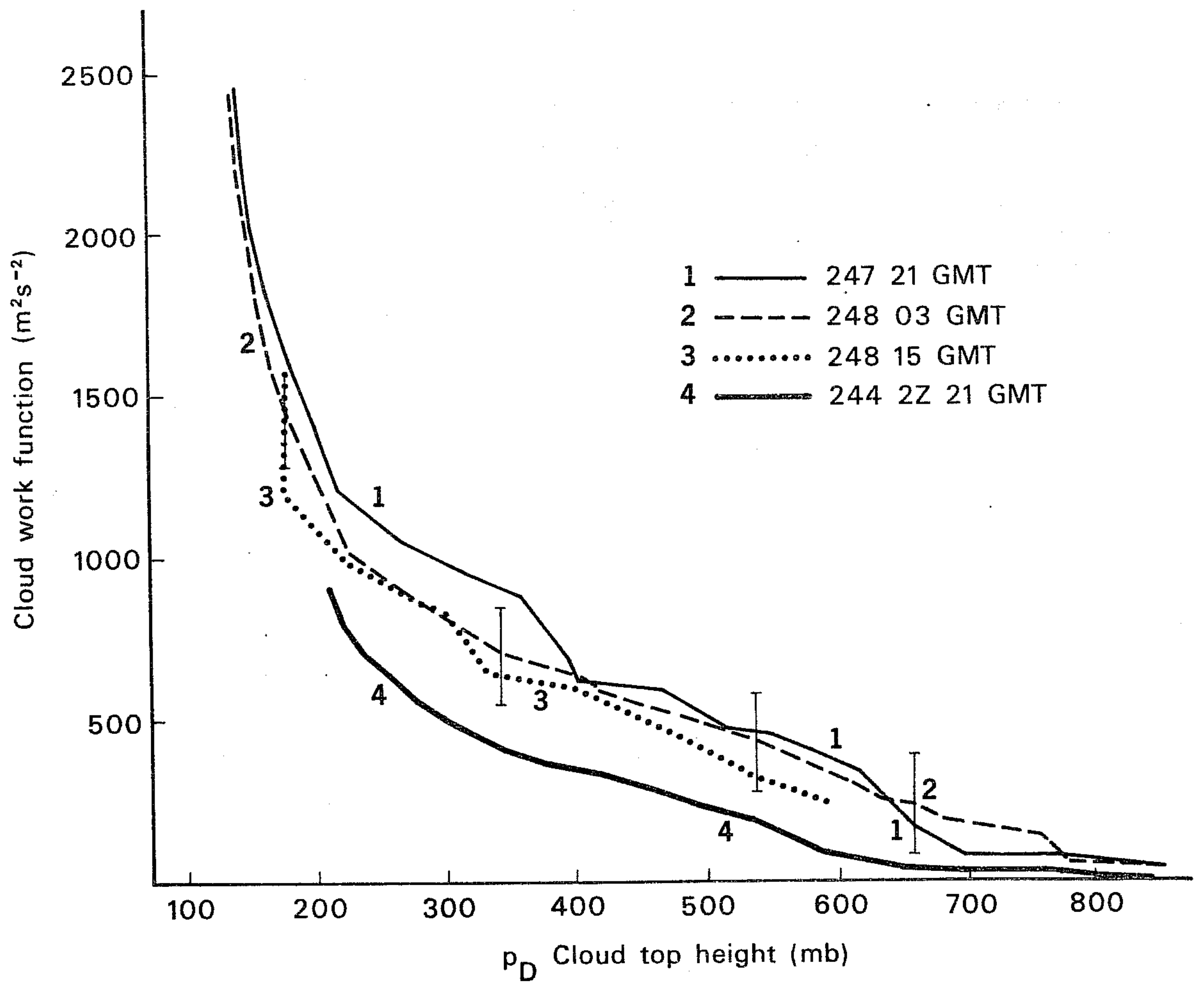

Fig. 4 Cloud work function as a function of cloud top level pressure p_D for four observation times.

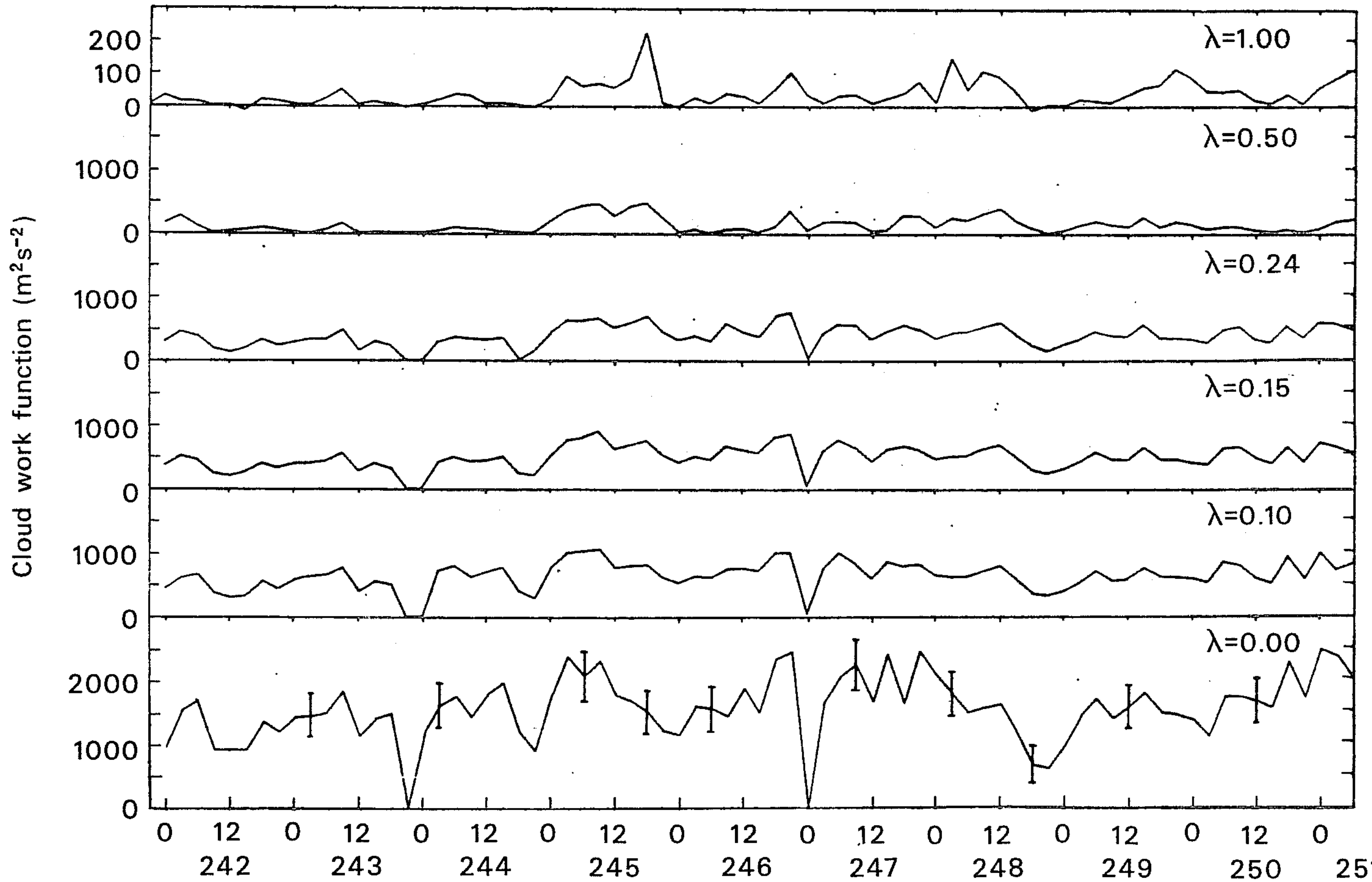

Fig. 5 Time series of cloud work functions for several entrainment rates (error bars are explained in the text).

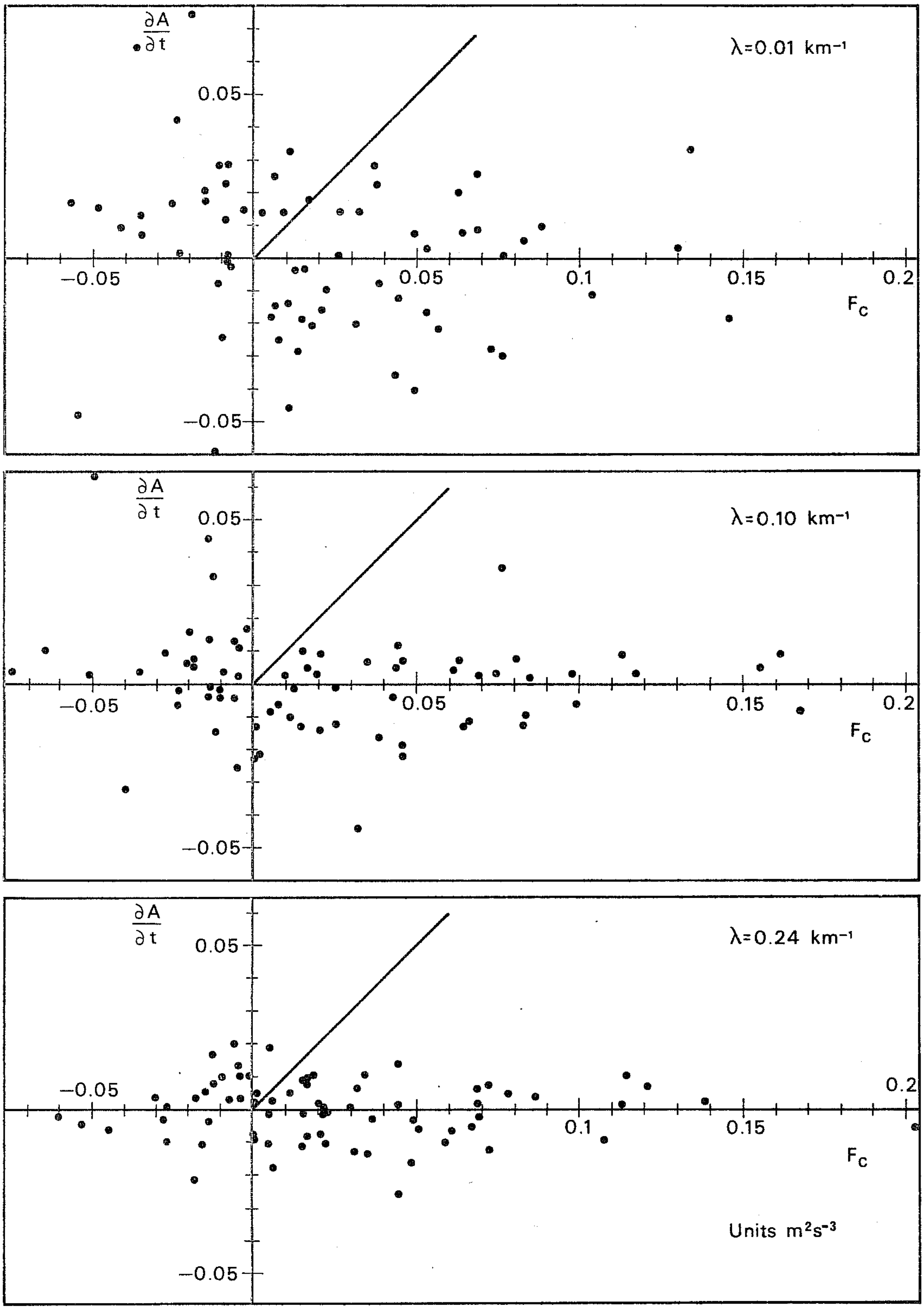

Fig. 6 Large-scale forcing $F_c(\lambda)$ and $\partial A(\lambda)/\partial t$ observed over a 3-hour interval (from König, 1982).

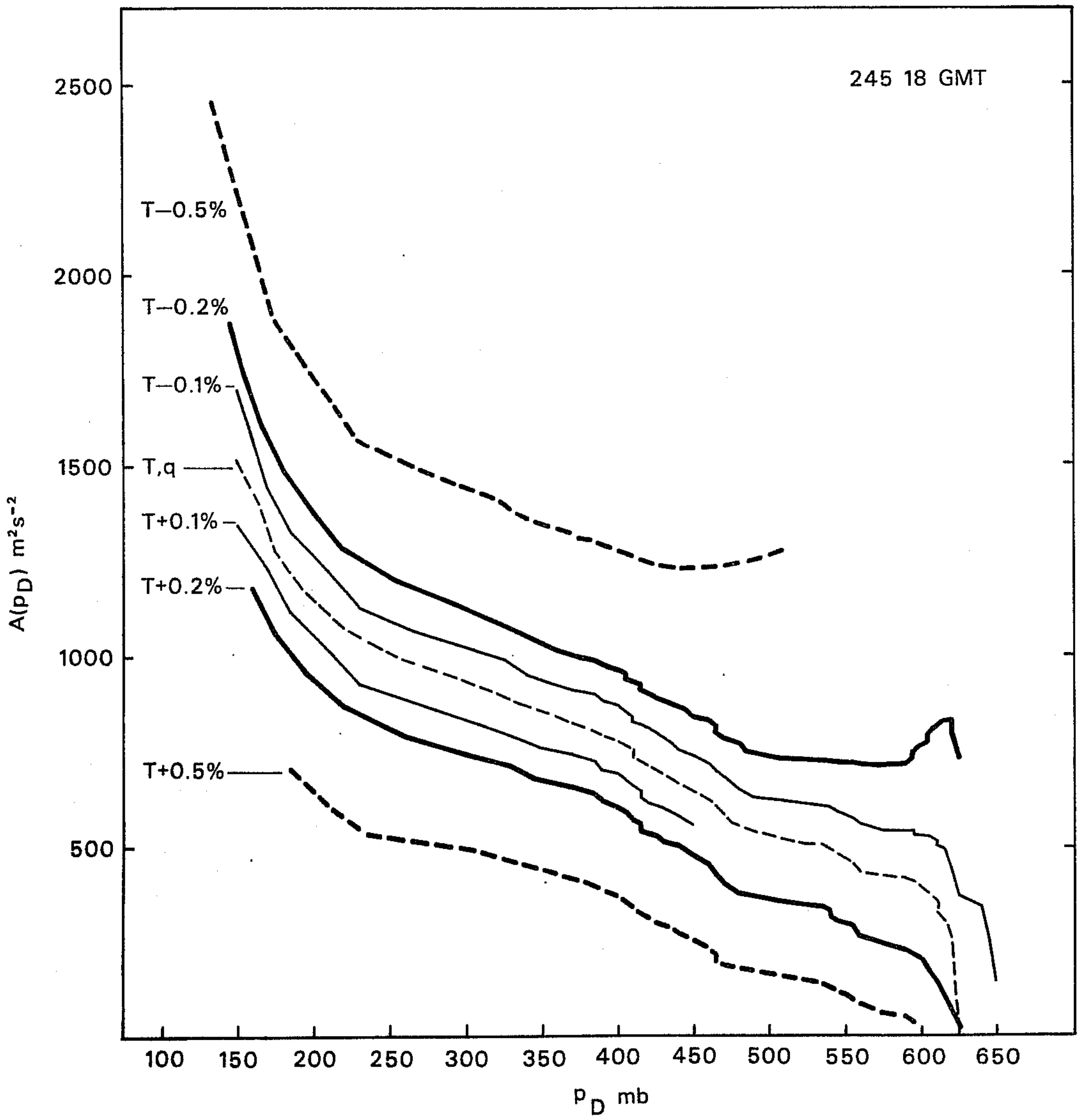

Fig. 7 Cloud work functions recalculated after modification of the temperature profile in the cloud layer.

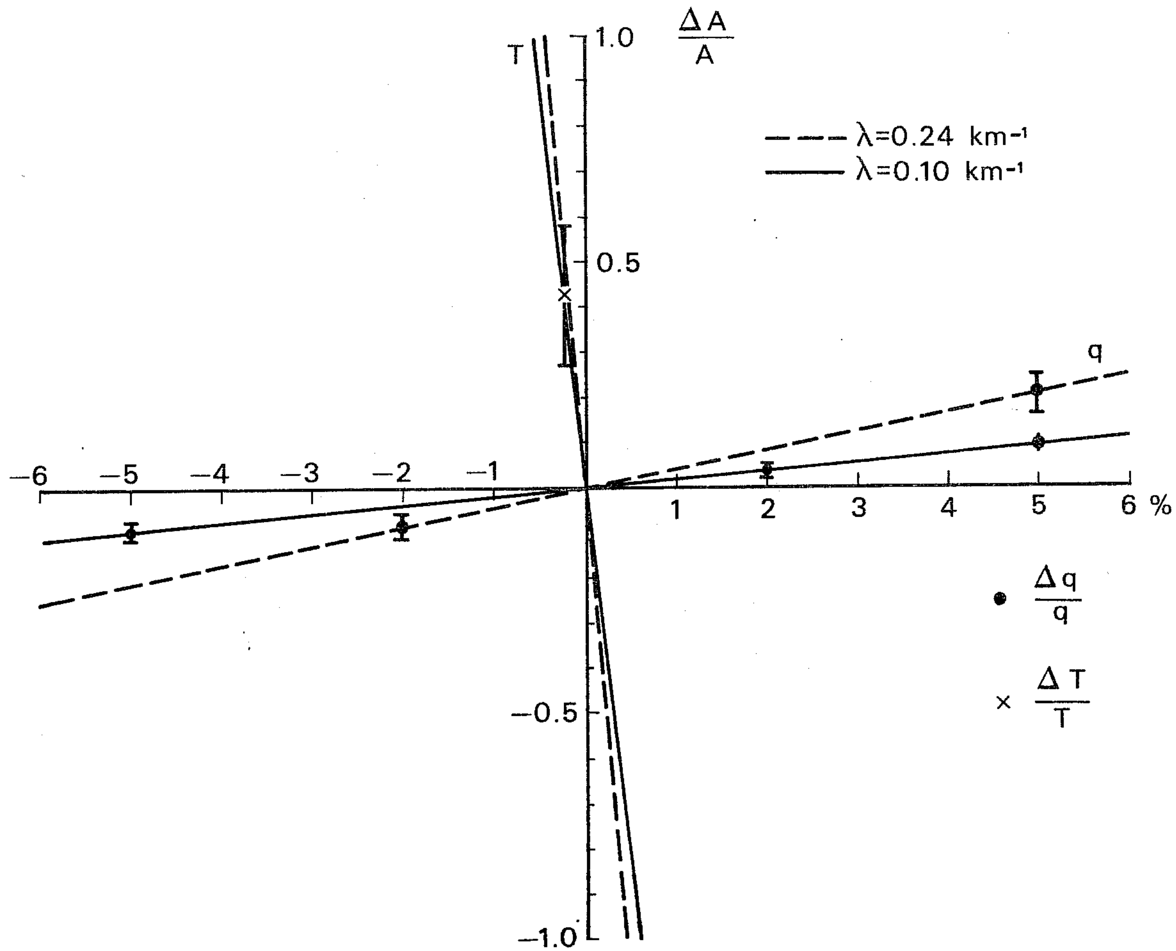

Fig. 8 Mean relative changes of the cloud work function after modifications of temperature and moisture profiles, respectively, in the cloud layer. Vertical bars indicate the variability of the changes of $A(\lambda)$.

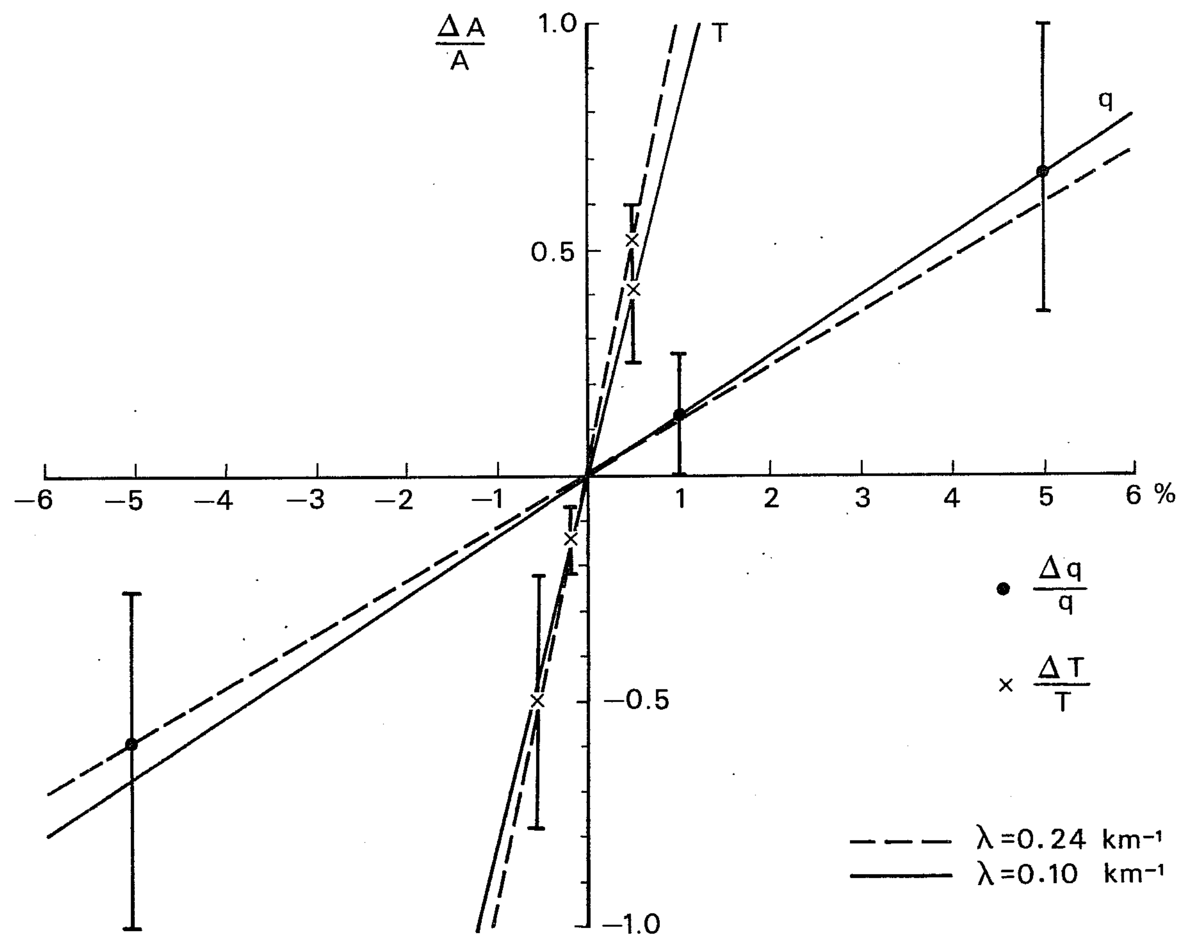

Fig. 9 Mean relative changes of the cloud work function after modification of temperature and moisture, respectively, in the surface layer. Vertical bars indicate the variability of the changes of A(λ).

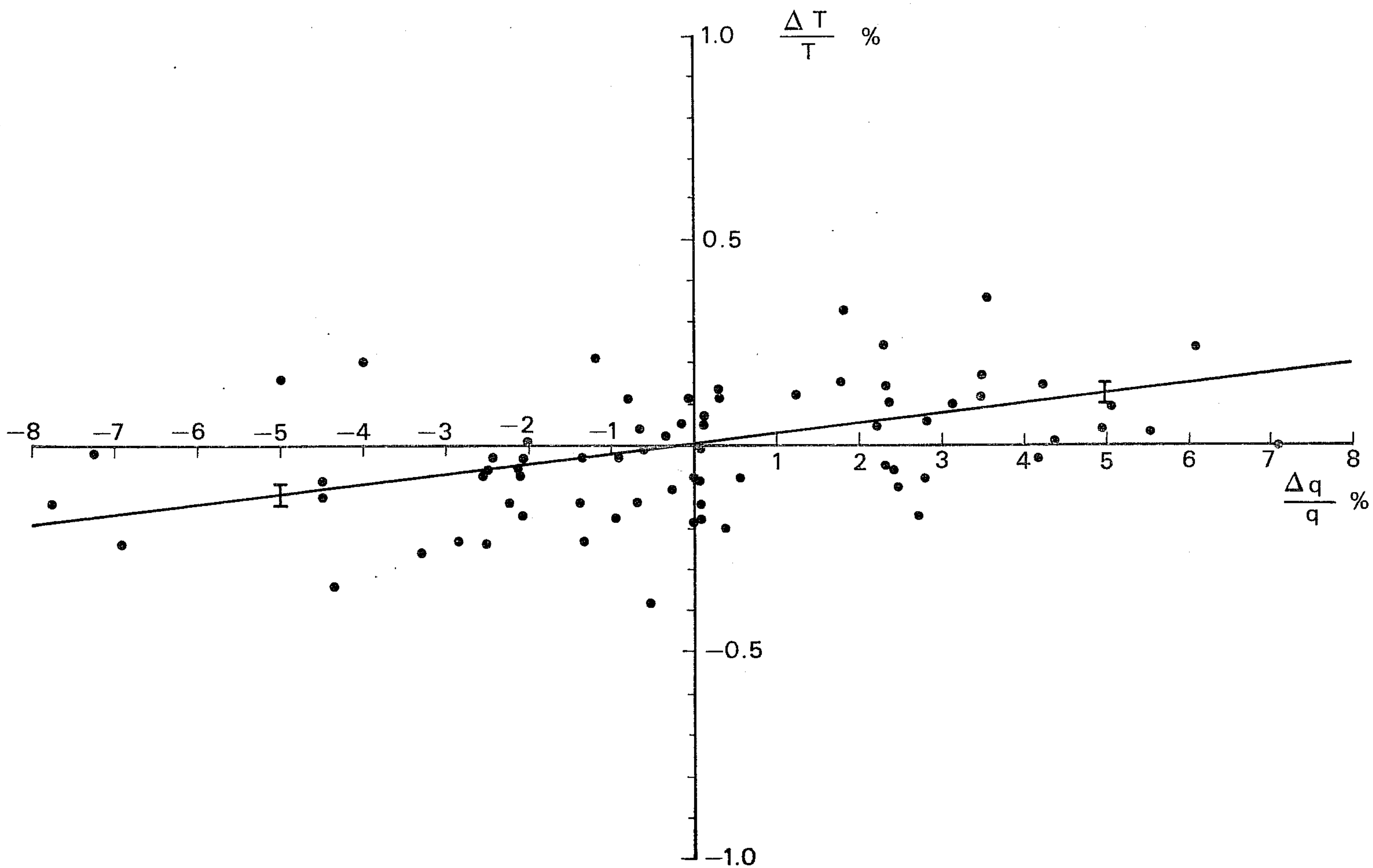

Fig. 10 The solid line depicts corresponding relative changes of temperature and moisture in the cloud layer for which A(λ) remains constant. The dots represent observed mean changes for the cloud layer for each 3-hour interval.