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FACTORS RELATING SURFACE VISIBILITY TO THE TOTAL OPTICAL DEPTH --ETC(U)

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The total aerosol optical depth, μ, is the sum of three components: the stratospheric, μ_s, the upper tropospheric, μ_t, and the marine boundary layer, μ_m. The extinction coefficient at the sea surface, α_o, can be calculated from

$$\alpha_o = f(\mu - \mu_s - \mu_t)/h$$

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) where h is the height of the boundary layer and f is a factor that accounts for the height dependence of aerosol extinction in the boundary layer. A boundary layer aerosol model is presented that explains the height dependence of α. Both f and h depend on the general synoptic weather pattern. This is demonstrated using a set of aircraft aerosol profiles measured over the North Pacific Ocean in the vicinity of Monterey, California.

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1.0 Introduction

This report describes some preliminary results of an effort to relate total aerosol optical depth at visible wavelengths to the visibility in the marine boundary layer (MBL). We present an atmospheric model which explains the observed height dependence of the aerosol extinction, examine aircraft and ship data from the MAGAT experiment, illustrate the influence of synoptic scale weather patterns on aerosol structure and present a simple model to relate α_o to total vertical depth. The ultimate goal of the project is to allow an estimation of IR ranges (due primarily to atmospheric water vapor density, Q) from satellite remote sensing data. A feasibility study on the concept was performed on two NPS data sets (JASIN and CEWCOM 78) using the relationship

$$Q/Q_s = a + b \exp\left[-1.25\, \alpha_o^{1/2}\, (7/U)^{3/2}\right] \qquad (0)$$

where Q_s is the saturation water vapor density at 13°C, α_o the surface extinction coefficient in km^{-1} and U is the wind speed in m/s. A least squares fit for 834 points yielded a = 1.02, b = -.27 and a correlation of 0.56.

2.0 Background

2.1 Optical Depth

Let the atmospheric transmission coefficient, T, due solely to aerosols be represented by

$$T = \exp(-\mu) \tag{1}$$

where

$$\mu = \int_0^\infty \alpha(Z)dZ \tag{2}$$

and α is the aerosol extinction coefficient, Z the vertical coordinate, and

$$\alpha = \int_0^\infty \pi r^2 \, dN/dr \, Q(\lambda,n)dr \tag{3}$$

with r the aerosol particle radius, dN/dr the aerosol number density spectrum and $Q(\lambda,n)$ the *Mie scattering* efficiency. If dN/dr is known from the surface to the top of the atmosphere, then μ can be calculated. Alternately, μ can be measured from satellites. The question is how is μ related to the surface visibility (extinction).

Consider an idealization of the atmospheric extinction coefficient vertical profile (Fig. 1)

$$\mu = \langle\alpha\rangle_m h + \mu_t + \mu_s \tag{4a}$$

$$\mu_t = \alpha_+ L \tag{4b}$$

where $\langle\alpha\rangle_m$ is the average extinction in a well mixed boundary layer of depth, h, α_+ is the extinction in the clearer air just above the boundary layer, L is an effective potential scale length for the decay of $\alpha(Z)$ for $Z > h$, μ_t is the optical depth of the troposphere above the mixed layer and μ_s is the optical depth of the stratosphere. This idealization is a result

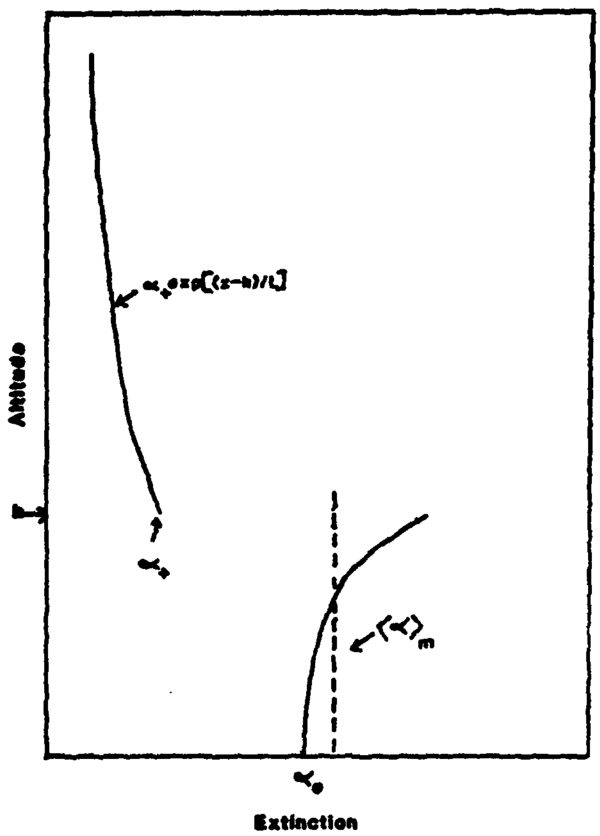

Figure 1. Schematic representation of the height dependence of aerosol extinction coefficient, α, within and above the marine boundary layer of depth h.

of the typical well-mixed nature of the marine boundary layer (Section 2.2). The surface extinction, α_o, is related to $\langle\alpha\rangle_m$ by the factor f

$$\alpha_o = f\langle\alpha\rangle_m \quad (5)$$

which is less than one due to the vertical structure of temperature and water vapor in the marine boundary layer.

If all of the relevant variables can be estimated, then we can calculate α_o using

$$\alpha_o = f(\mu - \mu_t - \mu_s)/h \quad (6)$$

For example, μ_s and μ_t could be obtained from the LOWTRAN Tropospheric Model, h from synoptic climatology and f established by model calculation and empirical measurement. Typical values of L are 2 to 5 km, α_+ might be 10^{-3} to 10^{-1} km^{-1} in the visible.

2.2 NPS Aerosol Boundary Layer Model Structure

The marine boundary layer meteorological structure is illustrated in Fig. 2. The aerosol structure in the well-mixed context is depicted in Fig. 3. The total aerosol volume spectral density, $V(r_o)$, is the sum of continental, V_c, and sea-salt, V_s, components, where $(V(r_o) \equiv dV/dr_o)$

$$V = V_s + V_c \qquad Z < h \quad (7a)$$

$$V = V_c \qquad Z > h \quad (7b)$$

at some reference humidity (we have assumed no clouds). The volume density is related to the number density by

$$V(r) = 4/3\ \pi r^3\ dN/dr \quad (8)$$

and the particle radius at saturation S is given by

$$r = r_o\ g(S) \quad (9)$$

The specification of V_s and V_c is based on empirical parameterizations. For example, V_c can be represented as a Junge distribution and V_s as a modified gamma function, F (Goroch et al, 1982)

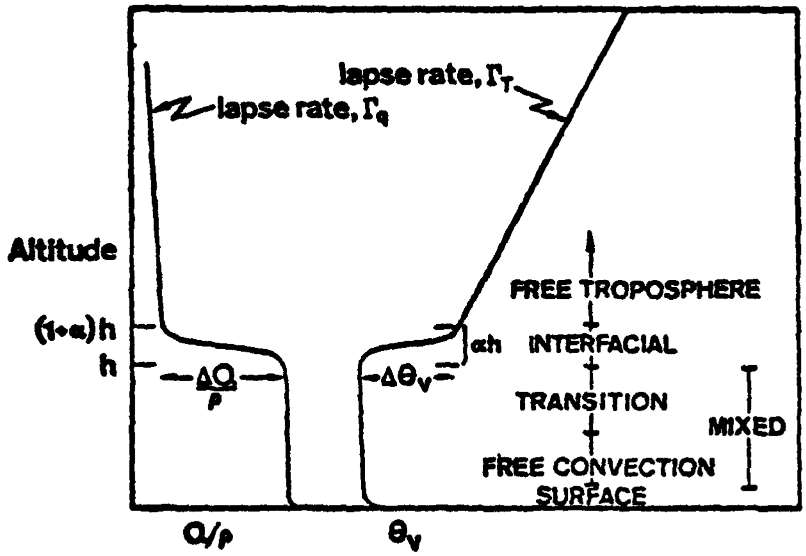

Figure 2. Marine boundary layer extinction for virtual potential temperature, θ_v, and water vapor density, Q, in the mixed-layer model structure.

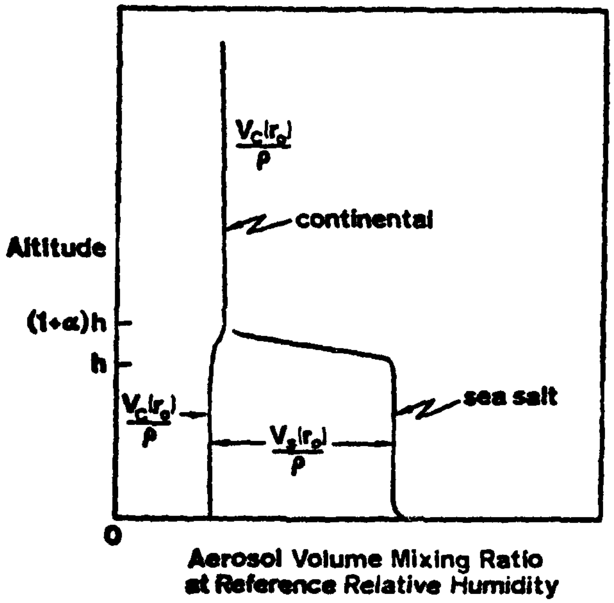

Figure 3. Similar to Fig. 2 but for the aerosol density.

$$V_c = A\, r_o^{-1} \qquad (10a)$$

$$V_s = V_o F(r_o, \beta, \gamma) \qquad (10b)$$

where V_o, β, and γ depend on wind speed.

Alternatively, one can use log-normal distributions to represent both components. In a recent study of atmospheric electrical conductivity this method (which included a log-normal cloud-droplet component, V_d) was found to be reasonable. The NPS log-normal aerosol number density model is as follows:

$$N(r) = N(r\sqrt{2\pi}\sigma_\ell)\, \exp[-(\ell n(r/r_m))^2/(2\sigma_\ell^2)] \qquad (11a)$$

$$\sigma_\ell = \ell n(\sigma) \qquad (11b)$$

where $r_{mo} = r_m/g(S)$ is the dry ($S = 0$) radius

$$g(S) = 0.8\ (1-\ell n(1-S))\ , \qquad S > 0.4 \qquad (12a)$$

$$g(S) = 1 \qquad (12b)$$

The model parameters are given in Table 1.

Table 1. Log-normal aerosol parameters for the NPS model. Wind speed is u(m/s) and cloud liquid water density is W(gm/kg). (Note that W depends on height within cloud.)

	r_{mo}, μm	σ	N
Cont.	.027	2.2	$10^2 - 10^5$
Sea Salt	.088 + .026 u	2.2	$0.0012\ u^{3.5}/r_{mo}^3$
Cloud	4 + 10 W	1.4	50 - 200

A typical Junge value ($A = 1$ at $S = .8$) corresponds to $N_c = 650$ particles per cm^3. A typical wind speed of 7 m/sec gives 55 sea-salt particles per cm^3 with a number density mode radius of 0.27 μm.

2.3 Relaxation of the Well-Mixed Assumption

Considerable evidence exists to suggest that the well-mixed assumption is an approximation. It is believed that this is due to the balance of surface flux, entrainment and the boundary layer mixing time. For the quantity, X, let F_o be the surface flux and F_h be the flux at the top of the boundary layer (fluxes defined positive upward). X can be θ_e, q or aerosols. Define three velocities, W_e, W_g and W_o.

$$W_e = -F_h/\Delta h \tag{13a}$$

$$W_o = F_o/\Delta_o \tag{13b}$$

$$W_g = \max(W_o, W_e) \tag{13c}$$

The Δ quantities are the jumps in X at the two interfaces

$$\Delta_o = X_o - X_{mo} \tag{14a}$$

$$\Delta_h = X_f - X_{mh} \tag{14b}$$

where X_o is the sea-surface value, X_{mo} the value of X at Z = 0, X_{mh} the value of X within the mixed layer at Z = h and X_f the free atmosphere value of X at Z = h (Fig. 4). The value of X within the mixed layer at height Z is given by

$$X(Z) = X_m + \xi(W_e/2W_g)^{K+1}\,\Delta_h + (1-\xi)(W_o/2W_g)^{K+1}\,\Delta_o \tag{15}$$

where $\xi = Z/h$, X_m is the average "well-mixed" value and K is an integer (K = 3 is presently used). Note that $W_o = C_X^{1/2}\,C_u^{1/2}\,u$ where C is the drag coefficient. A typical value for W_e is 3×10^{-3} while W_o is 9×10^{-3} at u = 7 m/s.

The application of Eqn (15) to θ_e and q leads to a different (more gradual) height dependence of S in the mixed layer. The application to aerosols leads to a slight decrease in the total number density with increasing height. Both of these factors result in a more gradual increase of extinction with increasing height in the mixed layer. Therefore, f will be closer to 1.0.

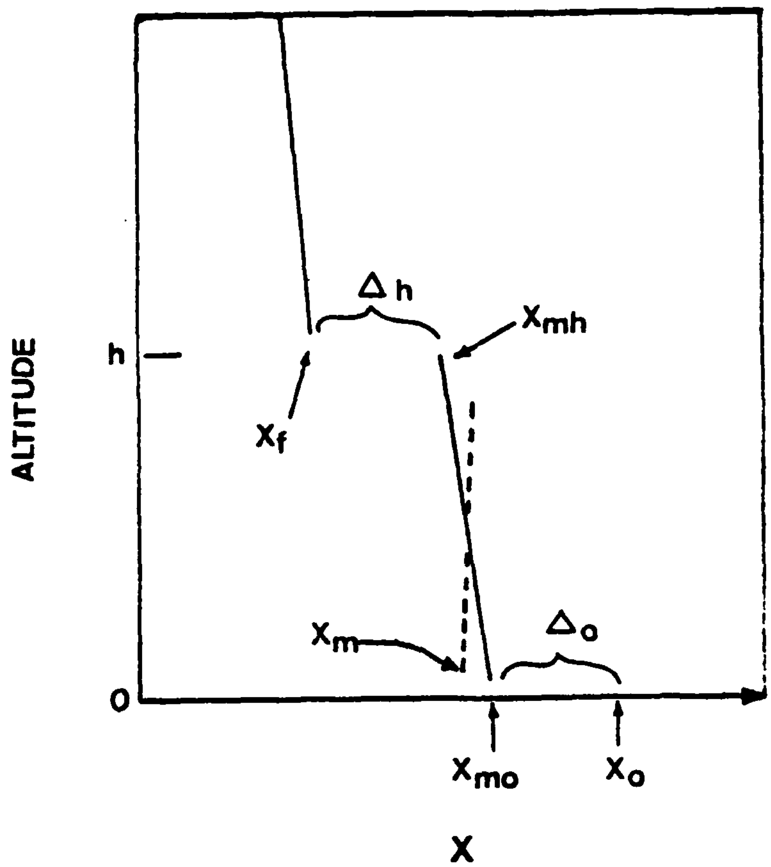

Figure 4. Representation of the gradient of a meteorological variable in the boundary layer when the well-mixed assumption is relaxed.

2.4 Mixed-Layer Depth

The application of Eqn (6) is critically dependent upon a reliable estimate of h. In mid-latitudes dominated by high pressure (e.g., U.S. West Coast) h is typically 200 to 800 m, in tropical regions h is typically 1 to 2.5 km. Note that h can vary a factor of two over a 24-hour period at a given location. It is hoped that h can be determined from climatology (combined with synoptic scale classification) or remote sensing of nearby cloud top temperatures.

2.5 Synoptic Classification

The method used for synoptic classification was taken from the Refractive Effects Guidebook (REG, COMTHIRFLT Tac. Mem. 230-2-75). Figure 5 is a sample synoptic chart from the REG. The REG classes are given below in Table 2.

Table 2. REG synoptic classes, typical duct heights, subsidence and air mass type (ST = subtropical, P = polar, T = tropical, M = modified).

TYPE	h,m	SUBSIDENCE
A	200	++ ST
B	600	+ ST
C	200	++ P
D	700	+ MP
E	1700	0 T
F	3000	0 MT
G	4800	- MT
H	100, 1700	0 T
I	High	- T
J	2400	0 MT
K	no inversions	0 Temp

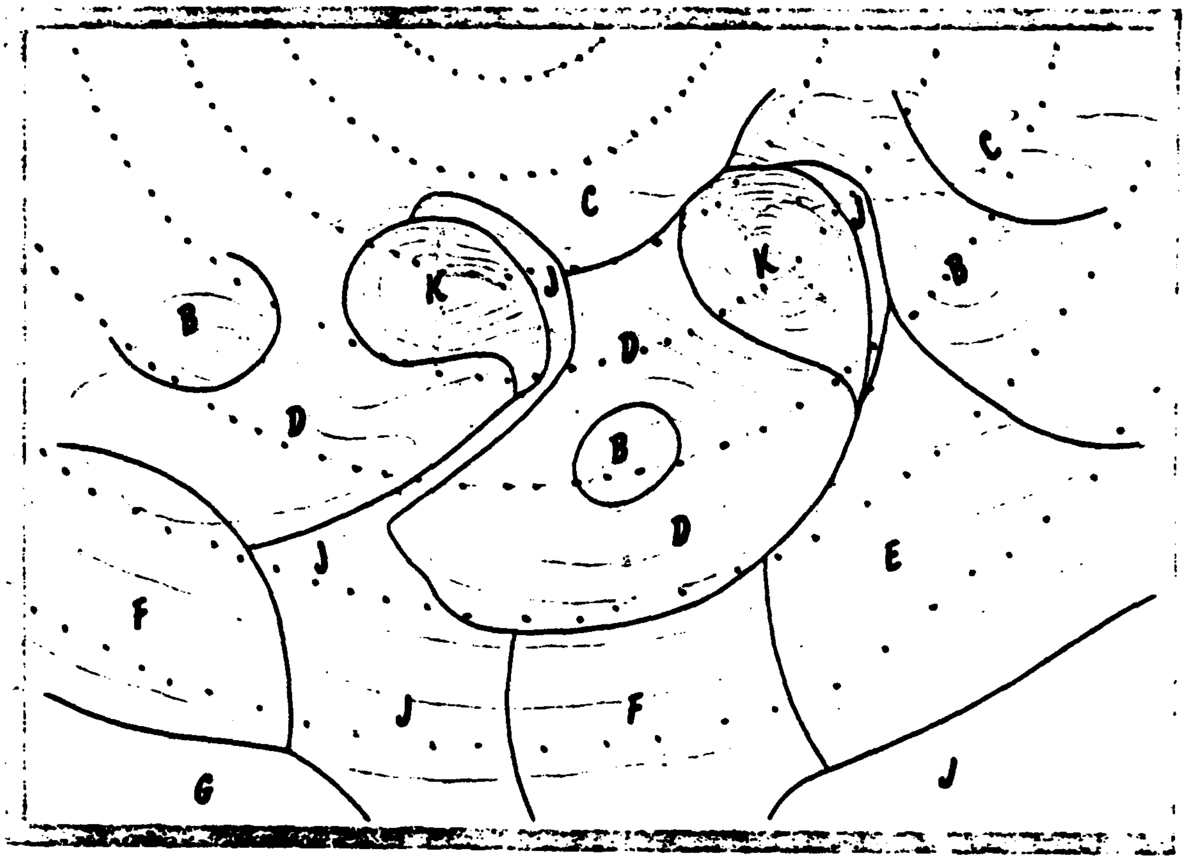

Figure 5. Sample synoptic weather chart for the North Pacific in Spring. The capital letters designate regions of different synoptic class

It must be remembered that the REG designations of duct height are based primarily on discontinuities in the water vapor profile. The lowest water vapor discontinuity may or may not correspond to the top of the mixed layer. For example, the E category data *from* MAGAT had insignificant water vapor jumps at the top of the mixed layer (typically h ~ 250 m). The major discontinuity in water vapor occurred above 1500 m, consistent with the value given in Table 2.

3.0 MAGAT Experiment

The Marine Aerosol Generation and Transport experiment (MAGAT) was held in Monterey in May, 1980. The instrumented platform participating were the R/V ACANIA (NPS) and the Airborne Research Associates (ARA) - Bellanca aircraft. Aerosol sampling devices were installed on both platforms (Fairall, 1981).

3.1 REG Classifications

Each day during MAGAT (4/29 - 5/09) was classified using the surface pressure chart analysis from FNOC. The results are given in Table 3.

Table 3. REG classes during MAGAT.

DATA	CLASS
4/29	E (Front 2300)
4/30	D
5/01	E (Front 2300)
5/02	D
5/03	D
5/04	D
5/05	E (Front 0700)
5/06	D
5/07	D
5/08	E (Front 1500)
5/09	E

3.2 Aerosol Extinction Profiles

Typical profiles for MAGAT D and E type classes are shown in Fig. 6. The MAGAT profiles were divided into cloud-free and cloudy profile subsets. A profile was designated as cloud-free if no cloud droplets were encountered during the profile measurements. This does not imply that no clouds were visible anywhere but simply means that this particular sounding did not pass through a cloud (Table 4).

The average value of f for the cloud-free cases was 0.90 with a standard deviation of 0.22 and an uncertainty in the mean estimate of $\pm$ 0.06. There was no significant difference in the average f for D and E classes but the variance for D (based on only four points) was much less. Note that the optical depth μ' in Table 4 is the total actually measured by the aircraft (typically to a maximum altitude of 1.5 km), not the total atmospheric optical depth. The average mixed layer height under cloud-free conditions was $\bar{h} = 0.29$ km while under cloudy conditions $\bar{h} = 0.49$ km. This simply implies that the average lifting condensation level (LCL) for the experiment was no greater than 0.3 km.

3.3 Tropospheric Extinction

A composite of all tropospheric extinction profiles from MAGAT ($Z > h$) is given in Fig. 7. Since the profiles do not indicate any significant height dependence on this scale (.4 to 1.5 km), the data were combined in a number distribution graph (Fig. 8). For D classes $\bar{\alpha}_+ = 1.2 \times 10^{-2}$ and for E classes $\bar{\alpha}_+ = 3.0 \times 10^{-2}$. The standard deviation for LGT (α_+) was 0.5. The difference between α_+ for the two classes is probably not due to a difference in aerosol content but a reflection of the greater relative humidity (RH > 40%) present above the mixed layer for REG class E.

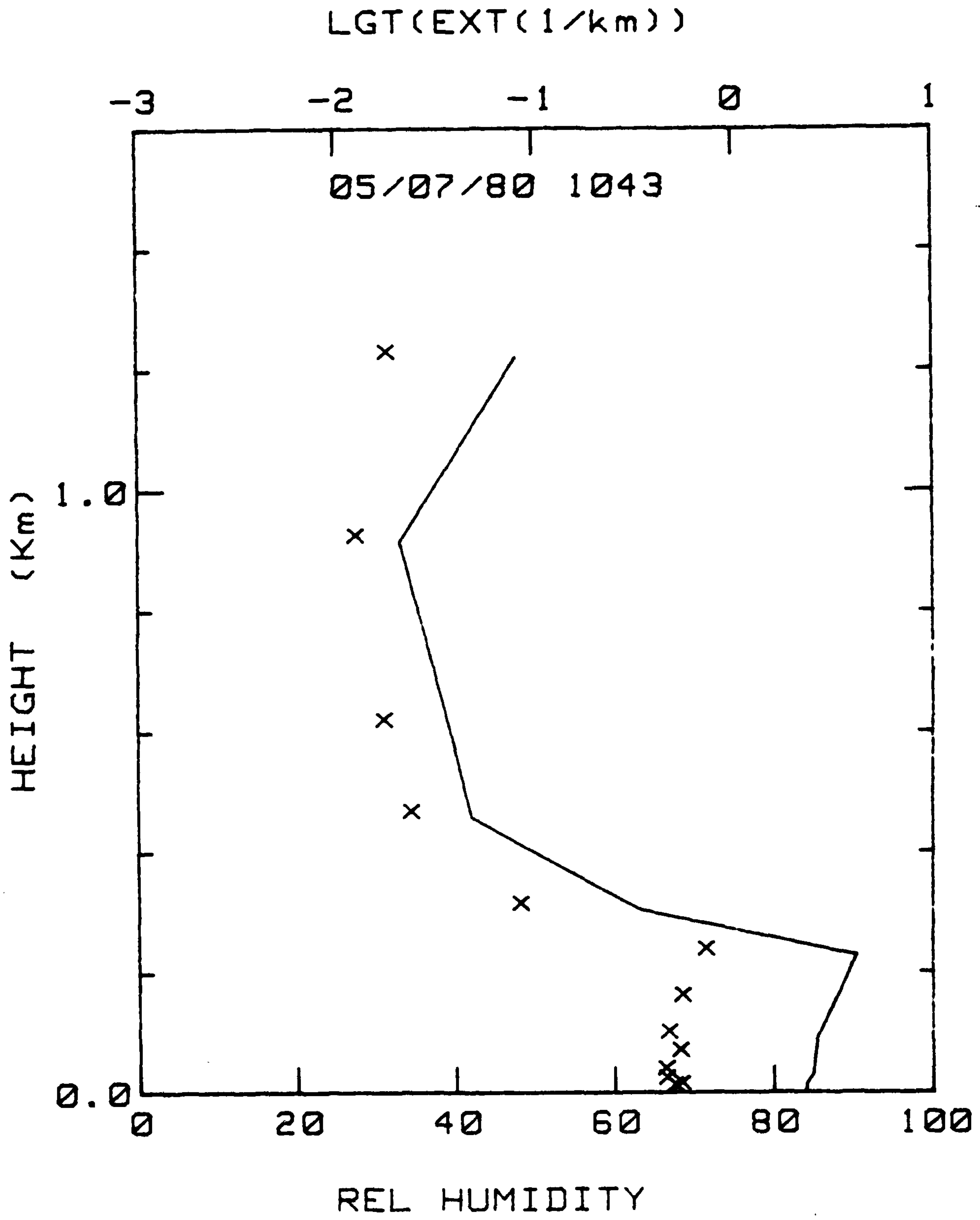

Figure 6a. Aerosol extinction coefficient (λ = 0.49 micron) for a D class day

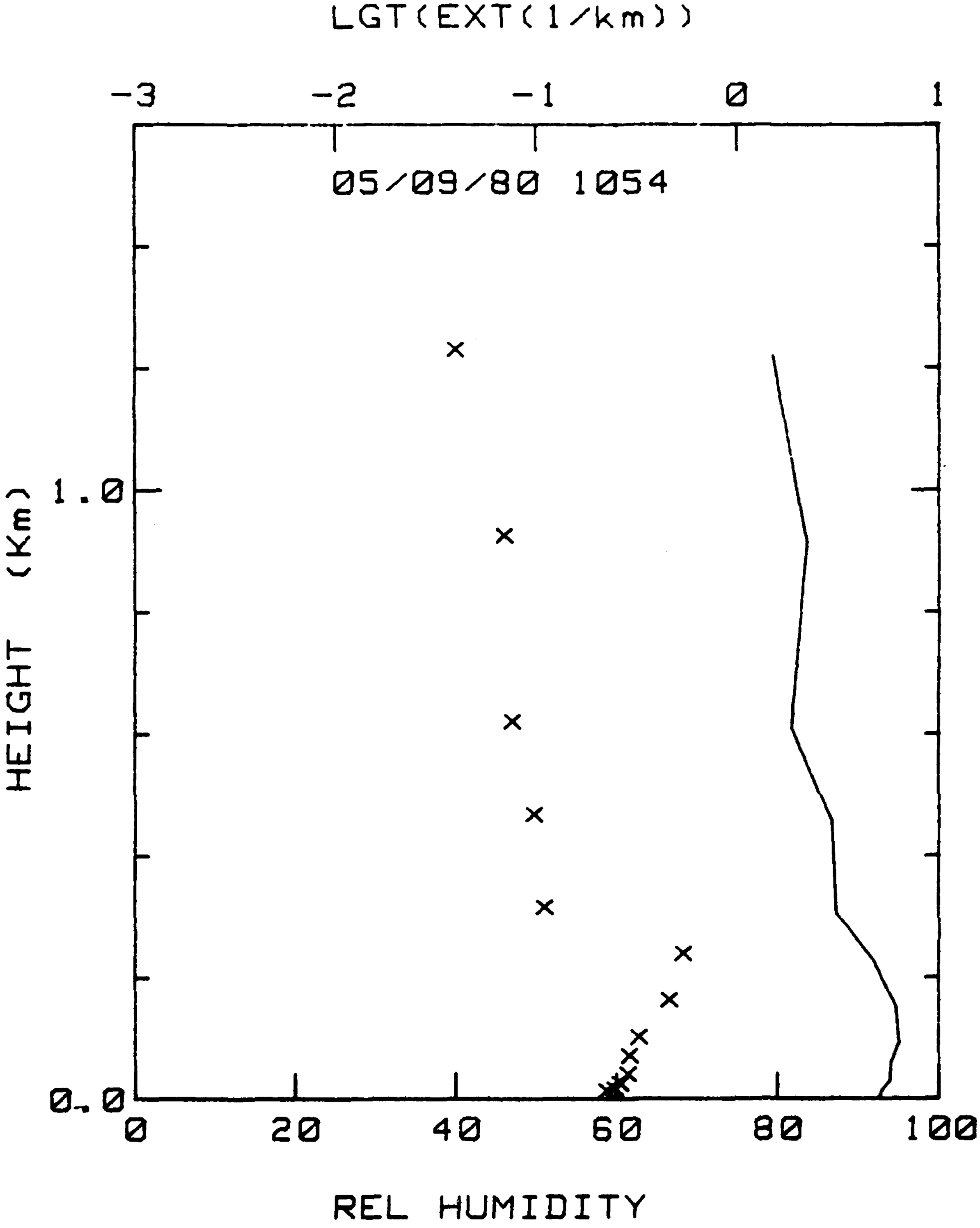

Figure 6b. Aerosol extinction coefficient (λ = 0.49 micron) for an E class day

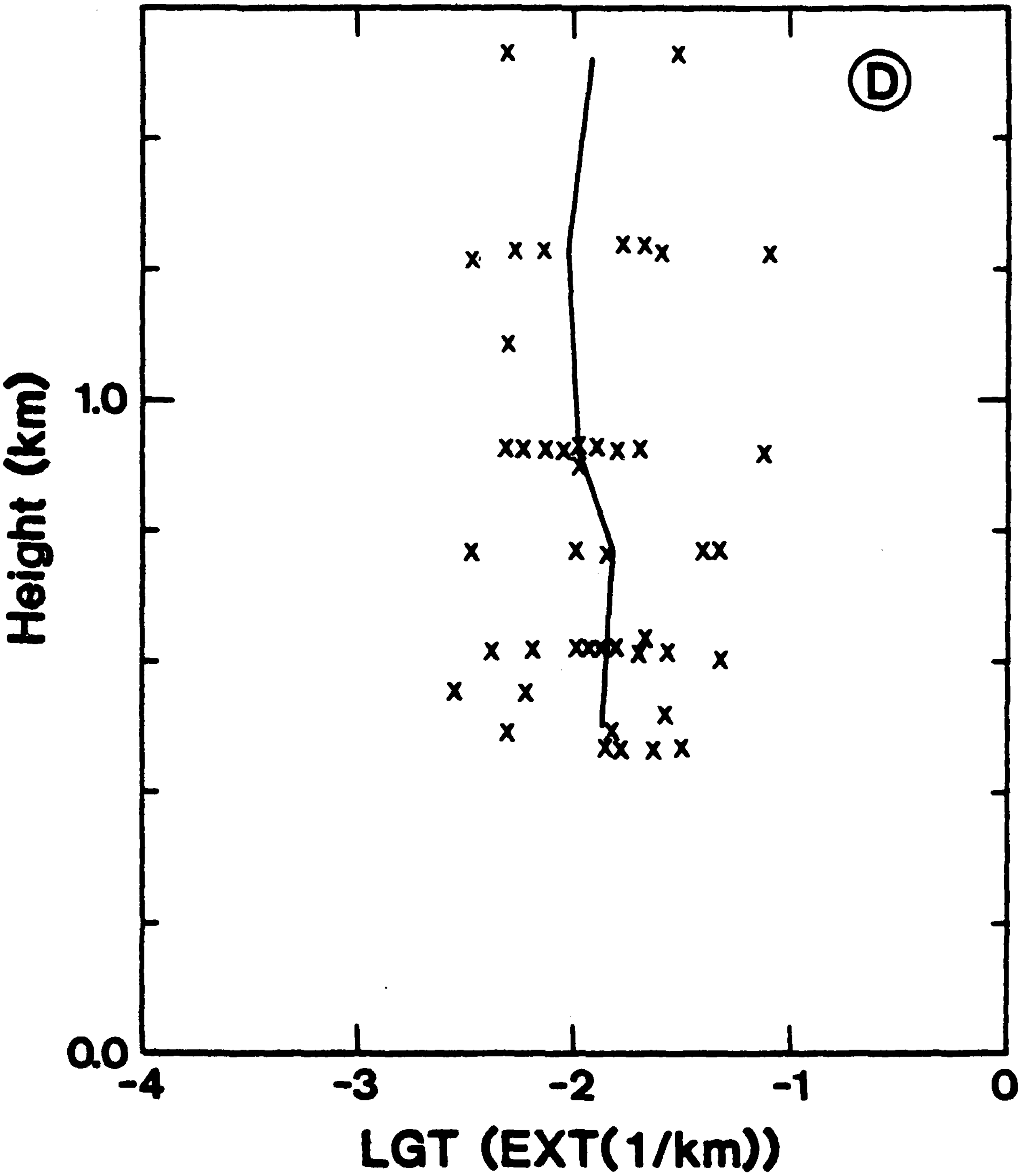

Figure 7a. Tropospheric extinction (λ = 0.49 micron) for Z > h and REG class D)

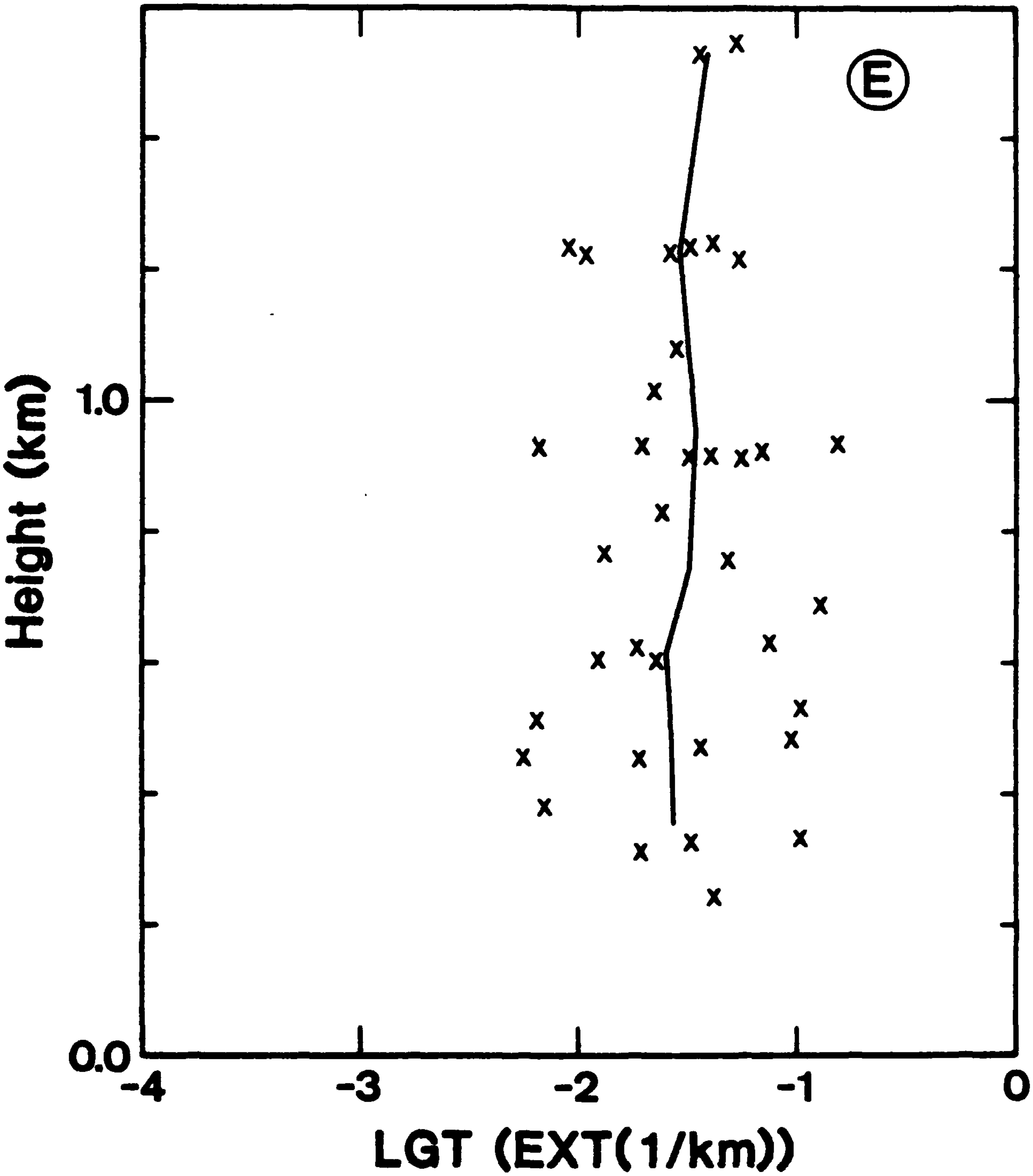

Figure 7b. Tropospheric extinction (λ = 0.49 micron) for Z > h and REG class E)

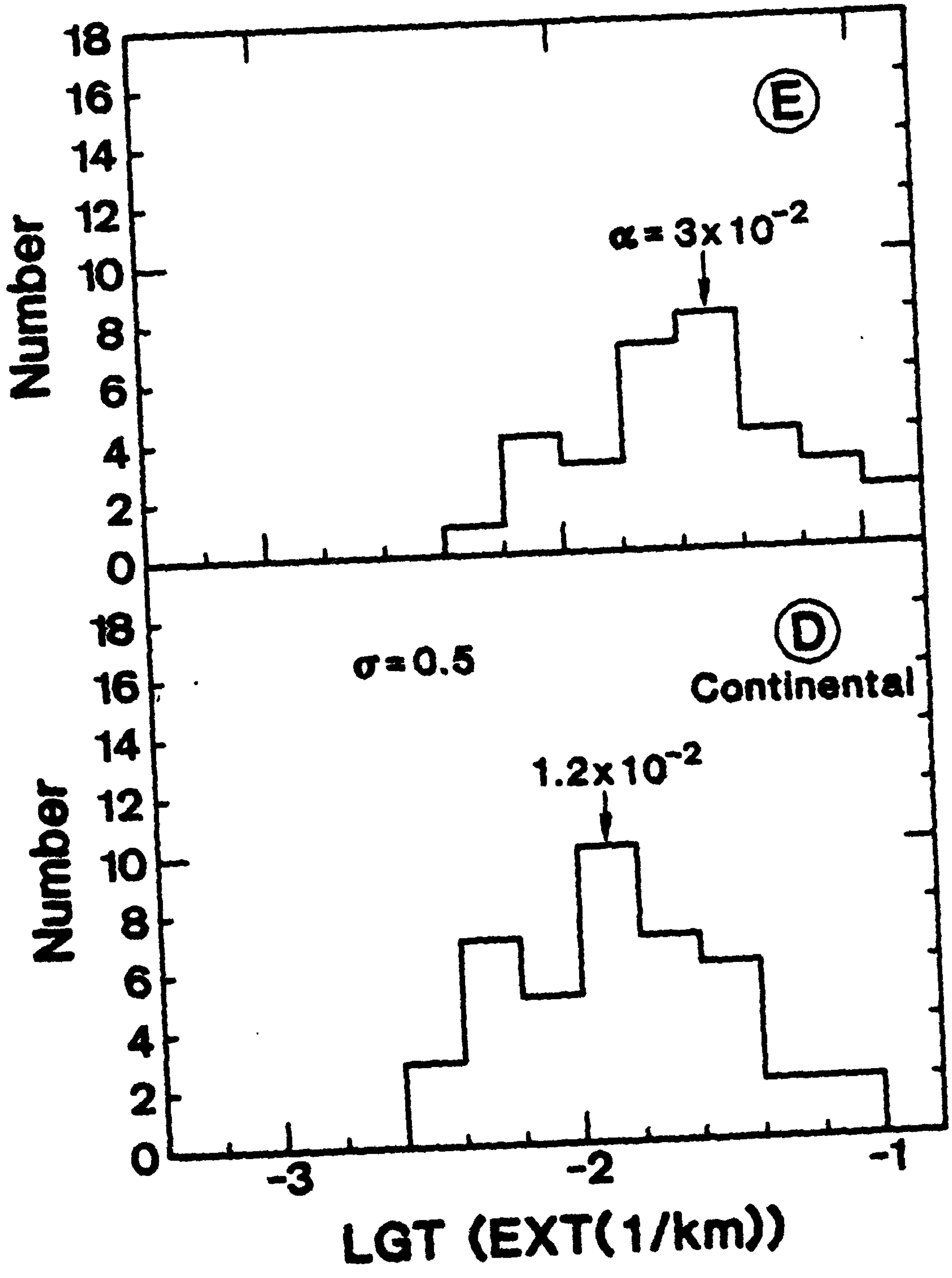

Figure 8. Number distribution of MAGAT tropospheric extinction for D and E classes

Table 4. Data summary for the 26 ladder profiles from MAGAT. μ' is the total optical depth to the maximum altitude measured and μ_m is the mixed layer optical depth.

CLEAR SKY

Date	#	α_o km^{-1}	μ'	μ_m	h,km	f	REG
4/29	1	.57	.33	.19	.31	.92	E
4/29	2	.46	.40	.37	.55	.68	E
4/30	4	.47	.20	.19	.34	.84	D
5/1	5	.14	.074	.018	.16	1.17	E
5/1	6	.23	.11	.082	.24	.67	E
5/4	14	.18	.065	.055	.25	.82	D
5/5	17	.17	.040	.019	.15	1.34	E
5/5	18	.13	.035	.012	.15	1.02	E
5/5	20	.10	.029	.020	.18	.9	E
5/6	22	.28	.18	.15	.53	.98	D
5/7	23	.46	.14	.12	.23	.88	D
5/9	26	.21	.15	.088	.23	.55	E
	Average =	.28	.15	.11	D .34 E .25	.9	

CLOUDY

Date	#	α_o km^{-1}	μ'	μ_m	h,km	f	REG
4/30	3	.5			.45		D
5/2	7	.18			.40		D
5/2	8	.15			.44		D
5/2	9	.19			.42		D
5/3	10	.21			.52		D
5/3	11	.26			.55		D
5/3	12	.19			-		D
5/3	13	.56			.50		D
5/4	15	.27			.60		D
5/4	16	.16			.42		D
5/5	19	.13			.32		E
5/6	21	.30			.60		D
5/7	24	.35			.50		D
5/8	25	.20			.90		E

The estimation of the tropospheric contribution, μ_t, requires a scale length L which is either the exponential decay length or the height of the tropospheric aerosol component h_t. If we take a typical value of L = 7.5 km, then μ_t = 0.75 for class D and μ_t = .225 for class E for MAGAT. Assuming a climatological mean for μ_s = .01 ± .005 (Toon and Pollack, 1976) then μ_m/μ = .11/.2 = .55 for D and μ_m/μ = .11/.35 = .32 for E cases. Alternatively, if we assume h_t = 2 km (based on REG data and some aircraft observations) then μ_m/μ = .11/.14 = .79 for D and μ_m/μ = .11/.18 = .61 for E cases. Thus, the mixed layer typically contributes 60% to 80% of the total optical depth for MAGAT.

3.4 Variability Analysis

The MAGAT data have yielded some estimates of the variability of the components in Eqn (6) which we can use for a simple error analysis (Table 5).

Table 5. Variability contribution of the items of Eqn (6) for MAGAT.

Parameter, X	f	μ_s	μ_t	h,km
Average, $\bar{X}$	0.9	0.01	0.09	0.3
ΔX	0.2	0.005	0.07	0.15
$\Delta\alpha_o$ contri.	$\Delta f\mu_m/h$	$f\Delta\mu_s/h$	$f\Delta\mu_t/h$	$f\mu_m\Delta h/h^2$
Value $\Delta\alpha_o$	0.07	0.015	0.21	0.17

*This value of μ_t is the estimated total μ_t, not the portion measured by the aircraft.

A sum of the variances (σ^2) of the four terms yields a total standard deviation σ = 0.28 km^{-1} for α_o (therefore $\Delta\alpha_o/\alpha_o$ = 0.85).

3.5 Algorithm Evaluation

The MAGAT data can be used to test Eqn (6) in a form optimized to the data set by using MAGAT mean parameters for the terms. If we assume α_+ =

0.01, $\bar{h}$ = 0.35 for class D and α_+ = 0.03 and $\bar{h}$ = 0.25 for class E, then

$$\alpha_o' = .9(\mu' - 0.013)/1.35 \text{ for class D} \quad (16a)$$

$$\alpha_o' = .9(\mu' - 0.033)/1.25 \text{ for class E} \quad (16b)$$

In Table 6 we show a comparison of α_o' with the measured α_o for the 12 MAGAT cloud-free profiles.

Table 6. Evaluation of Eqn (6) as optimized (Eqn (16)) for the mean conditions during MAGAT.

#	Class	μ_m	$\mu'-\mu_t$	α_o', km^{-1}	α_o, km^{-1}	α'/α_o
1	E	.33	.29	1.04	.57	1.82
2	E	.44	.40	1.44	.46	3.13
3	D	.20	.19	.49	.47	1.24
4	E	.074	.036	.13	.14	.92
5	E	.11	.072	.26	.23	1.13
6	D	.265	.052	.13	.18	.72
7	E	.04	0	0	.17	0
8	E	.035	0	0	.13	0
9	E	.029	0	0	.10	0
10	D	.18	.17	.44	.28	1.57
11	D	.14	.13	.33	.46	.72
12	E	.15	.11	.40	.21	1.9

An analysis of the data in Table 6 yields (α_o'/α_o) = 1.07 and $\Delta\alpha_o/\alpha_o$ = .92, which is consistent with the estimates of the previous section.

4.0 NPS Model Simulation

The NPS aerosol model, as described in Section 2.2, has not been run on the MAGAT data sets. A preliminary simulation was done for a typical climatological mean for open ocean conditions. The following parameters were selected: N_c = 650 cm^{-3}, u = 7 m/s, h = .35 km, RH(z = 10 m) = 80%, Ts = 15°C, T = 13°C, Δq = −5, $\Delta\theta_v$ = 10 and W_e = 0.1 cm/s. This case yielded μ_m = 0.33 and f = 0.72 (Fig. 9). The value of N_c was based on open

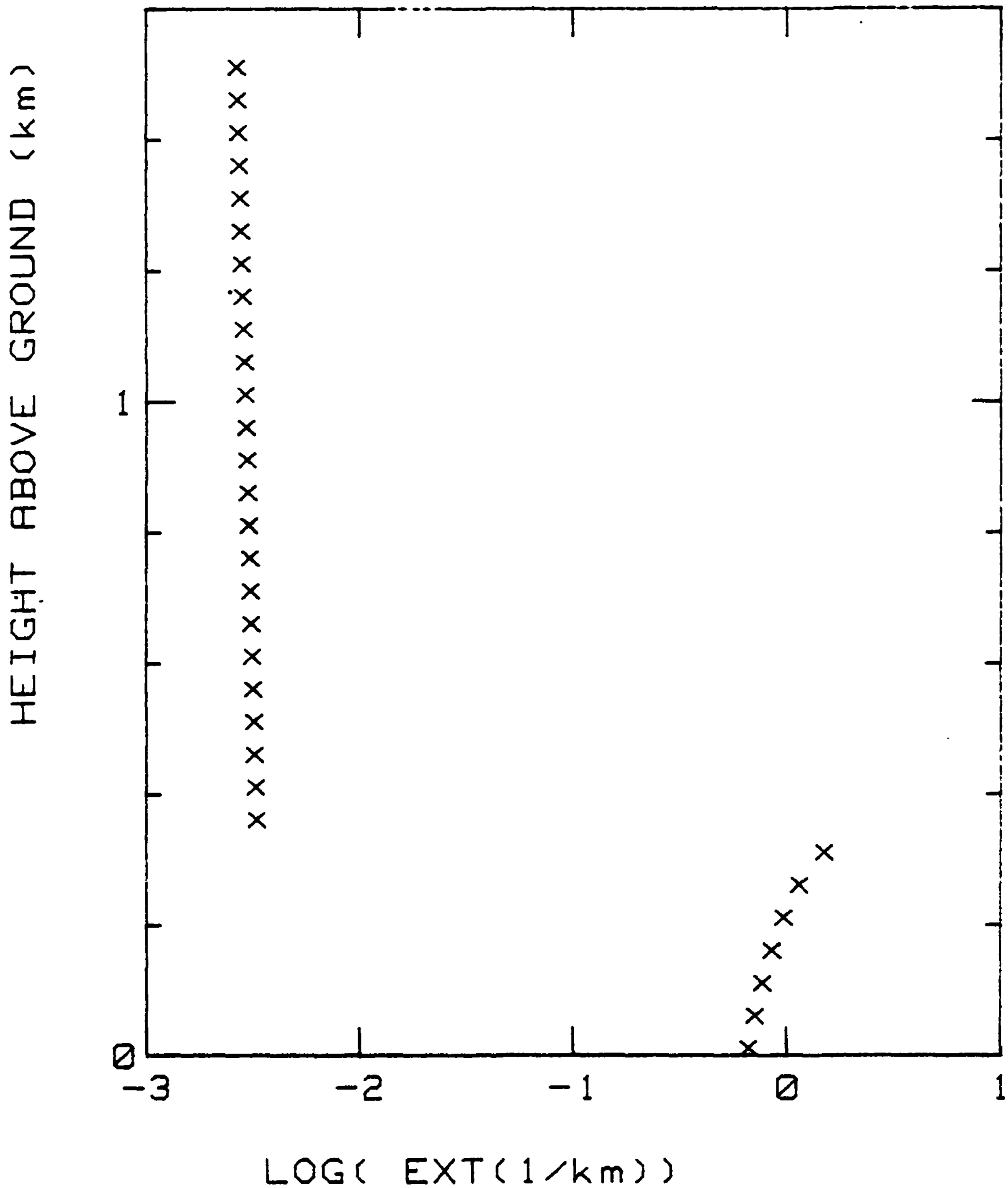

Figure 9. Sample NPS aerosol model simulation for typical open ocean climatological conditions (see text, section 3.4)

ocean measurements from CEWCOM-78, JASIN and STREX. Note that $N_c = 650$ cm^{-3} yields $\alpha_+ = 3 \times 10^{-3}$, which is considerably lower than the values found during MAGAT. The R/V ACANIA measurements of the continental component imply $\alpha_+ = 8 \times 10^{-3}$ which is in agreement with the aircraft data. The model gave $f = 0.77$ which is considerably less than the value of 0.9 found for the MAGAT data.

5.0 Conclusions

5.1 Concept

- The optical depth is considered to be made up of three atmospheric regions: mixed layer, tropospheric and stratospheric.
- The relationship of surface visibility (Eqn 6) is quite simple in the three layer context.

5.2 MAGAT Evaluation

- The REG synoptic categories were clearly correlated with certain features of the extinction profile (e.g. α_+ and h).
- The value of f of 0.9 indicates that it is a smaller correction than anticipated from model simulation.
- The tropospheric component of the optical depth varied about a factor of three.
- Using parameters optimized to the data, Eqn (6) could predict α_o to roughly a factor of 2.

5.3 NPS Aerosol Model

- The model reproduced the general mixed layer and tropospheric extinction profiles.
- Although the model allows some relaxation of the well-mixed assumption, it appears that the mixed layer gradients are slightly greater than given by the model.

- The primary utility of the model in the future for this project may be in its ability to indicate the presence of a cloud-free ($h <$ LCL) boundary layer.

5.4 General Comments

- The accuracy of the model (Eqn (6)) is primarily limited by the variability of h and μ_t (see Table 5).
- Global application of Eqn (6) using climatology only will probably allow estimates of α_o to about a factor of 3. (Note that it is the accuracy of the Wells-Munn-Katz model based on in-situ wind speed and humidity measurements.)

6.0 Acknowledgements

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