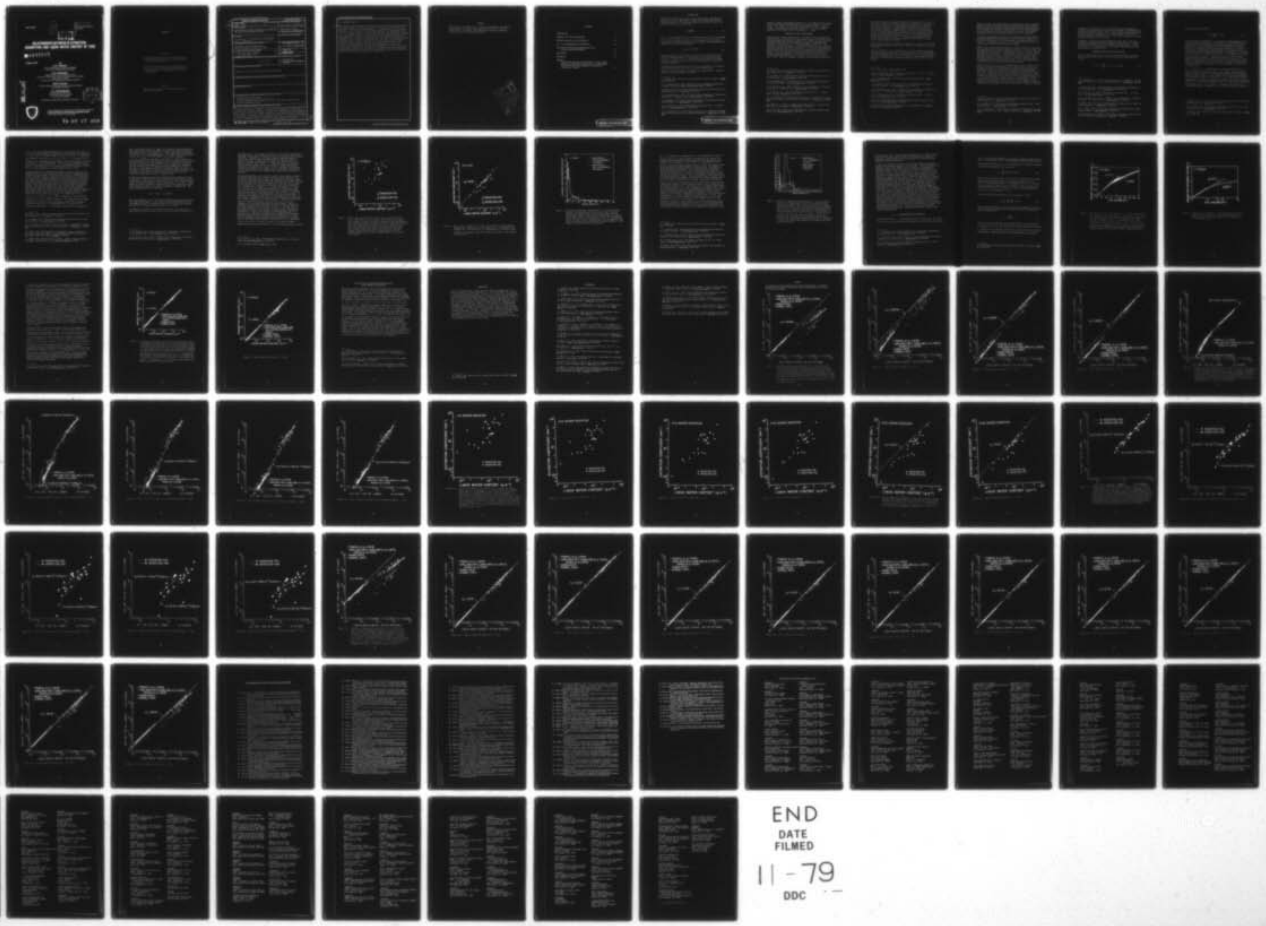
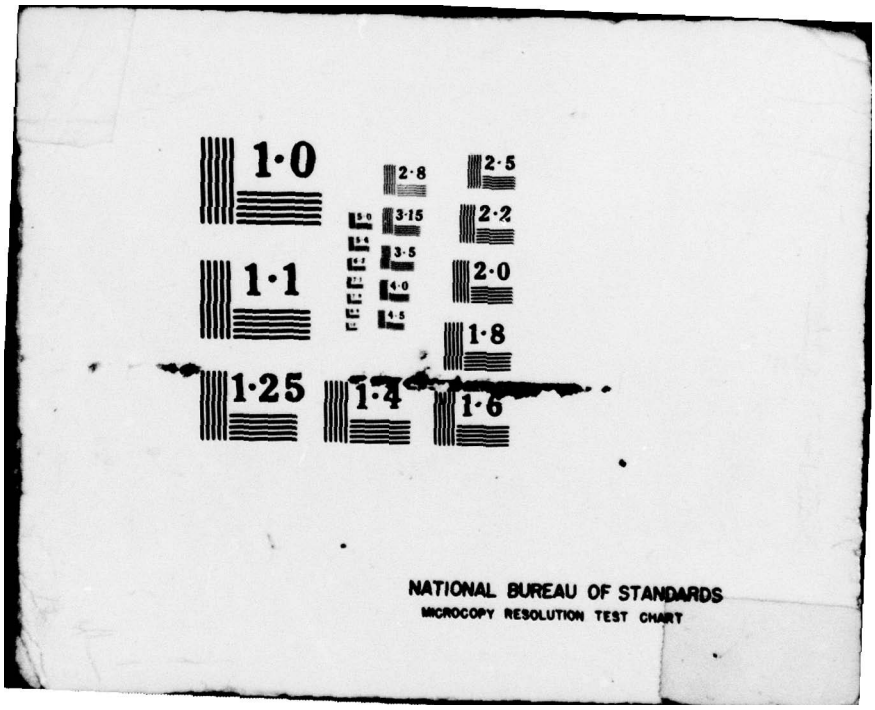
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RELATIONSHIPS BETWEEN IR EXTINCTION, ABSORPTION, AND LIQUID WATER CONTENT OF FOGS

AD A074395

August 1979

By

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

It is well known that atmospheric fog and haze particles degrade the performance of DOD electro-optical sensors. A quantitative assessment of these effects unfortunately requires knowledge of droplet size distributions, which generally have complex spacial and temporal variations. The problem would be simplified considerably if estimates of the radiative properties of fog and haze particles could be made without detailed knowledge of their size distributions. In this report, an attempt is made to find relationships between the radiative

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20. ABSTRACT (cont)

properties of fogs and hazes (in particular the volume extinction and absorption coefficients) and their liquid water content, that are relatively independent of droplet size distribution. It is found that definite relationships exist only at particular infrared wavelengths. At wavelengths around $\lambda = 11\mu m$, a linear relation exists between extinction and liquid water content, and at wavelengths around $\lambda = 3.8\mu m$, $9.5\mu m$ similar relations between fog and haze absorption coefficient and liquid water content exist that are nearly independent of the droplet size distribution. Thus the results suggest unique relations between integrated liquid water content along a path in fog and transmission (at $\lambda \doteq 11\mu m$) along that path (neglecting multiple scatter effects and forward scatter corrections), and between fog liquid water content at a particular point and the infrared emission (at $\lambda \doteq 3.8\mu m$, $9.5\mu m$) at that point. Finally, the correlation of visible and infrared extinction is investigated empirically using 341 droplet size distribution measurements made under a variety of meteorological conditions.

PREFACE

We gratefully acknowledge John A. Garland, Environmental and Medical Sciences Division, Harwell, who supplied his raw data of fog size distributions. One author (Petr Chýlek) was partially supported by a grant from the US Army Research Office.



CONTENTS

INTRODUCTION 7

SELECTED FOG SIZE DISTRIBUTIONS 8

NUMERICAL RESULTS OF FOG EXTINCTION 11

$Q_a = c'x$ APPROXIMATION FOR ABSORPTION 23

APPLICATION OF EXTINCTION-ABSORPTION-LIQUID WATER CONTENT RELATIONSHIPS 32

CONCLUSIONS 33

REFERENCES 34

APPENDIX

FOG AND HAZE EXTINCTION COEFFICIENT VS LIQUID WATER CONTENT, IR EXTINCTION COEFFICIENT VS VISIBLE EXTINCTION COEFFICIENT, AND ABSORPTION COEFFICIENT VS LIQUID WATER CONTENT 36

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INTRODUCTION

Chýlek[1] has recently shown that a linear relationship, independent of the form of the size distribution, should exist between the infrared extinction around $\lambda = 11\mu m$ and the liquid water content of fogs. The relation can be written in the form

$$\sigma_e = \frac{3\pi c}{2\rho\lambda} W, \tag{1}$$

where σ_e is the volume extinction coefficient measured at the wavelength λ, W is the liquid water content, ρ is the density of water, and the coefficient c is equal to the slope of a straight line approximating the efficiency factor for extinction Q_e by

$$Q_e (x, \lambda) \doteq c(\lambda)x. \tag{2}$$

The size parameter x is defined by the ratio of the particle circumference to the wavelength. An approximate value of the coefficient $c(\lambda)$ at $\lambda = 11\mu m$ is $c \doteq 0.31$. The conditions under which the approximation (2) is valid and the derivation of the relation (1) have been discussed elsewhere.[1]

In this report the validity of relation (1) is verified by calculating the volume extinction coefficient σ_e and the liquid water content W for 341 different fog droplet size distributions[2-7] measured under various meteorological situations.

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[1]P. Chýlek, 1978, "Extinction and Liquid Water Content of Fogs," J Atmos Sci, 35:296-300

[2]J. A. Garland, 1971, "Some Fog Droplet Size Distributions Obtained by an Impaction Method," Quart J Roy Meteorol Soc, 97:483-494

[3]M. Kumai, 1973, "Arctic Fog Droplet Size Distribution and Its Effect on Light Attenuation," J Atmos Sci, 30:635-643

[4]J. A. Garland et al., 1973, "A Study of the Contribution of Pollution to Visibility in a Radiation Fog," Atmos Environ, 7:1079-1092

[5]B. A. Kunkel, 1971, "Fog Drop-Size Distributions Measured with a Laser Hologram Camera," J Appl Meteorol, 10:482-486

[6]W. T. Roach et al., 1976, "The Physics of Radiation Fog: I-a Field Study," Q J Roy Meteorol Soc, 102:313-333

[7]R. G. Pinnick et al., 1978, "Vertical Structure in Atmospheric Fog and Haze and Its Effect on IR and Visible Extinction," J Atmos Sci, 35:2020-2032

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Further, a linear relationship, similar to (1), is shown to exist between the infrared absorption coefficient in the spectral regime λ = 3.5 to 5.3μm, λ = 8 to 10μm, and the liquid water content of fogs. Thus for example, the absorption coefficient of fogs at λ = 3.8μm is uniquely related to their extinction and absorption at λ = 10μm.

SELECTED FOG SIZE DISTRIBUTIONS

Relatively few reliable measurements of fog droplet size distributions have been made, particularly for which numerical data is available. The fog measurements used here were judged to be reliable and were chosen to represent a wide range of fog conditions ranging from maritime and continental advection fogs[3,5,2] to inland radiation fogs.[2,4,6,7] The early work on evolving fogs near the Atlantic Ocean in France and stable inland fog and haze near Paris by Arnulf et al.[8] was not used because it was not possible to obtain true droplet distributions from their figures. Arnulf et al. captured droplets onto spider threads (for which the capture coefficient depends on droplet size) but give only the uncorrected droplet distribution data. Results of the pioneering work of May,[9] using a specially designed two-stage impactor, were not used since

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[3]M. Kumai, 1973, "Arctic Fog Droplet Size Distribution and Its Effect on Light Attenuation," J Atmos Sci, 30:635-643

[5]B. A. Kunkel, 1971, "Fog Drop-Size Distributions Measured with a Laser Hologram Camera," J Appl Meteorol, 10:482-486

[2]J. A. Garland, 1971, "Some Fog Droplet Size Distributions Obtained by an Impaction Method," Q J Roy Meteorol Soc, 97:483-494

[4]J. A. Garland et al., 1973, "A Study of the Contribution of Pollution to Visibility in a Radiation Fog," Atmos Environ, 7:1079-1092

[6]W. T. Roach et al., 1976, "The Physics of Radiation Fog: I-a Field Study," Q J Roy Meteorol Soc, 102:313-333

[7]R. G. Pinnick et al., 1978, "Vertical Structure in Atmospheric Fog and Haze and Its Effect on IR and Visible Extinction," J Atmos Sci, 35:2020-2032

[8]A. Arnulf et al., 1957, "Transmission by Haze and Fog in the Spectral Region 0.35 to 10 Microns," J Opt Soc Am, 47:491-498

[9]K. R. May, 1961, "Fog Droplet Sampling Using a Modified Impactor Technique," Q J Roy Meteorol Soc, 87:535-548

the numerical data are no longer available.* Measurements of valley fog drop sizes obtained by exposing gelatin-coated slides to a stream of foggy air by Pilié et al.[10] were deemed not credible since the distributions were normalized to simultaneous measurements of extinction coefficient derived by a transmissometer. Fog drop measurements made with a light-scattering counter by Eldridge[11] were not utilized since errors in his measurements are suspected because of nonisokinetic sampling. The inlet of his counter was only 1 cm in diameter and became wet during the sampling process. In addition, some unexplained differences were caused by a dilution apparatus Eldridge used for high droplet concentration conditions.

Three different sampling techniques were employed to obtain the fog size distributions utilized in this study: impaction, holographic, and light scattering.

Garland,[2] Garland et al.,[4] and Roach et al.[6] used a modified two-stage Casella impactor designed by May[9] mounted horizontally in a wind tunnel to provide isokinetic sampling. Corrections to the collection efficiency based on the penetration curves of the impactor[12] were applied to the raw data. The size range of sensitivity of this device is 0.3 to 72μm radius.

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*K. R. May, private communication, 1978

[10]R. J. Pilié, 1975, "The Life Cycle of Valley Fog. Part II: Fog Microphysics," J Appl Meteorol, 14:364-374

[11]R. G. Eldridge, 1961, "A Few Fog Drop-Size Distributions," J Appl Meteorol, 18:671-676

[2]J. A. Garland, 1971, "Some Fog Droplet Size Distributions Obtained by an Impaction Method," Q J Roy Meteorol Soc, 97:483-494

[4]J. A. Garland et al., 1973, "A Study of the Contribution of Pollution to Visibility in a Radiation Fog," Atmos Environ, 7:1079-1092

[6]W. T. Roach et al., 1976, "The Physics of Radiation Fog: I-a Field Study, Q J Roy Meteorol Soc, 102:313-333

[9]K. R. May, 1961, "Fog Droplet Sampling Using a Modified Impactor Technique," Q J Roy Meteorol Soc, 87:535-548

[12]K. R. May, 1945, "The Cascade Impactor: An Instrument for Sampling Aerosols," J Sci Instr, 22:187-195

Kumai[3] also used a two-stage impactor to measure advection fog droplets formed over the Arctic Ocean at Point Barrow, Alaska, together with a gelatin-coated glass slide collection plate whose collection efficiency was calculable as a function of wind velocity. Also, imprint-droplet correction factors were applied to obtain true sizes. The combined methods yielded drop size concentration from 2.2 to 64μm radius.

In general, the primary deficiency of the impaction technique, besides requiring laborious data reduction, is the uncertainty in number concentration determination for near-micrometer and submicrometer size droplets. In addition, the size limit of detectability is about 0.3μm radius using conventional microscopy techniques.

Kunkel[5] used a laser hologram technique to measure droplets in advection fog propagating inland during nighttime at Otis Air Force Base, MA. The hologram camera was capable of sampling volumes of 4.5 cm^3 at a rate of five samples per minute, in a near-isokinetic fashion, and with minimal disturbance to the droplets. Droplets with radii of 2 to 40μm were detected. Because of the small number of droplets (normally < 50) in the distributions reported by Kunkel, all 17 of the reported droplet distributions were averaged together, which in any case represent only a 3-minute interval, to obtain a single distribution.

Finally, the radiation fog and haze measurements made by Pinnick et al.[7] during wintertime in West Germany with a commercially available light-scattering counter (the "Knollenberg" Classical Scattering Aerosol Spectrometer manufactured by Particle Measurement Systems, Boulder, CO) were used. This device works on the principle that as aerosol flows through an illuminated volume, light scattered by single droplets into a particular solid angle is measured and used to determine particle size by pulse height analyzing response pulses. Determination of droplet size from the response is indirect because of the dependence of the response on factors other than droplet size, namely, droplet refractive index and the lens geometry of the optical system. Particular attention

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[3]M. Kumai, 1973, "Arctic Fog Droplet Size Distribution and Its Effect on Light Attenuation," J Atmos Sci, 30:635-643

[5]B. A. Kunkel, 1971, "Fog Drop-Size Distributions Measured with a Laser Hologram Camera," J Appl Meteorol, 10:482-486

[7]R. G. Pinnick et al., 1978, "Vertical Structure in Atmospheric Fog and Haze and Its Effect on IR and Visible Extinction," J Atmos Sci, 35:2020-2032

was given to the calibration of this instrument using monodisperse particles of different sizes and refractive indexes. The manufacturer's advertised calibration was not used. Rather, droplet size distributions were determined by redefining the size pulse height channels as described in detail by Pinnick et al.[7] This counter is sensitive to water droplets with radii of 0.23 to 16μm.

Altogether, 341 different size distributions were used to check the validity of equation (1) in the atmospheric window around λ = 11μm; 25 fog distributions were taken from Garland[2] and Roach et al.,[6] 6 from Garland et al.,[4] 20 from Kumai,[3] 1 from Kunkel,[5] and 289 fog and haze distributions from Pinnick et al.[7]

NUMERICAL RESULTS FOR FOG EXTINCTION

A Mie scattering program and index of refraction of water as given by Hale and Querry[13] were used to calculate the volume extinction coefficient

$$\sigma_e(\lambda) = \pi \int r^2 \quad Q_e \ (\lambda, r) \quad n(r)dr \qquad (3)$$

---

[7]R. G. Pinnick et al., 1978, "Vertical Structure in Atmospheric Fog and Haze and Its Effect on IR and Visible Extinction," J Atmos Sci, 35:2020-2032

[2]J. A. Garland, 1971, "Some Fog Droplet Size Distributions Obtained by an Impaction Method," Q J Roy Meteorol Soc, 97:483-494

[6]W. T. Roach et al., 1976, "The Physics of Radiation Fog: I-a Field Study," Q J Roy Meteorol Soc, 102:313-333

[4]J. A. Garland et al., 1973, "A Study of the Contribution of Pollution to Visibility in a Radiation Fog," Atmos Environ, 7:1079-1092

[3]M. Kumai, 1973, "Arctic Fog Droplet Size Distribution and Its Effect on Light Attenuation," J Atmos Sci, 30:635-643

[5]B. A. Kunkel, 1971, "Fog Drop-Size Distributions Measured with a Laser Hologram Camera," J Appl Meteorol, 10:482-486

[13]G. M. Hale and M. R. Querry, 1973, "Optical Constants of Water in the 200 nm to 20μm Wavelength Region," Appl Opt, 12:555-563

and the liquid water content

$$W = \frac{4}{3}\pi\rho \int r^3\, n(r)dr \qquad (4)$$

for the previously mentioned 341 fog and haze size distributions n(r) at several different wavelengths λ. The numerical integrations were performed only over the range of particle radii measured for each size distribution, under the assumption that the differential size distribution n(r) is constant within each measured particle size channel. In other words, the measured distributions were not extended to larger or smaller particle sizes and were not smoothed. The results at λ = 0.55μm, 1.2μm, 4μm, and 11μm, together with the Q_e = cx approximation [equation (1)], are shown in figure 1. Additional results at other infrared wavelengths are shown in the appendix, figures A-1 through A-4. The Kumai[3] or Kunkel[5] results at λ = 0.55μm and 1.2μm have not been included since the contribution of particles with r ≲ 2μm (which neither Kumai nor Kunkel measured) to extinction at these wavelengths is suspected as being excessive.

At λ = 11μm the Q_e = cx approximation is a good approximation for all size distributions except those with a large number of droplets with radii r > 14μm.[1] Some fog size distributions used in our calculations contained droplets with r > 14μm; however, their contribution generally did not dominate either the extinction σ_e or the liquid water content W. Consequently, the linear relationship (1) between the volume extinction coefficient σ_e and the liquid water content W is expected to be reasonably well satisfied at λ = 11μm. Results of numerical calculations confirming the validity of equation (1) at λ = 11μm are shown in figure 1d.

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[3]M. Kumai, 1973, "Arctic Fog Droplet Size Distribution and Its Effect on Light Attenuation," J Atmos Sci, 30:635-643

[5]B. A. Kunkel, 1971, "Fog Drop-Size Distributions Measured with a Laser Hologram Camera," J Appl Meteorol, 10:482-486

[1]P. Chýlek, 1978, "Extinction and Liquid Water Content of Fogs," J Atmos Sci, 35:296-300

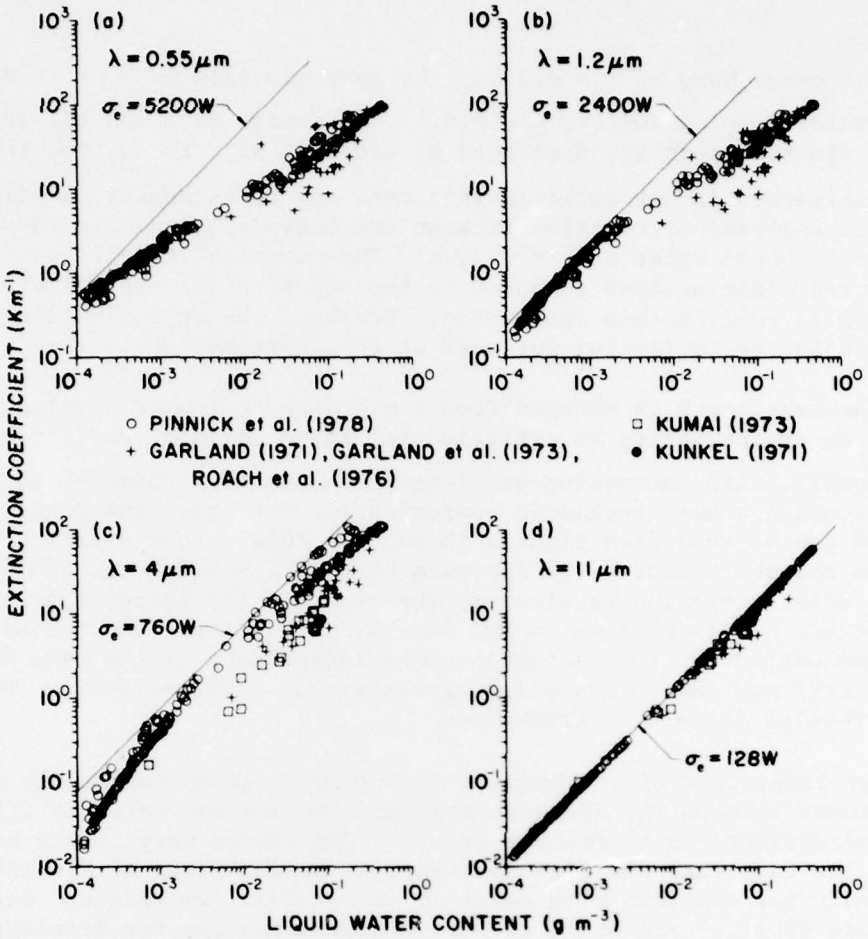


Figure 1. Variation of extinction coefficient with liquid water content in atmospheric fog and haze for 341 size distribution measurements made at different geographic locales and under a variety of meteorological conditions. In the infrared spectral region around λ = 11μm (d), there exists a linear size distribution independent relation between the volume extinction coefficient σ_e and the liquid water content W of the form of eq. (1). Consequently, the results of all measurements are close to a straight line. The predicted relation between extinction σ_e and liquid water content W according to eq. (1) is shown by the straight line, where σ_e is in km^{-1} and W is in g m^{-3}. On the other hand at λ = 0.55μm (a), the Q_e = cx approximation is not satisfied and no unambiguous relation between the extinction and liquid water content exists. The large spread of the points in the graph shows that the extinction coefficient is a function of the size distribution as well as of the liquid water content. As the wavelength is increased to λ = 1.2μm (b) and λ = 4μm (c), the Q_e = cx approximation is satisfied for larger droplets and the relation (1) shown by the straight lines is becoming a more realistic approximation for hazes and fogs.

On the other hand at $\lambda = 0.55\mu m$, the approximation $Q_e = cx$ is valid only for water droplets with $r \leq 0.5\mu m$.[1] Since most haze and all fog droplet size distributions are dominated by droplets with $r > 0.5\mu m$, the $Q_e = cx$ approximation is not valid in this case and consequently no size distribution independent relation between the extinction and liquid water content should exist at $\lambda = 0.55\mu m$. The numerical results based on the measured distributions compared to the equation (1) approximation in figure 1a confirm this conclusion. Further, the approximation grossly overestimates extinction for most of the distributions.

As the wavelength is changed from $\lambda = 0.55\mu m$ to longer wavelengths, the $Q_e = cx$ approximation is satisfied for larger droplet radii r. Consequently, with increasing wavelength the relation given by equation (1) is becoming a more realistic approximation for hazes and fogs. This trend can be seen from figures 1b and 1c, showing the numerical calculations and the equation (1) approximation at $\lambda = 1.2\mu m$ and $4\mu m$. Note that with increasing wavelengths the relation (1) better approximates the exact numerical results and finally at $\lambda = 11\mu m$ (figure 1d) the volume extinction coefficient becomes independent of the size distribution n(r) and the relation (1) agrees within a factor 2 with the numerical results for all distributions.

Closer inspection of the results in figure 1d shows noticeably better agreement between the Mie numerical results and the relation (1) for the size distributions of Pinnick et al.[7] The reason very likely has to do with the fact that the size distribution measurements of Pinnick et al. are only for droplets with radii up to $r = 16\mu m$, whereas the Garland,[2] Garland et al.,[4] and Roach et al.[6] measurements are for droplets with radii

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[1]P. Chýlek, 1978, "Extinction and Liquid Water Content of Fogs," J Atmos Sci, 35:296-300

[7]R. G. Pinnick et al., 1978, "Vertical Structure in Atmospheric Fog and Haze and Its Effect on IR and Visible Extinction," J Atmos Sci, 35:2020-2032

[2]J. A. Garland, 1971, "Some Fog Droplet Size Distributions Obtained by an Impaction Method," Q J Roy Meteorol Soc, 97:483-494

[4]J. A. Garland et al., 1973, "A Study of the Contribution of Pollution to Visibility in a Radiation Fog," Atmos Environ, 7:1079-1092

[6]W. T. Roach et al., 1976, "The Physics of Radiation Fog: I-a Field Study," Q J Roy Meteorol Soc, 102:313-333

up to r = 72μm; the Kumai[3] measurements are for droplets with radii up to r = 64μm, and the Kunkel[5] measurement is for droplets with radii up to r = 40μm. Since the maximum radius condition for the Q_e = cx approximation leading to relation (1) is for r_m = 14μm at λ = 11μm, none of the Pinnick et al. distributions can strongly violate this condition as no particles with r > 16μm were measured. Thus, the better agreement of the numerical results for the Pinnick et al. distributions with the relation (1) at λ = 11μm (and also at λ = 4μm [figure 1c]) may be partly a consequence of their inability to measure droplets with r > 16μm.

Another qualification concerning the results in figure 1 bears on the assumption that all fog and haze particles consist of homogeneous water droplets and have complex refractive indexes of water. Haze particles in particular may contain a significant volume fraction of contaminants such as sea salt or ammonium sulfate. The crucial question here is to what degree the particle refractive index is affected by such contaminants. The formation of fog is known to require atmospheric relative humidity (RH) to be near 100 percent. For the haze data appearing in figure 1, the relative humidity was close to 100 percent.[7] Hänel[14] and Hänel and Bullrich[15] have studied the effect of RH variations on mean complex refractive indexes of maritime and urban aerosols. Hänel[14] found that for RH $\geq$ 95 percent the real and imaginary parts of the complex refractive index n_{re} and n_{im} at λ = 0.55μm have values $1.33 \leq n_{re} \leq 1.36$ and $0 \leq n_{im} \leq 0.006$. Examination of Mie efficiency factors Q_e (m, x) for refractive indexes in this range shows the assumption that m = 1.33-0i in Mie calculations of extinction according to equation (3) and the Q_e = cx approximation (1) is a good one. At wavelengths longer than λ = 0.55μm, Hänel and Bullrich's formulae show

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[3]M. Kumai, 1973, "Arctic Fog Droplet Size Distribution and Its Effect on Light Attenuation," J Atmos Sci, 30:635-643

[5]B. A. Kunkel, 1971, "Fog Drop-Size Distributions Measured with a Laser Hologram Camera," J Appl Meteorol, 10:482-486

[7]R. G. Pinnick et al., 1978, "Vertical Structure in Atmospheric Fog and Haze and Its Effect on IR and Visible Extinction," J Atmos Sci, 35:2020-2032

[14]C. Hänel, 1976, "The Properties of Atmospheric Aerosol Particles as Functions of Relative Humidity at Thermodynamic Equilibrium with the Surrounding Moist Air," Adv in Geophys, 19:73-188

[15]G. Hänel and K. Bullrich, 1978, "Physico - Chemical Property Models of Tropospheric Aerosol Particles," Beitr Phys Atmos 51:129-138

that, providing RH values are higher than 95 percent, both maritime and urban aerosol mean refractive indexes are again not markedly different from those of water. For example at λ = 11μm, from Hanel and Bullrich's formulae the real and imaginary parts of the complex index are predicted to be $1.153 \leq n_{re} \leq 1.207$ and $0.0968 \leq n_{im} \leq 0.109$, compared to $m = 1.153 - 0.0968i$ for pure water. The effect of these refractive index variations in Mie calculations of extinction coefficient according to equations (3) and (1) are estimated to be not more than 10 percent. For fog, an additional argument can be made to support the assumption that the particle refractive indexes can be approximated by those of pure water. The argument is that the liquid mass content of fogs is on the order of 0.005 g m^{-3} or greater, and thus the volume fraction of any contaminant in fog droplets must necessarily be small so that the refractive indexes must be close to those of water.

Because of the Army's interest in relating infrared properties of fogs to atmospheric visibility (or visible extinction), the extinction versus liquid water content data have been plotted in the form of extinction at various infrared wavelengths λ versus extinction at λ = 0.55μm. These numerical results, together with empirical power-law expressions fitted to the numerical results, are shown in figures A-5 through A-11. The empirical expressions are of the form

$$\sigma_e(\lambda) = a[\sigma_e(\lambda = 0.55\mu m)]^b$$

where the parameters a and b are constants depending only on the particular infrared wavelength λ. The empirical power-law expressions are of only marginal value, as in general there is no unique relation between extinction in the infrared and extinction at λ = 0.55μm.

To examine more closely the fog results in figure 1 in terms of fog type, attention has been restricted to data of Garland,[2] Garland et al.,[4]

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[2]J. A. Garland, 1971, "Some Fog Droplet Size Distributions Obtained by an Impaction Method," Q J Roy Meteorol Soc, 97:483-494

[4]J. A. Garland et al., 1973, "A Study of the Contribution of Pollution to Visibility in a Radiation Fog," Atmos Environ, 7:1079-1092

and Roach et al.[6] The reasons are twofold: first, these measurements were made during fogs occurring under distinctly different meteorological conditions. Altogether, 37 different fogs were measured during a 5-year period under the gamut of meteorological conditions found in England. Secondly, measurements were made for a sufficiently broad range of particle sizes ($0.3\mu m < r < 72\mu m$) that errors in extinction and liquid water content due to the presence of larger and smaller droplets are estimated to be small. Of the 37 measured distributions, 3 were not used because the raw data were not available, 3 because ice crystals were present in the samples, and 5 because fog type was not specified.

The Garland and Roach et al. fog data, which already appear in figure 1, have been divided into two classes: radiation fog and advection fog. Garland has cautioned* that although the radiation fogs clearly formed in situ by radiation cooling, some fogs classified as advection type may have been mature radiation fogs transported by the wind from a distant area of formation. In any case, the data are replotted according to this classification in figure 2 ($\lambda = 0.55\mu m$) and figure 3 ($\lambda = 11\mu m$). At $\lambda = 0.55\mu m$, it is evident that radiation fogs are generally more effective scatterers, and hence more effective in reducing visibility, than advection fogs with the same liquid water content. To show the reason for this result, the differential extinction coefficients of a radiation fog (figure 2, solid circle) and an advection fog (figure 2, solid square) measurement with about the same liquid water content have been plotted versus particle radius (figure 4). Because the plots are made on a linear-linear scale, the areas under the curves are a measure of the corresponding extinction coefficients. Thus the radiation fog extinction coefficient ($35\ km^{-1}$) is more than twice the advection fog extinction coefficient ($15.8\ km^{-1}$). For the radiation fog, small droplets, let us say with $r \leq 3\mu m$, are very numerous and contribute 60 percent of the extinction without making a significant contribution to liquid water content. On the other hand for the advection fog, a broader size distribution is found and these smaller particles contribute only 6 percent of the extinction at $\lambda = 0.55\mu m$. Both the radiation and the advection fog size distributions strongly violate the maximum radius condition allowed in the $Q_e = cx$ approximation ($r_m = 0.5\mu m$ at $\lambda = 0.55\mu m$), so there is no reason to expect a unique relation between extinction at $\lambda = 0.55\mu m$ and liquid water content.

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[6]W. T. Roach et al., 1976, "The Physics of Radiation Fog: I-a Field Study," Q J Roy Meteorol Soc, 102:313-333

*J. A. Garland, private communication, 1978

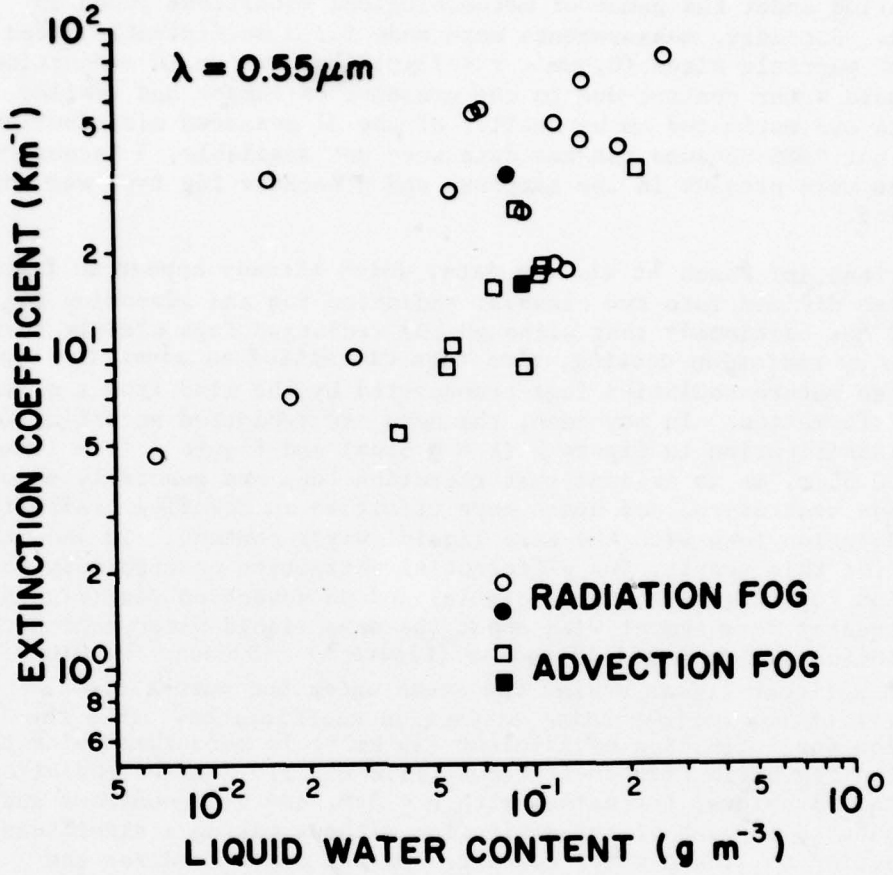


Figure 2. Same as fig. 1a except only the fog data of Garland, Garland et al., and Roach et al. are shown. The extinction and liquid water contents calculated from the 26 measured size distributions are divided according to radiation (circles) or advection (squares) fog. The figure shows that radiation fogs are generally more effective scatterers than advection fogs with the same liquid water content because they contain more droplets in the Mie resonance region that contribute a significant part of the extinction but contribute only a marginal amount to the liquid water content.

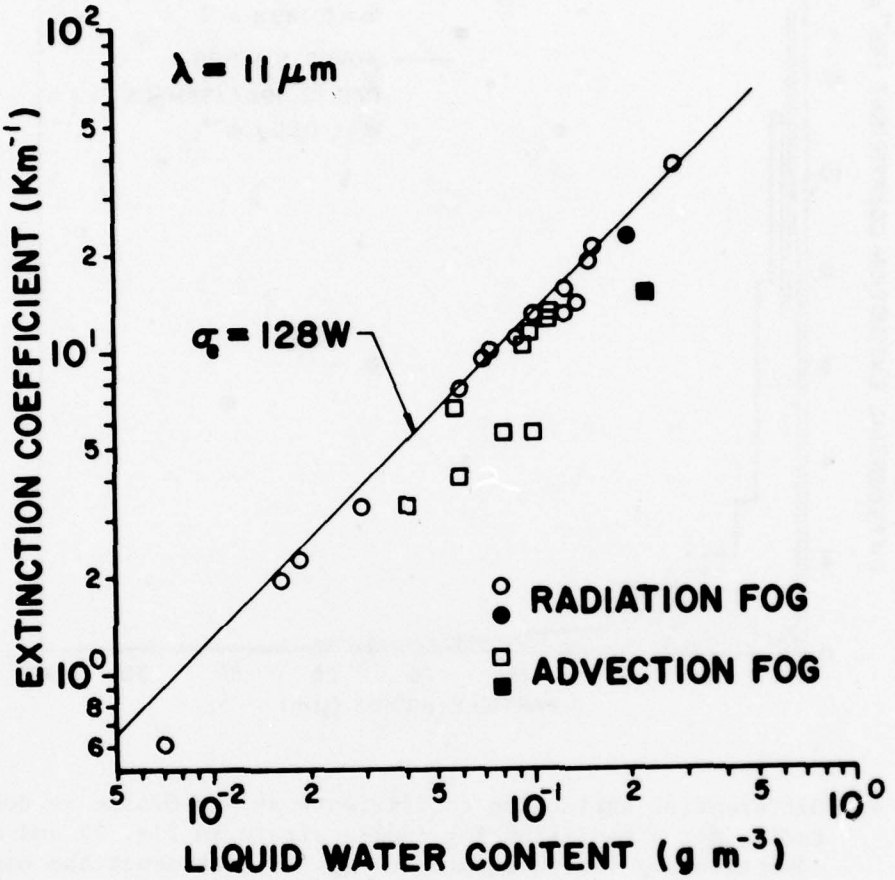


Figure 3. Same as fig. 2 except for λ = 11μm. The predicted relation between extinction and liquid water content given by eq. (1) is shown by the straight line. Because the $Q_e = cx$ approximation is generally better satisfied for radiation fogs, those points fall closer to the straight line prediction.

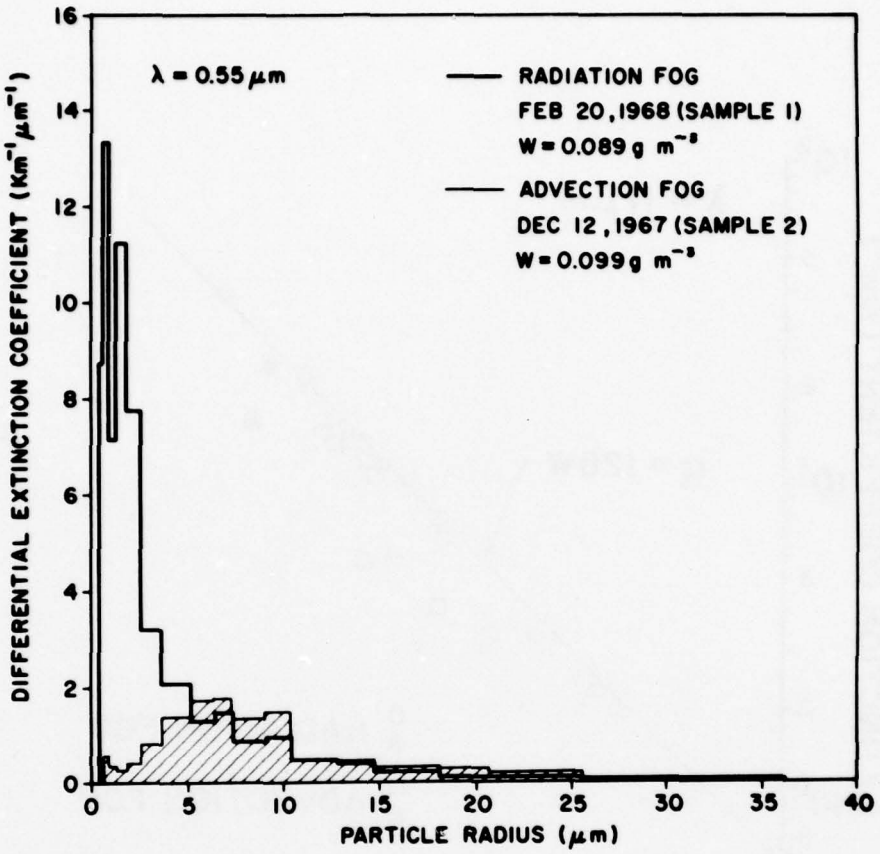


Figure 4. Differential extinction coefficients at λ = 0.55μm vs droplet radius for a radiation fog (solid circle in fig. 2) and an advection fog (solid square in fig. 2) with about the same liquid water content. The areas under the curves are a measure of the total extinction coefficients (35 km^{-1} for the radiation fog vs 15.8 km^{-1} for the advection fog). For the radiation fog, 60% of the extinction is contributed by droplets having $r \leq 3\mu m$, compared to only 6% for the advection fog.

At λ = 11μm (figure 3), although the $Q_e = cx$ approximation is within a factor of about 2 for both radiation and advection fog results, the approximation is generally in better agreement with the radiation fog results. The explanation is that the $Q_e = cx$ approximation is only strictly valid providing fog droplets have $r \lesssim 14\mu m$,[1] and radiation fogs better satisfy this condition than do advection fogs. The degree to which this maximum radius condition is violated can be determined for two fog examples from figure 5. The figure shows the differential extinction coefficient at λ = 11μm for a radiation fog (figure 3 solid circle) and an advection fog (figure 3 solid square) again having about the same liquid water content. For the radiation fog, 69 percent of the extinction arises from droplets with radii less than the maximum value $r_m = 14\mu m$, while for the advection fog this value drops to 33 percent.

A survey of all the differential extinction coefficient versus particle radius graphs similar to those shown in figure 5 for the radiation fogs of Garland[2], Garland et al.,[4] and Roach et al.[6] in figure 3 shows that in all cases extinction at λ = 11μm is dominated by droplets with $r \leq 14\mu m$. On the other hand, a survey of the differential extinction coefficient graphs for the advection fogs presented in figure 3, and also the advection fogs of Kumai,[3] shows that for about half of the distributions, extinction at λ = 11μm is dominated by droplets with $r > 14\mu m$. Since the extinction efficiency factor for these larger particles is overestimated by the $Q_e = cx$ approximation (see figure 3 of ref 1), the numerical calculation of the extinction for these advection fogs falls below the equation (1) prediction in figure 3. For the remaining half of the advection fogs, droplets with $r \leq 14\mu m$ dominate extinction and the points fall within 20 percent of the equation (1) prediction. Thus,

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[1]P. Chýlek, 1978, "Extinction and Liquid Water Content of Fogs," J Atmos Sci, 35:296-300

[2]J. A. Garland, 1971, "Some Fog Droplet Size Distributions Obtained by an Impaction Method," Q J Roy Meteorol Soc, 97:483-494

[4]J. A. Garland et al., 1973, "A Study of the Contribution of Pollution to Visibility in a Radiation Fog," Atmos Environ, 7:1079-1092

[6]W. T. Roach et al., 1976, "The Physics of Radiation Fog: I-a Field Study," Q J Roy Meteorol Soc, 102:313-333

[3]M. Kumai, 1973, "Arctic Fog Droplet Size Distribution and Its Effect on Light Attenuation," J Atmos Sci, 30:635-643

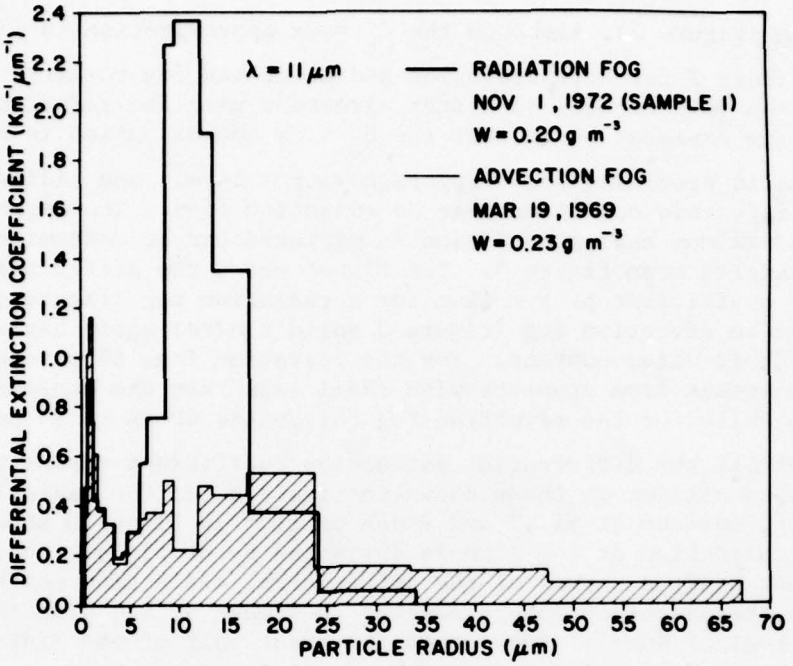


Figure 5. Differential extinction coefficients at λ = 11μm vs droplet radius for a radiation fog (solid circle in fig. 3) and an advection fog (solid square in fig. 3) with about the same liquid water content. The total extinction for the radiation fog is 22.6 km^{-1} compared to 15.0 km^{-1} for the advection fog. The fraction of extinction contributed by droplets with $r \leq$ 14μm (the maximum value allowed in the $Q_e = cx$ approximation) is 69% for the radiation fog, decreasing to 33% for the advection fog. Thus the prediction between extinction (at λ = 11μm) and liquid water content (given by eq. (1) and shown in fig. 3) is a better approximation for radiation fogs than for advection fogs.

while droplets with $r \leq 14\mu m$ dominate extinction at $\lambda = 11\mu m$ for radiation fog, this is not always the case for advection fog, where the presence of larger droplets partially destroys the size distribution independent linear relation (1).

To show the transition of the extinction versus liquid water content results for wavelengths between $\lambda = 0.55\mu m$ and $\lambda = 11\mu m$, included in the appendix (figures A-12 through A-17) are numerical calculations of extinction versus liquid water content for the fog distributions of Garland,[2] Garland et al.,[4] and Roach et al.[6] for $\lambda = 1.2\mu m$, $3\mu m$, $4\mu m$, $5\mu m$, $8\mu m$, and $10\mu m$. Again, because of the Army's interest in relating visibility to infrared extinction in fogs, these Garland and Roach results are replotted in the form of extinction coefficient at various infrared wavelengths versus extinction at $\lambda = 0.55\mu m$ (appendix, figures A-18 through A-24). The results are divided according to fog type (radiation and advection) in each figure. In addition to the Mie-calculated numerical results, empirical power-law relationships are shown that relate extinction at a particular infrared wavelength to extinction at $\lambda = 0.55\mu m$. These power-law relationships, which appear as straight lines in figures A-18 through A-24, represent a least square fit to the numerical results for radiation fogs and for the advection fogs. Because of the relatively large spread in the numerical result data points, the empirical relations derived from these data points are rather precarious, and should therefore be used only as a rough indication of the wavelength variation of extinction coefficient in radiation and advection fogs. These figures show that extinction in advection fogs tends to be more neutral (wavelength independent) than in radiation fogs (completely neutral extinction would correspond to a 45-degree line in figures A-18 through A-24). Such a result is expected because advection fogs generally have a broader distribution of droplet sizes than do radiation fogs.

$Q_a = c'x$ APPROXIMATION FOR ABSORPTION

Realizing that the $Q_e = cx$ approximation works reasonably well for fog at $\lambda \cong 11\mu m$, and for haze at shorter wavelengths, an investigation was made to

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[2]J. A. Garland, 1971, "Some Fog Droplet Size Distributions Obtained by an Impaction Method," Q J Roy Meteorol Soc, 97:483-494

[4]J. A. Garland et al., 1973, "A Study of the Contribution of Pollution to Visibility in a Radiation Fog," Atmos Environ, 7:1079-1092

[6]W. T. Roach et al., 1976, "The Physics of Radiation Fog: I-a Field Study," Q J Roy Meteorol Soc, 102:313-333

see if a similar approximation for fog droplet absorption might hold in the λ = 3 to 5μm and λ = 8 to 12μm atmospheric window spectral regions.

The absorption coefficient σ_a for a polydispersion of droplets described by the size distribution n(r) is given by

$$\sigma_a = \int \pi r^2 Q_a(m,x)\ n(r)\ dr \qquad (5)$$

where Q_a (m,x) is the Mie efficiency factor for absorption for a water droplet with refractive index m (λ) and size parameter $x = 2\pi r/\lambda$. Plots of the efficiency factor for absorption Q_a vs x for λ = 3.8 and 9.5μm are shown in figures 6 and 7. As Chýlek[1] found for extinction, the efficiency factor for absorption Q_a can be well approximated by $Q_a\ (x,\lambda) \doteq c'(\lambda)x$, providing $x \leq x_m$.

Using this linear approximation for Q_a in equation (5) gives

$$\sigma_a = \frac{3\pi c'}{2\lambda} \int \frac{4\pi r^3}{3}\ n(r)dr. \qquad (6)$$

Thus, explicit dependence on the size distribution disappears and leads to the absorption coefficient being linearly related to liquid water content W according to

$$\sigma_a = \frac{3\pi c'}{2\lambda\rho} W. \qquad (7)$$

As in the case of extinction, the restriction that $x \leq x_m$ need not be strictly satisfied, but water droplets with radii greater than the value $r_m = \frac{\lambda x_m}{2\pi}$ must not contribute excessively to either absorption or liquid water content. Numerical values of the maximum radii r_m at various

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[1]P. Chýlek, 1978, "Extinction and Liquid Water Content of Fogs," J Atmos Sci, 35:296-300

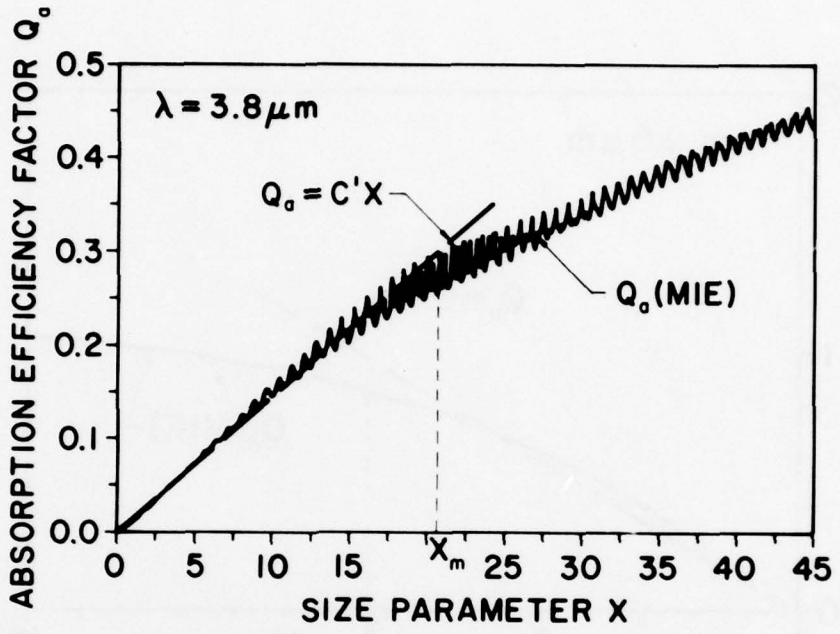


Figure 6. The efficiency factor for absorption Q_a for water versus droplet size parameter x at a wavelength λ = 3.8μm (index of refraction m = 1.364 - 0.0034i). The efficiency factor can be approximated by a straight line $Q_a = c'x$ providing $x \leq x_m$. The approximation overestimates the exact value of Q_a for some size parameters, but underestimates it for others. These two errors tend to cancel, leading to the absorption coefficient being linearly related to liquid water content according to eq. (7).

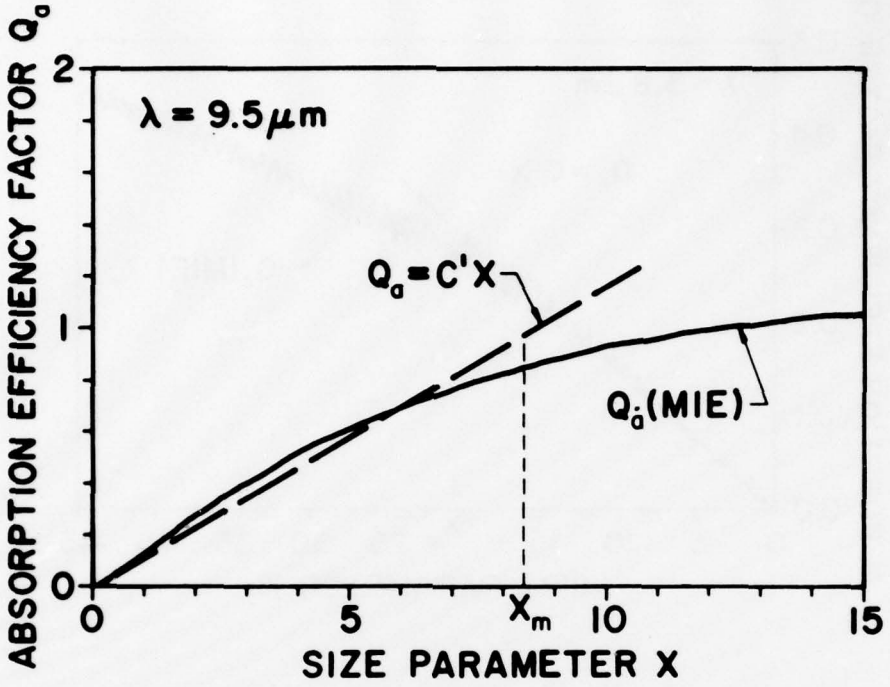


Figure 7. Same as fig. 6 except for λ = 9.5μm (index of refraction of water m = 1.243 - 0.0443i). The efficiency factor for absorption can again be approximated by a straight line Q_a = c'x providing $x \leq x_m$.

wavelengths λ, as well as the slope c' of a straight line approximating Q_a for $x \leq x_m$, are given in table 1. Also given are values of the quantity $\frac{3\pi c'}{2\lambda\rho}$ which if multiplied by the liquid water content give the absorption coefficient. In order that these predicted relationships (and maximum radius conditions) between droplet absorption and liquid water content may be compared to the corresponding results for extinction, the values of x_m, r_m, etc., for the $Q_e = cx$ approximation[1] for extinction also appear in table 1. The values of x_m, r_m, and c for extinction are sometimes slightly different from those of Chýlek[1] since there is some leeway in the subjective procedure for approximating the efficiency factor $Q_e(x)$ by a linear function of size parameter x. The table shows that the limiting radius r_m depends strongly on wavelength and is in general markedly different for absorption and extinction at a particular wavelength. An exception is at $\lambda = 9.5\mu m$, where the limiting radii are $r_m = 13\mu m$ for absorption as compared to $r_m = 12.5\mu m$ for extinction. Thus for fog droplet distributions that have radii $r < 12.5\mu m$ (i.e., most radiation fogs) from table 1 a prediction can be made that absorption contributes 29 percent of the extinction at $\lambda = 9.5\mu m$, independent of the form of the droplet size distribution. However, there is obviously no unique relation between fog absorption and extinction for all wavelengths.

Since the $Q_e = cx$ approximation for extinction at $\lambda = 11\mu m$, which requires droplets have maximum radius $r_m = 14\mu m$, is adequate for atmospheric fog, the $Q_a = c'x$ approximation for absorption should be adequate for fog at selected wavelengths also having $r_m \approx 14\mu m$. Table 1 shows that wavelengths $\lambda = 3.8\mu m$, $4\mu m$, $5.3\mu m$, and $9.5\mu m$ either satisfy or nearly satisfy this criterion. Therefore, a linear relation might be expected between fog absorption and fog liquid water content according to equation (7), independent of the droplet size distribution, for these particular wavelengths.

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[1]P. Chýlek, 1978, "Extinction and Liquid Water Content of Fogs," J Atmos Sci, 35:296-300

TABLE 1. PARAMETERS FOR THE LINEAR RELATION BETWEEN IR ABSORPTION, EXTINCTION, AND LIQUID WATER CONTENT OF FOGS

At a given wavelength λ the efficiency factor for absorption Q_a (and extinction Q_e) can be approximated by a straight line $Q_a = c'x$ ($Q_e = cx$) for size parameters $x \leq x_m$. The values of x_m and c' (and c) are determined from the efficiency curves (see for example figs. 6 and 7). If we know the maximum radius r_m of droplets in a given size distribution, from the table we can find the wavelength λ at which a linear relationship between absorption (or extinction) and liquid water content exists, and the appropriate value of the parameter c' (or c). The value of the quantity $\frac{3\pi c'}{2\lambda\rho}$ (or $\frac{3\pi c}{2\lambda\rho}$) multiplied by the liquid water content W gives the absorption coefficient σ_a (or extinction coefficient σ_e).

	ABSORPTION				EXTINCTION			
λ (μm)	x_m	$r_{m(\mu m)}$	c'	$\frac{3\pi c'}{2\lambda\rho}$ ($cm^2 g^{-1}$)	x_m	$r_{m(\mu m)}$	c	$\frac{3\pi c}{2\lambda\rho}$ ($cm^2 g^{-1}$)
3.0	2.3	1.1	0.58	9.1×10^3	3.2	1.5	0.85	13.3×10^3
3.5	14	8.0	0.037	0.50 "	5.9	3.3	0.72	9.6 "
3.8	21	13	0.015	0.18 "	6.5	4.0	0.66	8.2 "
4.0	22	14	0.018	0.22 "	6.7	4.3	0.64	7.6 "
4.5	14	10	0.047	0.49 "	7.0	5.0	0.59	6.1 "
5.0	14	11	0.044	0.41 "	7.2	5.8	0.56	5.3 "
5.3	16	14	0.035	0.31 "	7.5	6.3	0.56	5.0 "
8.0	7.6	9.7	0.10	0.61 "	7.3	9.3	0.51	3.0 "
8.5	8.2	11	0.11	0.60 "	7.9	10.7	0.45	2.5 "
9.0	8.0	12	0.11	0.57 "	8.0	11.5	0.44	2.3 "
9.5	8.4	13	0.12	0.58 "	8.2	12.5	0.41	2.0 "
10.0	7.0	11	0.13	0.60 "	8.8	14	0.38	1.8 "
10.5	6.0	10	0.16	0.70 "	8.6	14	0.33	1.5 "
11.0	4.1	7.2	0.21	0.93 "	8.1	14	0.31	1.3 "
11.5	3.1	5.7	0.30	1.26 "	5.0	9.1	0.37	1.5 "
12.0	2.3	4.5	0.42	1.65 "	4.9	9.3	0.44	1.7 "
12.5	1.9	3.7	0.58	2.2 "	3.7	7.3	0.58	2.2 "

To check this contention, a Mie scattering program was used to calculate the volume absorption coefficient $\sigma_a(\lambda)$ according to equation (5) for the previously mentioned 341 fog and haze size distributions at several different wavelengths. As in the extinction calculations, particle refractive indexes of water have been assumed, and thus refractive index differences that might be caused by the presence of contaminants such as sea salt and ammonium sulfate have been neglected. The results at λ = 3.8 and 9.5μm plotted as a function of fog liquid water content together with the $Q_a = c'x$ approximation (7) are shown in figures 8 and 9. The figures show that although the numerical results are slightly better approximated at λ = 3.8μm as compared to λ = 9.5μm, at both wavelengths the linear relation (7) is within a factor 2.5 of the numerical results for all 341 fog and haze size distributions. Examination of results at numerous other infrared wavelengths (given in the appendix, figures A-25 through A-37) shows that even though the maximum radius condition is sometimes violated, for λ = 3.5 to 5.3μm, and 8 to 10μm all numerical results for the 341 fog distributions are within a factor 2.5 of the predictions between absorption and liquid water content given by relation (7) and listed in table 1, and in most cases the agreement is within a factor 2. However, at wavelengths λ = 10.5 to 12μm, the numerical results differ by as much as a factor 4 from the linear relation (7).

Previously Platt[16] found an approximate linear relation between the absorption coefficient σ_a at λ = 11μm and liquid water content W of nonprecipitating stratocumulus clouds. Platt performed Mie calculations on 25 measured cloud droplet distributions, plotted the values of σ_a at λ = 11μm versus W, did a least squares fit through the resulting data points, and obtained $\sigma_a = 76.5$ W, comparing modestly well with the equation (7) prediction from table 1 of $\sigma_a = 93$ W, where the absorption is in km^{-1} and the liquid water content in g m^{-3}. The reason for the over-prediction of the absorption is that a significant number of droplets in Platt's distributions have radii greater than 7.2μm, the maximum value allowable in the $Q_a = c'x$ approximation at λ = 11μm. Had Platt chosen a slightly shorter wavelength, say λ = 9.5μm, he would have found an even better correlation of absorption and liquid water content, as well as better agreement with our linear prediction (7), since the maximum radius restriction is more nearly satisfied for clouds at the shorter wavelength.

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[16]C. M. R. Platt, 1976, "Infrared Absorption and Liquid Water Content in Stratocumulus Clouds," Q J Roy Meteorol Soc, 102:553-561

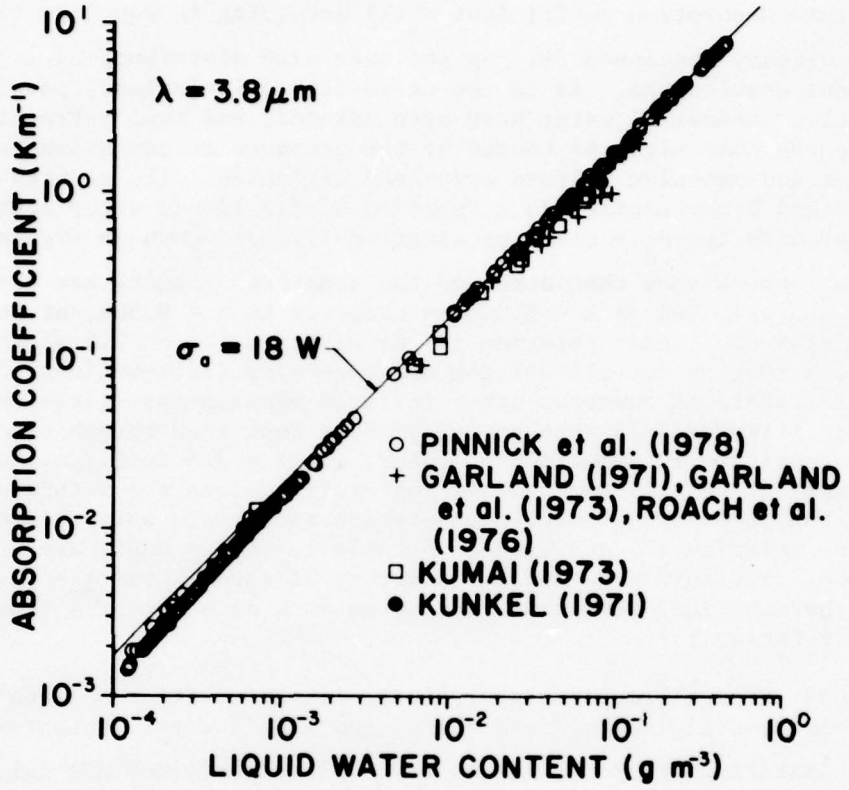


Figure 8. Variation of absorption coefficient with liquid water content in atmospheric fog and haze for 341 size distribution measurements made at different geographic locales and under a variety of meteorological conditions. In the infrared region around $\lambda = 3.8\mu m$, there exists a linear size distribution independent relation between the volume absorption coefficient σ_a and the liquid water content W of the form of eq. (7). Consequently, the results of all measurements are close to a straight line. The predicted relation between absorption σ_a and liquid water content W according to eq. (7) is shown by the straight line, where σ_a is in km^{-1} and W is in g m^{-3}.

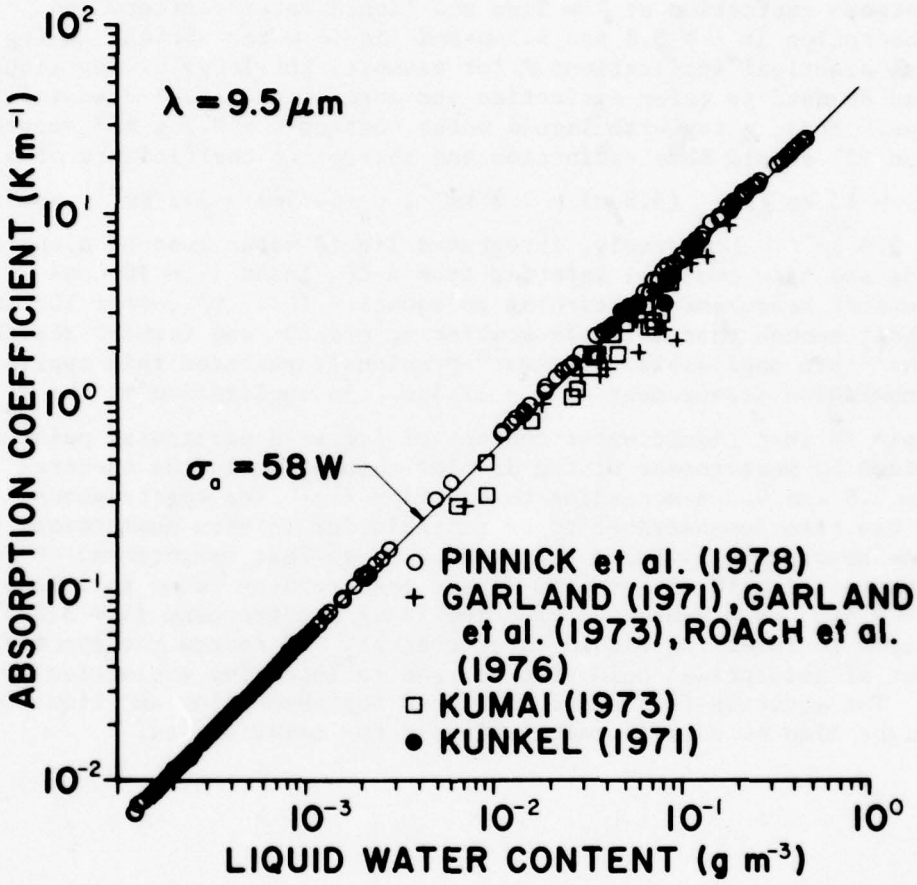


Figure 9. Same as figure 8 except for λ = 9.5μm.

APPLICATION OF EXTINCTION-ABSORPTION-LIQUID WATER CONTENT RELATIONSHIPS

The unique linear relationship, which is independent of the size distribution, between extinction at $\lambda \cong 11\mu m$ and liquid water content, and between absorption at $\lambda \cong 3.8$ and $9.5\mu m$ and liquid water content in fog has several practical applications. For example, knowledge of fog liquid water could be used to infer extinction and absorption at selected infrared wavelengths. Thus, a fog with liquid water content $W = 0.1\ g\ m^{-3}$ according to equation (1) should have extinction and absorption coefficients of σ_e ($\lambda = 11\mu m$) = $13\ km^{-1}$, σ_a ($3.8\mu m$) = $1.8\ km^{-1}$, σ_a($5.3\mu m$) = $3.1\ km^{-1}$, and σ_a ($9.5\mu m$) = $5.8\ km^{-1}$. Conversely, integrated liquid water content along a path in fog and haze could be inferred from a CO_2 laser ($\lambda = 10.6\mu m$) transmissometer measurement according to equation (1). Of course the path must be short enough that multiple scattering effects and forward scattering corrections[17] are negligible. Carlon[18] previously realized this application for a transmission measurement at $\lambda = 12.5\mu m$. An application of the $\sigma_a - W$ relationship is that liquid water content of fog at a particular point could be determined by measurement of fog droplet absorption in the spectral region $\lambda \cong 3.8$ and $9.5\mu m$ according to equation (7). The spectrophone technique has been demonstrated to be suitable for in situ measurement of particulate absorption by Bruce and Pinnick,[19] so that measurement of fog droplet absorption with either a CO_2 laser spectrophone tuned to a wavelength $\lambda \cong 9.5\mu m$, or a deuterium fluoride laser spectrophone ($\lambda \cong 3.8\mu m$) could be used to infer fog liquid water content. Of course the spectrophone measurement of absorption could also be used to infer fog extinction at $\lambda \cong 11\mu m$. The equation (7) relation between fog absorption and liquid water content might also be used in calculation of fog emissivities.

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[17]A. Deepak and M. A. Box, 1978, "Forward Scattering Corrections for Optical Extinction Measurements in Aerosol Media. 2: Polydispersions," Appl Opt 17:3169-3176

[18]H. R. Carlon et al., 1977, "Infrared Extinction Spectra of Some Common Liquid Aerosols," Appl Opt, 16:1598-1605

[19]C. W. Bruce and R. G. Pinnick, 1977, "In-situ Measurements of Aerosol Absorption with a Resonant CW Laser Spectrophone," Appl Opt, 16:1762-1765

CONCLUSIONS

Chýlek's[1] prediction of a linear relation, which is independent of the size distribution, between extinction at $\lambda \cong 11\mu m$ and liquid water content of fog has been verified within a factor 2 for 341 different fog and haze droplet distributions measured under a variety of meteorological conditions. The prediction generally works better for radiation fogs than advection fogs. A similar linear relation between fog droplet absorption at $\lambda \cong 3.8$ and $9.5\mu m$ and liquid water content has been derived and validated using the same 341 distributions. However, there exists no size distribution independent relation between extinction in the visible ($\lambda \cong 0.55\mu m$) and fog liquid water content. Three practical applications of these findings are suggested: (1) inference of fog integrated liquid water content along a path by measurement of laser transmission (at $\lambda \cong 11\mu m$) across that path; (2) inference of fog liquid water content at a particular point from measurement of fog droplet absorption with a deuterium fluoride or CO_2 laser spectrophone, and (3) calculation of fog emissivities in the infrared from knowledge of fog liquid water content.

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[1] P. Chýlek, 1978, "Extinction and Liquid Water Content of Fogs," J Atmos Sci, 35:296-300

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APPENDIX

FOG AND HAZE EXTINCTION COEFFICIENT VS LIQUID WATER CONTENT, IR EXTINCTION COEFFICIENT VS VISIBLE EXTINCTION COEFFICIENT, AND ABSORPTION COEFFICIENT VS LIQUID WATER CONTENT

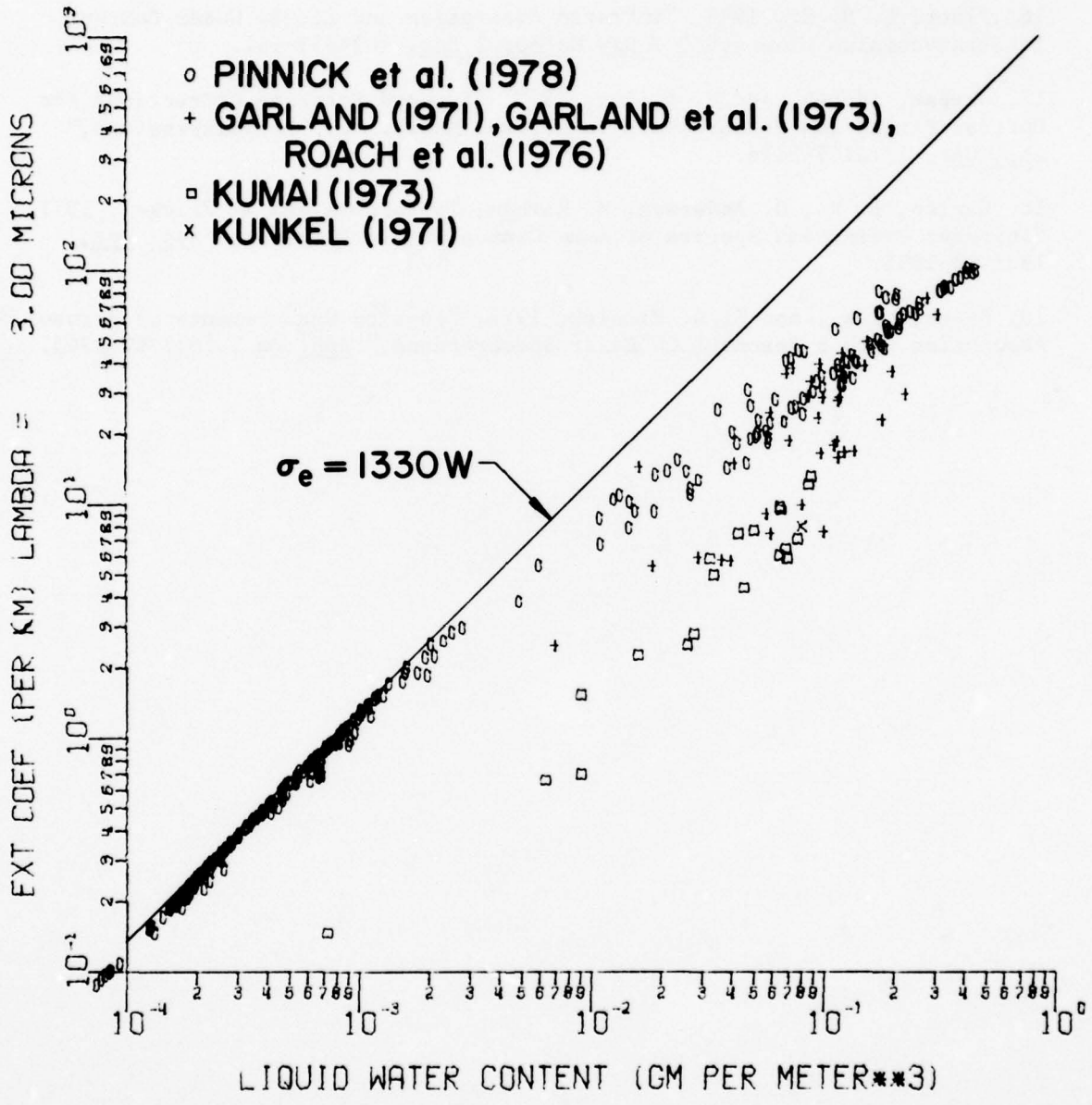


Figure A-1. Variation of extinction coefficient (at λ = 3.0μm) with liquid water content in atmospheric fog and haze for 341 size distribution measurements made at different geographic locales and under a variety of meteorological conditions. The large spread of the points in the graph shows that the extinction coefficient is a function of the size distribution as well as of the liquid water content. The predicted relation between extinction σ_e and liquid water content W according to eq. (1) is shown by the straight line, where σ_e is in km^{-1} and W is in g m^{-3}.

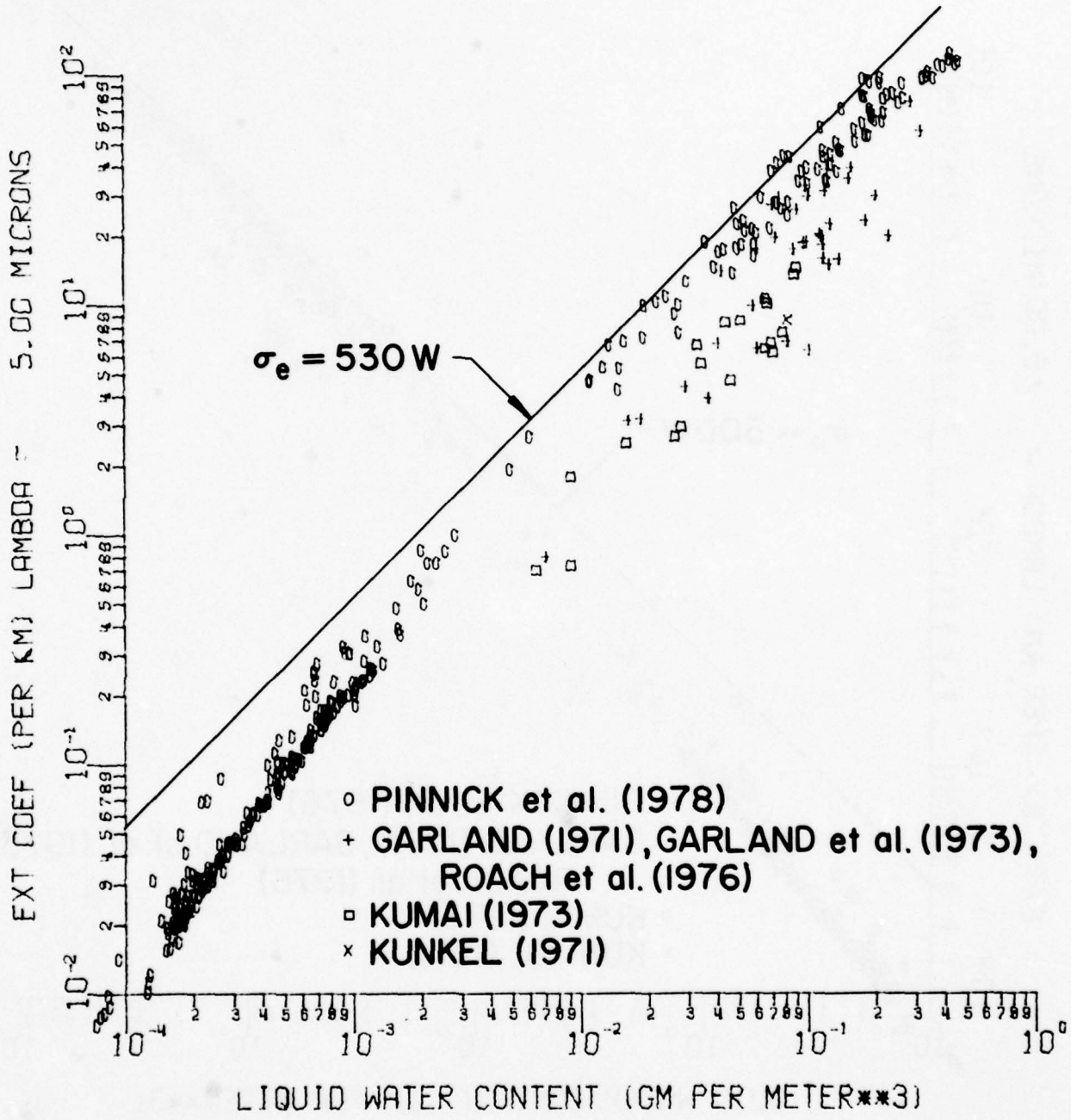


Figure A-2. Same as figure A-1 except for λ = 5μm.

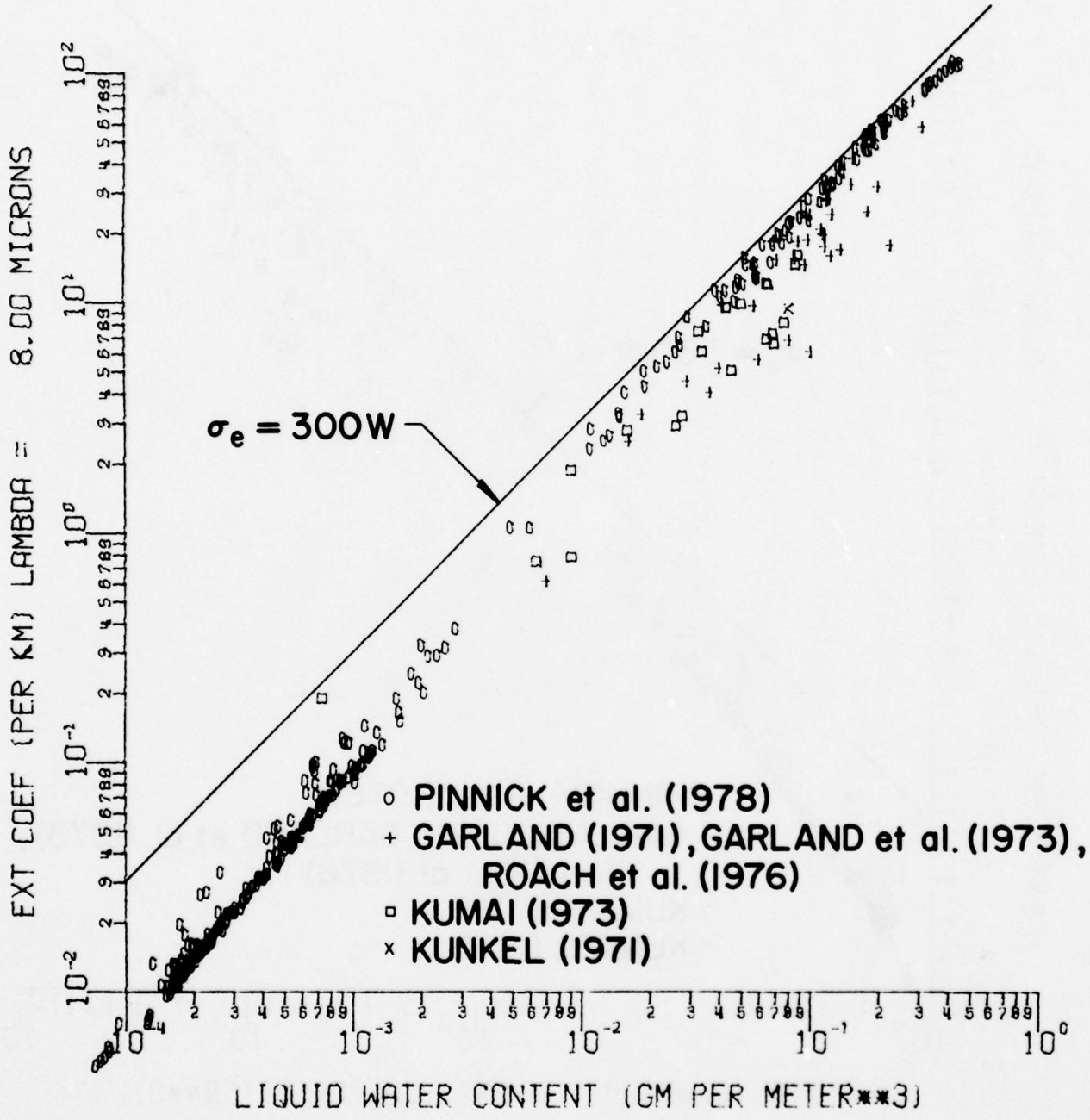


Figure A-3. Same as figure A-1 except for λ = 8μm.

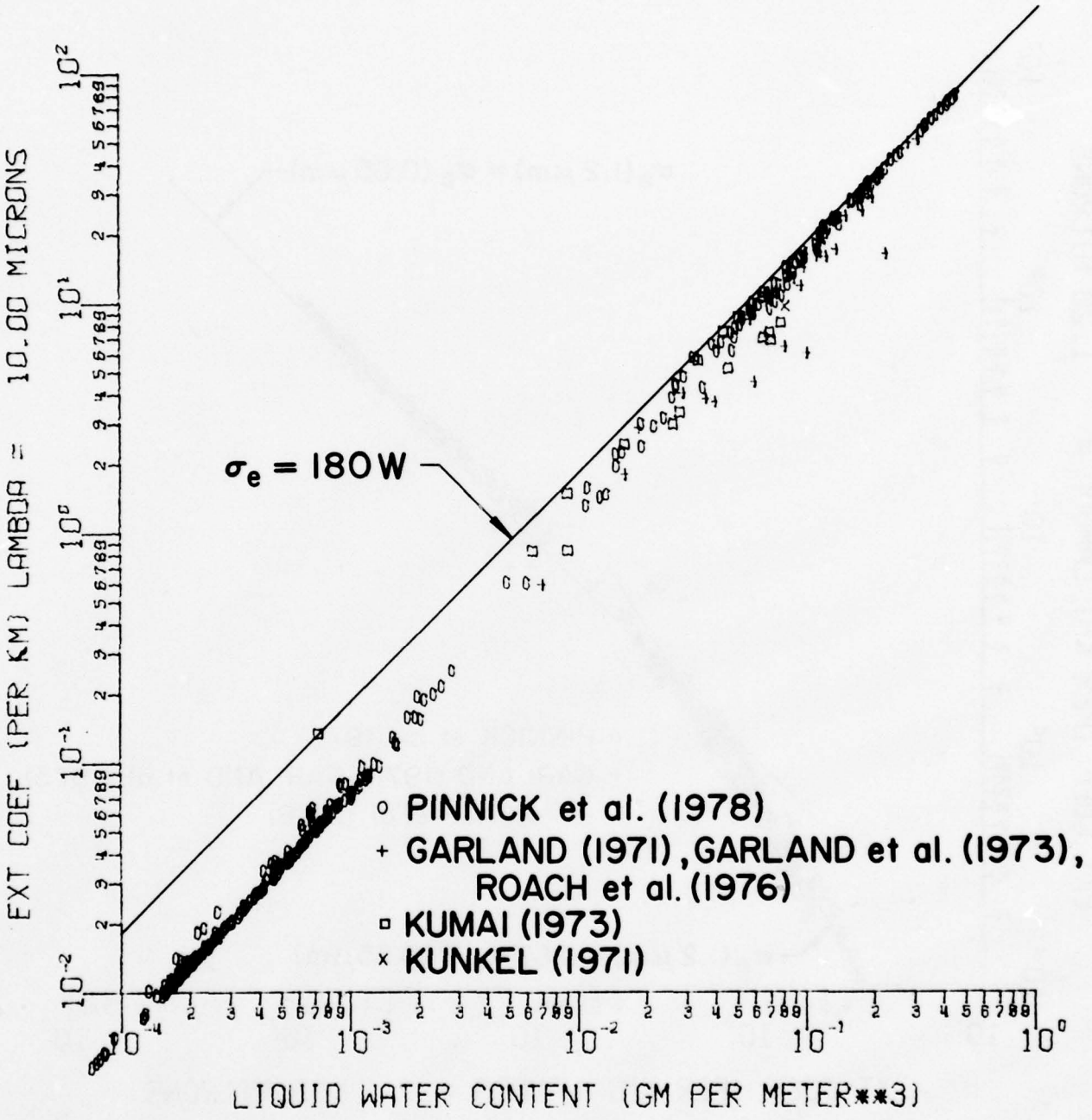


Figure A-4. Same as figure A-1 except for λ = 10μm.

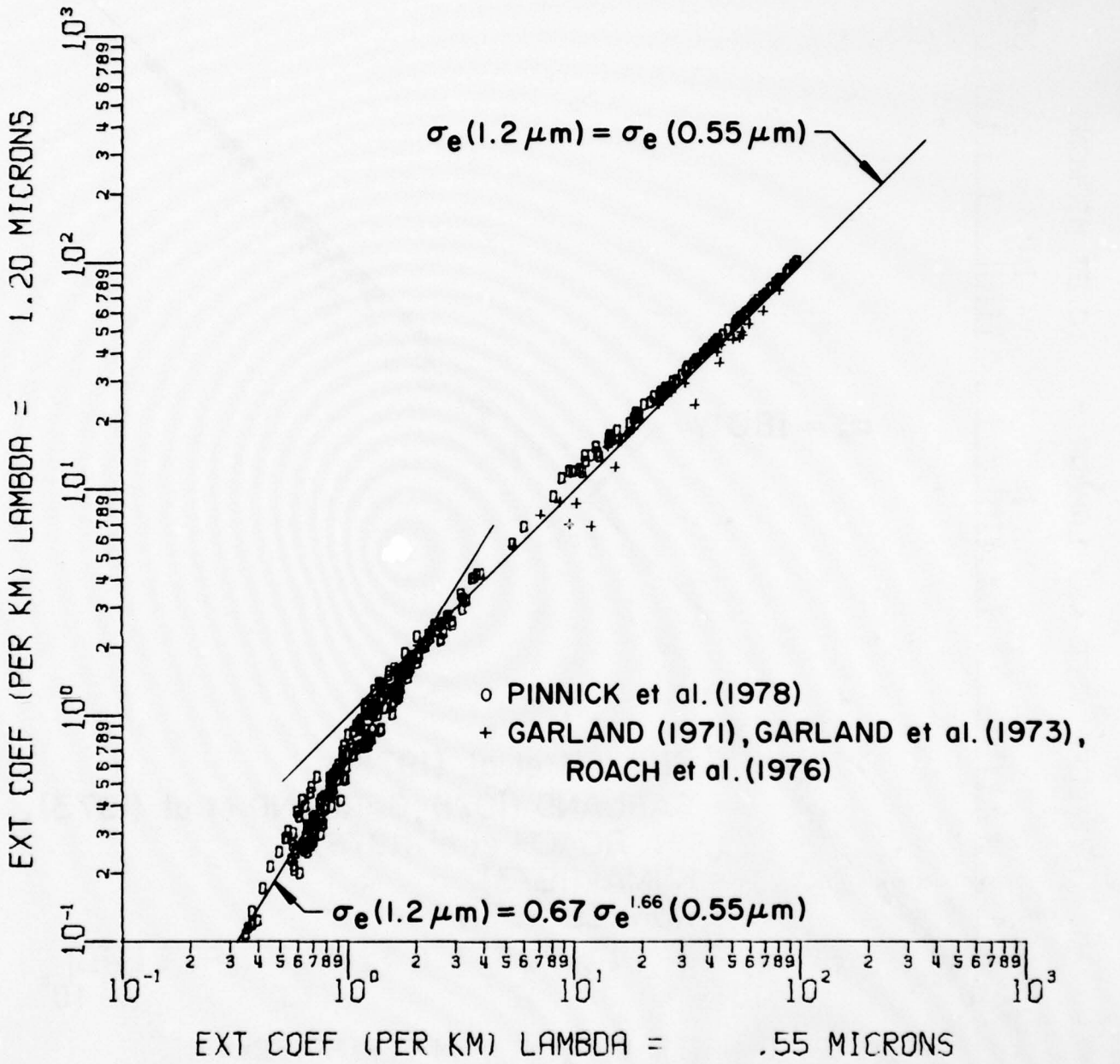


Figure A-5. Variation of the infrared extinction coefficient at λ = 1.2μm with visible extinction coefficient (λ = 0.55μm) in atmospheric fog and haze for 341 size distribution measurements made at different geographic locales and under a variety of meteorological conditions. The spread of the points in the graph shows that the infrared extinction coefficient is a function of the size distribution as well as of the visible extinction coefficient. Also shown are empirical power-law relationships fit to the Mie-calculated points.

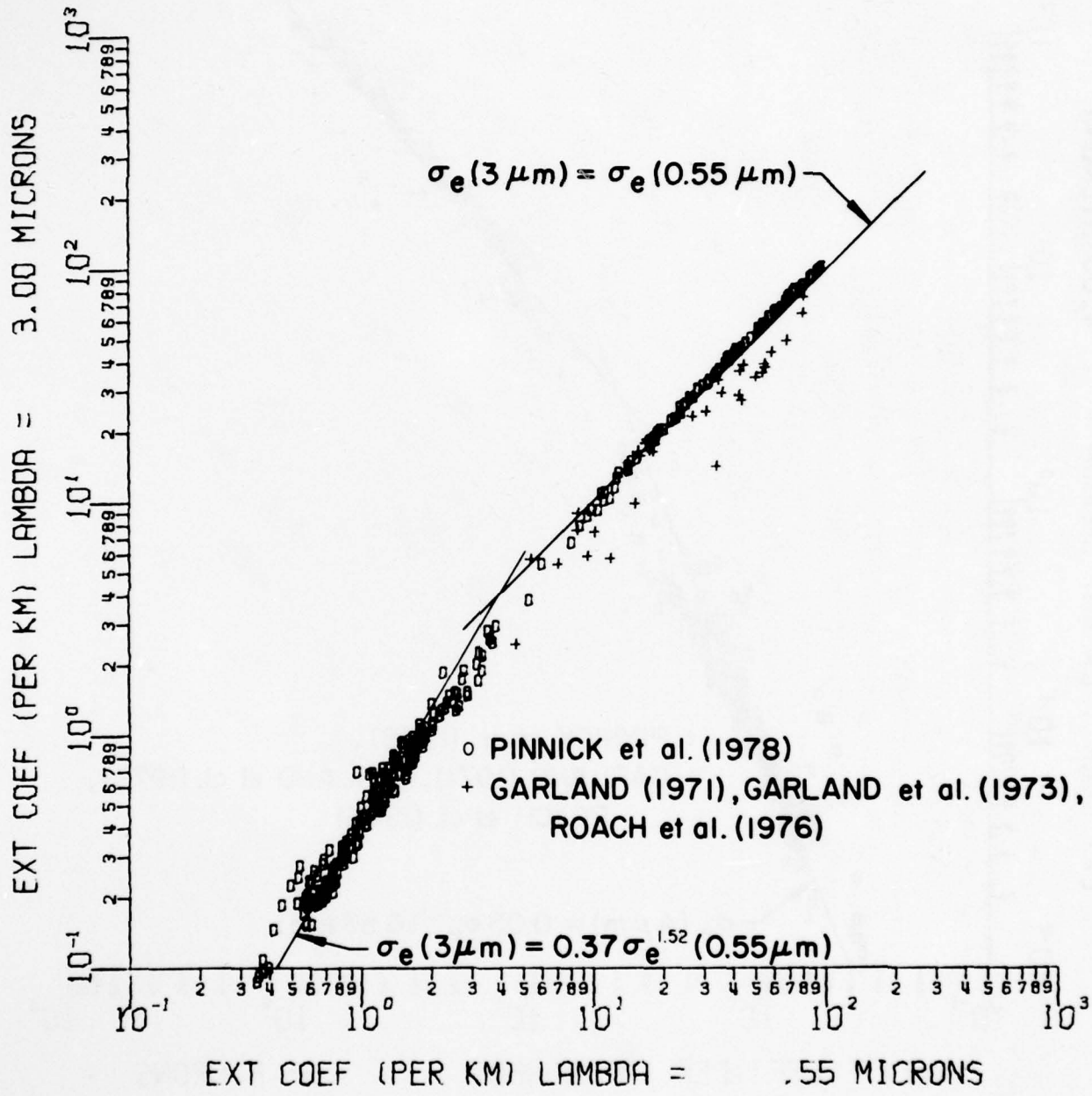


Figure A-6. Same as figure A-5 except for the infrared wavelength λ = 3μm.

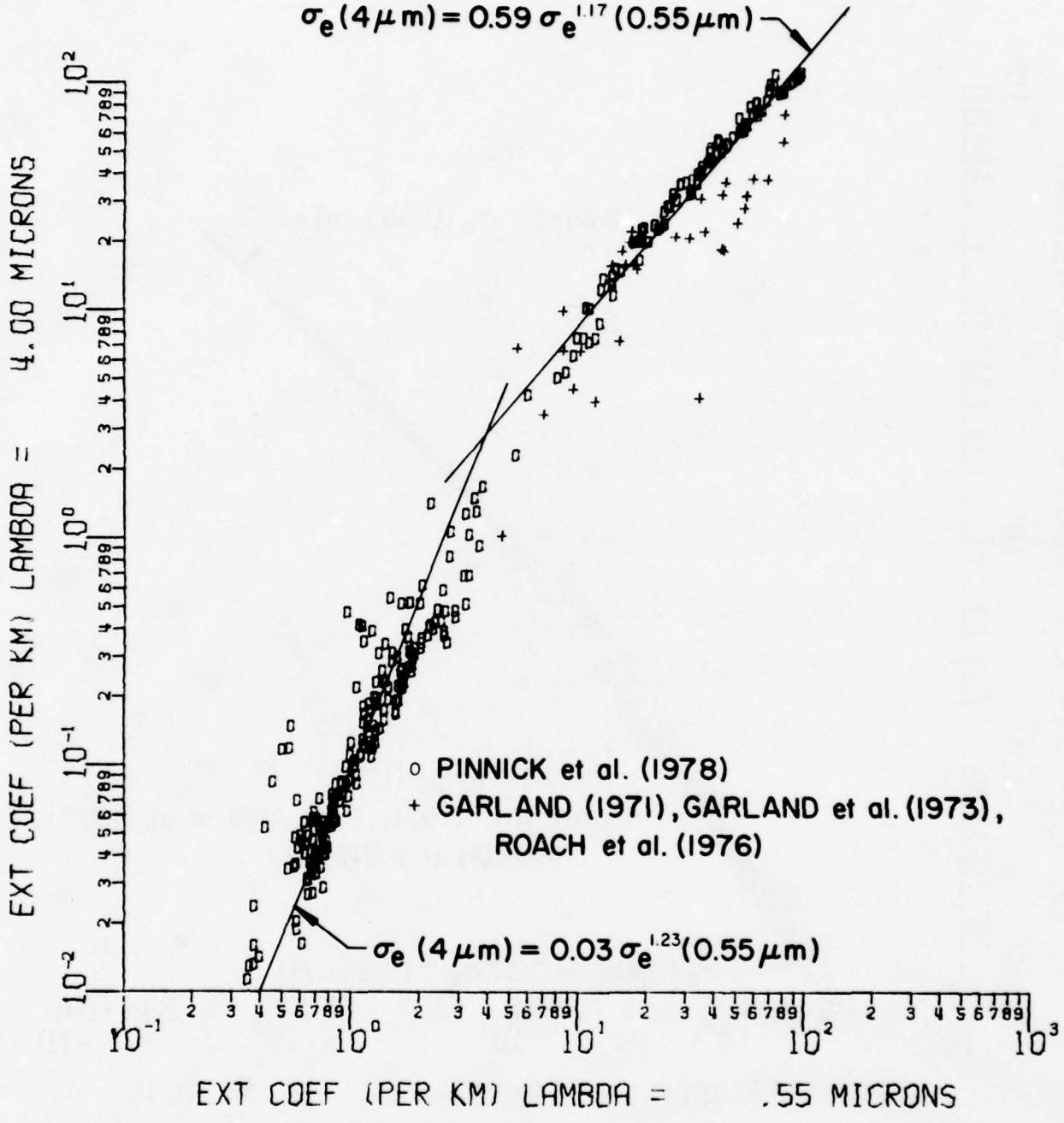


Figure A-7. Same as figure A-5 except for the infrared wavelength λ = 4μm.

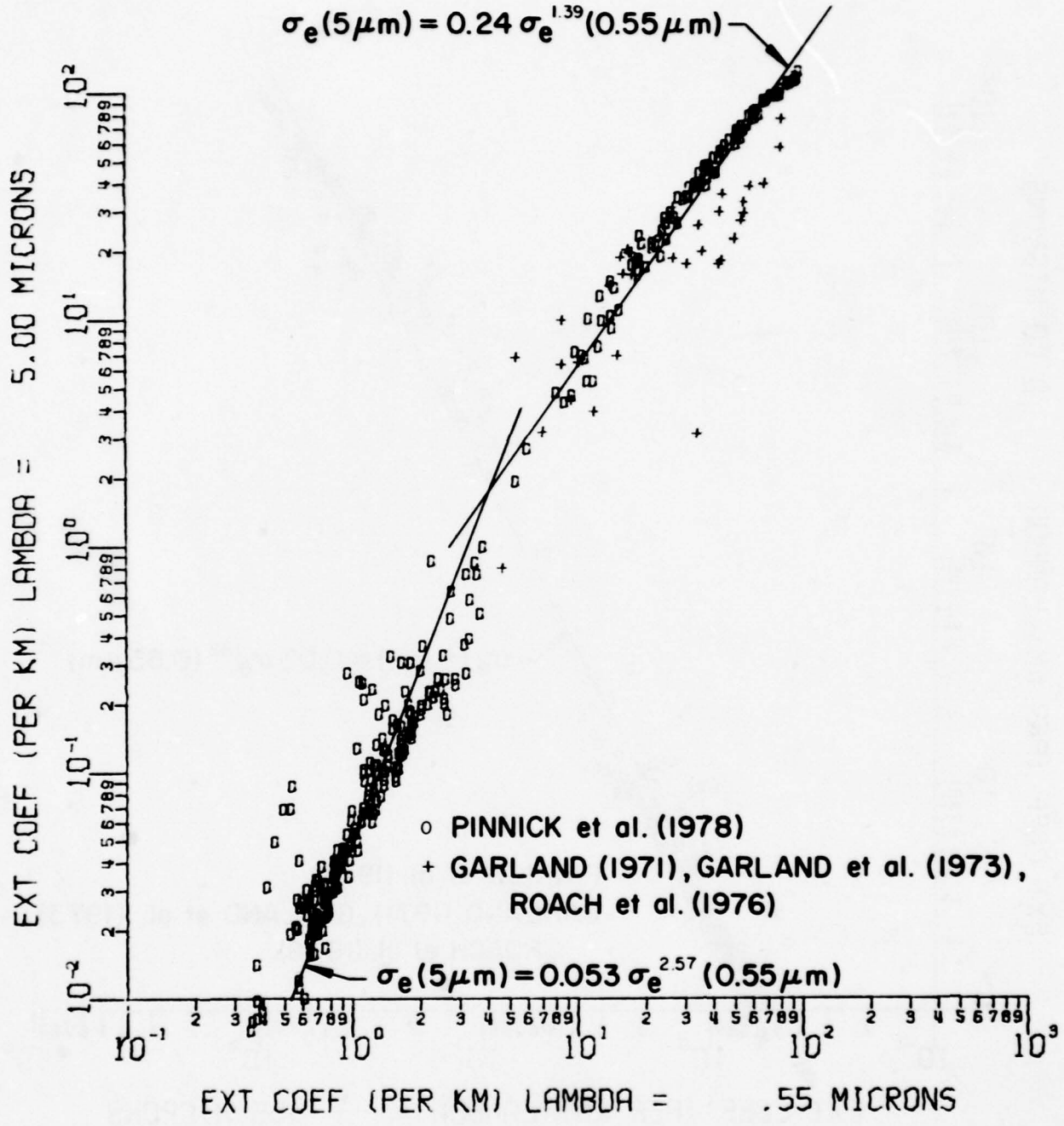


Figure A-8. Same as figure A-5 except for the infrared wavelength λ = 5μm.

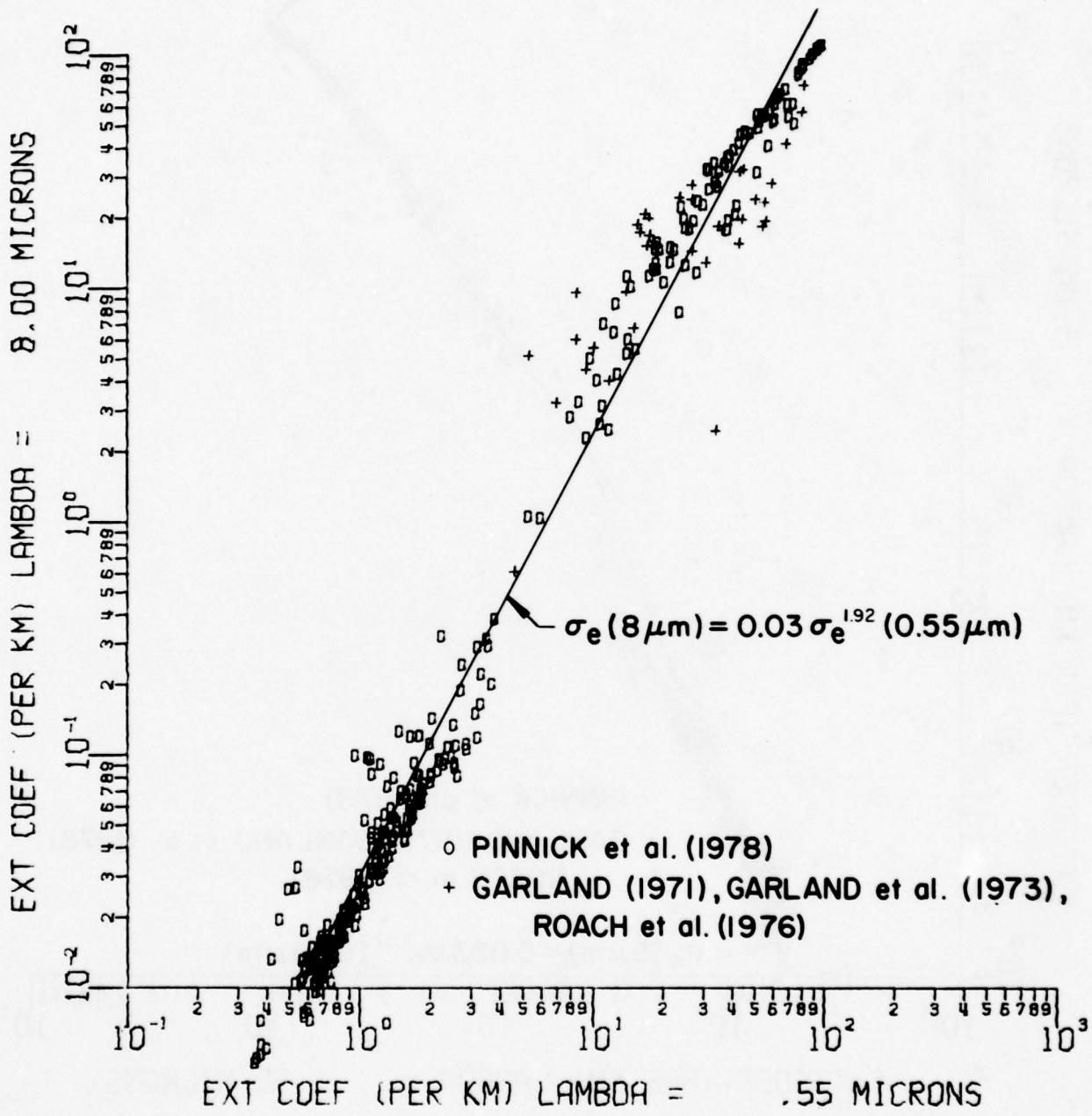


Figure A-9. Same as figure A-5 except for the infrared wavelength λ = 8μm.

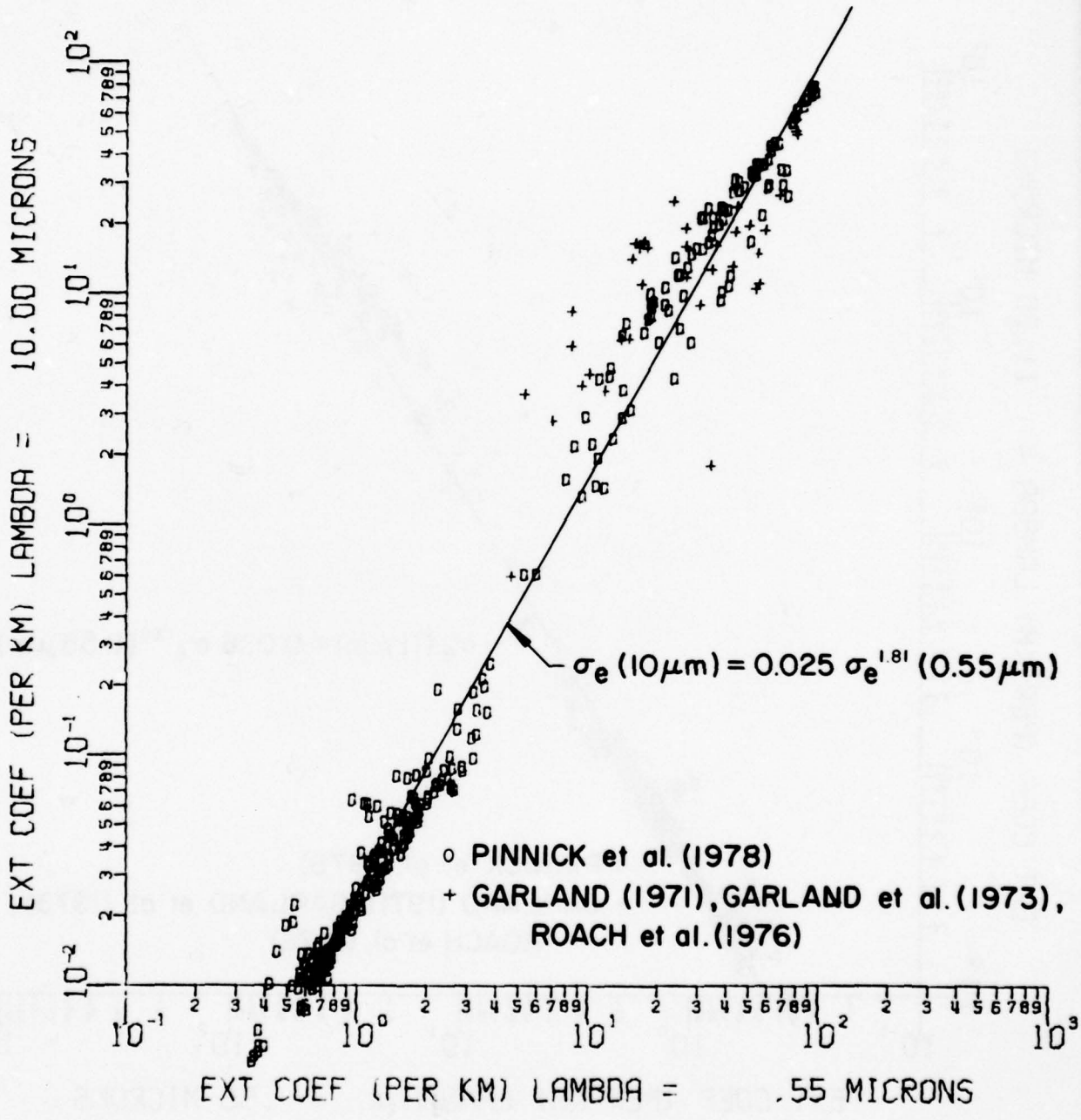


Figure A-10. Same as figure A-5 except for the infrared wavelength λ = 10μm.

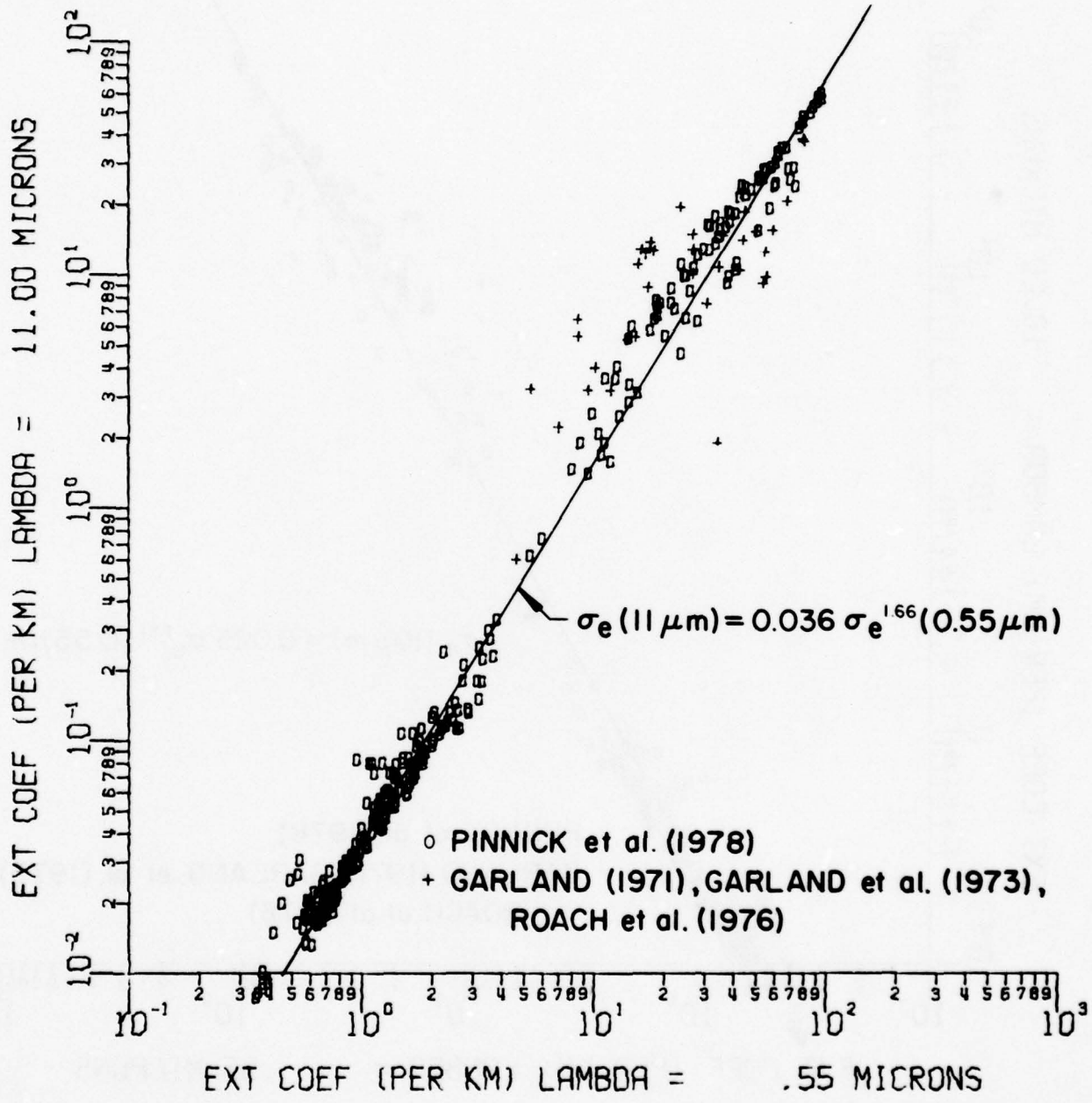


Figure A-11. Same as figure A-5 except for the infrared wavelength λ = 11μm.

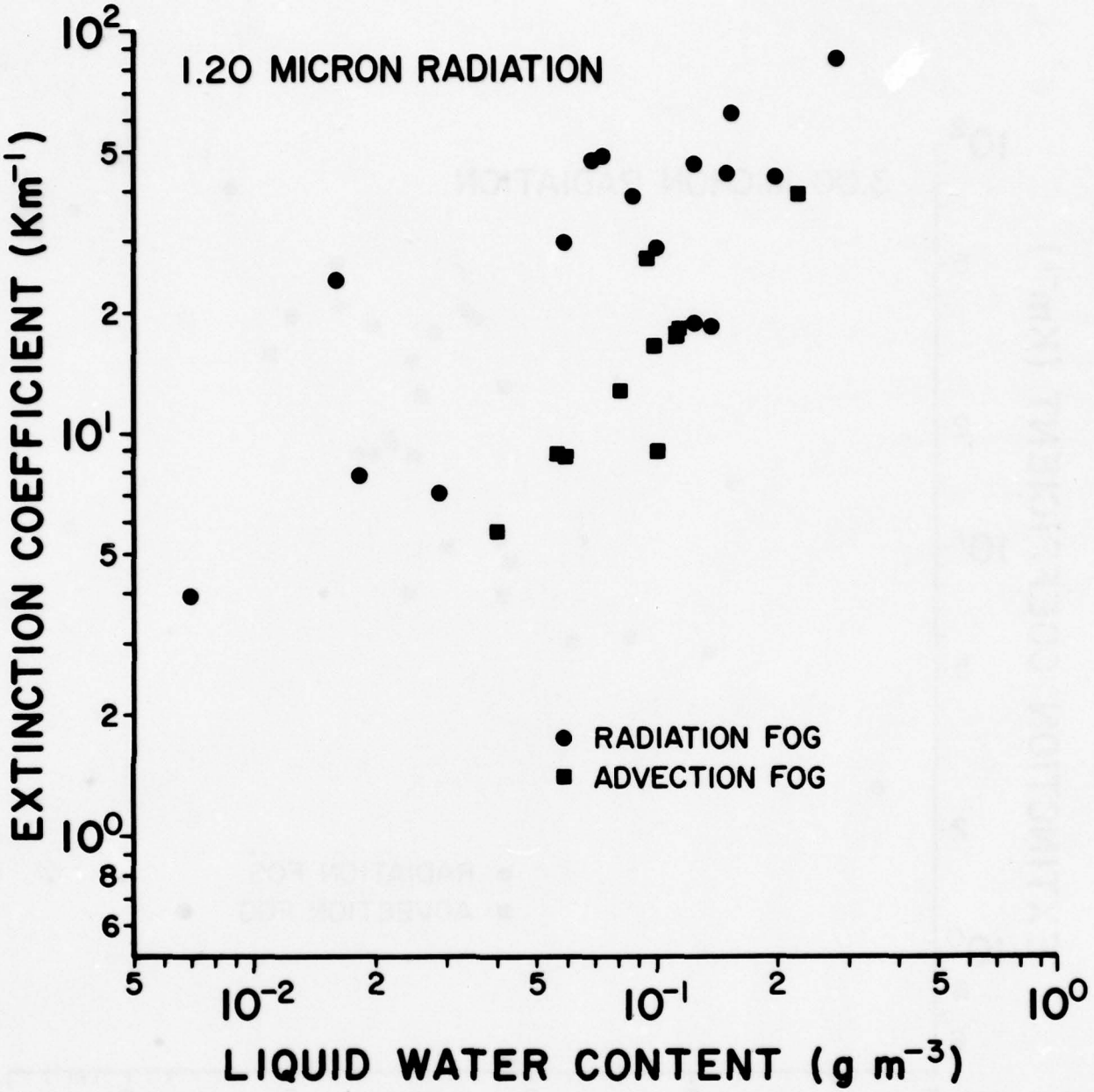


Figure A-12. Variation of extinction coefficient (at λ = 1.2μm) with liquid water content in atmospheric fog for 26 size distribution measurements made over an approximate 5-year period under a variety of meteorological conditions in England. The large spread of the points in the graph shows that the extinction coefficient is a function of the size distribution as well as of the liquid water content. The extinction and liquid water contents calculated from the measured size distributions are divided according to radiation (circles) or advection (squares) fog. We see from the figure that radiation fogs are generally more effective scatterers than advection fogs with the same liquid water content.

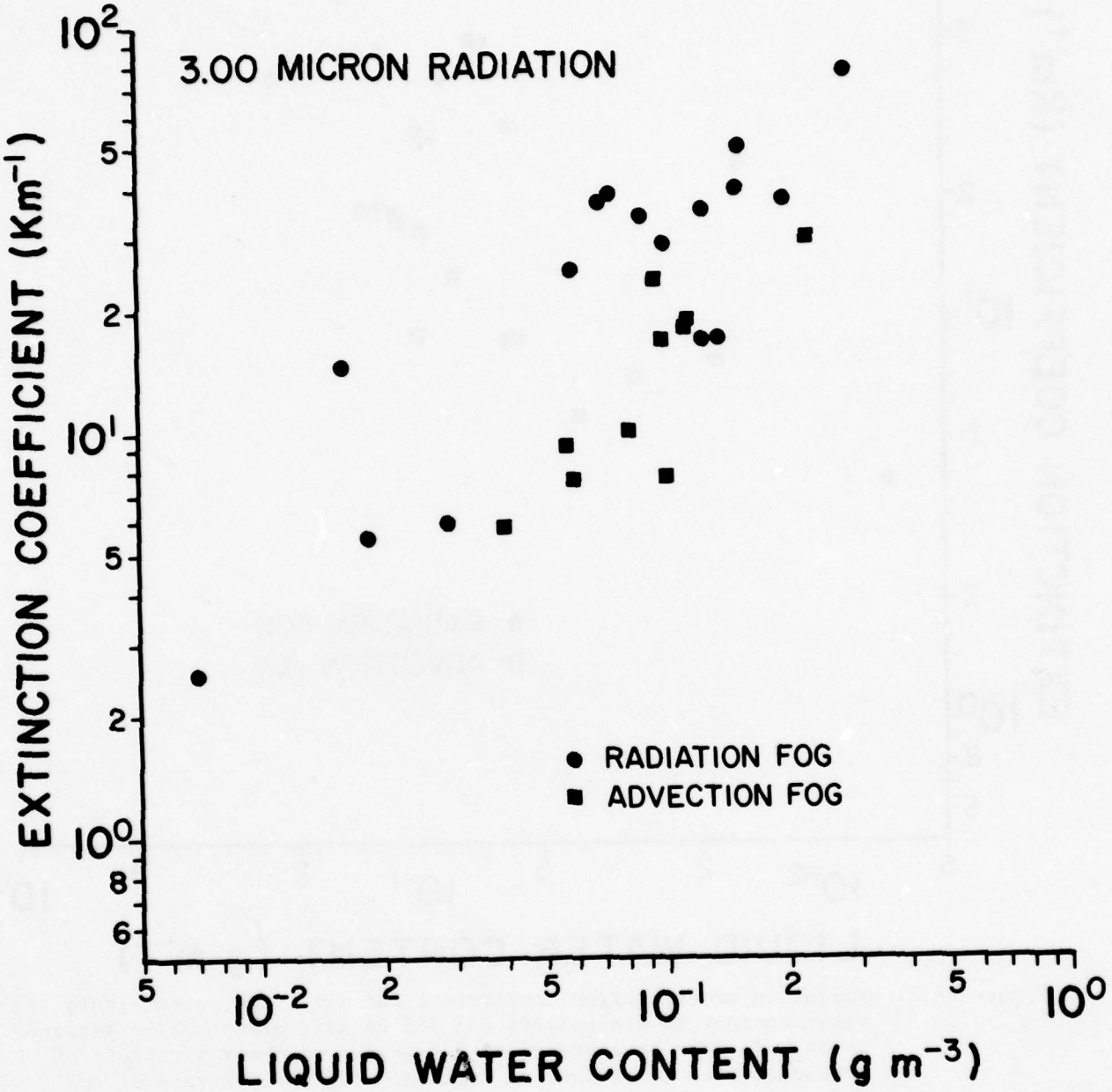


Figure A-13. Same as figure A-12 except for = 3.m.

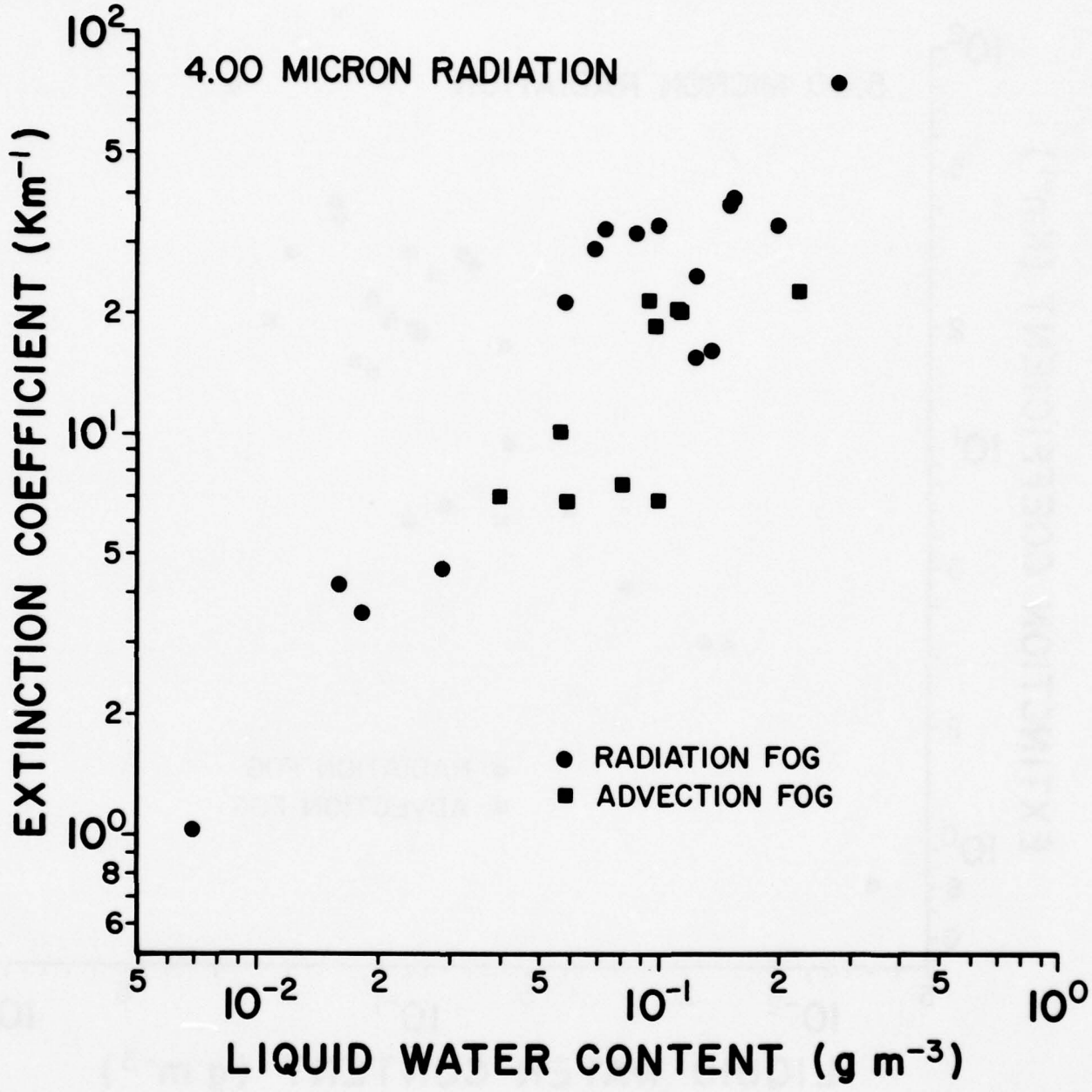


Figure A-14. Same as figure A-12 except for λ = 4μm.

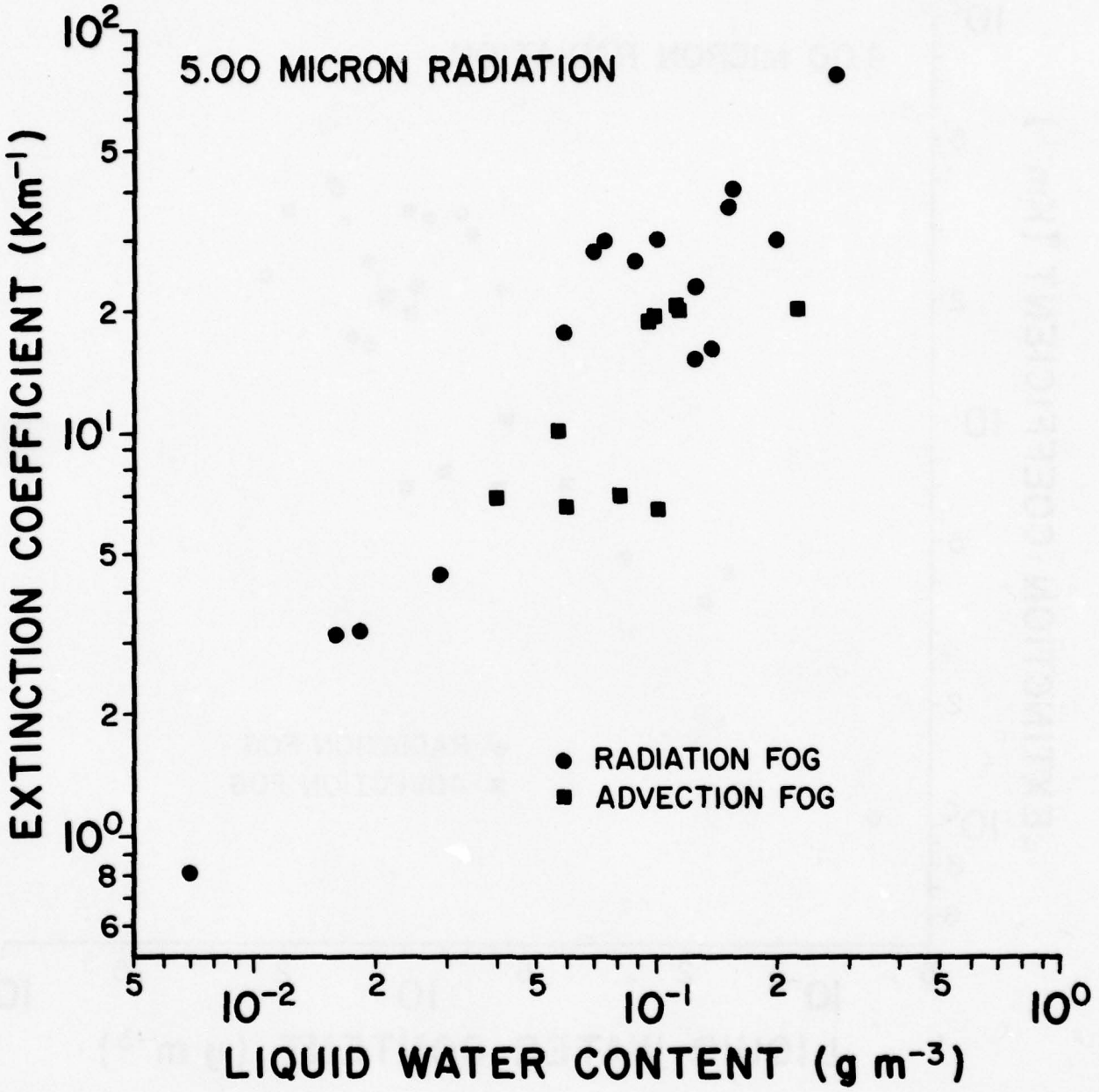


Figure A-15. Same as figure A-12 except for λ = 5μm.

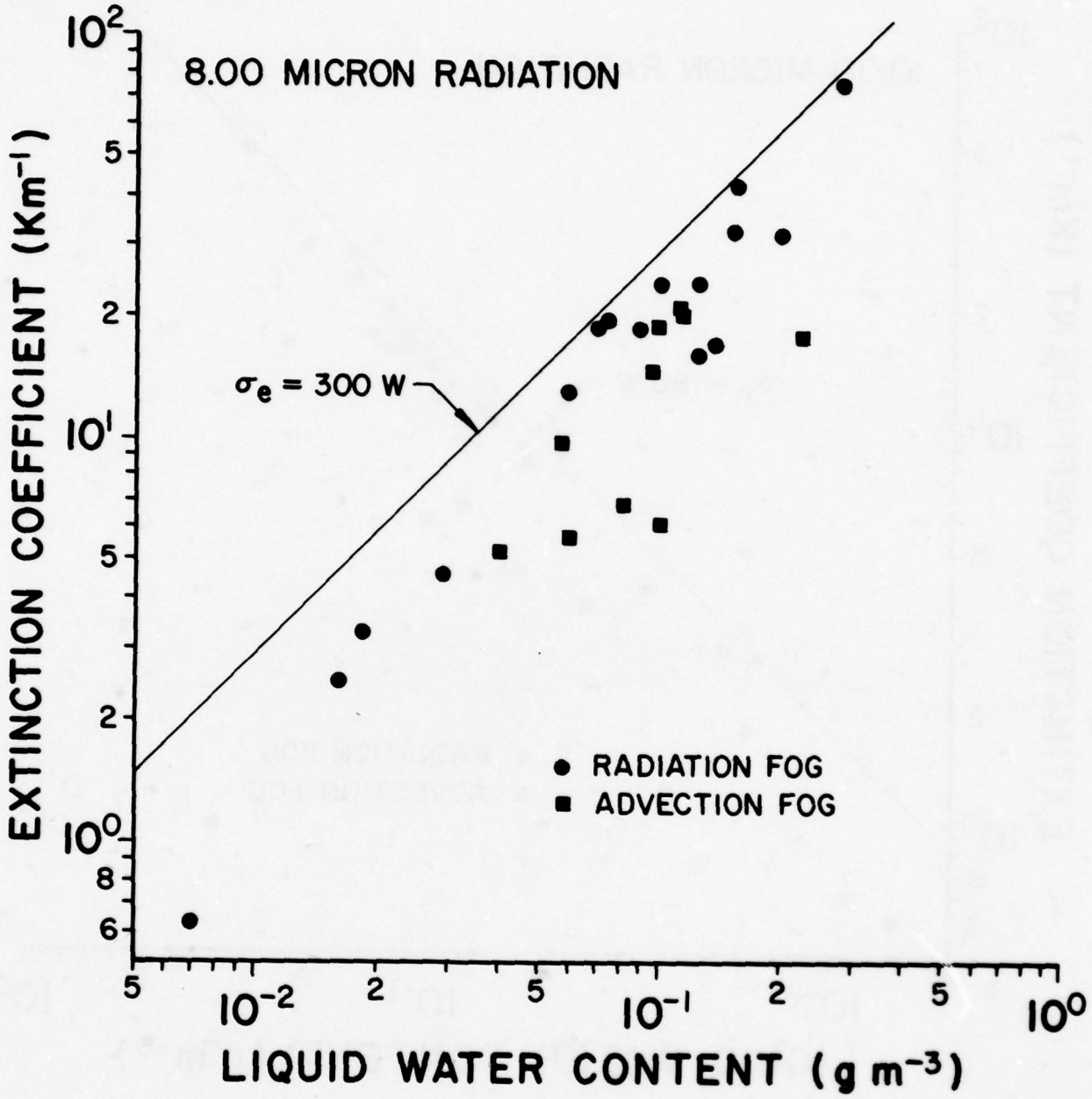


Figure A-16. Same as figure A-12 except for λ = 8μm. The predicted relation between extinction and liquid water content given by eq. (1) is shown by the straight line. Because the $Q_e = cx$ approximation is generally better satisfied for radiation fogs, those points fall closer to the straight line prediction.

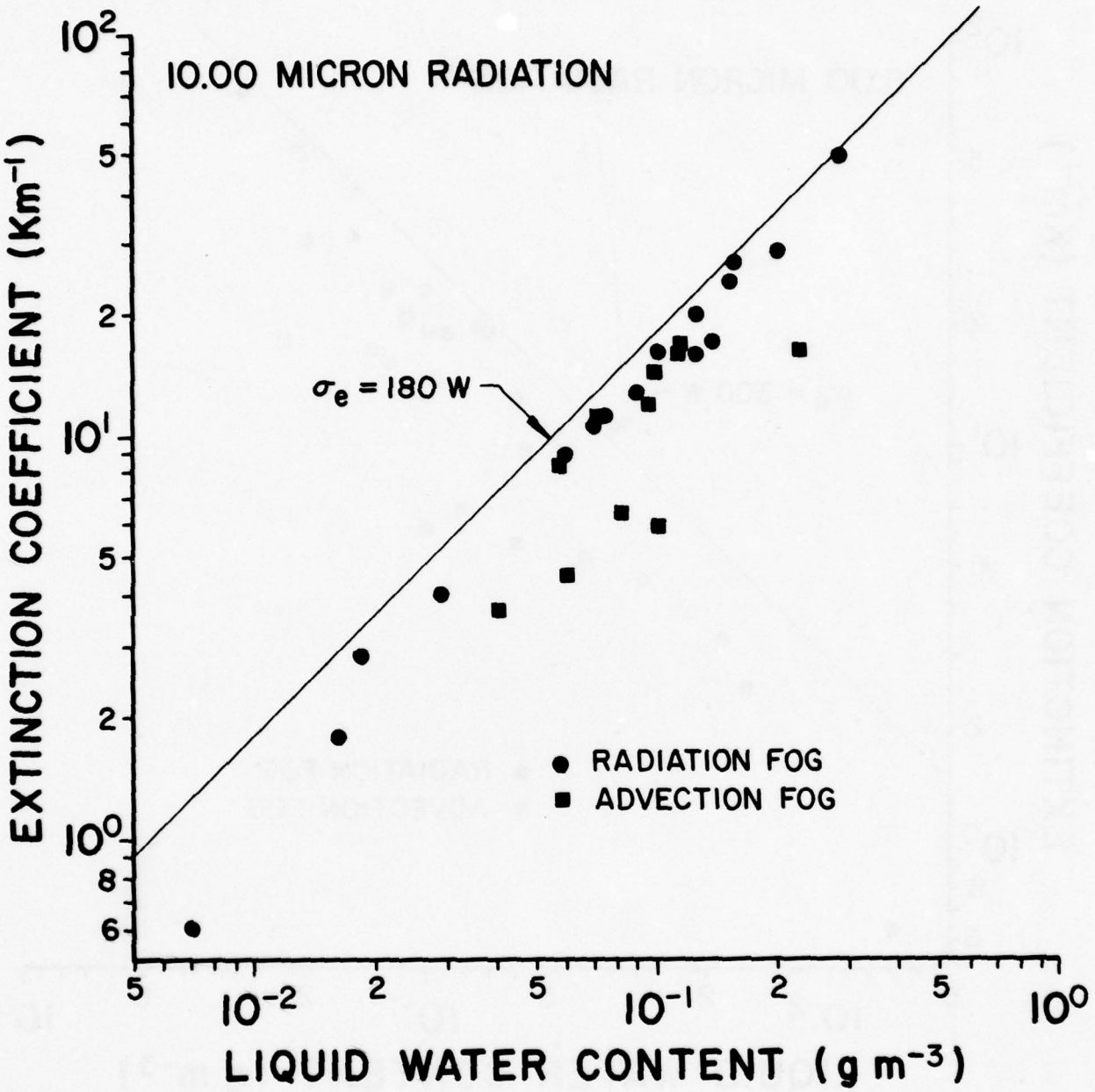


Figure A-17. Same as figure A-16 except for λ = 10μm.

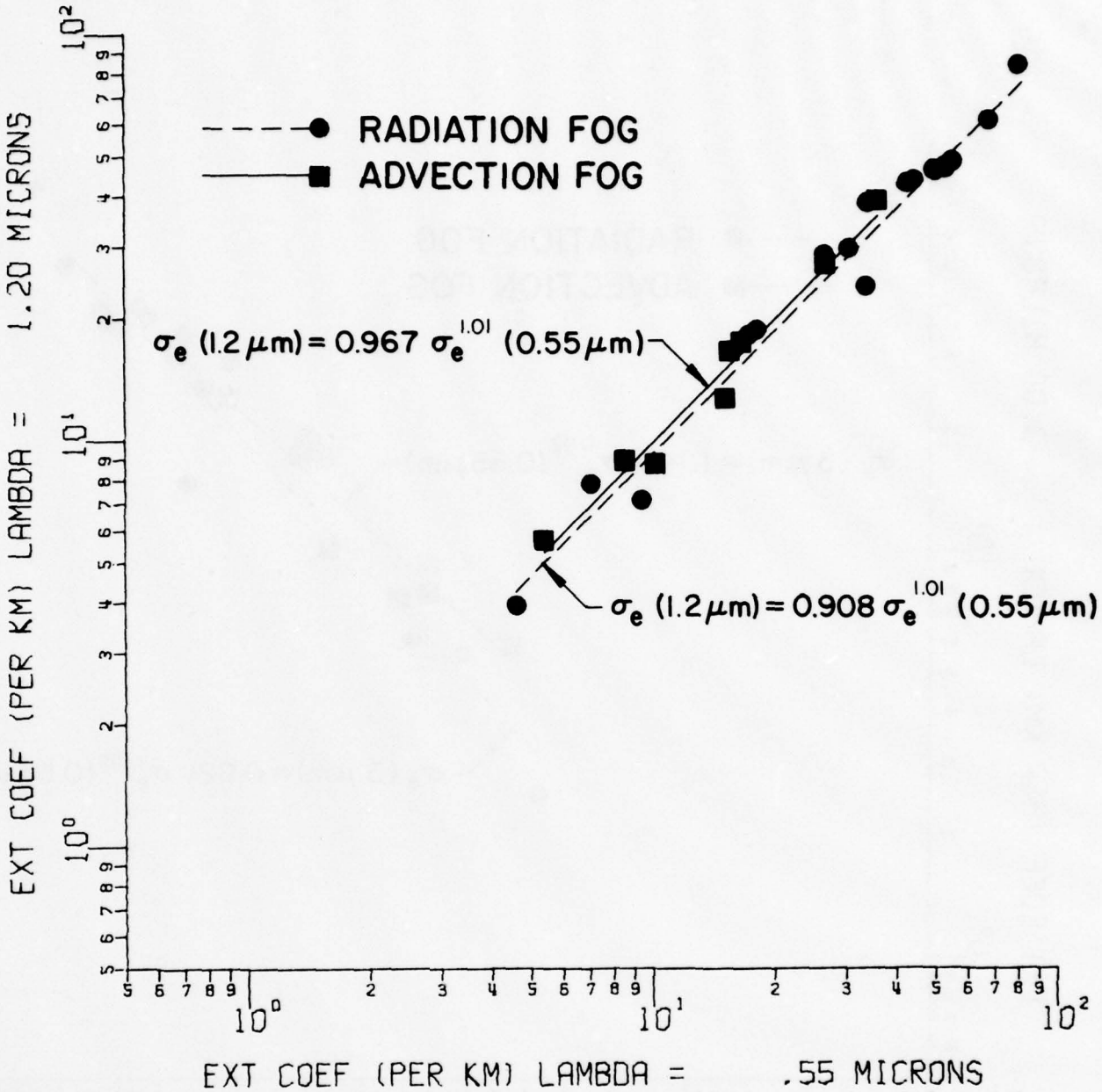


Figure A-18. Variation of the infrared extinction coefficient at λ = 1.2μm with visible extinction coefficient (λ = 0.55μm) in atmospheric fog for 26 size distribution measurements made over an approximate 5-year period under a variety of meteorological conditions in England. The spread of the points in the graph shows that the infrared extinction coefficient is a function of the size distribution as well as of the visible extinction coefficient. Also shown are empirical power-law relationships (one for radiation fog and one for advection fog) determined by doing least-square fits to the Mie-calculated points for radiation fogs (circles) and advection fogs (squares).

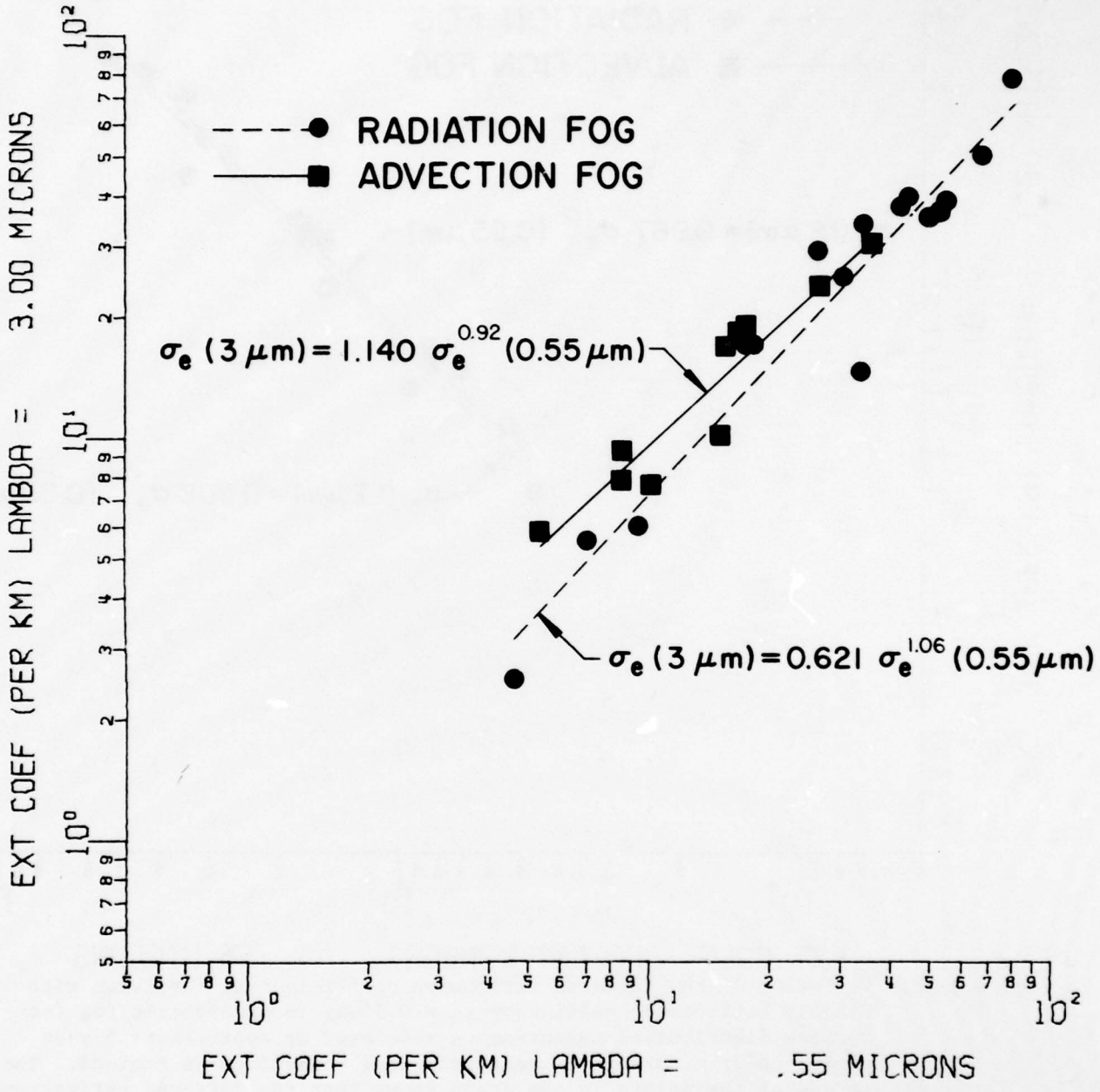


Figure A-19. Same as figure A-18 except for the infrared wavelength λ = 3μm.

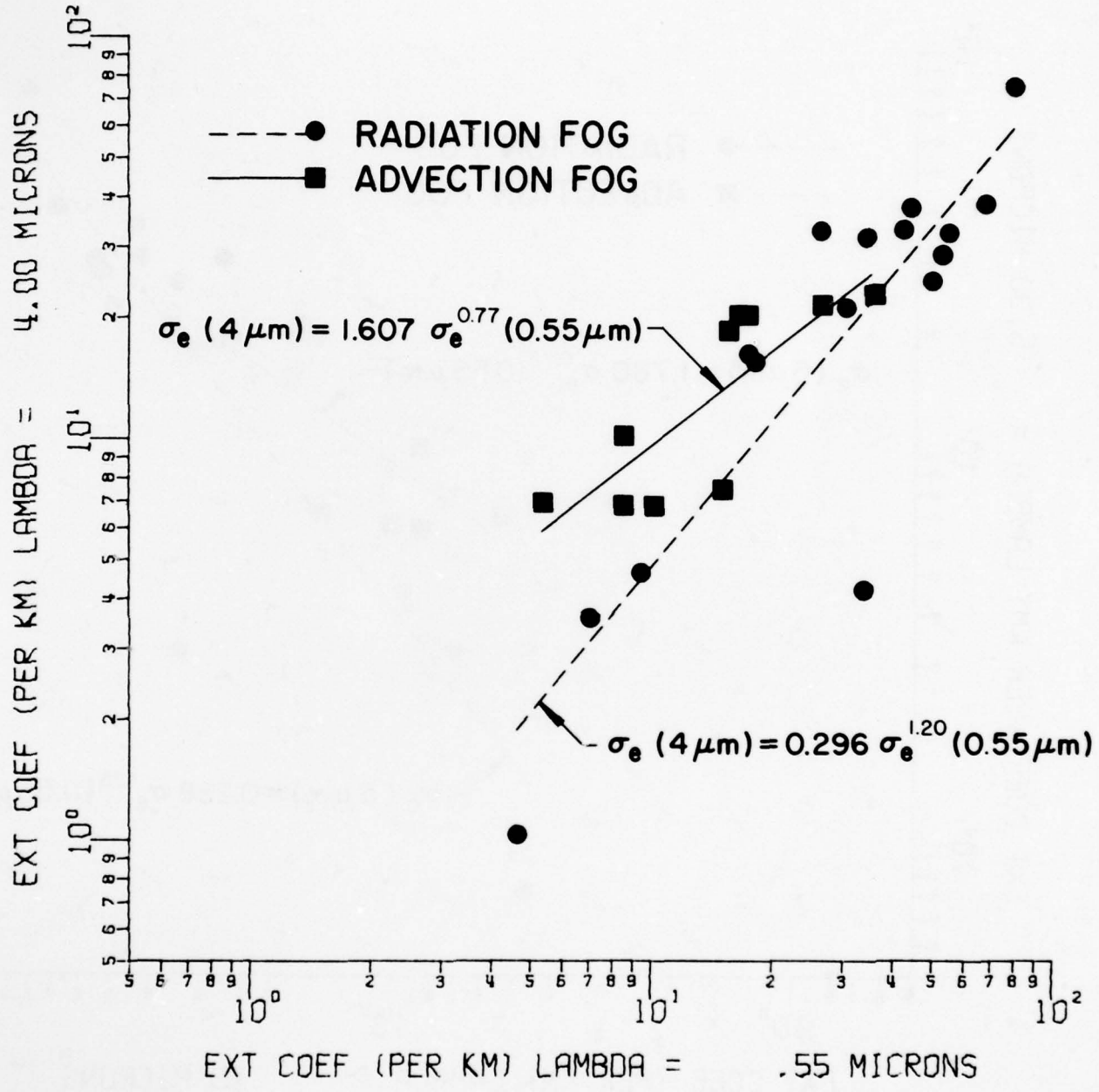


Figure A-20. Same as figure A-18 except for the infrared wavelength λ = 4μm.

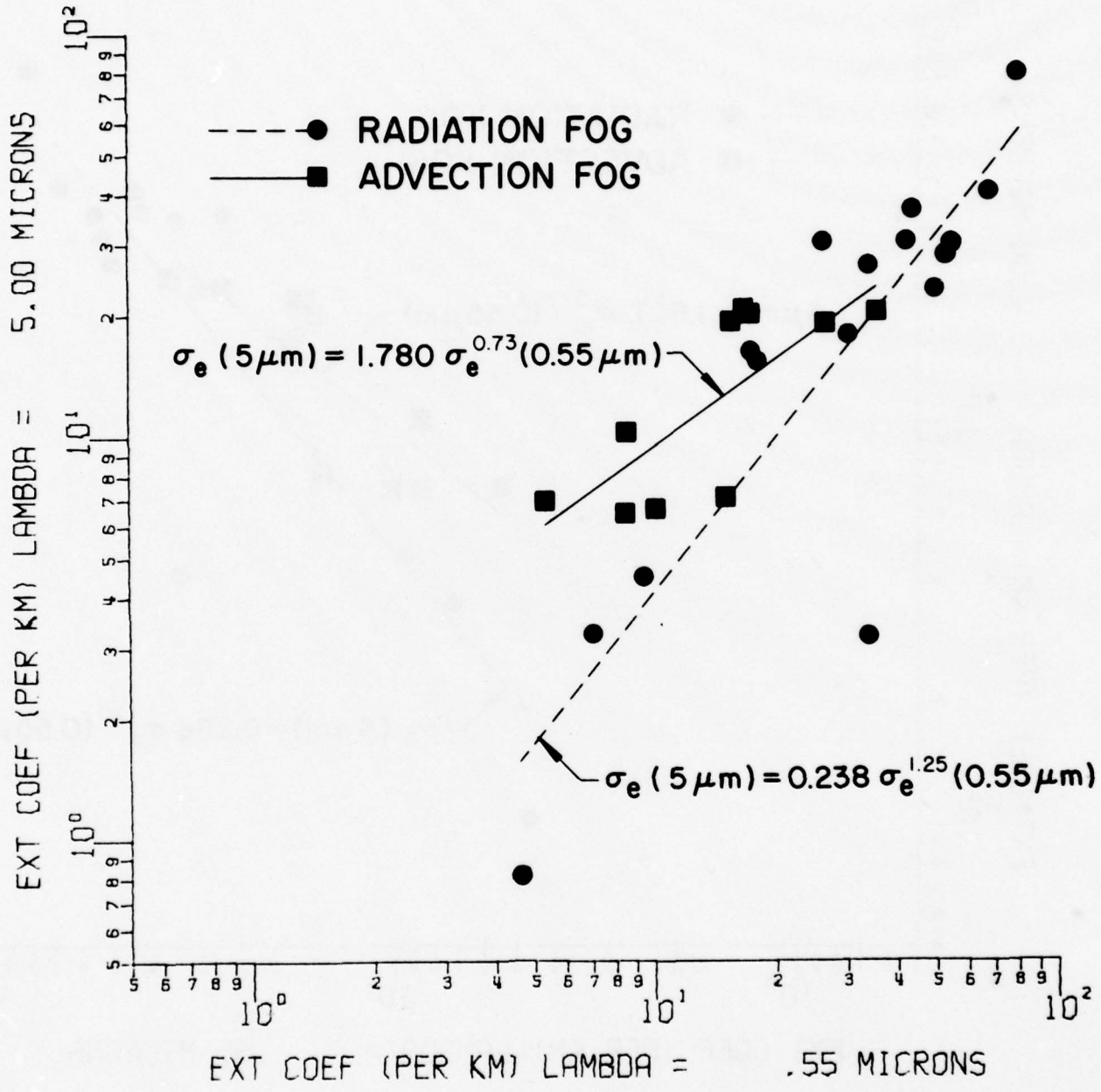


Figure A-21. Same as figure A-18 except for the infrared wavelength λ = 5μm.

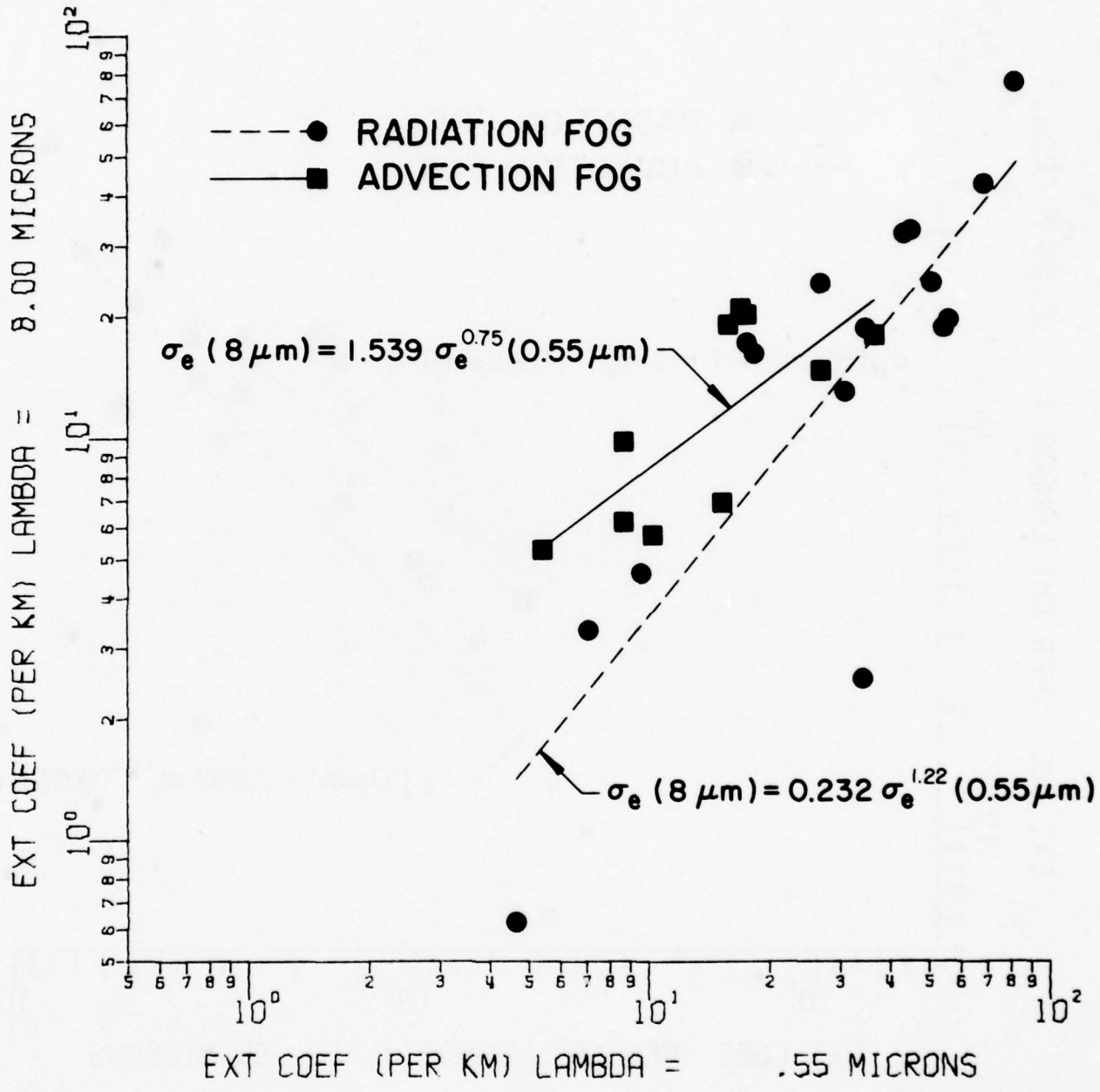


Figure A-22. Same as fig. A-18 except for the infrared wavelength λ = 8μm.

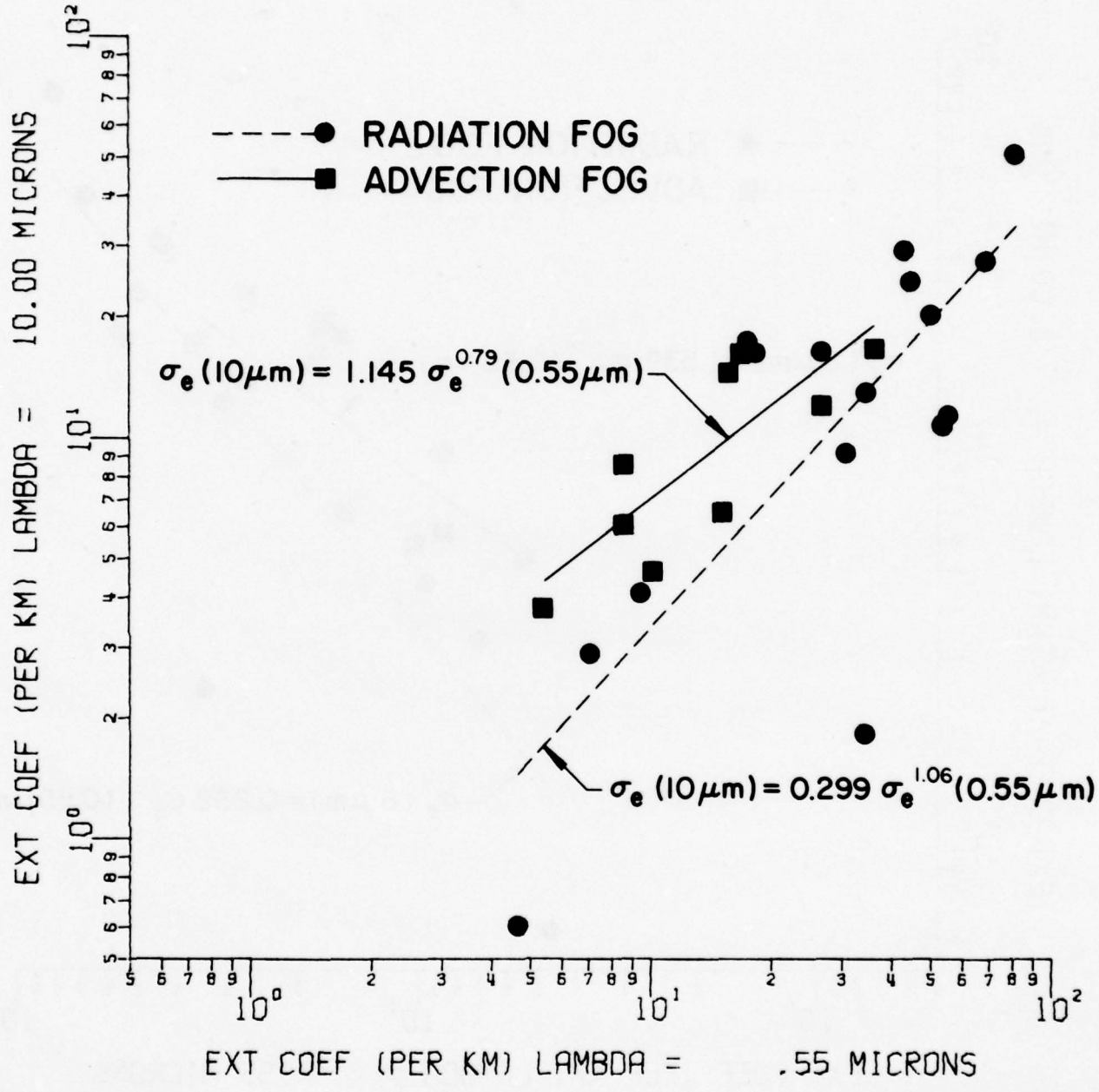


Figure A-23. Same as fig. A-18 except for the infrared wavelength λ = 10μm.

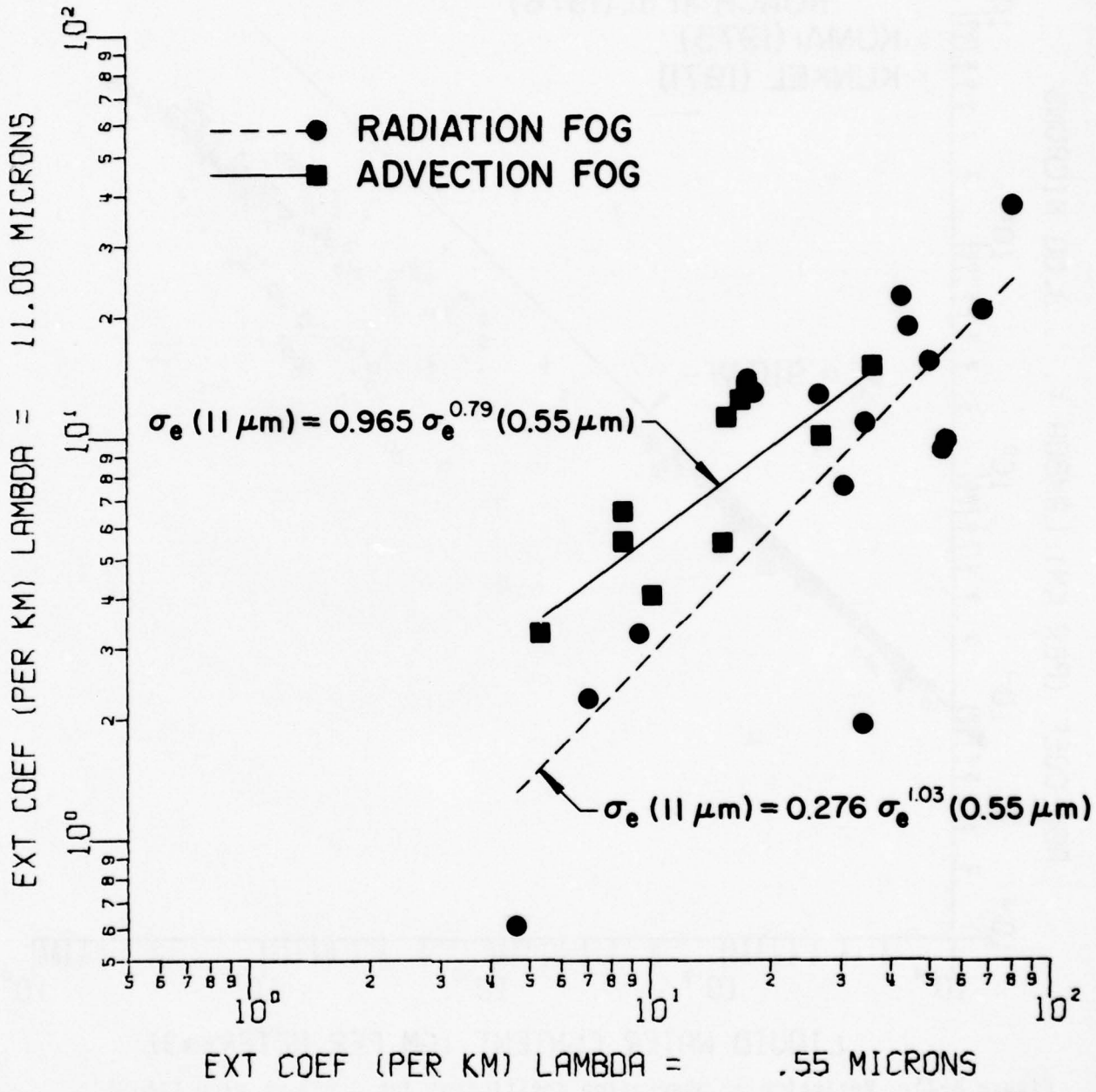


Figure A-24. Same as fig. A-18 except for the infrared wavelength λ = 11μm.

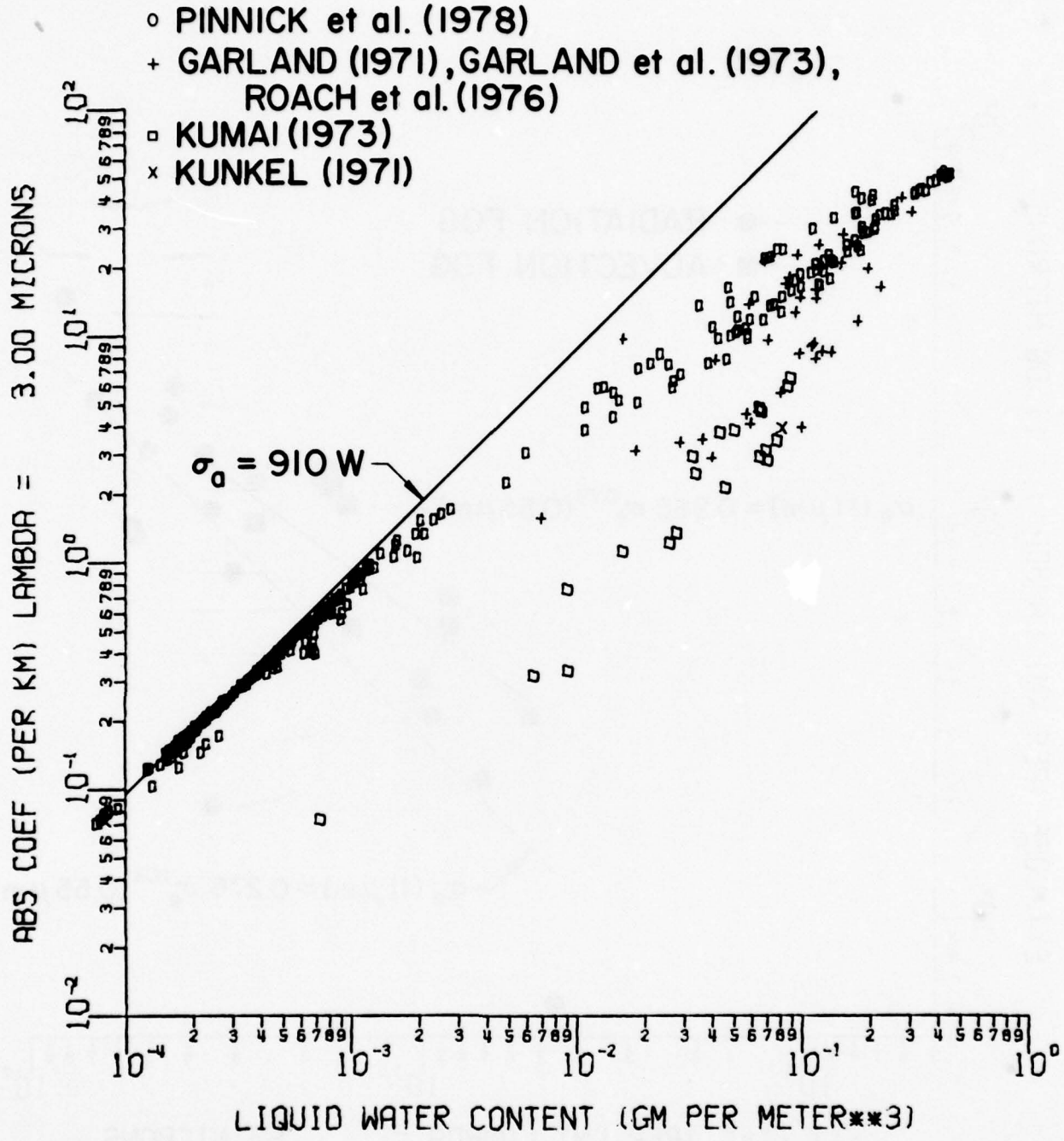


Figure A-25. Variation of absorption coefficient (at λ = 3μm) with liquid water content in atmospheric fog and haze for 341 size distribution measurements made at different geographic locales and under a variety of meteorological conditions. The spread of the points in the graph shows the absorption coefficient is a function of the size distribution as well as of the liquid water content. The predicted relation between absorption σ_a and liquid water content W according to eq. (7) is shown by the straight line, where σ_a is in km^{-1} and W is in g m^{-3}.

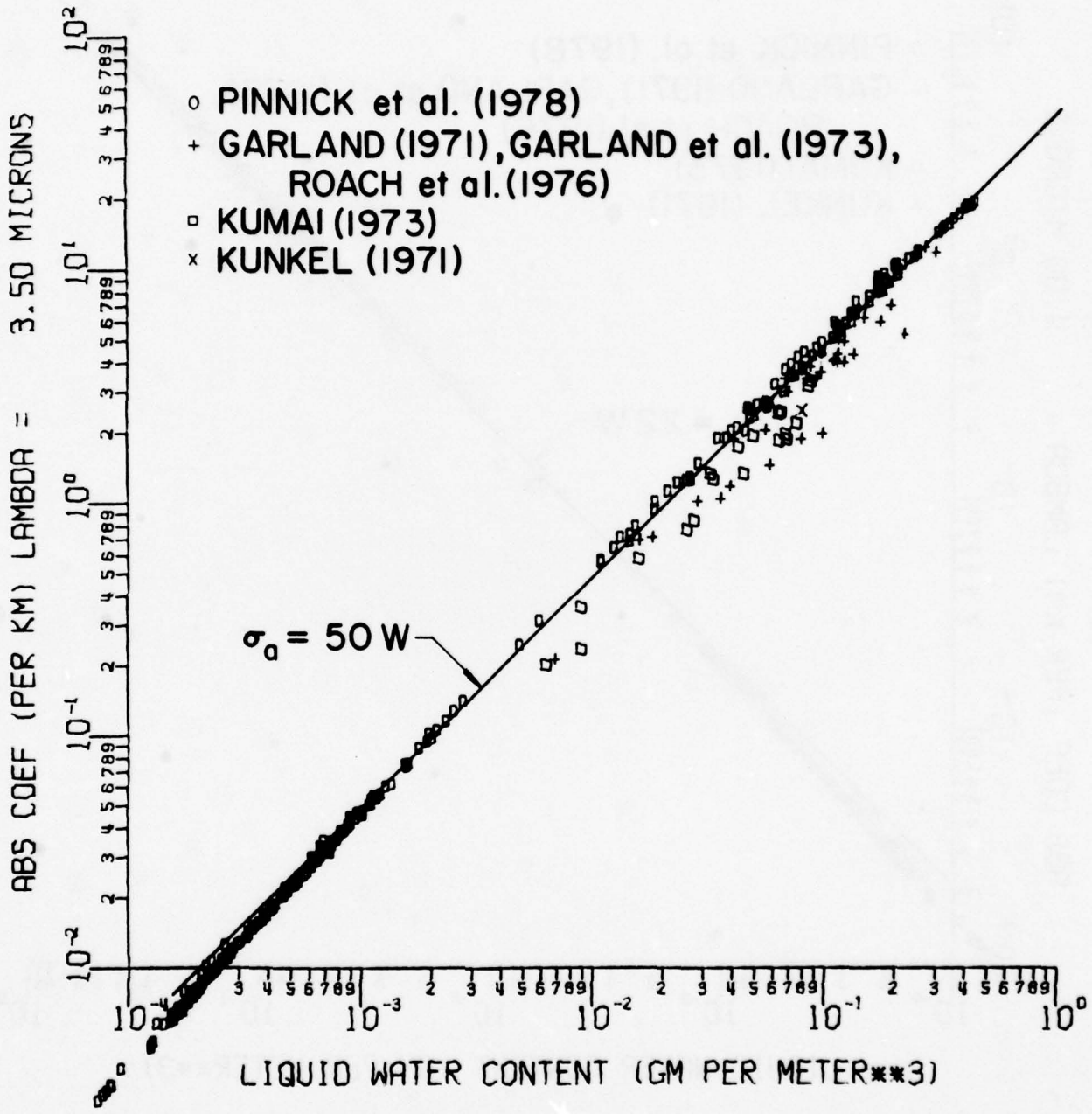


Figure A-26. Same as figure A-25 except for λ = 3.5μm.

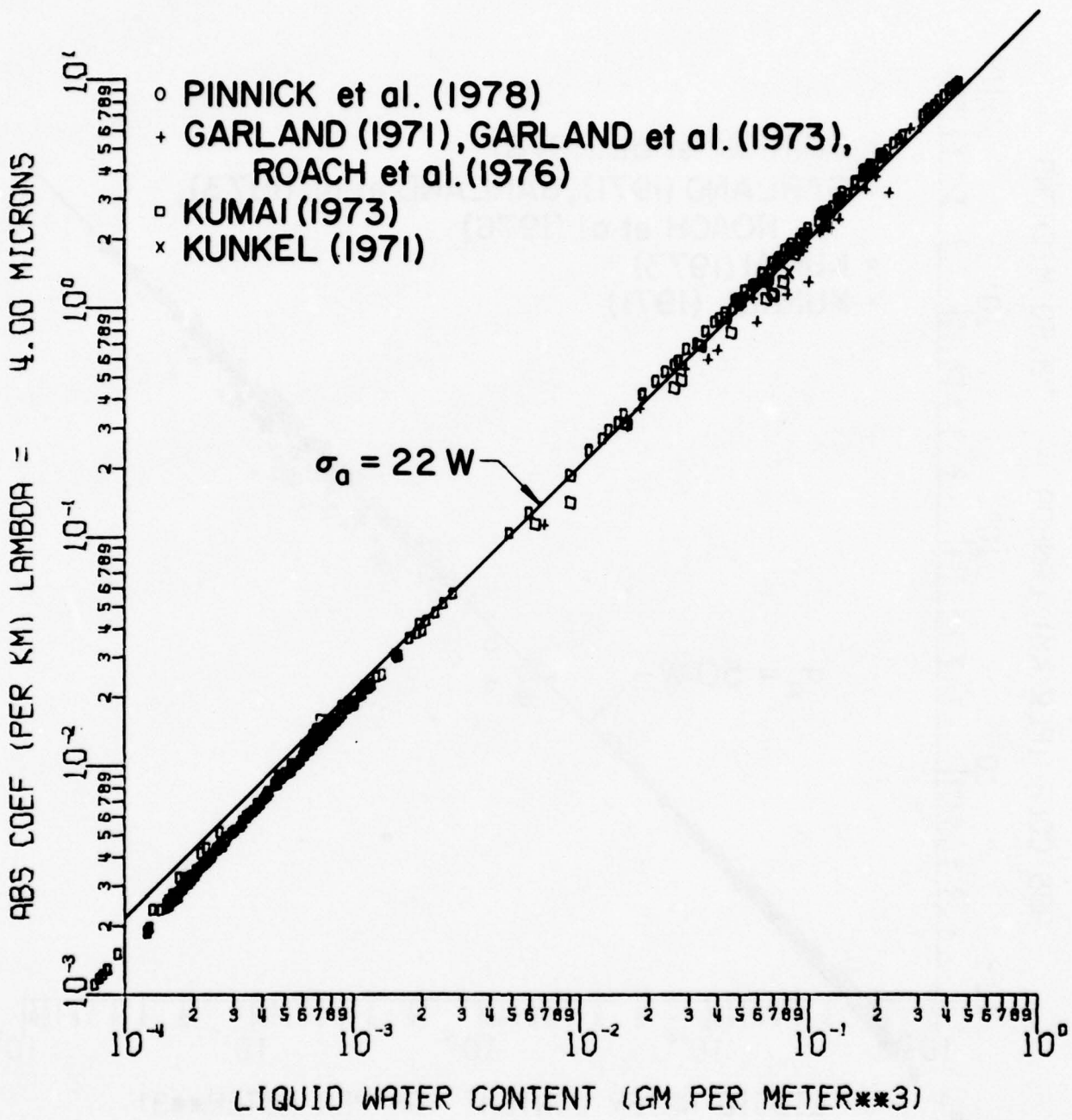


Figure A-27. Same as figure A-25 except for λ = 4μm.

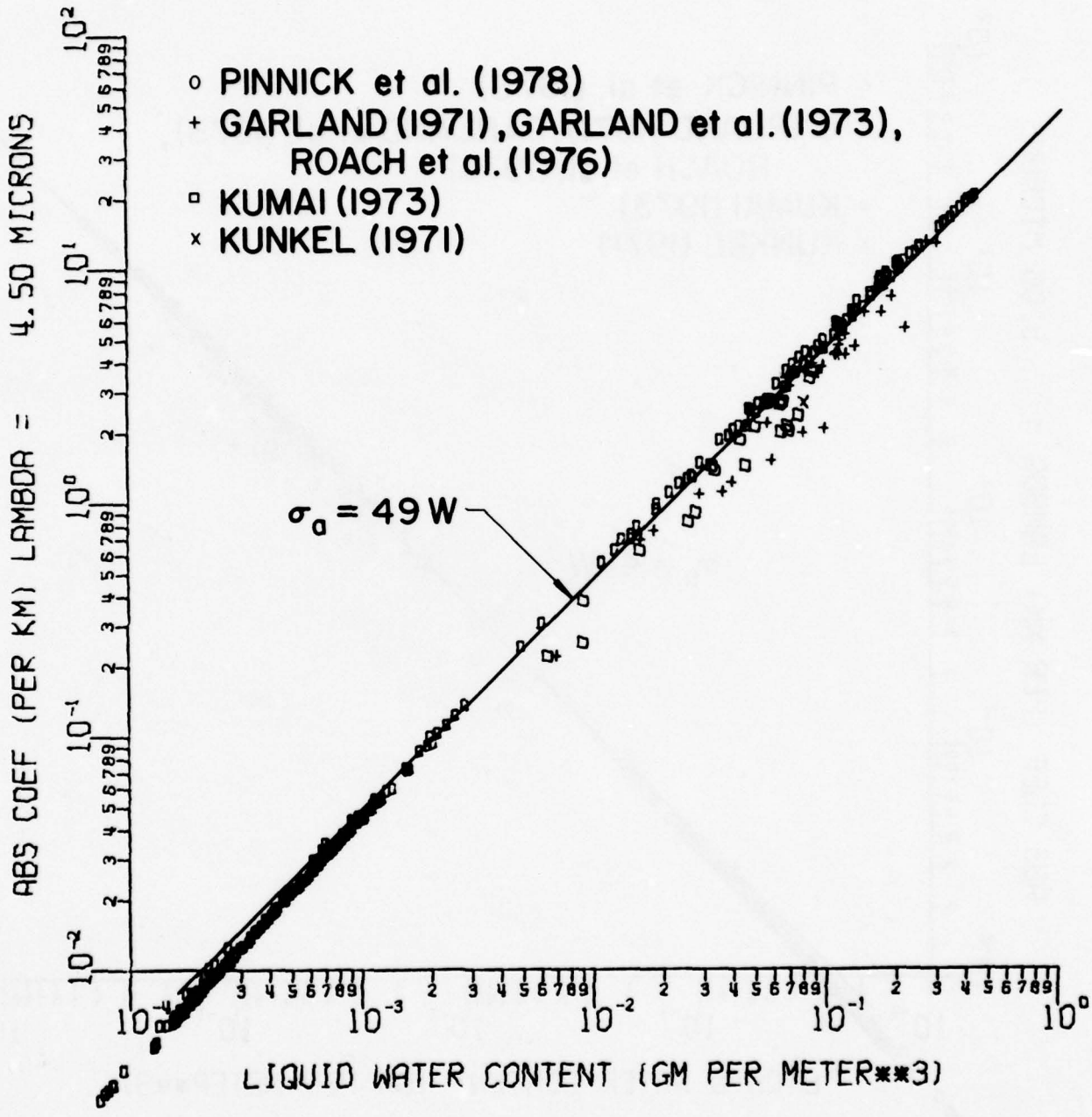


Figure A-28. Same as figure A-25 except for λ = 4.5μm.

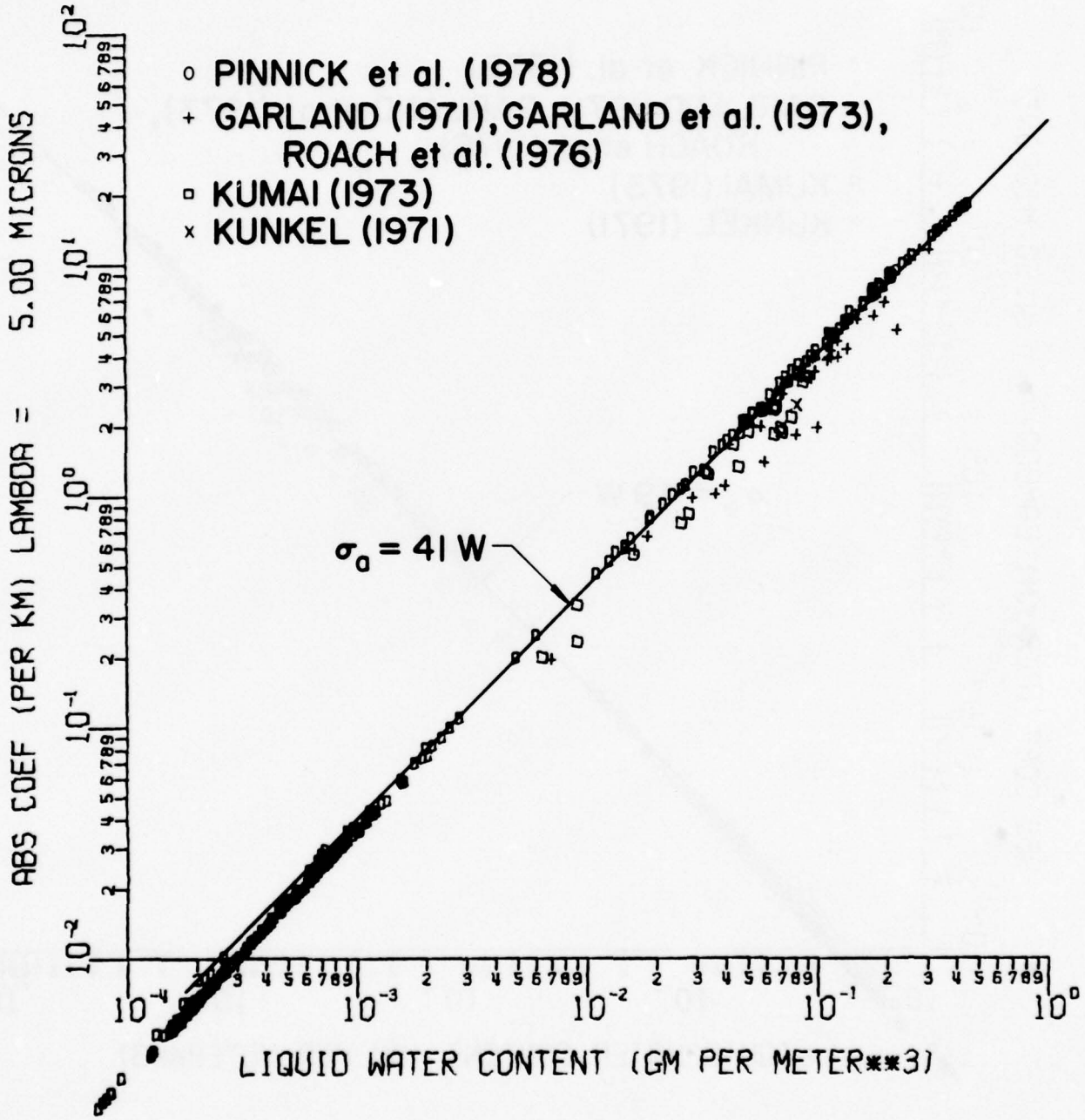


Figure A-29. Same as figure A-25 except for λ = 5μm.

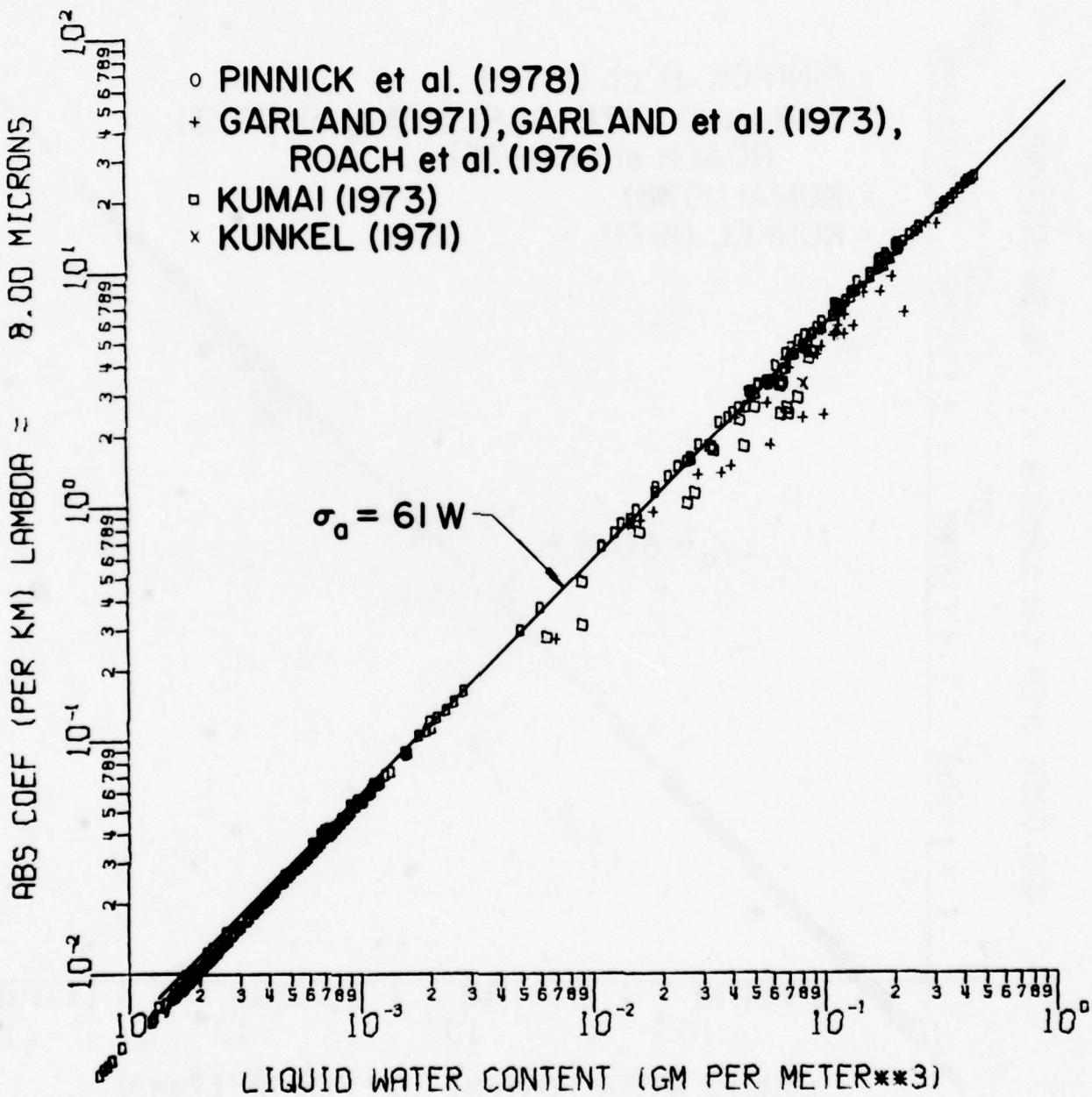


Figure A-30. Same as figure A-25 except for λ = 8μm.

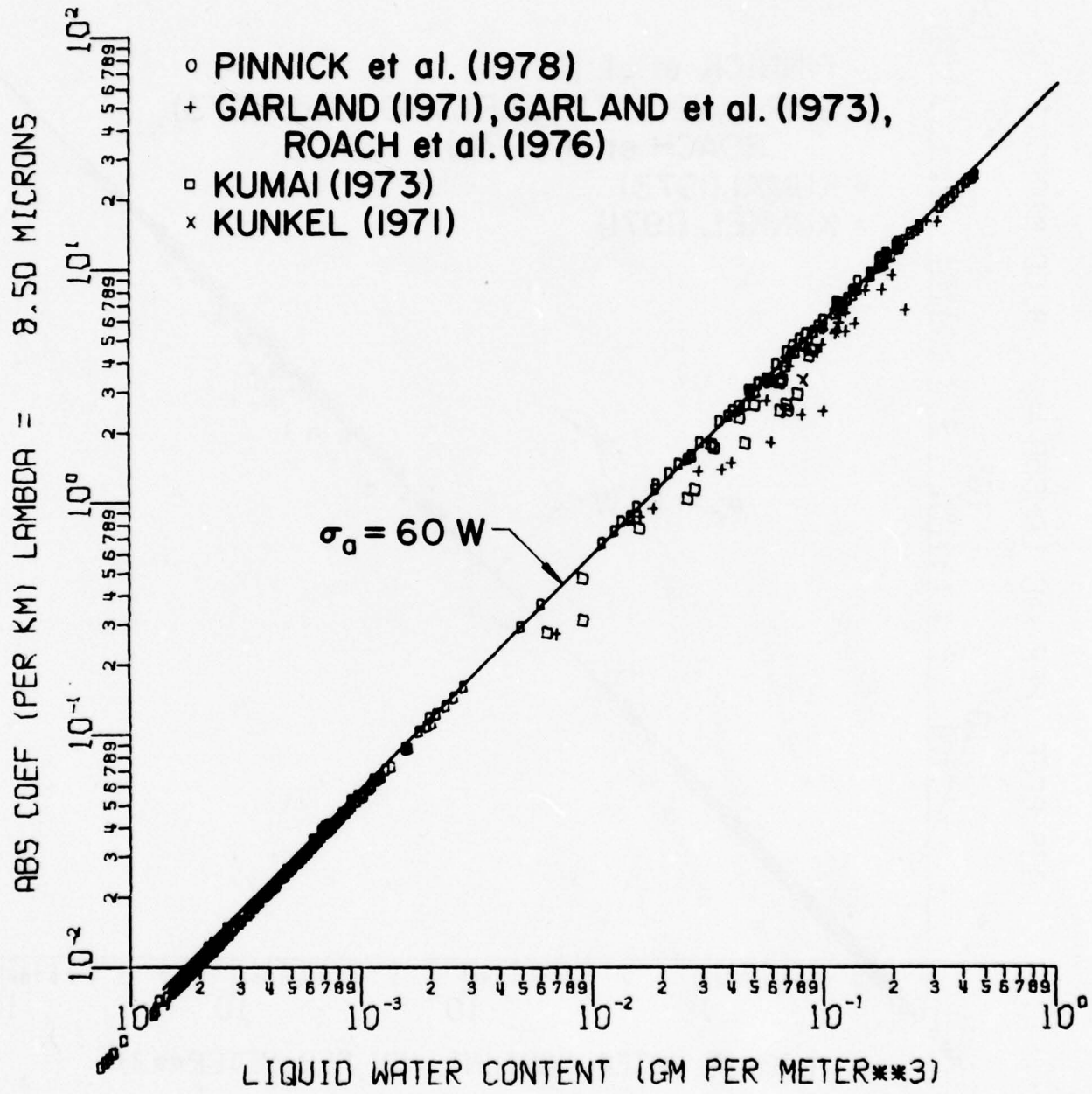


Figure A-31. Same as figure A-25 except for λ = 8.5μm.

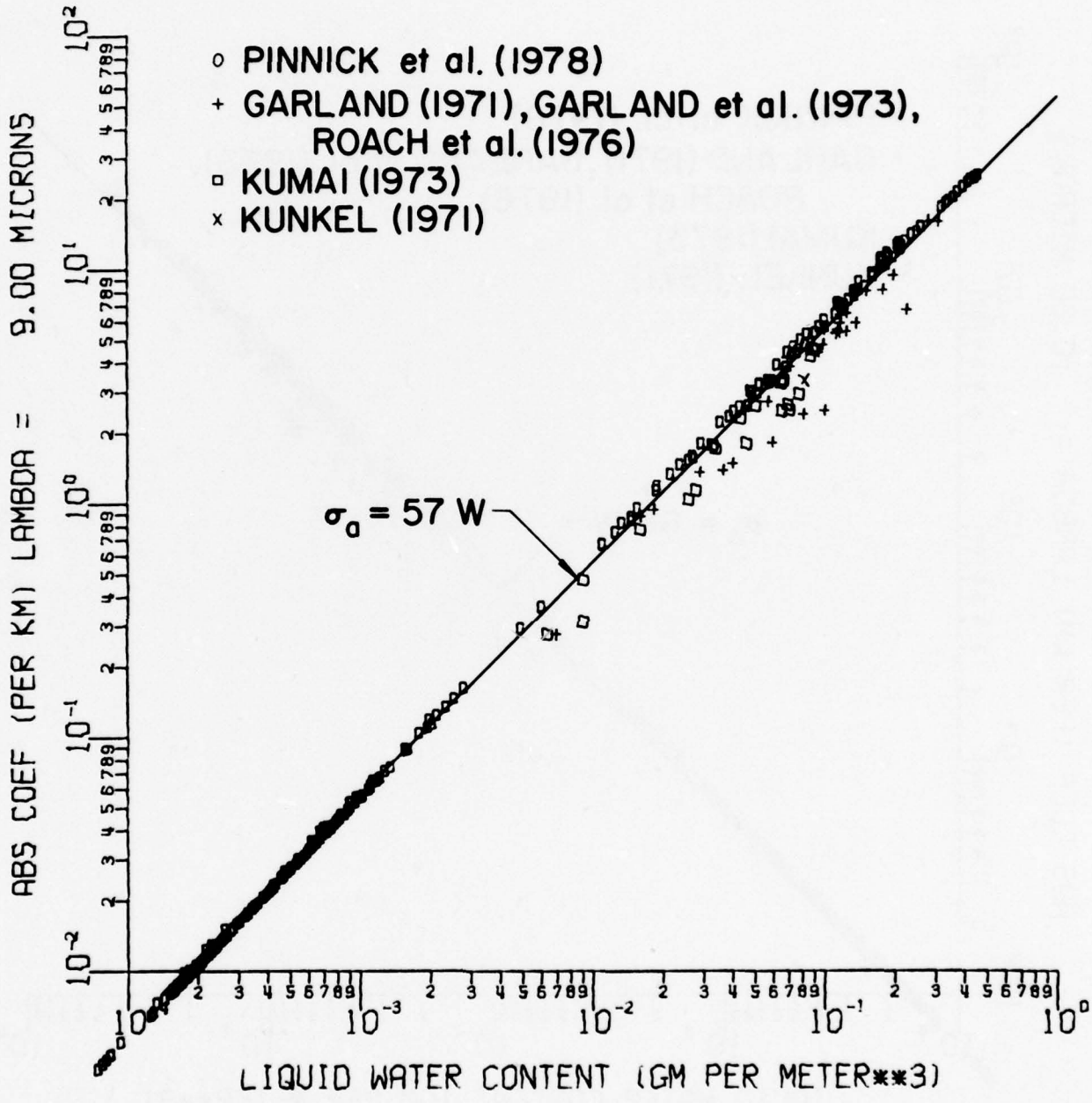


Figure A-32. Same as figure A-25 except for λ = 9μm.

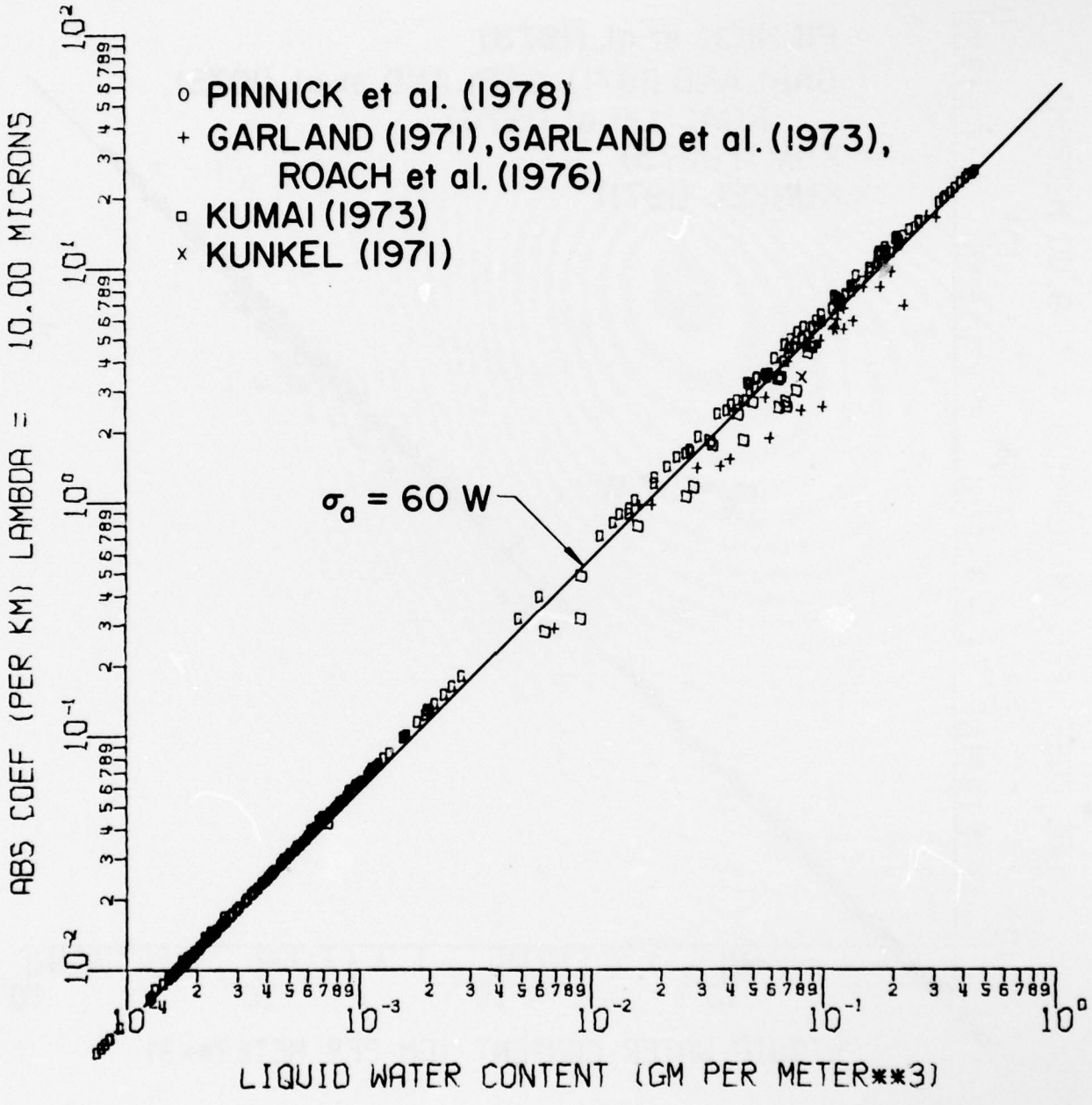


Figure A-33. Same as figure A-25 except for λ = 10μm.

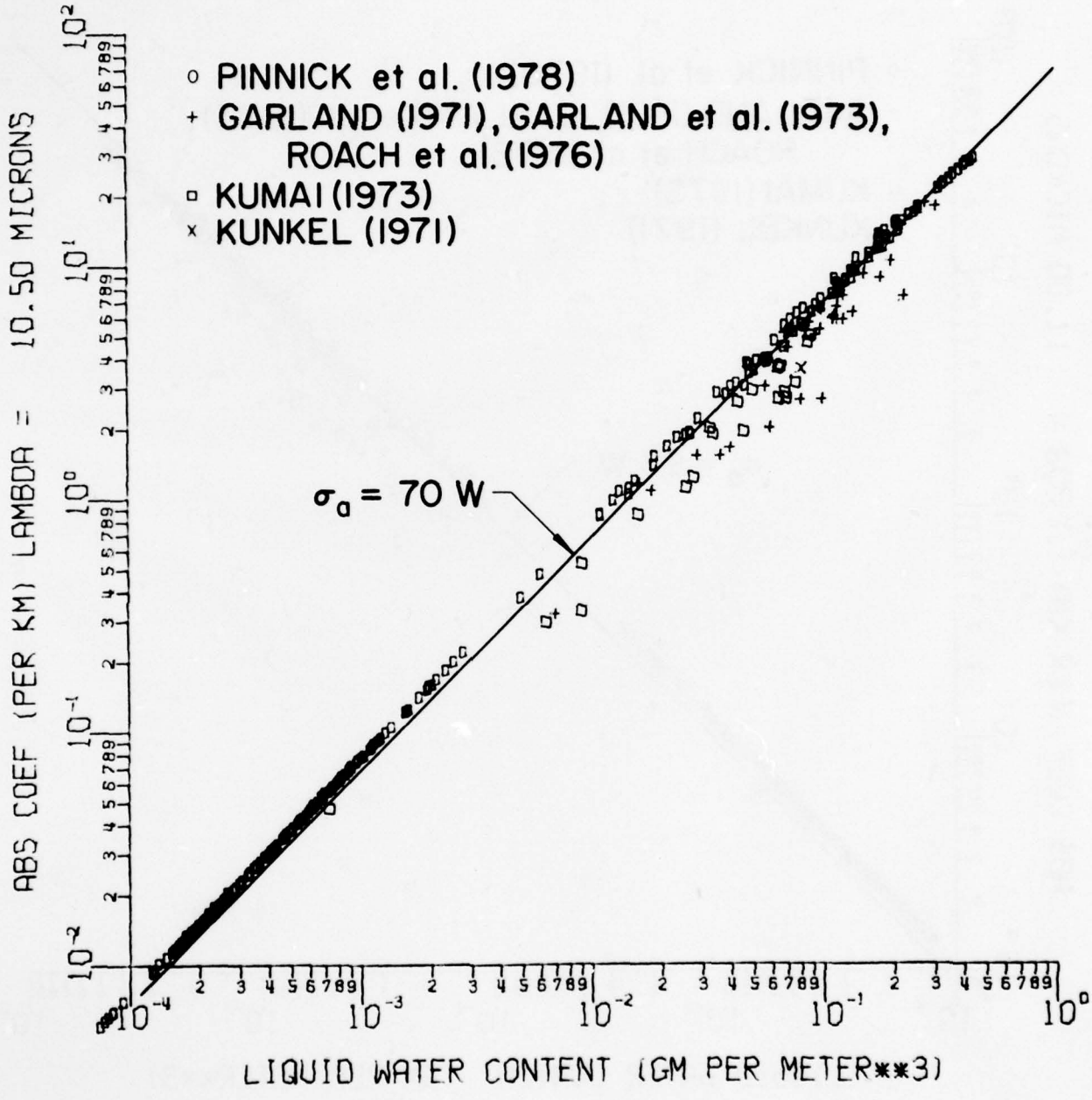


Figure A-34. Same as figure A-25 except for λ = 10.5μm.

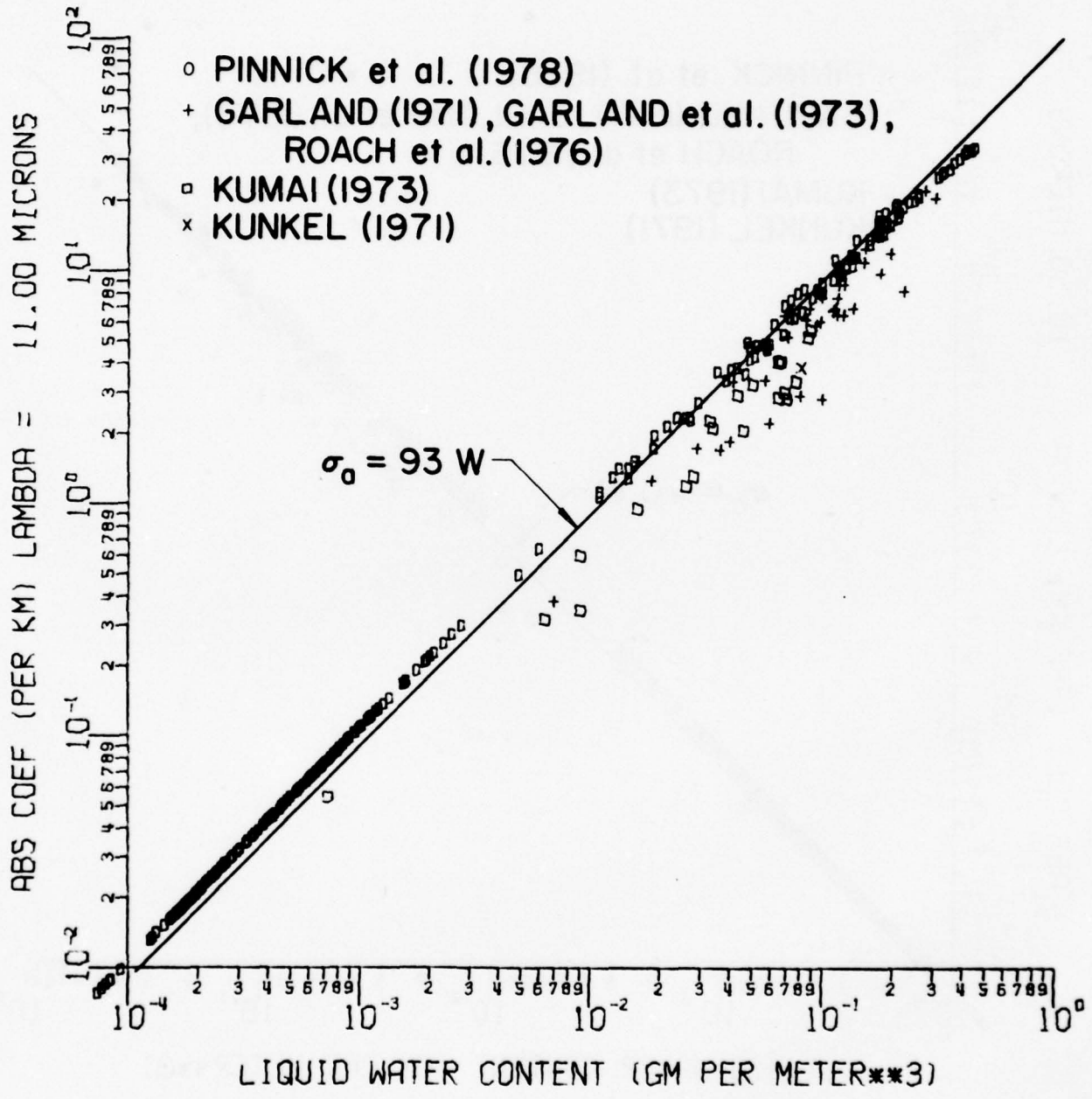


Figure A-35. Same as figure A-25 except for λ = 11μm.

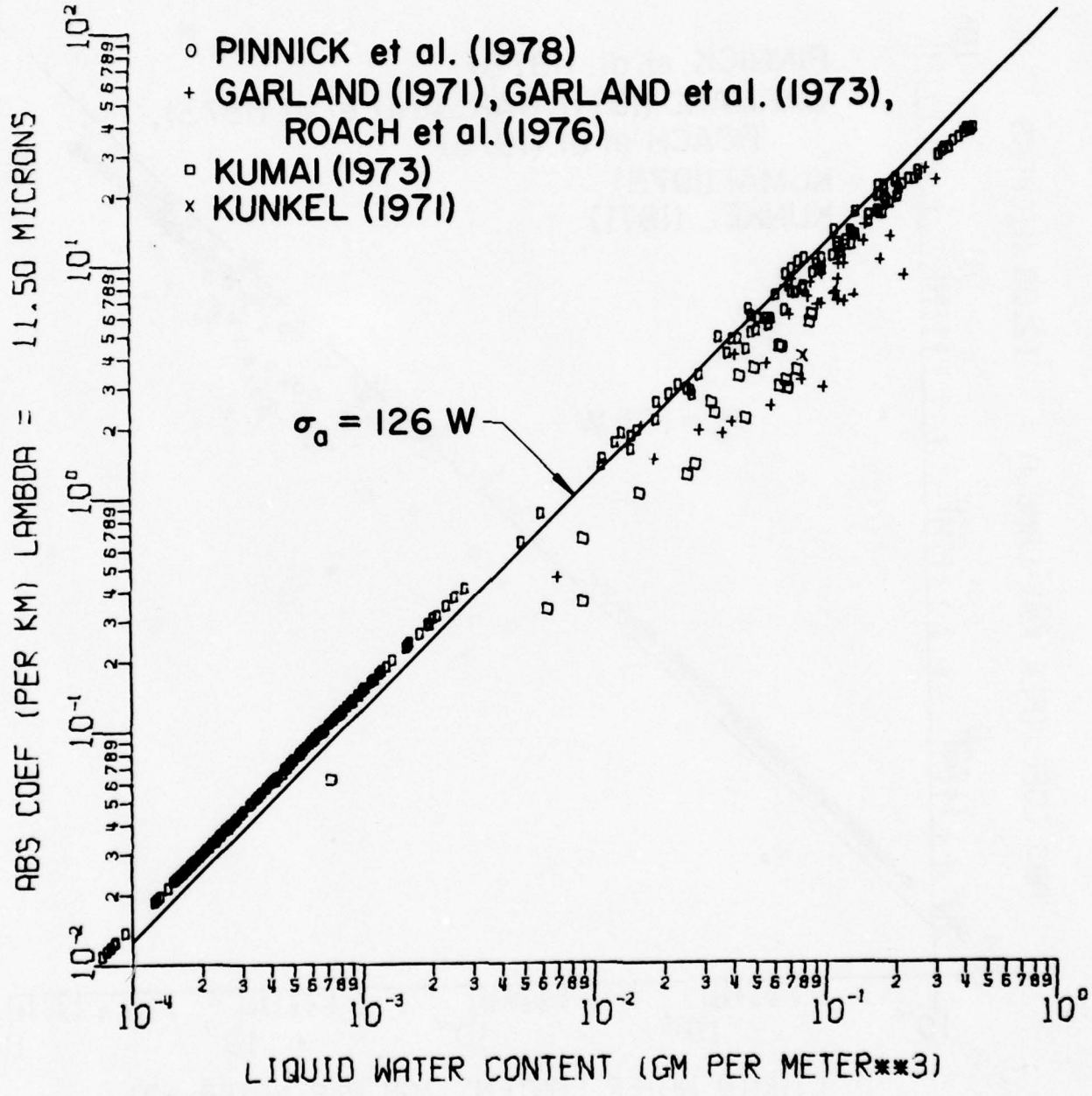


Figure A-36. Same as figure A-25 except for λ = 11.5μm.

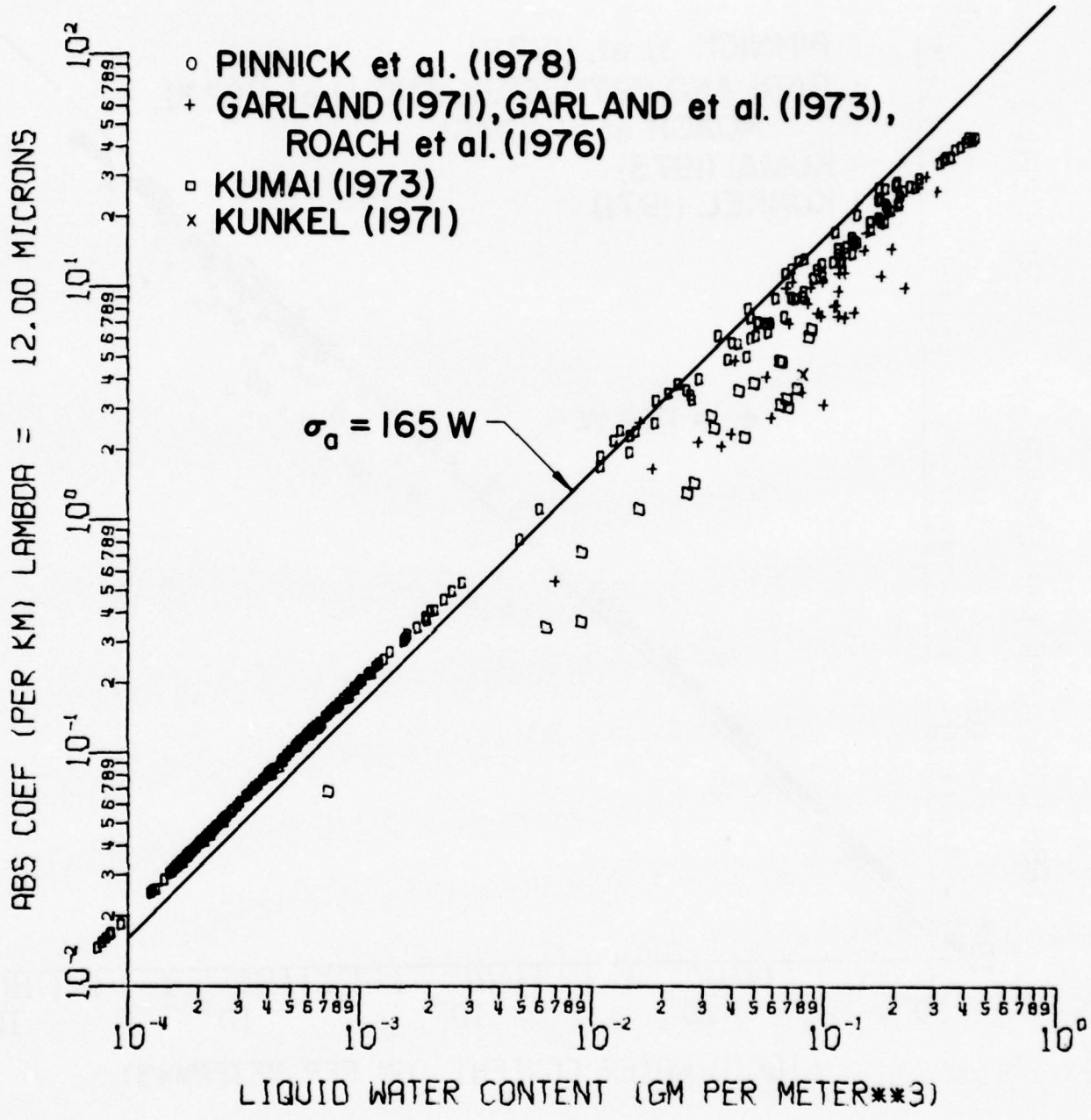


Figure A-37. Same as figure A-25 except for λ = 12μm.

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