Global and Environmental Consequences of Nuclear Exchange

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1. AUTHORS PREFACE

It would be normal in a symposium volume such as this to report recent research in which one has played a significant role. As it happens, however, my work on the subject of this paper was mostly done twenty odd years-ago. Specifically, I carried out a three year study on the environmental consequences of nuclear war, carried out at the Hudson Institute during the years 1962-65. In the short month that was given me to write this Chapter, amidst the press of other business there has certainly been no opportunity to undertake significant new calculations or even to do a thorough scholarly review of the recent literature. This is a sufficiently unusual circumstance to require an explanation of my involvement, which follows.

In November, 1983 ABC-TV presented a docu-drama "The Day After", purporting to be a realistic account of the conditions that might exist following a nuclear war. The docu-drama was criticized by some as an unwarranted and misleading attempt to influence the nuclear "freeze" debate, but the most surprising criticism came from the well-known ex-biologist and cosmologist, Carl Sagan of Cornell University who flatly asserted that the movie far *understated* the severity of the ~~of the~~ after effects. In fact, Sagan stated, in a televised interview immediately following the TV movie, that a nuclear exchange involving as little as 1000 megatons, with its associated fires, might inject enough fine dust and smoke into the atmosphere to intercase most of the incident sunlight, thus (in effect) putting the land surface of the northern hemisphere in a dense shadow that would cause a sudden and extreme cold wave. In fact, Sagan suggested that the temperature could drop by as much as 30°. This (hypothetical) phenomenon has since come to be known as the "nuclear winter". As it happens I predicted a much milder version of it in 1965, based on historical experience with large volcanic eruptions. More of this later.

I chanced to be present at a scientific meeting a few days later, where a small group including many of the authors represented in this volume assembled informally at the suggestion of Fred Singer to exchange notes and ideas on the "nuclear winter" phenomenon. Inevitably, my past interest in the problem emerged, as did the dramatic discrepancies between my 1965 predictions and those made recently by Sagan et al.[1] It was immediately obvious that the matter would have to be reconsidered--if only to satisfy my own curiousity. Has the available data changed since 1965? Has the state-of-the-art of atmospheric modelling changed so dramatically? Did I overlook something crucial? Or, is this one of those surprisingly common situations involving long and complicated chains of reasoning where

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[1] Actually, the key document on which Sagan apparently relied is entitled "Global Atmospheric Consequences of Nuclear War" (Draft Xerox, 140 pp). The authors are listed as: R.P. Turco, O.B. Toon, T.P. Ackerman, J.B. Pollack and C. Sagan. A brief condensation appeared in *Science* in December 1983. I will refer to this group hereafter as TTAPS.

reasonable people making apparently reasonable assumptions and using the same data end up coming to opposite conclusions?

Considering that no atmospheric nuclear tests have been carried out by the U.S. since 1961, I thought it unlikely that the data available to TTAPS would have differed significantly from that available to me in 1963-65. Nor did it seem likely that the improved sophistication of atmospheric modelling would account for the great difference in our quantitative predictions. But I couldn't do much about satisfying my curiosity until the TTAPS papers were published and the still unpublished backup document finally reached me (in January 1984) by a roundabout route. To anticipate the outcome, I now believe the discrepancies to be due to a combination of factors but no actual major mistakes of omission or commission on either side. This is an interesting conclusion, since it suggests the enormous sensitivity of complex chains of reasoning--such as the nuclear winter scenario--to very small and seemingly innocent assumptions by the analyst.

2. THE PHYSICAL BASIS OF THE "NUCLEAR WINTER" SCENARIO

The "baseline" nuclear war scenario of TTAPS [2] involves 10,400 nuclear bursts ranging in yield from .1 to 10 megatons (MT) of TNT equivalent land in altitude from the ground or water surface to beyond the atmosphere. These explosions were assumed to raise an average of 0.333 tons of dust in their clouds for each ton of explosive power in a land burst weapon and 0.1 tons of dust for near surface bursts into the stratosphere. The dust (9.6×10^8 tons in all) was assumed to have a log-normal particle size distribution for small radii with 8.4% of the mass consisting of particles with radii less than 1 micron (10^6) meter. The baseline scenario also assumed widespread fires of all kinds including urban/industrial fires (52% of emissions), fire storms (7% of emissions) wild fires (30%) and long-lived fires in

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[2] Unfortunately the TTAPS baseline" case described in the brief "Science" article is sharply different from the "baseline" describe in the backup document referenced therein. Many of the assumptions differ for reasons that are not explained.

exposed peat deposits, coal seams, etc (7%). These fires generate an assumed total of 2.25×10^8 tons of smoke emissions (soot and flyash) of which 5% reach the stratosphere. The remainder stays in the troposphere. The remainder stays in the trosphere for a period of up to several weeks before being washed out largely as "black rain". The soot and fly ash particles are assumed to be distributed around a very small model radius (0.1μ).

3. ATMOSPHERIC EFFECTS OF A NUCLEAR EXCHANGE

The meteorological/climatological effects can be differentiated into two categories, viz.

- short-term effects lasting a few weeks, resulting primarily from the dense smoke pall (due to fires)
- longer term effects resulting from the stratospheric dust layer.

In both cases TTAPS assumed that the primary effect would be a net cooling, due to the fact that very small particles (i.e., with diameters of less than 1μ tend to be very effective scatterers of light in the wavelengths characteristic of solar radiation. In fact, W. J. Humphreys (1940) long-ago calculated that the intensity of solar light passing through a monodisperse dusty layer, with index of refraction m = 1.5 falls off as $\exp(-\lambda x)$ path length of the light through the dusty layer in cm., and λ is the attenuation coefficient, where

$$\lambda_r \cong 2\pi r^2 \rho_o \times 10^{-8} \text{ cm}^{-1} \qquad (1)$$

$$(r < 1 \mu)$$

assuming ρ_o is the number of scatterers (all with radius r), per cubic centimeter. It is interesting to note that a 20% attenuation (i.e. 20% reduction in insolation at the earth's surface) would only require a mass of about 3.1×10^6 tons of particles, distributed in a uniformly cloud, if we assume (monodisperse) particle radii of 0.25 μ, index of refraction 1.5 and a density of 2gm/cm^3 corresponding roughly to silica. To cut the insolation level by 40% (instead of 20%) would require the mass of the dust cloud to be 7.0 x 10^6 tons. Reduced insolation would lead to cooling of the surface of the earth, discussed later.

Obviously in a polydisperse cloud with a distribution of particle radii, computation of the effective attenuation of insolation requires integration over the entire (log-normal) particle size distribution. Also, it must be pointed out that while most glassy particles have indexes of refraction with values close to 1.5, a correct scattering calculation should also consider take into account the absorption coefficient η, (which is usually defined as the imaginary part of the index of refraction). The effect of absorption is negligible in the U-V and visible part of the solar spectrum but becomes very significant in the I-R region. Absorbed radiation is re-radiated in the I-R wavelengths, at a rate depending on the temperature of the radiating body. TTAPS assumed for convenience that I-R absorption and re-radiation by the dust cloud in the infra-red would be negligible. However, this assumption deserves closer scrutiny, as will be pointed out later.

Returning to the basic dust scattering and attenuation phenomenon, it appears that a 20% to 40% reduction in surface insolation would require no more than 3 to 7 million tons of monodisperse scatterers with radii of 0.25 μ. The same effect would require proportionally smaller quantities of smaller radius particles, and conversely. In other words, for .5 μ. The same effect would require proportionally smaller quantities of smaller radius particles, and conversely. (In other words, for .5μ particles, roughly double the tonnage required). Obviously if the order of 10^{9}tons of dust and smoke are injected into the stratosphere by the nuclear bursts, the problem is potentially very severe. The critical questions are as follows:

- How rapidly would the particulates be diffused laterally into a uniform cloud layer.

- How rapidly would the particulates be removed from the atmosphere physical processes?

With regard to question (i), it must be recalled that almost all of the weapons would be exploded within the latitude range 30°-60°(N), constituting around 15% of the earth's surface. Normal tropospheric circulation is primarily west to east, with very little mixing across the equator. Mixing in each hemisphere is primarily due to the so-called jet streams, which hover at the boundary of the temperate zones and the tropics in summer and at the boundary of the temperate zones and the polar zones in winter. (See3-1). Thus the dust and smoke would diffuse (under normal conditions) only quite slowly out of the north temperate zone where it was first injected.

In this connection, TTAPS made two alternative simplifying assumptions, namely (1) instantaneous hemispheric mixing and (2) slow horizontal diffusion within the hemisphere. The first assumption is clearly unrealistic and merely provides a limiting case. The rate of diffusion observed in connection with large volcanic eruptions and other such events is of the order of 2×10^{11} cm^2/sec. In the event of an actual war with thousands of individual bursts, it is not unlikely that the mid-latitude zone would be completely covered by clouds within matter of days. However meridional diffusion over the whole of the northern hemisphere might still require several months.[3] During this period, however, most of the material initially in the clouds will have fallen out. Direct evidence of this fact can be found in the meridional distribution of fallout from past atmospheric nuclear tests, as shown in Fig.3-2

Dust particles are normally removed from the atmosphere by two basic mechanisms, viz. vertical diffusion (driven by gravity) and rain-scavenging. The latter

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[3] A three dimensional model simulation by Covey, Schneider and Thompson (1984) suggests that meridional diffusion would be greatly enhanced by thermal gradients produced by mid-traposphsric solar heating of the smoke/soot cloud postulated by TTAPS. However model does not address the problem of vertical diffusion and scavenging processes, discussed below.

Figure 3-1: Structure of Atmosphere in July

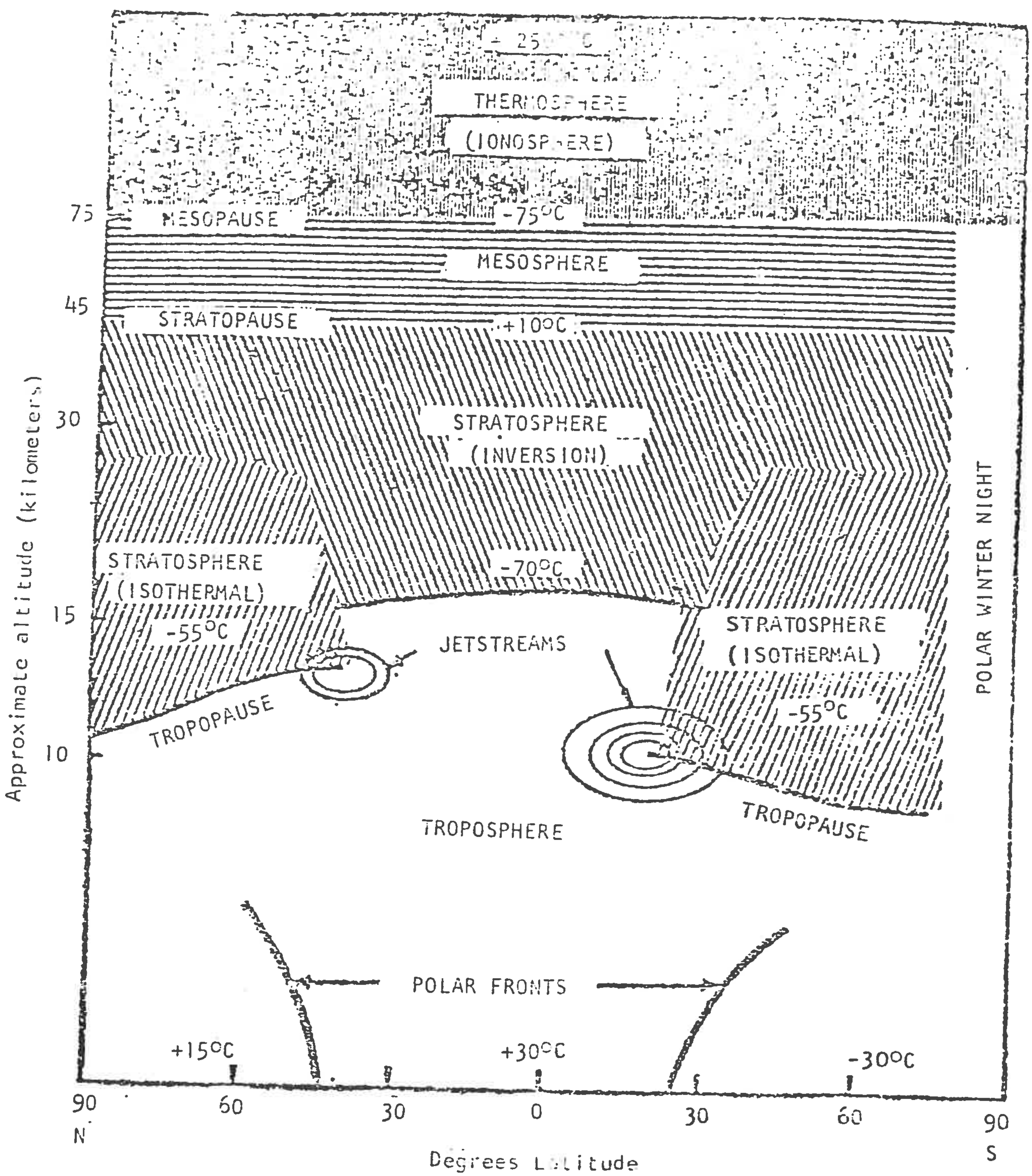
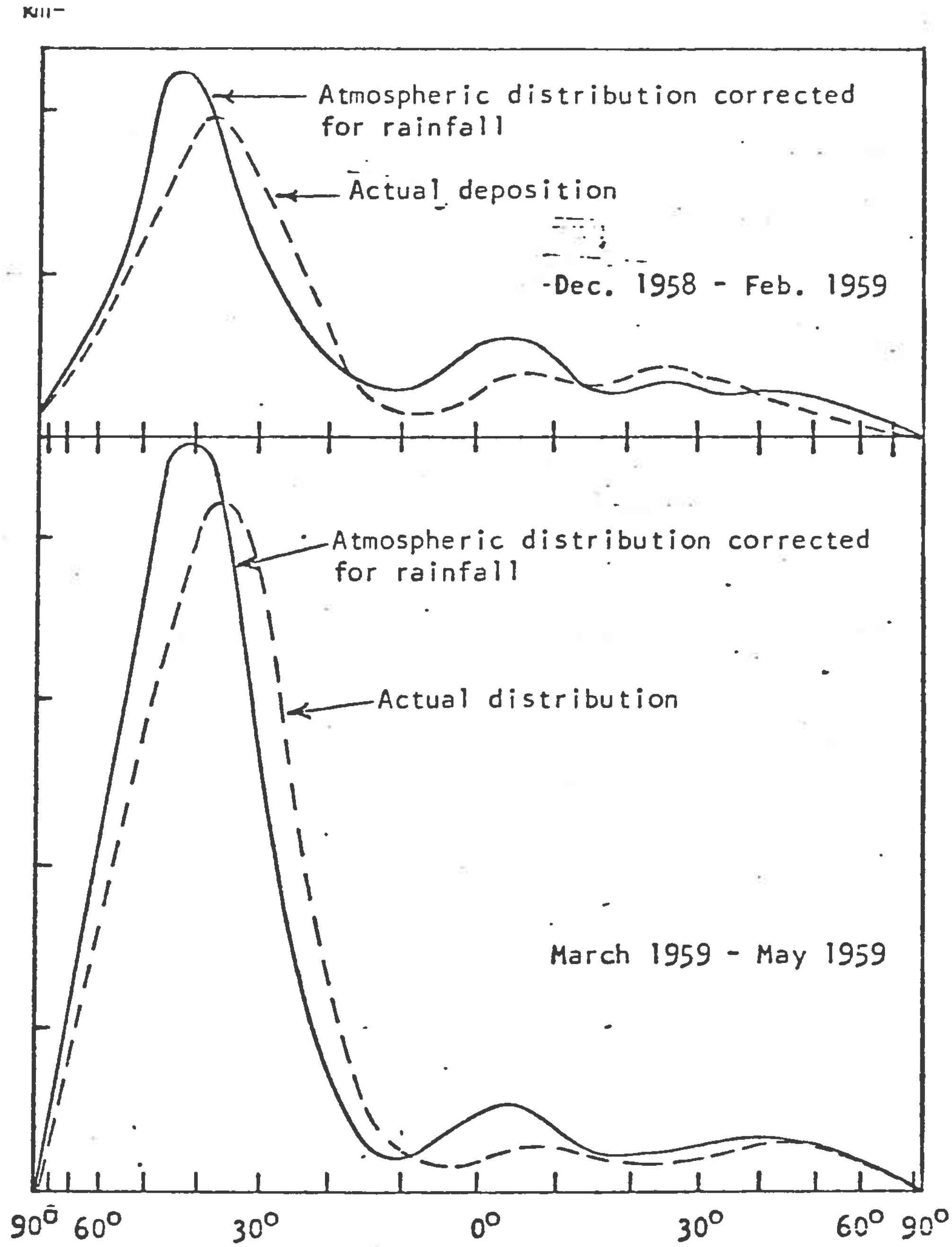


Figure 3-2: Meridional Distribution of World-Wide Fallout (Based on Sr-90 Data)



mechanism is by far the most rapid, where it is applicable--namely in the troposhere in the temperate zones. Much of TTAPS case for a very severe short-term "freeze" depends on suppression of the usual rain-scavenging process. While TTAPS acknowledges that fires caused by the Nagasaki and Hiroshima bursts were almost immediately followed by severe rain storms (that were probably induced by the fires), they speculate that a sufficiently dense smoke cloud *might* inhibit rain droplet formation, partly because fresh soot particles tend to be hydrophobic, partly because absorption of heat by the cloud could cause atmospheric inversions thus inhibiting convection, and partly because of suppression of normal evapotranspiration would cause reduced humidity.

This set of arguments is highly speculative and quite possibly wrong. In the first place, the combustion processes that generate smoke must also produce significant amounts of water vapor--a mechanism not considered by TTAPS, but pointed out by Singer (1984). For each ton of (dry) fuel burned approximately one ton of water vapor is generated in addition to the water content of the fuel itself. In fact, for typical fuel-loadings, the air column over the burned area--where the smoke cloud is concentrated--would double or triple its water-vapor content. Moreover, the rising air-column of a large fire automatically entrains surrounding air masses and tend to carry them to higher altitudes where they expand and cool-resulting in condensation of ambient water vapor and (often) precipitation. In the second place large fires would seem to increase--not suppress--atmospheric convection. Hence it is difficult to see how large-scale cloud-induced inversions could occur in the first place. Thus, while there is some uncertainty (admittedly, the condensation-precipitation phenomenon is not fully understood), it seems probable that the first few hours and days after a nuclear war would be characterized by violent and widespread storms and a greatly enhanced--not diminished--rate of rain scavenging and particulate deposition.

In any case, the scavenging issued has not been settled and deserves far more careful study. The most reasonable conclusion that can be drawn from TTAPS is that *if* troposheric scavenging mechanisms are suppressed for any reason after a nuclear war, the attenuation of solar radiation at the surface of the earth might be both severe and protracted.

With regard to the removal of particles from the stratosphere (i.e. above 10 km or so) there seems no doubt that so-called stokes law diffusion is the only applicable mechanism. The Stokes-Cunningham equation for the downward drift velocity $v(r_{1Z})$ in cm/sec for spherical particles of radius r (in cm) at altitude Z (in Km) is as follows:

$$v(r,z) = \frac{2}{9}\frac{gd}{\eta}r^2\left(1 + \frac{A}{rp(z)}\right) \qquad (2)$$

where g is the gravitational constant 981 cm/sec^2 d is the density ($\sim$ 2.3 gm/cm^3), η is the viscosity of the air, p(z) is the barometric pressure (in mm. Hg.) as a function of altitude z and A is an empirical constant with units of cm^2. Normally η is a function of temperature, but in an isothermal stratosphere (-55°c), one has

$$\eta = 1.416 \times 10^{-4} \text{ gm cm}^{-1} \text{ sec}^{-1} \qquad (3)$$

and A = 4.6332×10^{-3}. In the stratosphere, pressure (p(z) is numerically given (in millimeters of Hg) by

$$p(z) = 165 \exp[-0.146(z-10)] \qquad (4)$$

where z is in kilometers.

Now suppose the initial vertical distribution of the "stabilized cloud" is uniform of thickness D between lower and upper altitudes Z_1 and Z_2 ($Z_2 > 10$), so $D = Z_2 - Z_1$ This cloud can be thought of as a superposition of many monodisperse clouds. Define the drift distance $u(t) = X(o) - Z(t)$, or

$$Z = Z(0) - u \qquad (5)$$

whence,

$$V(r,t) = \frac{dZ}{dt} = \frac{du}{dt} \qquad (6)$$

Then, for a particle of radius v starting at the top of a cloud of thickness D, we obtain

$$\frac{du}{dt} = 11.2\, r^2 \left[1 + \frac{0.28 \times 10^{-4}}{r} \exp\left(0.146(D-u)\right)\right] \qquad (7)$$

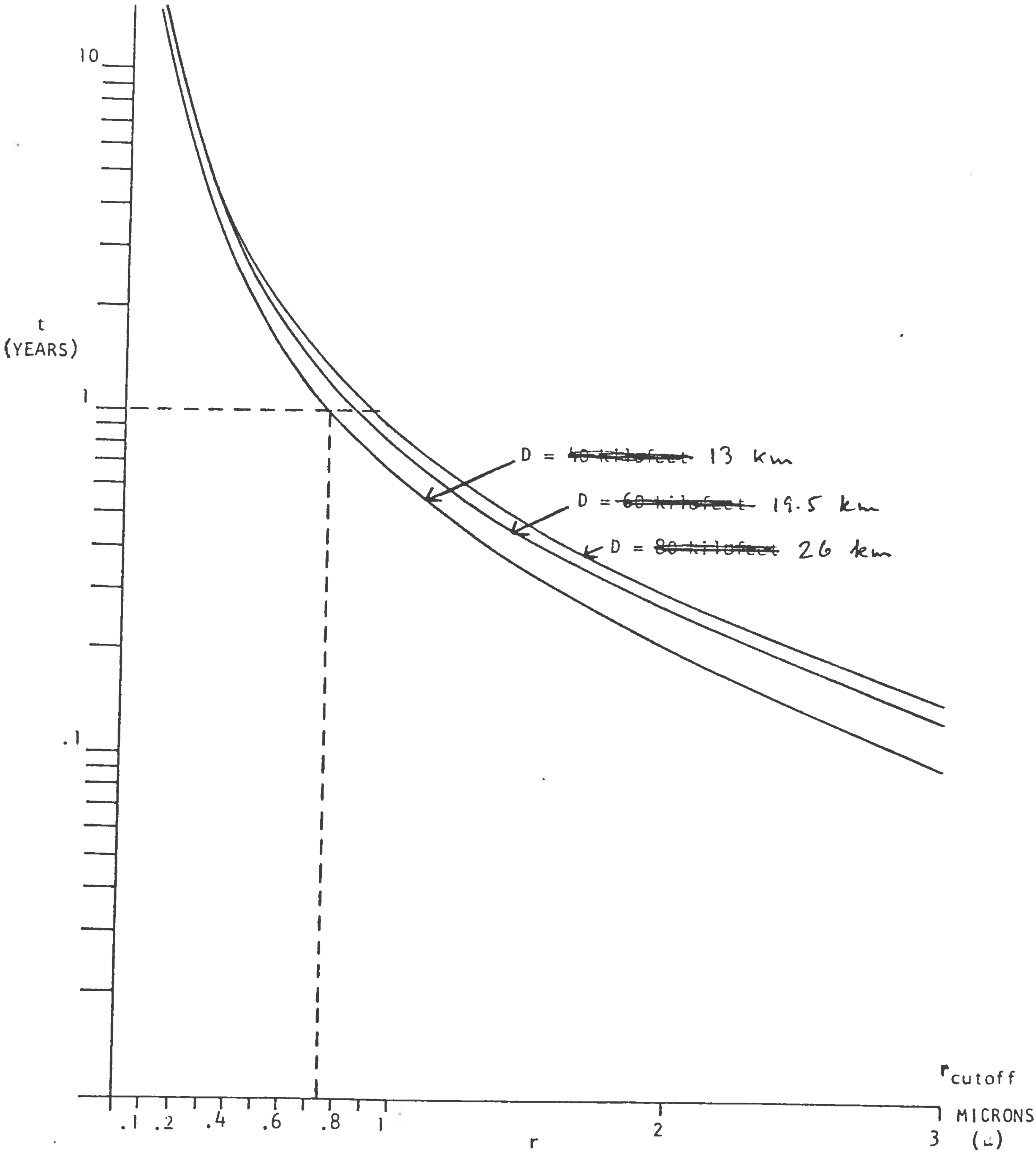
where r is measured in microns (10^{-4} cm) and D, U are in km and t in years. This expression can be integrated in closed form to yield

$$u(r,t) = 6.85 \ln\left\{\left[1 + \frac{0.28\times10^{-4}}{r}\exp(0.146D)\right]\exp(1.72\,r^2 t) - \frac{0.28\times10^{-4}}{r}\exp(0.146\,D)\right\} \qquad (8)$$

Clearly u can never exceed D, since by the time the top layer of the cloud has drifted down that far (the initial cloud thickness) it reaches the bottom of the stratosphere and is quickly removed by condensation and precipitation. Equation (6) therefore defines the longest time a particle of radius r can remain in the stratosphere. The results are plotted in Fig.3-3.

Even for very thick clouds extending up to 26 km, it can be seen from Fig.3-3 that essentially only particles with radii r = < 1 μ survive as long as one year. On the other hand, some particles with radius r = .25 μ can remain in the stratosphere for as long as ten years or more.

Figure 3-3: Cutoff Radius as a Function of Time for Dusty Layers of Different Thickness



Let me now return to the question of light scattering and attenuation of insolation at round level. A very crude order-of-magnitude estimate was given earlier, but it is possible to do a somewhat better job without excessive computational labor.

4. ATTENUATION OF SOLAR FLUX AT EARTH'S SURFACE

If we consider only direct illumination (ignoring contributions from scattered light) the net solar flux W arriving at a point on the surface of the earth as a function of latitude θ, and at an angle ϕ with respect to the zenith, will be given by an integral over all wavelengths of the solar flux arriving at the top of the atmosphere, times the attenuation factor

$$I = I_o \exp\left[-\gamma(\lambda,t,\theta)\, D \sec\theta \sec\varphi\right] \qquad (9)$$

In the above expression I stands for the intensity and $\gamma(,t,\theta)$ is the scattering cross-section per unit volume (of the cloud) in units of square microns (μ^2). Here a "unit volume" is a cylinder 1 μ^2 in cross-section and 1 kilometer in altitude. The angle ϕ is a phase-angle measured with respect to the zenith. The diurnal variation is averaged out by integrating over ϕ.

The scattering cross-section per unit volume--also called the "extinction coefficient"—is defined as follows:

$$\gamma(\lambda,t,\theta) = \pi\rho_o \int_0^\infty dr\, r^2\, Q(r,\lambda,\eta) \int_0^\infty dz\, F(r,z,\theta)$$

$$\cong \pi\rho_o\, g(\theta) \int_0^\infty dr\, r^2\, Q(r,\lambda,\eta)\, f_o(r) \left[1 - \frac{u(r,t)}{D}\right] \qquad (10)$$

$$g(\theta) = \begin{cases} 3\ \sin^2\theta\cos^2\theta & -\frac{\pi}{2} \le \theta \le 0 \\ & \text{(southern hemisphere)} \\ 12\sin^2\theta\cos^2\theta & 0 \le \theta \le -\frac{\pi}{2} \\ & \text{(northern hemisphere)} \end{cases} \qquad (11)$$

where $g(\theta)$ can be obtained (numerically) from Fig.3-2 or a similar source and approximated as in (11.), and $u(r,t)$ is given by (8) above. For convenience, I have used the simple log-normal form of particle-size distribution, i.e.

$$f_o(r) = (2\pi)^{-1/2}\ (\sigma r)^{-1}\ \exp\left[-(\ln \frac{r}{r_o})^2/2\sigma^2\right] \qquad (12.)$$

where $\sigma = \ln 2 = 0.69$ and r_o is assumed to be 0.5. This choice differs slightly from TTAPS assumption, but both were estimated from the same original source of data, (Russell and Nathans, 1966)[4] The kernel-function $Q\ (r,\lambda,\eta)$ is derived from the general theory of electromagnetic scattering of spherical particles with an absorption coefficient ξ. It can be approximated by the following (see Van de Hulst, p. 176):

$$Q(r,\lambda,\xi) = 2 - 4\exp\ (-R\ \tan\beta)\left(\frac{\cos\beta}{R}\right)\sin(R-\beta)$$

$$-4\exp(-R\ \tan\beta)\left(\frac{\cos\beta}{R}\right)^2\cos(R-2\beta) \qquad (13.)$$

$$+4\left(\frac{\cos\beta}{R}\right)^2\cos 2\beta$$

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[4] It must be pointed out that particle-size data were never measured directly, but were inferred from fallout from a *single* atmospheric nuclear weapon test the fallout was sampled by crude methods, for a very different purpose--to verify extant theories of fractionation of radioactive decay products.

where

$$R = \frac{4\pi(m-1)r}{\lambda} \tag{14}$$

and

$$\xi = \frac{1}{2} \tan \beta \tag{15}$$

Assuming a (real) index of refraction $m = 1.5$, (14) reduces to

$$R \cong 2\pi r/\lambda$$

Most glassy or crystalline substances will not differ substantially from the typical value $m = 1.5$, but the imaginary part of the index of refraction, η--i.e. the absorption coefficient--may vary considerably. Hence I have performed all calculations for a range of values of ξ. The extinction coefficient β is plotted as a function of wavelength in 4-1.

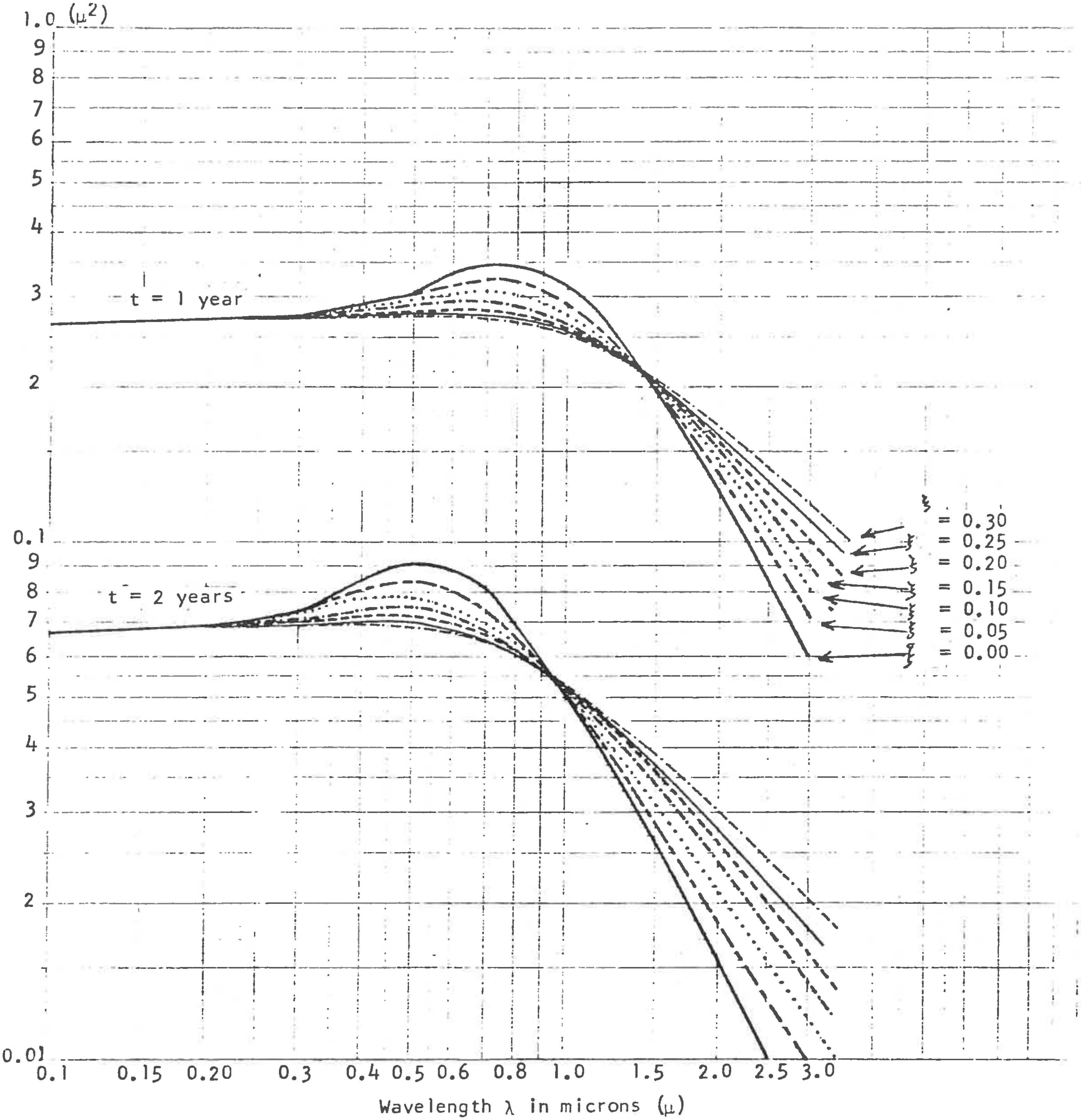
To compute the fractional net change in insolation on the surface of the earth, after a time t, at a latitude θ, one must integrate over all wavelengths (or frequencies) and phase angles ϕ

$$\frac{\delta W(\theta,t)}{W(\theta,t)} = \frac{\int_0^\infty d\nu\, S(\nu) \int_{-\pi/2}^{\pi/2} d\varphi \cos\varphi\, (I_o - I)}{\int_0^\infty d\nu\, S(\nu) \int_{-\pi/2}^{\pi/2} d\varphi \cos\varphi\, (I_o)}$$

$$= 1 - \frac{\int_0^\infty d\nu\, S(\nu) \int_{-\pi/2}^{\pi/2} d\varphi \cos\varphi \exp\left[-\frac{\gamma(\nu,t,\theta)}{\rho_o\, g(\theta)}\, \rho_o D g(\theta) \sec\theta \sec\varphi\right]}{\int_0^\infty d\nu\, S(\nu) \int_{-\pi/2}^{\pi/2} d\varphi \cos\varphi} \tag{16}$$

Figure 4-1: Values of $\gamma(\lambda,t)/p_o g(\theta)$ for Various Absorption Coefficients ξ

LOG-NORMAL DISTRIBUTION $\sigma = 0.69$ $r_o = 0.5\mu$

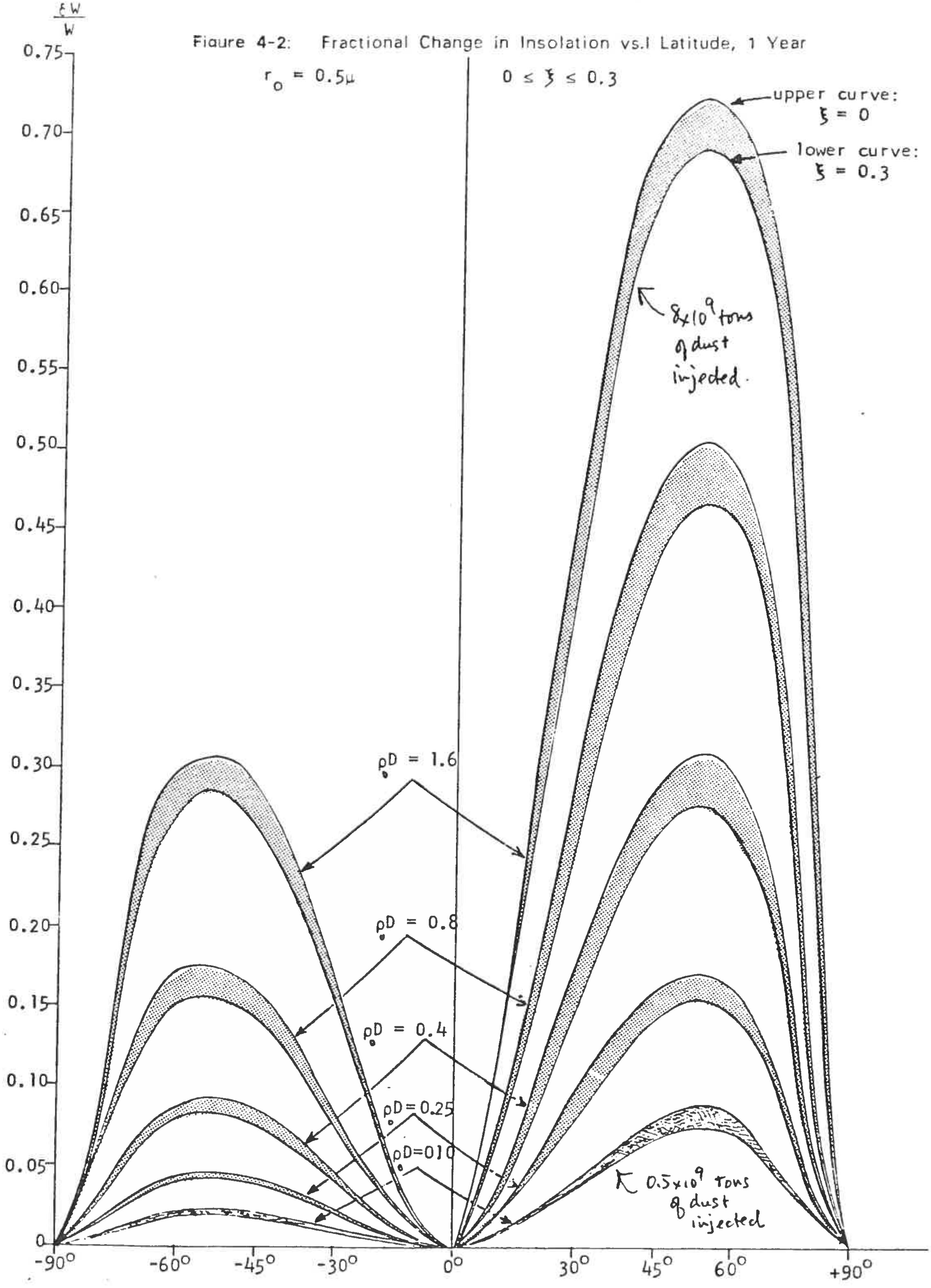


The function $S(\nu)$ is simply the sun's spectral distribution as a function of frequency. Since W has dimensions of energy flux, it is more convenient to integrate over frequency ν than wavelength (each photon has energy $h\nu$). The only parameter appearing in the integrand is the product p_oD. Sample results for insolation attenuation at the end of one year are shown in Fig.(4-2) for a range of values of this parameter. The curves for various values of absorption (h) lie close together, so I have chosen to indicate the envelope as defined by $\xi = 0$ and $\xi = 0.3$. Evidently, the results are fairly insensitive to ξ

The fractional net change of insolation as a function of latitude is probably more significant than the overall net change for the earth as a whole. The latter can be obtained, however, by integrating (16) over all latitudes θ, viz.

$$\frac{\delta W(t)}{W} = \frac{1}{2}\int_{-\pi/2}^{\pi/2} \frac{\delta W(\theta,t)}{W} \cos\theta \, d\theta \qquad (17)$$

It remains to show how the product p_oD depends upon the actual quantity of dust in the stratosphere. Dimensionally it is evident that p_oD is the normalizing constant



δW/W
Figure 4-2: Fractional Change in Insolation vs.l Latitude, 1 Year
$r_o = 0.5\mu$
$0 \leq \xi \leq 0.3$
upper curve: $\xi = 0$
lower curve: $\xi = 0.3$
8×10^9 tons of dust injected.
$\rho_o D = 1.6$
$\rho_o D = 0.8$
$\rho_o D = 0.4$
$\rho_o D = 0.25$
$\rho_o D = 0.10$
0.5×10^9 tons of dust injected
0.75
0.70
0.65
0.60
0.55
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0
-90°
-60°
-45°
-30°
0°
30°
45°
60°
+90°

proportional to the number of scattering centers in a vertical cylinder of 1 ($\mu 2$) cross-section and D (kilo-feet) in altitude. Since we are dealing with a collection of particles with a range of sizes, the average volume of material originally in the cylinder at time t = o is

$$\langle V_{cyl} \rangle = \rho_o D\, g(\theta)\, \frac{4\pi}{3} \int_0^\infty r^3\, f_o(r) dr = \rho_o D\, g(\theta)\, \frac{4\pi}{3}\, r_o^{\,3} \exp\left(\frac{9}{2}\sigma^2\right) \qquad (18)$$

for all distributions of log-normal form. In the case r_o = 0.5 (μ) and σ = ln 2 = 0.7, the average volume per particle works out to be ~5 (μ^3. The volume of dust over the whole earth is

$$\langle V_{Earth} \rangle = \rho_o D \int_{Earth} dA\, [g(\theta)] \cdot \frac{4\pi}{3}\, r_o^{\,3} \exp\left(\frac{9}{2}\sigma^2\right)$$

$$= \rho_o D\, 2\pi R^2 \int_{-\pi/2}^{\pi/2} g(\theta) \cos\theta\, d\theta \cdot \frac{4\pi}{3}\, r_o^{\,3} \exp\left(\frac{9}{2}\sigma^2\right)$$

$$= \rho_o D\, [4\pi R^2] \cdot \frac{4\pi}{3}\, r_o^{\,3} \exp\left(\frac{9}{2}\sigma^2\right) \qquad (19)$$

where R is the earth's radius. The area of the earth's surface is ~5 x 10^{26} (μ^2), whence it follows that the case indexed $p_o D$ = 0.1 resulted from a total original (t = 0) volume of material of 0.25 km^3 or ~.5 x 10^9 metric tons, for the log-normal distribution with r_o= 0.5μ. Note that assuming smaller particles (r_o=0.25) would result in (roughly) twice the attenuation effect for the same mass of dust.

It should be noted that 10^{10} metric tons of dust--the amount injected into the stratosphere by as little as 100 MT of groundburst nuclear weapons or 10,000 MT of is not a particularly large quantity on the geological scale. The weight of the atmosphere itself is of the order of ~ 3 x 10^{14} tons. Atmospheric CO_2 accounts for 2.2 x 10^{12} tons. The weight of the hygroscopic materials (salt and various sulfates) picked up and deposited annually is probably ~3 x 10^{10} tons (Woodcock, 1957). Each year more than 10^8 tons of air pollutants are injected into the atmosphere, in the U.S. alone, of which more than 10^7 tons are in the form of fly ash and other particulate wastes (e.g. smokes). Pollutants of biological origin may contribute a further 10^9 to 10^{10} tons of pollens, spores, and organic esters and terpenes. A major volcanic eruption of the explosive type may contribute 10^{10} tons or more e.g. the eruption of Krakatoa yielded ~5 km^3 or ~10^{10} tons (Royal Society, 1888) while micrometeorites from outer space contribute ~1.7 x 10+(7) tons per year to the upper atmosphere (Cadle, 1966).

5. INSOLATION AND THE EARTH'S HEAT BUDGET

An adequate and fully detailed analysis of the effect of a given fractional decrease in insolation ($\delta S/S$) on the climate of the earth is certainly beyond the scope of this paper, and probably impossible at the present time. Hence the following, highly schematized picture is presented merely in order to indicate some of the significant interactions. We may divide the major atmospheric energy transfer processes into three categories: (1) short-wave (optical) radiation, (2) long-wave (infra-red) radiation, and (3) other processes including convection, turbulent transfer, evapo-transpiration and condensation. For convenience these may be labeled SW, LW. and OP.

If the (SW) radiation arriving at the top of the atmosphere is arbitrarily set at 100 units, then the income and outgo for the atmosphere (as distinguished from the geosphere) are summarized approximately as shown in Table 1 compiled by Kondratiyev (1965) and reproduced below. The table indicates the relative importance of various major energy exchange processes affecting the thermal balance of the earth. Taking the estimates of Budyko, Yudin and T.G. Gerlyand (in the first column) as a basis for calculation, the situation can be summarized briefly in terms of aggregate inputs and outputs on the next page.

A highly simplified approximation can be expressed as the temperature adjustment equation

$$R \frac{\partial T_s}{\partial t} = \frac{S(1-\alpha)}{4} - F_{IR}(T_s) \qquad (20)$$

where R is the thermal inertia of the earth, T_s is the average surface temperature, S is the incoming solar flux, α is the earth's albedo (normally 0.3) and F_{IR} is the infra-red (long wave) flux escaping into space. The IR flux is approximately

$$F_{IR}(T_s) = a + b\,(T_s - 273^{\circ}C) \qquad (21)$$

where

$a = 0.289\ \text{cal.cm}^{-2}\text{min}^{-1}$

$b = 2.88 \times 10^{-3}\ \text{cal cm}^{-2}\ \text{min}^{-1 0K-1}$

It follows that, to first order, a 1% decrease in S causes a decline in the equilibrium average temperature of the earth's surface of 0.65°K. Most of this adjustment occurs on a scale of months. Clearly a better estimate requires the use of radiative-convective atmospheric circulation models. TTAPS initially used a 1-dimensional model (altitude only) which led to their prediction of a short-term 30°K temperature drop under the smoke cloud associated with a baseline nuclear war scenario (1983) assumed a similar nuclear war scenario and physical model but with a 2-dimensional RCM with meridional (latitude) circulation and more compensatory negative feedback effects predicted a more moderate 15°K drop. A Aleksandrov and Stenchikov (1983) obtained similar results with a quasi 3-dimensional (2-layer) RTM.

Most recently, Covey, Schneider and Thompson (1984) have utilized a 3 dimensional general circulation model (GCM) and obtained more complex patterns, but qualitative agreement with results of the simpler models. It must be reiterated, however, the precipitation and other smoke removal mechanisms cannot be fully modelled at

Table 1

Average Annual Thermal Balance of Earth

Components of the thermal balance(%)	Ref. 2	3	4	5
Shortwave radiation				
Received at the upper boundary of the atmosphere	100	100	100	100
Reflected from clouds into space	27	25	27	30
Reflected into space by atmospheric scattering	7	9	6	8
Absorbed by clouds	12	10	11	
Absorbed by the atmosphere				15
Solar radiation	6			
Radiation reflected by the earth's surface	2	9	3	
Reaches earth's surface;				
As direct solar radiation	30			30
As diffuse radiation	18			17
Absorbed by the earth's surface;				
Direct solar radiation	27	24	11	27
Diffuse radiation	16	23	34	16
Reflected from earth's surface;				
Direct solar radiation	3			3
Diffuse radiation	2			1
Thermal radiation				
Total thermal radiation of the atmosphere	151			146
Including:				
Radiation into space	55	66*	48	50
Atmospheric emission reaching the earth's surface	96	105		96
Thermal emission of the earth's surface	116	119		120
Including:				
Absorbed by the atmosphere	108			112
Radiation into space	8		17	8
Net radiation of the earth's surface	20	14	23	24
Other components of thermal balance				
Turbulent heat transfer from the earth's surface to atmosphere	4	10		-4
Latent heat of condensation (or evaporation)	19	23		23

*Including thermal radiation from the earth's surface.

present. However, there seems to be general agreement among the climatologists that long-term effects would be smaller in magnitudo and probably insufficient to trigger a new period of glaciation, for instance.

The results of simulations demonstrates some important qualitative conclusions, notably that *ceteris paribus*, injection of a large quantity of smoke into the troposphere (mainly 45°N-75°) in summer would dramatically alter the general circulation pattern in both hemispheres. The major features are (1) higher air temperatures in the upper troposphere of the northern latitudes (45°N-75°N) and significant differences extending as far as 330°S , (2) average surface cooling of 10°C or more in the north temperate zone between latitudes 50° and 70° and (3) acceleration of the upper level west-to-east winds and reversal of the lower level east to west circulation in the northern latitudes, and acceleration of the east-to-west flows at all altitudes in the equatorial regions. Generally speaking temperature gradients from the tropics to the north polar regions would be increased, and the "storm belt" should be moved to the north.

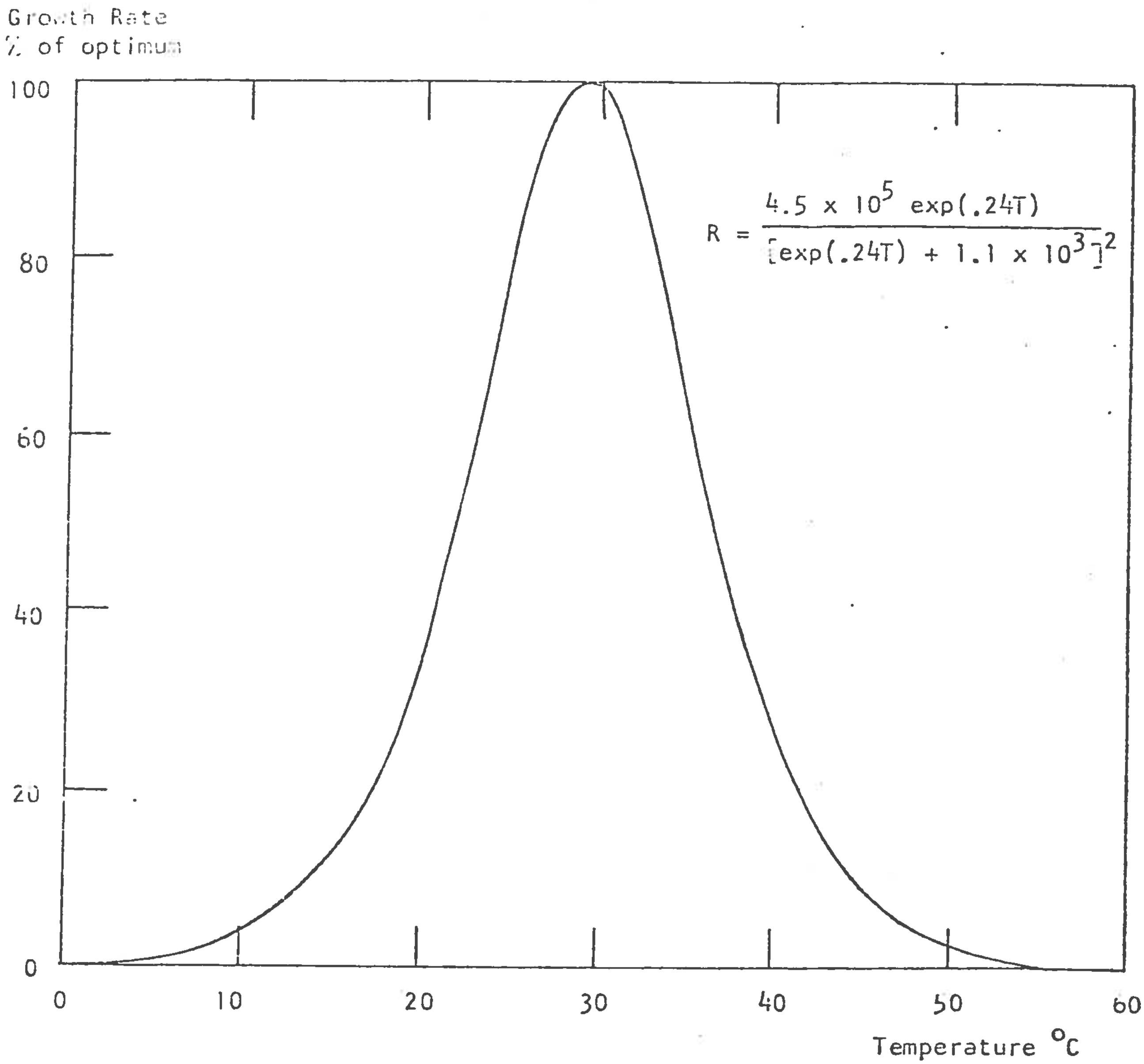
The biological impacts are clear at least qualitatively. If the war took place in the winter, the "freeze" would drive temperatures below the level of tolerance for many perennial species living near the northern edge of their natural range. Many trees species, for instance, would be killed outright or severely weakened and subject to later attack by pests and/or disease during the subsequent growing season. Most overwintering birds would die. On the other hand, dormant seeds of most annuals would be unaffected--as would crops.

On the other hand if the war took place in spring or summer crops would either be freeze-killed outright or their growth rates would be severely retarded. For example, winter wheat in the Pacific Northwest requires about 11050 day-degrees (centigrade) to ripen. A decline in average temperature of 10°C over a 30 day period would produce a deficit of 300 day-degrees by the time ripening normally occurs--enough to delay the harvest a month or more and allow time for insects, and disease to take a heavy toll.

Putting it another way, productivity of many crop plants would be far less than normal. In the case of corn, for instance, a 10° temperature differential extending throughout the season would reduce the yield by nearly 70% 5-1. However, the period of severe cold would probably be considerably shorter, and the productivity impact correspondingly less. (Actually, most crops in the field would be badly contaminated by radioactive fallout and perhaps unusable for that reason. It is also highly uncertain that crops could be harvested, given the likely breakdown in social infrastructure, transportation and distribution. But these are different problems.)

Given that periods of intense cold may be expected to occur throughout the latitudes where most of the weapons are used, for periods of anywhere from a few days up to a few months, depending on the nuclear scenario, the location and the effectiveness of tropospheric scavenging mechanisms, a critical question is the following: would the global environmental effects be so devastating *per se* that even the survivor of a successful preemptive first strike would be unable to survive the aftermath? What can probably be said with reasonable confidence on the basis of available evidence, is that the "nuclear winter" and its biological after effects--however bad--be nearly as severe as the direct damage caused by the use of nuclear weapons and the economic/social collapse that would almost certainly result from a large-scale nuclear exchange.

Figure 5-1: Corn Growth as a Function of Temperature



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List of Figures

FIGURE 2

CUTOFF RADIUS AS A FUNCTION OF TIME FOR DUSTY LAYERS OF DIFFERENT THICKNESS

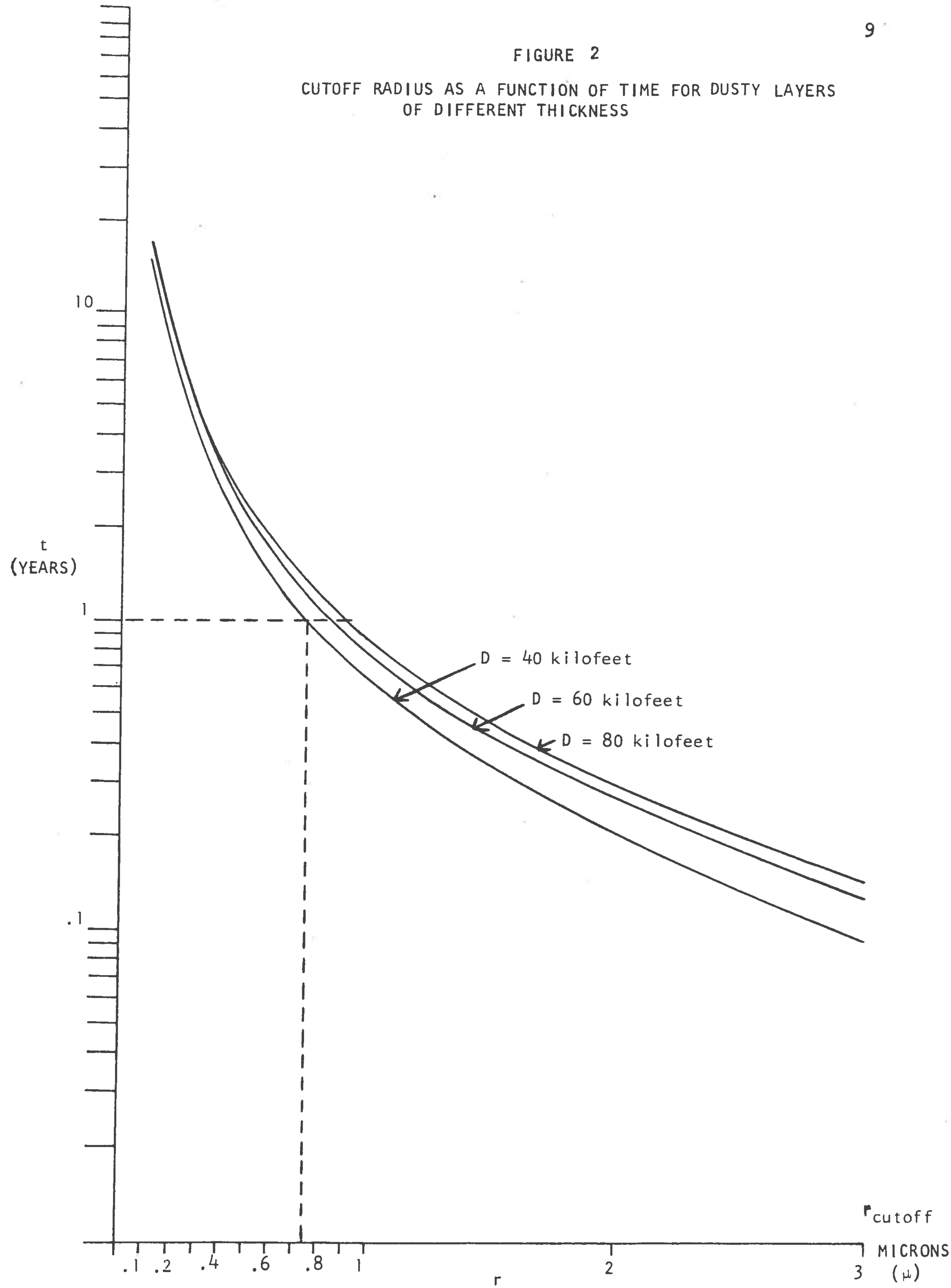

FIGURE 3

VALUES OF $\gamma(\lambda,t)/\rho_o\, g(\theta)$ FOR VARIOUS ABSORBTION COEFFICIENTS

LOG-NORMAL DISTRIBUTION $\sigma = 0.69$ $r_o = 0.5\mu$

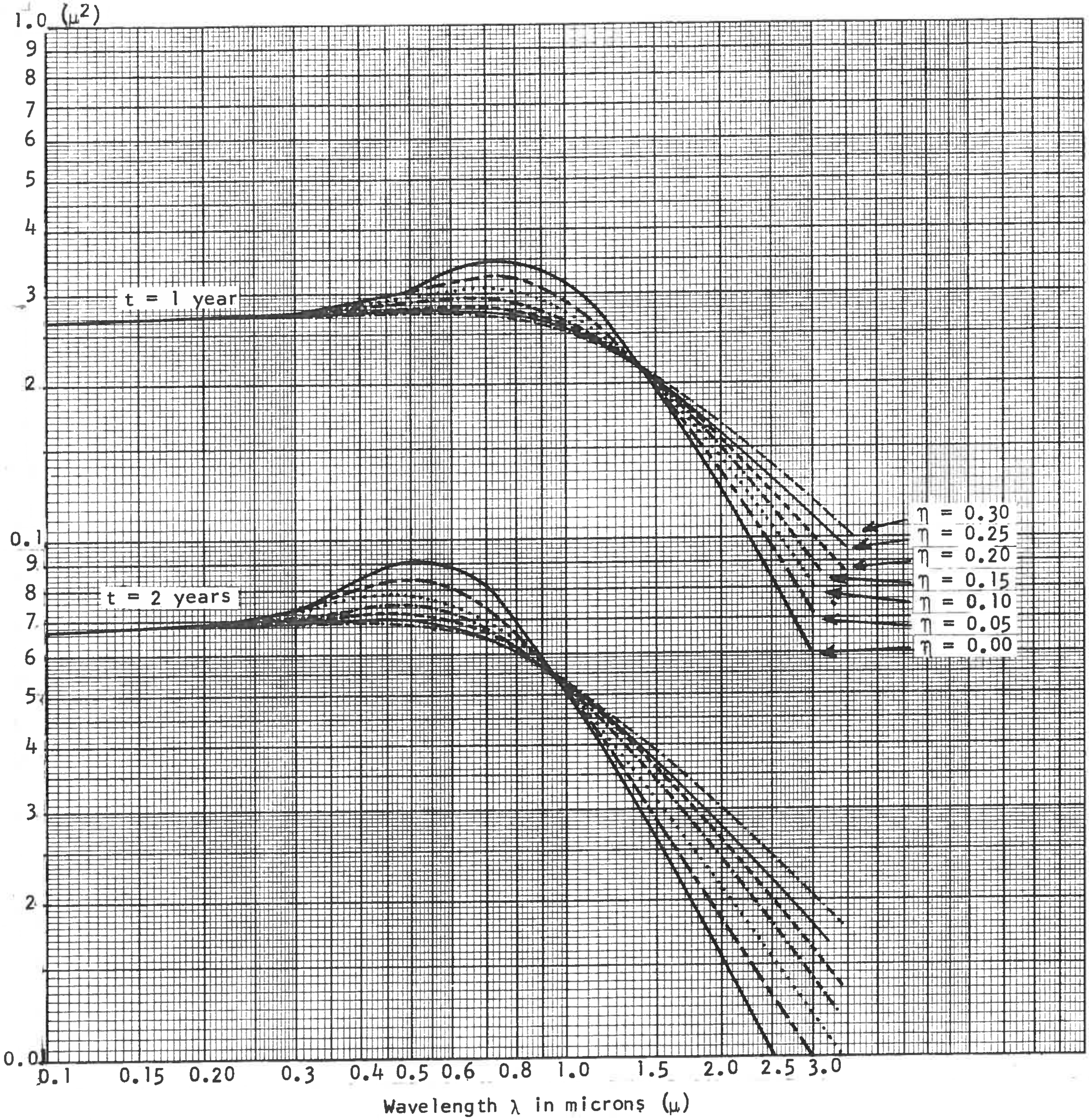

FIGURE 5

FRACTIONAL CHANGE IN INSOLATION VS. LATITUDE