Clouds and Radiation: A Primier

F. Zachariasen

February 1993

JSR-90-307

JASON
The MITRE Corporation
7525 Colshire Drive
McLean, Virginia 22102-3481
(703) 883-6997

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	February 25, 1993	

4. TITLE AND SUBTITLE

Clouds and Radiation: A Primer

5. FUNDING NUMBERS

PR - 8503A

6. AUTHOR(S)

F. Zachariasen

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

The MITRE Corporation
JASON Program Office A10
7525 Colshire Drive
McLean, VA 22102

8. PERFORMING ORGANIZATION REPORT NUMBER

JSR-90-307

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Department of Defense
Washington, DC 20301-7100

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

JSR-90-307

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Open for public release; distribution unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This paper addresses a previously unknown complex interdisciplinary process providing a feedback loop which may have a major impact on the effect on global climate of the steadily increasing growth of greenhouse gases in the atmosphere.

14. SUBJECT TERMS

solar radiation, cloud condensation

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAR

Contents

1 INTRODUCTION

Inclusion of the effects of clouds in climate models to a remarkably high degree of precision is almost certain to be a prerequisite to any reasonable degree of reliability in climate prediction because of the sensitivity of, for example, surface temperatures to cloud albedo. Unfortunately, many of the major physical processes taking place in clouds are still poorly understood. Some of them involve not only physics, but marine biology, oceanic and atmospheric chemistry, and other disciplines outside of physics, as well. It is likely, therefore, that not only do physical processes that are understood need to be modeled much more accurately than is now done, but many presently ignored processes have to be included as well. Indeed, this is the motivation behind DOE's Atmospheric Radiation Measurement (ARM) program.

This paper addresses, as an illustrative example, one such previously unknown complex interdisciplinary process providing a feedback loop which may have a major impact on the effect on global climate of the steadily increasing growth of greenhouse gases in the atmosphere. It is to be stressed that this is only one of a number of such feedback loops, many of which have probably not even been thought of yet, but all of which are entirely ignored in present day computer models.

Clouds influence climate in two major ways: they reflect incident short wavelength solar radiation thus preventing it from reaching the earth's surface and heating it, and they absorb outgoing long wavelength radiation from the earth thus reducing the earth's ability to cool itself. Which of these two competing, opposite sign, effects dominates is a sensitive function of the interaction of clouds with radiation, which is itself a sensitive function of the processes going on within various kinds of clouds.

Solar radiation is (to a good approximation) a black-body spectrum at 5,780°K, which peaks in the visible at a wavelength of about 0.5 μm. At the earth, the flux of solar radiation is 1,370 watts/m^2, and due to the existence of day and night and because the earth is a sphere, the average solar energy incident at the top of the atmosphere is one fourth of this. The average earth albedo is .3, so 30% of the incident radiation is reflected, leaving 240 watts m^2 to be absorbed by the earth's surface and atmosphere.

Radiation emitted from the earth is (to a relatively poor approximation) a black-body spectrum at 255°K, which peaks in the infrared at about 10 μm. There is essentially no overlap between the solar spectrum and the earth's spectrum. As the outgoing IR radiation passes through the atmosphere, some of it is absorbed and reradiated back toward the earth, but of course the net IR radiation escaping into space from the top of the atmosphere is also 240 watts/m^2, since the earth is (essentially) in equilibrium.

The black-body spectra and the principal atmospheric absorption bands are shown in Figure 1.

The albedo of the earth's surface (insofar as it can be measured from satellites) is no more than .15. The average cloud cover over the earth is observed to be 60% (65% over the ocean and 50% over the land). Hence, to

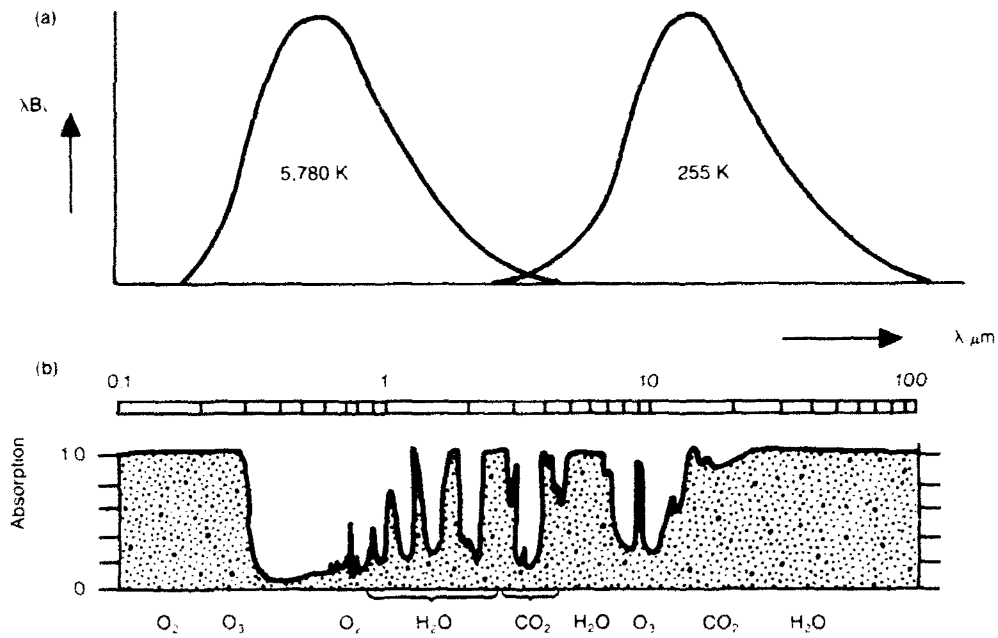

Figure 1. Curves of black-body energy B_λ at wavelength λ for 5,780 K (approximating to the sun's temperature) and 255 K (approximating to the atmosphere's mean temperature). The curves have been drawn of equal areas since integrated over the earth's surface and all angles the solar and terrestrial fluxes are equal. Absorption by atmospheric gases for a clear vertical column of atmosphere. The positions of the absorption bands of the main constituents are marked. (From R. M. Goudy "Atmospheric Radiation," Oxford, 1964.)

make up the average albedo of .3, the albedo of clouds is about .45. Clouds are therefore the most important component in the amount of reflected sunlight, and their existence is crucial in determining the surface temperature of the earth. In fact, (if other parameters were held constant) a change of cloud albedo by 2% would warm the earth's surface by 1°C[1]. Evidently, the modeling of clouds in climate models must be done very accurately.

Clouds are composed of water droplets and/or ice crystals, which form on cloud condensation nuclei (CCN). (In principle, condensation of water vapor can occur at humidities above 100%, but because the vapor pressure increases with the curvature of the surface at which condensation occurs, in practice humidities of above 300% are needed for pure water vapor to condense. Therefore actual cloud formation takes place because of the presence of relatively large aerosols. These aerosols constitute CCN.) Clouds occur in several different forms, depending on their altitude, formation mechanisms, hydrodynamic properties, etc. Table 1[2] shows the distribution of the various forms over land and ocean. The relative amounts of these types often have diurnal variations which are of considerable importance. For example, the ratio of stratus to stratocumulus varies from less than 20% at local noon to nearly 30% in the early morning, while cumulonimbus peaks at 30% in late afternoon or evening and vanishes early in the morning[2].

Table 1

Average % of Sky Cover over { Ocean / Land } of Various Cloud Types

Cumulus	12 5
Cumulonimbus	6 4
Stratus and Stratocumulus	34 18
Nimbostratus	6 6
Altostratus and Altocumulus	22 21
Cirrus	13 23

2 INCIDENT SOLAR RADIATION

For incident solar radiation, emission is irrelevant because at $\lambda \sim 0.5\mu m$, the black body spectrum at the earth's temperature of around 270°K is essentially zero. So only scattering and absorption count. To a first approximation, let us neglect scattering into the beam, and assume the incident solar radiation suffers only losses due to clouds. Thus the radiation intensity $I_\lambda(\hat{k}, z)$ of photons of wavelength λ travelling in the direction $\hat{k}$ satisfies[3]

$$dI_\lambda(\hat{k}, z) = -(\sigma_\lambda^{\text{abs}}(z) + \sigma_\lambda^{\text{scatt}}(z))N(z)I_\lambda(\hat{k}, z)dz, \qquad (2-1)$$

where σ are absorption and scattering cross sections and N is particle density. Therefore,

$$I_\lambda(\hat{k}, z_2) = I_\lambda(\hat{k}, z_1)e^{\tau(z_2, z_1)}, \qquad (2-2)$$

where the (dimensionless) optical depth τ is

$$\tau(z_2, z) = \int_{z_1}^{z_2} \sigma_\lambda^e(z)N(z)dz \qquad (2-3)$$

and

$$\sigma^e \equiv \sigma^{\text{abs}} + \sigma^{\text{scatt}} \qquad (2-4)$$

is the extinction cross section.

Each type of cloud has, at a given height z_1, a distribution $n(r, z)$ of sizes with particles of radius r (ice crystals are of course not spherically symmetric, though their absorption cross section does not differ markedly from that of liquid water droplets). In general, the cross section σ will also depend on the particle size. For wavelengths that are small compared to the particle size, as is typically the case for solar radiation (see Figure 2), the cross section is twice geometrical: $\sigma = 2\pi r^2$. Thus (if we take z_1 to be the top of the atmosphere where $\tau = 0$) the optical depth at height z is

$$\tau(z) = 2\pi \int_z^{\text{top}} dz' \int dr\, r^2\, n(r, z'). \qquad (2-5)$$

and $n(r, z')$ is the droplet size distribution, so that $N(z') = \int^{\infty} zn(r, z')dz'$. This equation is usually re-expressed in terms of the liquid water content (LWC) of the cloud, defined by

$$LWC(z) = \frac{4\pi}{3}\, \rho_w \int r^3\, n(r, z)dr, \qquad (2-6)$$

where $\rho_\omega = 10^6 g/m^3$ is the density of water. The effective radius is defined by

$$\frac{\mathrm{LWC}(z)}{r_{\text{eff}}(z)} = \frac{4\pi}{3}\, \rho_w \int r^2 n(r, z)dz. \qquad (2-7)$$

Therefore one finally writes the optical depth in the form

$$\tau(z) = \frac{3}{2}\, \frac{1}{\rho_w\, r_{\text{eff}}} \int_z \mathrm{LWC}(z')dz'. \qquad (2-8)$$

If z is below the cloud, then the total optical thickness of the cloud is

$$\tau^* = \frac{3}{2}\, \frac{\mathrm{LWP}}{r_{\text{eff}}\, \rho_w}. \qquad (2-9)$$

where the liquid water path is

$$\mathrm{LWP} = \int_{\text{bottom}}^{\text{top}} \mathrm{LWC}(z')\, dz'. \qquad (2-10)$$

Crudely, then, $LWP = LWC \cdot t$, where t is the cloud thickness The liquid water content varies greatly with cloud type, as shown in Table 2[4], as does the mean cloud thickness. Finally, when all of this is put together, and the average solar zenith angle of 60° is included, the previously inferred

Table 2

	LWC (g/m^3)	t (km)
Cumulus	.4	2
Cumulonimbus		
Tropical	1.0	5
Trade Wind	1.5	2
Midlatitude	1.5	2.5
Polar	1.5	2
Altostratus/Altocumulus	.1	.5
Stratus/Stratocumulus	.2	1
Nimbostratus	.1	3

average cloud albedo of .45 results from an average optical thickness $\tau^* = 6$, assuming a simple geometry of plane parallel clouds. Since in fact clouds are horizontally variable, and there is some absorption, this value is actually a lower bound.

Experimentally measured cloud albedos vary greatly, as a function of type, latitude, solar zenith angle, and other parameters. But overall, they are not inconsistent with the inferred value of .45. Therefore, we may have some confidence in the value of τ^* obtained above.

From the formula for τ^*, we see that it varies inversely with the effective droplet radius. Thus a cloud having the same LWP as another but a large number of smaller droplets, will have a larger τ^* and therefore a larger albedo.

If one asks, therefore, what changes may take place in cloud albedo (to which, as we've remarked earlier, the earth's surface temperature is extremely sensitive) due to man's activities, we must concentrate on r_{eff}. For example, an increase in r_{eff} of 10% (which corresponds to a decrease in ΔN of 30%) reduces the albedo enough so that ΔT surface = 1.3°C. Or, as another example, reducing N by a factor of 2 is equivalent to doubling the CO_2 concentration in the atmosphere.

A further effect of reducing droplet size, while keeping the total LWC constant, is likely to be an increase in cloud lifetime, and consequently of average cloud cover. Figure 2[5] shows that typical droplet sizes are now 5-10 μm. These do not rain out until they coalesce to form larger drops of 50 μm diameter or more. Therefore if the mean droplet size were to decrease, the time to coalesce to a size which rain will grow, thus increasing average cloud lifetime.

N and r_{eff} are largely determined by the number of CCN available. These vary widely between land and water (Figure 3)[6].

Overall, from the foregoing discussion of cloud albedo, any model purporting to predict global climate change due to greenhouse gas forcing, or anything else, needs to be able to evaluate the fractional surface areas of the earth covered by (particularly low) clouds, the liquid water content of the

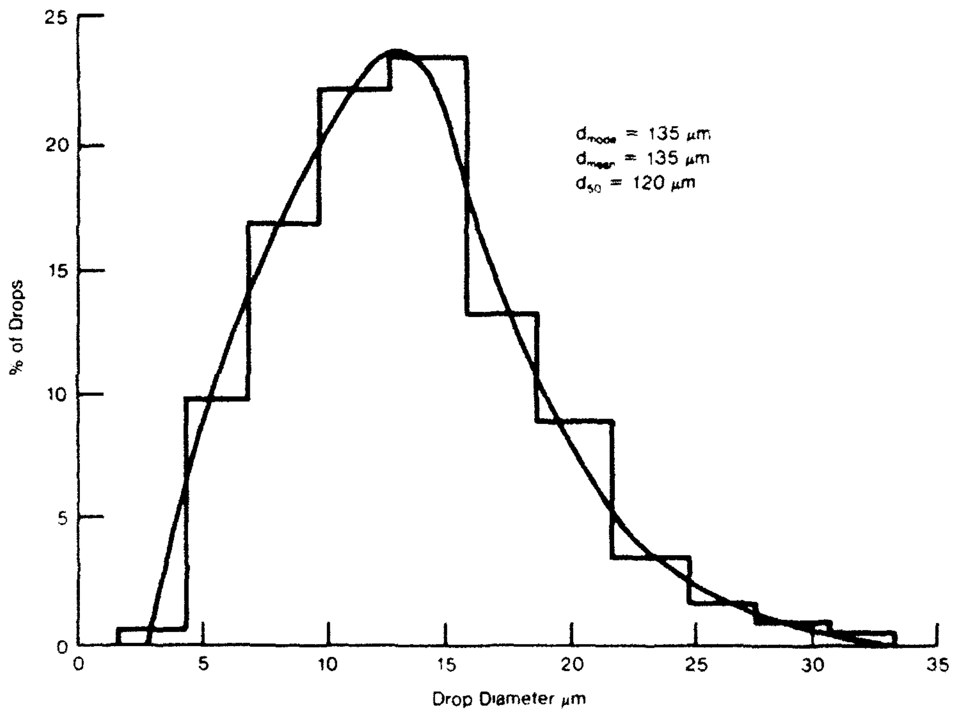

Figure 2. Average drop size spectrum for the arctic stratus clouds.

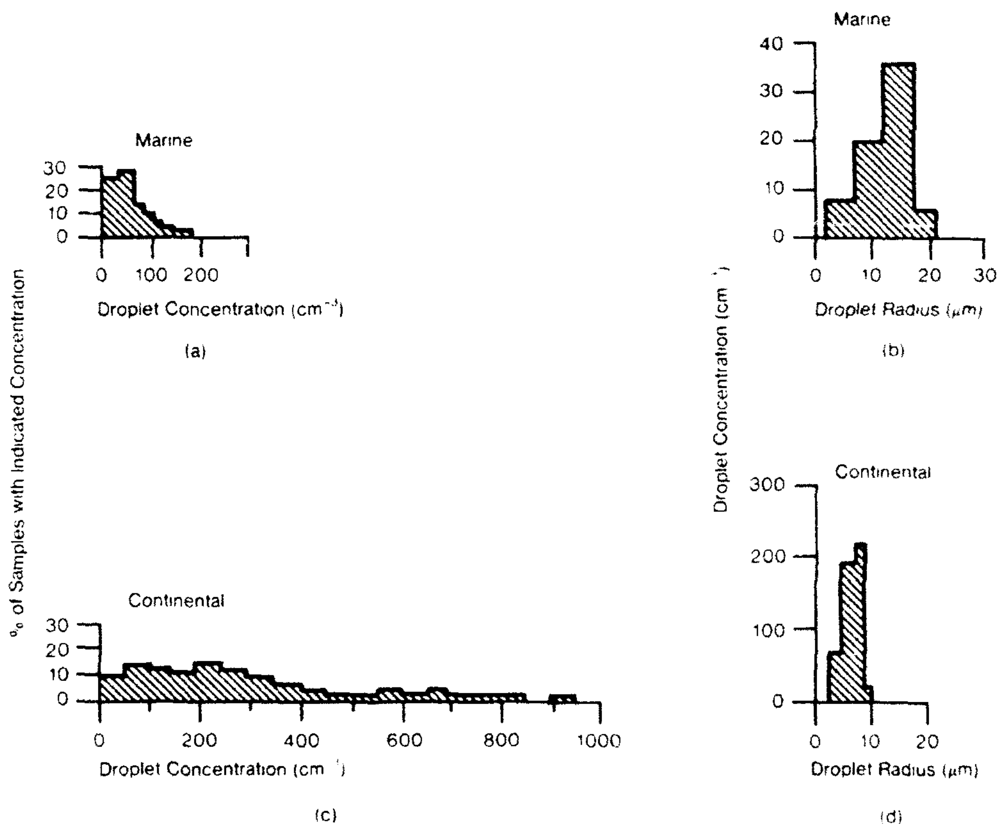

Figure 3. (a) Percentage of marine cumulus clouds with indicated droplet concentrations (b) Droplet size distributions in a marine cumulus cloud. (c) Percentage of continental cumulus clouds with indicated droplet concentrations. (d) Droplet size distributions in a continental cumulus cloud Note change in ordinate from (b)

clouds, the droplet effective radius, the droplet number, and the number of CCN, to an extraordinarily high degree of precision; less than 5% accuracy will be required in all of these quantities.

This is an exceedingly stringent requirement on GCMs, and on computing capacity. Nothing like this precision is now available, and, indeed, many of these parameters are not even included in present models.

3 CLOUD CONDENSATION NUCLEI OVER THE OCEAN

As greenhouse gases in the atmosphere increase, the earth warms, evaporation increases, and the liquid water content of all clouds except cirrus increases. Therefore, both the albedo and the absorption of outgoing IR radiation increases. Most GCMs predict that the net effect is a positive feedback, because of the simple observation that an increase of temperature at low altitude will decrease low clouds while a decrease of temperature at high altitude will increase high clouds. Various effects, however, may reverse this.

The impact of cirrus clouds is one uncertainty. Their effect is difficult to compute, since they are composed entirely of ice crystals, which are anisotropic and whose effect on radiation is not quantitatively well understood. They are also not well studied experimentally; they are very high and also often even difficult to see visually.

It is also unlikely that fractional cloud cover will remain unchanged if evaporation increases. Generally, an increase in cloud cover will be a negative feedback. Figure 4[7] shows measured changes in average cloud cover over the ocean from 1952 and 1980, as a function of latitude, annually averaged. Could this be due to global warming?

A major uncertainty is the effect of global warming on the number of CCN, particularly oceanic CCN.

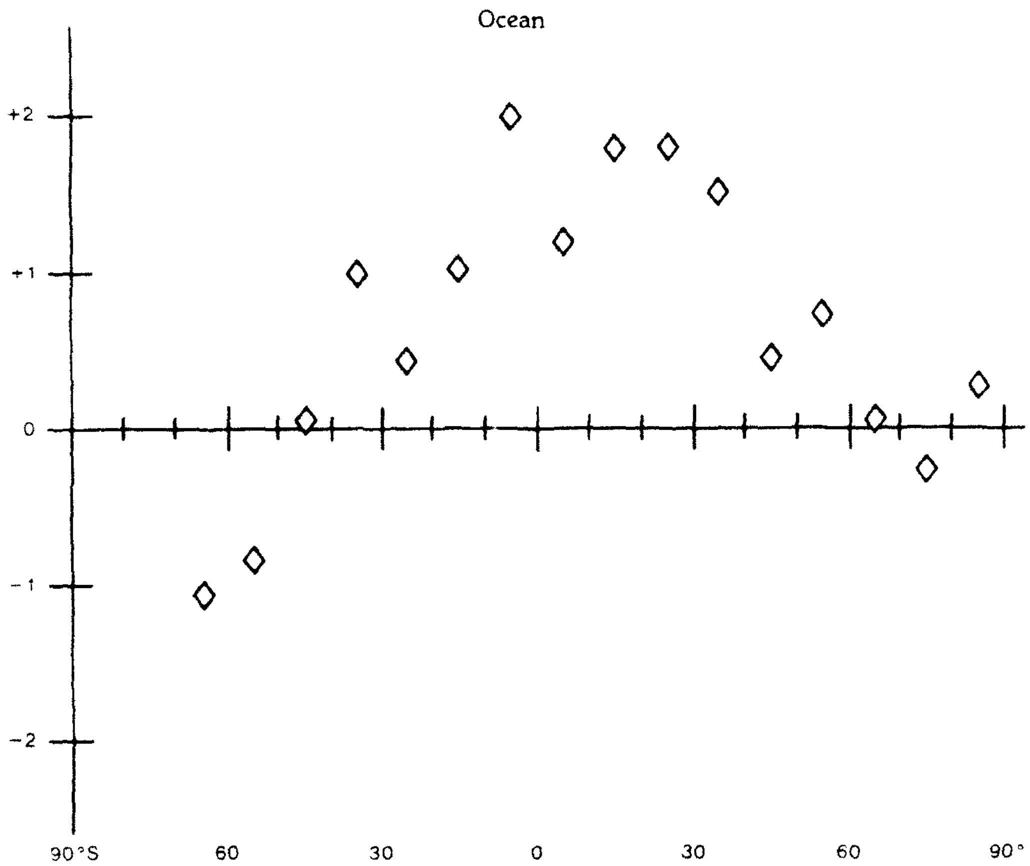

Figure 4. Change in % • cloud-cover from 1952 to 1981 (Annual).

Marine CCN have two major components; sea salt and non-sea salt sulfate (abbreviated NSS). By volume, these are comparable. But the sea salt component is composed of much larger particles, so by number NSS completely dominates (see Figure 5)[8].

To act as a CCN, an aerosol particle must be hydrophilic and above a critical size, which is a function of the degree of supersaturation of water vapor in the cloud. Over the ocean the critical size is thought to be in the range of .05 to .14 μm, corresponding to supersaturation of 0.1% to 0.5%. (See Figure 5 again.)

Empirically, the number of CCN over the ocean is around 100 per cm^3[9] (to be compared with tens of thousands per cm^3 over polluted land areas), and since this is about the same as the droplet number density in marine clouds, it is thought that the number of CCN available is a limiting factor in the growth of marine clouds.

If we accept the idea that NSS are the dominant CCN, we must next ask how a change in global climate will affect the number of NSS particles. (We recall the apparently very strong correlation with the ice age ending 15,000 years ago shown in Figure 6.)[9]

The present concept is that NSS is produced by the oxidation of various sulfur gases coming from the surface of the sea[9]. Dimethyl sulfide ($(CH_3)_2S$, abbreviated DMS) is alleged to be the major oceanic source, and it is believed to be of biologic origin. It has a measured concentration of about 100ng/liter at the sea surface, which varies relatively little over the whole

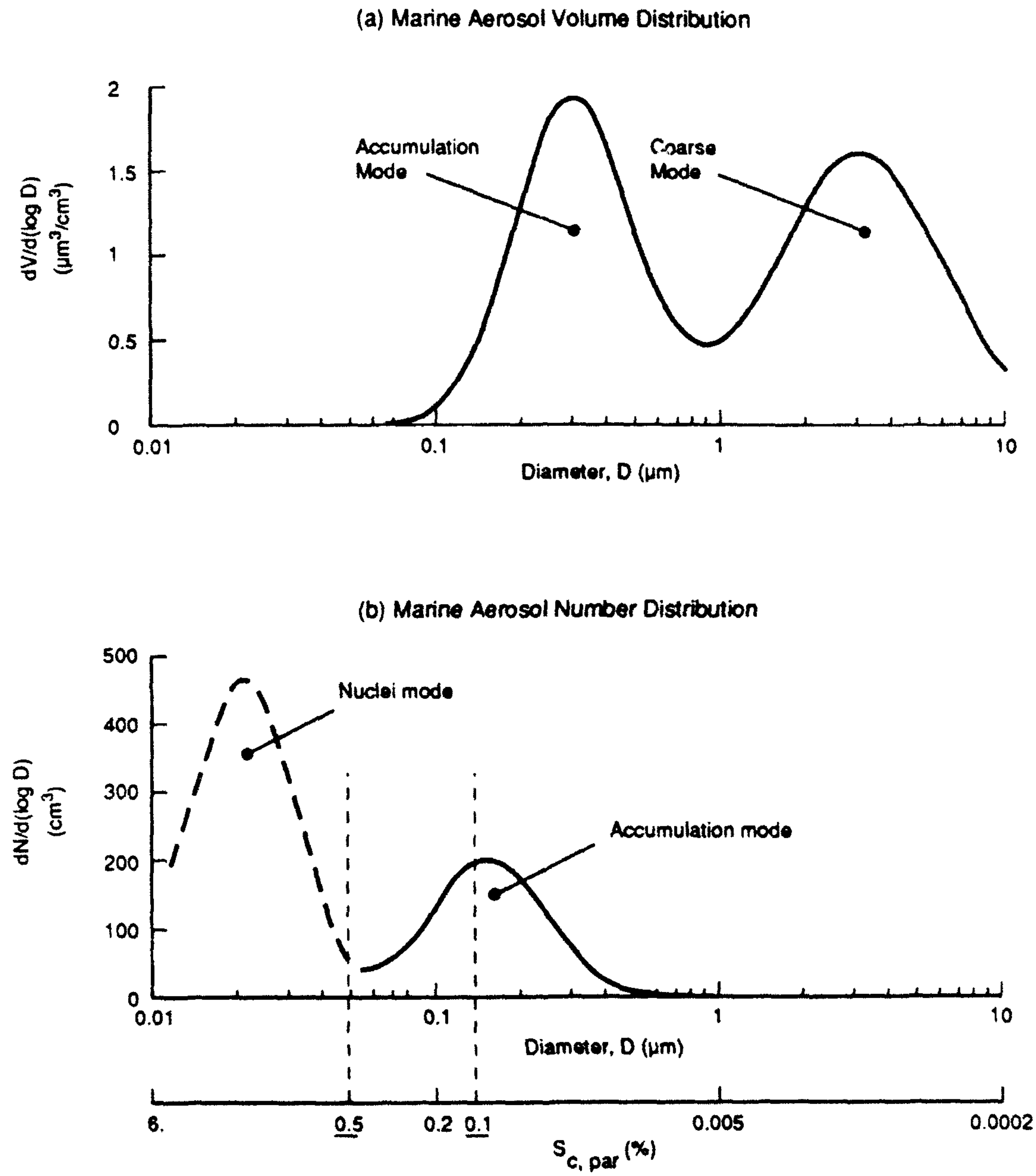
(a) Marine Aerosol Volume Distribution
dV/d(log D) (µm³/cm³)
2
1.5
1
0.5
0
Accumulation Mode
Coarse Mode
0.01
0.1
1
10
Diameter, D (µm)
(b) Marine Aerosol Number Distribution
dN/d(log D) (cm³)
500
400
300
200
100
0
Nuclei mode
Accumulation mode
0.01
0.1
1
10
Diameter, D (µm)
6.
0.5
0.2
0.1
0.005
0.0002
S c, par (%)

Figure 5.

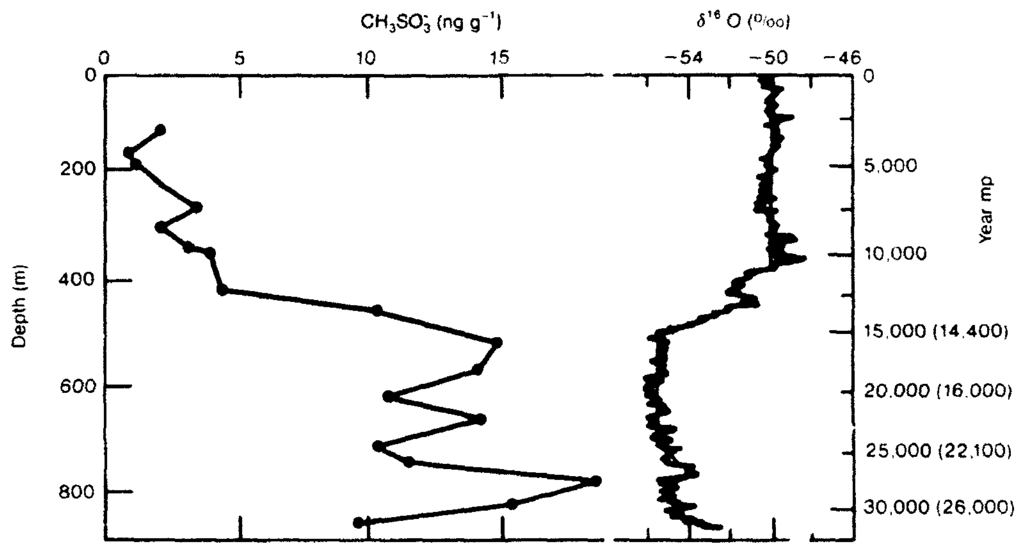

Figure 6. MSA ($CH_3SO_3^-$) down the Dome C core; the isotope profile (δD‰) indicate the Holocene and the end of the last ice age.

ocean surface (by a factor of no more than about 2). The entire chain of marine biochemistry leading to this concentration of DMS is very complex. involving a number of other molecules and many types of marine animals and plants. In Figure 7[9], displayed is the presently conjectured life cycle of DMS in the sea.

For our purposes it is not necessary to understand this intricate network of connections. The critical question is whether or not oceanic warming would increase or decrease DMS production, and with it, the number of CCN and hence both the albedo and cloud lifetime.

Figure 6 suggests a positive feedback; a colder environment produces an increase in sulfate CCN, which in turn increased cloud albedo which further cooled the earth. But in fact which way DMS production will change if the earth were to warm is not yet known. The effect could be either a positive or a negative feedback, and, given the extreme sensitivity of the earth's surface temperature to cloud albedo, as discussed earlier, the feedback effect could be very important.

Evidently, further research is needed on this topic, and very likely it must be incorporated in some way or other in computer models.

Finally, the existence of this potentially large feedback mechanism, so recently discovered, suggests that there are other important feedbacks which are still unnoticed. We are not yet ready for computers to hand us believable predictions about future climates, even on very gross scales.

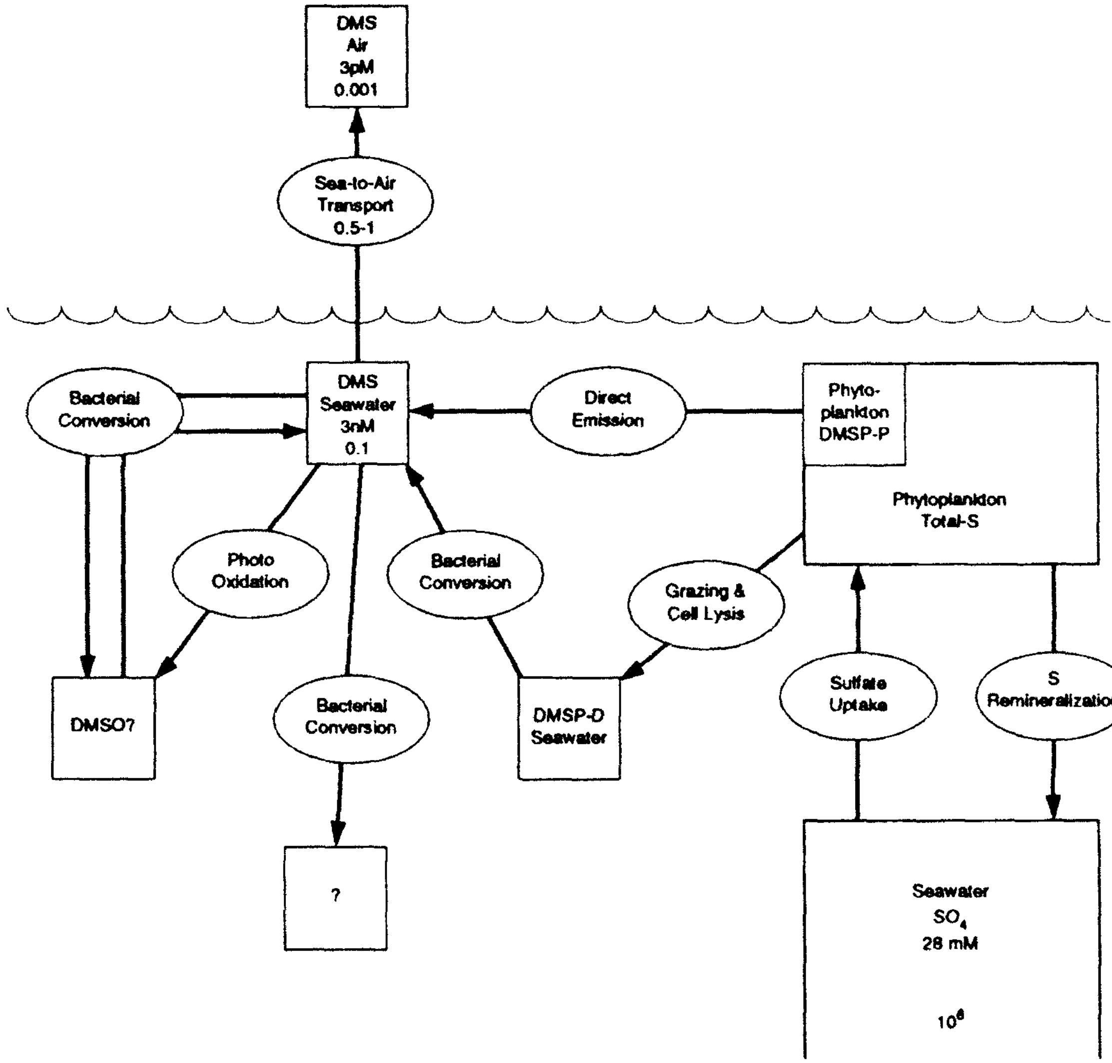
DMS
Air
3pM
0.001
Sea-to-Air
Transport
0.5-1
Bacterial
Conversion
DMS
Seawater
3nM
0.1
Direct
Emission
Phyto-
plankton
DMSP-P
Phytoplankton
Total-S
Photo
Oxidation
Bacterial
Conversion
Grazing &
Cell Lysis
DMSO?
Bacterial
Conversion
DMSP-D
Seawater
Sulfate
Uptake
S
Remineralization
?
Seawater
SO4
28 mM
10^6

Figure 7.

We would like to thank Stephen Warren and Marcia Baker of the Department of Atmospheric Sciences at the University of Washington for teaching us the rudiments of the interaction of radiation with clouds, and for providing essentially all of the information summarized in this report.

REFERENCES

1. Slingo, S., NACAR/0301/89-3, to appear in Nature.
2. Warren, S., briefing to JASON (1190).
3. See any book on radiation physics, or atmospheric physics, e.g., R. Goody, 1964,"Atmospheric Radiation," Oxford.
4. Hegg, X. Q., 1985, JGR **90** 3733.
5. Warren, S., 1990, briefing to JASON.
6. Tellus 1958, **10** 258.
7. Anderson, et al., 1990, as quoted by S. Warren at JASON.
8. Charlson, R., et al., 1987, Nature **326** 655.

DISTRIBUTION LIST

CMDR & Program Executive Officer
U S Army/CSSD-ZA
Strategic Defense Command
PO Box 15280
Arlington, VA 22215-0150

Mr John M Bachkosky
Deputy DDR&E
The Pentagon
Room 3E114
Washington, DC 20301

Dr Joseph Ball
Central Intelligence Agency
Washington, DC 20505

Dr Arthur E Bisson
DASWD (OASN/RD&A)
The Pentagon
Room 5C675
Washington, DC 20350-1000

Dr Albert Brandenstein
Chief Scientist
Office of Nat'l Drug Control Policy
Executive Office of the President
Washington, DC 20500

Mr. Edward Brown
Assistant Director
DARPA/NMRO
3701 North Fairfax Drive
Arlington, VA 22203

Dr H Lee Buchanan, I I I
Director
DARPA/DSO
3701 North Fairfax Drive
Arlington, VA 22203-1714

Dr Curtis G Callan Jr
Physics Department
PO Box 708
Princeton University
Princeton, NJ 08544

Dr Kenneth M Case
1429 Calle Altura
La Jolla, CA 92037

Dr Ferdinand N Cirillo Jr
Central Intelligence Agency
Washington, DC 20505

Brig Gen Stephen P Condon
Deputy Assistant Secretary
Management Policy &
Program Integration
The Pentagon, Room 4E969
Washington, DC 20330-1000

Ambassador Henry F Cooper
Director/SDIO-D
Room 1E1081
The Pentagon
Washington, DC 20301-7100

D A R P A Library
3701 North Fairfax Drive
Arlington, VA 22209-2308

D T I C [2]
Cameron Station
Alexandria, VA 22314

Mr John Darrah
Senior Scientist and Technical Advisor
HQAF SPACOM/CN
Peterson AFB, CO 80914-5001

DISTRIBUTION LIST

Dr Gary L Denman
Director
DARPA/DIRO
3701 North Fairfax Drive
Arlington, VA 22203-1714

Dr Nancy Dowdy
USACDA
320 21st Street NW
Washington, DC 20451

Mr John N Entzminger
Chief, Advance Technology
DARPA/ASTO
3701 North Fairfax Drive
Arlington, VA 22203-1714

Capt Kirk Evans
Director Undersea Warfare
Space & Naval Warfare Sys Cmd
Code PD-80
Department of the Navy
Washington, DC 20363-5100

Dr S William Gouse
Sr Vice President and
General Manager
The MITRE Corporation
Mail Stop Z605
7525 Colshire Drive
McLean, VA 22102

Col Randall Gressang
DARPA/DIRO
3701 North Fairfax Drive
Arlington, VA 22203-1714

Mr. Thomas H Handel
Office of Naval Intelligence
The Pentagon
Room 5D660
Washington, DC 20350-2000

Maj Gen Donald G Hard
Director of Space and SDI Programs
Code SAF/AQS
The Pentagon
Washington, DC 20330-1000

Dr Robert G Henderson
Director
JASON Program Office
The MITRE Corporation
7525 Colshire Drive
Mailstop Z561
McLean, VA 22102

Dr Barry Horowitz
President and Chief Exec Officer
The MITRE Corporation
202 Burlington Road
Bedford, MA 01730-1420

Dr William E Howard III [2]
Director of Advanced Concepts &
Systems Design
The Pentagon Room 3E480
Washington, DC 20301-0103

Dr Gerald J Iafrate
U S Army Research Office
PO Box 12211
4330 South Miami Boulevard
Research Triangle NC 27709-2211

DISTRIBUTION LIST

JASON Library [5]
The MITRE Corporation
Mail Stop W002
7525 Colshire Drive
McLean, VA 22102

Dr George Jordy [25]
Director for Program Analysis
U S Department of Energy
ER30
OER
Washington, DC 20585

Dr O' Dean P Judd
Los Alamos National Lab
Mail Stop A-110
Los Alamos, NM 87545

Dr Bobby R Junker
Office of Naval Research
Code 412
800 North Quincy Street
Arlington, VA 22217

Mr Robert Madden [2]
Department of Defense
National Security Agency
Attn R-9 (Mr. Madden)
Ft George G Meade, MD 20755-6000

Dr Arthur F Manfredi Jr [10]
OSWR
Central Intelligence Agency
Washington, DC 20505

Mr Joe Martin
Director
OUSD(A)/TWP/NW&M
Room 3D1048
The Pentagon
Washington, DC 20301

Mr Ronald Murphy
DARPA/ASTO
3701 North Fairfax Drive
Arlington, VA 22203-1714

Dr Julian C Nall
Institute for Defense Analyses
1801 North Beauregard Street
Alexandria, VA 22311

Dr Gordon C Oehler
Central Intelligence Agency
Washington, DC 20505

Dr Peter G Pappas
Chief Scientist
U S Army Strategic Defense Command
PO Box 15280
Arlington, VA 22215-0280

Dr Ari Patrinos
Director
Environmental Sciences Division
ER74/GTN
US Department of Energy
Washington, DC 20585

Dr Bruce Pierce
USD(A)D S
Room 3D136
The Pentagon
Washington, DC 20301-3090

Mr John Rausch [2]
Division Head 06 Department
NAVOPINTCEN
4301 Suitland Road
Washington, DC 20390

DISTRIBUTION LIST

Records Resource
The MITRE Corporation
Mailstop W115
7525 Colshire Drive
McLean, VA 22102

Dr Fred E Saalfeld
Director
Office of Naval Research
800 North Quincy Street
Arlington, VA 22217-5000

Dr John Schuster
Technical Director of Submarine
and SSBN Security Program
Department of the Navy OP-02T
The Pentagon Room 4D534
Washington, DC 20350-2000

Dr Barbara Seiders
Chief of Research
Office of Chief Science Advisor
Arms Control & Disarmament Agency
320 21st Street NW
Washington, DC 20451

Dr Philip A Selwyn [2]
Director
Office of Naval Technology
Room 907
800 North Quincy Street
Arlington, VA 22217-5000

Superintendent
Code 1424
Attn Documents Librarian
Naval Postgraduate School
Monterey, CA 93943

Dr George W Ullrich [3]
Deputy Director
Defense Nuclear Agency
6801 Telegraph Road
Alexandria, VA 22310

Ms Michelle Van Cleave
Asst Dir/National Security Affairs
Office/Science and Technology Policy
New Executive Office Building
17th and Pennsylvania Avenue
Washington, DC 20506

Mr Richard Vitali
Director of Corporate Laboratory
US Army Laboratory Command
2800 Powder Mill Road
Adelphi, MD 20783-1145

Dr Edward C Whitman
Dep Assistant Secretary of the Navy
C3I Electronic Warfare & Space
Department of the Navy
The Pentagon 4D745
Washington, DC 20350-5000

Mr Donald J Yockey
U/Secretary of Defense For Acquisition
The Pentagon Room 3E9333
Washington, DC 20301-3000

Dr Fredrik Zachariasen
California Institute of Technology
452-48
1201 East California Street
Pasadena, CA 91125

Dr Linda Zall
Central Intelligence Agency
Washington, DC 20505

DISTRIBUTION LIST

Mr Charles A Zraket
Trustee
The MITRE Corporation
Mail Stop A130
202 Burlington Road
Bedford, MA 01730