Reports

Atmosphere of Venus: Implications of Venera 8 Sunlight Measurements

Abstract. *Venera 8 measurements of solar illumination within the atmosphere of Venus are quantitatively analyzed by using a multilayer model atmosphere. The analysis shows that there are at least three different scattering layers in the atmosphere of Venus and the total cloud optical thickness is* ≈ 10. However, *because of the nature of the observations it is not possible to determine the vertical distribution of absorbed solar energy, which would reveal the drive for the atmospheric dynamics and the strength of the greenhouse effect. Future spacecraft observations should be designed to (i) measure both upward and downward solar fluxes, (ii) include measurements of the highest cloud layers, and (iii) employ narrow-band and broad-band sensors.*

On 22 July 1972, the Soviet spacecraft Venera 8 reached the planet Venus, made a parachute descent through the atmosphere, and landed on the planetary surface (*1, 2*). During the descent a visual photometer was used to obtain the first measurements of solar radiation within the atmosphere of Venus. Such measurements are important because they can potentially be used to determine the vertical distribution of solar heating and the layering of clouds. This information is required for understanding the nature of the atmospheric dynamics on Venus, for example, the 4-day circulation at the cloud tops (*3*) and the wind velocities in the deep atmosphere (*4*). Knowledge of the solar heating distribution is also necessary to establish whether a greenhouse effect (*5*) is responsible for the high surface temperature of Venus.

The photometer on Venera 8 measured the downward flux (*6*) of solar radiation in the spectral interval ~ 0.5 to ~ 0.8 μm. The 27 data points obtained are shown in Fig. 1; the bars represent the uncertainty in the measurements as estimated by the experimenters. The flux expected just outside the atmosphere was 55 ± 25 watt/m^2 for the solar elevation $5.5° \pm 2.5°$ estimated for the landing site (*7*). Thus, the solar flux was already attenuated by a factor of ~ 5 at the altitude of the first measurement (48.5 km). The final measurements near the surface of the planet reveal that a substantial amount ($\sim$ 1.8 percent) of the incident sunlight penetrates to the ground.

Qualitatively, the Venera 8 measurements suggest that the atmosphere is not homogeneous. The attenuation of the solar radiation is greatest in the region from the altitude of the cloud tops ($\sim$ 65 to 70 km) to $\sim$ 48 km (*8, 9*) and least in the region from $\sim$ 32 km to the ground. The experimenters interpret the measurements as indicating that the clouds have a lower boundary near 32 km, and that the region below 32 km is essentially free of aerosols with the aerosol optical thickness not more than 30 percent of the Rayleigh (gaseous) optical thickness.

We analyze the Venera 8 transmission measurements by comparing the observed data with results computed for multilayer model atmospheres. For each model the downward flux, the corresponding photometer reading, and the vertical distribution of absorbed energy are computed by the "doubling and adding" method (*10*). An atmospheric composition of 100 percent CO_2 is assumed in computing the contribution of Rayleigh scattering (*11*), but results are not sensitive to the uncertainties in the gaseous composition. The cloud particle properties are approximated as being independent of wavelength for the observed spectral interval (*12*). Thus the reflection and transmission properties of a given homogeneous layer in the atmosphere are a function of τ^c (the optical thickness of cloud particles in the layer), ϖ^c (the single scattering albedo of the cloud particles), and p^c (the phase function of the cloud particles). However, the transmission is nearly the same for different phase functions if τ^c and ϖ^c are scaled according to certain similarity relations (*13*). Therefore it is sufficient to make computations for isotropic scattering and determine for each layer in the atmosphere the range of τ^c and ϖ^c which fit the Venera 8 transmission data.

Theoretical results for a homogeneous atmosphere, that is, for a model in which the turbidity (*14*) and ϖ^c are constants, are included in Fig. 1. The transmission for a homogeneous atmosphere above a reflecting surface depends primarily on the parameters τ^c, ϖ^c, and the ground reflectivity R_g. Constraining the theoretical results to match the observed spherical albedo (0.9) and the observed transmission at the ground (1 watt/m^2) results in a one-parameter family of solutions. These are shown in Fig. 1 for ground albedos $R_g = 0$, 0.5, and 1. From the downward flux within the layer a unique solution could, in principle, be extracted by selecting the model which most closely matches the observed transmission profile, if the atmosphere were, in fact, approximately homogeneous. However, none of the solutions comes close to fitting the observed transmission profile. Computations for extreme solar zenith angles of 82° and 87° and spherical albedos of 0.8 and 0.95 yield results that are qualitatively similar to those shown, and also in complete disagreement with the observed data. This shows that the atmosphere of Venus is not homogeneous.

The simplest inhomogeneous atmosphere is a two-layer model. The Venera 8 observations suggest that a boundary between layers should be at $\sim$ 35 km, where there is an inflection point in the observed transmission profile. Quantitative calculations show that the observations below 35 km can indeed be fit with a single layer, that is, with ϖ^c and

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the turbidity constant below 35 km. However, with ϖ^c and the turbidity constant above 35 km the transmission in that region increases much faster with increasing altitude than does the observed profile. Thus at least a three-layer model atmosphere is required to match the Venera 8 observations.

In the results which we illustrate for three-layer models the layer boundaries were taken at 35 and 48.5 km. The absence of measured transmission data above 48.5 km precludes the consideration of a more detailed cloud structure above that altitude, and it also results in an ambiguity in the average cloud properties within that region. However, the most serious consequence of the absence of high-altitude data is the much larger ambiguity that is introduced for cloud properties in the lower levels of the atmosphere.

The source of the ambiguity for the optical properties in the top layer of the atmosphere is illustrated by Fig. 2. The coordinates ϖ^c and τ^c refer to the single scattering albedo and optical thickness of the cloud particles in the top layer. The combinations of ϖ^c, τ^c in the hachured areas can not attain a spherical albedo of 0.9, regardless of the reflectivity of the atmosphere below 48.5 km. The contours map ϖ^c, τ^c combinations that yield a spherical albedo of 0.9, with each contour for a specific reflectivity of the lower atmosphere. For large τ^c, the contours converge to the solution for an infinite atmosphere, with $\varpi^c = 0.9979$. Along each contour, the downward flux at the bottom of the layer increases monotonically as τ^c decreases. The locus of points where the transmission at 48.5 km equals 10.3 watt/m^2 is shown by the heavy dashed line for solar zenith angle ($\theta_\circ$) 84.5° and isotropic scattering. The dotted line is the same locus of points for anisotropic scattering, with the phase function being that derived from polarization observations of the visible clouds of Venus (*15*).

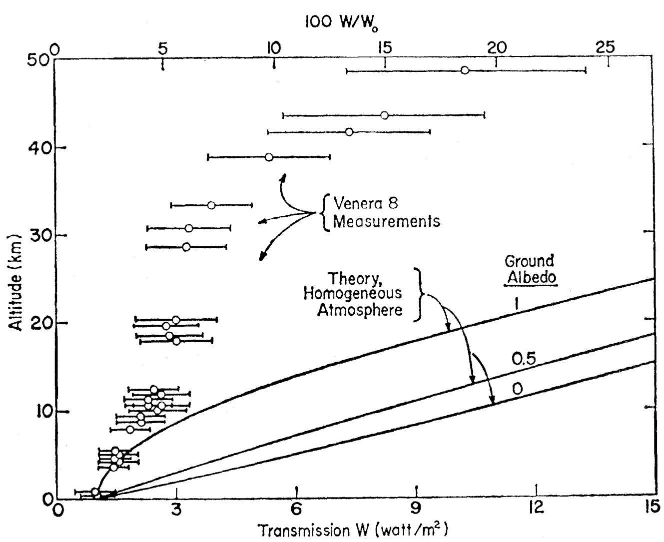

Fig. 1. Transmission of sunlight through the Venus atmosphere as measured by the photometer on Venera 8. The circles represent the measurements and the error bars are those given by the experimenters. The scale on the top of the figure is the ratio of the measured flux to that expected just above the atmosphere. The theoretical curves are for a homogeneous atmosphere, as explained in the text.

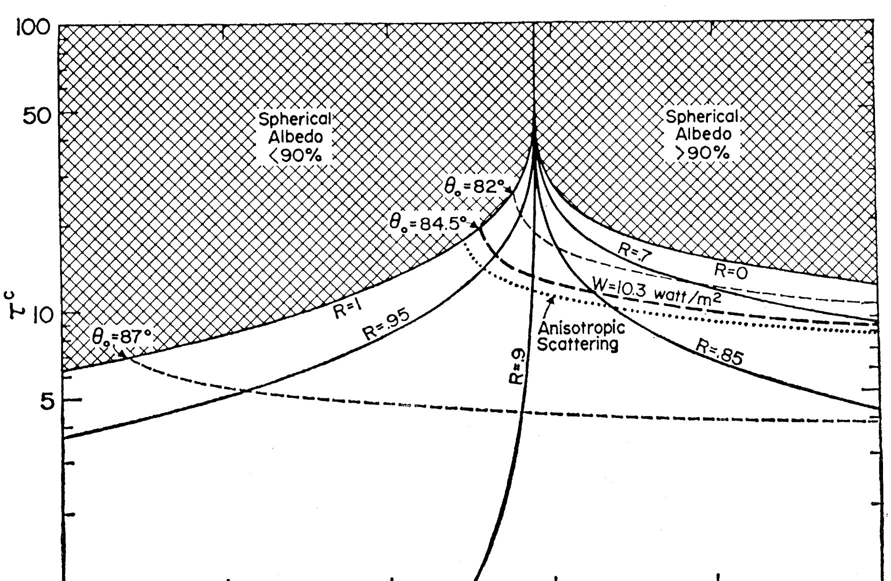

Fig. 2. Optical thickness (τ^c) and single scattering albedo (ϖ^c) for the cloud particles in the region above 48.5 km on Venus. These are effective values for that region obtained by approximating it as a homogeneous layer. All points within the area that is not hachured yield a spherical albedo for Venus of 90 percent, for some value of the reflectivity (R) of the atmosphere below 48.5 km. The heavy dashed line is the locus of points which yield the observed transmission at 48.5 km, $W = 10.3$ watt/m^2. The lighter dashed curves show the influence of the uncertainty in the local zenith angle. The numerical values for τ^c and ϖ^c apply to isotropic scattering and must be scaled for other phase functions. The dotted curve shows the locus of points which fit the transmission data if the phase function is that derived from the polarization of Venus (*15*).

The points on the heavy dashed line are the potential solutions for the optical properties of the top layer, for the solar zenith angle 84.5°. The ranges for the optical properties in the top layer are thus $8 \lesssim \tau^c \lesssim 19$ and $1 \gtrsim \varpi^c \gtrsim 0.9976$, where the values refer to isotropic scattering and must be scaled for any other phase function. Note that if the upward flux were measured the value of R would be known and a single point on the dashed line would be determined. That is, the ambiguity in the solution would be removed, to the extent that the top layer can be approximated as homogeneous and measurement errors can be neglected.

In reality, flux measurements will always result in some range of solutions for the optical properties in the top layer because of imprecisions in the measured fluxes, in the albedo of the planet, and in the zenith angle of the sun. For example, a 2½° uncertainty in the solar zenith angle means that the line of potential solutions in Fig. 2 must be replaced by the area bounded by the lines of light short dashes (labeled $\theta_\circ = 82°$ and $\theta_\circ = 87°$). The probable error in the observed transmission has a similar, but smaller, effect. A lesser (greater) spherical albedo moves the diagram to the left (right), also increasing the area of potential solutions on the ϖ^c, τ^c plane.

The range of solutions for the top layer greatly magnifies the range of acceptable optical properties for the lower atmosphere, even though transmission measurements are available throughout the lower atmosphere. As examples, we illustrate in Fig. 3 two extreme model atmospheres, both of which fit the observations within experimental error. Both models are for a three-layer atmosphere with the layer boundaries at 48.5 and 35 km. The parameters describing these two models are summarized in Table 1.

In model 1 practically all of the solar energy is absorbed in the top layer, above 48.5 km. In the lower two layers the measured flux is closely matched with nearly conservative scattering ($\tilde{\omega}^c = 0.999999$) and a very large cloud optical thickness ($\tau^c = 1078$). However, there is no upper limit for τ^c; acceptable solutions can be obtained in the limit as τ^c approaches infinity and $\tilde{\omega}^c$ approaches unity.

In model 2 no solar energy is absorbed in the top layer. This is a result of the conservative scattering in the top layer. Most of the absorption of solar energy in model 2 takes place in the middle layer. The absorption at the ground, averaged over all zenith angles, is ~ 1.4 percent for the wavelength interval 0.5 to 0.8 μm. However, this is not the upper limit for the amount of absorption at the ground; the uncertainties in the solar zenith angle and the planetary albedo allow the possibility of a larger absorption.

Model 1 corresponds essentially to the left endpoint of the heavy dashed line in Fig. 2, and model 2 corresponds to the right endpoint. The solutions for intermediate points on that line have optical properties that are between those of model 1 and model 2. Although the atmosphere of Venus is not likely to correspond exactly to either of the two extremes, it is not possible to reduce the range of plausible cases to a small segment of the dashed line.

We have also made computations for atmospheric models with as many as ten layers. Although this permits an even more precise fit to the observed transmission profile, the derived limits for the cloud properties are not greatly different from those obtained with three-layer models. The range for the optical thickness of the clouds above 48.5 km is $2 \lesssim \tau^c \lesssim 50$, if that region is approximated as a homogeneous layer. However, there is no upper limit on τ^c above 48.5 km if that region is permitted to be multilayered. For the entire atmosphere the limits on the optical thickness are $3 \lesssim \tau^c < \infty$. All these values refer to isotropic scattering and must be appropriately scaled for any other phase function. The scale factor for the visible clouds (*15*) is ~ 3.3, and it is probably not smaller than that deeper in the atmosphere. Thus the actual optical thickness of clouds for the complete atmosphere is at least of the order of 10.

The Venera 8 transmission data also indicate that the albedo of the region beneath the point of the last measurement is $\gtrsim 0.6$. Since the last measurement was at an altitude of ~ 30 m, this suggests that the ground albedo is in the same range, unless there is a heavy ground fog or aerosol layer. Such a high ground albedo would be somewhat surprising, especially since the Venera 8 analysis of surface material suggested a granitic composition (*16*). It should be cautioned, however, that the derived ground albedo depends critically on the accuracy of the final data points.

The main conclusions of our computations can be summarized as follows: (i) The atmosphere of Venus is inhomogeneous in the vertical direction. It requires a minimum of three layers with different optical properties to fit the Venera 8 transmission data. (ii) For each layer there is a wide range of τ^c and a corresponding range of $\tilde{\omega}^c$ which permits a fit to the observed data. (iii) The vertical distribution of absorbed solar energy can not be determined from the Venera 8 data. (iv) The optical thickness of the clouds is at least of the order of 10. (v) The transmission data near the ground, if accepted at face value, indicate an albedo $\gtrsim 0.6$ for the region below an altitude of 30 m.

We conclude that, although the Venera 8 measurements are valuable in revealing the significant penetration of sunlight throughout the atmosphere of Venus, the primary questions concerning the cloud distribution and the solar heating rates remain unanswered. For this reason the Venera 8 data neither confirm nor contradict the validity of proposed greenhouse mechanisms for the high surface temperature of Venus. Furthermore, the measurements do not answer the major questions regarding the drives for the atmospheric dynamics on Venus.

These negative conclusions lend added importance to the proposed Pioneer Venus mission of the National Aeronautics and Space Administration. Future spacecraft can obtain precise information on the atmospheric optical properties if the observational systems

Table 1. Parameters for the two model atmospheres in Fig. 1. Absorption is in percentage of solar flux for the wavelength interval 0.5 to 0.8 μm and averaged over all zenith angles. In these two models the spherical albedo of Venus was assumed to be 90 percent for $\lambda = 0.5$ to 0.8 μm. The values given for $\tilde{\omega}^c$ and τ^c refer to isotropic scattering.

Layer	Model 1			Model 2		
	$\tilde{\omega}^c$	τ^c	Absorption (%)	$\tilde{\omega}^c$	τ^c	Absorption (%)
1	0.997565	18.9	9.98	1.0	8.4	0.0
2	0.999999	561	~ 0	0.97328	4.4	8.62
3	0.999999	517	~ 0		0.0	0.0
Ground	0.995*		0.02	0.6*		1.38

*Ground albedo values.

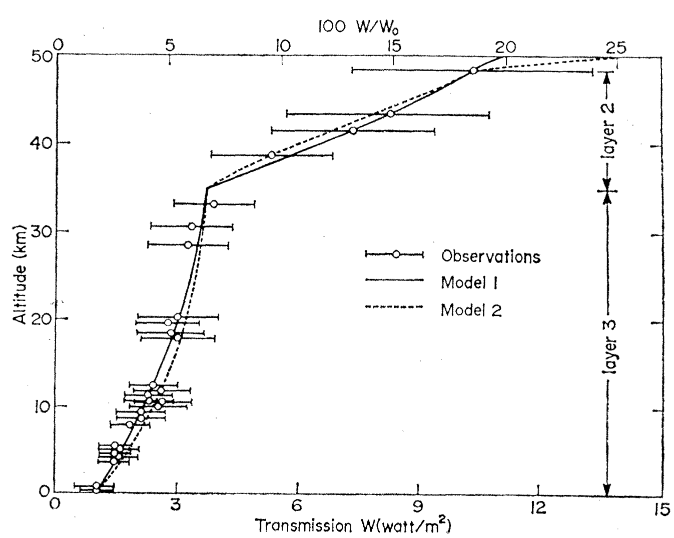

Fig. 3. Transmission of sunlight through the Venus atmosphere. The two theoretical curves are for two extreme models, one with practically no absorption below 48.5 km (model 1) and the other with all of the absorption below 48.5 km (model 2); see Table 1. Both models have three layers with the boundaries at 35 and 48.5 km.

incorporate the following features (*17*):

1) Measurements should be made throughout the entire atmosphere, including the highest cloud and haze layers. Entry probes should begin measuring the solar flux at as high an altitude as practical, and there should be complementary optical measurements from an orbiting spacecraft to obtain the atmospheric reflectivity and the scattering properties of the cloud top region.

2) Both the downward flux and the upward flux should be measured with entry probes. This provides a direct measurement of the vertical distribution of absorbed energy, and it allows a model-independent determination of the ground albedo.

3) Both narrow-band and broad-band measurements should be made. The cloud layering can best be obtained from narrow-band measurements, while the vertical distribution of absorbed solar energy requires integration over the entire solar spectrum (*18*).

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References and Notes

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5. C. Sagan, *Icarus* **1**, 151 (1962); J. B. Pollack, *ibid.* **10**, 314 (1969).
6. The photometer measured the quantity

$$W = \int_0^\infty S(\lambda)d\lambda 2\pi \int_0^{\pi/2} I(\lambda, \phi)P(\phi)\sin\phi d\phi$$

where $I(\lambda, \phi)$ is the intensity of radiation (watt m^{-2} μm^{-1} $ster^{-1}$) of wavelength λ at the angle ϕ from the vertical axis of the photometer, $S(\lambda)$ is the spectral sensitivity of the photometer, and $P(\phi)$ is its angular sensitivity; $P(\phi)$ was such that W is essentially the downward flux (*1*, *2*).
7. This flux includes the spectral sensitivity of the photometer. The uncertainty in the flux above the atmosphere arises primarily from the uncertainty in the location of the Venera 8 landing, which was such that the solar elevation above the horizon was $5.5° \pm 2.5°$. V. S. Avduevsky *et al.* (*2*) give the value 65 watt/m^2 for the flux just above the atmosphere. We obtain 55.5 watt/m^2 by using the spectral sensitivity in figure 1 of Avduevsky *et al.* and the solar flux of M. P. Thekaekara [*Sol. Energy* **14**, 109 (1973)].
8. The cloud top level, defined as the level where the cloud optical depth is unity, is at the pressure 50 ± 25 mbar (*9*). At the first Venera 8 data point (altitude 48.5 km) the temperature and pressure were measured as 329°K and 1.09 bars. The pressure 50 mbar corresponds to altitude ~68 km [see G. Fjeldbo, A. J. Kliore, V. R. Eshleman, *Astron. J.* **76**, 123 (1971)].
9. J. E. Hansen and J. W. Hovenier, *J. Atmos. Sci.* **31**, 1137 (1974).
10. The multiple scattering method which we use is described in A. A. Lacis and J. E. Hansen, *J. Atmos. Sci.* **31**, 118 (1974). At each wavelength the doubling method is applied to obtain the reflection and transmission for each homogeneous layer; the layers are combined by using the adding method to obtain the reflection and transmission from the complete inhomogeneous atmosphere and the vertical distribution of absorbed radiation; finally, the results are weighted by the solar flux and the photometer's spectral and angular response and integrated over wavelength to obtain the transmission which would be measured as a function of altitude.
11. The Rayleigh optical thickness above pressure P is

$$\tau^R = \frac{P}{g\bar{\mu}}\left[\frac{8\pi^3}{3\lambda^4 N^2} \sum_i v_i (n_i^2 - 1)^2 \frac{6 + 3\delta_i}{6 - 7\delta_i}\right]$$

where g is the acceleration of gravity, $\bar{\mu}$ is the mean molecular mass, N is the number density of molecules, v_i is the fraction by volume of gas i, n_i is the refractive index of gas i, and δ_i is the depolarization factor of gas i (see J. E. Hansen and L. Travis, *Space Sci. Rev.*, in press); Loschmidt's number may be used for N if the other quantities in the square brackets are evaluated at standard temperature and pressure.
12. This is an adequate approximation for particles which are larger than the wavelength and have little absorption. Polarization measurements show that the particles in the visible clouds have a radius of about 1 μm (*9*). Photometric observations show that the spherical albedo is high, of the order of 80 to 90 percent, for the wavelength region 0.5 to 0.8 μm [see W. M. Irvine, *J. Atmos. Sci.* **25**, 610 (1968)].
13. The similarity relations are discussed, for example, by H. C. van de Hulst and K. Grossman [in *The Atmospheres of Venus and Mars*, J. C. Brandt and M. B. McElroy, Eds. (Gordon & Breach, New York, 1968), p. 35] and J. E. Hansen [*Astrophys. J.* **158**, 337 (1969)]. We have verified that the similarity relations are accurate for the present problem by making computations with a number of different phase functions.
14. If τ^R is the Rayleigh optical depth due to scattering by air molecules and τ^c the optical depth due to cloud particles (including any aerosols or haze), then turbidity $\equiv d\tau^c/d\tau^R$. A numerical value can be assigned to the turbidity by choosing a reference wavelength.
15. The phase function was obtained from Mie scattering theory at $\lambda = 0.65$ μm for refractive index 1.44 and size distribution $n(r) \propto r^{(1-3b)/b} e^{-r/ab}$ where r is the radius, $a = 1.05$ μm and $b = 0.07$ (*9*). For anisotropic scattering τ^c and $\tilde{\omega}^c$ in Fig. 2 refer to the scaled quantities, $\tau^c(1 - \langle\cos\alpha\rangle)$ and $1 - (1 - \tilde{\omega}^c)/(1 - \langle\cos\alpha\rangle)$, where the asymmetry parameter $\langle\cos\alpha\rangle$ is 0.686.
16. A. P. Vinogradov, Yu. A. Surkov, F. F. Kirnozov, *Icarus* **20**, 253 (1973).
17. To some extent these recommendations are included in the plans for Pioneer Venus ("Pioneer Venus multiprobe mission preliminary scientific payload," Ames Research Center, Moffett Field, California, 1973). Radiometers on the entry probes will measure both upward and downward radiation. The entry probe measurements may begin as high as the 50-mbar level; this is higher than the level of the first Venera 8 measurements (~ 1 bar), but beneath a significant optical thickness of cloud and haze particles. No narrow-band measurements are planned for the entry probes. The instruments for the orbiting spacecraft had not been selected at the time of this writing.
18. The spectral region of the photometer on Venera 8, ~ 0.5 to 0.8 μm, contains only about 33 percent of the solar flux. The spectral albedo of Venus [see figure 2 in G. P. Kuiper, *Commun. Lunar Planet. Lab.* **101**, 1 (1969)] is such that the interval 0.5 to 0.8 μm contains only about 10 percent of the solar flux absorbed by Venus. Thus, even if accurate and complete data were obtained for that region, only a small part of the solar energy input would be defined.

1 March 1974

Carbonate Compensation Depth: Relation to Carbonate Solubility in Ocean Waters

Abstract. *In situ calcium carbonate saturometry measurements suggest that the intermediate water masses of the central Pacific Ocean are close to saturation with respect to both calcite and local carbonate sediment. The carbonate compensation depth, located at about 3700 meters in this area, appears to represent a depth above which waters are essentially saturated with respect to calcite and below which waters deviate toward undersaturation with respect to calcite.*

The variability of carbonate content in marine sediments was first observed almost a century ago by Murray and Renard (*1*), who reported the lack of carbonate-rich sediments in the deepest part of the oceans. Studies in subsequent years (*2*) have confirmed the observation of the *Challenger* expedition and showed that the transition zone between carbonate-rich and carbonate-poor sediments may be sharp. As the source of most carbonate material is at the ocean surface (tests and skeletons of marine plankton) and as its removal at depth is due to dissolution, this transition zone defines a horizon where the carbonate supply is compensated by the rate of dissolution. The depth of this boundary, usually referred to as the carbonate compensation depth, is not constant in the oceans as, by definition, it is related to surface productivity and the chemistry of deep ocean waters—both of which are variable. Investigation of the factors controlling calcium carbonate dissolution in the oceans is essential because carbonate deposition on the ocean floor is a major sink of carbon and hence an important factor in the mass balance of carbon on the earth.

The carbonate compensation depth was originally explained as the boundary line between supersaturated and undersaturated ocean waters (*1*). It was argued that below the compensation depth, seawater is undersaturated with