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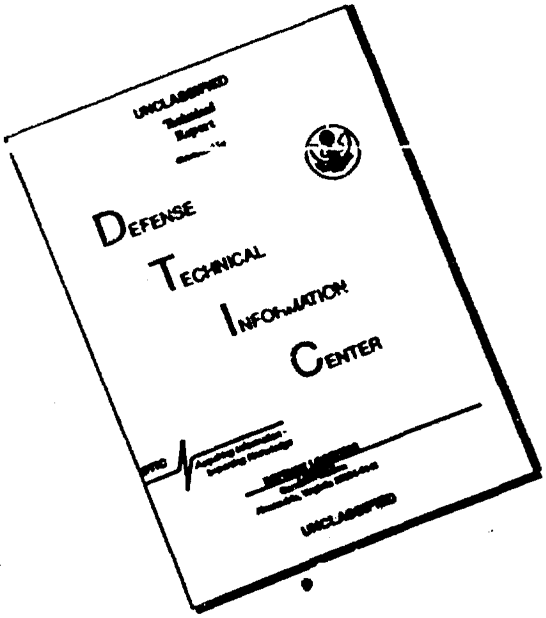

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Spectral and Spatial Variability of Solar Irradiance in the North Atlantic

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1. ABSTRACT

A model to predict the monthly solar irradiance incident at the ocean surface has been developed at seven wavelengths across the visible spectrum (390, 440, 490, 540, 590, 640 and 690 nm). The model incorporates specific monthly climatological databases of aerosols, ozone, and percent cloud cover derived from satellite observation for the North Atlantic from May 1979. The variations in the spectral irradiance fields in the North Atlantic are shown to be highly spatially variable in small scales (<100 km) in addition to being spectrally different. The irradiance distribution is dependent on the spectral characteristics of the transmittance parameters, and also on the small scale variability of the climatological data. The model indicates that the Rayleigh and aerosol transmittance has a pronounced affect on the spectral irradiance while the magnitude of the irradiance is controlled primarily by percent cloud cover and aerosol transmittance. The general trend in the North Atlantic indicated that the spectral irradiance intensity is similar to the solar spectrum (peaking at 490-540) and diminishing in the shorter and longer wavelengths.

2. INTRODUCTION

The incident solar irradiance at the sea surface, especially within the visible region (400-700 nm), has a significant influences on both biological and physical processes in the ocean. Photosynthetic pigments selectively absorb available spectral irradiance which is utilized for growth and uptake of carbon in the ocean. Carbon in the oceans has been shown to play an important role in the uptake of atmospheric carbon and dissolution into marine sediments. Rates of these processes are crucial in understanding the global carbon cycle. The spectral distribution of photosynthetic available radiation (PAR) at the ocean surface is important for characterizing biological processes. Additionally, heating in the upper ocean is partially driven by the incident visible solar irradiance. These heating rates define the upper ocean thermal gradients which are important for mixing and upper-ocean circulation. Visible solar radiation penetrates the water column resulting in subsurface heating. This heating are partially responsible for generation and degeneration of the seasonal thermocline.

The total spectral solar irradiance at the sea surface has been estimated based primarily from cloud cover.[2] However, the influence of aerosols concentrations was not included. Atmospheric aerosol concentrations is highly variable as a response to local regional and atmospheric conditions. Sahara dust storms which are common off the African coast, which extends far into the Atlantic waters and Mediterranean Sea have significant affect on the incident irradiance distribution.

Previous research has shown that atmospheric influence from Rayleigh and aerosol scattering accounts for 90% of the visible radiation sensed by satellites over the ocean surface.[3] To eliminate the aerosol path radiance in Coastal Zone Color Scanner (CZCS) ocean color satellite data, the 670 nm channel data is used as a weighted subtraction from the other visible wavelength channels (443, 520, 550 nm). The 670 nm radiance representation of the aerosol scattering is only valid over ocean waters since the ocean signal is assumed to be zero at this wavelength. In our computations of the aerosol optical thickness, the CZCS 670 nm monthly composite data for May 1979 is used to estimate the spatial variability of the aerosol concentrations in the North Atlantic for May

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1979. These aerosol radiances were used to estimate the spatial varying aerosol transmittance function for each location in the North Atlantic.

The Air Force Real-Time Nephanalysis (RTNEPH) database of the mean percent cloud cover was used to estimate the irradiance distribution. This database provides 3 hour observations of percent cloud cover coincident with the May 1979 CZCS aerosol data in the North Atlantic. Variations in ozone concentration are accounted for using the Total Ozone Mapping Spectrometer (TOMS) database, which is also coincident with the CZCS data.

The objectives of this study were to estimate the incident irradiance at the ocean surface at seven visible wavelengths using an extension of Bird's model [1]. The distribution of irradiance in the North Atlantic will be defined for these spectral irradiance results. Additionally, this effort will examine the sensitivity of the spectral irradiance at the sea surface to the input parameters of the model.

3. IRRADIANCE MODEL

The sea surface spectral irradiance model used in this effort is a modified version of the one originally developed by Bird.[1] The model has been modified to include cloud cover estimates and to include aerosol optical thickness from CZCS L_{a670} data. The model utilizes coincident monthly climatological databases as inputs for percent cloud cover, aerosol concentration and ozone concentration. The mean incident irradiance for May 1979 for the North Atlantic region is computed for selected wavelengths (390, 440, 490, 540, 590, 640 and 690 nm).

The solar irradiance at the sea surface is computed in a two step process by first computing the direct clear sky irradiance (i.e. the solar contribution) as given by Bird[1],

$$I_{d\lambda} = \cos(Z) H_{o\lambda} T_{r\lambda} T_{a\lambda} T_{o\lambda} T_{w\lambda} T_{u\lambda}, \quad (1)$$

where H_o is the extraterrestrial spectral irradiance, T_r, T_a, T_o, T_w, and T_u, are the transmittance functions for Rayleigh scattering, aerosol extinction, ozone absorption, water vapor absorption, and uniformly mixed gas absorption, respectively. The second step computes the diffuse irradiance term as a function of the percent cloud cover; this will be discussed further in section 3.2. The total irradiance at the sea surface is the sum of the direct and the diffuse irradiance.

3.1 Aerosol Transmittance

Satellite derived radiance in the red part of the spectrum has been used to estimate the concentration of aerosols, over oceanic regions, in atmospheric correction algorithms.[3,4] The assumption is that the water totally absorbs light in this part of the spectrum and that the resulting radiance detected at satellite altitudes is due to atmospheric aerosol and Rayleigh scattering. Since Rayleigh scattering can be computed and subtracted, the resulting radiances represent the distribution of the aerosol concentration. Haggerty et al. [5] have shown that radiance is related to optical thickness by:

$$L_a = \frac{\omega_0 F_0}{4\mu} p(\Phi) \tau_a, \quad (2)$$

where L_a is the upwelling radiance due to aerosol scattering, τ_a is the optical depth due to aerosol scattering, ω_0, the single scattering albedo, $\mu = \cos(\theta)$, where θ is the solar zenith angle, $p(\Phi)$ is the scattering phase function, where Φ is the scattering angle, and F_0 is the incoming solar radiative flux.[5] $p(\Phi)$, estimated by a two-term Henyey-Greenstein function.[6]

Equation 2 is solved for τ_a and thus, T_a is:

$$T_a = e^{-\tau_a}. \tag{3}$$

L_a in equation 2 is estimated by the L_{a670} channel data from the CZCS database. We assume that the aerosol scattering function is constant for the entire region and the radiance at 670 nm is directly proportional to the aerosol concentration. This assumes that the size, shape, and composition of the aerosol is the same throughout the North Atlantic and is represented as a typical Maritime atmosphere. Aerosol scattering at other wavelengths is determined by a scaling the optical thickness by the ratio of 670 to desired wavelength. This ratio is scale by the Angstrom coefficient [3,4] which is zero for Maritime atmosphere. Aerosol spectral scattering response is similar to Rayleigh scattering (increases at short wavelengths). We recognize the limitations in assuming a constant Angstrom coefficient but do not have an adequate database of the aerosol character or the scattering phase function. Future satellite sensors such as SeaWifs are designed to better define the aerosol scattering distribution.

L_{a670} is a monthly composite of the radiance at 670 nm, minus the Rayleigh scattering, detected by CZCS. All available cloud free CZCS data were compiled in the North Atlantic in May 1979 and averaged to determine the mean 670 radiance within a 20 km resolution (at the equator). Monthly averaged CZCS data are available for a 92 month life span of CZCS (November 1978 - June 1986) for 8 global regions, 4 in each hemisphere.[7] The May 1979 L_{a670} data for the North Atlantic region are represented as a 512 by 512 image area which was used in this effort, extends from 0°N to 90°N latitude and 81°W to 8°E longitude (**figure 1**). The aerosol data show small scale variability (< 100km) distributed over the ocean which should have significant affect on the surface irradiance spectra distribution. Note that CZCS did not collect data over land and did not provide continuous coverage as a result of cloud cover or the system was not operational. These areas are denoted as large black areas in the center of the image.

3.2 Clouds

Other researchers have estimated the effects of clouds in solar irradiance calculations.[2,8] Since our atmosphere is essentially handled as a single layer, a simple model is employed to account for the effects of clouds by relating the diffuse irradiance (i.e. sky light irradiance) to percent cloud cover.[9] According to Lestrade [9], the diffuse radiation, I_s, is 21% of the total radiation on a cloud free day, thus I_d from equation 1 is 79% of the total. For cloudy days, the percentage of diffuse radiation in the total is (Lestrade's equation 7)

$$h = 1.0 + 3.85c - 2.58c^2, \tag{4}$$

where c is the percent cloud cover. Since we get I_d from equation 1, I_s can be expressed in terms of I_d as

$$I_s = .21\frac{I_d}{.79}h \tag{5}$$

For cloudy days, I_d is attenuated by cloud cover by a factor of 1-c.

The RTNEPH database provides the values for c for coincident May 1979 locations in the North Atlantic as shown in **figure 2**. The cloud database is at a 25 nautical mile spatial resolution and has data available for each of the 8, 3 hour daily intervals.[10] We subsampled this data down to a 20 km resolution to match the CZCS data. The cloud cover data provides full coverage over both land and water, however, a mask of the "no data" areas, extracted from the L_{a670} data, is applied. Like the L_{a670}, the cloud data is highly variable and exhibits the same kind of small scale variability.

3.3 Ozone

The ozone transmittance function employed by Bird[1] is also used here with the TOMS database providing the input. The TOMS data is available as three day averages, coincident with CZCS at a latitudinally varying resolution of 5° to 20°.[11] The mean ozone distribution for May 1979 for the North Atlantic is shown in **figure** 3. This data set does not indicate the small scale variability observed in the aerosols concentrations and the cloud cover.

4. METHODOLOGY

The monthly mean specular irradiance at the sea surface is computed separately for each wavelength. The irradiance is calculated hourly, for a 24 hour day, for each pixel in the 512 x 512 image area, but only for locations with valid aerosol and ozone values. These hourly computations accounted for the Rayleigh scattering for each of the latitudinal and solar time affects. The appropriate solar zenith angle is computed for each pixel in the image based on time (year, day, hour), and location (latitude and longitude). Additionally, the hourly computation include input of the spatial variability of the atmospheric transmittance of aerosols, ozone and cloud cover. Each of the 24 hourly images generated represents the monthly mean irradiance at the sea surface for the given hour. These images are then averaged to give the total mean irradiance for the month (i.e. May 1979). [12] All of the processing was done on a SUN SPARC 2 workstation.

5. RESULTS

Figures 4-7 represent the mean incident solar irradiance at the sea surface for May 1979 in the North Atlantic at 440, 490, 540, and 690 nm. The bright image at 490 and 540 suggest that maximum irradiance is concentrated at these wavelengths. The darker image at 690 indicates that a substantial reduction in incident irradiance occur at this wavelength. This spectral dependence of surface irradiance is characteristic of the extra-terrestrial solar spectrum which shows the peak occurring at 450 - 550 nm. Each of the spectral irradiance images exhibits a similar small scale changes (<100km) which were evident in both the aerosol and cloud cover images. **Figure 5** clearly shows the expected latitudinal variations (i.e. low irradiance in the north and increasing southward). The long linear north - south striations observed at approximately 15° longitudinal spacing are artifacts of abrupt time zones changes. These time zone erroneously show higher irradiance in the western time zone. This time zone affects manifest themselves in the Rayleigh calculation. Modifications in the software are being addressed to use smaller time zones to minimize the time zone affects.

The effects of cloud cover and aerosol concentration are also evident in the spectral irradiance distribution. The low irradiance values in the Intertropical Convergence Zone (5° N) are attributable to high cloud cover. Conversely, in the area near 30°N and 30°W the irradiance is the highest due to the relatively low concentration of aerosols coupled with a modest amount of cloud cover (no more than 50%).

The spectral dependence of each of the transmittance functions were also systematically evaluated in a parametric study. The spectral influence of aerosol optical thickness for L_{a670} radiance 0.05, 0.11 and 0.25 is shown to be minor. (**Figure 8**). Model parameters were held constant and the aerosol radiance was varied. The aerosol transmittance is lower at shorter wavelengths similar to Rayleigh scattering affects. Also note that the higher the aerosol concentration the stronger the spectral influence. Higher aerosol concentrations will tend to reduce short wavelength irradiance incident at the surface and have smaller affects on at the higher wavelengths.

The spectral influence of ozone transmittance shows absorption between 540 to 640 nm (**Figure 9**). Note that the transmittance ranges from 0.94 to 0.98 and the ultimate impact of the surface irradiance is only slight.

The spectral transmittance function for Rayleigh (T_r), aerosol (T_a), ozone (T_o), water vapor (T_w) and uniform gas (T_g) are shown for a zenith angle of 30° (**Figure 10**). Rayleigh and aerosol transmittance functions are the most important in affecting on the spectral irradiance. These two functions compliment one another by strongly reducing the shorter wavelengths and having less affect at longer wavelengths. Changes in the intensity of the Rayleigh transmittance functions are also influenced by the solar zenith angle in addition to the spectral dependence.

The extraterrestrial spectral irradiance, H_o, and the reduced irradiance after propagation through the spectral transmittance functions is shown in **Figure 11.** Note that identical initial conditions (zenith = 30° , O_3 = 0.35, L_a = 0.11) shown in figure 10 were used in this calculation. The Rayleigh and aerosol transmittance functions tend to flatten the extra-terrestrial spectrum from 450 to 600 nm and strongly reduce the shorter (<450) irradiance.

The affect of cloud cover is significant on the **magnitude** of surface irradiance. However, the present model does not account for any spectral influence on surface irradiance. Previous results with this model have described the effects clouds can have on the irradiance distribution at the sea surface.[13]

6. SUMMARY

The spectral sea surface irradiance in the North Atlantic for May 1979 has been modeled using climatological databases of synoptical monthly aerosol concentration, ozone distribution , and percent cloud cover. The irradiance at 490 to 540 show the highest irradiance levels in the North Atlantic. A strong reduction in irradiance is observed at shorter (440 nm) wavelengths and even stronger reduction at 690 nm. Generally, this spectral dependence is similar with the extra-terrestrial solar spectral distribution. The tropical Atlantic (5° N) shows substantial reduction in the irradiance at all spectral wavelengths as a response to the cloud cover (Cloud cover is assumed to not influence on the spectral irradiance but only the irradiance intensity.) Exceptionally high irradiance levels were observed west of African 30° N at 490 and 540 nm as a result of the low cloud cover and low aerosol concentrations. The irradiance levels at the sea surface illustrate small scale variability (<100 km) which are similar to those observed in the percent cloud cover and aerosol concentrations. The convolved response of these the cloud cover and aerosol transmittance functions are responsible for the resulting spatial irradiance variability. These small scale irradiance variability may have significant affect on the photosynthetic processes in the upper ocean. Due to the high spatial variability of the aerosols observed in the CZCS imagery, their concentrations should not be assumed to be constant. In some areas the concentration of aerosols can be as important as the amount of cloud cover.

The atmospheric transmittance functions of Rayleigh and the aerosol transmittance have the primary influence on controlling the spectral irradiance at the sea surface. Both of these transmittance functions reduce the irradiance at the shorter wavelengths and have less affect on the longer wavelengths. Convolving these transmittance functions with the extra-terrestrial solar spectrum, tend to flatten the spectrum that reaches the sea surface between 450 -600 nm. Between these wavelengths similar irradiance levels are expected to be incident at the sea surface. The penetration of the incident spectral irradiance through the water column in dependent on selective spectral absorption of the optical properties of the water. These properties control the biological and thermodynamic processes in the upper ocean. Knowledge of sea surface irradiance is important in understanding both biological and physical processes present in oceanic environments. The data produced by this model is currently being used in models to predict ocean heating rates for the North Atlantic.[14]

7. ACKNOWLEDGMENTS

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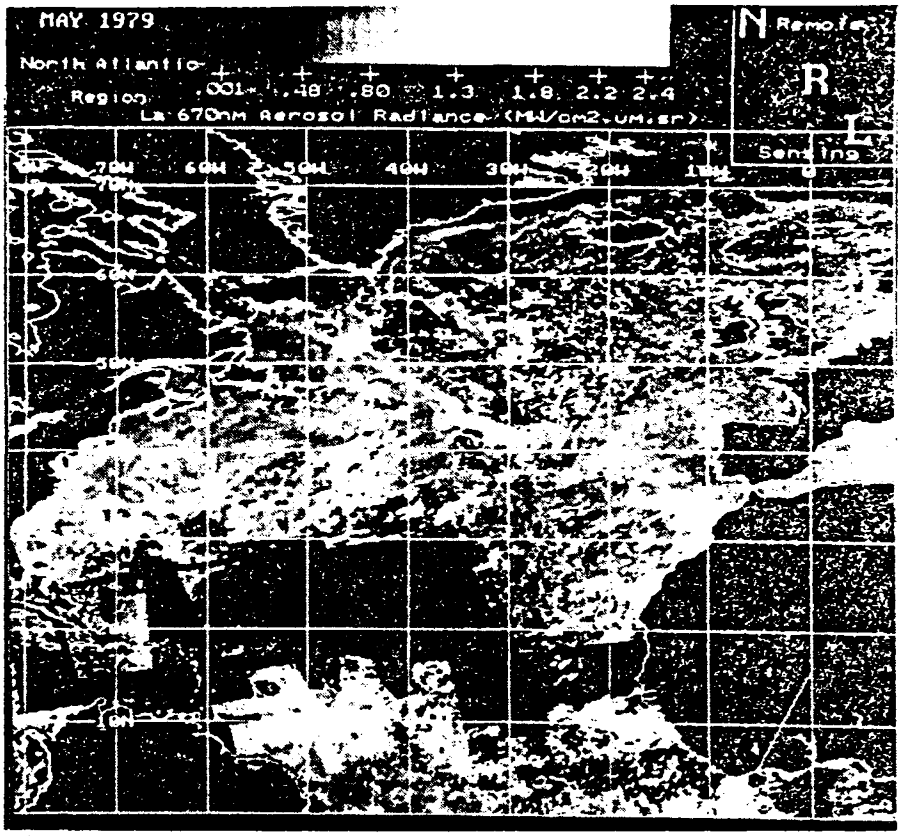

Figure 1. CZCS L_{a670} Aerosol Radiance for the North Atlantic, May 1979.

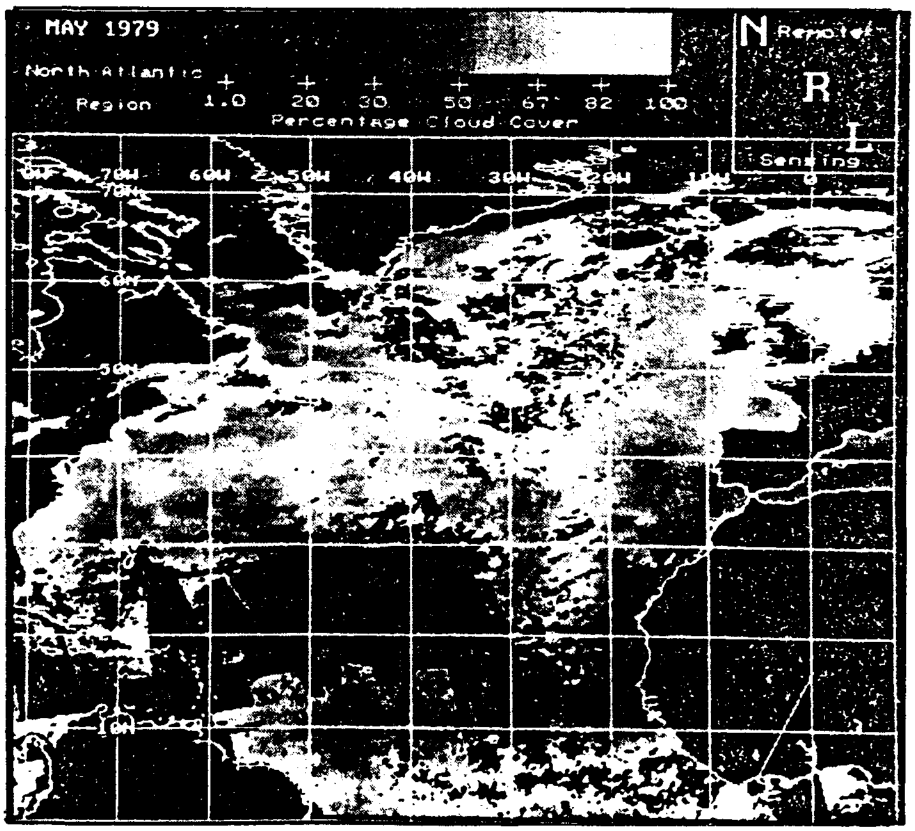

Figure 2. Percent Cloud Cover for the North Atlantic, May 1979.

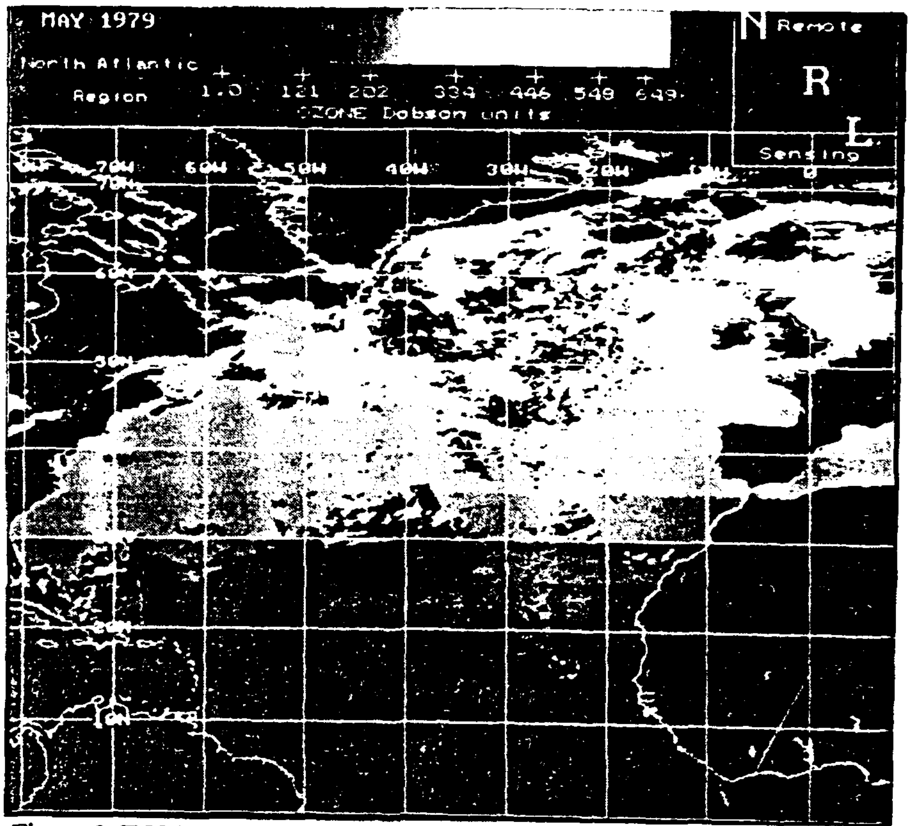

Figure 3. TOMS ozone distribution for the North Atlantic, May 1979.

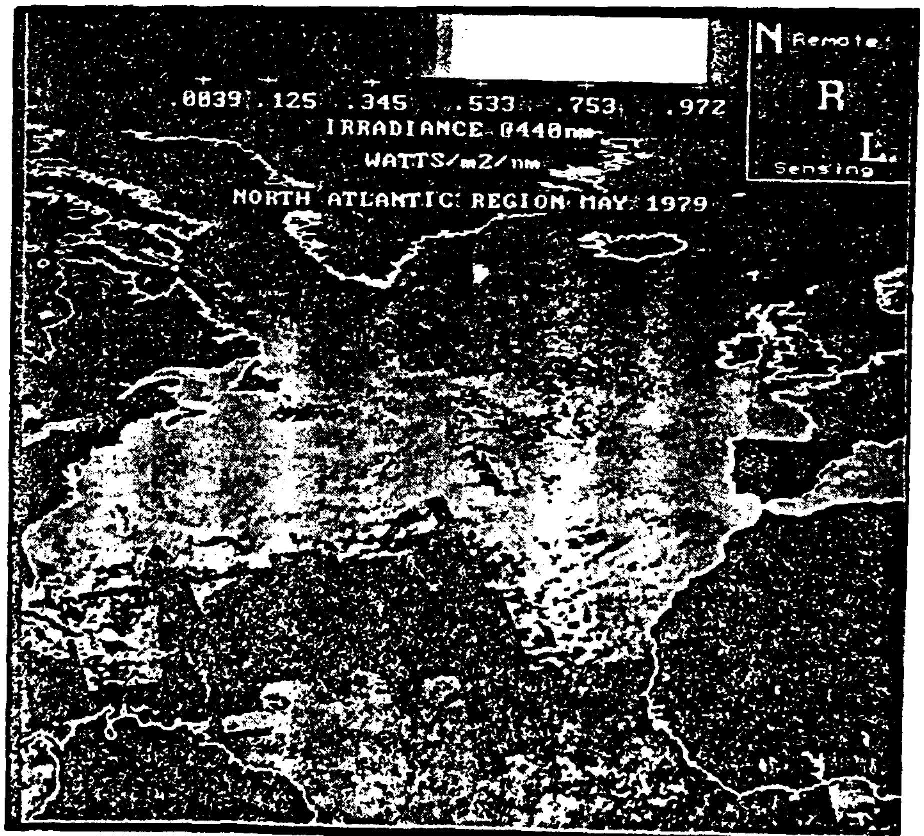

Figure 4. Mean Total Irradiance at 440 nm for the North Atlantic, May 1979.

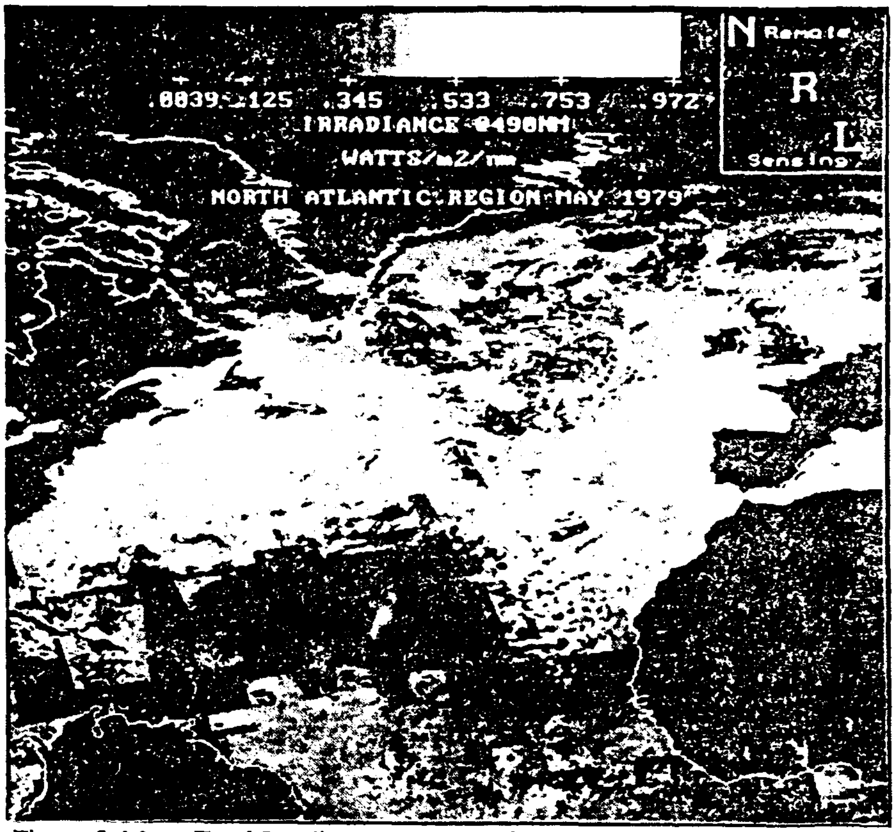

Figure 5. Mean Total Irradiance at 490 nm for the North Atlantic, May 1979.

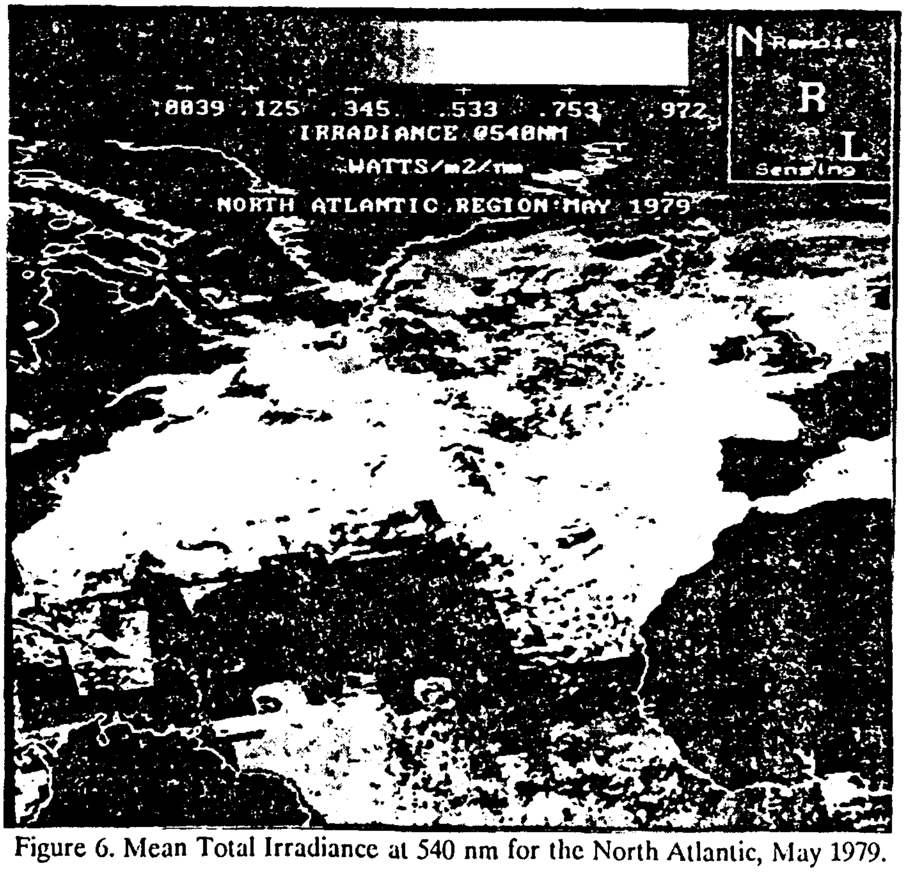

Figure 6. Mean Total Irradiance at 540 nm for the North Atlantic, May 1979.

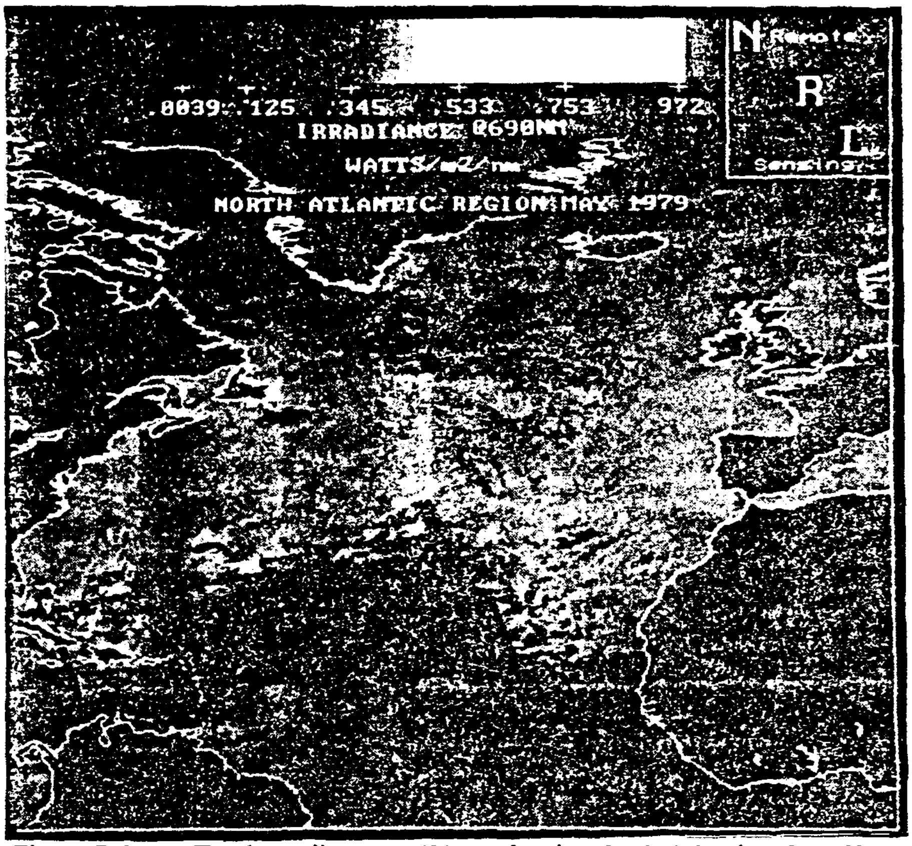

Figure 7. Mean Total Irradiance at 690 nm for the North Atlantic, May 1979.

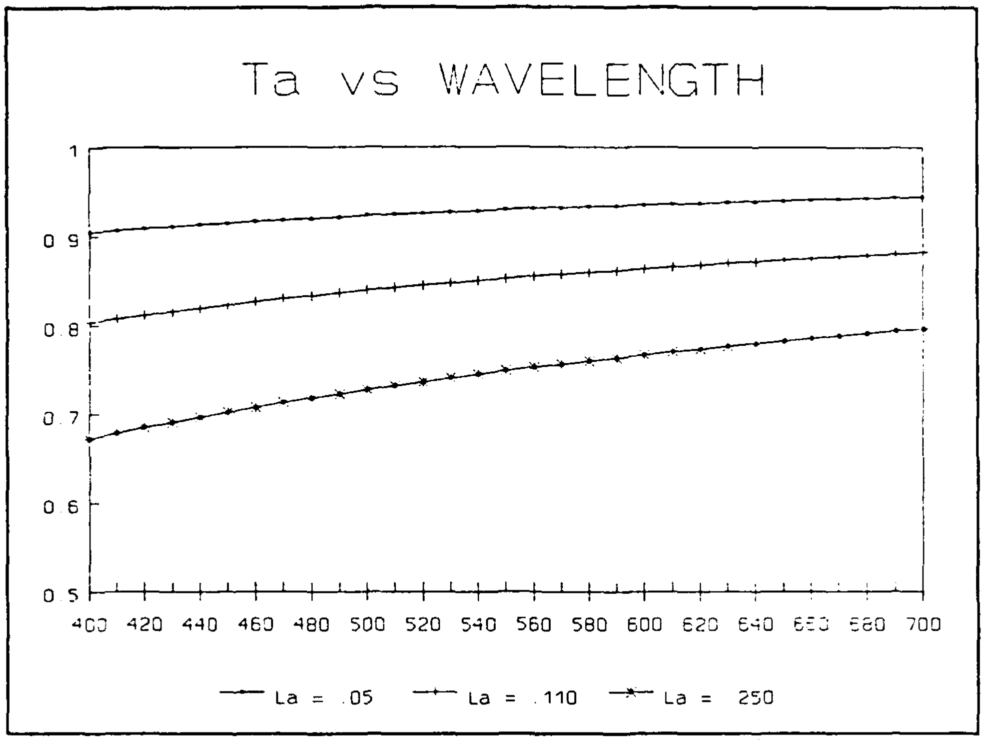

Figure 8. Ta vs wavelength for different values of L_{a670}. (mW/cm^2)

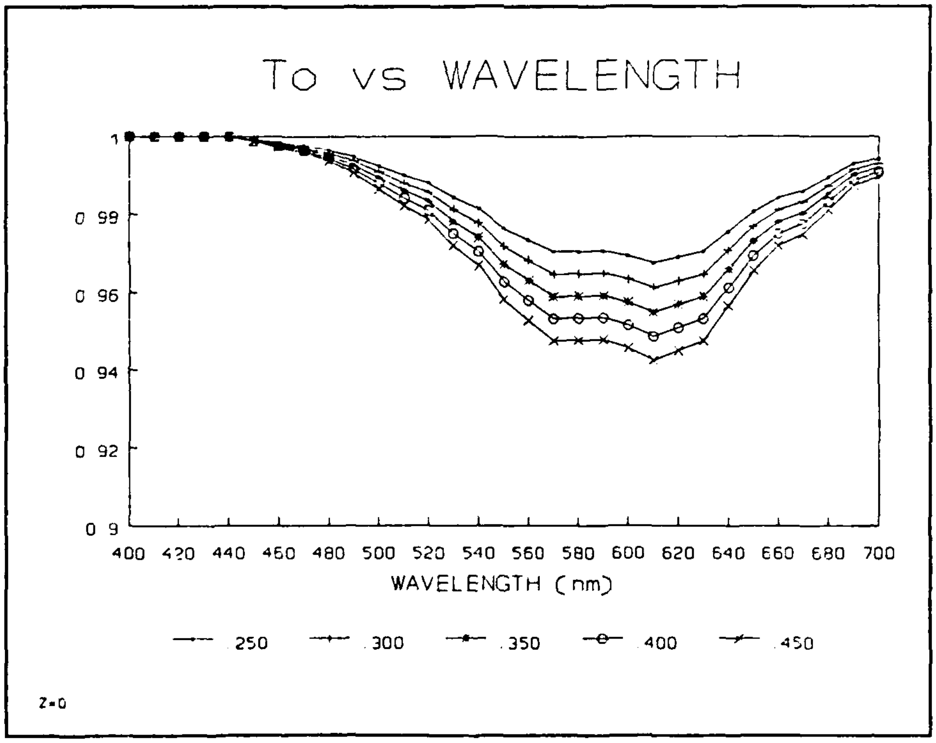

Figure 9. T_o for a range of O_3 and a zenith angle of 0°.

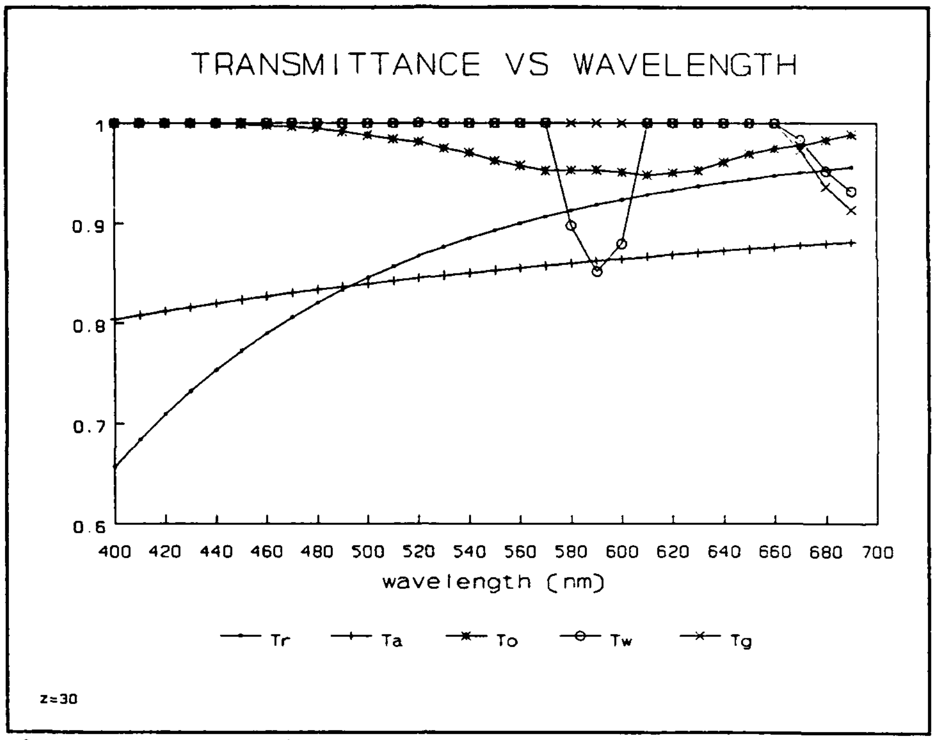

Figure 10. Comparison of transmittance functions for a zenith angle of 30°,O_3=.35, L_a=.11, and water vapor=2.0.

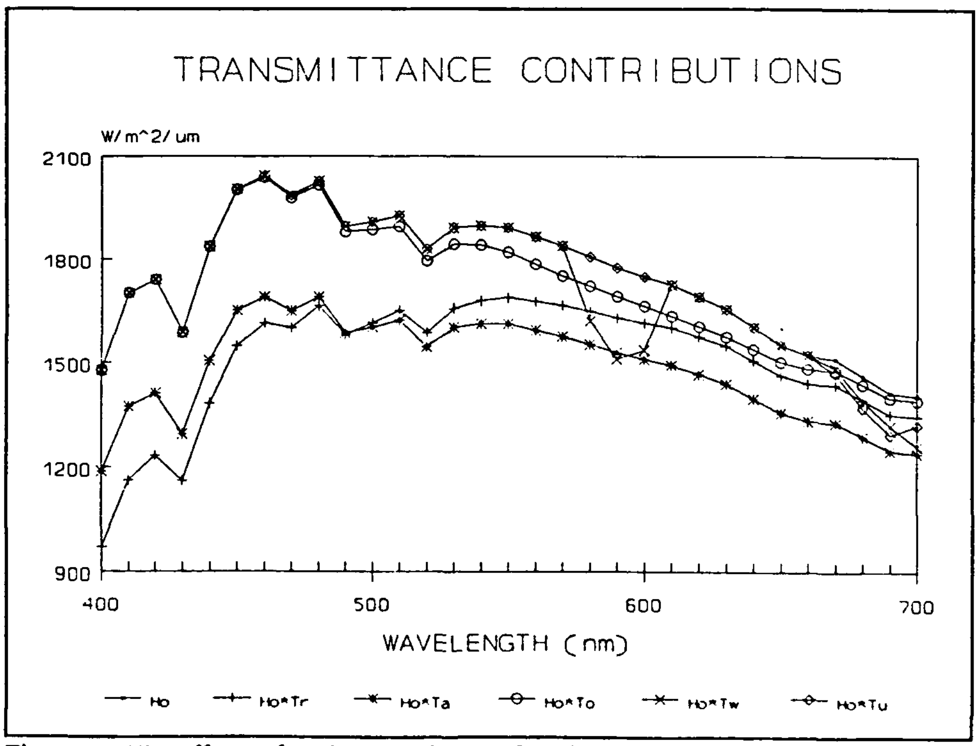

Figure 11. The effects of each transmittance function on H_o.