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A MULTI-SENSOR REMOTE SENSING APPROACH FOR MEASURING PRIMARY PRODUCTION FROM SPACE

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PROPOSAL SUMMARY

We proposed to develop a multi-sensor remote sensing method for computing marine primary productivity from space, based upon the capability to measure the primary ocean variables which regulate photosynthesis. The three variables and the sensors which measure them are: (1) downwelling photosynthetically available irradiance, measured by the VISSR sensor on the GOES satellites, (2) sea-surface temperature from AVHRR on NOAA series satellites, and (3) chlorophyll-like pigment concentration from the Nimbus-7/CZCS sensor. These and other measured variables would be combined within empirical or analytical models to compute primary productivity. With this proposed capability of mapping primary productivity on a regional scale, we could begin realizing a more precise and accurate global assessment of its magnitude and variability. Applications would include supplementation and expansion on the horizontal scale of ship-acquired biological data, which is more accurate and which supplies the vertical components of the field, monitoring oceanic response to increased atmospheric carbon dioxide levels, correlation with observed sedimentation patterns and processes, and fisheries management.

This proposal was intended as a collaborative effort between our UCSD group and Mary Jane Perry's group at University of Washington, Seattle. In this final report, we restrict our discussion to work done at UCSD only.

ACCOMPLISHMENTS

CZCS Algorithm Comparisons

During the first year and a half of this grant, we conducted a study of existing atmospheric correction algorithms for the CZCS sensor. The results of this study are presented in the first two appendices of the first renewal proposal, previously submitted from UCSD. Briefly, the study concluded that the various algorithms warranted a thorough comparison. Unfortunately, not one of these algorithms was implemented on our computer and the comparison was never completed.

CZCS Data

CZCS images for input into productivity models were obtained from Mark Abbott's West Coast Time Series archives and, already processed, from the Scripps Satellite Oceanography Facility (SSOF). Later, reduced resolution global CZCS composite images were made available from Goddard Space Flight Center over the Space Physics Analysis Network. Combined with other global data sets (sea-surface temperature, solar irradiance, winds, e.g.) these would readily yield global productivity maps for verification and study. Time and situations did not permit such an analysis under this grant.

AVHRR Processing

As detailed in the first renewal proposal, we implemented fully operational AVHRR processing capability, i.e., to read, calibrate, geographically correct, and navigate raw AVHRR data received at the SSOF, onto our computer system.

In addition to being able to produce sea-surface temperature images from AVHRR, we developed a method for mapping the three principle biological nutrients, phosphates, nitrates, and silicates from the temperature data. This method is based upon relationships put forth by Zentara and Kamykowski (1977). The capability of mapping nutrients from satellite enables us to use nutrient concentrations as direct input into productivity models such as included in Berger et al. (1987) and references therein.

Solar Irradiance

In collaboration with Dr. Robert Frouin of Cal Space and Karen Baker of the University of California Marine Bio-Optics group, we have investigated downwelling photosynthetically available irradiance at the ocean surface. At first, the studies focused upon the relationship between the photosynthetically available and the total irradiance (I-par and I-tot). Baker and Frouin (1987) had found that under clear skies the ratio of I-par to I-tot varies between 0.42 and 0.50, depending mainly upon solar zenith angle and clear-sky atmospheric conditions.

In the major paper published under this grant (Frouin et al., submitted to JGR in December 1988; see Appendix I), we present a simple analytical formula for computing both I-par and I-tot at the ocean surface from clear-sky atmospheric conditions. The inputs to the model are solar zenith angle, aerosol type, horizontal visibility, and vertically integrated concentrations of water vapor and ozone. The formula is accurate to within 1-2% for solar zenith angles less than 75^{o}.

The analytical formula can be used to convert more commonly collected I-tot measurements into less common I-par estimates with an accuracy within 0.03 units. More importantly, the formula provides an accurate base for determining downwelling irradiance under cloudy skies. Using satellite radiance measurement in the visible range (either from GOES/VISSR or from NOAA/AVHRR), we can obtain cloud albedo and thus transmittance. Multiplication of the computed clear-sky irradiance by the satellite- derived cloud transmittance would yield irradiance maps over entire regions, cloudy or not. Comparisons of cloudy sky I-par estimates from satellite data with corresponding field data from the BIOWATT experiments are in progress.

Implementation of Primary Productivity Models

During the California Space Institute's Summer Workshop on Climate and Remote Sensing in 1987, we collaborated with four other scientists (Eric J. Coolbaugh of USNA, Annapolis, MD; William M. Balch of Scripps, Institute of Marine Resources, and now at University of Miami, FL; Cecile Dupouy of ORSTOM Antenne du Centre IFREMER, France; and Guillermo P. Podesta, also of U. Miami) in producing the first satellite-derived images of primary productivity (see Appendix II, Lingner et al., 1988). We used modifications of two different productivity algorithms and data from both the AVHRR and CZCS sensors to produce the productivity images. The model of Collins et al. (1986) is based upon physical characteristics of the water column environment, such as light absorption and utilization efficiency, and respiration. In contrast, the LaFontaine and Peters (1986) model had been derived empirically, a stepwise multiple regression using hundreds of observations on several variables. We obtained processed AVHRR and CZCS pigment images for these studies from the SSOF. We programmed and ran our productivity model under the NASA Transportable Applications Executive (TAE) on the Cal Space computer system (see Appendix III, Dealy et al., 1988).

By comparing the satellite-derived productivity data with those measurements obtained at sea by Dr. Balch and co-workers (SCBS cruise 18) we were able to evaluate the two productivity models on a qualitative basis. The results from the Collins et al. (1986) model were found to correspond well with ship data; those from the model of LaFontaine and Peters (1986) were unacceptably low.

Later, both at Scripps and at Annapolis, we added CZCS-derived diffuse attenuation coefficients as an input parameter for the models, improving the results for both models. Replacement of the Southern California Bight average I-par with actual satellite-derived values for the time of interest and those for the two or three days prior to that time should add to the improvement.

Computer Developments

During the three years of this grant, much time and effort was spent improving our software and hardware satellite data processing capabilities. A detailed outline of some of these efforts has been presented in Dealy et al. (1988). Of interest here are the addition of TAE, remapping and coregistration using coastlines, advanced image display, manipulation, and recording methods, optical disc storage devices, streamlined AVHRR processing software, and access to nationwide networks, enabling use of the large regional and global CZCS data archives that are available.

PUBLISHED PAPERS AND PROCEEDINGS

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Frouin, R., D.W. Lingner, C. Gautier, K.S. Baker, R.C. Smith, 1988: A simple analytical formula to compute total and photosynthetically available solar irradiance at the ocean surface under clear skies. Submitted to JGR-Oceans.

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PRESENTATIONS AT MEETINGS

"Global oceanic primary productivity." Cal Space Research Lecture, La Jolla, CA, February 1987.

"Primary productivity from combinations of AVHRR sea-surface temperature and CZCS chlorophyll-a concentrations. California Space Institute Summer Workshop: Climate and Remote Sensing, La Jolla, CA, August 1987.

"Analytical formula to compute PAR at ocean surface under clear skies." NASA Workshop: Ocean Color in the GOFS Era, Annapolis, MD, September 1987.

"Analytical formula to compute PAR at ocean surface under clear skies." Scripps Canyon Mooring Workshop, La Jolla, CA, November, 1987.

POSTERS

"An investigation of methods used to model mesoscale primary productivity in the ocean using only remotely sensed data." American Geophysical Union: Ocean Sciences Meeting, New Orleans, LA, January 1988.

"Remote sensing research at the University of California: California Space Institute." Air/Space America 88 Exposition, San Diego, CA, May 1988.

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APPENDIX I

A SIMPLE ANALYTICAL FORMULA TO COMPUTE CLEAR SKY TOTAL AND PHOTOSYNTHETICALLY AVAILABLE SOLAR IRRADIANCE AT THE OCEAN SURFACE

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Abstract

A simple yet accurate analytical formula is proposed to compute total and photosynthetically available solar irradiance at the ocean surface under clear skies. The formula takes into account the most important processes occurring within the atmosphere, namely scattering by molecules and aerosols and absorption by water vapor, ozone, and aerosols. These processes are parameterized as a function of solar zenith angle, aerosol type, atmospheric visibility, and vertically integrated water vapor and ozone amounts. When compared with the radiative transfer model of Tanré *et al.* (1979), the formula shows excellent agreement (to within 1%) under most atmospheric conditions and solar zenith angles. There is also good agreement with formulas developed by other investigators to estimate total solar irradiance. Comparisons of calculated and measured total and photosynthetically available solar irradiances for several experiments in both tropical and midlatitude oceanic regions show 39 and 14 Wm^{-2} r.m.s. errors (6.5 and 4.7% of the average measured values) on an hourly time scale, respectively. The proposed formula is unique in its ability to predict surface solar irradiance in the photosynthetically active spectral interval. Furthermore, it may also be used for converting total irradiance measurements into photosynthetically available irradiance estimates. Combining the clear-sky irradiance formula with satellite techniques to retrieve cloud effect on solar irradiance, pigment concentration, and sea surface temperature would provide useful primary productivity estimates over large oceanic areas, and eventually the global oceans.

1. Introduction

The amount of solar irradiance reaching the ocean surface is important in both physical and biological oceanography. From the physical point of view, the incoming irradiance from the entire solar spectrum, or total solar irradiance, constitutes a major boundary forcing for oceanic circulation and acts as a crucial parameter for determining meridional heat transport. From the biological point of view, the solar irradiance in the photosynthetically active interval (350–700 nm), otherwise known as Photosynthetically Available Radiation (PAR), regulates marine primary productivity and, therefore, the evolution of aquatic ecosystems.

Currently, models to predict upper ocean properties such as temperature and primary productivity use either shipboard measurements or climatological light levels as input. *In-situ* measurements, generally confined to regions of research experiments, are sparse, while regional and seasonal averages, produced from meteorological data collected aboard ships-of-opportunity, are limited in both accuracy and coverage.

Interestingly, many models and formulas have been proposed for estimating total solar irradiance (*e.g.,* Kimball, 1928; Mosby, 1936; Laevastu, 1960; Berliand, 1960; Lumb, 1964; Reed, 1977; Atwater and Brown, 1974; and Davies *et al.,* 1975), but none for PAR. Until recently, most of the questions addressed in biological oceanography have involved space and time scales for which PAR can be directly measured. Furthermore, it has often proved satisfactory to take PAR as a more or less constant fraction of the total solar irradiance (*e.g.,* Jerlov, 1974, 1976; Jitts *et al.,* 1976). The relationship between PAR and total solar irradiance, however, depends upon atmospheric characteristics and radiation geometry (Baker and Frouin, 1987). As interest in mapping primary productivity over large oceanic areas grows, an accurate, rapid estimate of PAR for various atmospheric conditions becomes essential.

A simple yet accurate analytical formula is presented here in order to permit computation from a few common input parameters of total solar irradiance and of PAR at the ocean surface under clear skies. The formula is founded upon the principles of radiative transfer and is verified against other formulas and models.

A direct comparison of the formula's predictions with *in situ* measurements is presented as well. The effect of clouds on solar irradiance, although important, is not investigated here. This effect can be treated separately; in general, it is sufficient to multiply clear sky irradiance by cloud transmittance. Since techniques have been developed to estimate cloud transmittance from satellite measurements of the solar radiation that is reflected by the earth-atmosphere system (*e.g.,* Hay and Hanson, 1978; Tarpley, 1979; Gautier *et al.,* 1980), one could use a clear sky formula in conjunction with these techniques to provide an estimate of solar irradiance regardless of cloud conditions. So far, this approach has been investigated for total solar irradiance, but not for PAR. Estimating PAR from satellite data is work currenty in progress.

2. Analytical Formula's Derivation

In the spectral range of interest, 250–4000 nm, solar radiation is scattered by air molecules and aerosols and is absorbed primarily by ozone, water vapor, carbon dioxide, oxygen, and aerosols. Scattering and absorption processes interact in a complicated manner, but fortunately gaseous absorption can be treated separately. Qualitatively, the arguments are as follows. First, the ozone layer, located at high altitudes (30–40 km) where molecules are rarified, is traversed almost without scattering. Second, absorption by water vapor and carbon dioxide occurs mostly at wavelengths above 850 nm, where scattering is essentially due to aerosols. Since the aerosol phase function presents a predominantly forward peak, the photons at those wavelengths follow practically a direct path through the atmosphere. To account for ozone, water vapor, and carbon dioxide absorption, it is therefore sufficient to multiply the incoming irradiance by the transmittance of the respective gases along the *direct* path from the sun to the surface. Although such a treatment is more difficult to justify for oxygen absorption because molecular scattering is not negligible around 750 nm, it constitutes nonetheless a good approximation because oxygen absorption is very localized spectrally and the spectral intervals considered (the PAR range and the total solar spectrum) are comparatively wide. A more complete justification of decoupling gaseous absorption and scattering can be found in Deschamps *et al.* (1983) and Tanré *et al.* (1985). Neglecting the thermal emission of the atmosphere, and assuming that the surface is Lambertian and uniform, the irradiance reaching the surface in the wavelength range λ_1–λ_2 from the sun at zenith angle θ can be written as:

$$I_{\lambda_1-\lambda_2}(\theta) \simeq \int_{\lambda_1}^{\lambda_2} I_{0\lambda} \left(\frac{d}{d_o}\right)^2 \cos\theta \frac{e^{-\tau_\lambda/\cos\theta} + t_{d\lambda}(\theta)}{1 - r_\lambda s_\lambda} t_{g\lambda}(\theta) d\lambda \tag{1}$$

where $I_{0\lambda}$ is the monochromatic extraterrestrial solar irradiance, d/d_o is the ratio of actual to mean earth-zsun separation, τ_λ is the optical thickness (or turbidity) of the atmosphere , r_λ is the surface reflectance, $t_{d\lambda}$ is the diffuse sky transmittance, $t_{g\lambda}$ is the transmittance due to absorbing gases, and s_λ is the spherical albedo of the atmosphere. In this expression, $e^{-\tau_\lambda/\cos\theta}$ represents direct solar beam attenuation and $1 - r_\lambda s_\lambda$ accounts for photons that have experienced one or multiple surface reflections. The assumption of a Lambertian and uniform surface is not actually verified (r_λ depends on solar zenith angle, surface roughness, and water type), but remains reasonable because $r_\lambda s_\lambda$ is generally small (< 0.05). In the presence of sun glint, however, $r_\lambda s_\lambda$ reaches much higher values, and neglecting the bidirectional properties of r_λ introduces non-negligible errors.

According to Tanré *et al.* (1979), $t_{d\lambda}$ and s_λ can be expressed with good approximation as:

$$t_{d\lambda} \simeq e^{-(\alpha\tau_{r\lambda} + \beta_\lambda\tau_{a\lambda})/\cos\theta} - e^{-\tau_\lambda/\cos\theta} \tag{2}$$

$$s_\lambda \simeq (\alpha'\tau_{r\lambda} + \beta'_\lambda\tau_{a\lambda})e^{-\tau_\lambda} \tag{3}$$

where $\tau_{r\lambda}$ and $\tau_{a\lambda}$ are Rayleigh and aerosol optical thicknesses, respectively, and α, β_λ, α', and β'_λ are coefficients that are either constant (α, α') or dependent on wavelength and aerosol type (β_λ, β'_λ). Since $\tau_{a\lambda}$ is generally not measured, surface visibility, a parameter routinely observed aboard ships, may be used instead. One should bear in mind, however, that the relationship between $\tau_{a\lambda}$ and surface visibility is only a rough inverse proportionality. Thick layers of aerosols, for instance, may exist aloft with a clear atmosphere at the surface (*e.g.,* stratospheric aerosols produced by volcanic activity).

Strictly speaking, $t_{g\lambda}$, unlike $t_{d\lambda}$ and s_λ, cannot be expressed monochromatically because gaseous absorption varies much too rapidly with wavelength (line spectrum). We therefore define $t_{g\lambda}$ as the average transmittance over a sufficiently large spectral interval (typically 5 nm) centered at λ. With such a definition, the transmittance function for each absorbing gas i can be modeled accurately as:

$$t_{i\lambda} \simeq e^{-\alpha_{i\lambda}(U_i^*/\cos\theta)^{\beta_{i\lambda}}} \tag{4}$$

where U_i^* is a vertically integrated absorber amount, suitably scaled to account for the temperature and pressure dependence of absorption, and $\alpha_{i\lambda}$ and $\beta_{i\lambda}$ are coefficients derived from experimental measurements or calculated theoretically. According to theory (*e.g.*, Goody, 1964), $\beta_{i\lambda}$ takes values between 0.5 (strong absorption regime) and 1 (weak absorption regime). For a gas located mainly in the lower troposphere, such as water vapor, U_i^* is nearly equal to the actual total (vertically integrated) absorber amount U_i. This is not the case for ozone, carbon dioxide, and oxygen, but the influence of these gases is so weak in the spectral intervals considered that we can still express their transmittance fairly accurately as an explicit function of U_i instead of U_i^*. We shall therefore write:

$$t_{g\lambda} = \prod_i t_{i\lambda} \simeq \prod_i e^{-\alpha'_{i\lambda}(U_i/\cos\theta)^{\beta'_{i\lambda}}} \tag{5}$$

where $\alpha'_{i\lambda}$ and $\beta'_{i\lambda}$ are adjusted coefficients.

The previous considerations lead to the following analytical formula for $I_{\lambda_1-\lambda_2}$:

$$\begin{aligned} I_{\lambda_1-\lambda_2} \simeq & I_{o\,\lambda_1-\lambda_2} \left(\frac{d}{d_o}\right)^2 \cos\theta \frac{e^{-(a+b/V)/\cos\theta}}{1-\overline{r}_{\lambda_1-\lambda_2}(a'+b'/V)} \\ & \times e^{-a_v(U_v/\cos\theta)^{b_v}} e^{-a_o(U_o/\cos\theta)^{b_o}} \end{aligned} \tag{6}$$

where $I_{o\,\lambda_1-\lambda_2}$ is the monochromatic extraterrestrial irradiance integrated over λ_1–λ_2, $\overline{r}_{\lambda_1-\lambda_2}$ is the average surface reflectance over λ_1–λ_2, V is surface visibility, subscripts v and o denote water vapor and ozone, respectively, and a, a', b, b', a_v, b_v, a_o, and b_o are coefficients to be determined. These coefficients depend on the spectral interval λ_1–λ_2 considered. Some of them, namely a, a', b, and b', also vary with aerosol type. In (6), absorption by carbon dioxide and oxygen is not explicitly parameterized, but implicitly taken into account in the coefficient a, since the concentration of these gases is fairly constant (to simplify, we further assume $\beta'_{i\lambda} = 1$). Note also that the term multiplying $\overline{r}_{\lambda_1-\lambda_2}$ should involve higher orders of $1/V$ because $e^{-\tau_\lambda}$ appears in (3), but first order development is justified since $r_\lambda s_\lambda$ is generally small.

To determine the various coefficients of (6), a wide range of atmospheric and geometric conditions are considered, namely surface visibilities from 5–100 km, total water vapor amounts from 0.5–5 $\mathrm{g\,cm^{-2}}$, total ozone amounts from 0.1–0.5 atm-cm (100–500 Dobsons), and solar zenith angles from 0–80°. For these conditions, $I_{\lambda_1-\lambda_2}$ is first computed using Tanré's *et al.* radiative transfer model. In the calculations, $I_{o\lambda}$ is taken from Neckel and Labs (1984) and r_λ from Viollier (1980). The model of Tanré *et al.* has not been validated by direct measurements, but its predictions do not differ from exact calculations by more than 1%, except at solar zenith angles greater than 80° (*e.g.*, Duhaut, 1985). Such angles are not discussed due to the limited accuracy of Tanré's *et al.* model at large solar zenith angles. By inserting calculated irradiances and corresponding input parameters in (6), the analytical formula's coefficients are obtained by regression.

The eight coefficients are determined for three spectral intervals and two aerosol models. The spectral intervals are 250–4000 nm, representing virtually the total solar spectrum, 350–700 nm, the officially defined PAR range, and 400–700 nm, the band for which modern instruments measure PAR. Table 1 displays the top-of-atmosphere solar irradiance in each of these intervals. About 43% and 39% of the total solar irradiance originates from wavelengths within the 350–700 and 400–700 nm intervals, respectively. Even though only 99% of the extraterrestrial solar irradiance is confined to wavelengths between 250 and 4000 nm, using 1358.2 $\mathrm{Wm^{-2}}$ instead of the solar constant (1372 $\mathrm{Wm^{-2}}$, after Neckel and Labs, 1984) for $I_{o\,\lambda_1-\lambda_2}$ in the total solar spectrum is justified since practically no solar energy traverses the atmosphere outside the 250–4000 nm range. The aerosol models, selected from those proposed by the International Radiation Commission (WCP 55, 1983), correspond to typical maritime and continental aerosols. The maritime model consists mostly of a spectrally white and little-absorbing component, whereas the continental model is a spectrally red and more absorbing mixture of about 70% dust-like and 30% water-soluble components.

Table 2 gives the coefficients obtained for the three spectral intervals and the two aerosol models when V is expressed in km, U_v in $\mathrm{g\,cm^{-2}}$, and U_o in atm-cm. The coefficient b exhibits higher values in the short-wavelength intervals, which results from the higher atmospheric optical depth, τ, in these intervals. For maritime aerosols, b has nearly the same value in the 350–700 nm and 400–700 nm intervals despite a higher τ in the former; but the anisotropy factor of the aerosol phase function and, therefore, β in (2) are sufficiently lower in the 350–700 nm interval to compensate the effect of higher τ in this interval. In all spectral intervals, b is higher for maritime aerosols. This is not quite expected in the 250–4000 nm interval, since τ is lower for maritime aerosols; here, the effect of a higher β dominates. The same type of argument explains the variations of b', except that these now follow the variations of τ, even in the 250–4000 nm interval. Since aerosols only affect atmospheric visibility above a minimum concentration that depends on aerosol type, a and a' are not constant for maritime and continental aerosols. As expected, a_v is extremely low in the 350–700 and 400–700 nm intervals because water absorbs only weakly in the so-called "rain" bands between 570 and 700 nm; a_v is much higher (by 2.5 orders of magnitude) in the 250–4000 nm interval. Unlike a_v, b_v is much lower in the 250–4000 nm interval, a direct consequence of the strong water vapor absorption regime in the infrared. The small a_v values in the short-wavelength intervals suggest that water vapor absorption need not be included in our formula (in the moistest conditions and with the sun at zenith, neglecting water would result in at most a 1% overestimation of irradiance). Because of the large effect of water vapor upon the total irradiance, we have included the term in our formula for generality. As expected, a_o and b_o exhibit their lowest values in the 250–4000 nm interval (ozone absorption occurs below 390 nm and in the Chapuis bands around 600 nm). Moreover, since the peak of ozone absorption in the visible is closer to the red end of the spectrum than to the violet end, a_o is lower in the 350–700 nm interval than in the 400-700 nm interval. The lower b_o values in the 250–4000 nm interval are a manifestation of the strong ozone absorption regime below 290 nm.

Figure 1 shows the performance of the analytical formula when compared against Tanré's *et al.* model. Only the results for the 400–700 nm and 250–4000 nm intervals are presented since those for the 350–700 nm interval are quite similar to the former. In the comparison, we use the US62 standard atmosphere of McClatchey (1972), characterized by a 1.4 g cm^{-2} total water vapor amount and a 0.34 atm-cm total ozone amount, and consider two surface visibilities, namely 23 and 5 km. The agreement between our formula and Tanré's *et al.* model is generally very good, and best when the aerosols are continental and the visibility is equal to 23 km. For maritime aerosols, the formula underestimates solar irradiance at solar zenith angles below 30° and overestimates solar irradiance at solar zenith angles above 40°. Still, the differences are not more than 2% in either spectral interval, even at large solar zenith angles. For continental aerosols, the relative difference between the two models does not exceed 1% in either spectral interval, except at large solar zenith angles ($\theta > 75°$) and 5 km visibility, in which case the difference reaches a maximum of 4%. One notices in Fig. 1 that surface visibility has more effect on solar irradiance when the atmosphere contains continental aerosols.

Since it is often total solar irradiance and not PAR that is measured aboard ships, we have also examined the performance of our formula in predicting the ratios $I_{350-700}/I_{250-4000}$ and $I_{400-700}/I_{250-4000}$. Knowing these ratios gives access to a PAR estimate from a total solar irradiance measurement. Comparisons with Tanré's *et al.* model (not shown here) indicate that, for most atmospheric conditions and a sun within 70° of zenith, the agreement is better than 0.5%. For solar zenith angles above 70°, the agreement is not as good; differences of up to 5% exist between the two types of prediction (overestimation by our formula), which reflect the formula's much larger underestimation of $I_{250-4000}$ than $I_{400-700}$.

3. Comparison with Other Formulas

Among the various formulas that have been proposed to estimate total solar irradiance at the ocean surface, only those of Lumb (1964), Atwater and Brown (1974), and Davies *et al.* (1975) involve instantaneous radiation geometry. The other formulas, developed to compute daily integrals of solar irradiance directly, do not explicitly account for solar zenith angle variations during the course of the day. Rather, they use the average solar zenith angle during daylight hours or, alternatively, the noon solar zenith angle. In this section, our formula is compared to the three more detailed models which use the instantaneous radiation geometry.

Lumb developed his formula from surface radiation data collected aboard the stationary weather ship *Juliett* (52°30′N, 20°W). He found experimental evidence that under virtually clear skies, the ratio $I_{\mathrm{tot}}/S\cos\theta$, where the subscript "tot" refers to the entire solar spectrum and S is the solar constant, is a linear function of $\cos\theta$. This led to the following formula:

$$I_{\text{tot}} = S\cos\theta\,(a + b\cos\theta) \tag{7}$$

where a and b are determined by a least square fit. Taking $S = 1350\ \text{Wm}^{-2}$, Lumb found $a = 0.61$ and $b = 0.2$. Atmospheric absorption and scattering processes are not parameterized in (7); the formula only reflects average atmospheric conditions at *Juliett's* location. Lumb's formula, however, has subsequently proven satisfactory in other oceanic areas (*e.g.*, Simpson and Paulson, 1979; Lind *et al.*, 1984). This is not surprising, in fact, because the solar zenith angle is the most influential parameter on the solar irradiance reaching the surface and it can be calculated exactly.

Unlike Lumb's formula, Atwater and Brown's formula is based on theoretical considerations. In clear sky conditions, the incoming solar flux is written as:

$$I_{\text{tot}} = S\cos\theta P(G - A) \tag{8}$$

where P is the transmittance for aerosol scattering and absorption, A is the absorptance of water vapor, and G is the transmittance for molecular scattering and absorption by other gases (including ozone). The functions P, G, and A are defined as:

$$P = e^{-\tau_c \frac{p}{1013} / \cos\theta} \tag{9}$$

$$G = 0.485 + 0.515\left[1.041 - 0.16\left(\frac{0.000949p + 0.051}{\cos\theta}\right)^{0.5}\right] \tag{10}$$

$$A = 0.077\,(U_v/\cos\theta)^{0.3} \tag{11}$$

where p is the surface pressure in mb and τ_c characterizes aerosol opacity. In (11), U_v is expressed in $\text{g}\,\text{cm}^{-2}$. The essential physics of the problem are thus accounted for in (8), although no ozone variations are permitted. The formula takes into account the effect of pressure on atmospheric optical thickness, a feature that does not appear in our formula. This effect is secondary, but could be easily introduced, at least approximately, by multiplying the term $a + b/V$ in (6) by $p/1013$. One notices in (8) that the water vapor absorptance is subtracted from the transmittance of the dry, hazeless atmosphere. This procedure is not satisfactory, because it implies that

$G - A$ can be negative. In fact, the transmittance of the moist, hazeless atmosphere is more appropriately expressed as $G(1 - A)$. Since A is relatively small, using $G - A$ instead of $G(1 - A)$, although conceptually incorrect, has no noticeable effect. Examining (9) and (11), one also notices that G can be negative and A greater than 1 when the sun is near the horizon. This makes no physical sense, indicating that the form chosen for these functions is incorrect for some situations.

Finally, in Davies' *et al.* formula the solar irradiance reaching the surface is expressed as

$$I_{\text{tot}} = S \cos\theta \psi_{\text{wa}} \psi_{\text{da}} (\psi_{\text{ws}} \psi_{\text{rs}} \psi_{\text{ds}} + 1)/2 \tag{12}$$

where ψ_{wa}, ψ_{da}, ψ_{ws}, ψ_{rs}, and ψ_{ds} are transmission functions for water vapor absorption, aerosol absorption, water vapor scattering, Rayleigh scattering, and aerosol scattering, respectively. It is assumed in (12) that direct solar radiation is absorbed before being scattered, that half of the scattered radiation reaches the surface, and that aerosol attenuation is due equally to absorption and scattering. In addition, ozone absorption is neglected. Scattering by water vapor is considered separately from scattering by other molecules, which allows one to take into account the effect of changes in molecular density (due mainly to water vapor) on the scattering cross-section. The transmission functions are given by:

$$\psi_{\text{ws}} = 1 - 0.0225 U_v / \cos\theta \tag{13}$$

$$\begin{aligned} \psi_{\text{rs}} = {} & 0.972 - 0.08262/\cos\theta + 0.00933/(\cos^2\theta) \\ & - 0.00095/(\cos^3\theta) + 0.0000437/(\cos^4\theta) \end{aligned} \tag{14}$$

$$\psi_{\text{wa}} = 1 - 0.077 (U_v/\cos\theta)^{0.3} \tag{15}$$

$$\psi_{\text{ds}} = \psi_{\text{da}} = k^{\frac{1}{2}\cos\theta} \tag{16}$$

where k is a coefficient that depends on aerosol type and loading ($k < 1$) and U_v is expressed in $\text{g}\,\text{cm}^{-2}$. We again see that ψ_{ws}, ψ_{rs}, and ψ_{wa} become infinite as θ approaches 90°, which makes the approximations to these transmission functions not fully satisfactory. Note, finally, that the Davies *et al.* formula, as well as Atwater and Brown's, does not take into account interactions between the photons and the sea surface.

For the comparisons to be meaningful, it is indeed important that the same atmospheric conditions and solar zenith angles are considered for all formulas. Unfortunately, the aerosol input parameters are different from one formula to the next. We must therefore determine exactly how they correspond. This is done by equating each formula's terms that describe the aerosol effect. Neglecting the photons' multiple interactions with the sea surface in our formula, and assuming $p = 1013$ mb in Atwater and Brown's formula, we obtain:

$$k = \left[-0.5 + \left(0.5 + 4\epsilon^{-(a_a + \frac{b}{V})/\cos\theta}\right)^{\frac{1}{2}}\right]^{2\cos\theta} \tag{17}$$

and

$$\tau_c = a_a + \frac{b}{V} \tag{18}$$

where a_a corresponds to the aerosol particules that do not affect the surface visibility ($a_a < a$). The coefficient a_a takes the values 0.025 and 0.012 when the aerosols are continental and maritime, respectively. We see in (17) that k is a function of θ. The dependence, however, is slight (k varies less than 1% when θ varies from 0° to 80°). For each turbid atmosphere selected, we therefore fix k at its average value over the θ range 0°–80°.

Figure 2 shows the formulas' predictions for a US62 atmosphere with 23 km visibility and containing either continental or maritime aerosols. The agreement between formulas is generally good. Maximum differences of 60 and 30 $\mathrm{Wm^{-2}}$ are observed for maritime and continental aerosols, respectively. The predictions of Atwater and Brown's and Davies' *et al.* formulas agree within 3–4 $\mathrm{Wm^{-2}}$ at all solar zenith angles, but yield higher values than our formula by 20–25 $\mathrm{Wm^{-2}}$ depending on the type of aerosols (larger bias with maritime aerosols). Lumb's formula gives the best agreement with our formula for continental aerosols. In this case, the differences do not exceed 1% at solar zenith angles less than 60°, but reach 15% at larger solar zenith angles. It is interesting to note that turbidity measurements made at Lages, Azores (38°N, 27°W), a location not too far from *Juliett* where Lumb's formula was established, have shown that the aerosol optical thickness in that region varies spectrally with an annually averaged Ångström exponent of 0.93 ± 0.3 (anonymous, 1977), which is more characteristic of continental aerosols than maritime aerosols. Since the amount of solar radiation reaching the surface decreases as the atmospheric visibility decreases, Lumb's formula, which does not allow for aerosol loading variations, predicts higher solar irradiance values than does our formula at visibilities less than 23 km. In 5 km visibility conditions, for instance, the overestimation may reach 100 Wm^{-2}.

4. *In Situ* Comparisons

The predictive power of (6) for I_{par} and I_{tot} has been tested against five separate ground-truth data sets. Two of the experiments contain independent measurements of I_{tot} and I_{par}, thus providing an ideal validation situation. These two experiments were 1) the first Biowatt field experiment aboard the *R/V Knorr* in the Sargasso Sea (24–35°N, 70°W) during April 12–22, 1985 (Dickey, *et al.,* 1986), and 2) measurements taken at Scripps Institution of Oceanography's pier (33°N, 117°W) during April 12 to May 10 of 1984 in support of other bio-optical experiments at a nearby underwater mooring (Booth, *et al.,* 1987). The other three data sets contain I_{tot} data and no I_{par} data. These were 3) the Mixed Layer Dynamics Experiment (MILDEX), measurements of I_{tot} having been taken aboard *R/P FLIP* (Floating Instrument Platform) off Point Conception, California (34°N,126°W) during October 26 to November 12 of 1983 (Lind and Katsaros, 1987), 4) the Tropic Heat experiment, I_{tot} measurements from the *R/V Wecoma* in the tropical Pacific Ocean (3°S to 6°N, 140°W) during November 15 to December 4 of 1983 (Niiler, 1987), and 5) the Frontal Air-Sea Interaction Experiment (FASINEX), in which I_{tot} were measured from five surface moorings located southwest of Bermuda (27°N, 70°W) during February 5 to March 7 of 1986 (Pennington and Weller, 1986).

Each of the five data sets was culled to eliminate all but clear-sky measurements, as indicated ideally from direct observations of sky conditions. Cloud coverage data were available for MILDEX and for a subset of the SIO Pier data set. The remaining data (SIO Pier, Biowatt, FASINEX, and Tropic Heat) contained no cloud information. Therefore, irradiance-time plots, constructed from the original data, were evaluated to determine the likely sky state. Only those time segments that were smooth and approximated a cosine relationship were included among the clear-sky data.

The analytical formula (6) for I_{tot} and I_{par} requires six input parameters, two of which, the solar zenith angle and the ratio of the actual Earth-Sun distance to its annual mean, are known or can be computed from time and position data. The other four input parameters are aerosol type, visibility, and the vertically integrated concentrations of water vapor and ozone in the atmosphere. If not measured directly, these parameters can be estimated using monthly or seasonal climatological averages or indirect observational data.

The selection of the aerosol model was based upon wind velocity data from either the daily weather maps (*e.g.*, NOAA, 1984) or monthly average vector mean wind barbs and direction frequency diagrams from the U.S. Navy Marine Climatic Atlases of the World (*e.g.*, Meserve, 1974). Prevailing winds from a direction in which there is a nearby land mass are assumed to carry aerosols of continental origin; while those winds from predominantly oceanic regimes would convey maritime aerosols. The visibility was estimated from monthly average cumulative percent frequency diagrams in the Navy Climatic Atlases. Seasonal maps of mean concentrations and root-mean-square deviations of water vapor over the oceans, based upon three years (1979–1981) of remote sensing data from the Nimbus-7 Scanning Multichannel Microwave Radiometer (SMMR), plotted by Prabhakara, *et al.* (1985), were used to estimate total water vapor amount. Finally, latitude-time plots of total ozone compiled by Dutsch (1969) from three years of IGY-IGC data were used to determine monthly average vertically integrated atmospheric ozone concentrations. Table 3 lists average climatological values of the four parameters for the time of each experiment.

During the Biowatt cruise, a Biospherical Instruments, Inc. spectroradiometer (Smith, *et al.*, 1984) measured spectral downwelling irradiance above the ocean surface in twelve channels each having 10 nm half-bandwidths and together spanning the wavelength range from 410 to 769 nm. The instrument was calibrated against a standard lamp and the PAR irradiance was calculated by integrating the spectral data from 400 to 700 nm. The total irradiance was measured using an Eppley precision spectral pyranometer (Model PSP) with a WG7 clear glass cover transparent between 285 and 2800 nm. This pyranometer was calibrated against the entire solar spectrum (Hill, *et al.*, 1966) and has a precision of ±2%. Both instruments were located on the ship's flying bridge, approximately 4 m from a reflective stack and 15 m above the sea surface. Although the location for the instruments was selected to minimize exposure errors, contamination due to ship structure both obscuring part of and reflecting into the fields-of-view may affect nominal precision figures by a few percent. The Biowatt data represent 5-minute averages and cover solar zenith angles from 14° to 70°.

For the SIO Pier experiment, I_{par} was measured using a Biospherical Instruments, Inc. cosine PAR sensor, calibrated against a standard lamp. The total irradiance, I_{tot}, was measured using the same Eppley precision spectral pyranometer that was used during Biowatt. The two instruments were mounted side-by-side on a temporary wooden structure above the trailer at the end of the old SIO pier where there would be minimal obstruction from or reflection into the fields-of-view of the instruments. The SIO Pier data set comprises twenty-two sets of I_{par} and I_{tot} data with frequencies ranging from 0.2 to 15 min^{-1} and durations from 13 minutes to 3.5 days. These data were averaged over 30-minute time intervals that had been dubbed clear by one of the above criteria.

The total irradiance data from the FASINEX were taken using Eppley pyranometers (Model 8-48) placed atop each of five surface buoys. The pyranometers were calibrated with a precision of 5%. The data were averages of 64 samples per 450 seconds (Pennington and Weller, 1986), later combined into 30-minute averages which were used for this study.

For Tropic Heat, I_{tot} was measured from *R/V Wecoma* using an Eppley pyranometer (Model 8-48), calibrated to factory specifications. The data are hourly averages of measurements taken at two-minute intervals (Clayton Paulson, Oregon State University, personal communication).

For MILDEX, an Eppley precision spectral pyranometer, Model PSP, measured I_{tot} from *R/P FLIP* with only a few support wires within the immediate field-of-view of the instrument. The pyranometer was calibrated with an instrument error of 2% and an exposure error of 1%, resulting in a total precision of 2% for a single data sample. Individual samples (4 sec^{-1}) were block averaged over 32-second periods, then smoothed and combined into 30-minute averages for analysis (Lind and Katsaros, 1987).

Figure 3a shows predicted I_{par} plotted against measured I_{par} for the combined Biowatt and SIO Pier data sets. Figure 3b shows predicted vs measured I_{tot} for all five experiments. Goodness-of-fit statistics for the combined data sets are noted on Figs. 3a and 3b; those for the individual experiments are listed in Table 4.

For the combined data set, the calculated I_{par} values fit the surface data very well. The standard error (r.m.s. deviation) of the fit is 14 Wm^{-2}, or 4.7% of a nominal mean of 300 Wm^{-2}, and the bias (average deviation) is -5 Wm^{-2} (negative bias indicates that predicted values are, on average, lower than measured data.) Individually, the goodness-of-fit statistics for I_{par} are similar for both the Biowatt and the SIO Pier comparisons. The standard error for each of the two experiments are between 10 and 20 Wm^{-2}, and the biases both indicate an underestimation by the formula of about 5 Wm^{-2} in I_{par}.

For total irradiance, calculated values and *in situ* data from the combined five experiments differ by an average of $+8$ Wm^{-2}, indicating a slight overestimation of the data by the analytical formula. The standard error of the fit is 39 Wm^{-2}, or 6.5% of a nominal mean of 600 Wm^{-2}.

The overall good agreement between predicted and measured I_{tot} may be attributed mainly to the relative abundance of data (72% of all points) within the FASINEX data set. The biases for the five buoys range from $+11$ to -14 Wm^{-2} and the overall FASINEX bias is $+1$ Wm^{-2}. The individual statistics for the other four experiments exhibit biases within the range 20–30 Wm^{-2}, averaging $+25$ Wm^{-2}. So, with the one exception, (6) tends to overestimate the total irradiance by 3–4%, while underestimating I_{par} by around 2%.

In fact, one might argue that the FASINEX data is not an exception. If the maritime aerosol model were used in the prediction, and the other three parameters input as listed in Table 3, then the bias would be $+17$ Wm^{-2}, not $+1$ Wm^{-2}, for the combined FASINEX data. The continental aerosol model was chosen for FASINEX based upon wind vector data (Meserve, 1974) showing westerly winds at 2.2 knots on maps for both February and March at Station "34" (30°N, 70°W). A look at the wind direction frequency diagram (Meserve, 1974), in fact, shows a scalar mean wind speed of 13.8 knots spread evenly among the eight major compass points, indicating that assignment of the maritime aerosol model would not be totally improper. In this case, all five data sets would exhibit biases between +17 and +29 Wm^{-2} for the prediction of total irradiance. Standard surface pressure maps and nearby station data for the specific days of buoy deployment (NOAA, 1985), however, justify our choice of continental aerosols. Still, the apparent reproducibility of the overprediction in most data sets must be addressed.

One possibility is overestimation of atmospheric transmittance by the Tanré *et al.* model. Comparisons with exact calculations (Duhaut, 1985) indicate that part of the discrepancy might originate from decoupling of gaseous absorption and scattering processes. Correcting for the resulting errors, however, would yield higher I_{tot} values by less than 1% for $\theta_S < 60°$. Thus, model errors do not completely explain the observations. Another possible route to overprediction might be inadequate cloud screening of the original irradiance data. If some actually cloudy days had been included within the clear-day data set, then some of the irradiance predicted by the clear-sky model might have been blocked by those clouds and the measured irradiance values would have been lower. The attenuation, however, would have affected both the I_{tot} and I_{par} measurements, although clouds are more transparent in the visible. In any case, the similarity in standard errors for all five I_{tot} prediction data sets (30–50 Wm^{-2}) suggests that the cloud screening methods used were comparable, if not adequate. A third possible explanation might be measurement or calibration error. The 3–4% bias observed in the I_{tot} predictions of some data sets is close in magnitude to the precisions quoted for each pyranometer, but there is nothing to indicate any shortcomings in the accuracy of the instruments.

Aside from model errors and measurement and sampling errors, the positive bias for the I_{tot} predictions might yet be explained by the possibility that one or more of the input parameters for the formula may have been significantly different from the climatological averages used in the calculations. Each of the parameters would certainly vary widely from the mean on a daily basis, but of the four parameters (aerosol model, visibility, H_2O and O_3) for which climatological values were used as input to the formula, only the total water vapor, because of the spectral position of the water absorption bands, can significantly affect I_{tot} without also changing I_{par}. If visibility were actually lower than the climatological average, or ozone content higher, then both the I_{tot} and the I_{par} predictions would decrease by a similar proportion. So too would both quantities change proportionately if the aerosol model were actually the opposite from that predicted by published wind vector data.

In contrast, if the actual water vapor concentration were considerably higher than the climatological mean, then the predicted I_{tot} value would decrease and the predicted I_{par} would remain relatively constant. In fact, if input total water contents were increased by 2.5 $g\,cm^{-2}$ over the values in Table 3, with all other inputs remaining the same, then, with the exception of the FASINEX buoy sets, the predicted I_{tot} values would be reduced to values very close to the measured data. The bias for Biowatt would drop from +29 to +2 Wm^{-2}; for SIO Pier, from +28 to +3 Wm^{-2}; for MILDEX, from +23 to +4; for Tropic Heat, from +20 to +2 Wm^{-2}; and for FASINEX, from +1 to −16 Wm^{-2}. If the maritime aerosol model had been used for FASINEX, then raising the input total water amount by 2.5 $g\,cm^{-2}$ would have decreased the bias from +17 to zero Wm^{-2}. The same increase in total water of 2.5 $g\,cm^{-2}$ would affect predicted I_{par} values only slightly: for Biowatt, the bias in I_{par} would change from −4 to −5 Wm^{-2}; for SIO Pier, from −6 to −7 Wm^{-2}.

Two of the five data sets available happen to include surface air temperature and relative humidity data from which total water may be estimated (Smith, 1966). Although Smith's method assumes a typical shape for the vertical profile of water vapor concentration, it provides total water vapor amounts closer to reality than climatological averages, since water vapor is concentrated in the lower atmospheric layers. On the eleven clear days during the SIO Pier experiment for which direct weather observations are available, the total water content, calculated by the method of Smith, was 2.2 ±0.4 $g\,cm^{-2}$, or 22% higher than the climatological mean of 1.8 $g\,cm^{-2}$. (Note that the average observed visibility was 26 ±18 km, essentially the same as the climatological value of 25 km, and that in none of the eleven days were winds observed coming from any direction east of due north or due south, essentially validating the maritime aerosol model predicted by climatologies and weather maps.) Input of the actual observed total water and visibility data into the model for the SIO Pier experiment yields an improved fit for both I_{par} (bias for the eleven points decreases from −23 to −15 Wm^{-2}) and I_{tot} (bias down from +18 to +2 Wm^{-2}). For FASINEX, surface air temperature and relative humidity data are available throughout the experiment for four of the five buoys. Calculation of total water amount yields values all lower than the climatological mean of 2.8 $\mathrm{g\,cm^{-2}}$(Buoy A: 2.5 $\pm$0.5 Buoy B: 2.6 $\pm$0.6; Buoy C: 2.6 $\pm$0.6; Buoy E: 2.5 $\pm$0.6 $\mathrm{g\,cm^{-2}}$; overall range of values: 1.2 to 3.6 $\mathrm{g\,cm^{-2}}$). Input of these means for total water into (6) would certainly yield I_{tot} values higher than those predicted using the climatological water. The predicted I_{tot} values are also higher when the total water is calculated for each individual point and then input into the analytical formula (For Buoy A, the bias is changed from -0.1 to $+6$ $\mathrm{Wm^{-2}}$; Buoy B, from -14 to -11 $\mathrm{Wm^{-2}}$; Buoy C, from $+4$ to $+5$ $\mathrm{Wm^{-2}}$; Buoy E, from $+11$ to $+13$ $\mathrm{Wm^{-2}}$). Thus, the accuracy of the FASINEX prediction is not significantly improved by consideration of actual observations of surface humidity. In view of the observed total water numbers for the SIO Pier and FASINEX experiments, there is unfortunately no good reason to believe that total water climatological averages underestimate the actual total water contents for all five of the experiments considered. One specific reason for the 3–4% overprediction of total irradiance in some data sets has not been identified.

5. Summary and Conclusions

A fairly accurate analytical formula (6) has been presented for computing total and photosynthetically available solar irradiance at the ocean surface under clear skies. The formula is a parameterization of a more complex radiative transfer model (Tanré *et al.,* 1979) and requires inputs of date, solar zenith angle, visibility, aerosol type, and the vertically integrated concentrations of ozone and water vapor. Compared to Tanré 's *et al.* model, the formula is accurate to 1–2% for solar zenith angles below 75°. It also performs similarly to formulas developed by Lumb (1964), Atwater and Brown (1974), and Davies *et al.* (1975) for total solar irradiance, but the agreement is better with Lumb's formula for continental aerosols. It is expected, however, that in the case of high aerosol loading (low visibility), (6) will provide more accurate results than Lumb's formula, since the latter assumes constant aerosol characteristics, leading to overestimations.

Our formula has been tested against actual radiation data taken aboard ships and buoys during five experiments in various oceanic regions. In the comparisons, the formula's input parameters were specified from climatological data since they were not measured on the platforms carrying the radiation instruments. The results of these comparisons indicate a very good agreement between measured and calculated irradiances for both I_{tot} and I_{par}. On an hourly time scale, the standard error of estimate is 39 Wm^{-2} for I_{tot} and the bias 8 Wm^{-2}, the values being 14 Wm^{-2} and -5 Wm^{-2} for I_{par}, respectively. For all experiments except FASINEX, however, our formula overestimates I_{tot} by 20–30 Wm^{-2}. Although part of the discrepancy might originate from errors related to decoupling gaseous absorption and scattering processes in Tanré's *et al.* model, these cannot account quantitatively for 20–30 Wm^{-2}. We did not find convincing evidence that the discrepancy is linked to measurement procedure or instrument calibration, or to differences between actual and climatological values for the formula's input parameters.

Although instruments for directly measuring PAR are being used increasingly, total solar irradiance still remains the radiation parameter most commonly measured at sea. It is therefore worthwhile mentioning that our formula, by giving access to I_{par}/I_{tot} theoretically, allows one to convert an I_{tot} measurement into an I_{par} estimate. Using the I_{tot} and I_{par} data collected during the BIOWATT and SIO Pier experiments, one can even show that I_{par}/I_{tot} predicted by our formula is accurate to about 0.03.

Thus we have presented a method to estimate I_{tot} and I_{par} which is sufficiently accurate for most applications in biological and physical oceanography. The proposed formula can be used, with the appropriate sets of coefficients, for computing both I_{par} and I_{tot}. It also constitutes the only formula presently available to predict PAR at the ocean surface. We have indicated, in the course of comparing our results with *in situ* data, the type of climatological data sets that can be used as input to the formula. Only the case of clear sky conditions has been addressed in the present study, but the parameterization can be extended to cloudy conditions. In this case, it is generally sufficient to multiply clear sky irradiance by cloud transmittance, T_c. For PAR in particular, the problem is reduced to determining cloud albedo, A_c, since $T_c = 1 - A_c$ (clouds do not absorb in the PAR spectral interval). Determining A_c can be done using satellite radiance measurements in the visible. In fact, estimating PAR from space is of great interest in biological oceanography.

Combined with satellite estimates of pigment concentration and sea surface temperature, satellite estimates of PAR give another important parameter in the attempt to assess primary productivity over large oceanic areas, and eventually the global oceans.

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Figure Captions

Fig. 1: Comparisons of I_{par} and I_{tot} as predicted by the model of Tanré *et al.* (1979) and the analytical formula presented herein. The upper two curve pairs (1 and 2) are I_{tot}; the lower two (3 and 4) are I_{par}.

Fig. 2: Comparisons of various formulas that predict I_{tot}.

Fig. 3: Scatterplots of (a) I_{par} and (b) I_{tot}. Ordinates are values predicted by the analytical formula using climatological input parameters from Table 3. Abscissas are experimental data.

Table 1. Top-of-atmosphere solar irradiance in the spectral intervals considered.

Spectral Interval (nm)	Solar Irradiance (Wm^{-2})
350–700	584.9 (43%)
400–700	531.2 (39%)
250–4000	1358.2 (100%)

Table 2. Regression coefficients for analytical formula.

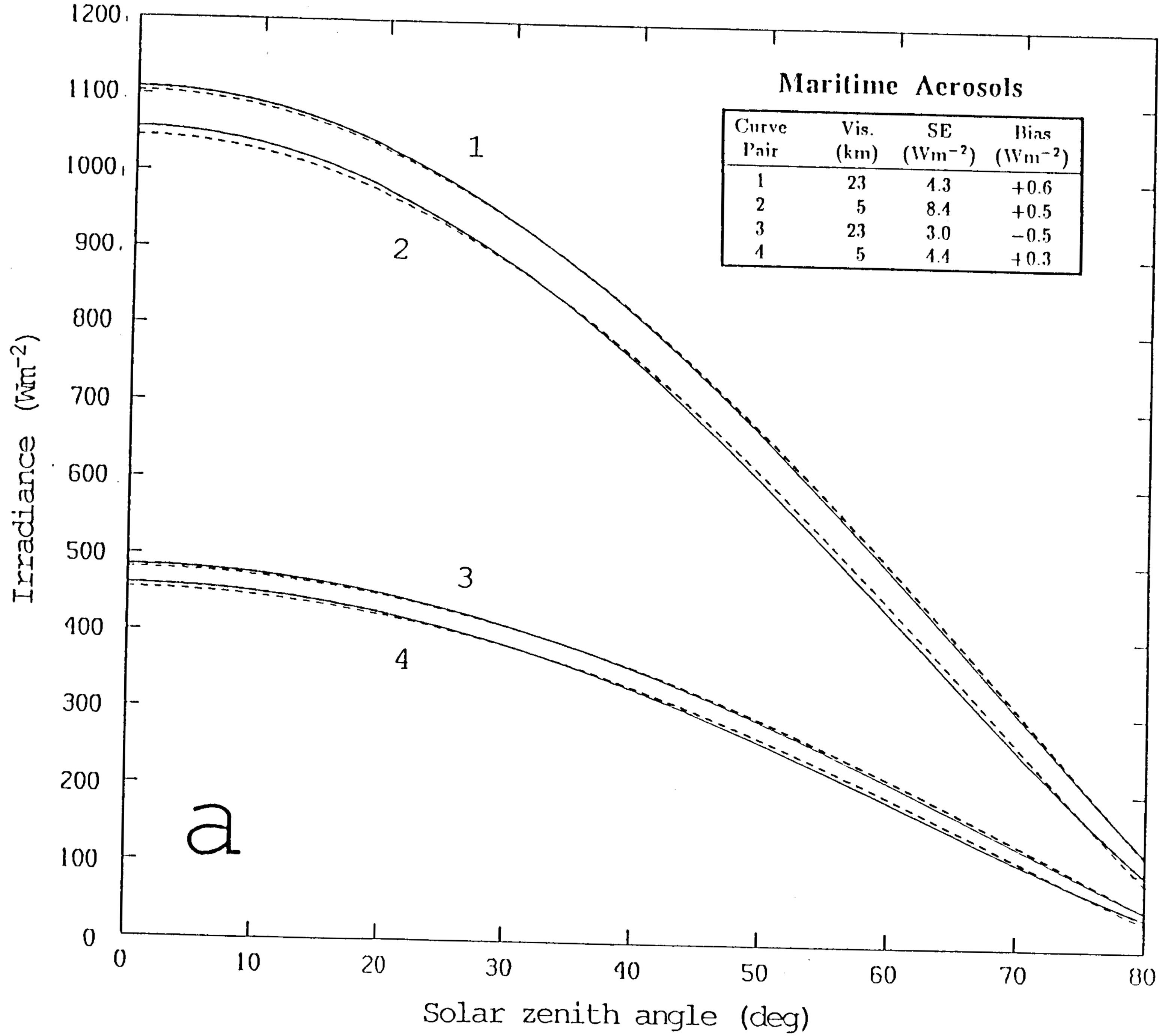
Spectral Interval	Aerosol Type	b	a	b'	a'	a_v	b_v	a_o	b_o
350–700 nm	Maritime	0.079	0.378	0.132	0.470	0.002	0.87	0.047	0.99
	Continental	0.089	0.906	0.138	0.576	0.002	0.87	0.047	0.99
400–700 nm	Maritime	0.068	0.379	0.117	0.493	0.002	0.87	0.052	0.99
	Continental	0.078	0.882	0.123	0.594	0.002	0.87	0.052	0.99
250–4000 nm	Maritime	0.059	0.359	0.089	0.503	0.102	0.29	0.041	0.57
	Continental	0.066	0.704	0.088	0.456	0.102	0.29	0.041	0.57

Table 3. Climatological data for each individual data set.

Data Set	Aerosol Model	Visibility (km)	Water Vapor Amount ($g\,cm^{-2}$)	Ozone Amount (atm-cm)
Biowatt	Continental	27	2.5	0.31
SIO Pier	Maritime	25	1.8	0.32
MILDEX	Maritime	30	2.0	0.28
Tropic Heat	Maritime	31	4.0	0.25
FASINEX	Continental	35	2.8	0.30

Table 4. Goodness of fit statistics (standard error and bias) for comparisons of predicted *vs.* measured irradiance within each individual data set.

Data Set	Number of Points	I_{par} SE (Wm^{-2})	I_{par} Bias (Wm^{-2})	I_{tot} SE (Wm^{-2})	I_{tot} Bias (Wm^{-2})
Biowatt	22	20	−4	50	+20
SIO Pier	224	13	−6	38	+28
MILDEX	42	—	—	32	+23
Tropic Heat	138	—	—	32	+20
FASINEX — all buoys	1101	—	—	41	+1
Buoy A	183	—	—	38	−0.1
Buoy B	230	—	—	37	−14
Buoy C	192	—	—	33	+4
Buoy D	246	—	—	50	+4
Buoy E	250	—	—	43	+11
All data: I_{par}	246	14	−5	—	—
All data: I_{tot}	1527	—	—	39	+8



Curve Pair	Vis. (km)	SE (Wm^{-2})	Bias (Wm^{-2})
1	23	4.3	+0.6
2	5	8.4	+0.5
3	23	3.0	−0.5
4	5	4.4	+0.3

Fig. 1a

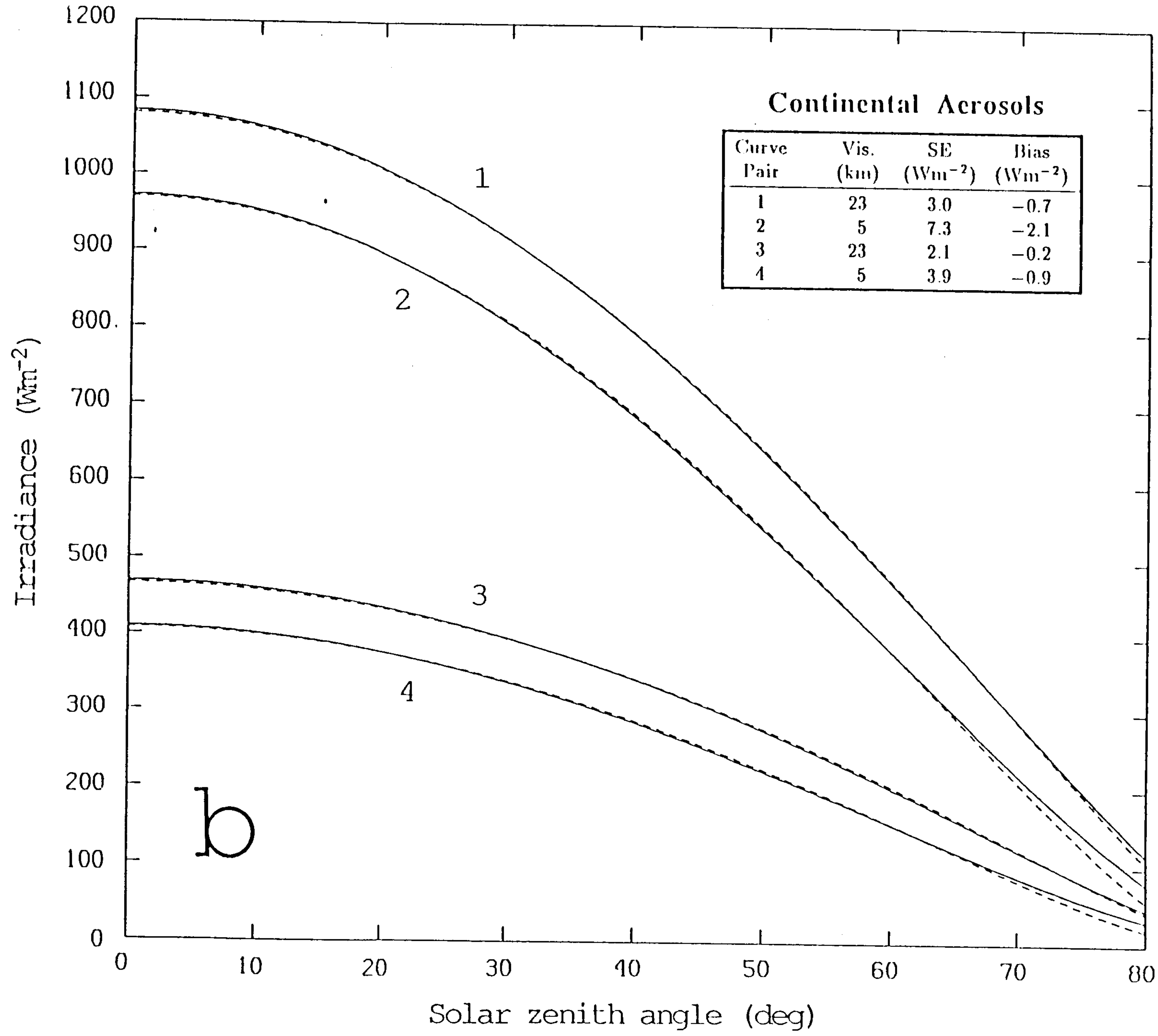

Continental Aerosols
Curve Pair | Vis. (km) | SE (Wm⁻²) | Bias (Wm⁻²)
1 | 23 | 3.0 | −0.7
2 | 5 | 7.3 | −2.1
3 | 23 | 2.1 | −0.2
4 | 5 | 3.9 | −0.9
1
2
3
4
b
Irradiance (Wm-2)
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
0
10
20
30
40
50
60
70
80
Solar zenith angle (deg)

Fig. 1b

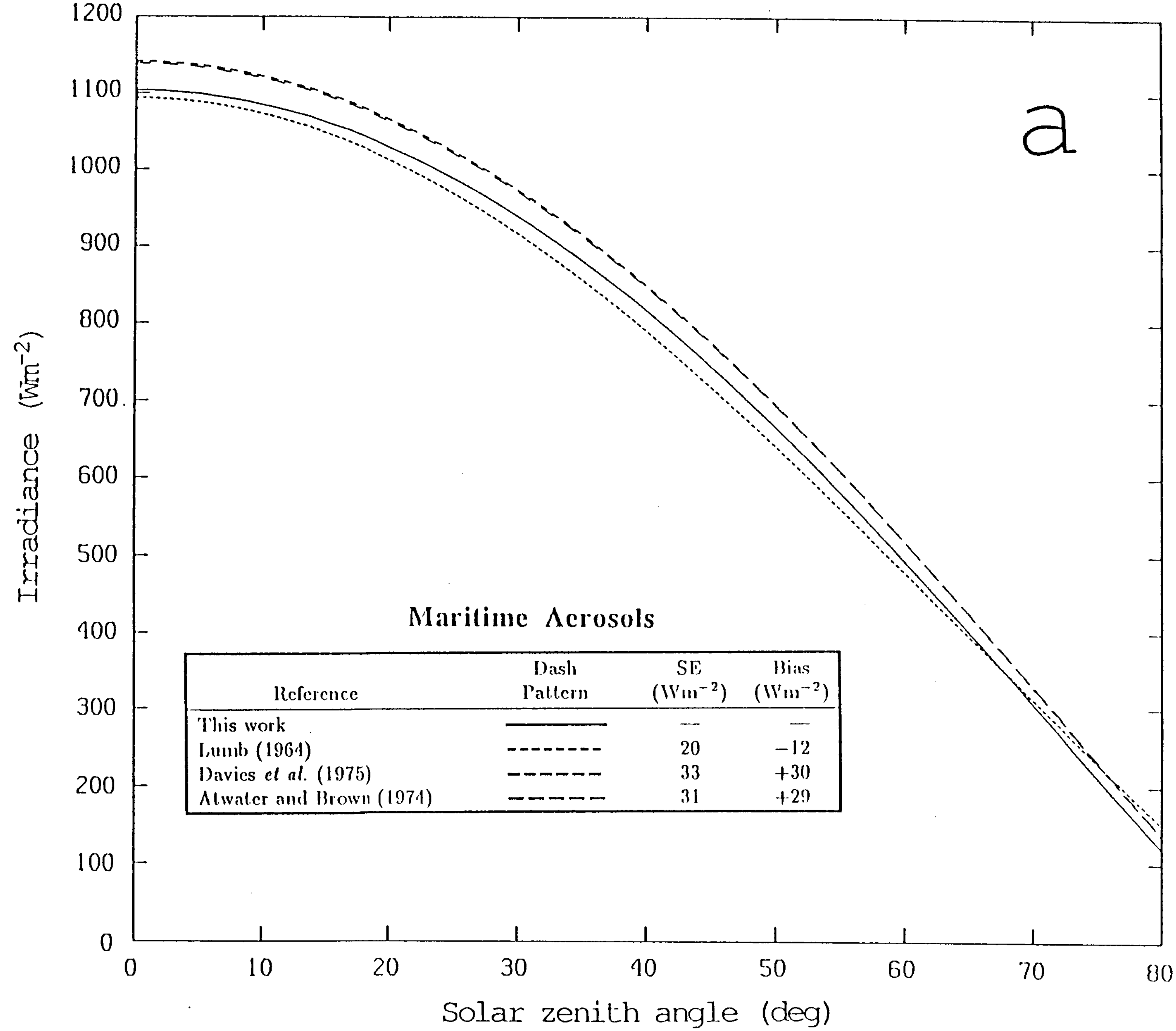
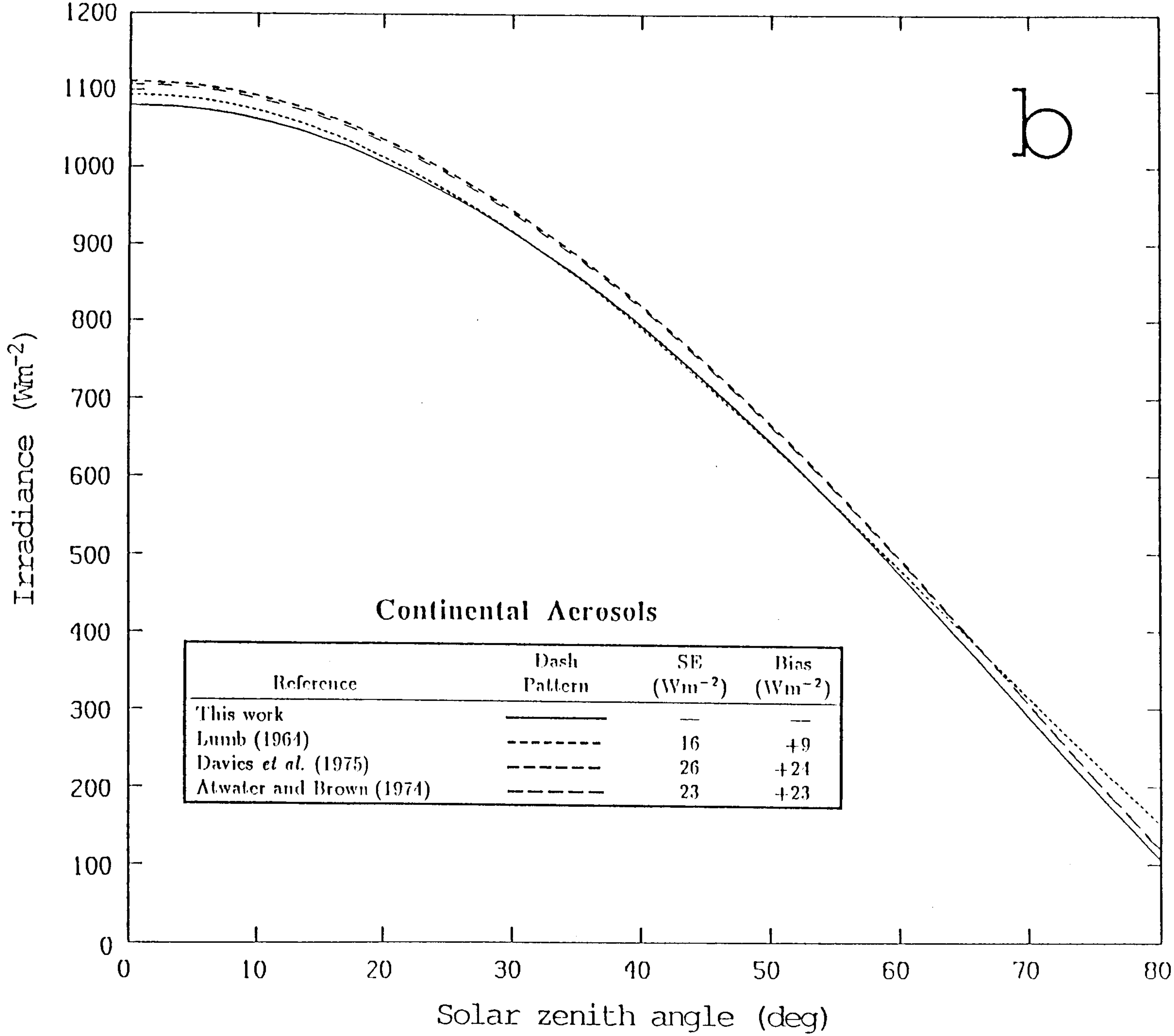
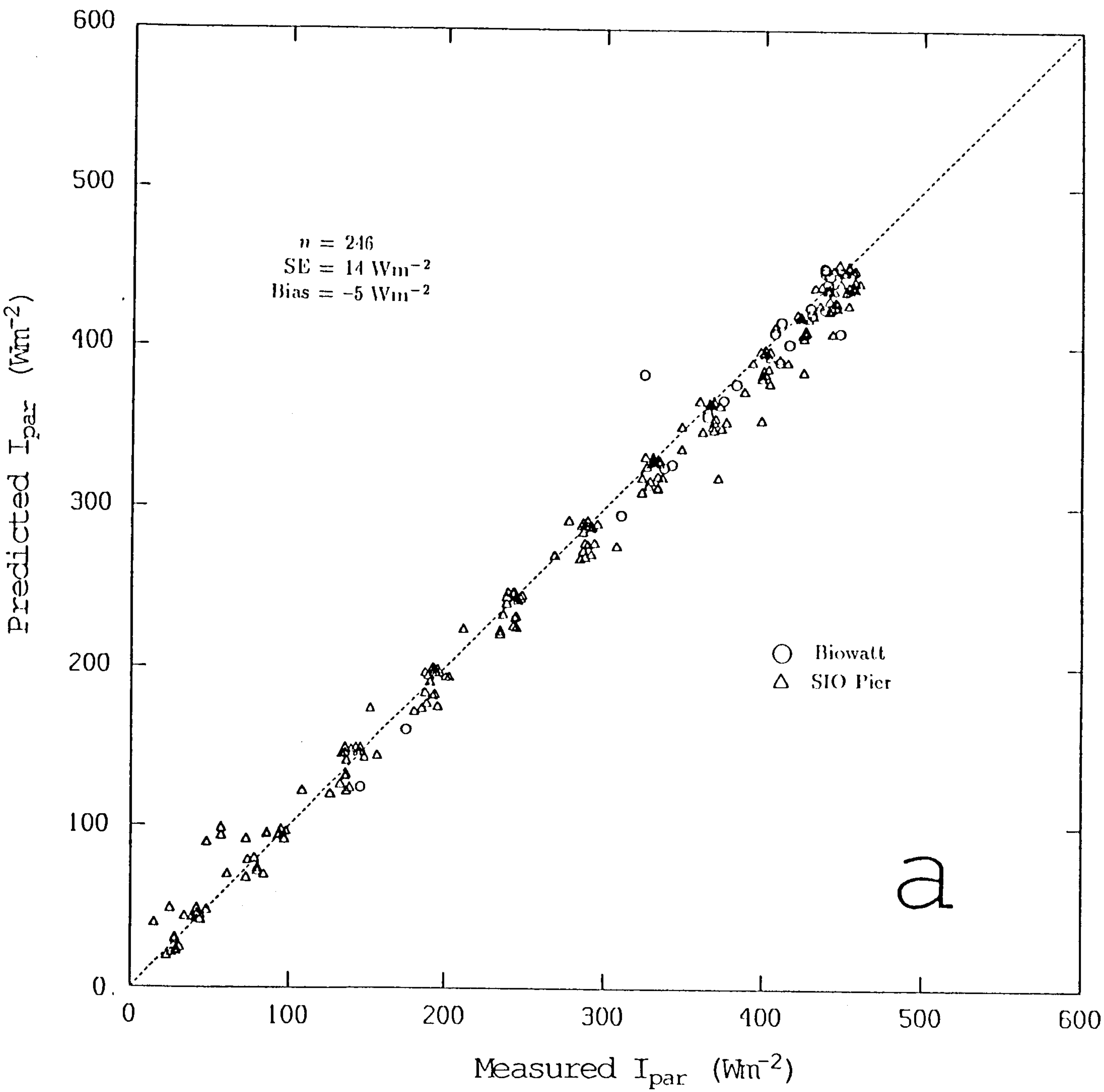

a
Maritime Aerosols
Reference
Dash Pattern
SE (Wm⁻²)
Bias (Wm⁻²)
This work
—
—
Lumb (1964)
20
−12
Davies et al. (1975)
33
+30
Atwater and Brown (1974)
31
+29
Irradiance (Wm⁻²)
Solar zenith angle (deg)
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
10
20
30
40
50
60
70
80

Fig 2a



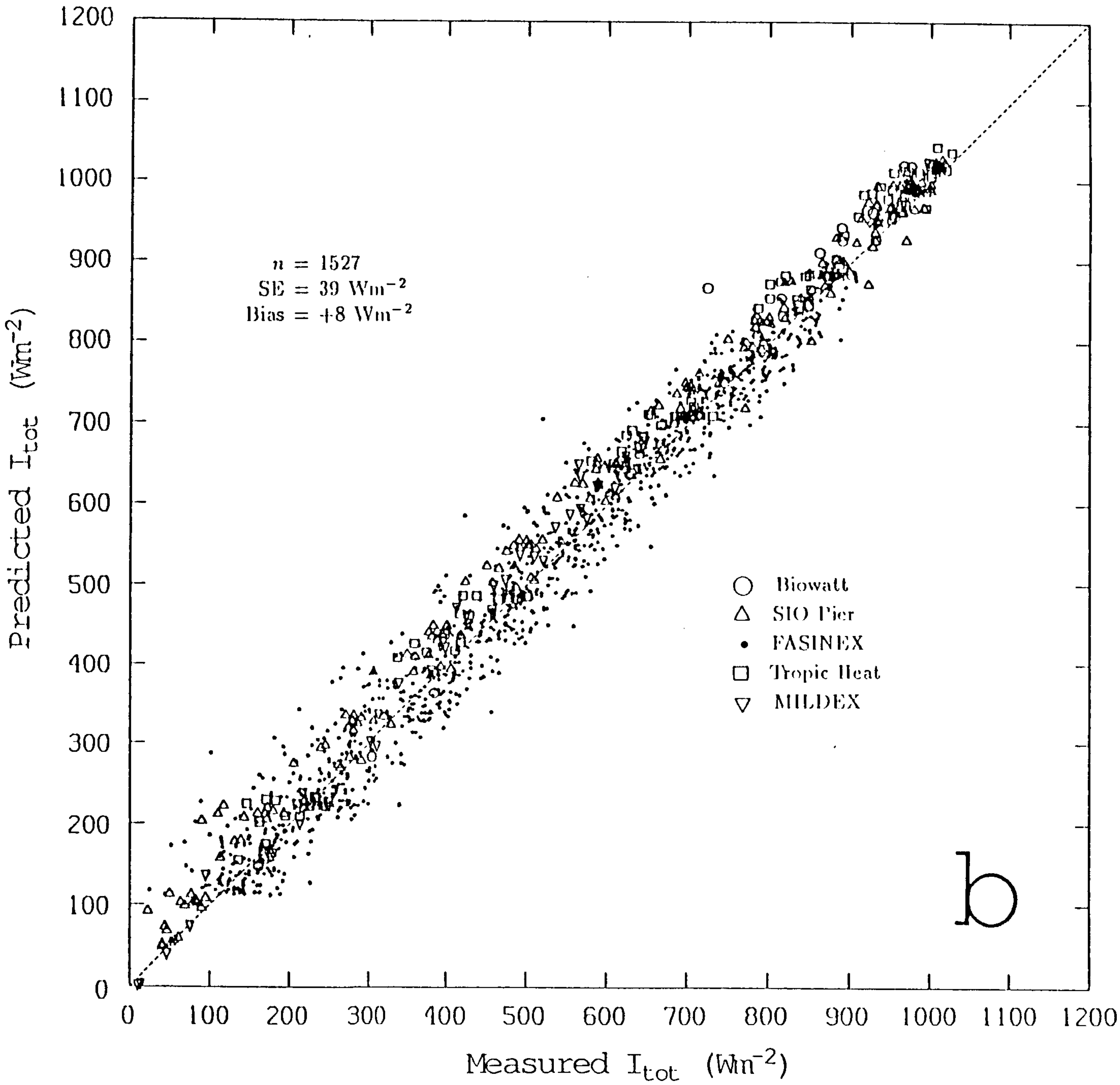
b
Continental Aerosols
Reference
Dash Pattern
SE (Wm⁻²)
Bias (Wm⁻²)
This work — —
Lumb (1964) 16 +9
Davies et al. (1975) 26 +24
Atwater and Brown (1974) 23 +23
Irradiance (Wm-2)
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
Solar zenith angle (deg)
0
10
20
30
40
50
60
70
80

Fig. 2b



$n = 246$
SE = 14 Wm^{-2}
Bias = -5 Wm^{-2}
Biowatt
SIO Pier
a
Predicted I_{par} (Wm^{-2})
Measured I_{par} (Wm^{-2})
0
100
200
300
400
500
600

Fig. 2.



n = 1527
SE = 39 Wm^-2
Bias = +8 Wm^-2
Biowatt
SIO Pier
FASINEX
Tropic Heat
MILDEX
b
Predicted I_tot (Wm^-2)
Measured I_tot (Wm^-2)
0
100
200
300
400
500
600
700
800
900
1000
1100
1200

THE SCRIPPS CLIMATE AND REMOTE SENSING WORKSHOP: A LOOK TOWARD INTERDISCIPLINARY EDUCATION

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1. Introduction

The workshop, conducted in association with France's Centre National d'Etudes Spatiales, took place from July 23 to August 6, 1987, at Scripps Institution of Oceanography. As the successor to the 1986 Franco-American workshop held in Roscoff, France (Climatology and Space Observations, 1986), the workshop was devised to place more emphasis on applications and attract participants from diverse disciplines. Coming from various countries and research institutions, thirty five students and seventeen guest lecturers participated in the workshop. In large part, the students were young scientists finishing their Ph.D.'s in earth process-related studies (e.g., oceanography, meteorology) that apply satellite observations. The lecturers comprised a diverse body of scientists investigating and applying new methods to analyze satellite observations.

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The purpose of this report is not only to give a description of the workshop's content but also to contribute to the ongoing discussion concerning the earth sciences, the emergence of global change studies, interdisciplinary investigation and education, and the use of satellite remote sensing as a common research tool. Within the context of conducting the workshop, this report attempts to address the ability of researchers and educators to adapt to new developments, ideas, and methods taking place in the earth sciences, particularly the trend toward interdisciplinary research. The following section provides some perspective about recent trends in the earth sciences and the rationale behind conducting the workshop. Section three describes the workshop's structure and content, and in conclusion, section four discusses the workshop results, educational ramifications, and some thoughts about the future.

2. Background and rationale

Within the evolution of the earth sciences several important developments have been taking place that affect the methods by which we conduct research and train young scientists. The traditional approach to studying earth components by discipline is under examination to develop interdisciplinary methods. These new methods emphasize the dynamic and integrated nature of the earth system and investigate the physical, chemical, and biological processes within and among the oceans, atmosphere, ice and land surfaces. This approach, while stressing the importance of understanding and describing earth processes over decades to centuries, aims at predicting changes induced by natural and human activities. Satellite observations, futhermore, are becoming a standard tool for the earth sciences because of their ability to globally and continuously monitor earth processes. As a result of such developments and the concurrent increase in global earth research projects to investigate earth processes and their interactions (e.g., World Ocean Circulation Experiment, Global Ocean Flux Study), there has been a growing consensus in the earth scientific community that recomends a new interdisciplinary approach to training scientists and preparing for the future.

The need for interdisciplinary research and collaboration can be perceived today in the growing number of co-authored studies and joint research efforts among disciplines to achieve better scientific results. Air-sea interactions studies, for instance, which represent a major topic in climate studies, rely heavily upon knowledge of oceanography and meteorology. In the short term, the increasing number of global research programs demand that scientists from various disciplines work effectively together. In the long term, however, it is implicit that in order to conduct interdisciplinary science effectively, new methods for educating scientists are required. The rapid expansion of scientific knowledge and technology during the past decades, coupled with the earth system's complexity, require that methods be devised to help assimilate knowledge of the earth sciences in a comprehensive and interrelated fashion. At the same time, the traditional approach of individual research projects must give way to broader, collaborative efforts whereby individuals carve out niches and make specific contributions to solving a larger problem. Taken together, these developments point toward achieving a comprehensive understanding of the earth as a dynamic and integrated system.

For the short two week workshop on Climate and Remote Sensing, we did not attempt to address the complex issues of conducting interdisciplinary education; instead, we attempted to promote the idea of a new interdisciplinary education and took a practical approach to linking disciplines by creating a diverse workshop enrollment and structure. The workshop was designed to serve as a medium through which students from various backgrounds could expand their sphere of scientific interests by having hands-on experience and contact with other scientists. We used two common themes to unite several disciplines, namely climate and remote sensing.

Climate was selected to incorporate the interrelated and global studies of oceanic, atmospheric, cryospheric, and terrestrial processes. Coming from various disciplines and backgrounds, the participants were asked to select a specific research project related to climate studies and utilizing satellite data. Remote sensing, chosen because of its importance to the earth sciences, provided the first-hand experience required to understand the technical intricacies involved in satellite data processing and interpretation. Furthermore, it enabled participants to get a feeling for satellite data at the most basic level. Some participants, for instance, had theoretical backgrounds or were only secondary users of satellite-derived products. As a result, they had preconceived notions of remote sensing techniques, consisting in some respects of reading magnetic tapes into a black box to obtain scientific results.

3. Organization

Objectives

As mentioned previously, the workshop was designed to mix scientific theory with hands-on training in satellite remote sensing techniques. To achieve its goals, the workshop was split in two components: lectures and research projects. Given the two-week time limit, a busy daily schedule was followed that included morning and afternoon lectures and approximatly four to eight hours of satellite data processing and analysis on the California Space Institute's Oceanic and Atmospheric Satellite Imaging System (OASIS, Dealy et al., 1988). This structure was created with the following three educational and scientific objectives in mind:

1) To present a lecture series varied enough to promote a stimulating exchange of ideas between disciplines (e.g., biological and physical oceanography) and yet specific enough to provide new information to specialists.

2) To stimulate interdisciplinary education and collaboration for global, integrated research programs that apply satellite observations.
3) To promote active workshop participation through the realization of a small research project requiring processing and analysis of raw satellite data.

In addition to these were two technical objectives:

4) To construct and test a flexible, user-friendly, and comprehensive software system capable of ingesting and processing various satellite sensor data for diverse

projects.

5) To gather input and experience for developing new software tools for generic applications and education.

Lectures

Since this document is not devoted to addressing specific scientific problems but rather a general discussion concerning the workshop and interdisciplinary science, we present here only a brief outline of the lecture series and speakers.

Mark Abbott, Scripps Institution of Oceanography--Ocean Biological Activity: Discussed the Coastal Zone Color Scanner (CZCS) and its use in determining biological activity in the oceans. Interpretation of space observations of ocean color was covered. The algorithm for processing CZCS data was presented and then results of monthly mean pigment images for the period 1980 to1983 were shown to demonstrate the El Niño effect of lower pigment concentration in 1983. In conclusion, he discussed proposed future sensors, such as SeaWiFS, to be flown on Landsat-6 in the early 1990's.

Mark Anderson, California Space Institute--Sea Ice: Outlined remote sensing of the sea ice and land snow, as well as specific properties such as thickness, age, and position. The problems associated with this type of sensing were presented i.e., the need for polar orbiters, the similarity between surface brightness temperatures and clouds, the proximity between ocean surface temperature and sea ice, the persistent cloudiness in sea ice regions, and the polar seasonal darkness. Explanation was given how to overcome these problems using passive microwave sensing with its all season, all weather capability.

John Bates, California Space Institute--Sea Surface Temperature: Reviewed radiation transfer theory in the infrared and derived the multichannel approach for obtaining the sea surface temperature (SST). This included illustrating techniques for determing cloud-free data and presenting results of SST measurements using VAS and AVHRR data. He discussed strengths and weaknesses of using either VAS or AVHRR derived SSTs. Finally, a method for determining low-level moisture content from split-window measurements was introduced.

Francois Becker, NASA/Goddard Space Flight Center--Land Surface Processes: Discussed the satellite-measureable quantities and their relationship to land surface processes. These land surface processes included the water cycle, heat, radiation, and gas exchange. The differences between ocean and land observations and their respective difficulties were pointed out. The difficulties of land observations stem from the great heterogeneities of the surface along with larger diurnal variations of properties. Satellite data were specifically looked at in terms of inferring vegetation indices and soil fluxes.

Alain Chedin, Centre National de Recherche Scientifique--Physical Basis For Atmospheric Retrievals: Discussed passive remote sensing of the atmosphere and the difficulties in solving the radiative transfer equation (RTE) when using it to retrieve atmospheric profiles of temperature and moisture. The RTE's non-linearity and non-uniqueness require knowing a conditioning of the system before a stable solution can be found. This motivates the search for a method that constains the solution while not biasing it towards climatology or a forecast first guess. **Atmospheric Retrievals:** Described the "3I" (Improved Initializaton Inversion) approach to solving the RTE, which relies on a pattern recognition to indentify the most appropriate first guess. This approach uses as much *a priori* information of the system as possible to find an ensemble of similiar, already observed configurations from the "TIGR" data set (TOVS Initial Guess Retrieval) to use as initial conditions for the inversion process.

Dudley Chelton, Oregon State University--Radiative Transfer: Presented an overview of remote sensing principles, beginning with propagation of electromagnetic radiation and its interaction with matter. This was developed into fundamentals of remote sensing, specifically radiative transfer from and through the ocean and atmosphere. **Surface Winds:** Introduced basic equations of radar theory and developed three methods for measuring wind speed. These three methods, scatterometry, altimetry, and passive microwave, were described and compared.

Robert Frouin, California Space Institute--Earth Radiation Budget: Overviewed the earth's radiation budget, its components, what affects these components locally (e.g., clouds), seasonally, and zonally, and how these components are measured from satellite. The satellite sensors that are currently used for these measurements were described. Applications that use or could use radiation budget measurements were presented. These include investigations of energy transport in the ocean, sea surface and air energy exchange, climate sensitivity studies and determination of local and global climate trends.

Catherine Gautier, California Space Institute--Ocean Surface Radiation: Discussed the motivation for determining net shortwave radiation (NSW) at the surface, which is the main component of the earth heat budget and main driver of ocean circulation. The NSW impresses its seasonal and diurnal cycle on many earth processes. Radiation transfer models were discussed to demonstrate how radiation transfer equations are solved when the surface SW radiation measurements are influenced by parameters such as zenith angle, scattering, absorption, etc. Two points were noted: 1) the number of cloud layers and their vertical position are unimportant, just the amount of water in the column is important, and 2) models can describe accurately the SW radiation at the surface without requiring large amounts of daily data.

Timothy Liu, Jet Propulsion Laboratory--Surface Heat Fluxes: Described the determination of the transfer coefficient for the latent heat flux parameterization and the possibilities of obtaining the heat flux at time scales shorter than a month. He then spoke about latent heat flux effects on the SST, and illustrated some results showing anomalous events occurring during the 1982-1983 El Niño.

Jean Francois Minster, Centre National D'Etudes Spatiales/GRGS--Altimetry I & II: Described the calibration techniques of altimetric data and the removal of the geoid and orbit uncertainties for both large and mesoscale sea level variability. Measurement methods were reviewed, such as crossover and repeat track techniques, and each method's problems and virtues were discussed. Stressed the idea of using as much *a* *priori* knowledge in one's model as possible, such as known large scale features in a mesoscale model.

James Simpson, Scripps Institution of Oceanography--Objective Interpolation, Pattern Recognition and Artificial Intelligence: Described simple pattern recognition, rule based systems, and relaxation procedures. Propagation of numeric constraint within rule based systems, edge detection, and optimal interpolaton were also presented.

Robert Stewart, Scripps Institution of Oceanography and Jet Propulsion Laboratory--Accuracy of Satellite Altimetry Measurements: Discussed the error-related properties of satellite altimetry, including errors resulting from geoid measurements, orbit determination, and those associated with propagation and the instrument itself. The error determination/correction procedure for each was also examined.

George Sugihara, Scripps Institution of Oceanography-- Fractal Analysis: Discussed the need to develop quantitative tools for pattern classification and analysis using remotely sensed imagery. In particular, descriptive models are needed of spatial patterns that can be related to the dynamics of the underlying biological and physical processes occurring on the ground. Introduced fractal models and reviewed how they may be used to investigate problems of scaling in pattern analysis.

Chang Kou Tai, Scripps Institution of Oceanography-- Ocean Circulation From Altimetry: Illustrated techniques for extracting the ocean's dynamic topography from altimetry measurements. Measurement of the geoid and satellite orbit along with their associated errors and errors in propogation were described.

Although the daily schedule was full, we tried to maintain as much flexibility as possible during the workshop in order to adjust to student needs. In the case of the lectures, for instance, when a few of the biological oceanographers requested additional background in theoretical mixed-layer modeling, the following supplemental lecture was arranged and given by one of the students with expertise in the field.

Phillipe Gaspar, Centre Nationale de Recherche en Meteorology--Ocean Mixing: Reviewed oceanic mixed layer physics in terms of what the mixed layer is, why it exists, and how it can be modeled. Comparisons of integral diffusive, kinetic energy, transient, and turbulent closure models were presented. The integral model was recommended for SST determination, while the kinetic energy model was recommended for determining the depth of the mixed layer.

Projects

In an effort to solicit active participation during the workshop, all participants were required to submit an application along with a short and feasible project proposal making use of satellite data. The students were encouraged to work outside their own specialty by using unfamiliar satellite data or by studying some new phenomenon. To accomplish the projects during the two week period, the projects were refined prior to the workshop in collaboration with one of the lecturers. The last two days of the workshop were dedicated to presenting project results. An incentive for the students was to have their project results published in the workshop proceedings, with the highest quality papers, as determined by the lecturers, to be submitted for publication in the journal of Ocean-Air Interactions.

Because of the scientific and technical difficulties associated with satellite remote sensing techniques, the projects were intended to expedite the learning process by helping students through pitfalls and basic problems already encountered by other scientists. In addition to giving students a fundamental feeling for satellite data, the projects obliged them to confront all the procedural intricacies related to satellite sensor data processing. Most importantly, the projects exposed them to the characteristic and crucial problems of the satellite remote sensing tool: continually checking results along each step of the data processing while not letting the proximity to the processing interfere with the scientific problem at hand.

Presentations

With few exceptions, the students sufficiently advanced their projects so that results could be presented during the last two days. One project conducted by a group of students examined the correlation between the California Current's geostrophic velocity variability, derived from GEOSAT data, and estimates of surface velocity using the displacement of the Current's thermal patterns, derived from AVHRR infrared data. Another topic of interest among several students was estimation of the atmosphere-ocean heat flux using various approaches. For instance, students computed the latent heat flux over large regions of the ocean using SMMR data. These fluxes were used in one case to better understand the onset of the summer monsoon over India.

Using other innovative approaches, two students working independently estimated the atmosphere-ocean heat exchange by running atmospheric and oceanic boundary layer models in an inverse mode. One student's approach used the equilibrium state of a cloud-topped marine boundary layer model for conditions during the Mixed Layer Dynamics Experiment (MILDEX) to relate cloud properties observed from satellite to mixed-layer properties, such as temperature, humidity profiles, and surface fluxes. Preliminary comparisons between predicted and observed atmospheric structure were very encouraging. In the other student's approach, a fully turbulent ocean mixed-layer model was run in a simple inverse mode, forced and constrained by satellite observations of shortwave radiation and sea surface temperature, to derive the surface heat flux and upper ocean thermal structure during the Long Term Upper ocean Study (LOTUS) experiment. The upper ocean isotherm evolution during the 14-day period analyzed compared extremely well with the oceanic observations.

Using Seasat altimeter and Nimbus-7 radiometer data over the antarctic, one student examined the effects of the Katabatic Winds over the ice sheet and the consequent effects on surface emissivity observed from the passive microwave measurements. This study indicated that about 36% of the emissivity's variance results from wind speed, with 25% resulting from the direct action of wind on grain size.

Because of the importance of land surface processes to climatological and meteorological studies, two students examined the effects of atmospheric absorption and surface emissivity while determining the surface temperature from space. They proposed a method to correct for atmospheric absorbtion that involves a radiative transfer model and atmospheric retrievals from infrared sounder data. They also presented evidence for spectral variations of surface emissivity in the two AVHRR thermal infrared channels. Consequently, the split window techniques currently applied over the oceans cannot be readily applied over land.

Working as a group, five of the students endeavored to combine data from satellite sensors to make a regional map of marine primary productivity along the coast of California. They chose two different published models relating production to various environmental parameters and developed software to combine CZCS-derived chlorophyll pigment concentrations and AVHRR-derived sea surface temperatures into a single productivity image. One of the models proved quite accurate when satellite data was compared with coincident shipboard data taken in the Southern California Bight during a cruise of the Food Chain Research Group (Scripps). Such Multisensor approaches are of ever increasing importance for synoptic observation and study of complex earth process interrelationships.

4. Results, Educational Experience, and Future

As organizers of the workshop, we were naturally anxious about the outcome. As in any meeting, organizers take risks when preparing an ambitious and demanding program, hoping in the end their efforts will be successful and appreciated. When the presentation concerns education, however, the results can be viewed more critically. To help us interpret the workshop's results and determine how well we achieved our educational objectives, we sent out a questionnaire to all the student participants. The overall response to the workshop was favorable, with essentially all agreeing that such workshops should be held on an annual or biannual basis. Such a positive response to the spirit of the workshop, however, should not conceal some of its shortcomings and logistic problems. It is not a simple task to conduct a successful workshop, create a congenial working atmosphere, promote interaction among the different personalities, and supply all the necessary working facilities.

The two biggest problems during the workshop were the large number of students and the short two week time limit. Because of the many highly qualified applicants, intriguing research proposals, and a number of late applications, we became less strict with our participation limit. We finally accepted thirty five students, ten over our original limit. As a result, an excessive burden was placed upon both staff and facilities. With everything running a little bit slower, especially the computers, the two week period became more restrictive.

Projects

The most positive and negative criticisms about the workshop concerned accomplishing the research project. Overall the students were extremely enthusiastic and devoted a surprising amount of time and effort to complete their projects. After the first day's introductory lectures, participants quickly got to work on the computers, which instilled a friendly competitiveness to achieve results before the workshop's end. During the workshop's last days many students worked around the clock to finish their projects. Some of the enthusiasm to complete the projects derived from a sincere desire for hands-on experience and limited access to remote sensing tools (i.e. hardware, software, and data) at their home institutions. All the participants felt that the hands-on experience offered an effective and enjoyable means by which to learn satellite analysis and processing techniques.

While working on the projects some students were occasionally frustrated by the overburdened computer system and processing difficulties. In order to facilitate the first days of processing, we ingested as many of the satellite data sets as possible onto the system prior to the workshop and tested most of the application software. We also supplied documentation covering the operating system and the application software, but often it was not read, with people prefering to learn by doing. Even though people adapted quickly to the user-friendly system, a handful of participants realized that, in order to effectively accomplish the projects during the two weeks, more project preparation should have been completed before arriving to alleviate the last minute software modification and data manipulation.

There were a few deficiencies in areas of the on-line application software. Given a number of our own constraints, we were unable to foresee some of the problems that eventually took place. For instance, despite many hours of programmer effort, a couple of data tapes could not be read on the system due to unrecognizable data formats. We also ran into problems with our operational software when we tried using it with new data sets.

All things considered, the system stood up reasonably well to the thirty five users and various projects. One of workshop's goals, nonetheless, was to test our system's capability to ingest and process various satellite sensor data and to obtain input for developing new software tools for generic applications and education. The workshop reinforced the idea that such a system is functional, especially for educational use, if it incorporates simplicity (e.g. online help), flexibility, modularity, and compatibility. These qualites are essential in order to spend less time gathering, ingesting, and processing the often unstandard data formats and varying sensor resolutions. As a result, they allow quicker scientific interpretation, new software integration, and standardization among geometrical corrections and grids.

Lectures

Throughout the workshop the lectures ran the smoothest and were least affected by the high attendance. The lectures incorporated varying levels of expertise and were generally well prepared and presented. While it is implicitly difficult to please all the people all the time, the questionnaire responses demonstrated that the lectures were informative for the audience at large and yet (most of the time) specific enough for specialists. As an example of the difficulty in trying to please, one student stated his displeasure with the lectures being interrupted by questions, while another student said that the flexibility in answering questions during the lectures was particularly helpful. Although few students felt that the lectures directly aided in accomplishing their research projects during the workshop, they said the lectures provided an excellent overview of the "state of the art" and introduced them to innovative topics, such as pattern recognition and fractal analysis. Moreover, they were exposed to unfamiliar research areas and different investigating approaches.

A little surprisingly, two participants felt that some lecturers, while getting stuck on technical details, tended to ignore addressing the problems and limitations of remote sensing and how best to apply it scientifically. Although these sorts of shortcomings in the lectures were usually compensated by project work, the workshop as a whole illustrated how the intricacies of remote sensing represent an important issue. A few lecturers were grateful for the exposure to their collegues' work and problems. One lecturer, for instance, after listening to a lecture outside his domain and working with one student using the unfamiliar satellite data, expressed his astonishment at how unmanageable the satellite data were. This difficulty, he said, could not be appreciated without firsthand experience and is something usually not addressed in published papers.

On a more organizational note, many students recommended that preprinted lecture notes be supplied prior to the lectures. Even though we supplied copies of the speakers' tranparencies before and sometimes just after the lectures, students still felt that in order to help assimilate the large amount of material, more detailed outlines were needed. Furthermore, it was felt that lecture notes could help present a quick introduction and background to the subject, which some of the lectures overlooked. Parts of the lectures were overlapping, and a look at the lecture schedule reveals a particular emphasis upon altimetry. This was in part due to the workshop's Franco-American sponsorship, which slightly biased it toward altimetry because of the upcoming joint Ocean Topography Experiment mission (TOPEX/POSEIDON).

To organize the lectures we invited noted scientists to lecture on their field of remote sensing expertise. This may have been a slight oversight from the workshop point of view because several participants commented that there was not enough cohesiveness between the lectures and projects. They suggested that the projects should have been structured around prearranged computer tutorials dealing with specific scientific problems and aspects of remote sensing. Different tutorials, for example, could deal with various data sets, e.g. AVHRR, CZCS, and SMMR. In turn, the tutorials could be directly related to the lectures, and each could be prepared with the other in mind. Consequently, less time would be spent on data and program manipulation and more time on scientific understanding and interpretation.

The question of including short turtorials has mixed benefits. On the one hand, structuring the projects around prearranged tutorials with so-called "canned" programs would have severely limited freedom and ingenuity during the workshop. Morever, it may not have conveyed an accurate picture of remote sensing, as a sometimes intractable scientific tool, with its occasionally fading sensors and incompatible data set resolutions. A previous outside user of satellite observations commented, for instance, upon his amazement with how many things could go wrong and how long analyses actually take.

On the other hand, in retrospect we are convinced that in order to conduct an effective workshop that emphasizes collaboration and interaction, an initial group structure is needed. Although prearranged tutorials might have been too restrictive, it seems that lectures and prearranged working groups based on themes or research areas could have stimulated even more collaboration and interaction among the participants. Organizing working groups under themes aimed at promoting interdisciplinary research could have served to generate more interaction. Such an arrangement would also allow individuals to concentrate on areas of interest and work with others, while permitting the lectures to remain general enough for all participants to have a broad overview. In addition, more time could be efficiently spent analyzing the scientific questions and working with one of the assigned lecturers.

Presentations

The last two days of the workshop were devoted entirely to the presentations. Each presentation lasted about fifteen to twenty minutes and was followed by suggestions and comments from lecturers and students not directly involved in the work. The presentations tested the students' ability to present their work in a clear and concise manner and provided a valuble forum for exchanging ideas and technical approaches among the various disciplines.

During the workshop the presentations served as the best setting to familiarize oneself with other students' work and to exchange ideas. Unfortunately, as this took place on the last two days, it became clear that many students were unfamiliar with other people's work. This shortcoming was not entirely due to poor organization; it does, however, illustrate another difficulty in organization, namely that despite the best intentions to structure the workshop, some students' preparation was incomplete. Prior to the workshop we distributed abstracts of all the proposed projects, but in general these were not read. Nonetheless, several students complained about learning too late of other students' related or similar projects. With hindsight, it appears that perhaps the first day should also have included a brief introduction to each person's proposed work.

As another example of difficulties in workshop organization, one question on the questionnaire asked: With the perspective you now have, was it a reasonable idea to work on a research project and present your results during the workshop? The majority answered yes but still objected to either the time restrictions or lack of project preparation. One student, however, responded differently by saying, "It was not the idea to include a project that had to be reasonable; our project had to be reasonable." The person added, "I think that one of the reasons for the workshop was precisely to find a reasonable subject. This taught us to learn our limits and to evaluate our capacities over a given time period."

General structure

Something should be said about accomodation and working conditions. If interdisciplinary science and collaborative research projects are to be productive, it is necessary to pay attention to the working environment. In a workshop setting, where unfamiliar people with varying personalities, professional experiences, and backgrounds come together to collaborate, it is extremely important to instill an easy going and comfortable atmosphere from the start. For us, as is often the case, the workshop became most effective and appreciated during the last few days. After people became less inhibited and more familiar with one another, they began talking and exchanging ideas. In the questionnaire many people regretted that they had not taken more advantage of the opportunity to communicate, and those who did were very grateful for it.

A productive and intense working environment is disrupted if participants are inconvenienced by lodging or other logistic problems. In our case, we were somewhat limited in providing the most convenient atmosphere by budget restrictions and the university's remote facilities. Nevertheless, what we want to emphasize here is the need to instigate communication and bring people together because they may not always do so themselves. Moreover, measures can be taken to help foster a congenial working atmosphere and spark discussion. One participant, for instance, suggested that informal afternoon teas be held that focus on scientific discussion.

It is of course impossible to force group cooperation, and in any group setting there will be both quiet and outspoken people with varying levels of expertise. Some participants will always desire to lead and organize, while others will be more inclined to work alone or follow the lead of others. Collaboration, however, does not necessitate equality among the group members. When productive, synergistic work is accomplished with group participants teaching and sharing their knowledge with others, then interdisciplinary research will become unmatched.

Conclusion

Our intention in hosting the workshop was to obtain a better understanding of how to prepare for the future in the earth sciences and for the various interdisciplinary-global change research projects. By conducting the workshop we desired to gain a clearer perspective of the status of earth science education, its present strengths and weaknesses, and its ability to prepare young scientists for the enormous challenges the many interdisciplinary-global change experiments pose. Although the workshop provided both students and organizers with a beneficial first experience in the new domain of interdisciplinary education, it left us with many questions.

The past five years, for instance, have produced marked advances in the organization and implementation of interdisciplinary science and global change studies. With strong leadership having been taken by national and international scientific agencies, comprehensive strategies have been put forth, specific goals set, programs enacted, and groups formed. While these laudable and challenging measures have been taken, it is apparent that less effort and attention has been paid to devising concurrent educational strategies to complement the many ambitious global earth system projects and address the problems they present. A few universities, however, have taken initiatives to de-emphasize departmental division, subdivision, and specialization within and among the sciences (e.g., biology, marine biology) by uniting them under the umbrella of earth system science or similar departments.

This approach of uniting the earth sciences seems most practical for the short-term, but is it sufficient for the long-term? That is, instead of creating union through the de-emphasis of existing departmental division and specialization, would it better to build bridges and links among them? Or, is some completely new approach needed in order to adapt earth science education to future global research projects? In any case, answering such questions requires as much thought and planning as the future earth system science, global change projects themselves. Without a clearer recognition of the present educational system's limitations and weaknesses, as well as its strengths, and, more importantly, without a more precise definition of an interdisciplinary curriculum, future scientists might find themselves with wonderful opportunities but lacking the proper training and tools.

In closing, if future research projects investigating global change and the earth system are to be successful, it is imperative that reseachers understand each other's scientific contribution and collaborate effectively. To that end, the workshop afforded many students an initial cooperative research experience and an occasion to work as a team. It also allowed them to appreciate other people's work and expertise, which, without prior experience, is sometimes difficult to do. As in any first time experiment, we have learned from our mistakes and are now in a better position for the next time. Although the two week workshop could hardly be considered comprehensive interdisciplinary education, it was a positive step forward. The participants' favorable response to the workshop and the collaboration that has been initiated as a result of it encourages us to continue this type of interdisciplinary work and reaffirms that such eduction is not only needed, but headed in the right direction.

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List of acronyms

AVHRR - Advanced Very High Resolution Radiometer
CZCS - Coastal Zone Color Scanner
LOTUS - Long Term Upper Ocean Study
MILDEX -Mixed Layer Dynamics Experiment
OASIS - Oceanic and Atmospheric Satellite Imaging System
RTE - Radiative Transfer Equation
SMMR - Scanning Multichannel Microwave Radiometer
SST - Sea Surface Temperature
TIGR - TOVS Initial Guess Retrieval
TIROS - Television Infrared Observational Satellite
TOVS - TIROS Operational Vertical Sounder
VAS - VISSR Atmospheric Sounder
VISSR - Visible and Infrared Spin Scan Radiometer
3I - Improved Initialization Inversion