

3D Time Dependent Stokes Vector Radiative Transfer in an Atmosphere-Ocean System Including a Stochastic Interface

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LONG-TERM GOALS

The major objective of this proposal is to calculate the 3-D, time dependent radiation field both within the ocean and in the atmosphere in the presence of a stochastically varying interface which may also be perturbed by sea foam, air bubbles, surfactants, rain, etc. This study will serve as the genesis to the future evolution of an inversion algorithm whereby one could reconstruct images that have been distorted by the interface between the atmosphere and the ocean or the ocean itself. This study will rely heavily on both the spectral and polarimetric properties of the radiation field to deduce both the sea state and the perturbations produced on it. A second phase of this study will be to explore the asymptotic polarized light field and to determine how much information can be obtained about the IOP's of the medium by measuring it. The third phase of this proposal will deal with the problem of improving image resolution in the ocean using some novel polarimetric techniques that we are just beginning to explore. Once these studies have been completed using a passive source, it will be rather straightforward to extend them to active sources where we can explore the use of both photo-acoustic and ultrasound-modulated optical tomography to improve image resolution.

OBJECTIVES

The new Navy initiative is focusing on one of the most formidable problems in radiative transfer theory; namely, calculating the full 3D time dependent radiation field (with full Mueller matrix treatment) in a coupled atmosphere-ocean system where the boundary separating the two has both spatial and temporal dependence. Although a great deal of work has been done on obtaining power spectra for ocean waves, I know of no work that has yielded similar results for the radiation field within the ocean. It is clear that as long as the surface has a significant effect on the internal light field, it will leave its signature on the radiation field within the ocean and the relative strength of this field compared to the ambient field will determine the success or failure of inversion algorithms. However, as we go deeper within the ocean we start to enter a region called the asymptotic region where all photons lose memory of their origin and the light field then remains stationary and becomes independent of the azimuthal angle. The depth dependence becomes simply exponential, i.e. $L(z+h, \theta) = L(z, \theta) \exp(-kh)$ where k is called the diffusion exponent. It should be noted at this juncture that this asymptotic light field is still polarized which is why we used the bold-faced vector notation. We were the first to compute the degree of polarization for this asymptotic light field for Rayleigh scattering and

Report Documentation Page				Form Approved OMB No. 0704-0188	
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1. REPORT DATE 2009		2. REPORT TYPE		3. DATES COVERED 00-00-2009 to 00-00-2009	
4. TITLE AND SUBTITLE 3D Time Dependent Stokes Vector Radiative Transfer in an Atmosphere-Ocean System Including a Stochastic Interface				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Texas A&M University, Dept. of Physics, College Station, TX, 77843-4242				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report (SAR)	18. NUMBER OF PAGES 11	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

were able to obtain an analytic expression for both the polarized radiation field and the diffusion exponent (see ref. 1). In addition, we were also able to set up a numerical scheme to compute the polarized radiation field as well as the diffusion exponent for any single scattering Mueller matrix. The interesting feature about the asymptotic light field is that it depends profoundly on both the single scattering albedo as well as the phase function of the medium. We also found that substantial errors will occur in both the ordinary radiance and the diffusion exponent if they are calculated from scalar rather than vector theory

APPROACH

There are several stages to our approach that we will enumerate. The sine qua non for this entire project will be the development of a fully time dependent 3-D code capable of calculating the complete radiation field, i.e. the complete Mueller or Green matrix at any point within the atmosphere-ocean system. This of course implies that both horizontal as well as vertical IOP's must be accounted for. It should also be noted that the code must be capable of handling internal sources as well in order to explore both fluorescence and bioluminescence. At present there are several 3D codes that are able to compute various radiometric quantities in inhomogeneous media; however, as far as we know, none exists which will couple both atmosphere and ocean with a time dependent stochastic interface. One of the earliest 3D radiative transfer (RT) codes was developed by Stenholm, et. al² to model thermal emission from spherical and non-spherical dust clouds. It was based on an implicit discretization of the transfer equation in Cartesian frames. To our knowledge, the first 3D-scalar RT code using discrete ordinates was written by Sánchez³ et al.; however, it did not make use of spherical harmonics and lacked efficiency and accuracy particularly for small viewing angles. The addition of polarization to the 3D discrete ordinates method was done by Haferman⁴ et al. Almost concurrently, a 3D-scalar RT code was written by K. F. Evans⁵ which used both spherical harmonics and discrete ordinates. This method uses a spherical harmonic angular representation to reduce memory and CPU time in computing the source function and then the RT equation is integrated along discrete ordinates through a spatial grid to model the radiation streams. We have already obtained this code and will use it for validation of our 3D scalar Monte Carlo code for both the atmosphere and ocean components. Several Monte Carlo codes both scalar and vector have been published for solving specialized problems in atmospheric optics usually dealing with finite clouds^{6,7,8,9}. Without exception, these codes are using quite primitive, also called "brute force", methods. None of them will do what we are proposing in our approach to the fully time dependent 3D solution applicable to both atmosphere and ocean. It should be mentioned that we have already successfully added to our Green matrix Monte Carlo code the capability to handle internal sources such as fluorescence, bioluminescence and even thermal emission.

Once we have developed our 3D code to handle both the ocean and atmosphere without the interface included, we will then develop a 3D form of 1D matrix operator theory that we worked out in two seminal papers published in Applied Optics^{10,11}. The basic idea of the method is that if one knows the reflection and transmission operators of say two layers, then it is rather straightforward to get the reflection and transmission operators for the combined layer. With this method we can start from an infinitesimal layer and build large and even semi-infinite layers in a rapid way, i.e. if we start with a layer of thickness Δ then in N steps we can reach a thickness of $2^N \Delta$. Another very relevant feature of this method is that it will allow us to add the interface to the "bare" ocean, i.e., one without an interface, to get the combined ocean-interface operator and then add this layer to the atmosphere for the final reflection and transmission operators for the combined system. The question immediately arises is why not solve the entire system at the same time? The answer is that by doing it this way we only have to use the adding feature to combine the time dependent interface thus avoiding performing

the entire calculation at each instant in time. This method has also become known as the adding-doubling method. These operators are effectively the impulse response or Green matrix for the upper and lower boundaries of the medium. Therefore, if we know the external radiance input into both upper and lower layers, we can then obtain the output at both the upper and lower boundaries of the combined system. A pictorial description of the method is shown in Fig. 1. It should be emphasized that this method will also handle internal sources as well such as bioluminescence, fluorescence, and even thermal emission. This method can also handle detectors at any interior point in the medium. Another bonus of matrix operator theory is that one can easily obtain the path radiance between source and detector which is a sine qua non for image analysis.

In order to add a interface which is spatially inhomogeneous in the y direction but homogeneous in the x direction, we will need the reflection (R) and transmission (T) operators for both the atmosphere and ocean now as a function of time t and both z and y ; namely $R(y-y_0, z, t, \theta, \phi)$ and similarly for T . It is important to note that we only have to obtain the response of the atmosphere or ocean to a single line source at the point y_0 and then using the translational invariance of the medium in the y -direction will have the reflection and transmission operators at every point in the y -direction. The only method we know to create these 2-D operators is Monte Carlo. Once these are obtained, we can use the output from each layer as the input to the surface boundary whose reflection and transmission properties are either known or calculable. For instance if the surface consists of just capillary or gravity waves, then we just need the Fresnel coefficients to give us the requisite reflection and transmission operators for the interface. Now once these operators are obtained then we can use extended matrix operator theory to get the final time dependent radiation field that a detector will see. Let us consider the simplest case where the surface is 1-D and we know its power spectrum. It should be emphasized at this point that it is not sufficient to have just a wave-slope distribution since it will only give us statistically averaged results for the radiance field. The introduction of the spatial and temporal dependent interface destroys the symmetry and makes all 1-D codes essentially useless in this domain. At each instant in time, the surface will have a distinct shape that will evolve in time. We have developed a method using linear filter theory whereby we can take an ocean power spectrum and using a random number generator create a realistic surface that will match the original power spectrum and will still exhibit both stationarity and ergodicity. Now the nice feature about what we are proposing is that we can now concentrate on just the effects of the surface on the detectors since as the surface evolves in time so too will the radiance field as recorded by the detectors. Now both the spatial and temporal profiles will be constantly changing; however, we will have created them from a medium which has been assumed stationary and only the interface produces the time dependence and the horizontal spatial inhomogeneities, i.e. the R and T operators for both the atmosphere and ocean need only to be computed **once**. This is clearly a first-order solution to the more complex problem; however, it should tell us a great deal about future complexities of inversion and also the efficacy of pursuing the next level of difficulty. If the surface is perturbed by foam, bubbles, etc. then these can be added and the matrix operator theory will be used to calculate the effective reflection and transmission operators of the perturbed surface. It should also be stated that this project is enormously computationally intensive; however, the type of codes we will produce are ideally suited for large-scale parallel processors, which we do have access to.

The next level of difficulty is where we will use Monte Carlo methods to compute a full 3-D distribution of the time dependent radiation field, which now may include 3-D inhomogeneities in both the ocean and atmosphere. This will be a computational tour de force requiring a major new computer program that must be capable of placing IOP's of both the atmosphere and ocean at each point in a large 3-D grid. Matrix operator theory will again be used but it will now be much more complicated

since our reflection and transmission operators now become functions of three spatial variables. In fact, the complete solution to this problem could approach the complexity of the general circulation models used in weather forecasting. Due to the large volume of data that will be generated, we will clearly have to develop methods to easily display animated sequences of this time dependence.

These projects were worked on by Dr. Pengwang Zhai, who left for NASA Langley Research Center in August of 2008, and are now being worked on by Dr. Yu You, a postdoctoral research associate.

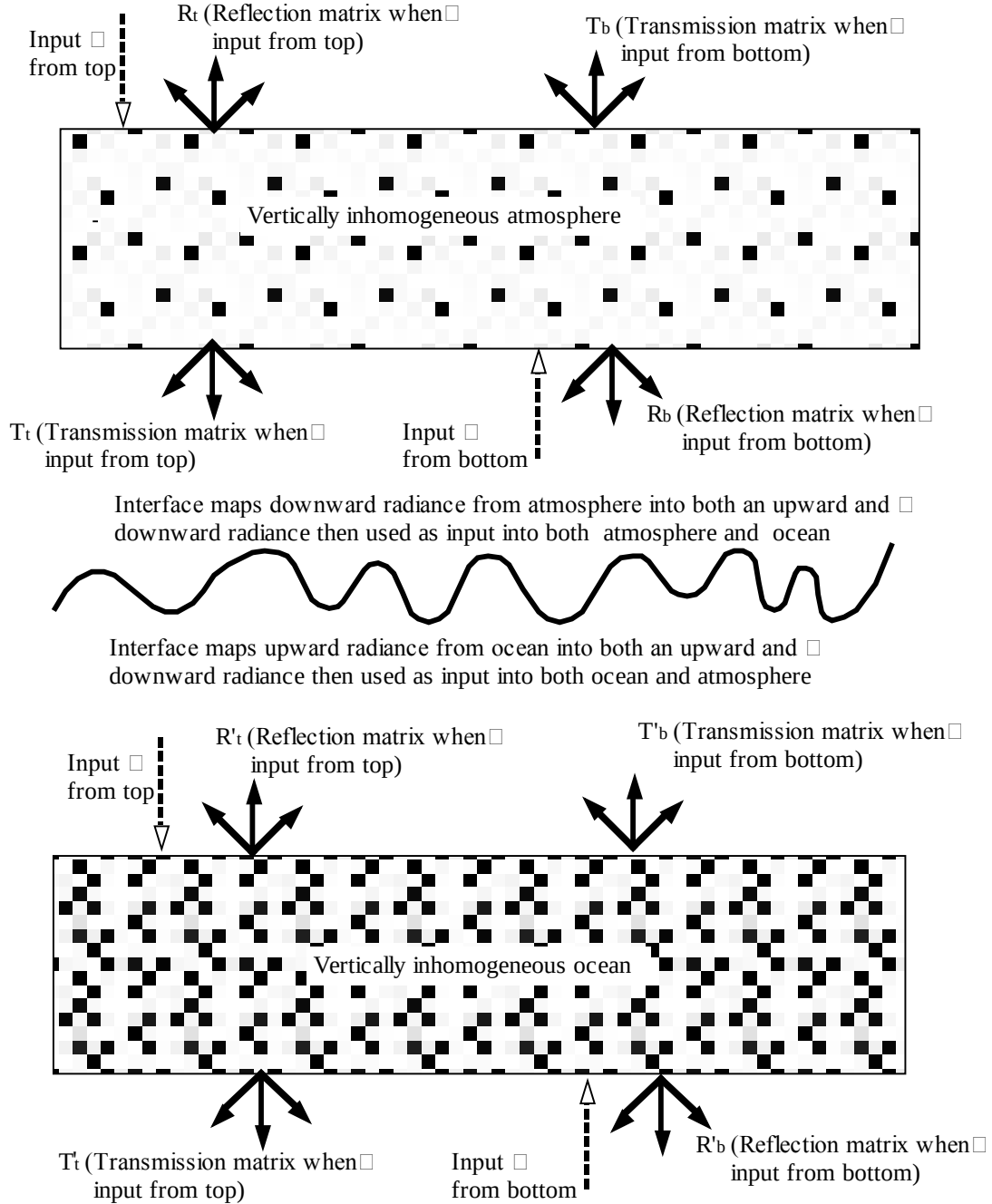


Fig.1 Schematic representation on the use of matrix operator theory to calculate the time dependent radiation field within the ocean

WORK COMPLETED

- a) We have investigated the scattering and radiative properties of mineral dust aerosols at violet-to-blue and red wavelengths, as well as the effect of including full polarization treatment in forward radiative transfer simulation on dust property retrieval. A paper on this work has been published in *J. of Aerosol Sci.*, 40, 776-789 (2009).
- b) We have investigated the influence of the assumed ice particle microphysical and optical model on inferring ice cloud optical thickness (τ) from satellite measurements of the Earth's reflected shortwave radiance. A paper on this work has been published in *Atmos. Chem. Phys.*, 9, pp. 7115-7129 (2009).
- c) We have studied the single-scattering properties of inhomogeneous ice crystals containing air bubbles using a combination of the ray-tracing technique and the Monte-Carlo method. A paper on this work has been published in *J. Geophys. Res.*, 114, D11203 (2009).
- d) We have completed a study of an invisibility cloaking design using metamaterial, and have numerically confirmed the cloaking effect of the design using the generalized discrete-dipole approximation (DDA) method. A paper on this work has been published in *Optics Express*, 17, 6591-6599 (2009).
- e) We have completed an investigation of the single-scattering properties of randomly oriented triaxial ellipsoids with size parameters from the Rayleigh to geometric-optics regimes using a combination of the DDA technique and an improved geometric optics method (IGOM). A paper on this work has been published in *Applied Optics*, 48, 114-126 (2009).
- f) We have applied the previously developed hybrid matrix operator–Monte Carlo (HMOMC) method to simulations of time series of polarized light fields under dynamic surface waves, as well as time series of the underwater image of an object above the ocean surface. A paper on this work has been published in *Applied Optics*, 48, pp. 3019-3029 (2009).
- g) We have completed simulations of the color ratio associated with the backscattering of radiation by ice crystals at 0.532 and 1.064- μm wavelengths. A paper on this work has been accepted for publication in *J. Geophys. Res.*
- h) We have developed a fast radiative transfer model for simulating the temporal fluctuations of the underwater downward irradiance in shallow waters due to the focusing effect of surface waves. We have applied this model to simulations of irradiance in water bodies with the same IOPs as those measured during the Santa Barbara Channel cruise, and have achieved impressive consistency between the model-simulated and measured temporal variance and flash statistics in the downward irradiance. A paper on this work is in preparation.

RESULTS

- a) Using the previously-developed HMOMC method, we have simulated the dynamic variations in the radiance and polarization fields in shallow waters under a wind-driven ocean. Our 3-D radiative transfer simulations assumed a coupled-atmosphere-ocean system, where the atmosphere and ocean both had a physical depth of 10 m, and had an optical depth of 0.25 and 10, respectively. The

atmospheric scattering was described by the Rayleigh phase matrix, while the oceanic scattering was governed by the Henyey-Greenstein phase function with an asymmetry parameter of $g = 0.95$, and all other elements of the oceanic phase matrix were determined by letting the elements of the reduced phase matrix ($\tilde{P}_{ij} = P_{ij} / P_{11}$) be equal to those of the reduced Rayleigh phase matrix. A single scattering albedo of 0.5 was assumed for the atmosphere, the ocean and the Lambertian ocean bottom. The ocean surface waves are generated by the power spectral density (PSD) method that includes both gravity waves and swells assuming a surface wind speed of 10 m/s (Fig. 1). Here we can see the propagation of the swells from right to left. In the simulations, the sun was at the zenith, and the detectors were set to measure the downward polarized radiance field. We had an array of nine detectors at the same level around the center of the computational domain, which has an area of 21 m by 21 m.

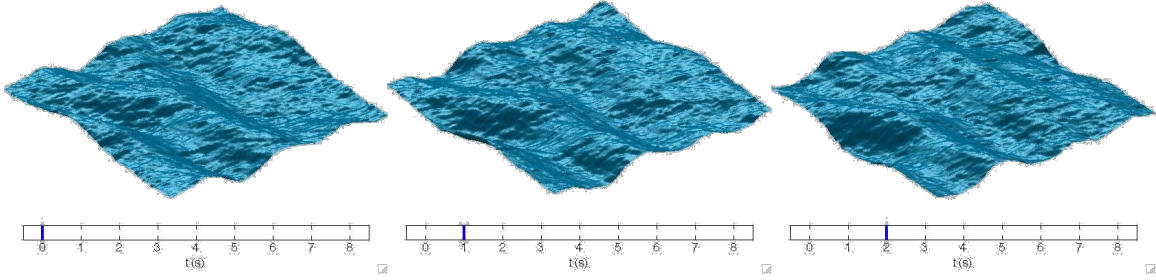


Fig. 1. The hypothetical wind-driven ocean waves used in the simulation of the underwater radiance and polarization fields. Simulations were for a temporal evolution over a time duration of 8 seconds with a frame rate of 5 frames per second, and shown here are snapshots at $t = 0, 1$ and 2 seconds. The wind speed was 10 m/s. The area of the surface patch is 21 m by 21 m.

Figure 2 shows the observed angular distributions of downward radiance (or the I component of the Stokes vector, upper panel) and the downward degree of polarization U/I (lower panel) when the detectors are just below the ocean surface (optical depth $\square_{\text{det}} = 0.001$). For each pixel of the image, the magnitude of the radiance is shown by a color. A pixel at the center shows the radiance with a polar angle of 180° and a pixel at the outer edge shows the radiance with a polar angle of 90° . A pixel's azimuthal angle shows the corresponding azimuthal angle of the radiance. The bright regions with sharp boundaries in the radiance patterns are the Snell cone—the region that the sky radiance can reach. Figure 3 shows the same angular distributions, but for a detector at a greater optical depth $\square_{\text{det}} = 5$. The results shown in Fig. 2 suggest that the polarized light field just below the surface changes drastically over time as a result of the movement of the dynamic surface waves. These changes are pronounced in the distributions of both the radiance and the degree of polarization. On the other hand, at a relatively large depth of $\square_{\text{det}} = 5$, the temporal variations in the distribution of radiance are substantially reduced as multiple scattering in the ocean has smoothed out most of the surface effects and blurred the Snell cone; however, the distribution of the degree of polarization still shows intense temporal variations originated from the surface waves (Fig. 3).

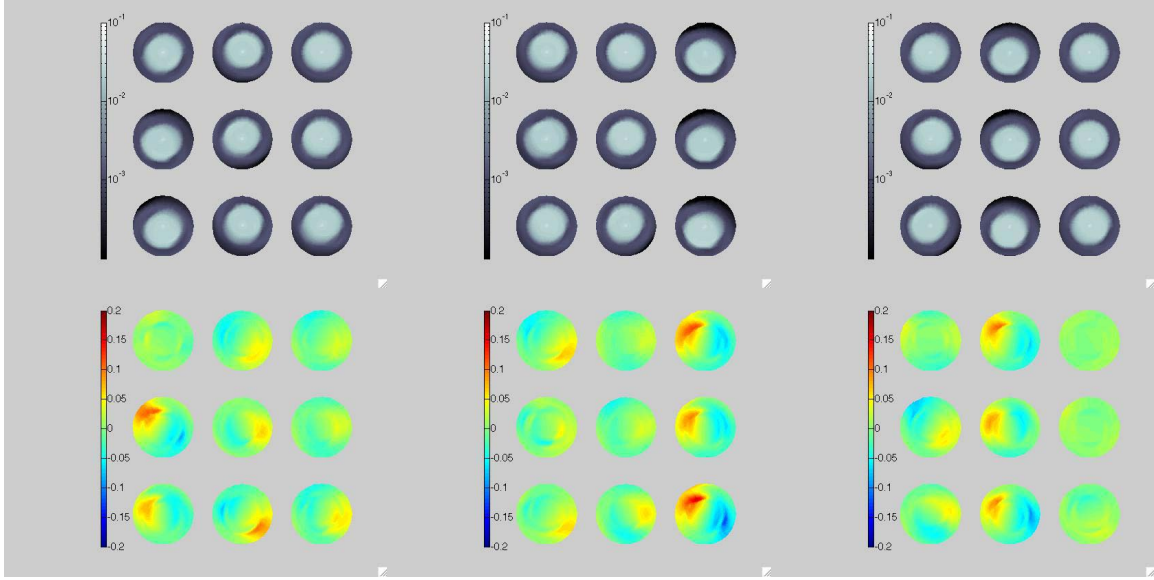


Fig. 2. Snapshots from a time series of the angular distributions of the downward radiance or the I component of the Stokes vector (upper panel) as well as the downward degree of polarization U/I (lower panel) at nine detectors just below the ocean surface with $\tau_{det} = 0.001$. The three columns correspond to the three time instances shown in Fig. 1.

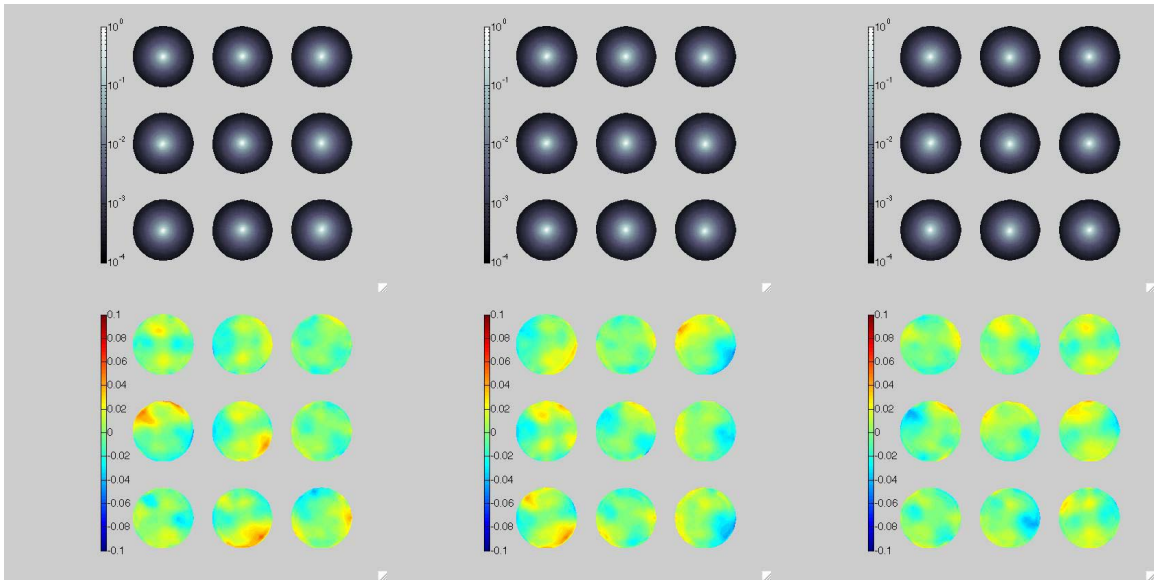


Fig. 3. Same as Fig. 2, but for detectors at a greater optical depth, $\tau_{det} = 5$, below the ocean surface.

- b) We have used the fast irradiance model to simulate the temporal variance and flash statistics in the downward irradiance in shallow waters, and compared them with their counterparts from measurements. In the fast model, only the first-order terms are kept in the matrix operator algorithm and the computational time is substantially reduced. This enables us to run simulations with extremely high temporal and spatial resolutions comparable to those in field measurements. The Rayleigh phase matrix is chosen for the conservative atmosphere, and the optical thickness of the atmosphere is determined by an empirical atmosphere model. Measured ocean IOPs from

Stramski (University of California at San Diego) and Darecki (Polish Academy of Sciences) were used as inputs to the modeled ocean; measured wind speed was used to generate the wind-driven ocean surface waves using the aforementioned power spectral density (PSD) method. In this study, we only considered capillary-gravity and gravity waves. We assumed a 2 meters by 2 meters computational domain with a spatial resolution of 2.5 millimeters. The temporal resolution was 1 millisecond such that the results can be comparable to the measurements with a sampling rate of 1 kHz. We have simulated time series of irradiance at three detector depths, $z = 0.87$ m, 1.70 m and 2.85 m, and at three wavelength, $\lambda = 443$ nm, 532 nm and 670 nm. A 10-minute time series was simulated for each combination of detector depth and wavelength. The results are compared with their counterparts measured by Stramski and Darecki on September 11, 2008. Figure 4 shows comparisons of the normalized downward irradiance from model simulations and from Santa Barbara Channel measurements in the green channel, $\lambda = 532$ nm. From these 20-second segments, similarity between the simulated and measured temporal variances is obvious at the same depth. Specifically, we can see irradiance “flashes” up to around 6, 4 and 2 times the mean irradiance $\langle E_d \rangle$ at the three depths, respectively.

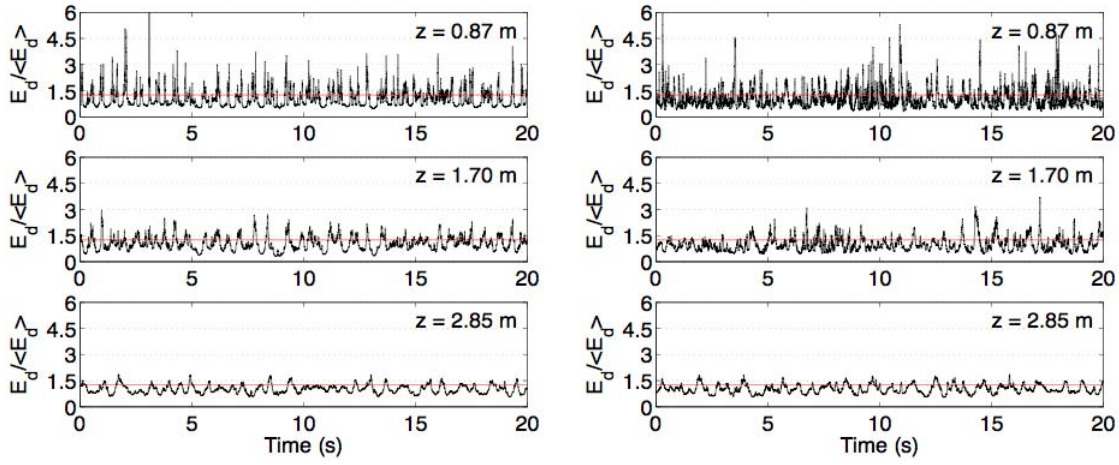


Fig. 4. Time-series of normalized downward irradiance $E_d(t)/\langle E_d \rangle$ from the model simulation (left) and from the Santa Barbara Channel measurement (right). Shown are results in the green channel, $\lambda = 532$ nm.

We have analyzed the flash statistics in the modeled time series of downward irradiance and compared them with those from measured data. Previous studies have shown that there is a simple exponential relationship between the frequency of flashes N and the thresholding irradiance E_{ds} , $N = N_0 e^{-AE_{ds}}$. Figure 5 shows comparisons of the frequency of flashes (left), the slope parameter A (center) and the mean flash duration (right) from model simulations and measurements. It is obvious that the model-simulated flash statistics are consistent with the measured ones.

In addition, we have also investigated the frequency content of the irradiance fluctuations via their spectral density (Fig. 6). The frequency contents of the measured and simulated signals are in good agreement for frequency components faster than several Hertz. The dominant frequencies from the measured and simulated data agree very well. It can be noticed that the simulated signals have less fluctuations with frequencies slower than 1 Hz, especially at $z = 0.87$ m and 1.70 m. This is probably due to the neglect of swells in the PSD-generated surface waves. The above results

confirmed that the fast irradiance model is capable of predicting the high-frequency temporal variations in the light field in shallow waters.

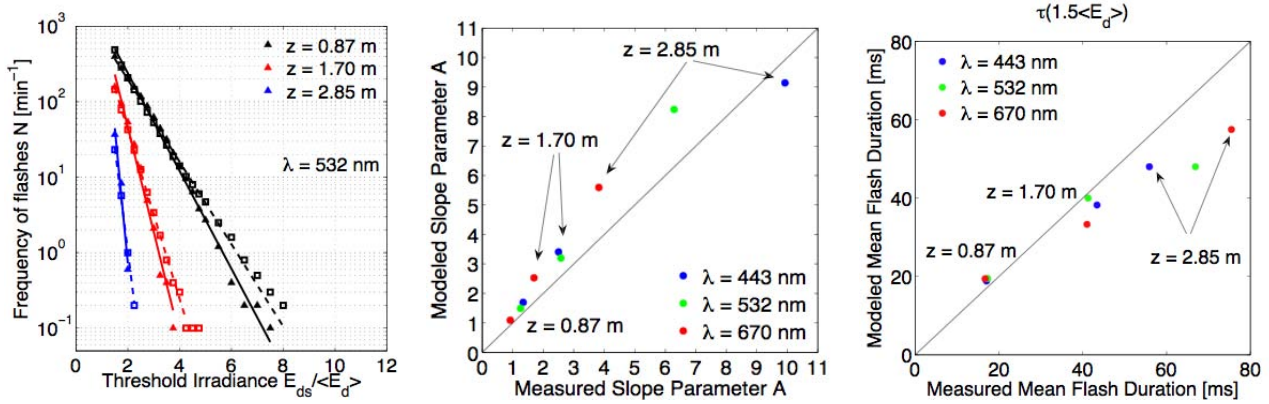


Fig. 5. *Left: Comparison of the frequency of flashes N as a function of the thresholding irradiance computed from model simulations (solid triangles) and measurements (open squares) at 532 nm as well as the corresponding exponential relations from the least squares fitting; center: comparison of the slope parameter A calculated from model simulations and measurements; right: comparison of the mean flash duration for the thresholding irradiance $1.5\langle E_d \rangle$ calculated from model simulations and measurements.*

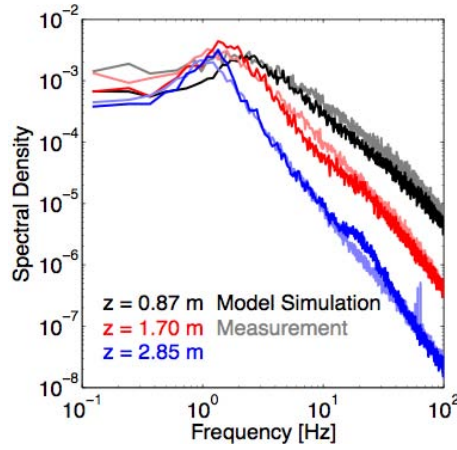


Fig. 6. *Spectral densities of the fluctuation in the irradiance time-series at $\lambda = 532$ nm, computed from measurements (light colors) and model simulations (dark colors).*

IMPACT/APPLICATION

The HMOMC code and the fast irradiance code will become powerful tools to investigate the effects of a dynamic wave profile on the radiance field, especially on the polarization states and fast fluctuations of the light field. The fast irradiance code will also be helpful in understanding the fast-varying environment surrounding ocean creatures, which is part of an ONR funded MURI project on underwater camouflage.

TRANSITIONS

Due to the efficiency and versatility of this new code, it will be directly applicable to understanding one of the most formidable problems in global warming, i.e. the effect of broken clouds on the reflectivity of the atmosphere. My colleague, Dr. Ping Yang in the Department of Atmospheric Sciences at TAMU, will use it to interpret the measurements of the satellites, Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO), Moderate Resolution Imaging Spectroradiometer (MODIS), and Polarization and Directionality of the Earth's Reflectances (POLDER). This code can also be used in biomedical studies, such as numerical simulations of the light propagation in skin tissue.

RELATED PROJECTS

We use the results from our other ONR Grant to use as input to our codes in the RaDyO study.

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