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Ocean Optics XVI, 2002

OPTICAL IMPACTS ON SOLAR TRANSMISSION IN COASTAL WATERS

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ABSTRACT

The quantification of transmission of solar energy is important for assessment of ocean radiant heating and primary productivity. Upper ocean physical processes and optical parameters have been shown to affect solar transmission through the alteration of the in-water solar attenuation coefficient and the sea surface albedo. In the open ocean, models indicate that cloud cover, solar zenith angle, and chlorophyll concentration have the largest effects on solar transmission. Studies of the influences of coastal ocean processes on solar transmission have been limited until recently.

We utilize an extensive time series data set of physical and optical measurements to characterize the physical processes and optical parameters that contribute to the variability of solar transmission through the upper water column in coastal waters. The data were collected on a mooring in 24 m water depth during the Hyperspectral Coastal Ocean Dynamics Experiment (HyCODE) in summer 2001. Coherence analyses of daily noontime values over a 41-day period indicate that cloud cover, chlorophyll concentration, and particulates plus gelbstoff have the greatest effects on solar transmission in the upper ocean in the visible wavelengths. All of these parameters are significantly coherent (negative phase) with solar transmission on a scale of about 1 week. Values of solar transmission at the mixed layer depth (MLD; between 1 to 15 m) range from 0.7 to 63% (average is 19%). The average decrease in solar radiation over the 41-day period is 188 W m^{-2} (wavelength range of 400-800 nm; average solar radiation is 239 W m^{-2} and average MLD is 6 m). The maximum decrease in solar radiation is 285 W m^{-2} (for surface solar radiation of 287 W m^{-2}, transmission of 0.7%, cloud cover of 6%, and MLD of 13 m).

INTRODUCTION

Knowledge of properties and processes influencing solar transmission is essential for understanding of ocean radiant heating and for development of methodologies and models to quantify the heat budget. Ocean radiant heating affects the intensity and depth of upper water column stratification (Klein, 1980; Simpson and Dickey, 1981; see review in Dickey and Falkowski, 2002), which in turn can have impacts on upper ocean ecology and water quality. A strong and shallow thermocline can limit the vertical transport and entrainment of nutrients residing below the thermocline, trap nutrients in the near-surface waters for phytoplankton utilization, and cause photobleaching of phytoplankton and photo-oxidation of colored dissolved organic matter (CDOM) by trapping primary producers and CDOM in surface waters of high intensity solar radiation. In coastal areas with riverine or sewage inputs, fresh water, pollutants and suspended matter can also be trapped in the upper water column.

Meteorological and upper ocean physical processes and optical properties have been shown to affect solar transmission through the alteration of the in-water solar attenuation coefficient and the sea surface albedo (Simpson and Dickey, 1981; Zaneveld et al., 1981; Lewis et al., 1983; Katsaros et al., 1985; Kirk, 1988; Morel and Antoine, 1994; Siegel et al., 1995; Ohlmann et al., 2000). Most of the past studies of solar transmission and heating have utilized numerical models to parameterize the upper ocean with respect to meteorological and physical processes and bio-optical properties. Studies involving observations of optical properties and heating have been executed in the open ocean (e.g., Siegel et al., 1995). Ohlmann et al. (2000) utilized irradiance measurements in the equatorial Pacific and the radiative transfer model, Hydrolight, to investigate optical influences on ocean radiant heating. Their radiative transfer simulations indicate that cloud cover, solar zenith angle, and chlorophyll concentration have the largest effects on solar transmission and heating in the open ocean.

Studies of the influences of coastal ocean processes on solar transmission have been limited until recently. We utilize a coastal ocean time series data set of physical and bio-optical measurements to characterize the meteorological and physical processes and bio-optical parameters that contribute to the variability of solar transmission, albedo, and radiant heating rate (RHR) through the upper water column. We also employ radiative transfer simulations (Hydrolight 4.1; Mobley, 1994) to evaluate the effects of bio-optical properties and meteorological processes on solar transmission, albedo, and RHR. We hypothesize that in addition to chlorophyll concentration, CDOM and detritus can have a significant impact on solar transmission in the coastal ocean. Also, similar to open ocean results, we believe that cloud cover and solar angle greatly affect transmission of radiation through the upper water column.

METHODS

We present two different analyses utilizing observations and the radiative transfer model, Hydrolight 4.1. Time series observations were made using instruments deployed on a mooring during the Hyperspectral Coastal Ocean Dynamics Experiment (HyCODE) between June 19 and August 6, 2001. These instruments concurrently collected high temporal resolution physical and bio-optical measurements at several depths off of the coast of New Jersey (about 39°20'N, 74°05'W) in 24 m water depth (Figures 1 and 2 in Chang et al., 2002). Physical and bio-optical instruments included: hyperspectral radiance (2, 5, and 11 m) and irradiance (above the surface, 5, and 11 m) sensors (Satlantic, Inc. MiniSpecs; 3.3 nm resolution for $\lambda = 350 - 800$ nm); spectral absorption-attenuation meters (WET Labs, Inc. ac-9s) at 5, 11, and 20 m; beam transmissometers (660 nm) and fluorometers at 5 and 11 m; a backscattering instrument (HOBI Labs HydroScat-6) at 5 m; temperature sensors at about every 1 m; and salinity sensors (Figures 1 and 2 in Chang et al., 2002). Volume scattering functions (VSFs) were measured several times at our mooring location on July 25, 2001 with a prototype shipboard VSF meter (Lee et al., submitted; Chang et al., in prep). A nearby meteorological tower measured hourly wind speed and direction, short-wave radiation, air temperature, barometric pressure, and relative humidity. For more details regarding mooring instrumentation and a description of physical processes and bio-optical properties at the HyCODE site, see Chang et al. (2002).

1) We employed empirical orthogonal function (EOF; see Emery and Thomson, 1997) analysis to determine the dominant modes of variability of our time series. In addition, we utilized time series statistical analyses to determine the important processes (cloud cover, solar angle, and wind speed) and bio-optical properties (chlorophyll concentration, absorption, and attenuation) that influence solar transmission, albedo, and RHR variability at the HyCODE site. Our computations (see details below) involved daily noontime values of all relevant parameters in addition to hourly values between 6 am and 6 pm during the sunniest day (July 2, 2001; SR_{max}; see below) to assess the effects of solar angle. Coherence and associated phase functions were used to quantify the relationships between variables at a range of time periods. Coherence and phase estimates were made between cloud cover, solar angle, chlorophyll concentration, absorption at 412 nm, and attenuation at 650 nm with solar transmission, albedo, and RHR. Statistical significance levels were calculated according to Thompson (1979).

A brief description of our calculations follows. We computed cloud cover index, CI, using: $CI = 1 - (SR / SR_{max})$, where SR is measured daily noontime short-wave radiation and SR_{max} is the maximum value of measured daily noontime short-wave radiation throughout the 41-day time series. Therefore, CI = 0% is a cloud-free sky. The solar transmission function, Tr(z), is defined as the ratio of spectrally integrated net irradiance measured at a depth, z, to spectrally integrated downwelling irradiance measured just above the sea surface: $Tr(z) = E_n(z) / E_d(0^+)$, $E_n(z) = E_d(z) - E_u(z)$. We define depth, z, as the mixed layer depth (MLD), computed using our high vertical resolution temperature measurements and a 0.25° temperature criterion. Spectrally integrated (visible wavelengths, $\lambda = 400 - 800$ nm; the infrared wavelengths are absorbed strongly in the upper half meter of the water column) values of $E_d(0^+)$ and $E_d(z)$ were determined using our hyperspectral radiometric measurements assuming a logarithmic profile of irradiance with depth throughout the mixed layer. $E_u(z)$ was calculated using the following: $E_u(z) = E_d(z) \times [E_{uHL}(z) / E_{dHL}(z)]$, where $E_{uHL}(z)$ and $E_{dHL}(z)$ are values computed using Hydrolight simulations (with measured boundary conditions and IOPs as inputs). Spectrally integrated values for $E_u(0^-)$ were similarly calculated for albedo, α, and RHR quantification: $\alpha = 1 - [E_n(0^-) / E_d(0^+)]$ and $RHR = [E_n(0^-) - E_n(z)] / (\rho\, c_p\, z)$, where $E_n(0^-) = E_d(0^-) - E_u(0^-)$, ρ is seawater density and c_p is the specific heat of seawater ($c_p = 4180$ J kg^{-1} °C^{-1}). Seawater density was computed using temperature and salinity measurements and the equations of state. Spectral solar transmission function and albedo were also calculated for wavelengths, $\lambda = 400 - 800$ nm.

2) Hydrolight simulations were used to investigate the effects of CI, solar angle, chlorophyll concentration, absorption, and attenuation on solar transmission, albedo, and RHR. Measured parameters were used as inputs (spectral absorption and attenuation, chlorophyll concentration, VSF). The average wind speed and MLD over the entire 41-day time series was employed in all Hydrolight runs (5 m s^{-1} and 6 m, respectively). A simple sensitivity analysis was performed to select the optimum VSF out of several VSF measurements made near our HyCODE mooring. Details regarding Hydrolight simulation inputs follow.

a. We varied CI = 0, 20, 40, 60, 80, and 100% with the other variables fixed: solar angle = 17.85° (noontime average over the 41-day time series), chlorophyll concentration ≈ 3.0 μg l^{-1} (mean over the 41-day time series), and absorption and attenuation values corresponding to the chlorophyll concentration, i.e., chlorophyll concentration was found

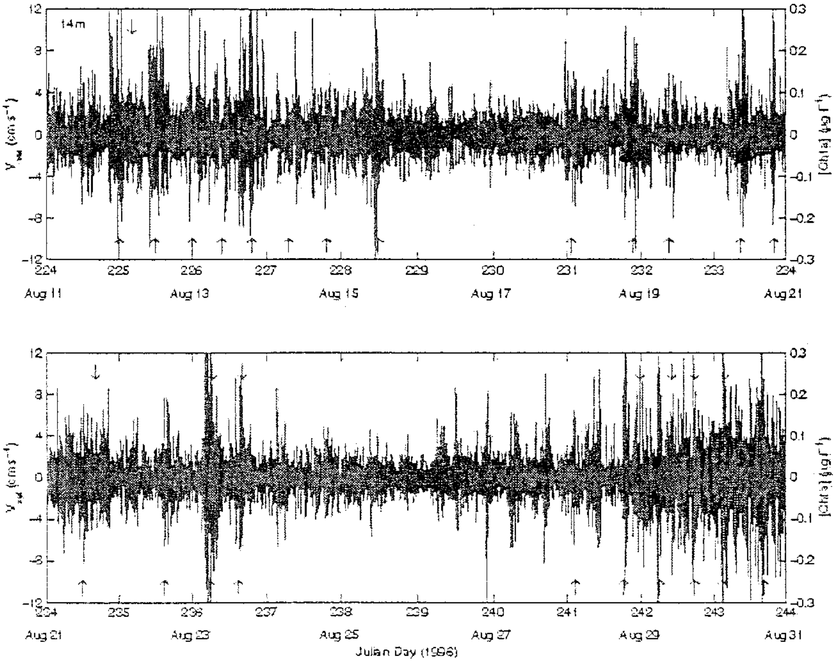
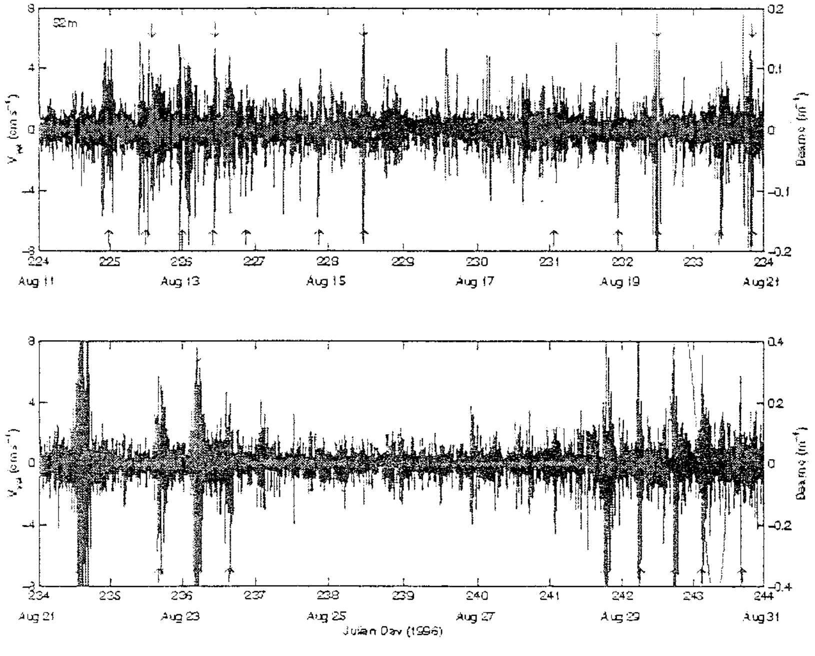


Figure 2. Time-series of band-passed filtered north-component velocity (dark) measured at 15 m and chlorophyll a concentration (light) measured at 14 m. The arrows represent times when internal solitary waves were observed.



1) EOF analyses indicate that 83% of the total variance in our time series is described by the first three modes. Chlorophyll concentration, $a_{t\text{-}w}(412)$, and $c_{t\text{-}w}(650)$ dominate the first mode, which explains 38% of the total variance (not shown). Hence, particles and dissolved material in the water column dominated the time series variability. Modes 2 and 3 are described by 30% and 15% of variability, respectively. Modes 2 and 3 illustrate an inverse relationship between chlorophyll concentration and $a_{t\text{-}w}(412)$ with solar transmission (not shown). This simply states that the presence of particulate (biogenic and non-biogenic) and dissolved material led to decreased solar transmission in all cases at the HyCODE site.

Additional results from analysis (1) indicate that other than MLD, cloud cover, chlorophyll concentration, and $a_{t\text{-}w}(412)$ are significantly coherent with solar transmission on timescales of about one week, all with negative phase (not shown). $c_{t\text{-}w}(650)$ is not significantly coherent with transmission; therefore, CDOM was most likely a larger influence on transmission as compared to detrital particles. Past open ocean studies (Lewis et al., 1983; Ohlmann et al., 2000) have focused on chlorophyll concentration as the only bio-optical influence on solar transmission. We find that CDOM may have a significant effect on solar transmission in coastal waters. This is important for the development of stratification near river outflows, thus resulting in photo-oxidation of CDOM present, possible photobleaching of phytoplankton trapped in the surface mixed layer, and reduced transport (advection and entrainment) of nutrients to the upper water column.

Figures 2 (spectrally integrated), 3 and 4 (spectral) illustrate the results from analysis (2). Spectrally integrated solar transmission, albedo, and RHR change at different rates as CI, solar angle, chlorophyll concentration, $a_{t\text{-}w}(412)$, and $c_{t\text{-}w}(650)$ vary (Figure 2). Chlorophyll concentration appears to be the parameter of most influence on integrated transmission and solar angle, and cloud index is the most influential on integrated albedo and RHR. Similarly, chlorophyll concentration has the greatest influence on spectral solar transmission, as seen in the variance and standard deviation (Figure 4). Following chlorophyll concentration, $a_{t\text{-}w}(412)$ and $c_{t\text{-}w}(650)$ have a significant impact as well. To a lesser extent, solar angle and CI lead to variability in spectral solar transmission. However, solar angle and CI have the greatest impact on spectral albedo, followed by chlorophyll concentration, $c_{t\text{-}w}(650)$, and $a_{t\text{-}w}(412)$ (Figure 4). This is to be expected as angle of incidence has been shown to have the most influence on the intensity of reflection off of a water body (e.g., Katsaros et al., 1985). The results for spectral solar transmission differ significantly from what has been found in past open ocean studies. Ohlmann et al. (2000) found that cloud index and chlorophyll concentration are the most important factors for solar transmission in the equatorial Pacific.

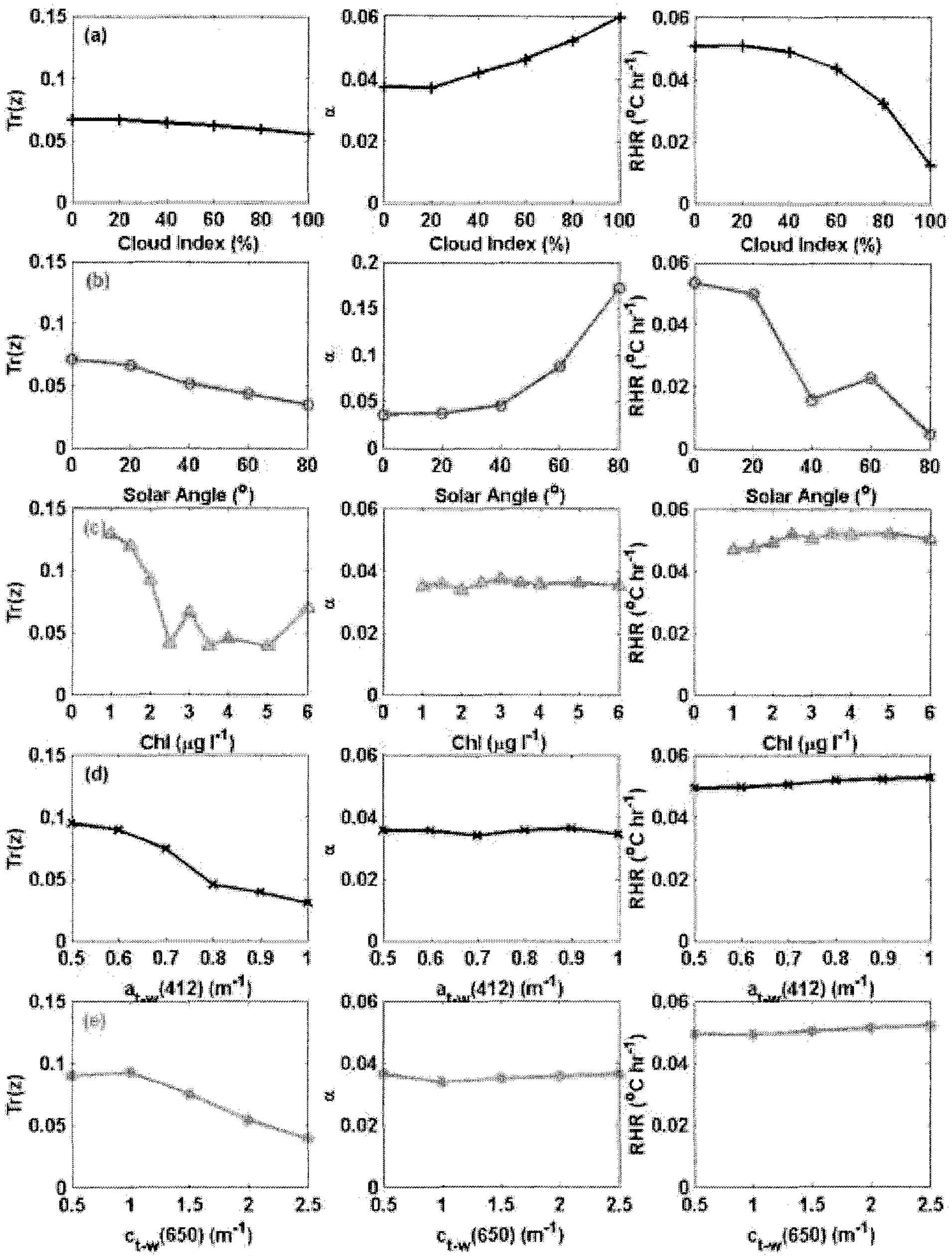


Figure 2. Results from Hydrolight simulations in analysis (2). Spectrally integrated solar transmission function (column 1), albedo (column 2), and radiant heating rate (RHR; °C hr^{-1}; column 3) as (row a) cloud index varies (black +); (row b) solar angle is varied (magenta o); (row c) chlorophyll concentration varies (green Δ); (row d) absorption at 412 nm varies (blue x); and (row e) attenuation at 650 nm is varied (orange •).

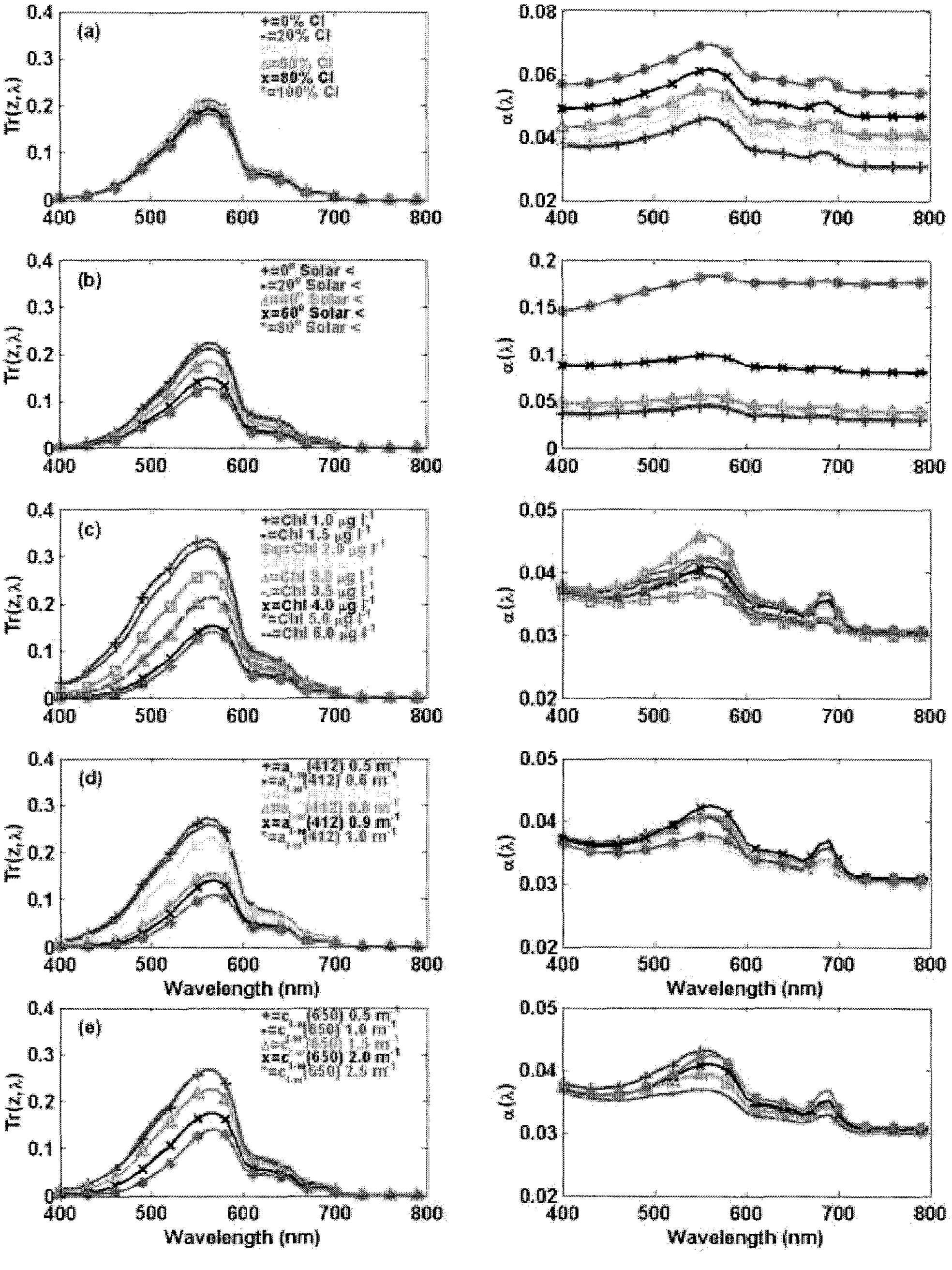


Figure 3. Results from Hydrolight simulations in analysis (2). Spectral solar transmission function (column 1) and spectral albedo (column 2) with varying (row a) cloud index; (row b) solar angle; (row c) chlorophyll concentration; (row d) absorption at 412 nm; and (row e) attenuation at 650 nm.

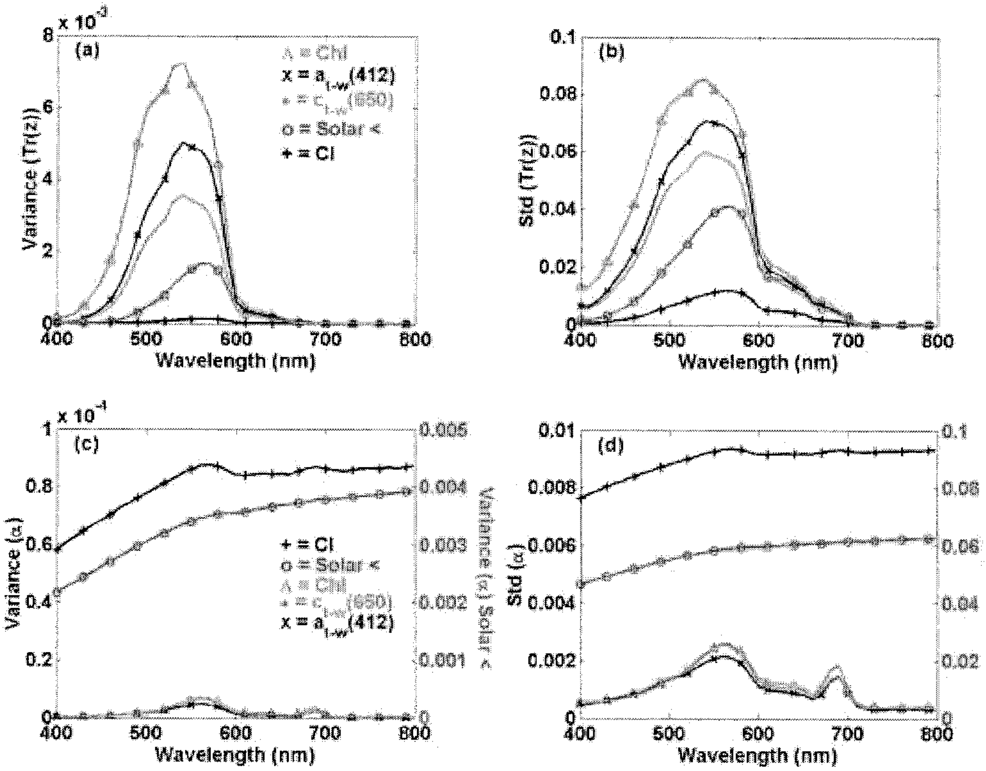


Figure 4. Results from Hydrolight simulations in analysis (2). (a) Variance and (b) standard deviation of spectral solar transmission with varying cloud index (black +), solar angle (magenta o), chlorophyll concentration (green Δ), absorption (412 nm; blue x), and attenuation (650 nm; orange •); (c) variance and (d) standard deviation of spectral albedo with varying parameters.

SUMMARY

We utilized an extensive time series data set of physical, meteorological, and bio-optical measurements in coastal waters to characterize the processes and bio-optical parameters that contribute to the variability of solar transmission, albedo, and RHR of the upper water column. The data were collected on a mooring in 24 m water depth during HyCODE in summer 2001. EOF analysis results show that the time series variability is dominated by particulates and dissolved matter in the water column. Coherence analyses of daily noontime values over a 41-day period indicate that cloud cover, chlorophyll concentration, and particulates plus gelbstoff have the greatest effects on solar transmission variability in the upper ocean in the visible wavelengths ($\lambda = 400 - 800$ nm). All of these parameters are significantly coherent (negative phase) with solar transmission on a timescale of about 1 week.

Hydrolight simulations were employed to investigate effects of meteorological and bio-optical properties on solar transmission, albedo, and RHR. Results demonstrate that chlorophyll concentration, followed by absorption at 412 nm and attenuation at 650 nm, has the most significant impact on spectral and integrated transmission variability within the MLD. Solar angle and cloud cover greatly influence spectral and integrated albedo.

This study is among the first to utilize physical and bio-optical observations coupled with radiative transfer simulations to explore the influence of bio-optical properties on solar heating of a water body. Also, this is one of the first studies of solar transmission and RHR performed for coastal waters. Our findings suggest that dissolved material and possibly detritus may have a significant impact on the transmission of solar radiation through the upper water column. This has implications on the development of stratification in coastal waters and thus, phytoplankton ecology in addition to environmental effects. Future studies will involve investigations of solar transmission effects on thermocline depth variability, the effects of stratification on photobleaching of phytoplankton, and the impact of particulates on radiant heating of the upper ocean.

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