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Spectral effects of Saharan dust on photosynthetically available radiation in comparison to the influence of clouds

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ABSTRACT

Measurements of downward irradiance at sea level in the area off Northwest Africa in February 2008 were analyzed to determine the spectral effects of atmospheric dust and clouds on solar irradiance and photosynthetically available radiation. For the first time not only the pure spectral effects of dust and clouds were considered but also the spectral modifications by sky conditions with dust and clouds together in the atmosphere.

The influence of dust on spectral distribution of downward irradiance is smaller than that of clouds reducing the incoming radiation. The spectral effect of pure dust causes deviations of up to 6% at 400 nm compared to the clear sky case. In contrast, the deviations in the case of clouds are up to 31%. Furthermore, atmospheric dust modifies the spectral effect of clouds. In the case of clouds reducing the incoming radiation, the spectral effect depends mainly on the ratio between clouds and dust in the atmosphere. The spectral dependence changes if the optical properties of clouds or dust predominate. Dust increases the spectral effect of clouds mainly in the blue spectral range in the case of clouds enhancing the incoming radiation.

An important result was the parameterization of the spectral effects of different atmospheric conditions by power functions. The functions depend on the wavelength and the introduced normalization factors describing the effect of clouds and atmospheric dust on the magnitude of downward irradiance. The parameterization was used to investigate the influence of the spectral effects on photosynthetically available radiation. Their correct knowledge is important for many applications such as biology experiments and ecological modeling. The influence of spectral effects compared to clear sky case is in the order of few percents for all considered atmospheric cases. The spectral effects of different types of clouds reduce or enhance the photosynthetically available radiation up to 6.1% or 1.9%, respectively. Atmospheric dust modifies the influence of spectral effects of clouds on photosynthetically available radiation in dependence on the ratio of clouds to dust.

1. Introduction

The present study quantifies the impacts of different sky conditions on the magnitude and spectrum of incident solar radiation and investigates their influences on photosynthetically available radiation.

Sky conditions with dust in the atmosphere, different types of clouds or combinations of both modify the energy flux to the earth and influence the spectral distribution of the incident solar radiation by physical processes like absorption, scattering or reflection (e.g. Carlson and Benjamin, 1980; Stephens and Tsay, 1990; Nann and Riordan, 1991; Frederick and Erlick, 1997). The study area off Northwest (NW) Africa is well-known for sporadic Saharan dust storms (e.g. Chiapello and Moulin, 2002; Kaufman et al., 2005), which transport dust aerosols from the land surface to the Atlantic Ocean (Prospero and Carlson, 1972; Kalu, 1979). The cloud and dust coverage are strongly variable (Peixoto and Oort, 1992; Highwood et al., 2003; Goudie and Middleton, 2006; Söhne et al., 2008) and depend on atmospheric processes (e.g. Newton, 1992; Philander et al., 1996; Gao et al., 2001; Tulet and Mari, 2007). The intertropical convergence zone is mainly responsible for the seasonal modification of dust and cloud conditions (e.g. Barry and Chorley, 1992; Jankowiak and Tanre´, 1992; Diedhiou et al., 1999; Karyampudi et al., 1999; Parker et al., 2005), and by that for the variation of the amount of sunlight reaching the earth. The mixing and stratification of atmospheric layers containing dust and clouds is very complex (e.g. Ansmann et al., 2011; Knippertz et al., 2011; Petzold et al., 2011; Toledano et al., 2011; Weinzierl et al., 2011). Atmospheric dust and clouds change the spectral distribution of the incident radiation, which may

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influence light dependent biological processes like phytoplankton growth and its composition (Claustre et al. 2002; Wozniak and Stramski, 2004; Stramska et al., 2008; Zhou and Cao, 2008).

Although it is known that atmospheric dust and clouds change the amount of the incident solar radiation (Monteith and Unsworth, 1973; Kirk, 1994), the spectral effect of dust was poorly quantified (Adeyefa et al., 1995; Sokolik et al., 2001; di Sarra et al., 2002; Otto et al., 2009) and that of clouds was considered only in few studies (Frederick and Erlick, 1997; Bartlett et al., 1998, Siegel et al., 1999). Up to now, the spectral effects of different mixtures of atmospheric dust and clouds were not discussed.

Atmospheric dust reduces the incoming radiation especially in the blue spectral range (di Sarra et al., 2002; Otto et al., 2009). The reduction depends on the content of Saharan dust in the atmosphere. Values of 21% at 400 nm and 5% at 700 nm were found in May 2006 (Otto et al., 2009). Dust aerosols with an optical depth of 0.5 at 415 nm produced an irradiance reduction at 350 nm between 20% and 25% (di Sarra et al., 2002). A linear relationship between aerosol optical depth and irradiance reduction was derived by Ohde and Siegel (2012). They determined a decrease of photosynthetically available radiation of 1.2% by an increase of dust aerosol optical depth of 0.1.

Different results were obtained for cloudy skies. Autumn clouds over Halifax attenuated the incident solar radiation according to a nonlinear wavelength dependent relationship (Bartlett et al., 1998), but a linear relationship was derived for clouds in the western equatorial Pacific Ocean (Siegel et al., 1999). The maximum reduction of spectral solar irradiance by clouds in the area off NW Africa was up to 67.2% at 400 nm and up to 84.4% at 700 nm compared to clear sky conditions (Ohde and Siegel, 2012). Isolated cumulus clouds in an otherwise clear sun and sky enhanced the incident radiation by increasing the diffuse part of solar radiation (Kirk, 1994). The maximum measured increase by clouds was 21.9% at 400 nm and 34.0% at 700 nm in the area off NW Africa (Ohde and Siegel, 2012). The spectral effect of clouds appears to be site dependent as a function of cloud type and ground albedo (Bartlett et al., 1998).

The present paper investigates the spectral effects of different dusty and cloudy skies in the area off NW Africa on the basis of downward irradiance measurements at sea level. The main objective is the quantification of the spectral modification of different atmospheric conditions. Especially, mixtures of dust and clouds are included. The influence of spectral effects on downward irradiance and photosynthetically available radiation is characterized.

2. Methodology

2.1. Method

Irradiances measurements at sea level off NW Africa in February 2008 are analyzed and classified in relation to the atmospheric conditions. The measurements during clear skies, dust events, different cloud conditions and their combinations are identified by study of the corresponding meteorological datasets, by analysis of the irradiance spectra, by comparison to the dust aerosol optical depth and by correlation to modeled irradiances (Sections 2.3, 3.1–3.2). The modifications of the amount (magnitude effect) and of the spectral distribution (spectral effect) of the incident solar radiation by atmospheric dust, clouds as well as different ratios of dust to clouds are studied (Sections 3.3–3.4) using the theoretical approach of Section 2.2 and the data base of Section 2.3. The parameterized spectral effects and the measured magnitude effects of different atmospheric conditions (Sections 3.3–3.4) are applied to investigate their influence on photosynthetically available radiation (Section 3.5), an important factor for the marine environment in relation to algae growth and their compositions in the water column.

2.2. Theory

2.2.1. Downward irradiance just above the water surface

The approach of Bartlett et al. (1998) used to investigate the spectral effect of clouds attenuating the incoming radiation is applied to different atmospheric conditions. The underlying method is based on the separation of the clear sky case from the cloud and dust cases, respectively, by introducing terms describing their influences on the irradiance spectra.

The observed spectral downward (d) irradiance $E_{d,x}(\lambda)$ just above the water surface (λ-wavelength) is related to the modeled (mod) clear sun and sky (cs) irradiance $E_{d,cs}^{mod}(\lambda)$ by

$$E_{d,x}(\lambda) = E_{d,cs}^{mod}(\lambda) N_x(490\ \text{nm}) S_x(\lambda, N_x). \tag{1}$$

The term $N_x(490\ \text{nm})$ describes the modification of the amount of the incident solar radiation caused by different atmospheric conditions (magnitude effect). The term $S_x(\lambda, N_x)$ determines the change of spectral distribution of the incident solar radiation by clouds, dust or mixtures of clouds and dust (spectral effect). Both terms, N_x and S_x, will be determined from own radiation measurements in Section 3.4.1. The subscript x is introduced for the distinction of different atmospheric conditions (clear sky, atmospheric dust, different kinds of clouds, dust and clouds together in the atmosphere).

The modeled clear sky irradiance $E_{d,cs}^{mod}(\lambda)$ of Eq. (1) is given by

$$E_{d,cs}^{mod}(\lambda) = E_{d,cs}^{gc}(\lambda) \overline{M}_{cs}(\lambda), \tag{2}$$

where $E_{d,cs}^{gc}(\lambda)$ is the clear sun and sky irradiance (gc) determined by the radiation model of Gregg and Carder (1990) (Section 2.2.3). The term $\overline{M_{cs}}(\lambda)$ is a correction term and is given by

$$\overline{M_{cs}}(\lambda) = \frac{\sum_{i=1}^{n} M_{cs,i}(\lambda)}{n} \quad \text{with} \quad M_{cs,i}(\lambda) = \frac{E_{d,cs,i}(\lambda)}{E_{d,cs,i}^{gc}(\lambda)}. \tag{3}$$

This factor describes the mean deviation of the measured clear sky irradiances $E_{d,cs,i}(\lambda)$ from the modeled clear sky irradiances $E_{d,cs,i}^{gc}(\lambda)$. In the ideal case, the terms $M_{cs,i}(\lambda)$ would be equal to 1 for all wavelengths. Sources for deviations could be the neglect of special physical effects (e.g. presence of thin background aerosol layers in the atmosphere or contributions of ground-air multiple interactions; see Section 2.2.3) and the accuracy of the irradiance measurements (6% to 10%; see Section 2.3.2). The quantity $\overline{M}_{cs}(\lambda)$ will be estimated for each wavelength of the used radiation instrument taking into account measurements (n-number of observations) during clear sky (see Section 3.3).

The normalization factor N_x in Eq. (1) identifies the influence of different atmospheric conditions on the magnitude of irradiance spectra at 490 nm and is defined by

$$N_x(490\ \text{nm}) = \frac{E_{d,x}(490\ \text{nm})}{E_{d,cs}^{mod}(490\ \text{nm})}. \tag{4}$$

Eq. (4) is the ratio of the observed downward irradiance $E_{d,x}(490\ \text{nm})$ to the modeled clear sky irradiance $E_{d,cs}^{mod}(490\ \text{nm})$, which is given according to Eq. (2) by

$$E_{d,cs}^{mod}(490\ \text{nm}) = E_{d,cs}^{gc}(490\ \text{nm}) \overline{M_{cs}}(490\ \text{nm}). \tag{5}$$

The term $E_{d,cs}^{gc}(490\ \text{nm})$ is the clear sky irradiance at 490 nm determining by the model of Gregg and Carder (1990). The term $\overline{M_{cs}}(490\ \text{nm})$ is the correction factor at 490 nm. The quantity $N_x(490\ \text{nm})$ is equal to one in the case of clear sky.

Eq. (1) describes different cases like clear sky ($x = cs$), dusty sky without clouds ($x = du$), cloudy sky without dust ($x = c_I$, $x = c_{II}$) and skies with atmospheric dust and clouds together ($x = c_I du$,