Satellite observation of Chromophoric Dissolved Organic Matter (CDOM) variability in the wake of hurricanes and typhoons

Frank E. Hoge

National Aeronautics and Space Administration, Goddard Space Flight Center, Wallops Flight Facility, Wallops Island, Virginia, USA

Paul E. Lyon

E. G. & G. Inc., Goddard Space Flight Center, Wallops Flight Facility, Wallops Island, Virginia, USA

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[1] Satellite observation of Chromophoric Dissolved Organic Matter (CDOM) absorption coefficient variability in the wake of numerous hurricanes and typhoons is reported here for the first time. Storm-induced vertically-mixed CDOM from deeper depths has a higher absorption coefficient than the photochemically degraded CDOM within the undisturbed pre-storm upper mixed layer. Principal findings are: (1) Little variability is observed prior to storm encounter at which time the CDOM-defined wake rapidly develops a notable right side asymmetry. (2) The more robust right-side CDOM absorption coefficient elevation is visible up to ~30days depending on storm intensity. In a way that is similar to existing sea surface temperature imagery applications, the techniques in this paper are proposed as a complementary new research tool for the study of atmosphere-ocean interactions. *INDEX TERMS:* 4504 Oceanography: Physical: Air/sea interactions (0312); 4572 Oceanography: Physical: Upper ocean processes; 4847 Oceanography: Biological and Chemical: Optics; 4552 Oceanography: Physical: Ocean optics. **Citation:** Hoge, F. E., and P. E. Lyon, Satellite observation of Chromophoric Dissolved Organic Matter (CDOM) variability in the wake of hurricanes and typhoons, *Geophys. Res. Lett.*, *29*(19), 1908, doi:10.1029/2002GL015114, 2002.

1. Introduction

[2] Dissolved organic matter (DOM) in seawater represents one of the largest reservoirs of reduced carbon on the earth's surface [*Hedges and Farrington*, 1993]. There is as much carbon in DOM in the oceans as there is carbon in CO_2 in the atmosphere [*Hansell and Carlson*, 1998]. The absorbing form can be remotely observed and is frequently described as chromophoric or colored dissolved organic matter (CDOM). The CDOM absorption coefficient is quite easily retrieved from satellite observations by inversion of an oceanic radiance model [*Hoge et al.*, 1995; *Hoge et al.*, 2001]. However, this CDOM absorption coefficient varies (1) temporally as downwelling irradiance photodegrades or photo-oxidizes the material in the upper ocean layer and (2) with depth since CDOM molecules receive less irradiance at-depth and thus incur less photodegradation [*Vodacek et al.*, 1997; *Chen and Bada*, 1992; *Siegel and Michaels*, 1996]. Vertical differences in the CDOM absorption coefficient are especially pronounced under stratified conditions where a strong thermocline acts as an effective barrier separating the overlying water mass (which is exposed to high solar radiation) from the underlying water mass (which receives little or no insolation). During the period of maximum hurricane activity (July–September) stratification of the oceans of the northern hemisphere are at a maximum, extending as far north as hurricanes are sustained.

[3] Prior to the work reported herein, the principal satellite-derived observations of hurricane forcing of the upper ocean mixed layer have been via sea surface temperature (SST) [*Bates and Smith*, 1985; *Stramma et al.*, 1986; *Shay et al.*, 1992; *Shay et al.*, 2000]. These observations (and modeling studies) have shown that the maximum SST response generally occurs to the right of the storm track and is known as the rightward bias. This rightward bias of the maximum SST cooling is dominated by vertical mixing processes [*Shay et al.*, 1992; *Price et al.*, 1994]. Sea surface fluxes and upwelling underneath the hurricane track generally contribute less to the SST cooling pattern [*Jacob et al.*, 2000].

[4] The application of satellite-derived inherent optical properties imagery to vertical redistribution of chromophoric dissolved organic matter (CDOM) by hurricanes and typhoons is reported here for the first time. Herein, we hypothesize that CDOM, vertically mixed from deeper depths as a result of storm-forcing, provides the source of the CDOM absorption coefficient increases observed in the SeaWiFS retrievals described in this paper. The techniques in this paper are proposed as a complementary new research tool for the study of atmosphere-ocean interaction in much the same way sea surface temperature imagery has historically been used.

2. Methods

2.1. Retrieval of Oceanic Inherent Optical Properties (IOP) from SeaWiFS Water-Leaving Reflectances

[5] All the SeaWiFS global area coverage (GAC) Level 2 reflectances for the complete September 1997 to December 2001 were processed by linear matrix inversion of an oceanic radiance model [*Hoge and Lyon*, 1996; *Hoge et al.*, 1999a; *Hoge et al.*, 1999b; *Hoge and Lyon*, 1999; *Hoge et al.*, 2001]. The inherent optical properties (IOPs), CDOM absorption coefficient, phytoplankton absorption coefficient, and backscattering coefficient, at each invertible pixel are binned into 0.09 square degree bins. When a bin contains more than one valid pixel for a single day of

orbits, then the pixels are averaged together. Multiple pixels in a single bin typically exist only near the polar regions due to the SeaWiFS global coverage period of ~2 days. The complete global averaged binned data are called daily global maps.

[6] The oceanic CDOM variability images to be discussed later were created from a 25-day sliding mean global IOP map, where 24 previous daily global maps and the current day's global map are averaged together. Thus, for the next day's image, the oldest day's data is dropped and a new day's data is included to constitute the new 25 day mean. The process is progressively repeated as each oldest day is dropped and a new day is added. Due to orbit configurations and cloud cover, each sliding mean bin does not necessarily contain an average of 25 valid pixels, but is usually an average of less than 12 valid pixels. The 25-day sliding mean results in more contiguous imagery by removing the clouds from the images and reduces uncertainty in the retrieved IOPs (effects caused by errors in the atmospheric correction to the reflectance spectra).

[7] Data used in the hurricane and typhoon track line extractions (encounter diagrams to be discussed) were produced with a 3-day sliding mean of the daily global maps to eliminate artifacts in the encounter diagrams that are caused by the global coverage period of SeaWiFS. The 3-day sliding mean also allows better estimates of the duration and rate of the increase seen in the CDOM absorption coefficient than the 25-day sliding mean data.

3. Results

[8] We have observed CDOM wakes in at least 40 hurricanes/typhoons during global survey of the 1997, 1998, 1999, 2000 CDOM signatures derived from SeaWiFS reflectances. Although our studies are continuing, CDOM wakes have been found in ~50% of the hurricanes/typhoons in the North Atlantic Ocean and Eastern Pacific Ocean. In the Western Pacific Ocean the occurrence of CDOM wakes is highly variable ranging from ~10% to 50% of the typhoons depending on the location: typhoons that traverse low CDOM areas were much more likely to leave tracks than the typhoons that mainly traverse very high CDOM absorption waters (the latter providing little visual contrast).

4. Summary and Discussion

[14] It has been shown that wakes from major oceanic storm events can be identified by their CDOM absorption coefficient increases measured relative to (a) pre-storm values, (b) adjacent undisturbed regions, (c) post-storm photochemically degraded surface waters. The right-side asymmetry seen in the CDOM absorption coefficient is consistent with historic sea surface temperature findings from satellites, aircraft, ships, and buoys. CDOM absorption coefficient increases of ~100–200% are common. Non-contemporaneous ship data [*Vodacek et al.*, 1997] strongly suggest that these CDOM absorption coefficient increases are due to vertically-mixed [*Shay et al.*, 1992; *Price et al.*, 1994] water whose CDOM has not yet been photochemically degraded to the lower prevailing values routinely found at the sea surface. No change in the average number of carbon atoms in the water column is inferred from these observations; simply a higher optical activity for those chemical species brought to the surface by the storm [*Siegel and Michaels*, 1996]. While satellites can offer observations over large space and time scales, cloud cover can severely limit timely observations. This is true of SST as well as ocean color measurements. The delay time until the cloud cover clears can induce unwanted diurnal heating in the case of (a) SST and (b) CDOM photodegradation/mixing in the case of ocean color. The photodegradation is however mitigated somewhat by the reduced sunlight due to cloud cover.

[15] The current state of our analysis of the SeaWiFS post hurricane/typhoon imagery permits us to retrieve CDOM absorption changes over oceanic basin wide scales. We have made no attempt to tie these findings to observations made by other investigators using data acquired from satellite SST imagery or to any physical oceanographic data that may have been collected by moorings or drifters (if these even exist for hurricane Gert or super typhoon Keith). These observations were discovered in the course of developing SeaWiFS CDOM absorption imagery to observe its distribution in the world's oceans. One of the goals of this paper is to introduce new observational methods to the physical oceanography and meteorological communities who study coupling of intense storms into the upper ocean. We hope that this new tool will complement the physical oceanographic measurements now in use. The large dynamic range of the change in CDOM absorption coefficient may enable more detailed studies of the effects caused by ocean and atmosphere interactions.

[16] The enhanced CDOM absorption coefficient has been seen in numerous named storms and can possibly be seen in less intense storms but these lesser magnitude storms have not yet been sought nor studied by our group. However, it seems safe to conjecture that their effects may eventually be seen under certain pre-existing/storm-driven wind, wave, and current conditions. The CDOM increases have been seen within the tropical storm portions of Gert and Keith (tropical storm wind speeds of ~17 to ~33 m/s). We have seen, but have not yet reported, significant CDOM increases due to known periodic sustained wind events. Thus, the threshold wind speed for CDOM absorption coefficient increases is yet to be established for specifically defined or pre-existing oceanographic conditions.

[17] The phytoplankton absorption coefficient showed no significant signature within the imagery and therefore are not shown. Absence of a phytoplankton bloom is validated by the concurrent absence of an increase in the backscattering coefficient that would accompany phytoplankton growth.

[18] While outside the scope of this paper, numerous studies can be devised by the reader using this CDOM absorption coefficient signature. First, nutrients have been found to be correlated with CDOM [*Chen and Bada*, 1992] and thus studies of the absence of detectable nutrient-facilitated phytoplankton growth and its associated absorption within the CDOM wake is recommended. Second, assuming a known photobleaching rate and upwelling/vertical mixing coefficients, an estimate of the storm energy transfer rate may be possible. Third, an investigation of the intensity and duration of the signature relative to location may be of interest.