ANALYSIS AND VISUALIZATION OF INHERENT OPTICAL PROPERTIES OF THE GULF OF MAINE OBSERVED FROM A TOWED VEHICLE

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ABSTRACT

Inherent optical properties (IOPs) of the Gulf of Maine were measured in situ with a custom-built vehicle towed from a research vessel in a vertically undulating pattern. The BIOMAPER II vehicle, designed for monitoring plankton distributions and physical properties, carried CTD sensors, multi-frequency acoustic transducers, a Video Plankton Recorder, and a suite of optical sensors including a chlorophyll fluorometer, spectral radiometers, and spectral absorption, attenuation and backscattering meters (ac-9 and Hydroscat-6). Absorption and attenuation of dissolved and particulate material were separated based on filtration. Special techniques for analysis and quality control of the data generated during the extended continuous deployments of IOP sensors were required, particularly for estimation of absorption coefficients. Calibration offsets determined at sea (based on clean water analysis) and effects of measurement lag due to filtration and pumping were especially important. During five cruises between October 1997 and December 1999, we surveyed the deep basins of the Gulf of Maine and 3-D visualizations of IOPs are presented.

INTRODUCTION

The optical properties of coastal waters are highly variable in space and time so that conventional station sampling is often insufficient for mapping patterns. New observational methods with capabilities to rapidly sample at high resolution are required. One approach for improving spatial resolution and coverage is to make measurements from underwater vehicles towed behind a research vessel. These types of vehicles can carry a wide range of sensors and many can be deployed in vertically undulating patterns at relatively high ship speeds, thus allowing properties to be measured throughout the water column much more rapidly than can be achieved with equivalent vertical profiles at fixed stations. Here we describe a towed vehicle equipped with optical sensors, discuss some data processing issues for this type of extended sensor deployment, and present observations of inherent optical properties from several cruises in the Gulf of Maine.

BIOMAPER II

The BIOMAPER (Bio-Optical Multi-frequency Acoustical and Physical Environmental Recorder) underwater towed vehicles were designed and built at the Woods Hole Oceanographic Institution specifically to carry a payload of multi-frequency up- and down-looking acoustic transducers for biological research (Wiebe et al. 1997). The second-generation vehicle, BIOMAPER II (Fig. 1), has been modified to carry an additional suite of multi-spectral optical sensors including up- and down-welling

radiometers (Satlantic Inc., OCI series), a pair of dual path absorption and attenuation meters (WETLabs, Inc. ac-9s - one sampling whole water and the other sampling material passing through a 0.2 µm cartridge filter), and a backscattering meter (HOBILabs, Inc. Hydroscat-6). Other standard sensors on BIOMAPER II include a single camera Video Plankton Recorder (Seascan, Inc.), CTD sensors, a chlorophyll fluorometer, a single wavelength transmissometer, plus roll and pitch sensors.

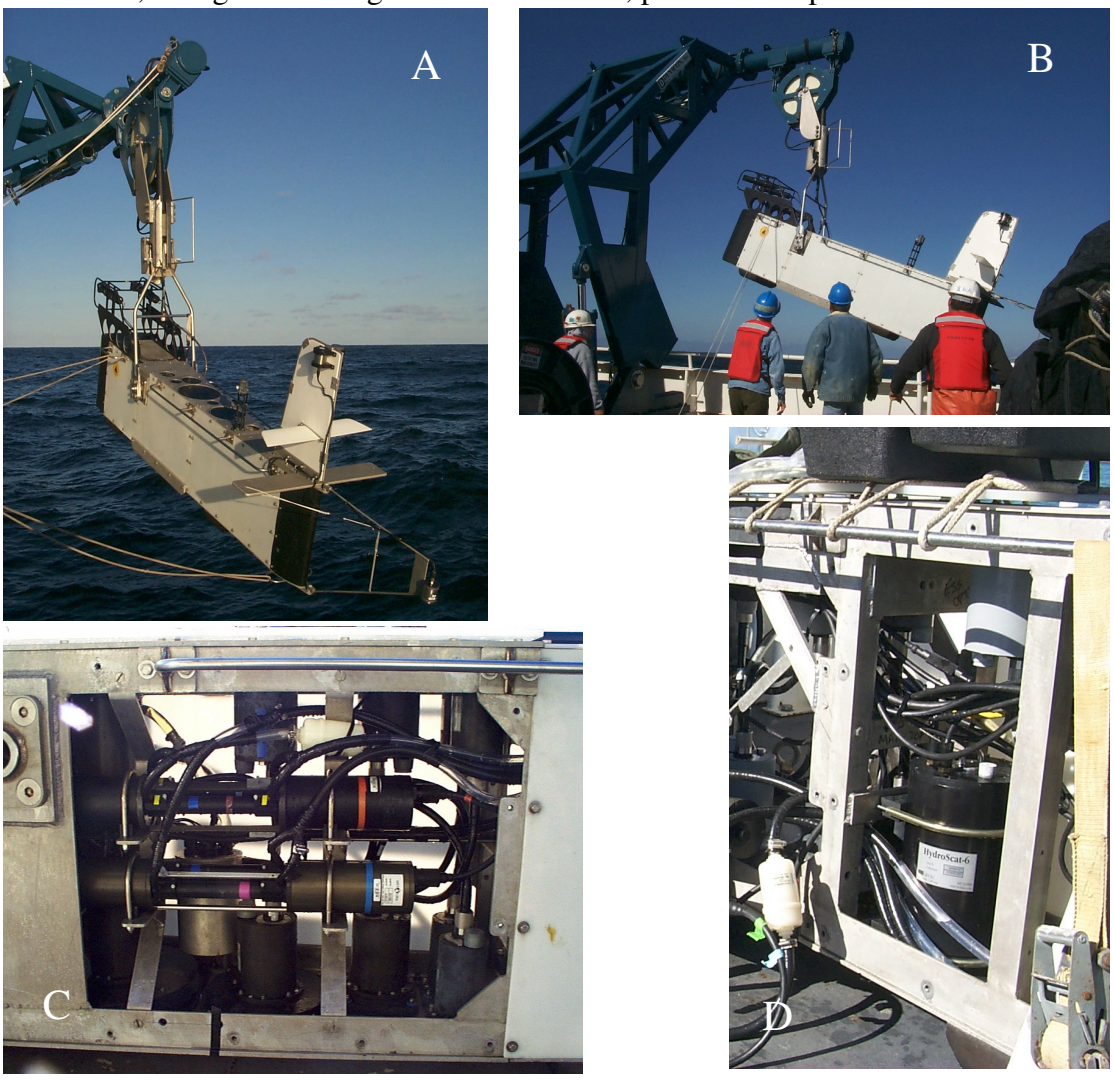

Figure 1. The BIOMAPER II towed vehicle during operations at sea. A-B) BIOMAPER II being deployed with its dedicated handling system. The downwelling and upwelling radiometers are visible on top of the fin and on the aluminum tail frame, respectively. A single wavelength transmissometer and upward-looking acoustic transducers are visible on the top mid-section of the vehicle. The VPR is mounted on the nose, just forward of the weight-bearing harness and fiber optic connection. Computer systems for instrument control, power, and data handling are enclosed in the vehicle body. C) View of the mid-section of the vehicle with side-panels removed for access to the ac-9 meters. Water is pumped through the ac-9s from openings in the right side of the vehicle. D) The Hydroscat-6 is mounted in the bay just behind the ac-9s projecting through a port in the bottom of the vehicle.

Power and two-way communication with BIOMAPER II are provided through a tow cable containing copper conductors and optical fibers; all data are logged on shipboard computers connected via an Ethernet with the computer systems on the vehicle. In the latest upgrade, serial communication with the Hydroscat-6 was accomplished by adding a Micro Serial Server (Lantronix) to the underwater telemetry unit; this server, combined with port redirector software on a shipboard computer, allows transparent communication with any serial device over the Ethernet. GPS time and position are received on the ship and logged through the environmental sensing system (with CTD and auxiliary sensor data). BIOMAPER II is deployed with a dedicated motion-compensating handling system (Dynacon, Inc.) and is manually controlled (based on ship speed and winch operation) to produce "tow-yo" or other flight patterns. The complete system (Wiebe et al. 2000), and more specifically the optical subsystem (Sosik et al. 1998), have been described in detail elsewhere.

BIOMAPER II was deployed to survey areas of the Gulf of Maine on five cruises during October and December of 1997, 1998, and 1999. During this work, emphasis was on characterization of 3-D spatial variability in the major deep basins of the Gulf – Wilkinson, Jordan, and Georges Basins (Fig. 2).

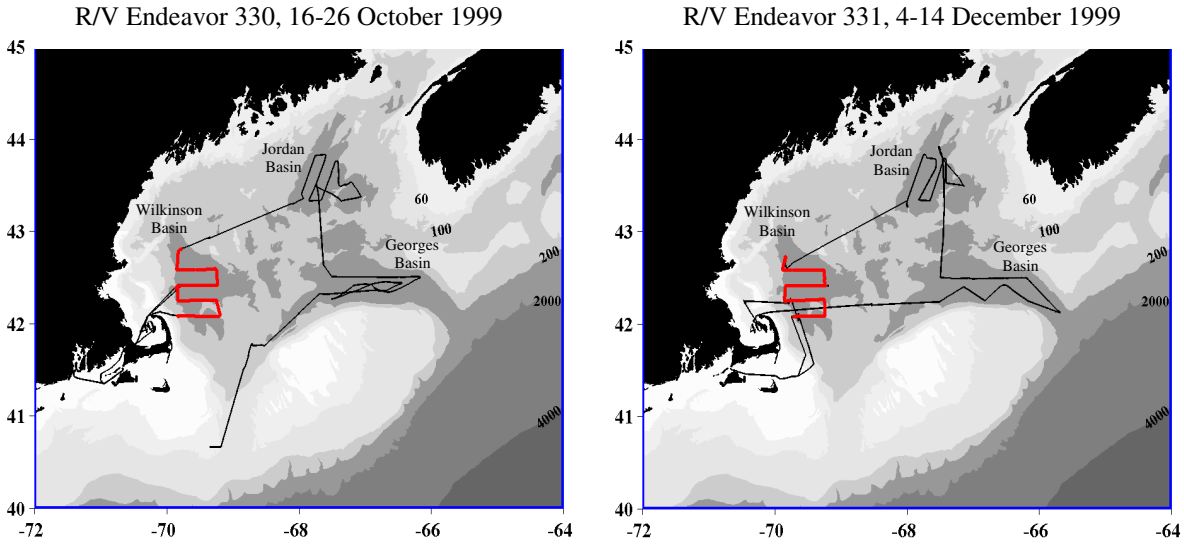

Figure 2. Cruise tracks from the two 1999 BIOMAPER II surveys of the Gulf of Maine superimposed on bathymetry (in meters) of the region. The Wilkinson Basin portion indicated in red is the area presented in Fig. 9.

OPTICAL INSTRUMENT CALIBRATION AND DATA PROCESSING

Processing of the optical data collected from BIOMAPER II involves multiple steps dealing with issues relating to calibration, merger with environmental data, and quality control (Fig. 3). For pumped instruments, such as the ac-9 meters, time lags relative to those sensors sampling ambient conditions essentially instantaneously (such as the Hydroscat-6) can be significant. Here we present an overview of processing necessary to derive spatial distributions of inherent optical properties [absorption (a), scattering (b), and backscattering (b_b) coefficients].

Absorption and scattering from ac-9 measurements – To derive high quality absorption and scattering coefficients (412, 440, 488, 510, 532, 555, 650, 676, and 715 nm) from ac-9 measurements, the data must be calibrated, adjusted for temperature, salinity, and scattering effects, and located with respect to depth, latitude, and longitude (Fig. 3). Initially, raw data is converted into absolute values based on the factory-derived calibration or "device" file (Fig. 3); this step includes correction for internal temperature dependence specific to each instrument.

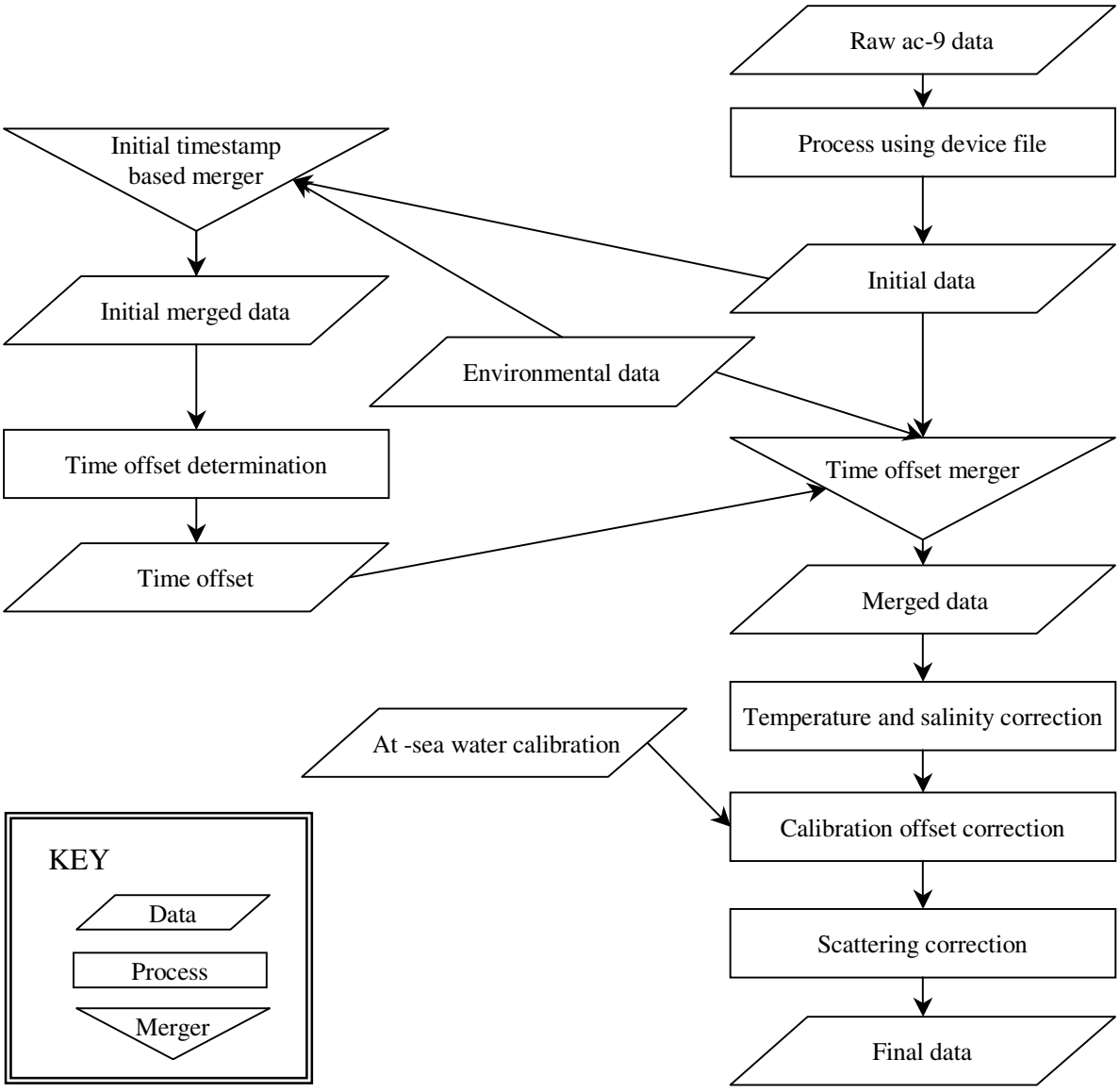

Figure 3. Flow diagram showing the processing steps for ac-9 data collected from BIOMAPER II. See text for details.

These initial calibrated data are then merged with environmental parameters (water properties, depth, position) based on independent time stamps logged with the separate data streams. Time logged with the environmental data is based on GPS information; however, our current acquisition system for the optical data uses computer clocks that do not keep time with sufficient accuracy and does not permit automated periodic syncing to GPS-based time. For this reason, we use comparison between the unfiltered ac-9 data and the open path transmissometer (logged with the environmental data) to correct for time offsets between the two subsystems (Fig. 4). An additional lag is always apparent for the filtered ac-9 due to the volume and resistance associated with the water filter; this latter lag is based on comparison of uncorrected absorption at 715 nm with water temperature (Fig. 5). These time offsets are determined for individual tow-yos using an objective optimization that searches for maximum correlation. During a typical 1-2 day deployment of the tow vehicle, changes in clock synchrony (due to subsystem resets) and increases in the lag due to filter clogging are often observed (Fig. 6).

Once the temporally resolved time offsets between the ac-9 and environmental systems are determined, there is a final time-based merger between the two data streams. This merged dataset contains absorption/attenuation values accurately co-registered with water properties, thus allowing correction for temperature and salinity effects on the optical properties of water according to Pegau et al. (1997). These corrections account for differences between the original calibration water and the in situ water properties (exclusive of particulate and dissolved constituents besides salts) and are applied as discussed in Twardowski et al. (1999).

Because ac-9 calibration can change over time (e.g.,Twardowski et al. 1999), it is important to monitor signals obtained with optically pure water during fieldwork. We used a Milli-Q water purification system (Millipore) to generate water, which was stored in polycarbonate bottles pre-cleaned with a process similar to that used for trace metal clean chemistry (e.g., Fitzwater et al. 1982). At sea calibrations were performed by gravity-feeding this water directly from the carboy (using similarly cleaned Tygon tubing) through the optical tubes of ac-9 meters mounted on BIOMAPER II. These calibrations are made whenever possible during cruises, typically before and after each 1-2 day deployment; instrument optical windows and tubes are cleaned with methanol and lens paper between post- and pre-deployment calibrations. Calibration offsets (relative to the factory calibration) are determined by analyzing the resulting data files using the factory-derived device file, and then correcting as discussed above for the difference between water temperature of the factory calibration and the field calibration (as measured each time on the ac-9 outflow). The resulting calibration offsets for both absorption and attenuation are added to the time merged in situ data, although they could in principle be applied at any previous step in the processing sequence (even at the initial raw data conversion – as long as the temperature correction is properly applied).

Final calibrated absorption coefficients are then derived by applying a correction for scattering errors as described by Zaneveld et al. (1992, 1994) based on the assumption that true particle scattering at 715 nm is negligible. Estimated scattering coefficients are determined by difference between the measured attenuation coefficients and the scattering corrected absorption coefficients.

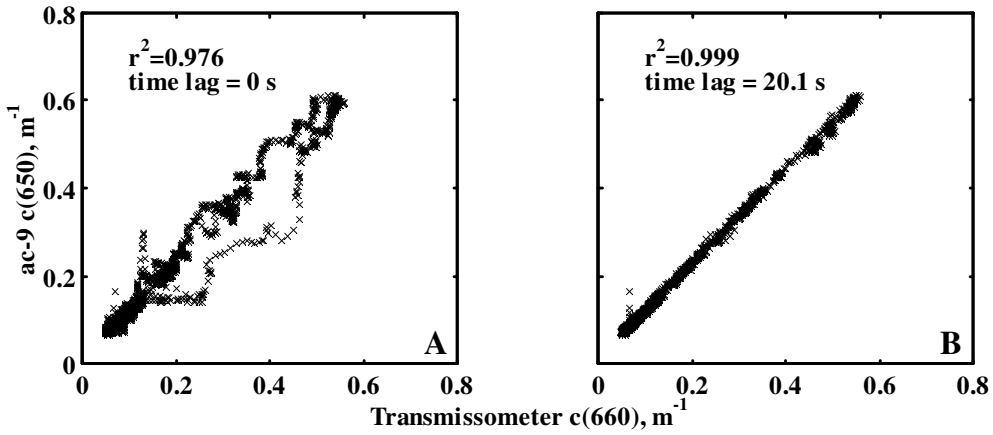

Figure 4. Beam attenuation measured with the unfiltered ac-9 (at 650 nm) and with an open path transmissometer (at 660 nm) for the up and down legs of a single tow-yo in Jordan Basin during Dec. 1999. A) Relationship between the two measurements with no time lag applied to the ac-9 data. B) Relationship with the highest possible correlation was found with a 20 s time lag. Most of this lag is attributed to imperfect time keeping among computer clocks in the data acquisition systems.

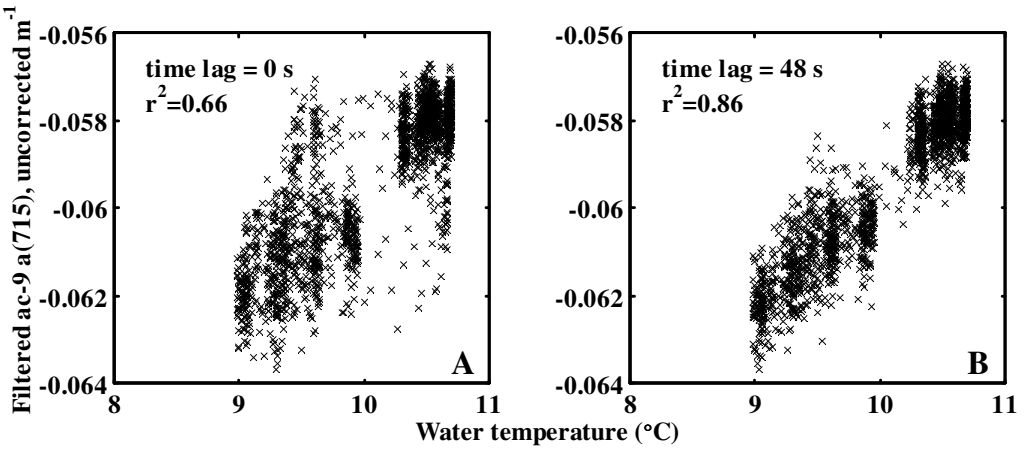

Figure 5. Uncorrected absorption at 715 nm from the filtered ac-9 compared to water temperature logged on the separate environmental sensing system in high gradient portions of a tow-yo (120-200 m depth) in Jordan Basin during December 1999. A) Relationship between the two measurements with no time lag applied to the ac-9 data. B) Relationship with the highest possible correlation was found with a 48 s time lag. This total lag is attributed to a combination of imperfect time keeping among computer clocks and effects of the water filter.

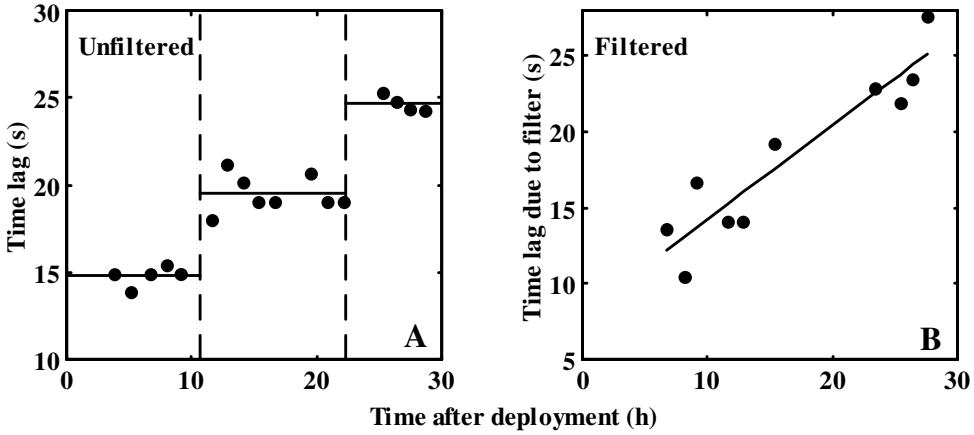

Figure 6. Summary of ac-9 time lag results for a nearly 30 h deployment of BIOMAPER II in Jordan Basin on December 6, 1999. A) For the unfiltered ac-9 the apparent lag changed at two times during the deployment due to clock resets (indicated by dashed lines) that occurred when the optical system was restarted. B) An additional lag was apparent for the filtered ac-9, with an approximately linear increase over time (after subtraction of the lag for the unfiltered ac-9) attributed to filter clogging.

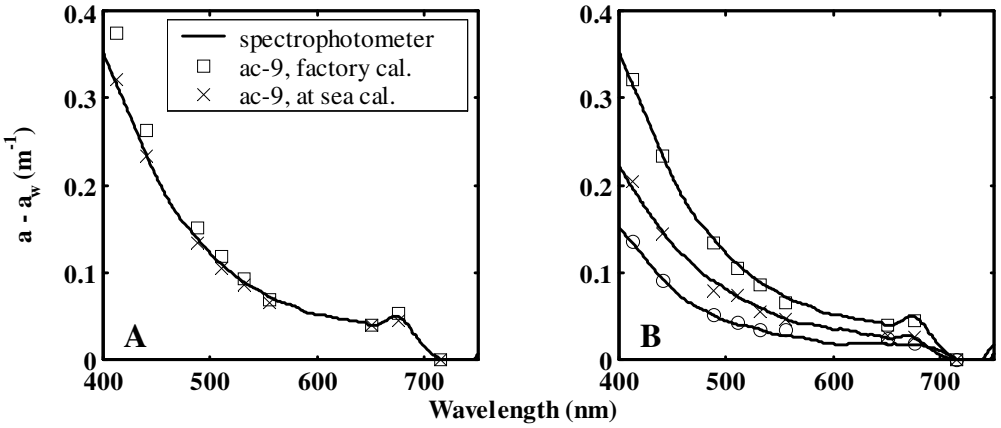

Figure 7. Total spectral absorption (minus water) determined based on spectrophotometric analysis of discrete water samples (solid lines - a_p plus a_{CDOM}) compared to the closest (in depth and time) data from the BIOMAPER II towed vehicle (symbols - unfiltered ac-9). A) Example comparing spectrophotometric results with ac-9 values based on the factory calibration and those based on the water calibrations performed during the cruise. B) Spectrophotometric and ac-9 results based on at-sea calibration from different depths and locations in the GOM during December 1999 representing some of the variability in magnitude and spectral shape observed with both approaches. Overall for this cruise, a linear relationship between the two methods was observed with slope = 1.013, intercept = 0.0023, and r^2 = 0.93 (N = 240).

The magnitude and spectral dependence of the calibration offsets and various correction factors can be significant, but we are confident our approach is effective since we have obtained good agreement between results from ac-9 measurements and independent estimates of absorption by particulate and dissolved material determined from spectrophotometric analysis of discrete water samples collected at stations occupied during our BIOMAPER II cruises (Fig. 7).

Backscattering from Hydroscat-6 measurements – A similar, though simpler, processing routine is applied to derive backscattering coefficients (442, 488, 532, 589, 620, and 671 nm). Hydroscat-6 data are collected continuously at 2 Hz. Raw data are then converted to absolute units based on factory-derived calibration information, and resulting b_b values are corrected for attenuation effects according to Maffione and Dana (1997). These results are then merged with time and position data logged by the environmental sensing system in a similar manner as described for the ac-9 data. The Hydroscat-6 includes an integrated pressure sensor, so determination of time lag with respect to the environmental sensing system is determined based on pressure comparisons. In contrast to the ac-9, for which calibration drift is well documented, for the Hydroscat-6, we have relied on pre- and post-cruise factory calibration information only.

VISUALIZATION AND OBSERVED IOP DISTRIBUTIONS

One approach we have taken for evaluating patterns of spatial and temporal variability in the optical dataset resulting from BIOMAPER II surveys is to generate contour maps for properties in a selected region. Examination of a specific quantity (e.g., absorption at one wavelength) along a survey transect provides a means to compare spatial patterns in physical and optical properties between different time periods (Fig. 8). These distributions can be derived by interpolation of observations to a regular grid over depth and distance or location along the transect, and then displayed using various contouring methods. All surface plots presented here were generated with routines available in the MATLAB software package (Mathworks, Inc.). The same type of information can also be compiled for longer periods of sampling to provide 3-dimensional views of an entire basin, for example (Fig. 9). In this case, interpolated values must be determined based on time or distance traversed to allow for directional changes during the survey, and results can be contoured in two dimensions, and then displayed as a 3-D surface plot (e.g., Fig. 9), which can be viewed from different angles. For our results, these representations of the tow vehicle data quickly reveal that differences in stratification between October and December are manifest in optical property distributions, as are effects of biologically derived particles in the surface layer and resuspension in bottom waters. These representations also reveal qualitative information about spatial patchiness. Other quantities, such as the relative contribution of particles compared to dissolved material, the ratio of absorption to scattering, and spectral ratios for different coefficients, can also provide information about variability in important constituents. Yet another useful approach is to compare depth dependence of spectral properties averaged horizontally over a limited region (example not shown).

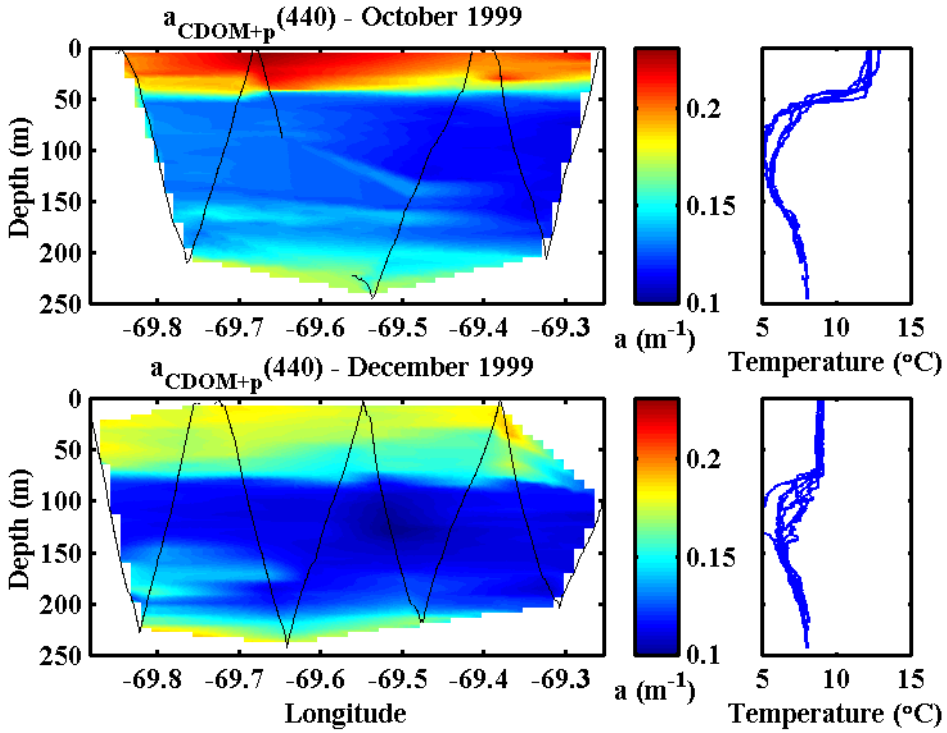

Figure 8. Interpolated vertical distribution of total absorption (minus water) at 440 nm for transects across Wilkinson Basin in Oct. (upper) and Dec. (lower) 1999. Black lines indicate the location of actual observations collected during the approximately 5 h BIOMAPER II tow-yo trajectories. Temperature profiles for the transects are shown in the right panels, indicating a deeper mixed layer in December when the surface high absorption layer was thicker and lower in magnitude than in October.

FUTURE DIRECTIONS

The method of sampling and type of observations we have described here have the potential to contribute to better understanding of optical variability in dynamic coastal and open ocean environments, as well as to fundamental knowledge about plankton distributions and processes. In future work on the Gulf of Maine, we hope to use our observational dataset to help constrain 3-D coupled physical and biological models for the region, to describe aspects of spatial and temporal patchiness in this environment, and to evaluate and improve optical algorithms such as those used to interpret ocean color imagery.

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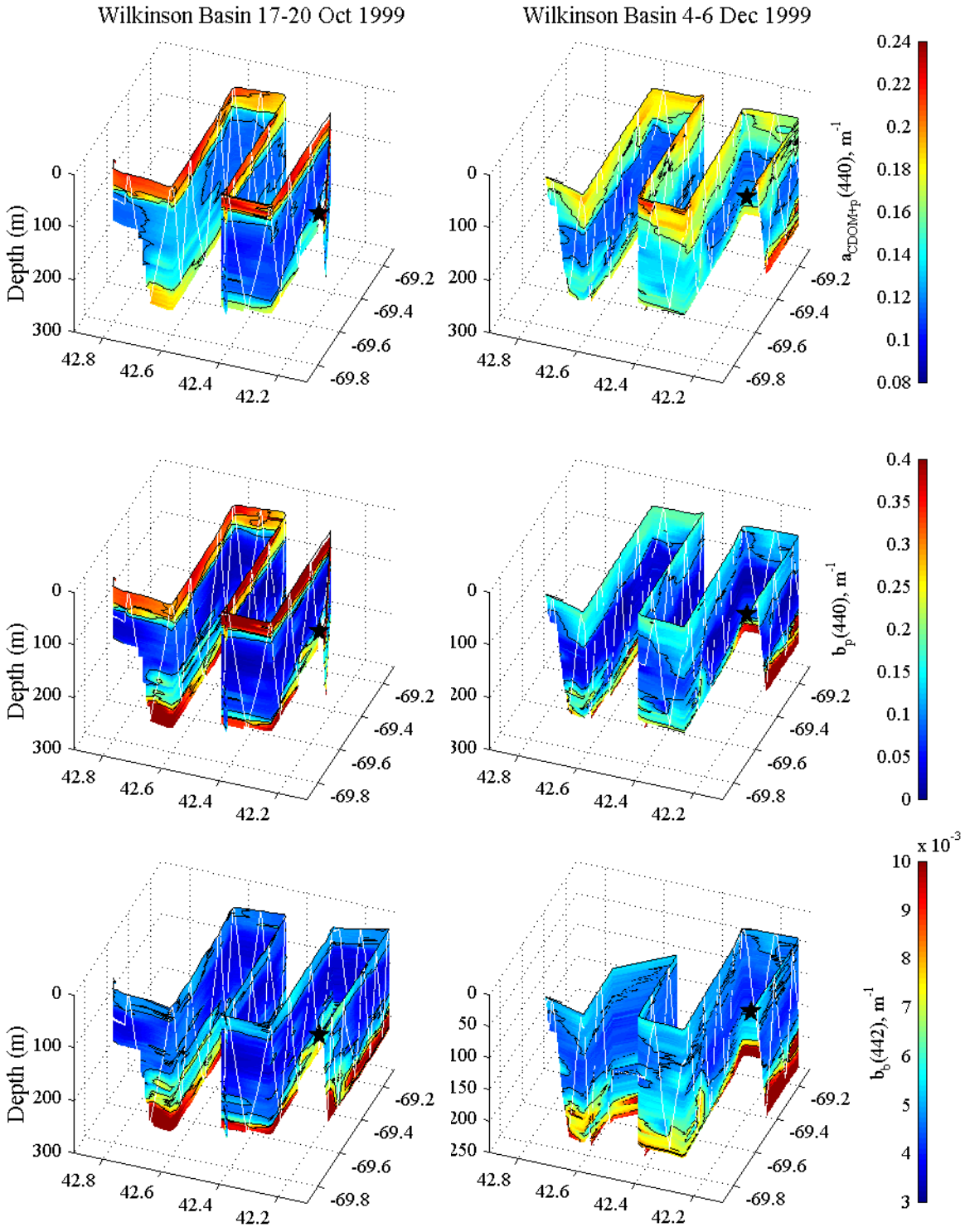

Figure 9. Three-dimensional representations of absorption (top), scattering (middle), and backscattering (bottom) coefficients at 440 nm measured from BIOMAPER II in Wilkinson Basin during ~2 days in Oct (left) and Dec 1999 (right). The black star indicates the survey starting point and white lines show the tow vehicle path. The transects displayed in Fig. 8 correspond to the lines along approximately 42.65° N.

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