The Evolution of Optical

The origins of quantitative water mass classification probably date to the first deployment of the Secchi disc from the papal yacht *L'Immaculata Concezion* on April 20, 1865. Invented at the request of the Commander of the papal navy by Father Pietro Angelo Secchi, the Secchi disc continues in widespread use (Figure 1). Secchi depth atlases provide a broad view of the variability of optical properties in natural waters (Arnone, 1985). Although these measurements represent the largest assemblage of *in situ* optical data, they are extremely limited in spatial and temporal coverage.

By the late 1800s and early 1900s, transparency measurement was enhanced by the use of color-based comparators invented by the Swiss limnologist Françoise-Alphonse Forel. His instruments were the first to show that "water color" could be used to define water masses. However, the approach simply classifies water samples with reference to a series of standards (Figure 2); it is a nonquantitative approach that does not take into account the way different constituents of the water contribute to ocean color.

Upon the development of reliable underwater radiometry toward the end of World War II and the publication of large-scale empirical data sets by Roswell Austin, Raymond Smith, Karen Baker, John Tyler, and Nils Gunnar Jerlov, optical water mass classification formally became a quantitative science. In the 1950s, Jerlov developed the first quantitative classification method to represent the world's oceans; his approach was based on spectral diffuse attenuation coefficients and used data collected with spectral irradiance instrumentation (Jerlov, 1951). His most elaborate classification entailed three open-ocean classes and nine coastal water types (Figure 3). Application of this classification scheme is also limited by data availability, but improves upon the Secchi classification by quantifying the optical properties with *in situ* instrumentation.

The current explosion of interest in optical water-mass classification owes its birth to developments in both biology and physics. Quantitative description of the absorption spectra of

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Figure 1. Oceanographic Secchi discs, first introduced in 1865, are used to measure the clarity of water in both the open-ocean and the coastal zone. A Secchi disc is lowered into the water until it just disappears from view; this depth is recorded and the disc lowered a bit further. The average of the initially recorded depth and the depth at which the disc first reappears upon ascent is referred to as the "Secchi depth." The deeper the Secchi depth, the clearer the water. Secchi depths measured in the clearest waters are typically on the order of 40 m (e.g., 41 m in the Eastern Mediterranean; Megard and Berman, 1989). Photo courtesy of David Phinney, Bigelow Laboratory for Ocean Science.

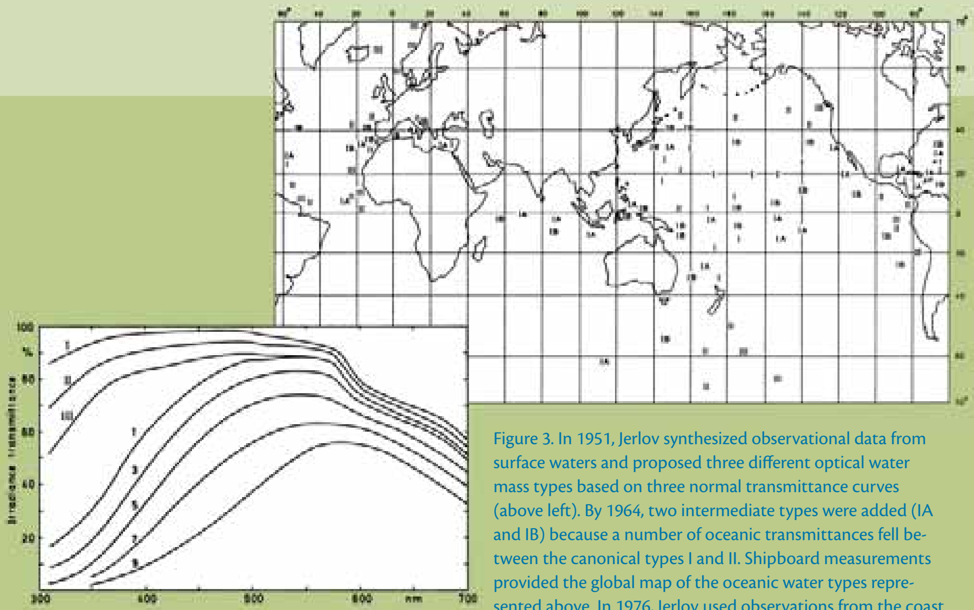

Figure 3. In 1951, Jerlov synthesized observational data from surface waters and proposed three different optical water mass types based on three normal transmittance curves (above left). By 1964, two intermediate types were added (IA and IB) because a number of oceanic transmittances fell between the canonical types I and II. Shipboard measurements provided the global map of the oceanic water types represented above. In 1976, Jerlov used observations from the coast of North America and Scandinavia to expand the system to include nine coastal transmittance types (above left). Figures reprinted from Jerlov (1976) with permission.

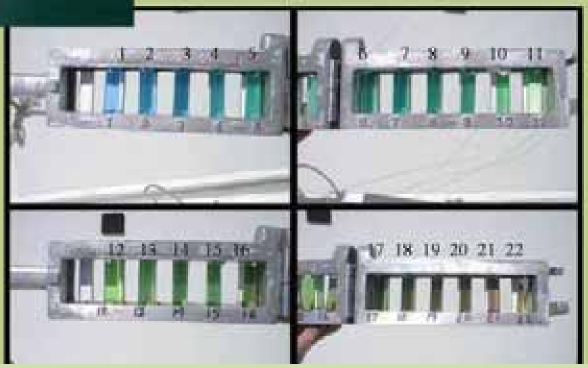

Figure 2. One of the oldest empirical methods for categorizing water color, the Forel-Ule color scale, is still available commercially. Water color, observed against a white background, is compared to the color of 22 standards ranging from deep blue to brown; the original Forel scale was introduced in 1889 by Swiss limnologist Françoise-Alphonse Forel, and was expanded upon three years later by the German limnologist Willi Ule (Hutchinson, 1975). Photo courtesy of Janet Vail, Grand Valley State University.

Water Mass Classification

BY ROBERT A. ARNONE, A. MICHELLE WOOD, AND RICHARD W. GOULD, JR.

algal pigments, the development of methods to extract these pigments from environmental samples, and the development of radiative transfer theory laid the foundation for the derivation of algorithms to retrieve important optical properties from ocean-color measurements made from space (Figure 4).

Initially, Morel and Prieur (1977) classified water masses as simply Case 1 or Case 2, based on spectral reflectance and attenuation. Case 1 waters are those in which variation in color are dominated by phytoplankton and their associated degradation products. As noted by Mobley et al. (this issue), the Case 1/Case 2 dichotomy continues to provide a central focus for debate and discussion.

Remote-sensing algorithms are being developed for many optical properties of seawater, including spectral absorption and spectral backscattering. These can be applied universally to coastal and offshore waters and are being evaluated in a number of regional field studies. Multivariate combinations of these satellite-derived optical parameters provide a basis for generating unique optical fingerprints for different water masses. As illustrated in Figure 5, three of the main components of ocean color (absorption by phytoplankton, detritus, and colored dissolved organic matter [CDOM]) can be used to classify coastal waters. Because the parameters used in this approach are very sensitive to biological and chemical processes, multivariate optical water mass classification has the potential to extend our understanding of fundamental ecological processes in the ocean in the same way that classification systems based on temperature and salinity have led to fundamental advances in our understanding of physical oceanography.

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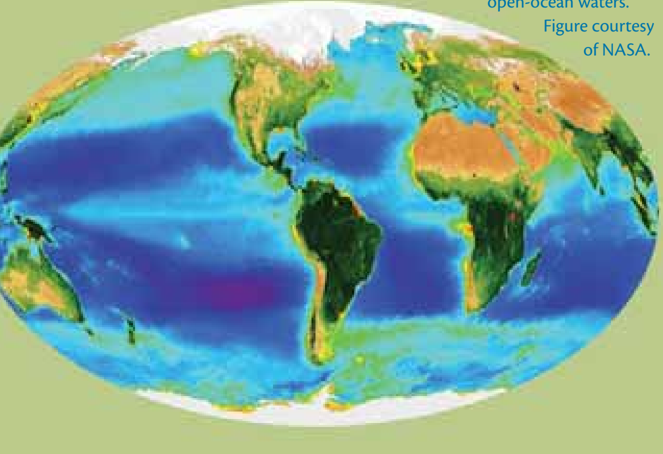
Morel, A., and L. Prieur, 1977: Analysis of variations in ocean color. *Limnol. Oceanogr.*, 22(4), 709-722.

Figure 4. The Coastal Zone Color Scanner in the 1980s provided the first global look at regional changes in ocean color by using chlorophyll and the attenuation coefficient at 490 nm (k490) to illustrate the variability of optical properties. Follow-on sensors from SeaWiFS (Sea-viewing Wide Field-of-view Sensor) and MODIS (Moderate Resolution Imaging Spectroradiometer) capitalized and refined spaceborne ocean-color measurement. These optical data (e.g., SeaWiFS chlorophyll image to the left) provide quantitative information on global ocean bio-optical properties and have clearly demonstrated the correlation between oceanic productivity and global circulation. Precision radiometric sensitivity available from ocean color satellites provides methods to monitor optical properties with sufficient spatial and temporal resolution to track changes in coastal and open-ocean waters. Figure courtesy of NASA.



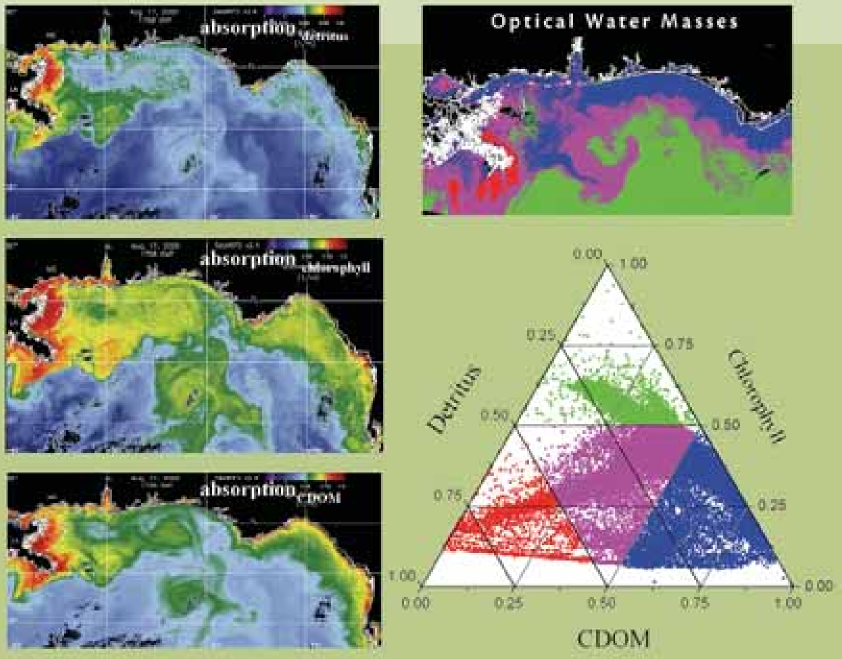


Figure 5. Quantitative bio-geo-optical information derived from SeaWiFS data permit scientists to decouple the sources of ocean color. Absorption coefficients from detritus, chlorophyll, and colored dissolved organic matter (CDOM) calculated from SeaWiFS (left top, middle, and bottom) from the northern Gulf of Mexico are used to estimate the percent each component contributes to total absorption in each pixel (plotted in three-dimensional space, bottom right). Optical water masses in which the majority of absorption is due to CDOM, detritus, and chlorophyll are coded blue, red, and green, respectively, in the ternary plot (bottom right); the color code is used to display the distribution of each optical water mass type (upper right). In this image, high contribution from detritus characterizes the Mississippi River plume and high CDOM concentration characterizes the near-coastal water.