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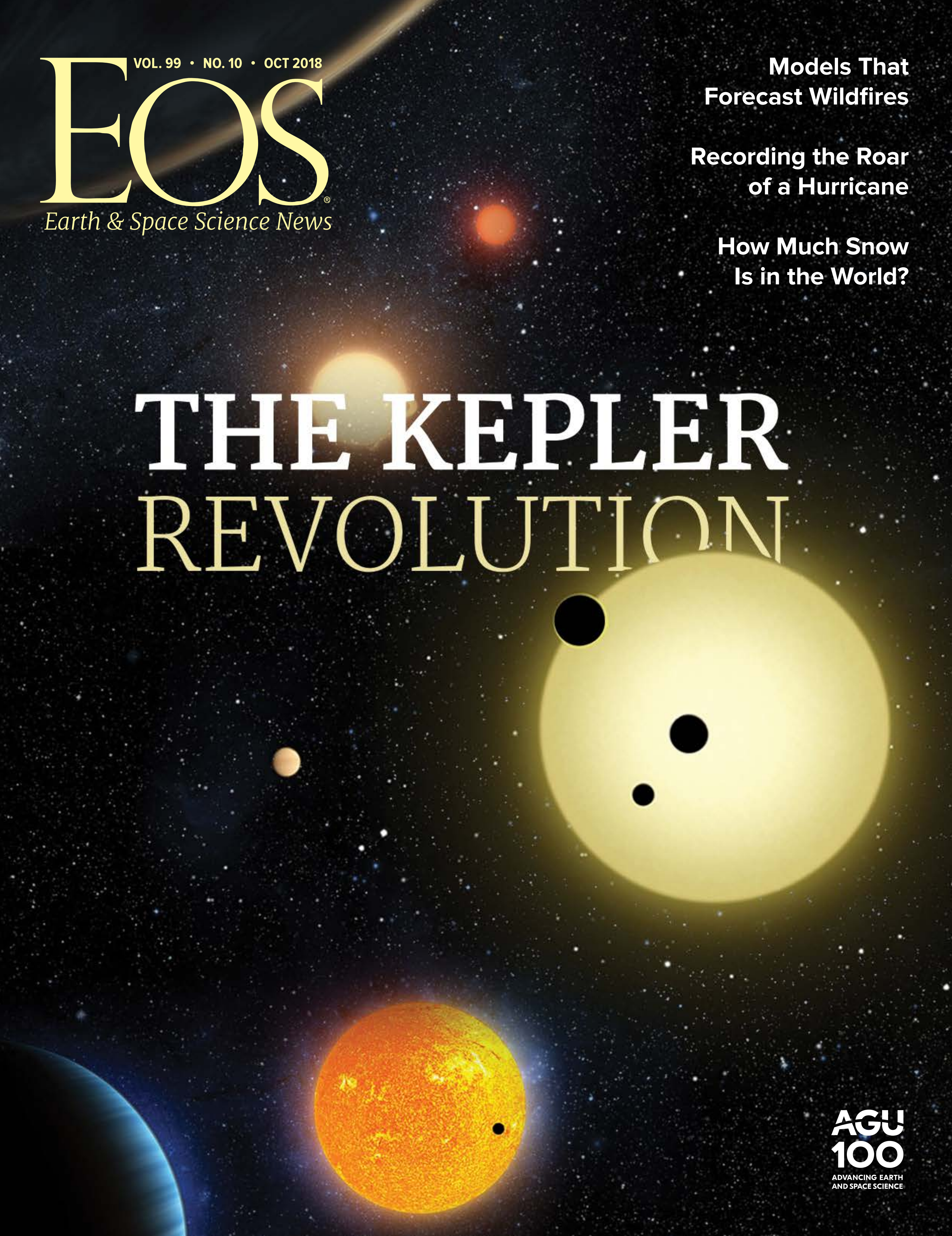

Global Water Clarity: Continuing a Century-Long Monitoring

Aquatic systems worldwide are changing because of increasing climate variability and human activities. Yet it is difficult to capture such changes without standardized long-term observations.

Water transparency or clarity is commonly represented as Secchi depth (Z_{SD}), measured with a Secchi disk. Secchi depth is determined by lowering the disk into the water and recording the depth at which it is no longer visible to an observer at the surface.

The measurement provides a first-order indicator of water quality and ecosystem health. Unlike other optical parameters, Z_{SD} can be easily and cost-effectively measured in the field. It has been measured for more than a century in global seas and lakes (Figure 1). Furthermore, Z_{SD} can be estimated from satellite radiometry.

By combining historical and continued Z_{SD} with satellite products, scientists could produce a standardized global Z_{SD} product. Such a product would represent a unique, century-long Earth system data record that would enable researchers to assess changes in water clarity in global seas and lakes. With such data, scientists could improve their evaluations of changes to phytoplankton abundance, river sedimentation, fisheries productivity, agriculture's effect on downstream ecosystems, and more.

Going in Depth on Secchi Depth

The observation and recording of water clarity dates back more than 300 years. In an effort to understand the phenomena behind changing water clarity, Europeans started systematically documenting water clarity in the early 18th century with wooden boxes, colored plates, and white and red cloths. But it was the development of the Secchi disk by Pietro Angelo Secchi (1818–1878) [*Secchi,* 1864] that led to the standardized monitoring of water transparency from 1865 onward by scientists and interested citizens.

The standard Secchi disk is a circular white disk with a diameter of 0.30 meter (disks with diameters of 0.5 or 1 meter were also used when the water was extremely clear). The design has remained largely unchanged since it was first developed, although black-and-white disks are commonly used in monitoring lakes.

Studies have found that Secchi disk observations are remarkably insensitive to variability in observer technique, local meteorological conditions, or the solid white versus black-and-white disks (see http://bit.ly/Secchi-study). As a result, roughly 1 million Z_{SD} measurements across the world's marine and inland water bodies have been collected over the past 150+ years, all with similar uncertainties (~10%–15%).

Field Programs to Measure Z_{SD}

Because Z_{SD} measurements are quite observer independent and are easy and cost-effective to deploy, various government-supported and citizen science programs have been developed to collect water quality data via Secchi disks. These have significantly increased the breadth and length of data records.

For instance, the state of Wisconsin has estimated that citizen-collected Z_{SD} observations since 1986 have a monetary value of ~$4 million. These data are freely accessible and have been used to provide water clarity trends of more than 8,000 lakes in the state. The data also help educate and engage the public on the health of their lakes.

Broader programs also exist. The Secchi Dip-In program, which is administered by the North American Lake Management Society, now boasts more than 41,000 records on more than 7,000 separate water bodies in the United States and Canada. In parallel, the Secchi Disk, EyeOnWater, and Seen-Beobachtung Program projects initiated in Europe have accumulated tens of thousands of Z_{SD} observations from lakes to open oceans.

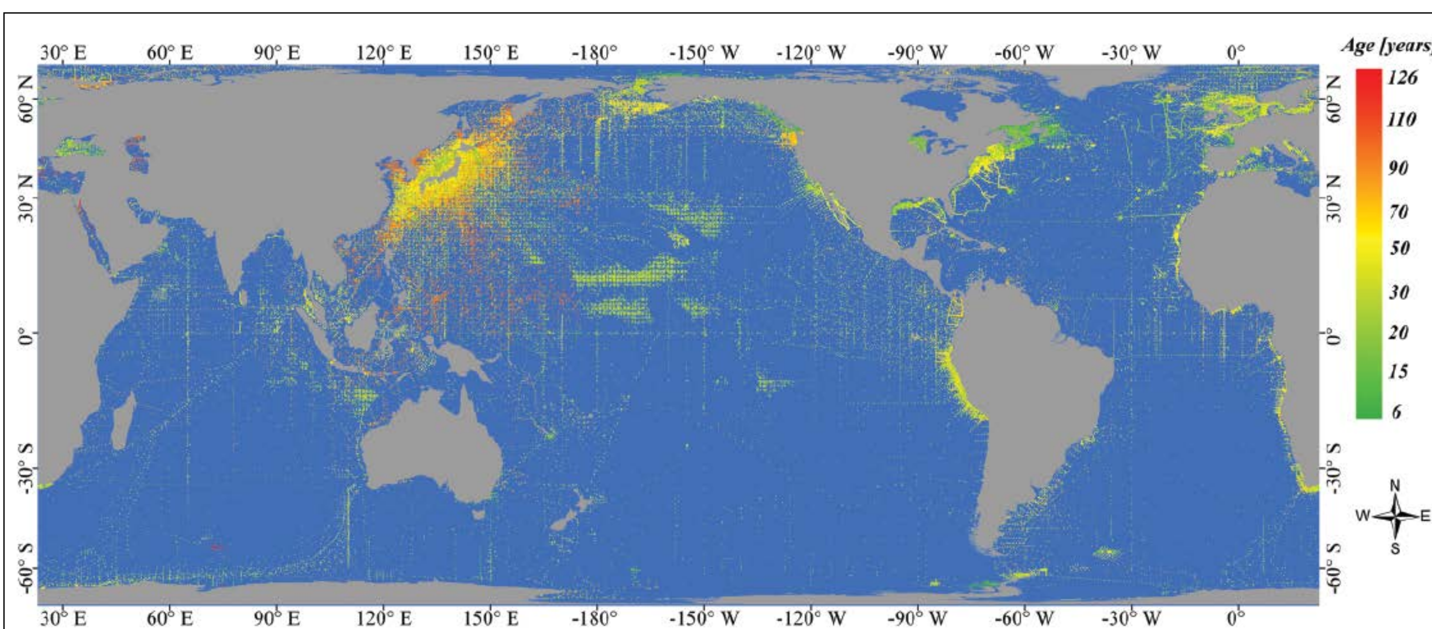

Fig. 1. Global map of some publicly available in situ Z_{SD} data. Colors depict the time series span (how long before 2016 the measurements were made) of available observations. Gray depicts landmasses, and blue depicts oceanic areas for which no in situ observations are available in our database.

Remote Sensing Approaches and Platforms to Estimate Z_{SD}

Z_{SD} can also be estimated from airborne or satellite radiometry, thus greatly increasing the geographic and temporal availability of water clarity observations. An early effort to collect such estimates started with empirical regressions that were used to relate multispectral Landsat signals to Z_{SD} in lakes (see http://bit.ly/Landsat-clarity).

Lower-resolution sensors such as the Moderate Resolution Imaging Spectroradiometer (MODIS) and Medium Resolution Imaging Spectrometer (MERIS) have also been effective in estimating Z_{SD} in estuaries and offshore marine waters. The combination of a series of Earth-observing satellite sensors, including the most recent Visible Infrared Imaging Radiometer Suite (VIIRS) and Sentinel-3, could enable the production of a near-daily record of global ocean color measurements now spanning nearly 2 decades.

Furthermore, Landsat 8 and Sentinel-2 have significantly improved radiometric precision and spectral sampling relative to their predecessors, making it possible to retrieve accurate water color at high spatial resolution for coastal waters and lakes. Thus, the research community is well on its way to providing Z_{SD} products at various spatial and temporal scales with sufficient accuracy through a combination of medium- and high-resolution satellite sensors, offering great potential for assessing water clarity changes on a routine basis at both local and global scales.

However, to date, there is no standardized Z_{SD} product from any of these satellite missions. The reason for this is, in part, a lack of community consensus on an appropriate algorithm to relate water color to Z_{SD} on the global scale. Recently, though, *Lee et al.* [2015] developed a new theory to interpret Z_{SD}. It has profound implications for Z_{SD} remote sensing, as it eliminates the need for local tuning as encountered in earlier estimations from satellite measurements. Examples of satellite-based Z_{SD} products are presented in Figure 2.

Tim Plude takes a Secchi reading on Wisconsin's Lake Tomahawk, October 2012. Credit: Laura Herman

Examples of Applications

If a standardized global Z_{SD} map at various time points could be created, opportunities for science studies would be manifold. Several realms could see significant scientific gains.

Evaluation of long-term changes in phytoplankton. A prerequisite to understanding the state of the world's waterways is obtaining standardized long-term measurements. For example, studies report that 40–60 years of standardized observations are required to reliably estimate time trends in phytoplankton concentration (see http://bit.ly/standard-time-trends), and a lack of such data may be responsible for conflicting reports of time-dependent changes in phytoplankton biomass. Coastal seas and inland waters often show a decline in water clarity, with some of these changes driven by pollution or climate change, whereas other areas show increases in transparency due to remediation. Scientists could achieve increased confidence in long-term changes in water clarity with standardized Z_{SD} products because of their direct representation and long-term data record (1865 to present).

Ecosystem monitoring. Scientists have found that Z_{SD} data are very valuable for consistent and systematic monitoring of ecosystems. Not only is Z_{SD} a good indicator of suspended particulate matter, but also it has been used as a trophic indicator for coral reef and overall

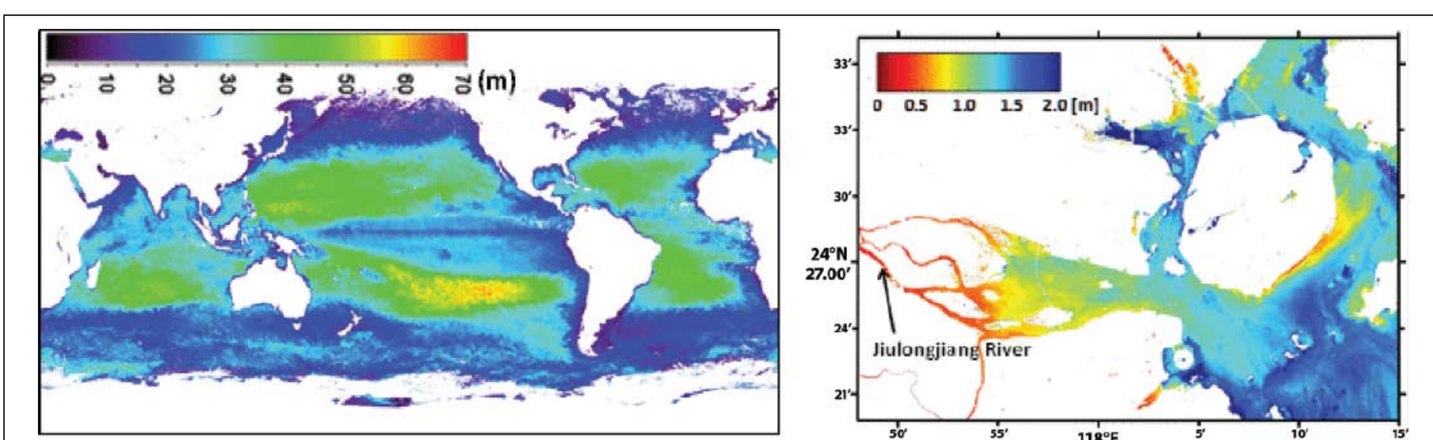

*Fig. 2. Global- to fine-scale Z_{SD} data derived from satellite measurements. (left) Global Z_{SD} derived from MODIS data (in autumn 2008); (right) Z_{SD} in the Jiulongjiang River estuary derived from Landsat 8 data collected on 4 August 2013. Credit: MODIS/Landsat/*Lee et al. *[2016]*

estuarine ecosystem status. Lake managers have used the metric to assess the status of lakes, where a lake's trophic state and algal biomass are related to Z_{SD}. Also, euphotic zone depth, an important indicator of ecosystem state, can be predicted from Z_{SD}.

Fisheries. Phytoplankton biomass production sets the carrying capacity of marine ecosystems and is highly correlated with commercial fishery landings, making Z_{SD} a valuable indicator of a fishery's productivity. Over most of the global ocean, where phytoplankton plays a dominant role in modulating water clarity, phytoplankton chlorophyll or primary production can be reasonably estimated from Z_{SD} measurements. Using such an approach, Z_{SD} observations could be used to explore changes in ocean ecosystems to support fisheries and to anticipate critical transitions in fish productivity. Separately, water clarity affects the predation dynamics within aquatic ecosystems, particularly for highly visual predators, which may affect ecosystem structure and fisheries.

Other users. Secchi disk and Z_{SD} products are also valuable for many other applications, such as coastal recreation and valuation of waterfront properties. For example, the U.S. Navy has used Z_{SD} products for many applications, including diver visibility and water mass classification.

Decades ago, a Secchi depth atlas was developed for the world's coastlines for waters less than 500 meters deep [*Arnone et al.*, 1985] as an initial effort to define coastal water optics for hydrographic charting systems that are constrained by water clarity. With advancements in both remote sensing algorithms and satellite sensors, a significantly revised atlas with improved spatial coverage, resolution, and accuracy will better meet many users' needs.

More broadly, variations in the attenuation of visible radiation in the upper ocean, which directly relate to changes in Z_{SD}, alter local heating and consequently have an effect on the thermal and fluid dynamical processes for the ocean-atmosphere system. Thus, a global, time-varying Z_{SD} product would provide a convenient way to measure local heating for inclusion in weather and climate models.

Z_{SD} in the Future

Understanding how aquatic environments will respond to ongoing human- and climate-related changes requires long-term time series. Although satellite measurements are spatially extensive, their coverage across time is limited (currently 1978–1986 and 1997–2017), making it difficult to differentiate trends driven by natural variability from those that are directed. The archive of Z_{SD} over the past century provides one of the longest-running (1865 to present) and most spatially extensive (global) standardized records to monitor Earth's aquatic environment.

Through careful calibration, historical Z_{SD} observations can and have been combined with new measurements and satellite products to greatly increase the spatial and temporal scales at which ocean changes are considered [e.g., *Boyce et al.*, 2017]. This database can also serve a critical need: to gauge the response of aquatic environments to a changing climate.

To date, however, Z_{SD} has not been a standard product of satellite missions. Although expanding the product suite of ocean color satellite missions to include Z_{SD} might be relatively easy because these contemporary sensors are well characterized and monitored, dedicated efforts are required to systematically evaluate Z_{SD} products from Landsat 8– and Sentinel-2-type land-targeted sensors to achieve sound monitoring on finer spatial scales.

Bridging Past and Future

Because of the deployment of advanced optical-electronic systems to measure inherent optical properties of waters, there is a tendency for reduced field measurements of Z_{SD} in contemporary oceanic surveys. Although the optical data provide more details about water constituents, the measurement systems are not yet mature, and the collections will never match the time span of the historical data record of Z_{SD}.

It is therefore critically important to continue monitoring Z_{SD} in both marine and freshwater environments to bridge the past and the future. With more than 150 years of global shipboard Z_{SD} records and synoptic Z_{SD} products of past (Coastal Zone Color Scanner (CZCS)) and future satellite sensors, the research community will not only obtain a clear picture of the current status of water clarity of the world's water bodies but also develop a more complete understanding of how and why water clarity is changing globally.

Acknowledgments

We dedicate this article to our coauthor Marcel Wernand, who recently passed away. Marcel was a pioneering researcher on the color and clarity of the sea. We are indebted to all scientists and citizens who provided the long record of Z_{SD} for community use, and we thank Xianfu Liu (South China Sea Marine Engineering and Environment Institute) for creating Figure 1 and Yonghong Li (Xiamen University) for creating Figure 2. The views expressed in this paper are those of the authors and do not represent the views or policies of the U.S. Environmental Protection Agency, the National Oceanic and Atmospheric Administration, or NASA.

References

Arnone, R. A., S. P. Tucker, and F. A. Hilder (1985), Secchi depth atlas of the world coastlines, *Proc. SPIE, 489,* 195–201, https://doi.org/10.1117/12.943305.

Boyce, D. G., et al. (2017), Environmental structuring of marine plankton phenology, *Nat. Ecol. Evol., 1,* 1,484–1,494, https://doi.org/10.1038/s41559-017-0287-3.

Lee, Z., et al. (2015), Secchi disk depth: A new theory and mechanistic model for underwater visibility, *Remote Sens. Environ., 169,* 139–149, https://doi.org/10.1016/j.rse.2015.08.002.

Lee, Z., et al. (2016), A semi-analytical scheme to estimate Secchi-disk depth from Landsat-8 measurements, *Remote Sens. Environ., 177,* 101–106, https://doi.org/10.1016/j.rse.2016.02.033.

Luksch, J. (1901), *Untersuchungen ber die Transparenz und Farbe de Seewassers. Wissenschaftliche Ergebnisse XIX. Expeditionen SM Schiff "Pola" im Mittellndischen, gischen und Rothen Meere in den Jahren 1890–1898. Berichte der Commission für Oceanographische Foeschungen. Collectiv-Ausgabe aus dem LXIX Bande der Denkschriften Kaiserlichen Akademie der Wissenschafte. A. Forschungen im Rothen Meere. B. Forschungen im Östlichen Mittelmeere.* Hof- und Staatsdruckerei, Vienna.

Secchi, P. A. (1864), Relazione delle esperienze fatte a bordo della pontificia pirocorvetta l'Immacolata Concezione per determinare la trasparenza del mare, in *Memoria del P. A. Secchi, Nuovo Cimento, 20,* 205–237, https://doi.org/10.1007/BF02726911.

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Editor's Note: Additional figures and hyperlinks to various studies discussed in this article can be found in its online version (http://bit.ly/Eos-Secchi-Depth).