A look into the physical properties of oceans: Response to the 2017 NRC Decadal Survey Request for Information

Cecile S. Rousseaux[1,2], Thorsten Markus[1], Watson W. Gregg[1], Paul Stysley[1], Carlos Del Castillo[1], Stephanie Uz[3], Tiffany Moisan[1], Ivona Cetinic[1,2], Anastasia Romanou[4,5], Antonio Mannino[1], Frank Muller-Karger[6]

[1] NASA Goddard Space Flight Center, Greenbelt, Maryland, USA; [2] Universities Space Research Association, Columbia, Maryland, USA; [3] Global Science & Technology Inc., Greenbelt, Maryland, USA; [4] Columbia University, New York, USA; [5] NASA Goddard Institute for Space Studies, New York, USA; [6] University of South Florida, Tampa, USA

Executive Summary

Temperature and salinity are two of the most important properties defining the state of seawater. Together they control density, which is a major factor governing the vertical movements of ocean waters and the biogeochemistry of the oceans. An instrument capable of deriving vertical profiles of temperature of the world's ocean quickly and repeatedly would significantly advance our current knowledge of the ocean dynamics. These potentially groundbreaking measurements would be useful in operational modeling, including for short-term prediction of weather (e.g. hurricane forecast), currents (e.g. transportation and oil spills), resource mapping of biodiversity and in fisheries management, in seasonal-to-interannual forecasting (e.g. El Niño), and for initializing decadal predictions of the ocean/atmosphere climate system (such as those of the IPCC). Lidar technology has been successfully used to derive the vertical profile of temperature using Brillouin scattering and achieve an accuracy of 0.07°C at 1 m horizontal spatial resolution in laboratory experiments [*Rudolf and Walther*, 2014]. While this technology is still in its infancy, the feasibility of the concept has been demonstrated and several methods have been proposed to improve the accuracy of the measurements.

IMPORTANCE:

The physical properties (temperature, salinity) of the upper layers of the ocean determine, to a large part, the global ocean circulation and its response to climate variability. Current satellite measurements of temperature have substantially improved our understanding of the oceans, but these integrated measurements are heavily biased towards surface waters. Currently scientists rely on buoy data to obtain vertical information on the temperature of oceans. The ARGO network has played a key role in our understanding of oceans. Recent technological developments have demonstrated the potential for Lidar to detect vertical profiles of temperature with an accuracy of up to 0.07°C by relying on the active generation and detection of spontaneous Brillouin scattering [*Rudolf and Walther*, 2014]. This technological development, in combination with the horizontal resolution achieved by current passive systems and the ARGO float network, could represent a major breakthrough in our ability to understand global as well as regional ocean dynamics. **The Quantified Earth Science Objective is to 'detect global spatially resolved vertical profiles of temperature in the oceans at a horizontal spatial scale of 1-km with an accuracy of ±0.07°C and a vertical resolution of 1 m'.**

The scientific progress that could be achieved with an instrument capable of deriving vertical properties of temperature in the oceans would directly contribute to the Decadal Survey Theme III: Marine and Terrestrial Ecosystems and Natural Resource Management. It could improve our understanding of temporal and spatial variability of ocean circulation and mixing as well as its direct feedback on the atmosphere circulation. It could also contribute to Focus Area of II: Weather and Air Quality: Minutes to Subseasonal because of the strong influence of ocean surface temperature on the atmospheric circulation including extreme weather events such as cyclones and hurricanes. Finally the assimilation of those vertical profiles of temperature into Earth System Models contribute to the fourth Focus area defined by the Committee on Earth Science and Applications from Space "IV. Climate Variability and Change: Seasonal to Centennial".

UTILITY:

Temperature, along with salinity, is one of the most important characteristics of seawater. Together they control its density which is a major factor governing the vertical movements of ocean waters, which in turns affects the biogeochemistry of the oceans. Global coverage of vertical temperature profiles are needed for our understanding of the mechanisms driving the ocean dynamics including ocean circulation, water mass characteristics, mixed layer depth, heat exchange, primary production and carbon fluxes. The dynamics and variability of these properties are of critical importance to our understanding of global climate system and how they interact with the oceans. An instrument capable of deriving global vertical profiles of temperature would significantly advance our current knowledge of the ocean dynamic. These groundbreaking measurements could be assimilated into operational modeling, for short-term prediction of currents (e.g. offshore oil spills) and temperature (e.g. fisheries), for seasonal-to-interannual forecasting (e.g. El Niño) and for initializing decadal predictions of the ocean/atmosphere climate system (such as those of the IPCC).

QUALITY:

Current measurements of vertical profile of temperature are limited in time and space coverage (e.g. ARGO floats) or provide only surface measurements (i.e. SSTs from satellite). Although maps of ARGO floats distribution can provide the sense of global coverage, it is important to note that on a daily basis the global coverage is far from uniform and heavily driven by currents and surface winds leaving some areas devoid of any measurements. They also sample each depth only once every 9 days. This can lead to considerable interpretation problems since the data are not only sparse but also biased spatially with a the average number of profiles in the northern hemisphere about 40% greater than in the southern hemisphere [*Roemmich and Gilson*, 2009]. These floats are designed to last about 4 years and therefore the distribution of floats and therefore vertical temperature profile can considerably change from year to year. The cost of maintaining this array is of ~24 million US$ a year with 28 countries contributing to this effort. Changes in the economy of any of these countries could change the current coverage.

Lidar technology used to study the vertical profile of temperature is based on Brillouin scattering principle. Laser pulses travel vertically into the ocean and the light scatters off thermal density fluctuations. The scattered light exhibits a frequency shift compared to the initially transmitted laser line. This Brillouin shift allows the determination of vertical water temperature and potentially salinity. While preliminary results have shown promising results, the efforts have been limited to a few international development teams [*Lee et al.*, 2001; *Rudolf and Walther*, 2014]. Currently, the variety of parameters that can be derived from Lidar instruments has not been fully explored and should be a focus of future developments. To achieve the Quantified Earth Science objective, developments should investigate the: (1) selection of optimal wavelengths as well as development of a multi-wavelength Lidar system to discriminate among water constituents including temperature and salinity, (2) scanning-approach or alike of the Lidar system, similar to the technology used on NASA's Operation IceBridge to allow for improved horizontal spatial resolution, and (3) different instrument configurations including receivers and laser combinations. These improvements should be done in coordination with proper calibration and validation of the systems using *in situ* (i.e. ARGO floats).

AFFORDABILITY:

Lidar systems have the capability to revolutionize the way we look at oceans and opening a new era of research leading to improved understanding of oceans, their circulation, role in the global carbon cycle and their feedback to the atmosphere. While the cost of active systems is greater than those of passive systems, the information that they would provide on the vertical dimension as well as the potential new parameters they could provide would significantly contribute to the field of Earth Science. Lidars have been used widely for applications ranging from mapping products to military applications and elevation maps of land, ice and coastal shorelines. Lidar technology can provide active capabilities that are currently unavailable from remote sensing platform; *(1)* by increasing the operational footprint in the vertical (deeper into the ocean) and horizontal (polar regions), and *(2)* by increasing the number of measurable parameters. So while these systems are more costly than current passive systems used, this new technology would strongly benefit from a support by the Earth Science Technology Office. Successful laboratory experiments have demonstrated the potential for lidar systems to remotely measure temperature profiles in water with an accuracy of 0.07°C at a spatial resolution of 1 m [*Rudolf and Walther*, 2014]. In clear ocean water, a detection depth of about 60 m can be expected [*Rudolf and Walther*, 2014]. The next step for this instrument development is to test its accuracy on a mobile platform before proceeding to a satellite mission. While several challenges are likely to be encountered when using the Lidar system on a mobile platform, the use of Lidar system in aircraft systems has been previously demonstrated for other key variables. For example, the High Spectral Resolution Lidar developed by NASA Langley is a Lidar system that has successfully measured vertical profile of particle backscattering and attenuation coefficient from an airborne instrument over the past few years. These developments could eventually benefit from each other and/or result in one single Lidar mission measuring a variety of oceanic variables.

SUMMARY

In summary, a Lidar instrument that detects vertical profiles of temperature in the oceans would greatly enhance our ability to monitor, model and forecast ocean circulation. Major developments are still required before becoming a satellite mission, but the proof of concept and first measurements have been successful. While this is a high risk mission, the potential return of an instrument that could provide global and systematic profiles of vertical temperature and salinity profiles in the ocean would revolutionize many areas of Earth Science including weather forecast and the effects of climate variability and change on oceans.

REFERENCES

Lee, K.-J., Y. Park, Y.-J. Shin, A. Bunkin, G. Lyakhov, S. Pershin, and K. Voliak (2001), LIDAR Measurement of Water Temperature by Using Frequency-Shifted Raman Scattering, JOURNAL-KOREAN PHYSICAL SOCIETY, 38(6), 659-665.

Roemmich, D., and J. Gilson (2009), The 2004–2008 mean and annual cycle of temperature, salinity, and steric height in the global ocean from the Argo Program, Progress in Oceanography, 82(2), 81-100.

Rudolf, A., and T. Walther (2014), Laboratory demonstration of a Brillouin lidar to remotely measure temperature profiles of the ocean, Optical Engineering, 53(5), 051407-051407.