therefore, has the potential to contribute to an emerging literature by examining the effects of climate change on international rivers and specifically the impact of changing river boundaries on conflict and cooperation. The new approach can generate knowledge through case studies, as the researchers show in a very preliminary form in the context of Southern Africa. In their assessment, the authors consider those river boundaries where mean annual runoff projected to 2080 exceeds 20%. The physical factors are then juxtaposed with socio-political factors identifying tensions that have historically existed between the riparians. Although causal connections are not made, the authors provide a good starting point for further investigation. In addition to the case-study approach, an analysis of a large number of observations (that is, a large-*n* study) to test a series of hypotheses can also be undertaken. Border length as well as other physical and socio-political factors can be considered in a systematic fashion. Insights into which border areas are most at risk as well as which basins have proper institutional capacity to deal with water variability along river boundaries can then be gleaned and useful policy implications provided. ❐

Shlomi Dinar is in the School of International and Public Affairs, Florida International University, SIPA 525, 11200 SW 8th Street, Miami, Florida 33174, USA.
e-mail: dinars@fiu.edu

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OCEANOGRAPHY

Where's the heat?

In recent decades, over nine-tenths of Earth's top-of-the-atmosphere energy imbalance has been stored in the ocean, which is rising as it warms. Combining satellite sea-level data with ocean mass data or model results allows insights into ocean warming.

Gregory C. Johnson and John M. Lyman

One could say that global warming is ocean warming. Quantifying how fast, and where, the ocean is warming is vital to understanding how much and how fast the atmosphere will warm, and seas will rise[1–4]. Historically, sparse and sometimes uncertain *in situ* ocean temperature data have made that quantification challenging[5]. Writing in *Nature Climate Change*, Paul Durack and colleagues[6] argue that previously published 0–700 m ocean warming rates based on *in situ* ocean temperature data are underestimated in the more sparsely sampled Southern Hemisphere, at least from 1970 until the advent of the Argo array of profiling floats[7] in the early 2000s. They reach this conclusion by analysing the *in situ* data together with satellite sea-level data and climate model results. Another study[8] published in *Nature Climate Change* concludes that the deeper half of the ocean (below 2 km depth) has, on average, not warmed from 2005 to 2013. William Llovel *et al.*[8] arrive at this result by combining satellite sea-level and ocean-mass-change data with unprecedentedly dense and high-quality Argo *in situ* temperature data from the upper half of the ocean volume (to depths of 2 km).

Changes in sea level and ocean temperature are closely linked by the fact that seawater expands as it warms. However, at least three factors complicate inferring one from the other directly. First, the transfer of water from land to ocean also contributes to sea-level rise, at a comparable magnitude to ocean warming[1]. This transfer has mostly been owing to melting of glaciers and ice sheets over recent decades. Second, the amount of sea-level rise depends on where the ocean warming occurs, because colder seawater can absorb several times more thermal energy than warmer water while contributing to the same amount of sea-level rise. Finally, regional redistributions of ocean salinity[9] and mass[10] also affect sea level.

Durack *et al.*[6] exploit the close relationship between upper-ocean warming and sea-level rise, the latter being well measured by satellites since 1992, to refine estimates of global ocean warming rates. They find good agreement between modelled and observed sea-level rise and poorer agreement between modelled and reported upper-ocean warming rates from 1970 to 2004, especially in the Southern Hemisphere. They argue that observational estimates of ocean warming rates in the Southern Hemisphere are likely biased low owing to the sparse historical temperature data there, and suggest that these estimates should be increased by 48–152% based on the ratio of observed sea-level rise and upper-ocean warming in the better-observed Northern Hemisphere.

Their results[6] are of importance because they imply an increase of 0.04–0.13 W m^{-2} in the global energy imbalance from 1970 to 2004, important for evaluating the performance of climate models. Also, quantifying how much of sea-level rise is owing to expansion of warming seawater versus transfer of water from land to ocean is important for understanding how much and how fast sea level will rise. However, as noted above, there are other, neglected, contributions to variations in sea level that could affect the results.

Llovel *et al.*[8] report that sea level has been rising at a global average rate of 2.78 mm yr^{-1} from 2005 to 2013 as estimated from satellite altimetry data. Over that period, ocean expansion from warming in the upper 2 km has accounted for 0.9 mm yr^{-1} of that rise, according to *in situ* ocean measurements, and transfer of freshwater into the ocean 2.0 mm yr^{-1}, according to satellite measurements of Earth's changing gravity field. The residual of those numbers implies a deep ocean cooling equivalent to a decrease in sea level of −0.13 mm yr^{-1}. This residual calculation was not possible before the advent of satellite gravity measurements in 2003 and the achievement of near-global measurements of ocean temperature and salinity in the upper 2 km by Argo starting around 2005.

Their result[8] is interesting because first, in contrast, analyses of sparse ship-based measurements below 2 km depth reveal that the deep ocean warmed from the 1990s to about 2005, contributing about 0.11 mm yr^{-1} of sea-level rise[11]. Second, the uncertainty for their residual estimate of the rate of deep ocean temperature change, equivalent to 0.44 W m^{-2} distributed over the surface area of Earth, is two-thirds the size of their central estimate, 0.64 W m^{-2}, of the net ocean warming from 2005 to 2013. Although their residual calculation is suggestive, its uncertainties are large.

Eliminating the deep-ocean measurement gap would reduce uncertainties and increase confidence in the robustness of sea-level and planetary energy-imbalance budgets by allowing complete cross checks among ocean mass, ocean warming and sea-level measurements. Argo has revolutionized large-scale observational physical oceanography for the upper 2 km of the ocean[7], but more temperature data and salinity data are now required in the half of the ocean volume below 2 km depth. Global ship-based oceanographic surveys, while invaluable in the accuracy and variety of data they collect, are too expensive to gather the quantity of deep ocean temperature and salinity data needed.

To close this deep-ocean measurement gap, work is proceeding on 'Deep Argo', on which one of us, G.C.J., is a principal investigator. This project is a proposed global array of profiling floats capable of measuring temperature and salinity to high accuracy and to depths of 6 km. In June 2014, scientists deployed two Deep Argo floats (Fig. 1) east of New Zealand. Scientists of various nations are developing regional Deep Argo pilot arrays in other areas that have exhibited large abyssal and deep-ocean temperature and salinity variability, including the Southern and North Atlantic oceans. With hard work and commitment, a decade from now, the fledgling regional Deep Argo arrays could grow and merge to become global. If they do, ocean heat content and sea-level budgets will no longer be hampered by a residual term.

Both studies published this month highlight the importance of ocean temperature measurements to understanding and predicting our changing climate — including future increases in atmospheric temperature and sea level. Durack *et al.*[6] use satellite sea-level data and the better-sampled Northern Hemisphere ocean temperature record, along with climate model results, to make inferences about sparsely measured warming in the Southern Hemisphere upper ocean, before Argo achieved near-global coverage. Llovel *et al.*[8] estimate ocean warming in the sparsely sampled lower half of the ocean volume below 2 km depth using the residual of satellite measurements of sea level, ocean mass and near-global Argo measurements of temperature in the upper 2 km. Both studies take advantage of advances in the observing system, but also rely on correlations or residuals from budget calculations to compensate for missing observations. It is time to close the deep-ocean measurement gap and reduce the uncertainties in global planetary energy and sea-level budgets. ❒

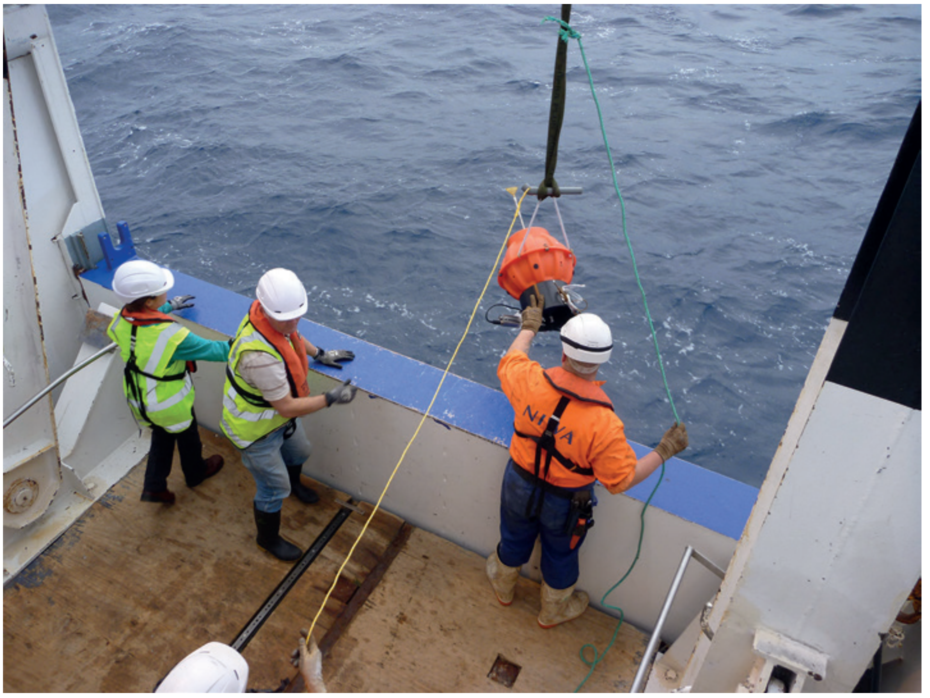

Figure 1 | Deep Argo float deployment. Scientists and technicians deploy the first of two Deep Argo floats from RV *Tangaroa* in June 2014 over the abyssal plain east of New Zealand, a deep (>5.5 km) ocean region where bottom waters that spread north after sinking near Antarctica have exhibited significant warming over recent decades[11]. These floats, designed and built at the Scripps Institution of Oceanography, are capable of profiling to depths of 6 km, allowing sampling of almost all of the ocean volume. The orange plastic case covers a glass flotation sphere containing machinery, circuitry and batteries, and a GPS and Iridium antenna is pointed away from the ship. Part of the scientific sensor package is visible to the left of the black plastic cylinder. Photo: LEARNZ www.learnz.org.nz — part of CORE Education http://www.core-ed.org/

Gregory C. Johnson[1] and John M. Lyman[1,2] are at the [1]National Oceanic and Atmospheric Administration Pacific Marine Environmental Laboratory, 7600 Sand Point Way NE, Building 3, Seattle, Washington 98115, USA and [2]University of Hawaii Joint Institute for Marine and Atmospheric Research, 1000 Pope Road, Marine Science Building, Honolulu, Hawaii 96822, USA.
e-mail: gregory.c.johnson@noaa.gov; john.lyman@noaa.gov

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