externally driven cooling caused by a succession of volcanic eruptions. The legacy of this new understanding will certainly outlive the recent warming slowdown. This is particularly true in the embryonic field of decadal climate prediction, where the challenge is to simulate how the combined effects of external forcing and internal variability produce the time-evolving regional climate we will experience over the next ten years[35]. ❐

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References

1. Flato, G. *et al.* in *Climate Change 2013: The Physical Science Basis* (eds Stocker, T. F. *et al.*) Ch. 9 (IPCC, Cambridge Univ. Press, 2013).
2. Trenberth, K. E. *Science* **349,** 691–692 (2015).
3. Morice, C. P., Kennedy, J. J., Rayner, N. A. & Jones, P. D. *J. Geophys. Res.* **117,** D08101 (2012).
4. Karl, T. R. *et al. Science* **348,** 1469–1472 (2015).
5. Hansen, J., Ruedy, R., Sato, M. & Lo, K. *Rev. Geophys.* **48,** RG4004 (2010).
6. Fyfe, J. C., Gillett, N. P. & Zwiers, F. W. *Nature Clim. Change* **3,** 767–769 (2013).
7. Easterling, D. R. & Wehner, M. F. *Geophys. Res. Lett.* **36,** L08706 (2009).
8. Lewandowsky, S., Risbey, J. S. & Oreskes, N. *Sci. Rep.* **5,** 16784 (2015).
9. Rajaratnam, B., Romano, J., Tsiang, M. & Diffenbaugh, N. S. *Climatic Change* **133,** 129–140 (2015).
10. Santer, B. D. *et al. J. Geophys. Res.* **116,** D22105 (2011).
11. Meehl, G. A. *et al. J. Climate* **26,** 7298–7310 (2013).
12. Kosaka, Y. & Xie, S.-P. *Nature* **501,** 403–407 (2013).
13. England, M. H. *et al. Nature Clim. Change* **4,** 222–227 (2014).
14. Steinman, B. A., Mann, M. E. & Miller, S. K. *Science* **347,** 988–991 (2015).
15. Risbey, J. *et al. Nature Clim. Change* **4,** 835–840 (2014).
16. Meehl, G. A., Teng, H. & Arblaster, J. M. *Nature Clim. Change* **4,** 898–902 (2014).
17. Nieves, V., Willis, J. K. & Patzert, W. C. *Science* **349,** 532–535 (2015).
18. Dai, A., Fyfe, J. C., Xie, S.-P. & Dai, X. *Nature Clim. Change* **5,** 555–559 (2015).
19. Solomon, S. *et al. Science* **333,** 866–870 (2011).
20. Cowtan, K. & Way, R. G. *Quart. J. Roy. Meteorol. Soc.* **140,** 1935–1944 (2014).
21. Mears, C. A., Wentz, F. J., Thorne, P. & Bernie, D. *J. Geophys. Res.* **116,** D08112 (2011).
22. Christy, J. R., Norris, W. B., Spencer, R. W. & Hnilo, J. J. *J. Geophys. Res.* **112,** D06102 (2007).
23. Santer, B. D. *et al. Nature Geosci.* **7,** 185–189 (2014).
24. Meehl, G. A. *et al. Nature Clim. Change* **1,** 360–364 (2011).
25. Domingues, C. M. *et al. Nature* **453,** 1090–1093 (2008).
26. Lewandowsky, S., Risbey, J. & Oreskes, N. *Bull. Amer. Meteorol. Soc.* http://dx.doi.org/10.1175/BAMS-D-14-00106.1 (2015).
27. Marotzke, J. & Forster, P. M. *Nature* **517,** 565–570 (2015).
28. Meinshausen, M. *et al. Climatic Change* **109,** 213–241 (2011).
29. Huber, M. & Knutti, R. *Nature Geosci.* **7,** 651–656 (2014).
30. Sherwood, S. C. & Nishant, N. *Environ. Res. Lett.* **10,** 054007 (2015).
31. Po-Chedley, S., Thorsen, T. J. & Fu, Q. *J. Climate* **28,** 2274–2290 (2015).
32. Schmidt, G. A., Shindell, D. T. & Tsigaridis, K. *Nature Geosci.* **7,** 158–160 (2014).
33. Hawkins, E., Edwards, T. & McNeall, D. *Nature Clim. Change* **4,** 154–156 (2014).
34. Thoma, M., Greatbatch, R. J., Kadow, C. & Gerdes, R. *Geophys. Res. Lett.* **42,** 6454–6461 (2015).
35. Meehl, G. A. *et al. Bull. Amer. Meteorol. Soc.* **95,** 243–267 (2014).

Acknowledgements

We thank Thomas Karl, Susan Solomon, Jochem Marotzke, Stefan Rahmstorf, Steve Lewandowsky, James Risbey and Naomi Oreskes for their comments on earlier drafts. We acknowledge the Program for Climate Model Diagnosis and Intercomparison and the World Climate Research Programme's Working Group on Coupled Modelling for their roles in making the WCRP CMIP multi-model datasets available. Portions of this study were supported by the Regional and Global Climate Modeling Program (RGCM) of the US Department of Energy's Office of Biological & Environmental Research (BER) Cooperative Agreement # DE-FC02-97ER62402, and the National Science Foundation.

Author contributions

J.C.F. and G.A.M. conceived the study. J.C.F. undertook the calculations and wrote the initial draft of the paper. All the authors helped with the analysis and edited the manuscript.

COMMENTARY:

Keeping the lights on for global ocean salinity observation

Paul J. Durack, Tong Lee, Nadya T. Vinogradova and Detlef Stammer

Insights about climate are being uncovered thanks to improved capacities to observe ocean salinity, an essential climate variable. However, cracks are beginning to appear in the ocean observing system that require prompt attention if we are to maintain the existing, hard-won capacity into the near future.

Temperature is probably the first thing that springs to mind whenever climate change is mentioned; however, changes to the global water cycle — where, when and how it rains, and the corresponding changes to water availability — are as pressing an issue and a fundamental focus for research. The global ocean is the best place to ascertain these water cycle changes, as it contains 97% of the Earth's water and is where 80% of fluxes — water exchanges at the Earth's surface — occur[1,2] (Fig. 1).

Thanks to the efforts of many generations of oceanographers, scientists currently undertaking oceanographic research are living in the 'golden age' of ocean observation. The backbone of ocean measurements that were originally obtained from ocean research dating back to the original *RV Challenger* cruise in 1872 and subsequent vessels have been supplemented since 1999 by automated profilers called Argo[3], and a coherent global network of repeat ocean section sampling is being undertaken by the GO-SHIP Program[4]. Argo has provided the first continuous, near-global salinity (and temperature) observing system, taking measurements for the top 2,000 metres and a target density of one float per 3 × 3 degrees of the global ocean, cycling at ten-day intervals in near real-time. This has significantly increased measurement coverage and density in both hemispheres (see Supplementary Figs 1,2). The remote measurements from Argo are quality controlled and validated against the ship-borne measurements obtained from the GO-SHIP program, with this program also solely responsible for all observations deeper than 2,000 metres along with the complementary measurements of carbon, trace metals and CFCs. Additionally, sea surface salinity (SSS) has been measured from space since May 2010 by the European Space Agency's Soil Moisture and Ocean Salinity (SMOS) mission, and by NASA's Aquarius and Soil Moisture Active-Passive (SMAP) missions during August 2011 to June 2015, and since April 2015 respectively. These satellite systems complement the *in situ* network by providing global coverage of SSS, with denser spatial and temporal sampling than the Argo or GO-SHIP networks. Collectively, these multi-platform measurements close out what is now truly a global observing system for ocean salinity.

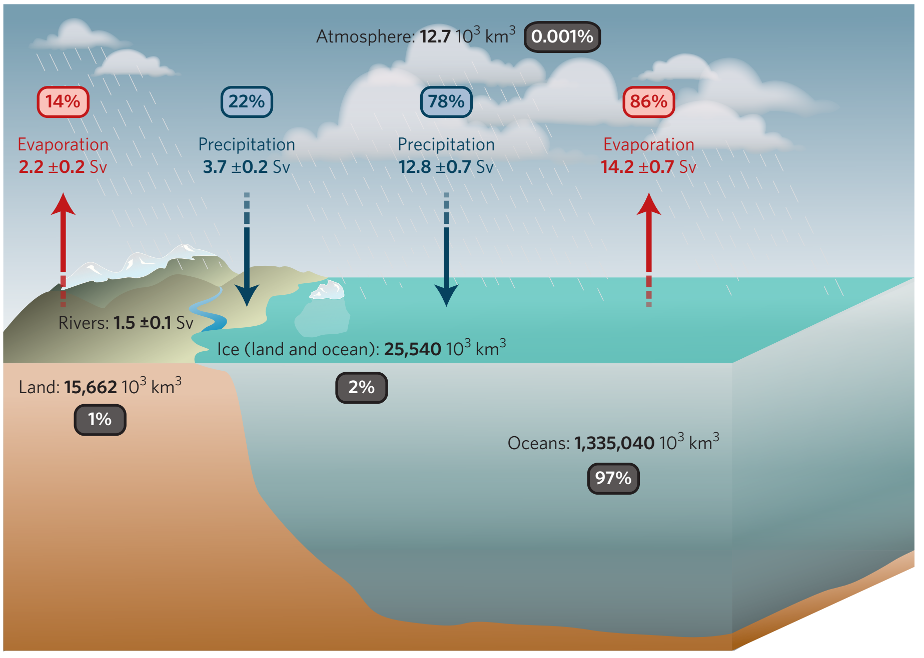

Figure 1 | The global water cycle — the oceanic perspective. Reservoirs are represented by grey boxes with units 10^3 km^3. Fluxes are represented by arrows and the red and blue boxes with units of Sv (Sverdrups; 10^6 m^3 s^{-1}). Data from refs 2, 31–35.

A boom in ocean research

The establishment of this expanded measurement network has led to a boom in ocean research and considerable progress in understanding the 71% of the Earth's surface that is ocean. In particular, Argo provides the bulk of Southern Hemisphere *in situ* observations — a historically poorly sampled part of the ocean — with more than three times greater coverage than earlier ship-based hydrographic profiles that collectively comprise the World Ocean Database 2013[5] of the National Oceanic and Atmospheric Administration (NOAA). The improved salinity observing capacity has facilitated exciting research, focusing on many aspects of ocean variability and change, along with atmosphere–ocean and terrestrial–ocean interactions. In an effort to document research progress, new results regarding ocean salinity were recently presented at the Open Science Conference on Salinity and Freshwater Changes in the Ocean, held in Hamburg, Germany, in October 2015.

Presentations highlighted the utility of salinity as a water cycle predictor of rainfall for regions in Africa and the United States[6], interactions between salinity and atmospheric rain cells[7,8], as an independent constraint on ocean–atmosphere CO_2 exchanges[9] and in ocean heat and freshwater flux estimates[10,11]. Salinity additionally provides an independent insight into atmospheric moisture transport, and interactions between the terrestrial and oceanic water cycles through river runoff[12,13]. The roles of salinity in ocean dynamics were also highlighted, and include changes to sea level[14,15], inter-ocean freshwater exchanges[16] and variability associated with oceanic features such as planetary waves[17], fronts[18] and eddies[19].

Without this systematic global ocean salinity observing system and the research it has facilitated, the significant progress reported in the IPCC Fourth and Fifth Assessment Reports[20,21] would not have been possible. An optimistic oceanographer could say that due to the coordination of the global ocean research community over the past two decades, systematic ocean observations leapfrogged their better-established atmospheric counterparts. This advance has underpinned research into the Earth's changing energy budget[4,22–25], water cycles[1,4,26,27] and ocean circulation and ocean state estimation[10], considerably reducing uncertainties. Thanks to the systematic measurements provided by Argo and GO-SHIP new light has been shed on climate system components that up until recently oceanographers were still 'in the dark' about. The importance of salinity measurements have been further highlighted because ocean salinity is now considered an Essential Climate Variable and an important part of the World Meteorological Organisation's Global Climate Observing System (GCOS), and the ocean-centric Global Ocean Observing System.

Stability of ocean observing capacity

Although this commendable progress in observing and improving our understanding of the ocean system should be celebrated, there is no room for complacency when it comes to preserving and maintaining the existing measurement coverage. In some senses the profound success of the past decade of ocean observation is its biggest challenge. With over 30 nations currently contributing to Argo (Supplementary Fig. 1), no single country or funding agency is solely responsible for the program. So far, United States agencies, principally NOAA, have funded about half of the global Argo deployments and they have achieved this with fixed funding over the past decade. "While the large number of presently active floats is a sign of Argo's success to date, flat or declining Argo support levels in many nations pose a serious challenge to sustaining the array," said Dean Roemmich from Scripps Institution

Figure 2 | Historical and projected Argo float deployments and the resulting global array density. Due to a reduction in projected Argo float deployments, the array is anticipated to drop beneath 3,200 in 2018.

of Oceanography and the co-chair of the global Argo Program. So far, the funding slide has been masked by improvements in Argo float technology, both in terms of battery life and float reliability. Recently deployed floats have longer average lifetimes than their predecessors, but these efficiency gains may be plateauing. Further reductions in the number of floats deployed will lead to a fall in active float numbers and will threaten the comprehensive measurement coverage (Fig. 2). "It takes some time for cracks to appear in Argo coverage, and if these are in remote regions then we're really in trouble as it takes long-term planning to get floats back out there," said Susan Wijffels from CSIRO Oceans and Atmosphere Flagship and co-chair of the global Argo Program. All these challenges are occurring in parallel to a significant broadening of the original Argo Program, which is now expanding into full-depth ocean sampling along with ocean biogeochemistry[3].

Future forecasts are inherently difficult to generate, due to the short-term nature of national budgets, along with unanticipated technology and deployment problems or new technology breakthroughs. These are further confounded by a critical dependence on each and every nation that contributes to the array — and a loss of just one of these key contributors will have a profound impact. However, using current projections, floats in the current 3,900-strong Argo array are anticipated to drop below 3,200 — the global array minimum target — in 2018 (Fig. 2). Such a large decrease in operational floats would considerably undermine the ability of the observing system to monitor and measure the global ocean, which would blast a big hole in the GCOS. Currently, even with the full-strength observing network in place, there are parts of the ocean that are not adequately observed[3,28,29] (Supplementary Fig. 2), and any reduction in measurement coverage is a big backward step in global climate observation and monitoring. In 2014, the New York Times highlighted Argo as "one of the scientific triumphs of the age"[30] and this transformational ocean measurement program should be nurtured, grown and improved by all nations.

The situation with GO-SHIP is similar — currently 11 nations share responsibility for the 53 repeat ocean transects in the program (Supplementary Fig. 3). GO-SHIP activity levels have been reduced year on year, due to inflationary cuts and the realignment of national research priorities of the funding nations. While cruises are planned up to 2023, fewer cruises are currently committed when contrasted with previous years. As summarized by Lynne Talley from Scripps Institution of Oceanography and the US GO-SHIP co-chair, "sustaining the ship-based, full-depth ocean measurements coordinated through GO-SHIP is a very high priority, particularly because we anticipate accelerating changes to the ocean system in the coming decades." As noted by NOAA oceanographer and US GO-SHIP co-chair, Gregory Johnson "Argo cannot exist in a vacuum as these are remote platforms subject to calibration drift; consistency checks with the GO-SHIP repeat hydrographic surveys provide the measurement calibration bedrock that is pivotal in maintaining Argo measurement accuracy in the face of long-term changes that are being uncovered by new research. In addition, GO-SHIP is the only observing network that routinely samples beneath 2,000 metres depth, and has shown that salinity and temperature are changing there, as well as actively measuring other key ocean variables throughout the water column."

For spaceborne systems, the Aquarius mission (the only mission solely dedicated to measuring SSS) ended in June 2015 after a power failure of the spacecraft. Although SSS is being retrieved from SMAP, the mission was designed for land applications so it is difficult to achieve the accuracy of Aquarius's SSS using SMAP measurements, even though they provide better spatial resolution. SMOS is five years into its mission life time. No satellite mission devoted to SSS has been commissioned for the coming decade, and consequently a gap in spaceborne SSS measurements is looming.

Maintenance and augmentation

There is an explicit assumption that the global ocean observing system is here to stay. Whether from researchers, assuming that ocean measurements will continue and are made available to underpin their proposed research, or for operational climate and weather centres that are developing a dependence on these comprehensive data streams to assimilate into their analyses. However, this assumption and expectation is becoming questionable if prompt action to supplement these programs is not made.

It is important to note that funding for Argo and GO-SHIP is not guaranteed. Funding is secured through competitive research grants, requiring justification of the utility of these programs each and every time the funding cycle repeats. This effort is becoming more and more difficult in the new paradigm of reduced budgets and burgeoning research priorities and foci.

In spite of holes in *in situ* measurement coverage looming large on the near-term horizon, both the Argo and GO-SHIP teams are working hard to preserve and maintain the ocean observing capacity. But they need additional support to achieve this aim. In the case of GO-SHIP, new nations are becoming involved, "We're welcoming new contributors to GO-SHIP, with Ireland a new partner for an upcoming North Atlantic transect. However, we're in need of more support to maintain coverage in the North Pacific and Indian Oceans," said Bernadette Sloyan from CSIRO Oceans and Atmosphere Flagship and the co-chair of the global GO-SHIP program (see Supplementary Fig. 3). Without new funding and help from currently unengaged nations, the measurement coverage provided by the existing Argo and GO-SHIP arrays remains in jeopardy.

In addition to the requirement for continuing satellite SSS measurements, there is also a critical need for innovative technology to improve their accuracy, especially in high-latitude oceans where the current L-band radiometers (for example, on SMOS, Aquarius and SMAP) have poor sensitivity to salinity. It is also important to improve the spatial resolutions of satellite SSS to better resolve mesoscale variability and to capture sub-mesoscale features that are important to ocean dynamics and marine ecosystems, particularly in coastal regions and marginal seas that provide direct linkages to the terrestrial element of the water cycle.

With new data showing that 2015 was the hottest year since instrumental records began, and with even larger changes expected into the future, it underscores the importance of this comprehensive observing capacity for the global climate system. Considering that the ocean has been responsible for more than 90% of the additional heat storage in the climate system[21,24,25], and the crucial role it plays in the global water cycle[1,4,26,27], it is fundamental that we maintain and augment our current ocean observing capacity now and into the distant future. ❐

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References

1. Durack, P. J. *Oceanography* **28,** 20–31 (2015).
2. Rodell, M. *et al. J. Clim.* **28,** 8289–8318 (2015).
3. Riser, S. C. *et al. Nature Clim. Change* **6,** 145–153 (2016).
4. Talley, L. D. *et al. Annu. Rev. Mar. Sci.* **8,** 185–215 (2016).
5. Boyer, T. P. *et al.* NOAA Atlas NESDIS 72 (ed. Levitus, S.) 209 (World Ocean Database, 2013); http://go.nature.com/rnJyxp
6. Liu, W. T., Xie, X. & Katsaros, K. B. *Remote Sens. Environ.* **123,** 593–599 (2012).
7. Boutin, J. *et al. J. Geophys. Res.-Oceans* **119,** 5533–5545 (2014).
8. Asher, W. E., Jessup, A. T., Branch, R. & Clark, D. *J. Geophys. Res.-Oceans* **119,** 5483–5500 (2014).
9. Fournier, S., Chapron, B., Salisbury, J., Vandemark, D. & Reul, N. *J. Geophys. Res.-Oceans* **120,** 3177–3192 (2015).
10. Vinogradova, N. T. & Ponte, R. M. *J. Geophys. Res.-Oceans* **118,** 3190–3201 (2013).
11. Köhl, A., Sena Martins, M. & Stammer, D. *J. Geophys. Res.-Oceans* **119,** 5449–5464 (2014).
12. Grodsky, S. A., Reverdin, G., Carton, J. A. & Coles, V. J. *Remote Sens. Environ.* **140,** 14–22 (2014).
13. Korosov, A., Counillon, F. & Johannessen, J. A. *J. Geophys. Res.-Oceans* **120,** 268–283 (2015).
14. Durack, P. J., Wijffels, S. E. & Gleckler, P. J. *Environ. Res. Lett.* **9,** 114017 (2014).
15. Llovel, W. & Lee, T. *Geophys. Res. Lett.* **42,** 1148–1157 (2015).
16. Gordon, A. L., Giulivi, C. F., Busecke, J. & Bingham, F. M. *Oceanography* **28,** 32–39 (2015).
17. Lee, T. *et al. J. Geophys. Res.-Oceans* **119,** 8375–8394 (2014).
18. Kao, H.-Y. & Lagerloef, G. S. E. *J. Geophys. Res.-Oceans* **120,** 1096–1106 (2015).
19. Bryan, F. & Bachman, S. *J. Phys. Oceanogr.* **45,** 724–736 (2015).
20. Bindoff, N. L. *et al.* in *Climate Change 2007: The Physical Science Basis* (eds Solomon, S. *et al.*) Ch. 5, 385–432 (Cambridge Univ. Press, 2007).
21. Rhein, M. *et al.* in *Climate Change 2013: The Physical Science Basis* (eds Stocker, T F. *et al.*) Ch. 3, 255–315 (Cambridge Univ. Press, 2013).
22. Roemmich, D., Gould, W. J. & Gilson, J. *Nature Clim. Change* **2,** 425–428 (2012).
23. Roemmich, D. *et al. Nature Clim. Change* **5,** 240–245 (2015).
24. Gleckler, P. J., Durack, P. J., Stouffer, R. J., Johnson, G. C. & Forest, C. E. *Nature Clim. Change* http://dx.doi.org/10.1038/nclimate2915 (2016).
25. Von Schuckmann, K. *et al. Nature Clim. Change* **6,** 138–144 (2016).
26. Helm, K. P., Bindoff, N. L. & Church, J. A. *Geophys. Res. Lett.* **37,** L18701 (2010).
27. Durack, P. J., Wijffels, S. E. & Matear, R. J. *Science* **336,** 455–458 (2012).
28. Heuzé, C., Vivier, F., Le Sommer, J., Molines, J. M. & Penduff, T. *J. Geophys. Res.-Oceans* **120,** 7960–7978 (2015).
29. Wunsch, C. *Annu. Rev. Mar. Sci.* **8,** 1–33 (2016).
30. Gillis, J. *New York Times* (11 Aug 2014); http://go.nature.com/aH7vmX
31. Baumgartner, A. & Reichel, E. *The World Water Balance: Mean Annual Global, Continental and Maritime Precipitation, Evaporation and Runoff* (Elsevier, 1975).
32. Schmitt, R. W. *Rev. Geophys.* **33,** 1395–1409 (1995).
33. Trenberth, K. E., Smith, L., Qian, T., Dai, A. & Fasullo, J. *J. Hydrometeorol.* **8,** 758–769 (2007).
34. Schanze, J. J., Schmitt, R. W. & Yu, L. L. *J. Mar. Res.* **68,** 569–595 (2010).
35. Steffen, K. *et al.* in *Understanding Sea-Level Rise and Variability* (eds Church, J. A., Woodworth, P. L., Aarup. T. & Wilson, W. S.) Ch. 7, 178–225 (Blackwell, 2010).

Acknowledgements

The authors would like to thank Dean Roemmich, Susan E. Wijffels, Lynne D. Talley, Gregory C. Johnson and Bernadette M. Sloyan for providing information for the international Argo and GO-SHIP programs respectively. We also thank Mathieu Belbeoch, Argo Coordinator at JCOMMOPS, for providing Argo deployment and active float activity data. The work of P.J.D. from Lawrence Livermore National Laboratory, is a contribution to the US Department of Energy, Office of Science, Climate and Environmental Sciences Division, Regional and Global Climate Modeling Program under contract DE-AC52-07NA27344. The work by T.L. was carried out at the Jet Propulsion Laboratory, California Institute of Technology under a contract with the National Aeronautic and Space Administration (NASA). The work by N.T.V. was supported by NASA's Physical Oceanography Program.

Additional information

Supplementary information is available in the online version of the paper.