These Frequently Asked Questions (FAQs) have been written in support of "Quantifying Underestimates of Long-Term Upper-Ocean Warming" By Paul J. Durack, Peter J. Gleckler, Felix W. Landerer and Karl E. Taylor – published in *Nature Climate Change* online 5th October 2014
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Graphics and media materials are available from j.mp/warmingocean

Why is it important to understand ocean temperature changes?
The heat capacity of the Earth's entire atmosphere is equalled by the top 3.5 meters of the ocean, a very small fraction compared to the amount of heat stored by the full-depth ocean. Accordingly, the ocean's massive heat capacity accounts for more than 90% of the heat gained by the climate system over the last several decades as greenhouse gas concentrations have increased. Thus, to obtain an accurate estimate of how much the Earth has warmed, it is critical that we have accurate global ocean temperature measurements.

What are the implications of long-term underestimates to ocean warming?
Quantifying how much heat is accumulating in the Earth system is critical to improving our understanding of climate change already underway and to better assess how much more we can expect in decades and centuries to come. Our key result is that the warming of the global ocean in recent decades has been substantially underestimated. These findings will likely lead to a revisit of previous sea-level and climate sensitivity estimates, and to a re-examination of how scientists deal with poorly sampled aspects of the climate system. A key lesson to be learned from our work is that observing the global ocean is critical, and that prior to the recent improvement in global coverage of ocean observations, a substantial and very important part of the global climate system was under-observed. In order to better understand past and future climate changes it is imperative that the global ocean is adequately observed, as it plays a critically important role in the Earth's climate and its change.

How do scientists measure ocean temperature?
The first subsurface ocean temperature measurements were made in 1772, when Captain James Cook embarked on his second voyage to circumnavigate the globe. The measurement methods have evolved through this time, and today ocean temperatures are measured by specialised equipment on scientific research vessels, automated robotic floats from the Argo programme, and from expendable measurement devices deployed from ships of opportunity. These ocean subsurface measurement "profiles" are collected by data centers and made available for examination by scientists. Development of the robotic drifting ocean profiling instrument called Argo has radically changed the amount of ocean information available to scientists. Since 1999, the fleet has grown to more than 3,600 Argo floats. They drift freely in the oceans providing oceanographers with measurements of temperature to 2,000-meter depths. Thanks to Argo, we now have a much better observational coverage of the global oceans, particularly for the Southern Hemisphere (which comprises 60% of the Earth's ocean area) where previously few observations were collected. These automated floats are providing considerably more information than the limited observations obtained from shipboard equipment ever could.

How do satellites measure changes to ocean temperature, particularly changes deep in the ocean?
Ocean warming causes sea water to expand and increase in volume – sea level rises as water warms. Since mid-1992, satellite radar altimeters provide near-global, highly accurate observations of sea level changes (to date, global total sea level has risen some 68 mm since 1992 from ocean warming and land-ice melt). We use this 20-year long data record to evaluate the rates of sea level rise in the Northern and Southern Hemispheres. Rather than directly comparing the observed sea level increases to those simulated with climate models, we focus on the ratios of sea level rise between the two hemispheres – in this way, we reduce the effects of climate variability (e.g., El Nino events) that make direct observation and model comparisons difficult. Our results demonstrate that climate models are consistent with observed sea level changes – this allows us to calibrate the poorly observed Southern Hemisphere Ocean warming before the network of Argo floats provided good Southern Hemisphere coverage.

Are climate models reliable tools to investigate observed changes to ocean temperature?
Climate models are routinely tested by comparing them to observations, and discrepancies are mostly due to a combination of model errors and incomplete observational coverage. However, there are some cases where consistency tests between climate models and observations have helped uncover problems with observational data, for example with satellite based microwave measurements of lower atmospheric temperature. For the oceans, the key difficulty is that few measurements exist for the Southern Hemisphere, so techniques must be used to estimate the global temperature for the limited areas where measurements do exist. We know that models generally reproduce the large scale features of the global climate (e.g. averages over entire ocean basins, the Pacific Ocean) better than they simulate the small scale regional features. In our study, we show that models are able to simulate the relative rate of sea level changes in the Northern and Southern Hemispheres observed using precise satellite instruments, but that model estimates of ocean heat content change are inconsistent with observed *in-situ* estimates. This suggests that there is likely a problem with the *in-situ* ocean heat content change estimates. Furthermore, as we don't rely on the absolute temperature changes but rather on the relative changes between the Northern and Southern Hemisphere, we have reduced the impact of model systematic errors. The use of high precision satellite observations, in conjunction with model simulations allows us to highlight important deficiencies in observationally-based estimates of global ocean heat content change.

How does this work relate to the Llovel *et al*. (2014) paper in the same issue of *Nature Climate Change* which investigated changes to deep-ocean warming?
The work of Llovel *et al*. (2014) investigated changes to ocean heat content over 2005 to 2013, which is a much shorter time period than we assessed (1970 to 2004). Importantly, the Llovel *et al*. (2014) result provides a confirmation that for the modern period (when Argo data provides near-global upper-ocean temperature coverage), the observed ocean has continued to take up significant amounts of heat. This supports the conclusion of our study, that the inconsistency between upper-ocean warming in models and observations disappears when the more recent and better observed period is compared to models and satellite observations. While Llovel *et al*. (2014) find no detectable warming of the ocean below 2,000 meters since 2005, the upper-ocean has continued to take up significant amounts of heat consistent with numerous independent studies which examine the effects of human-induced climate change.

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