LETTERS
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Uncovering an anthropogenic sea-level rise signal in the Pacific Ocean

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Internal climate variability across a range of scales is known to contribute to regional sea-level trends[1–7], which can be much larger than the global mean sea-level trend in many parts of the globe. Over decadal timescales, this internal variability obscures the long-term sea-level change[3,6,8], making it difficult to assess the effect of anthropogenic warming on sea level. Here, an attempt is made to uncover the sea-level rise pattern in the tropical Pacific Ocean associated with anthropogenic warming. More specifically, the sea-level variability associated with the Pacific Decadal Oscillation is estimated and removed from the regional sea-level trends computed from satellite altimetry measurements over the past two decades. The resulting pattern of regional sea-level rise uncovered in the tropical Pacific Ocean is explained in part by warming in the tropical Indian Ocean, which has been attributed to anthropogenic warming[9]. This study represents one of the first attempts at linking the sea-level trend pattern observed by satellite altimetry to anthropogenic forcing.

Addressing and mitigating the effects of changes in sea level involves accurately determining the contributing factors and associated impacts to past, present and future sea-level rise and variability. Providing such a regional assessment is a challenging task that requires expertise across a wide range of disciplines and a variety of data sources. On the basis of satellite altimetry measurements over the past two decades, regional sea-level trends can be as much as four times the rate of global mean sea level (GMSL; Fig. 1a, note the GMSL trend of $\sim 3\,\mathrm{mm\,yr^{-1}}$ is removed from the figure). This severely limits the utility of any global sea-level metric for planning and adaptation purposes at the regional level. In some regions, internal climate variability on decadal timescales can lead to apparent trends that are significantly larger than the long-term trend. Identifying and explaining signals contributing to regional and global sea-level variability and trends have been frequently studied problems in recent years (for example, refs 1–7). Removing trends associated with known climate variability may allow for identification of the underlying warming trend associated with anthropogenic forcing (for example, refs 3,6–8).

Separating the longer-term secular trends and accelerations from internal climate variability is a challenge, however, given the available observations of sea level. The modern satellite altimetry record, although offering nearly global coverage, spans only twenty years. The tide gauge record, on the other hand, provides a much longer record of sea level but has very poor coverage of the global ocean, particularly in the first half of the twentieth century. One possible solution to these sampling challenges is provided in the form of sea-level reconstructions (for example, refs 10–15). A sea-level reconstruction is a data set with the spatial resolution of satellite altimetry and the record length of the tide gauges, constructed by combining these two data sets. Sea-level reconstructions provide the opportunity to study the effect of longer-timescale natural climate variability on sea-level trends. Here, we build on and extend previous work that used sea-level reconstructions to extract the component of sea-level rise—on a global scale—associated with the Pacific Decadal Oscillation[6] (PDO). The PDO is a decadal-scale pattern of predominantly North Pacific climate variability, with the associated variability commonly tracked by computing the first empirical orthogonal function of the North Pacific sea surface temperature[16,17] (SST). Several studies have looked at the relationship between the PDO and sea level in the Pacific using both observational and model analyses (for example, refs 4,6,7,18–21). The high sea-level rise in the western tropical Pacific (WTP) and lower than average sea-level rise off the western coast of North America have been attributed in large part to the PDO, and the assumption has been made that when the PDO shifts phases, the sea-level trends will similarly reverse course. One study in particular[18] attributed the fast WTP sea-level rise during the past couple of decades to internal variability, because similar east–west dipole patterns in the tropical Pacific were found in simulations of climate models with and without anthropogenic forcing. Although the results of ref. 7 corroborate the conclusion that Pacific decadal climate modes are associated with basin-wide sea-level patterns, it was determined that the large sea-level trends observed in the WTP cannot be entirely explained as internal variability.

In an attempt to address these differing conclusions and quantify the contribution of the PDO to sea-level trends, ref. 6 used a sixty-year reconstructed sea-level record and a simple trend analysis to extract the PDO contribution to twenty-year trends in GMSL. An empirical orthogonal function (EOF) analysis is conducted on twenty-year trend patterns computed from the sea-level reconstruction spanning the time period from 1950 to 2010 (see ref. 15 and Supplementary Information for additional details of the sea-level reconstruction used here). The first EOF resulting from this trend analysis has a 0.96 correlation with a widely used SST-derived PDO index[17] and qualitatively shows a strong agreement with the spatial pattern of variability in the North Pacific commonly associated with the PDO. In the previous study[6], it was found that the PDO accounted for $0.5\,\mathrm{mm\,yr^{-1}}$ of the approximately $3.2\,\mathrm{mm\,yr^{-1}}$ rate of GMSL rise since 1993. Whereas the previous study focused largely on the relationship between the PDO and

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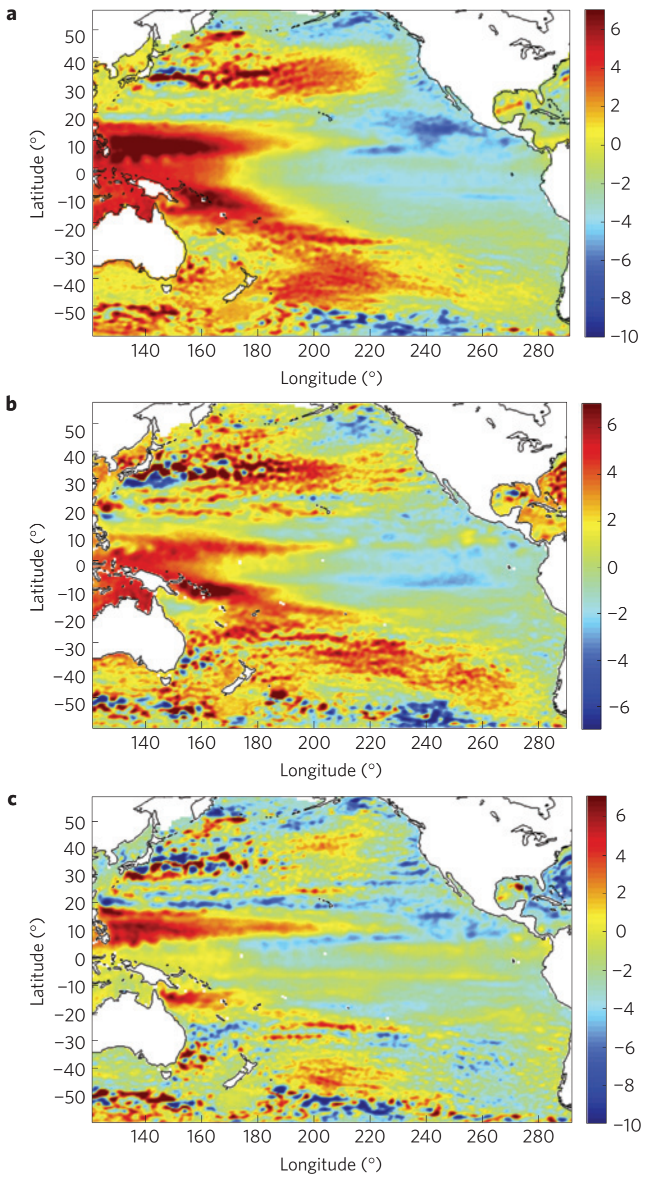

Figure 1 | Pacific Decadal Oscillation (PDO)-related sea-level trends. **a**–**c**, Sea-level trends (mm yr^{-1}) from 1993 to 2010 for Archiving, Validation and Interpretation of Satellite Oceanographic (AVISO) data (**a**), Hamlington *et al.*[6] PDO contribution estimated by empirical orthogonal function analysis of sea-level reconstruction (**b**), and AVISO minus the PDO contribution (**c**). Note, the global mean sea-level trend has been removed from the AVISO data.

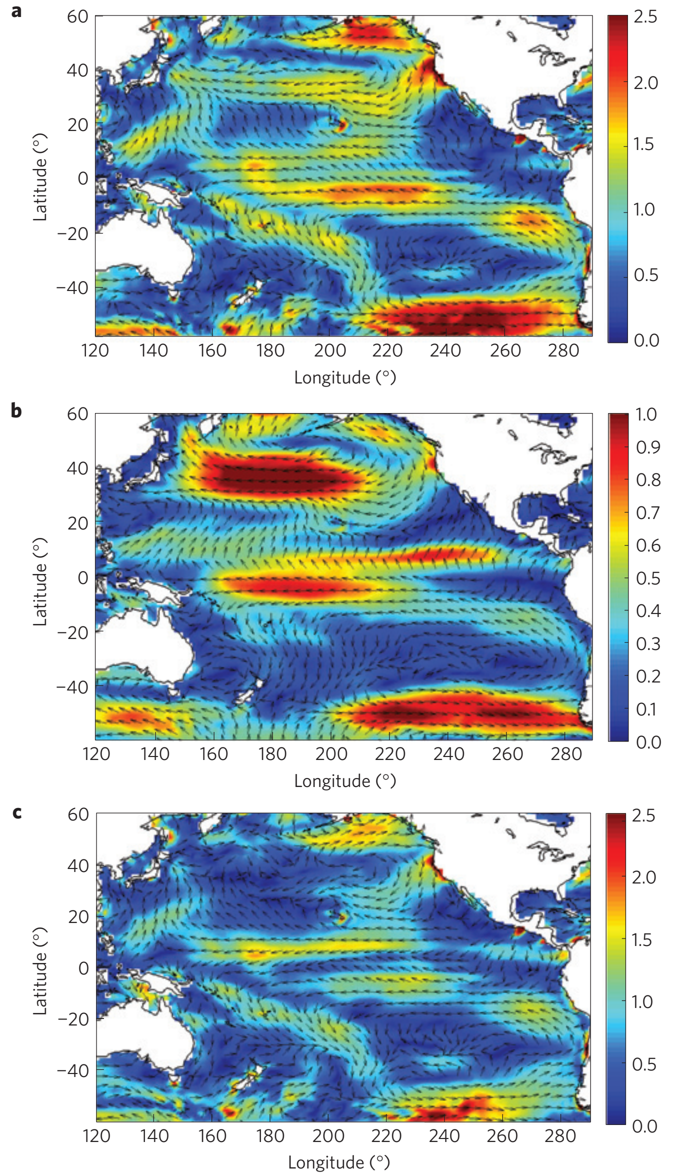

Figure 2 | Pacific Decadal Oscillation (PDO)-related wind-stress trends. **a**–**c**, Wind-stress trends (mPa yr^{-1}) from 1993 to 2010 for Operational Ocean Re-Analysis Series 3 (ORA-S3) data (**a**), PDO contribution (**b**), and ORA-S3 trends minus PDO trends (**c**).

GMSL, here we extend the analysis to provide an estimate of the contribution of the PDO to regional sea level. In Fig. 1a, the regional trend pattern from the Archiving, Validation and Interpretation of Satellite Oceanographic (AVISO) merged multi-altimeter sea surface height data from 1993 to 2010 is shown (note, the GMSL trend is removed). The subsequent PDO contribution to regional sea-level trends from 1993 to 2010 estimated from the first EOF of the trend analysis is shown in Fig. 1b (see Supplementary Information for an error analysis of this trend). By removing the sea-level trends resulting from the PDO from the AVISO sea-level trends, it is possible to isolate the long-term trend from the internal variability contributed by the PDO. The differenced sea-level trend pattern is shown in Fig. 1c. The large sea-level trends (>1 cm yr^{-1} with GMSL trend included) over the past two decades around the Equator near Indonesia and Papua New Guinea are greatly reduced by removing the PDO contribution. Off the coasts of the Philippines and northeastern Australia, however, the sea-level trends are still large (~ 1 cm yr^{-1}, with GMSL trend included). Although the PDO contribution has been removed, it should be noted that other low-frequency internal variability is probably still present in Fig. 1c and could contribute to the trend pattern.

To explain the residual pattern of sea-level trends seen in Fig. 1c, we perform a similar analysis on wind stress to isolate and remove the contribution of the PDO over the past twenty years. Using data from the Operational Ocean Re-Analysis Series 3 (ORA-S3) data set from 1959 to 2010, the PDO contribution to the wind-stress trends since 1993 was estimated and removed (see Supplementary Information for information on data and methods). As in the sea-level trend analysis, the trend in the ORA-S3 wind-stress data since 1993 was computed (Fig. 2a). The PDO contribution to the wind-stress trends over the same time period (Fig. 2b) was then subtracted from the original data trends to remove the influence of the internal variability related to the PDO and isolate the wind-stress trend

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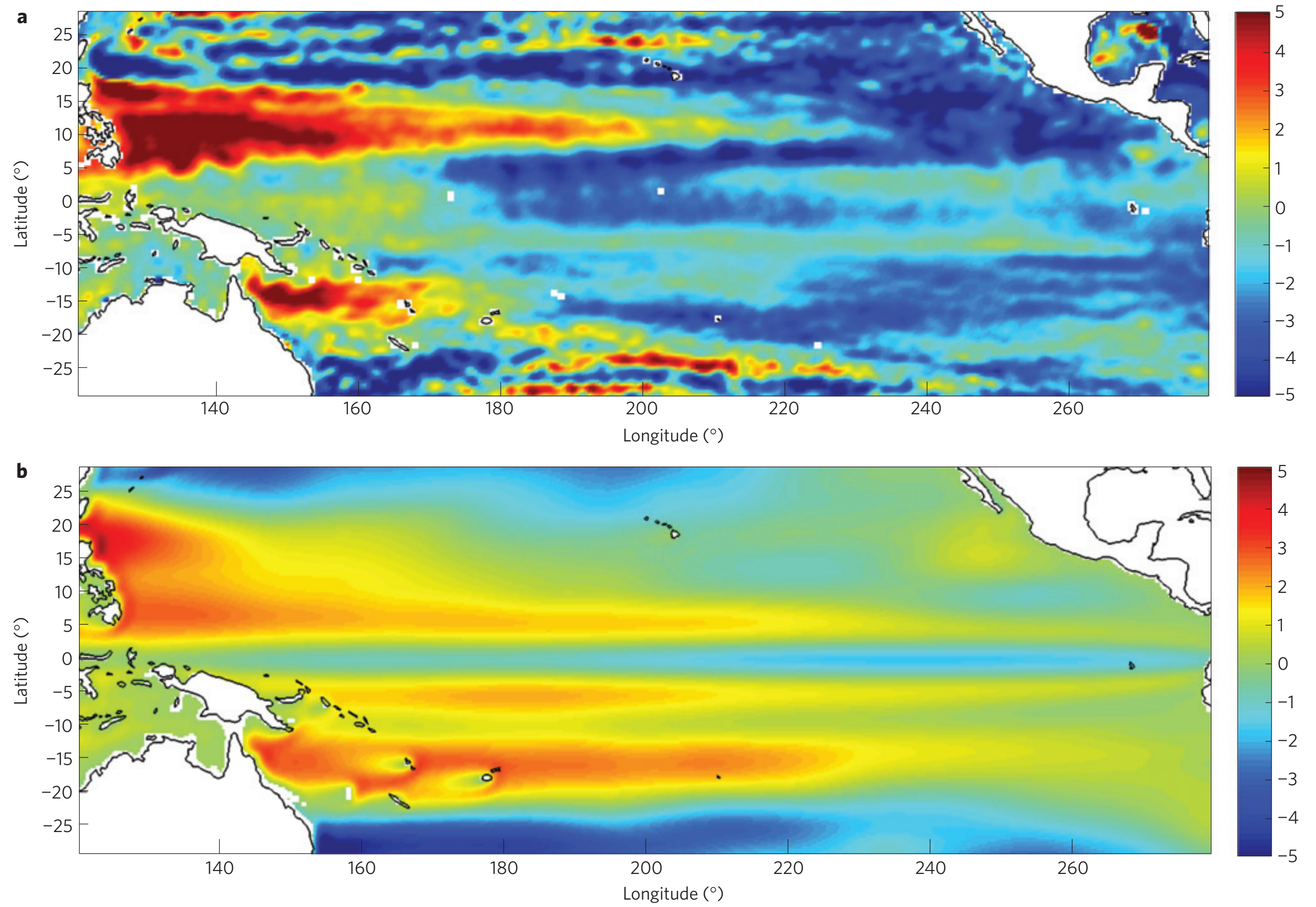

Figure 3 | Sea-level trend data–model comparison. a,**b**, Sea-level trends (mm yr^{-1}) in western tropical Pacific from Archiving, Validation and Interpretation of Satellite Oceanographic data minus Pacific Decadal Oscillation contribution (**a**; as in Fig. 1c), and model result obtained from 0.5 °C tropical Indian Ocean warming (**b**).

pattern associated with the long-term sea-level trends (Fig. 2c). The strength of trends in the Pacific trade winds since 1993 is greatly reduced by removing the PDO influence. The residual wind stress after removing the PDO, however, still shows strong easterly trends in the tropical Pacific (Fig. 2c). This residual wind-stress pattern agrees with the residual sea-level trend pattern shown in Fig. 1c, implying an increase in sea level off the coast of the Philippines. An increase in sea level and deepening of the thermocline in the western Pacific warm pool region are an expected result of the stronger tropical easterlies seen in Fig. 2c (ref. 22). This suggests that although the large sea-level trends observed in the WTP in the past two decades are largely explained by the PDO in some areas, other regions are experiencing sea-level change that cannot be attributed to the PDO, a natural climate mode of variability.

If not internal climate variability associated with the PDO, then to what can we attribute the sea-level rise in those regions of the WTP relatively unaffected by the removal of the PDO? Using climate models, ref. 7 demonstrates that tropical Indian Ocean (TIO) warming acts in concert with the warm WTP and cold central-eastern tropical Pacific to enhance the easterly trades in the central WTP, which subsequently increases the WTP sea level. Ref. 23 discusses in detail the role of the Indian Ocean warming in modulating Pacific Ocean climate change. To further assess this warming effect on sea level and attempt to attribute the sea-level trend pattern shown in Fig. 1c, we perform two idealized experiments using the National Aeronautics and Space Administration Seasonal-to-Interannual Prediction Project Atmospheric General Circulation Model (see Supplementary Information for information on data and methods). The difference between the two experiments is an additional 0.5 °C of warming in the TIO, which is set according to analysis of available SST data products that show the upper bound of the warming in the TIO is ~0.5 °C within 10° S–10° N from 1993 onwards. By differencing the results of the two experiments, the regional effect in the WTP of the TIO warming including the associated sea-level change can be isolated.

The modelled WTP sea-level trends resulting from the mechanism of 0.5 °C TIO warming (Fig. 3b) are shown for comparison to the trends estimated from the AVISO satellite altimetry data after the removal of the PDO (Fig. 3a). Despite some discrepancies in magnitude due largely to the idealized model experiment and the presence of other internal variability in the residual pattern, significant areas of agreement between the model and observations are seen. In particular, the large rates of sea-level rise off the coasts of the Philippines and northeastern Australia are seen in both results. This leads to the conclusion that the sea-level rise seen in these regions can be related, at least in part, to the influence of TIO warming on the WTP. Previous studies have attributed the steady Indian Ocean warming since the middle of the twentieth century to anthropogenic greenhouse gases[9]. As discussed in ref. 7, in the past two decades, the in-phase relationship between the PDO and TIO has changed, with the PDO entering a negative phase and the TIO continuing to warm. This change in the relationship between the TIO and PDO suggests the presence of a persistent warming trend in the TIO that has been attributed to anthropogenic warming[9]. The agreement between the residual sea-level trend pattern (Fig. 3a) and modelled sea level (Fig. 3b) indicates that the rapid WTP sea-level rise during recent decades is at least in part anthropogenic.

Using the longer record provided by sea-level reconstructions, it is possible to separate and remove internal climate variability and identify the underlying trends in the altimeter record that may be attributable to anthropogenic forcing. Here, the influence of the PDO is removed from the past two decades of sea-level observations provided by satellite altimetry. Several studies have related the rapid sea-level rise in the WTP to the PDO, and removing the effect of this internal variability does have a significant impact on the resulting spatial trend pattern (Fig. 1c), as would be expected. Extending beyond these previous studies, however, this is the first time that the PDO contribution to sea-level trends has been quantified regionally and removed from the satellite altimeter trends to create a trend map that provides an opportunity to study the anthropogenic contribution to altimeter-observed sea-level trends. Perhaps most importantly, using a model, the residual sea-level trend pattern is found to be physically meaningful and can be attributed to TIO warming, which in turn, has been linked to anthropogenic forcing. Attributing a portion of the sea-level trends observed by satellite altimeters to anthropogenic forcing significantly affects our interpretation and understanding of sea-level trends in the past two decades, and begins to answer the question of how much of the observed trend map is a result of natural forcing versus anthropogenic forcing. The prevailing thought has been that once the PDO shifts and changes phases, the sea-level rise in the WTP will ease and future decades will hold much more manageable levels of sea-level change for the region. Although this seems to be the case for areas near Indonesia, in the light of the results presented here, the high rate of sea-level rise near the Philippines and northeastern Australia should not be similarly expected to abate over the next couple of decades.

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Author contributions

B.D.H. and R.R.L. conceived of the analysis conducted here; B.D.H. performed the analysis and wrote the paper. M.W.S. assisted in performing the data analysis. W.H. conducted the model experiments and assisted in writing the paper. K-Y.K. provided analysis tools. K-Y.K., R.R.L. and R.S.N. assisted in the synthesis and presentation of the results.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to B.D.H.

Competing financial interests

The authors declare no competing financial interests.