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Global secular changes in different tidal high water, low water and range levels

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Key Points:
- Changes in tidal levels are globally distributed and large at some sites
- Mechanisms ranging from global to local affect the trends in tidal levels
- Significant differences exist between trends in different tidal levels

Supporting Information:
- EFT2_60_SuppFigures.docx
- EFT2_60_TableS1.xlsx
- EFT2_60_TableS2-1.xlsx
- EFT2_60_TableS2-2.xlsx
- EFT2_60_TableS2-3.xlsx

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Abstract Tides exert a major control on the coastal zone by influencing high sea levels and coastal flooding, navigation, sediment dynamics, and ecology. Therefore, any changes to tides have wide ranging and important implications. In this paper, we uniquely assess secular changes in 15 regularly used tidal levels (five high water, five low water and five tidal ranges), which have direct practical applications. Using sea level data from 220 tide gauge sites, we found changes have occured in all analyzed tidal levels in many parts of the world. For the tidal levels assessed, between 36% and 63% of sites had trends significantly different (at 95% confidence level) from zero. At certain locations, the magnitude of the trends in tidal levels were similar to trends in mean sea level over the last century, with observed changes in tidal range and high water levels of over 5 mm yr^{-1} and 2 mm yr^{-1}, respectively. More positive than negative trends were observed in tidal ranges and high water levels, and vice versa for low water levels. However we found no significant correlation between trends in mean sea level (MSL) and any tidal levels. Spatially coherent trends were observed in some regions, including the north-east Pacific, German Bight and Australasia, and we also found that differences in trends occur between different tidal levels. This implies that analyzing different tidal levels is important. Because changes in the tide are widespread and of similar magnitude to MSL rise at a number sites, changes in tides should be considered in coastal risk assessments.

1. Introduction

Tides are a major control on the coastal zone. For example, coastal communities are vulnerable to extreme high sea levels and coastal flooding [*Nicholls et al*., 2007], in which tides play an important role along the majority of the world's coastlines [*Haigh et al*., 2011; *Pugh and Woodworth*, 2014]. Navigation to and from ports is constrained by the height and timing of high and low water [*Gill and Schultz*, 2001]. Tidal range influences the spatial extent of species in coastal ecosystems [*Stumpf and Haines*, 1998], while tidal currents control sediment transport [*Allen et al*., 1980] and the tidal energy potential [*Mackay*, 2008]. Furthermore, tidal levels relative to chart datum are used as the legal basis for many national and international boundaries [*Pugh and Woodworth*, 2014]. Therefore, any changes to tides have wide ranging and important practical and scientific implications.

Changes in tides are known to have occurred over thousands of years, in response to large (up to 130 m) variations in mean sea level (MSL) associated with glacial and inter-glacial cycles [*Egbert et al*., 2004; *Green*, 2010], and over much longer time-scales with the evolution of ocean basins and continents [*Sündermann and Brosche*, 1978; *Müller et al*., 2011]. However, for many applications, tides have generally been considered to have undergone little change over the last century and it is often presumed that they will not change over the next century, because the astronomical forces that generate them are virtually constant [*Cartwright and Tayler*, 1971; *Cartwright and Edden*, 1973; *Cartwright*, 1985].

However, several studies have detected measurable changes in tides during the 20th century and early part of the 21st century at a number of locations [*Woodworth*, 2010]. For example, significant trends in the mean tidal range (MTR), calculated from mean high water (MHW) and mean low water (MLW), have been observed over the time span of direct sea level measurements. These trends have been observed: at sites around the United Kingdom (UK) [*Woodworth et al*., 1991; *Haigh et al*., 2010]; in the German Bight [*Töppe and Führböter*, 1994; *Hollebrandse*, 2005; *Mudersbach et al*., 2013]; around the coastline of Japan [*Rasheed and Chua*, 2014]; and at many sites around the United States of America (USA) [*Flick et al*., 2003]. Amplitudes of particular tidal constituents have also been shown to change over these time-scales: in studies of individual tide gauge sites (e.g., *Cartwright* [1971] for St. Helena in the South Atlantic; *Cartwright* [1972] for Brest in France; *Araújo and Pugh* [2008] for Newlyn in the UK); in regional studies (e.g., *Amin* [1993] for Australia; *Ray* [2006], *Ray* [2009], and *Jay* [2009] for the USA; *Araújo* [2005] for the West European Coast, *Torres and Tsimplis* [2011] for the Caribbean Sea; *Mudersbach et al*. [2013] for the German Bight; *Zaron and Jay* [2014] for open ocean sites in the Pacific Ocean); and in two comprehensive studies that assessed quasi-global sea level datasets [*Müller et al*., 2011; *Woodworth*, 2010]. In many of these studies, the magnitude of observed changes in both tidal levels and tidal constituents was comparable to, increases in MSL at certain sites. For example, during the latter half of the 20th century, Anchorage in Alaska and Wilmington in North Carolina, were found to have trends in diurnal tidal range (DTR) of over 5 mm yr^{-1} [*Flick et al*., 2003], while trends in MTR in the German bight exceeded 3 mm yr^{-1} [*Töppe and Führböter*, 1994; *Mudersbach et al*., 2013]. Therefore, changes in the tide are large enough, at certain locations, that they should be accounted for in coastal engineering, management and planning applications, where sea level is an important factor [*Woodworth et al*., 1991; *Müller et al*., 2011].

With the astronomical forcing remaining near constant over the time span of tide gauge observations, these measurable changes in tidal levels and tidal constituents are likely caused by changes in terrestrial factors, such as water depth and coastal geomorphology, which generate differences in the timing and magnitude of the observed tide [*Pugh and Woodworth*, 2014]. Possible terrestrial mechanisms have been summarized in previous papers [e.g., *Woodworth*, 2010; *Müller*, 2012] and include: interactions between the tide and the continuum of the non-tidal variations [*Munk and Cartwright*, 1966]; changes in water depth due to variations in global average sea level and/or isostatic changes in the solid earth, which lead to modifications in tidal wavelengths [e.g., *Flather et al*., 2001; *Müller et al*., 2011; *Pickering et al*., 2012]; morphological changes in coastal waters, harbors or estuaries [e.g., *Bowen*, 1972; *Araújo et al*., 2008]; changes in the internal tide, expressed as small changes in its surface expression [e.g., *Ray and Mitchum*, 1997; *Mitchum and Chiswell*, 2000; *Colosi and Munk*, 2006]; and seasonal variations caused by changes in sea ice cover [*St-Laurent et al*., 2008], mean currents [*Cummins et al*., 2000] and water column stratification [*Kang et al*., 2002; *Müller*, 2012] (Note: the latter could have a large influence over longer time-scales as global warming causes widespread changes in the global oceans).

The well-documented rise in global MSL over the past 150 years [*Church et al*., 2013] has been explored as a potential mechanism causing the observed regional changes in the tide. For example, *Woodworth et al*. [1991] found a positive correlation between the trends in MTR and MSL around the United Kingdom. *Müller et al*. [2011] illustrated, using a global tidal model, that a 1 m increase in MSL could lead to a 1%–2% change in tidal range, while modeling studies of the North Sea suggest that the change in tidal wave speed, in response to MSL change, can lead to spatially variable and non-linear responses [*Pickering et al*., 2012; *Ward et al*., 2012; *Pelling et al*., 2013; *Pickering*, 2014]. These responses, that include standing wave resonance from the reflection of the incident tidal wave, frictional effects, coastline geometry, and inertial effects [*van Rijn*, 2011], mean that although some regional patterns are observed, at other sites, local effects appear to dominate [*Woodworth*, 2010].

In summary, research has shown that changes in the tides over the last approximately 150 years are: widespread, but highly spatially variable; large in certain locations; and predicted to increase with future sea level rise. They should therefore be considered an important factor in impact assessments of sea level change.

In this paper, we build on the two comprehensive quasi-global assessments of changes in tide that have been undertaken to date [*Woodworth*, 2010; *Müller et al*., 2011]. However, rather than investigating changes in individual tidal constituents, as these previous studies have done, we assessed changes in several widely used tidal levels, which have direct practical applications. Examining changes in tidal constituents is useful to understand the processes responsible for the observed changes in tides. However, it is difficult to quantify in terms useful to practitioners (i.e., coastal engineers, port authorities, planners, etc.), exactly how these observed changes in individual tidal constituents combine to alter the observed tidal curve at a specific site; hence our focus on tidal levels. The past studies that have assessed changes in tidal levels [e.g., *Woodworth et al*., 1991; *Töppe and Führböter*, 1994; *Flick et al*., 2003; *Mudersbach et al*., 2013; *Rasheed and Chua*, 2014] have been limited to small data-dense regions. In addition, these previous studies exclusively analyzed MTR or DTR, and associated tidal high water (HW) and low water (LW) levels.

Table 1. Summary of Selected Tidal Levels and a Description of Their Calculation

Tidal Range Method	High Water/Low Water Levels	Description
Greater Diurnal Tidal Range (GDTR)	Mean Higher High Water (MHHW) Mean Lower Low Water (MLLW)	Annual average of highest high water minus the lowest low water of each day.
Mean Tidal Range (MTR)	Mean High Water (MHW) Mean Low Water (MLW)	Annual average of all high waters minus the average of all low waters.
Lesser Diurnal Tidal Range (LDTR)	Mean Lower High Water (MLHW) Mean Higher Low Water (MHLW)	Annual average of lowest high water minus the highest low water of each day.
Spring-Tropic Tidal Range (STTR)	Mean High Water Spring-Tropic (MHWST) Mean Low Water Spring-Tropic (MLWST)	Annual average of all high waters minus all low waters during spring-tropic periods.
Neap-Equatorial Tidal Range (NETR)	Mean High Water Neap-Equatorial (MHWNE) Mean Low Water Neap -Equatorial (MLWNE)	Annual average of all high waters minus all low waters during neap-equatorial periods.

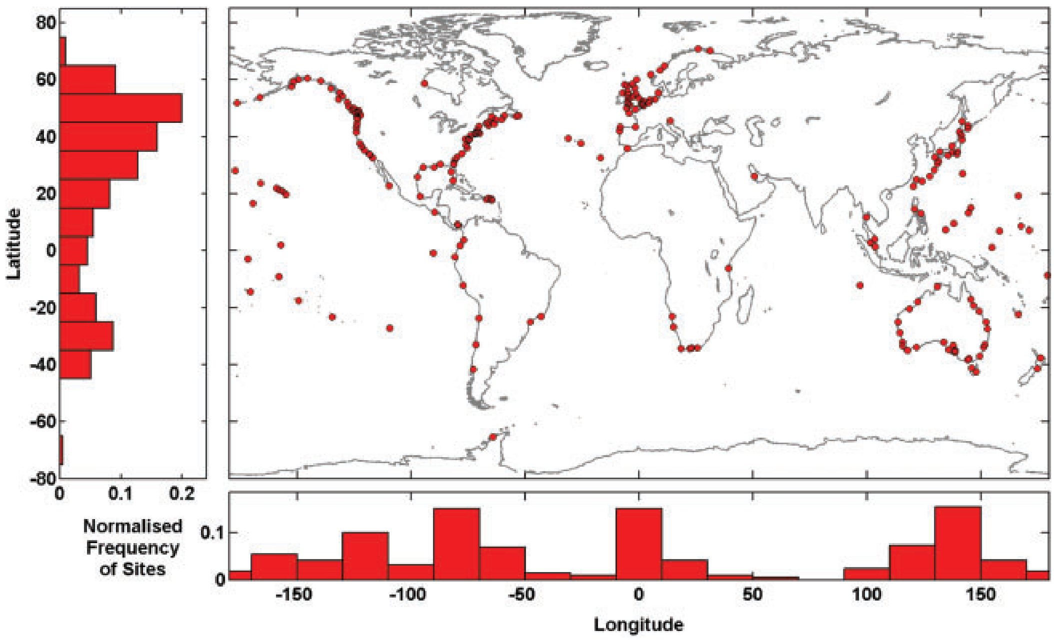

Figure 1. Location map of 220 selected sites used in the analysis. Normalized frequency histograms are plotted along the *x*-axis for longitude and *y*-axis for latitude.

Many more tidal levels are available and regularly used for a variety of applications (see Table 1). Before now, it has not been clear whether changes in different tidal levels are consistent or whether changes in tidal levels match those observed in the main tidal constituents. Therefore, in this paper, which builds on a preliminary, smaller study [*Mawdsley et al*., 2014] we investigate the changes in 15 tidal levels at 220 tide gauges (Figure 1). Five of the tidal levels are high water levels, five are low water levels, and five are tidal ranges, calculated from the difference of the respective high and low water levels (see Table 1).

The structure of the paper is as follows: Section 2 discusses the sea level data analyzed and the methodology is detailed in section 3. The results and discussion of our work are described in sections 4 and 5, respectively, while the conclusions are presented in section 6.

2. Datasets

The sea level data used in this study is an extension of the Global Extreme Sea Level Analysis (GESLA) dataset. This dataset was originally collated by staff from the Permanent Service for MSL at the National Oceanography Centre, Liverpool in the UK and the Antarctic Climate & Ecosystems Cooperative Research

Centre in Australia. The GESLA dataset has primarily been used to assess changes in extreme sea levels [e.g., *Woodworth and Blackman*, 2004; *Menéndez and Woodworth*, 2010; *Hunter*, 2012; *Hunter et al*., 2013] but, as outlined earlier, has also been used to assess changes in the main tidal constituents [*Woodworth*, 2010]. It is probably the best source of information available for such global wide studies [*Woodworth*, 2010].

The original GESLA dataset comprised records from 452 unique locations with the data ending in 2008 at the latest. We extended all data sets, where possible, through to the end of 2013, and added three new datasets, at Knysna and Mossel Bay in South Africa, and Luderitz in Namibia. Records were extended using research quality data downloaded from the following web sites: University of Hawaii Sea Level Center for global sites; British Oceanographic Data Centre for the UK; National Oceanic and Atmospheric Administration for the USA; Marine Environmental Data Service for Canada; Bureau of Meteorology for Australia; and Norwegian Mapping Authority for Norway.

As the quality control procedures of the different institutes varied, further data checks consisting of identifying and removing spikes, and datum or phase offsets, were conducted on all sites. This extra quality control removes obvious timing errors and reduces the 'smearing' of tidal energy across a wider range of frequencies. This 'smearing' can reduce the energy attributed to tidal constituents during harmonic analysis [*Zaron and Jay*, 2014]. Data clearly affected by tsunamis were also removed, since the occurrence of these non-climate related events are unpredictable and can skew results, particularly when assessing the meteorological component of sea level. Small tsunami signals are difficult to separate from the non-tidal residual, and therefore some events remain in the data.

Many records in the GESLA dataset were considered too short or had too many years of invalid data, and were excluded from this analysis by a number of criteria designed to ensure that data were of sufficient length and quality for robust analysis. First, a calendar year was included in the analysis only if it contained at least 75% of the hourly values in that year. If large sections of the data were missing then seasonal cycles in the tide may skew the magnitude of tidal levels. Second, the time span between the first and last years (based on the first criteria) of the record was required to be at least 28 years so that the lunar-nodal cycle could be adequately represented. The lunar-nodal cycle has a period of 18.61 years and results from the precession of the lunar ascending node and an associated variation in the declination of the Moon's orbit that causes a large proportion of the variability in tidal levels [*Haigh et al*., 2011]. A 28-year record is approximately 1.5 lunar-nodal cycles, and this therefore allows an approximation of its phase and magnitude [*Woodworth et al*., 1991]. Third, the record was required to contain at least 15 calendar years of data, over the prescribed 28-year length [*Woodworth et al*., 1991]. Lastly, to ensure datasets were representative of current trends, the records were required to end after the year 2000.

This resulted in 220 sites being considered eligible for the analysis, the locations of which are shown in Figure 1. The longest dataset is at Brest in France and spans 146 years. Eighty-two records are longer than 50 years and 14 records are longer than 100 years. The nature of tide gauges means that all sites are along the coast and geographical bias toward the Northern Hemisphere and Australasia is evident.

3. Methodology

At each of the 220 study sites, the observed sea level was separated into its three main component parts: MSL, tide, and non-tidal residual [*Pugh and Woodworth*, 2014]; and only the tidal component was considered further. Typically, researchers calculated annual MSL values and removed this from sea level records, but here we use a 30-day running mean. This not only removes the centennial time-scale signals caused by global average sea level change and land movement related to glacial isostatic adjustment or localized land subsidence; but also removes the seasonal cycle, the majority of which has oceanographic or meteorological, not gravitational, origins. By doing this we remove the small annual (S_a) and semi-annual (S_{aa}) constituents that are directly related to astronomical forcing, but have a negligible effect on our results. The remaining record, without MSL, was separated into calendar years, with each year then run through the harmonic analysis software T_Tide [*Pawlowicz et al*., 2002], to separate the tide and non-tidal residual. We used the standard set of 67 constituents, which are separable from a 1-year record based on the Rayleigh criterion [*Foreman*, 1977]. The amplitude and phase lag of each constituent is determined by T_Tide and then used to predict the tide for the given year. Analyzing the records in this way meant that

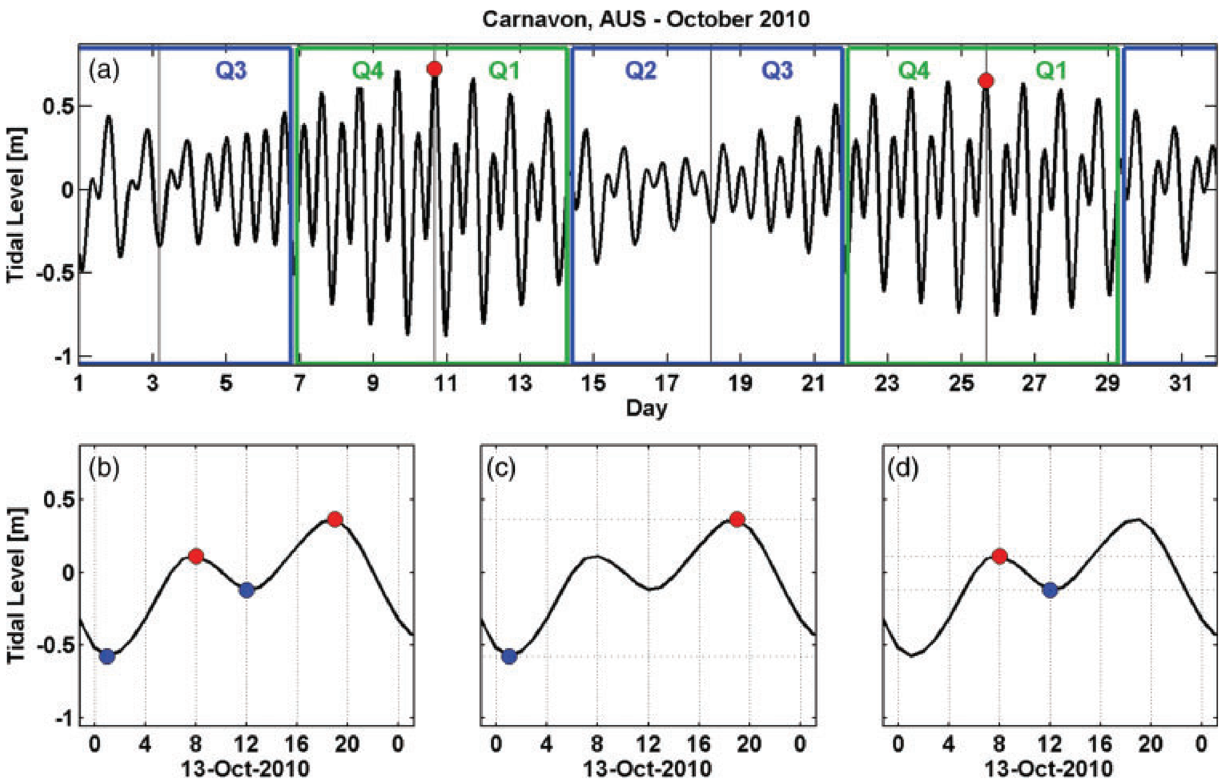

Figure 2. Example, from Carnavon, Australia, of the high water and low water subsets used for calculation of the different tidal levels. (a) periods of spring-tropic (green box) and neap-equatorial (blue box) periods based upon the timing of the highest high water of a 14-day period; (b) daily HW and LW used for MTR calculation; (c) daily highest HW and lowest LW used for GDTR calculation; (d) daily lowest HW and highest LW used for LDTR calculation.

the nodal cycle was not removed at this stage but it is accounted for later in the analysis. The non-tidal residual (which we only used for data quality control), was calculated by subtracting the predicted tide from the measured sea level time-series. Note other methods exist for extracting the non-tidal residual, such as that used by *Bromirski et al*. [2003].

Tidal levels in this paper are all reported relative to MSL and were calculated from different subsets of the extracted daily or twice daily predicted tidal HWs and LWs. Every tidal HW and LW was extracted by locating the turning points of the tide time series. Time-series of MTR were calculated by subtracting the annual mean of all LWs from the annual mean of all HWs. Time-series of greater DTR (GDTR) were computed by subtracting the annual mean of each daily lower LW, from the annual mean of each daily higher HW; while time-series of the lesser DTR (LDTR) were calculated using the lower HW and the higher LW for each day. We also distinguish between changes occurring in periods of larger or smaller tides. The periods of larger or smaller tides that we analyze in this paper repeat over approximately 14 days [*Zetler and Flick*, 1985b] and relate to two forcing mechanisms. The spring-neap cycle dominates in semi-diurnal tidal regimes and relates to the phase of the moon and sun, while the tropic-equatorial cycle dominates in diurnal tidal regimes and relates to the declination of the moon. Spring and tropic tides refer to the periods of high tidal range in these two cycles, respectively. These periods were defined by using the highest HW of successive 14-day periods, as shown in Figure 2. The time between each pair of consecutive highest HW was split into quarters, with the spring-tropic period defined as the quarter before (Q4) and the quarter after (Q1) a highest HW; while the neap-equatorial period was quarters 2 (Q2) and 3(Q3). This definition ensured that the two periods contained mutually exclusive HW and LW. Spring-tropic tidal range (STTR) was calculated from the mean of all HW minus the mean of all LW in the spring-tropic period, with the same true for neap-equatorial tidal range (NETR) and the neap-equatorial period.

Each tidal level was calculated per annum to give a time-series of heights to which a linear regression model with a nodal term was fitted. Equation 1 gives the example for MTR.

$$\mathrm{MTR}(t) = a + bt + c\cos(\omega t - d) \tag{1}$$

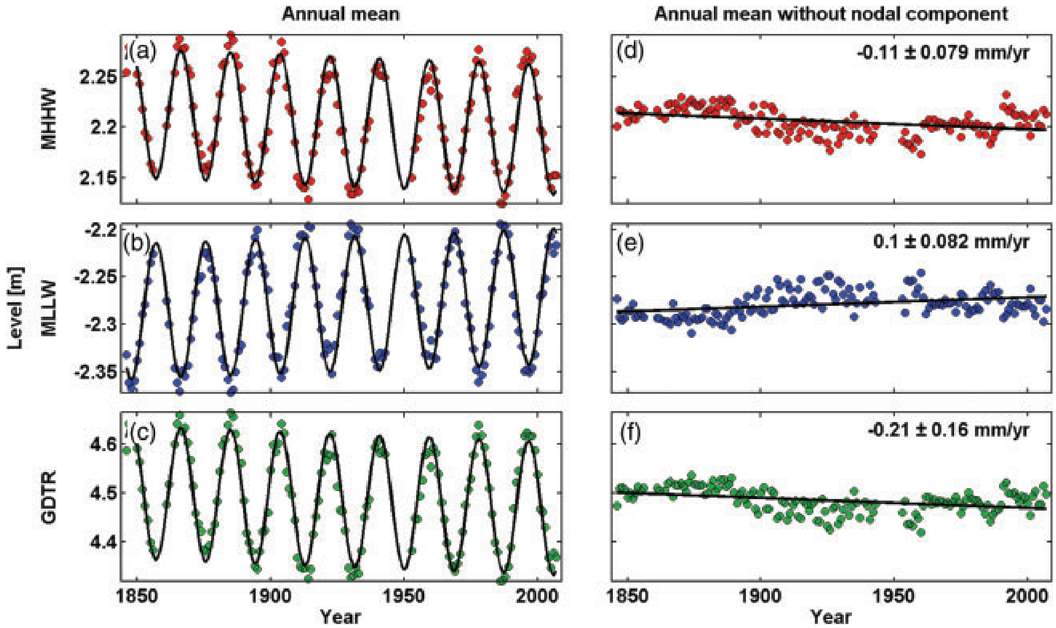

Figure 3. (a–c) Time-series of annual values of MHHW, MLLW and GDTR relative to MSL at Brest in France, (d–f) and the same time-series with the variation caused by the lunar-nodal cycle removed. The fitted model with or without the lunar-nodal component is plotted as black line.

where t is time in years, b is the linear trend in MTR, $\omega = 2\pi/18.61$ radians yr^{-1}, and a, c and d are constants. The nodal term ($c\cos(\omega t - d)$) is included to ensure that trends are not biased by the lunar-nodal cycle [*Woodworth*, 2011]. Figures 3a–3c show the fits of the above regression model to tidal levels calculated for Brest in France, with the nodal variation included. Time-series with the nodal cycle removed are shown in Figures 3d–3f. Throughout the paper confidence intervals are quoted at the 95% confidence level (i.e., approximately two standard errors) and were estimated using a Lag-1 autocorrelation function to allow for any serial autocorrelation in the residuals [*Box et al*., 1994]. From here on when we use the term significant trends, this means the trends are statistically (at 95% confidence) different from zero.

4. Results

Results from our analysis show that significant (95% confidence) secular changes have occurred in all tidal levels, and at sites on every continent and around every ocean basin, over the time span of the observations. Global maps showing where trends in MHHW, MLLW, and GDTR are significantly positive (red dots), significantly negative (blue dots), or not significant (black dots), are shown in Figures 4a–4c, respectively. Similar plots showing trends in the other tidal levels are included in the Supporting Information. From Figure 4 it is clear that although changes are observed around the world, there is no discernible global pattern. However, several regions do exhibit spatial coherence, as is evident in the magnitude of the trends in GDTR for North America, Europe and Australasia (see. zoomed in plots of these data-dense regions in Figure 5).

On the north-west American coast, nearly all sites have significant positive trends in GDTR and MHHW and significant negative trends in MLLW. This is also observed in the German Bight (Figure 5b), Australia and southeast Asia (Figure 5c) and South Africa; although these last two regions have lower data coverage and therefore may not capture all the changes occurring in the tide. Regions exhibiting spatially coherent decreases in GDTR and MHHW, and increases in MLLW are typically smaller and the coherence within these areas is weaker. They include areas on the northeast American coast (Figure 5a), which alternate with small regions where trends have the opposite sign, and Japan (Figure 5c). Even within regions of mostly coherent signals there are local variations. For example, negative trends in MHHW at Tofino, Canada and Willapa Bay, USA, contrast with the positive trends observed at other sites along the northwest American coast. In other regions, the sign of the trend is the same as neighboring sites but the magnitude is very different.

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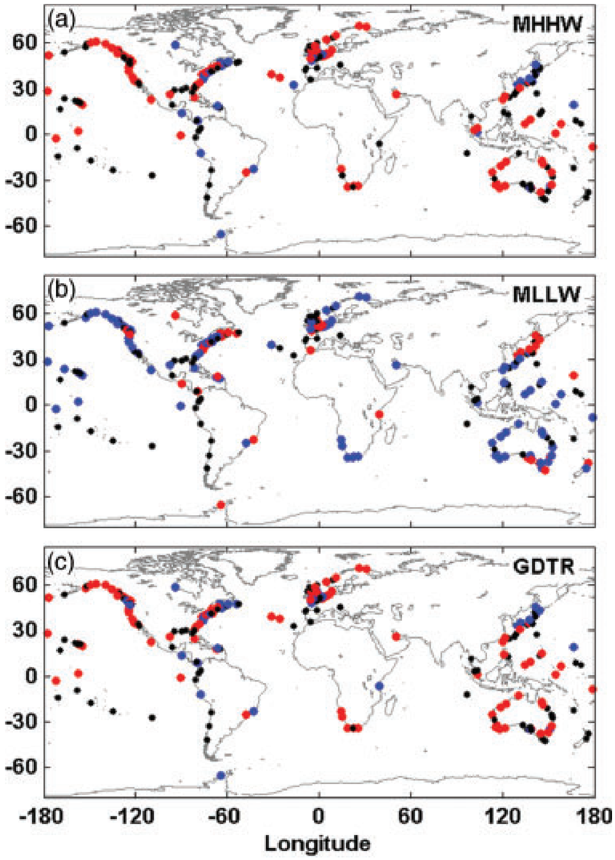

Figure 4. Global map showing where trends in MHHW (a), MLLW (b), and GDTR (c) are: significant positive (red), significant negative (blue) or nonsignificant (black). Significance means trend is significantly different to zero.

Wilmington, North Carolina in the USA, has a trend in GDTR of 5.2 mm yr^{-1} (Figure 6i), while surrounding sites have trends of less than 1 mm yr^{-1}.

The largest positive trend we observed in any tidal level was the 6.1 mm yr^{-1} increase in STTR at Calais, France (Figure 6d). The largest negative trend was −3.5 mm yr^{-1} in STTR at Churchill in Canada (Figure 6e). The magnitude of trends in HW levels varied from 3.1 mm yr^{-1} in MHWST at Calais (Figure 6d), to −2.0 mm yr^{-1} in MHWST at Churchill (Figure 6e), while the magnitude of trends in LW levels lay between 1.6 mm yr^{-1} in MLWST at Delfzijl in the Netherlands (Figure 6f) and −3.5 mm yr^{-1} in MLWST at Wilmington, in USA (Figure 6i). Large trends of over 5 mm yr^{-1} were observed in different tidal regimes, ranging from mixed-diurnal micro-tidal, such as Manila in the Philippines (Figure 6g), to semi-diurnal macro-tidal, such as Calais (Figure 6d).

Determining realistic percentage change is difficult, because the magnitude of some tidal levels, such as MLHW, can have values close to zero. Therefore, in these cases, small changes in magnitude equate to large changes in percentage terms. However, the maximum trends by magnitude reported above, equate to changes of 1.0% per year in both STTR and MHWST at Calais (Figure 6d), 2.1% per year in GDTR at Manila (Figure 6g) and 4.4% per year in STR at Wilmington. Global maps of the percentage change in MHHW, MLLW, and GDTR are presented in Figures 7a–7c and show the regionally coherent patterns described above as, well as the sites with localized trends. Similar maps for all other tidal levels listed in Table 1 are included in Supporting Information, and show comparable patterns of spatial coherence, although with slightly different numbers of positive and negative significant trends.

The percentage of sites with significant trends varies depending on the selected tidal level, from 63% for MLLW to 36% for MHWNE, as shown in Figure 8. The stacked bar chart shows the frequency and percentage of sites where trends in annual time-series of each tidal level are significant positive (red), significant negative (blue) and nonsignificant (black). This figure also shows that for tidal range and HW levels there are more positive trends than negative trends, while for LW tidal levels the opposite is true. For all tidal levels we performed a chi-squared (χ^2) test to determine whether there was a statistically significant difference between the number of positive and negative trends (note we only did this for the positive and negative trends that were themselves significant at the 95% confidence level). The rejected null hypothesis was that there would be an equal number of significant positive and negative trends for each tidal level. This null hypothesis assumed that the distribution of sites was not geographically biased toward regions with or without coherent spatial signals. For all tidal range and HW levels, we found that there were significantly more positive than negative trends; while for all LW levels there were significantly more negative trends.

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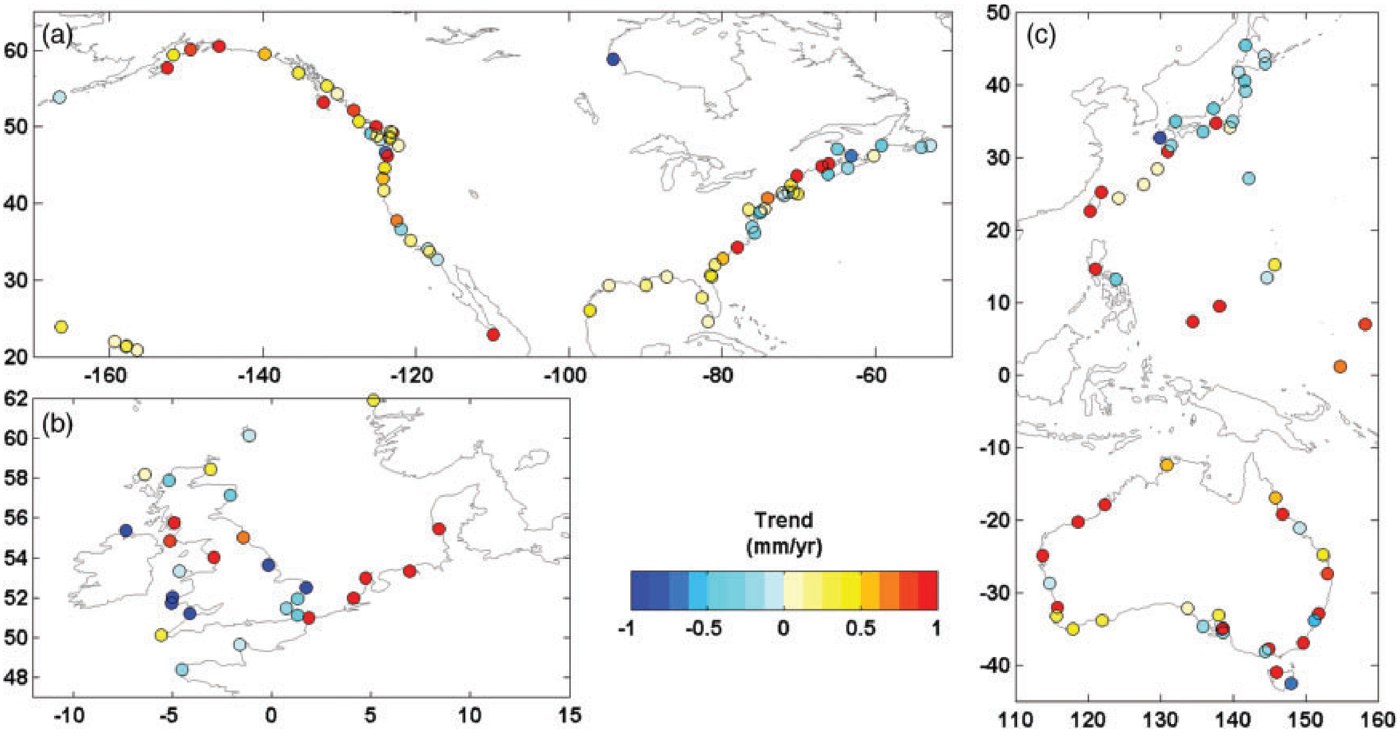

Figure 5. Regional map of North America showing percentage changes in % yr^{-1} for MHHW (a), MLLW (b), and GDTR (c) for all locations.

Although the largest changes occurred in the spring-tropic tidal levels, large changes occurred in all tidal levels. At many sites, there are significant differences in the trends observed between each of the five different tidal levels used for tidal range, HW and LW. Differences between trends in tidal levels are presented for selected sites in Figure 9, and for all sites in the Supporting Information. Each plot shows the magnitude of trends in the five tidal ranges, listed on the *x*-axis, as large green dots, with the limits of the 95% confidence level shown as small green dots. The contribution to the tidal range trend of the associated HW level is represented by the red bar, while the trend in the associated LW level is shown by the blue bar (see Table 1 for associated tidal levels). A positive trend in HW level and a negative trend in the LW level, both have a positive contribution on the trend in tidal range, and vice versa for a decrease in HW levels and increase in LW level. For example, at Brest in France the negative trend in MHHW of −0.11 mm yr^{-1} (Figure 3d) and the positive trend in MLLW of 0.10 mm yr^{-1} (Figure 3e) both give a negative contribution toward the magnitude of the trend in GDTR of −0.21 mm yr^{-1} (Figure 3f).

At 38 of the 220 sites, significant (95% confidence) differences exist between at least one pair of tidal ranges. At six sites, the trends in tidal ranges have different signs. These sites are: Vernadsky in Antarctica (Figure 9g) and Kaohsiung in Taiwan, where trends in GDTR and LDTR have opposite signs; Bunbury in Australia (Figure 9i), where it is GDTR and MTR Stornoway (Figure 9c) in the UK, where STTR and NETR have opposite signs; and Port Pirie in Australia where the difference in trend signs occurs between MTR and NETR. Most significant differences occur between the STTR and NETR, such as at San Francisco (Figure 9f) in the USA, Wyndham (Figure 9j) in Australia, Lowestoft in the UK, Pohnpei in Micronesia and Port Elizabeth (Figure 9h) in South Africa, among others. Significant differences also occur between GDTR and LDTR. Along with those listed above, these occur at Hamada and Toyama in Japan, Keelung in Malaysia and Seward (Figure 9a) in Alaska, USA. Differences between HW tidal levels and LW tidal levels also occur. However, the sites where differences are observed are not all the same, meaning that in total 56 sites have significant differences in trends of the same set of tidal levels (i.e., tidal range, HW or LW). Sites with differences between at least two HW tidal levels include Aburatsu in Japan, Flores in the Azores and Walvis Bay in Namibia. Sites with differences between at least two LW tidal levels include Campbell River in Canada, St. Petersburg in the USA and Williamstown in Australia.

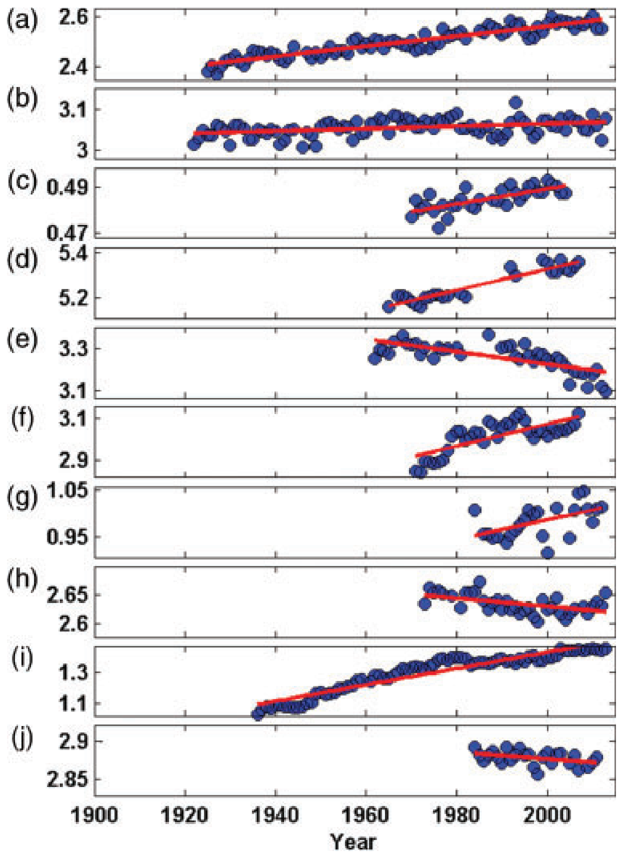

Figure 6. Time-series of annual GDTR values (in meters) without nodal component for 10 selected sites: (a) Astoria, USA, (b) Boston, USA, (c) Bunbury, Australia, (d) Calais, France, (e) Churchill, Canada, (f) Delfzijl, the Netherlands, (g) Manila, Philippines, (h) Willapa Bay, USA, (i) Wilmington, USA, (j) Zanzibar, Tanzania.

In summary, changes in tidal levels are globally distributed and the magnitude of trends is large at some locations. Magnitudes in STTR reaches 6.1 mm yr^{-1} at Calais, which is more than the increase in MSL observed at this site. Although the largest changes in magnitude are in the spring-tropic tidal levels (i.e., STTR, MHWST, and MLWST), we also found large changes in all the other tidal levels analyzed. Results also show importantly, that at 38 sites significant differences in trends between at least one pair of tidal ranges (i.e., between STTR and NETR) exist, and a further 18 sites have differences between a pair of either the HW or LW levels. Despite differences between trends in tidal levels, the spatial patterns are similar between all tidal levels, although with the direction of the trend reversed for LW levels. Regionally coherent increases in HW levels and decreases in LW levels are observed on the western North American coast, around Australia and in the German Bight, while decreases in HW levels and increases in LW levels are observed for small areas on the eastern North American coast and around the Japanese coast. Although no clear global pattern is visible, there are significantly more positive than negative trends in tidal range and HW levels, and vice versa for LW levels.

5. Discussion

To our knowledge, this study is the most comprehensive assessment of changes in tidal levels to date. Using sea level data from 220 sites around the world, we have shown that significant changes have occurred in time-series of 15 commonly used tidal levels at sites around the world. While this paper analyzes changes in tides at some new sites, the spatial patterns observed are broadly consistent with changes observed in previous studies using either tidal levels or major tidal constituents.

The largest spatially coherent trend we observed was along the western North American coast, which is consistent with the increased amplitude of the M_2 and K_1 constituents found by *Jay* [2009] at sites north of 18°N. However, along the east coast of North America, the decrease of up to 10% in the amplitude of the S_2 constituent observed by *Ray* [2009] is not replicated in the tidal level changes we found. Instead we observed an alternating pattern of smaller regions of increases and decreases (Figure 5a). This pattern is also observed in the response of tidal constituents and MTR to scenarios of sea level rise in a global ocean modeling study undertaken by *Pickering* [2014]. Our results in this region correspond most closely to his 2 m sea level rise scenario (generated from 1 m of meltwater from each of Greenland and western Antarctica). However, in this scenario, patterns in other regions compare poorly with the findings of this paper.

Around Australia, the coherent positive trends we observe in tidal range and HW levels are consistent with the the increased amplitude of the M_2 and S_2 constituents at most sites, as shown by Woodworth (2010). The generally positive trends in tidal range and HW levels continues through the sparse dataset in south-east Asia, but we find a consistent decrease in tidal range and HW levels around Japan.

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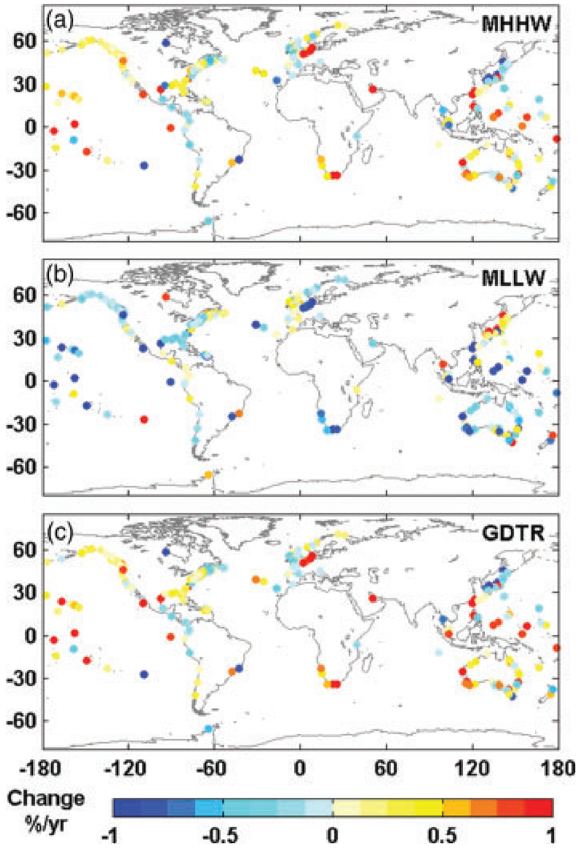

Figure 7. Global map showing percentage changes in % yr^{-1} for MHHW (a), MLLW (b), and GDTR (c) for all locations.

Woodworth [2011] found similar patterns in the magnitude of M_2 and K_1 constituents around Japan, but *Rasheed and Chua* [2014] found increases in MTR, DTR, MHW, and MHHW over the same region. On smaller spatial scales, a coherent increase was observed in both MTR [*De Ronde*, 1983; *Töppe and Führböter*, 1994] and the amplitude of major constituents in the German Bight [*Woodworth*, 2010]. Our results are consistent with these findings and those that show that consistent spatial trends do not extend, across the North Sea, to the UK [*Woodworth et al*., 1991; *Haigh et al*., 2010].

Although no spatial coherence has been observed around the UK, trends in MTR have previously been shown to have a positive correlation with trends in MSL [*Woodworth et al*., 1991]. In other studies, changes in MSL have been suggested as a cause of secular changes in the tide, because the propagation of the tidal wave is controlled by water depth. Many studies using hydrodynamic models have investigated the response of the tide to changes in MSL. Several of these studies focused on the north-west European shelf, and the North Sea in particular, where spatially variable and non-linear responses were observed [*Flather et al*., 2001; *Pickering et al*., 2012; *Ward et al*., 2012; *Pelling et al*., 2013; *Pickering*, 2014]. These changes manifest as small shifts in the position of amphidromic points [*Pickering et al*., 2012; *Ward et al*., 2012], but the direction and distance of the shift is dependent on the coastal boundary conditions imposed [*Pelling et al*., 2013]. Where vertical walls were applied at the present day coastline, changes were caused by the alteration of the propagating tidal wave. However, when the coast was allowed to flood the response was controlled by the increased dissipation of the newly flooded cells [*Pelling et al*., 2013]. The consistent increase in the magnitude of tidal range and HW levels observed at Dutch and Danish sites in this study, agrees with findings of the modeling studies [*Pickering et al*., 2012; *Pelling et al*., 2013], suggesting that the models findings and the proposed mechanisms (e.g., shift in amphidromic points) are valid.

Modeling studies generally suggest that the magnitude of MSL rise at which changes in tides are likely to become important is large (>2 m) [e.g., *Flather et al*., 2001; *Pickering et al*., 2012]. Our research, along with other previous studies of historic changes, suggests that significant variations in tides are occurring already, but there is contrasting evidence as to whether this may be caused by MSL change. *Woodworth et al*. [1991] found a positive correlation between trends in MSL and MTR at UK site, but we find no significant correlation for any tidal level, even for UK sites, as shown in Figure 10. Conversely, there are more positive than negative trends in tidal range and HW levels, and vice versa for tidal LW levels. This finding suggests that one or more mechanisms are affecting tides on a global scale. As the gravitational forces driving the tides are virtually constant over the observed timescales, the most likely cause of global change in tides is global MSL rise. These contradictory findings suggests that MSL is an important mechanism at a number of sites but that other mechanisms may dominate on a regional or local scale.

There are a number of mechanisms associated with the rise in sea level, which can cause changes in the tides. The movement of amphidromic points is one such mechanism, and has been suggested for the

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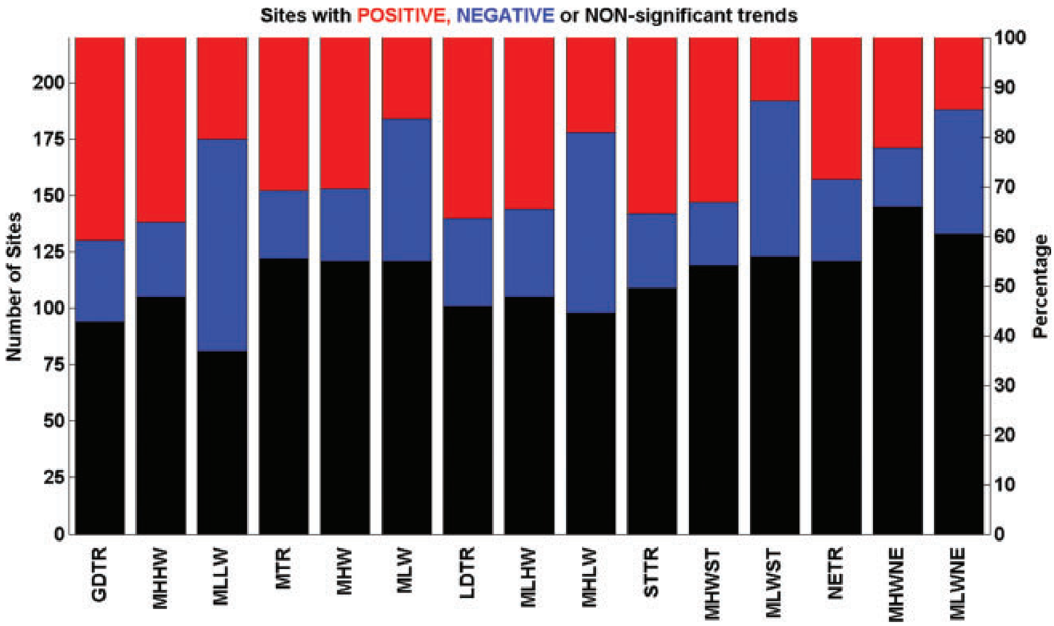

Figure 8. Stacked histograms showing the frequency of sites with significant positive trends (red), significant negative trends (blue) and nonsignificant trends (black). Significance means trend is significantly different to zero.

changes in North Sea [*Pelling et al*., 2013], and the coherent increase in the amplitude of the M_2 and K_1 constituents along the western North American coast [*Jay*, 2009]. However, possible causes of the shifts which include changes in the internal tide due to changes in stratification [*Jay*, 2009], and changes in the mean vorticity of the upper ocean in response to large-scale changes in wind-driven circulation [*Kolker and Hameed*, 2007] are speculative and require further research. The scale of the spatial coherence suggests large-scale ocean processes are the cause, but because increases are observed in both diurnal and semi-diurnal constituents, frequency-dependent mechanisms such as resonance were ruled out along the western North American coast [*Jay*, 2009].

Frequency-dependent mechanisms are important in other regions. The amplitude of the tide increases where the natural resonance of the basin is close to the frequency of a major constituent. Standing wave resonance is responsible for most large tidal ranges, including the largest in the world in the Bay of Fundy which is close to resonance with the dominant M_2 tidal constituent [*Pelling and Green*, 2013]. The primary resonant period of the Bay of Fundy and the whole of the Gulf of Maine is believed to be between 12.5 and 13.3 h [*Greenberg et al*., 2012]. With MSL rise, this period is expected to decrease and move closer to the M_2 period of 12.42 h. This study finds that significant positive trends in MTR in the Gulf of Maine (Figure 5a) are primarily caused by an increase in the amplitude of the M_2 tidal constituent. The system is non-linear though, with a double peak in resonance observed in the Gulf of Maine [*Arbic et al*., 2007; *Müller*, 2008], meaning that future MSL change will have complex effects on the tide. Nonetheless, sea level rise and the subsequent shift in resonance is believed to be an important factor in the increases observed in the amplitude of the M_2 constituent [*Ray*, 2006; *Woodworth*, 2010; *Müller et al*., 2011], and tidal range and HW levels at a number of sites in this study, such as in the Gulf of Maine.

The mechanisms of frequency dependence and energy dissipation, that have been shown to be important on regional scales, can also impact on local scales. Bathymetric changes in coastal waters, harbors or estuaries are a suspected major cause of changes in the tide. These changes include natural changes such as vertical land movements, and accretion and erosion in river deltas [*Araújo et al*., 2008]; or anthropogenic causes such as dredging of a navigation channel or creation of a sea wall. Changes in instrumentation can also lead to discontinuities but these effects should be removed during quality control. The examples of Tofino, Canada, and Willapa Bay, USA, where negative trends in MTR contrast with the positive trends in MTR observed at other sites along the northwest American coast, show local effects are important. However, this is highlighted most clearly by the annual values of GDTR at Delfzijl (Figure 6f), and its

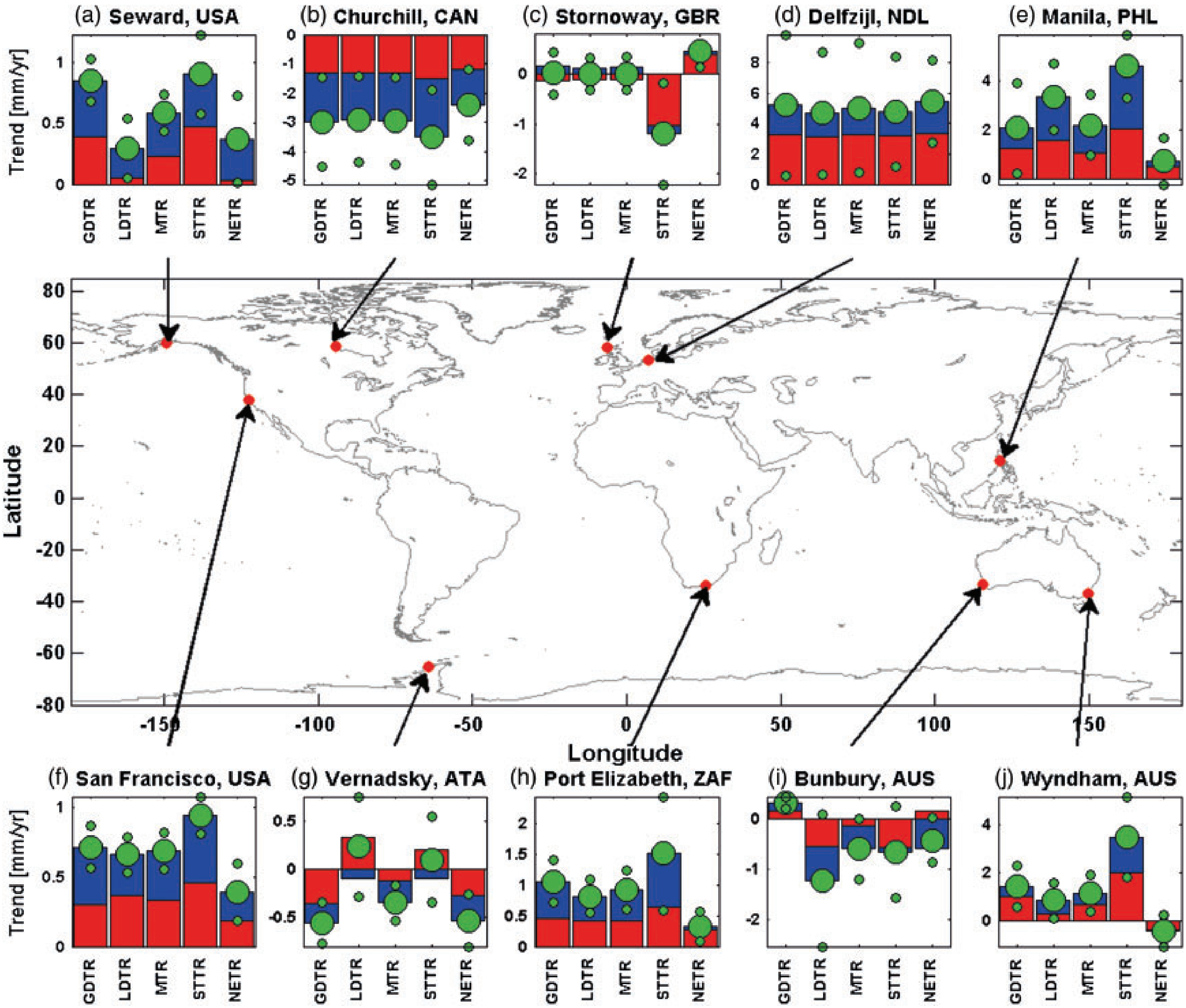

Figure 9. Map showing position of selected sites (red dots). Plots surrounding the map show the magnitude of linear trends in tidal levels at 10 sites referenced in the text. The trend in tidal ranges (large green dots) is plotted with 95% confidence limits (small green dots) for five tidal ranges (see Table 1). Stacked bar charts show the contribution toward the tidal range trend of changes in the respective HW subsets (red) and LW subsets (blue). For example, at Delfzijl the contribution toward STTR from HW is positive (i.e., trend in MHWST is positive) while the contribution from LW is negative (i.e., positive trend in MLWST).

neighboring site Den Helder, in the Netherlands, which show a discontinuity around 1978. Realignment of the Dutch coast as part of the Deltaworks programme, where the largest engineering schemes finished around 1978 [*Bijker*, 2002] may have influenced the tides in this region. Verification of the cause of the changes of the tides along the German and Dutch coast is not possible with the GESLA dataset since no high-resolution sea level data are available before the start of the Deltaworks. A modeling study by *Kang et al*. [2013] of the Yellow Sea showed that the tidal regime there changed in response to large-scale land reclamation on the Korean coast.

The trend in MHHW at Delfzijl is 2.0 mm yr^{-1}, which is a similar magnitude to the 2.9 mm yr^{-1} trend observed in MSL at this location. The increase in global MSL over the 20th century is estimated to be 1.7 mm yr^{-1} and this has accelerated over the latter part of the 20th century to over 3 mm yr^{-1} [*Church et al*., 2013]. Its impact on extreme high sea levels is a major concern, and as trends in HW tidal levels are

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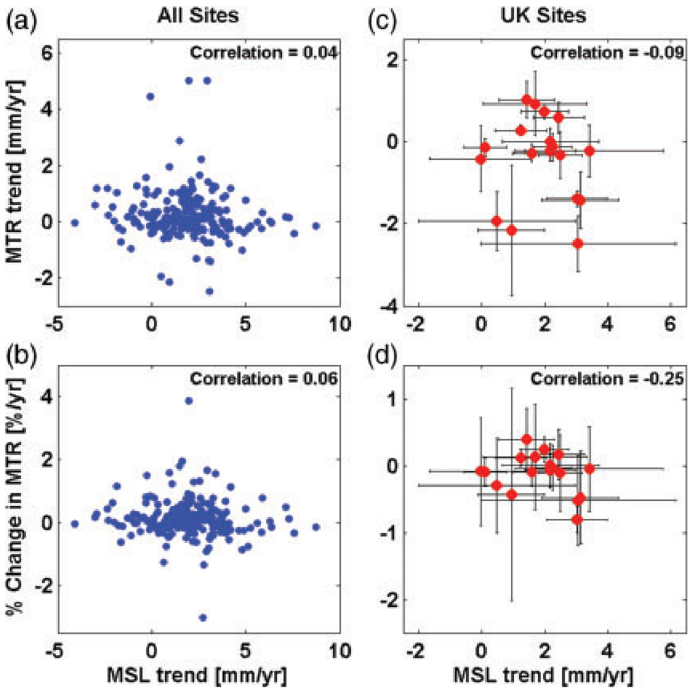

Figure 10. Scatter plots showing correlation coefficients for MTR trend (a, c) and percent change in MTR (b, d) against MSL trend for global sites (a, b) and UK sites (c, d).

in addition to the effect of MSL change, large underestimation of extreme high sea levels will occur where changes in tide are not accounted for. For example, current predictions of extreme high sea levels around the UK do not account for changes in the tide [*McMillan et al*., 2011], despite the fact that significant changes have been reported since the early 1990s at several sites [*Woodworth et al*., 1991].

A first step in improving the estimation of extreme sea levels would be to include changes in tide. However, because this study has shown that trends vary between tidal levels, accounting for the complexity of the changes in tides is difficult. Extreme sea levels occur more regularly at peaks in various tidal cycles, including spring-neap and lunar-nodal cycles [*Cartwright*, 1974; *Amin*, 1979; *Zetler and Flick*, 1985a; *Haigh et al*., 2011]. This is because the base level upon which a storm surge event adds is greater during spring-tropic tides and around the peak of the lunar-nodal cycle. Changes in the magnitude of spring-tropic tidal levels, such as MHWST, will therefore lead to larger changes in magnitude of extreme sea levels, than changes in neap-equatorial tidal levels. Most differences between trends in tidal levels are between the spring-tropic and neap-equatorial tidal levels as the high or low waters they include are mutually exclusive. These findings show that the tide is changing in far more complex ways than would be revealed if just changes in time-series of MTR or DTR were assessed. It is also clear that calculating the trend of a particular tidal level should be done directly and not inferred from other levels without prior investigation.

Although we analyzed changes in tide at 220 tide gauge sites around the world, the results are still limited by the availability of data in several regions. Datasets in some under-represented areas such as India and China are difficult to access while in Africa, records are rare and typically short. Considerable recent effort has been made to create a network of tide gauges around the coast of Africa [*Woodworth et al*., 2007], which will help ensure a more representative global dataset for future studies. The nature of tide gauges also creates a geographical bias toward coastal sites and away from the open ocean. However, many different coastal morphology types are represented in the data from estuarine (e.g., Wilmington, USA) to Pacific Islands (e.g., Pago Pago, American Samoa). These data sparse regions could skew our results, as a key assumption is that the geographical distribution of sites was not biased toward regions with trends of a particular sign. Data quality issues are also a particular problem with tidal data analysis, because small changes in the location of the tide gauge or in the surrounding coastal morphology can lead to clear shifts in the magnitude or phase of tidal constituents or levels. Determination of what constitute real change can be difficult, with both natural and anthropogenic mechanisms often acting on the tide. As discussed above, discontinuities in the trends in tidal levels, such as Delfzijl (Figure 6f), mean the linear trend applied to all sites is not always the most suitable model. However, the changes in tidal levels at these sites are real, even if their cause is most likely anthropogenic, and they are included in the analysis.

6. Conclusions

In this paper, we have used a quasi-global sea level dataset at 220 tide gauge sites to analyze changes in 15 tidal levels: five high water levels; five low water levels; and five tidal ranges (calculated from the difference of the respective tidal high and low water levels). Our results show that statistically significant trends are evident in all tidal levels at many sites around the world. For each of the 15 tidal levels assessed, between 36% and 60% of the selected sites had trends that were significantly (95% confidence) different from zero. A coherent global pattern of change is not evident, but regionally consistent patterns are observed in the northeast Pacific, the German Bight, and around the coast of Australia and Japan. There are significantly more positive trends in tidal range and HW levels, and more negative trends in low water levels. This suggests a global mechanism has an impact on trends but we find no correlation between the trend in MSL and the trend of any tidal levels, despite previous studies observing a correlation, and hydrodynamic models showing that MSL rise can cause changes in the tide.

The magnitude of the trends are similar to rates observed in MSL at some locations. Thirty-seven sites had a trend greater than 1 mm yr^{-1} in MTR, and while for MHW this number was only eight, the magnitudes of these changes means that they are similar to trends in MSL. At 56 sites, we find significant differences between the magnitudes of different tidal levels within the same set (i.e., tidal range, HW or LW). In some cases the sign of the trend is different. The largest differences between tidal level trends were between spring-tropic and neap-equatorial tidal levels, and this has implications for extreme sea level analysis. High extreme sea levels are more likely to occur during spring-tropic periods and increases in HW during this period would result in larger increases in extreme sea levels.

The number and global distribution of sites with significant changes, and the large magnitude of these changes at certain sites, strongly suggests that trends in the tide should be considered when predicting sea levels in the future for applications including coastal defenses, navigation, coastal management, and tidal power extraction. The inclusion of changes in tides for prediction of future sea levels is complicated by the finding that there are differences in trends, both in terms of magnitude and some cases sign, between different tidal levels. Prediction is further complicated by inadequate understanding of the mechanisms causing the observed changes Further work is necessary to seperate out the impact of mechanisms occurring on global, regional and local scales.

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