Response to Reviews of:
'Are tidal predictions a good guide to future extremes? - a critique of the Witness King Tides Project', submitted to Ocean Science

1 Note to the Editors

While Ivan Haigh provided a useful technical review of the manuscript, I was quite disappointed with the reviews of Phil Watson and Ben Hague. These latter two reviews did not address the technical details of my manuscript at all, but rather mounted strident defences of the Witness King Tides project and made only broad recommendations, which would effectively result in a very different manuscript with very different aims. I have therefore responded to these generalities but found no suggestions that would warrant modification of my manuscript. Luckily, the manuscript was also reviewed by a colleague who gave a number of detailed technical recommendations, most of which have been incorporated. I have likewise addressed the helpful technical comments of Ivan Haigh, the majority of which have also been incorporated.

My responses, below, are in red. Line numbers refer to the original manuscript.

2 Reviewer: Ivan Haigh

2.1 The Full Review

In this paper John Hunter uses records from a quasi-global tide-gauge dataset to determine in which regions of the world the Witness King Tide (WKT) Project would perform well and other regions where it would not perform well. Overall, I find the paper to be interesting, novel and well written - and commend the author for a nice study. The statistical approach is robust. Therefore, I recommend it for publication. However, I have a few moderate/minor corrections that I feel should be undertaken to strengthen the paper.

Moderate Comments

I think it might be useful, in the introduction, to include a short paragraph describing why the predicted tidal height changes through the year and maybe even include a figure showing a year of tidal predictions at a semi-diurnal and diurnal example site. I still find people don't appreciate or understand the differences in height and timing in a given year between semi-diurnal, diurnal or mixed tidal sites. For example, you could mention that the largest semidiurnal tidal range occurs in March and September during the equinoxes, while the largest diurnal tidal range occurs in June and December during the solstices. The day of largest tide varies with phasing of the spring and neap tidal cycle and influence of moons distance to earth (e.g., perigee).

I wondered whether it would be interesting, for one year or a couple of years, to plot the actual date when the maximum tide occurs, as this will vary quite a bit around the world depending on whether the site has semi-diurnal, diurnal or mixed tides.

No where do you mention the 4.4 and 18.6 tidal cycles - these can be important in influencing both the timing and height of the annual maximum predicted tide from year to year, but also in a given year. I assume these are accounted for in the tidal analysis.

In the paper there is no mention of storm-surges induced by tropical cyclones. These can be very large. I was just wondering how such events might influence/bias the results around the tropics.

I don't feel too strongly about this, but I wonder whether a short paragraph, or few sentences could be added to briefly highlight the papers that have looked at sunny day or nuisance flooding, as this has some relevance here.

Minor Comments

Page 1, Line 11 - you could add that this has become known as 'Sunny day flooding' nor 'nuisance flooding'.

Page 1, line 6 - maybe add a sentence or two to describe why there might be more than one astronomical tides of similar magnitude to the maximum. For example, larger than average tides occur twice per year around either the equinoxes or solstices depending on whether you have semi-diurnal or diurnal tides.

Page 2, line 3 - I would replace 'and tidal observations' with 'and sea level observations' as you are considering both tide and surge.

Page 2, line 14 - some justification is need for the first selection. How much data was ignored based on this selection.

Page 2, line 15 - I am not sure what you mean by 'binned' - do you mean averaged or interpolated.

Page 3, line 5 - which tidal analysis software was used? Sorry for my delay in posting this review.

2.2 The Response

I thank Ivan Haigh for his thoughtful review in which he makes a number of useful suggestions for improving the manuscript.

1. '...you could mention that the largest semidiurnal tidal range occurs in March and September during the equinoxes, while the largest diurnal tidal range occurs in June and December during the solstices. The day of largest tide varies with phasing of the spring and neap tidal cycle and influence of moons distance to earth (e.g., perigee).' (Page C2, paragraph 1.):

   Good idea - this has been addressed - see point (7), below.

2. 'I wondered whether it would be interesting, for one year or a couple of years, to plot the actual date when the maximum tide occurs, as this will vary quite a bit around

the world depending on whether the site has semi-diurnal, diurnal or mixed tides.' (Page C2, paragraph 2.):

I tend to think that the manuscript already has quite enough plots and complexity, and that this information would not really help anyone to assess the feasibility of performing Witness King Tides (WKT) at a given site. As noted in the Conclusions, such preliminary information can be obtained from Figs. 2 to 10 of the manuscript and 'it is suggested that, prior to initiating a WKT project, local tide-gauge records that are longer than 20 years are analysed in ways similar to those described here ... to provide a more detailed assessment of the viability of WKT'.

3. 'Nowhere do you mention the 4.4 and 18.6 tidal cycles - these can be important in influencing both the timing and height of the annual maximum predicted tide from year to year, but also in a given year. I assume these are accounted for in the tidal analysis.' (Page C2, paragraph 3.):

   Firstly, I have expanded the final paragraph of Section 2 with the addition of a final sentence: 'Astronomical arguments and tidal frequencies were generated by software provided by the (then) Proudman Oceanographic Laboratory (now the National Oceanography Centre, Liverpool, U.K.)'.

   Secondly, yes - the 4.4 and 18.6 tidal cycles are accounted for, in two ways: (a) tidal modulations are accounted for by 'nodal' corrections, calculated by the routines described above, and (b) the tidal analysis (for 102 constituents) is performed on a two-year time series centred on the middle of the year being analysed. This therefore represents a 'running' analysis, which would give a reasonable representation of the tidal modulations, even if 'nodal' corrections (a) weren't applied. A 'running' analysis is used in order to remove interannual variability and to minimise the effects of unidentified vertical datum shifts in the records. A sentence to this effect has been included in the previous paragraph to the one that describes the tidal analysis: 'This removes signals of period longer than about two years, and most of the effects of any vertical datum shifts in the tide-gauge records'.

4. 'In the paper there is no mention of storm-surges induced by tropical cyclones. These can be very large. I was just wondering how such events might influence/bias the results around the tropics.'

   There has been no attempt to separate surges induced by tropical cyclones from other surges (e.g. those induced by mid-latitude synoptic systems). The main problem with surges from tropical cyclones is that there are relatively infrequent and probably under-sampled in some of the records (all of which contained at least 20 valid years). This could possibly contribute to the uncertainty in the results at some locations, but further analysis of this effect is beyond the scope of the manuscript, which is to provide preliminary guidance as to the feasibility of a WKT project.

5. 'I don't feel too strongly about this, but I wonder whether a short paragraph, or few sentences could be added to briefly highlight the papers that have looked at sunny day or nuisance flooding, as this has some relevance here.'

   I don't like the term 'sunny day flooding' as it infers that 'nuisance flooding' only relates to periods when the storm surge is small compared with the tide (i.e. that it occurs on 'sunny days', rather than during storms). However, the term 'nuisance flooding' describes the effect (flooding which is of low level, and which only causes minor rather than major disruption or property damage), rather than the cause; therefore it can exist in surge-dominated environments as well as tidally-dominated ones. I have dealt with this issue in the next item (6).

6. ‘Page 1, Line 11 - you could add that this has become known as “Sunny day flooding” or “nuisance flooding”.

   I agree (but I will not use the term ‘sunny day flooding’ for the reason given above): I have added, at the end of the sentence ‘WKT is a citizen-science project designed to collect photos of the shoreline at the time of annual highest astronomical tide, with the aim of indicating the flooding that may occur routinely with sea-level rise’ (page 1, lines 9-11), the reference ‘(e.g. Moftakhari et al., 2015)’, followed by the sentence:

   ‘Such flooding, if it is of low level and only causes minor rather than major disruption or property damage, is generally referred to as “nuisance flooding” (Moftakhari et al., 2018).’

7. ‘Page 1, line 6 - maybe add a sentence or two to describe why there might be more than one astronomical tides of similar magnitude to the maximum. For example, larger than average tides occur twice per year around either the equinoxes or solstices depending on whether you have semi-diurnal or diurnal tides.’

   I’ve added, on page 2, line 6, after the sentence ending ‘of similar to the maximum’, the sentence:

   ‘If the tides are predominantly semidiurnal, the largest maxima occur near the equinoxes (March and September) and, if the tides are predominantly diurnal, the largest maxima occur near the solstices (June and December); for example, see Ray and Merrifield (2019).’

8. ‘Page 2, line 3 - I would replace “and (in) tidal observations” with “and (in) sea level observations” as you are considering both tide and surge.’

   Thank you - of course, I meant ‘sea-level observations’ - I have changed it.

9. ‘Page 2, line 14 - some justification is need(ed) for the first selection. How much data was ignored based on this selection.’

   After ‘observed heights that departed by more than 10 standard deviations from the average were rejected’ I have inserted ‘(this is a simple check to remove extreme outliers; in the entire GESLA-2 data set of over 300 million data points, only 190 values were rejected in this way)’.

10. ‘Page 2, line 15 - I am not sure what you mean by “binned” - do you mean averaged or interpolated.’

    I mean averaged into bins (e.g. see the Wikipedia article). I have changed ‘binned’ to ‘averaged into bins’.

11. ‘Page 3, line 5 - which tidal analysis software was used?’

    See item (3), above.

3 Reviewer: Phil Watson

3.1 The Full Review

From the outset, I have no concern over the quite detailed analysis undertaken and presented within the manuscript which for all intents and purposes provides an interesting insight into the difference between the highest predicted astronomical tide during any given year and the actual highest recorded water levels around the world's coastlines.

However, as a critique on the utility of the actual 'Witness King Tides Project', I have concerns that the modest objectives of the original projects in Australia have been unwittingly misrepresented in the manuscript as to confer a more measurable, scientific output from these citizen science endeavours.

As noted correctly by the author, the idea had its origins in January 2009 in NSW, Australia but the objectives of the exercise were indeed quite modest from a scientific perspective. The intention first and foremost was to use the predictable coincidence of a king tide visible during daylight hours, to raise public awareness at the more fundamental local level about the prospect of predicted sea level rise from climate change and how that might impact local landscapes using a king tide as a visual reference plane of sorts. In its crudest form, the public messaging was as simple as visualising water levels possibly up to a metre deeper than what you observe of the king tide by the end of the century under high range sea level projections.

The day needed to be set well in advance to have the opportunity to condition the public and align state and local government staff participation in what proved a stunningly successful public awareness initiative that has grown roots and expanded rapidly with more accessible internet and telecommunications tools. The event itself was augmented by numerous publications, presentations and media to explain the relationships between predicted tides, actual water levels and sea level projections into the future. The initiative quickly evolved into a national and more recently international event.

The paper makes the point at line 13 that 'A critical assumption of WKT is that the annual highest astronomical tide is a good proxy for the actual highest water level during the year, both in timing and height' and then goes on to scientifically address this assumption. However, this as described in the objectives outlined above, was never a critical assumption in developing the concept. A high predicted tide, visible during daylight hours, with sufficient time to promote, provide technical support and public messaging, coordinate and attend to relevant IT requirements were all key considerations in planning such an undertaking. Despite technological advancements and well-established modern WKT networks, engaging with the public in a meaningful way through these citizen science style projects still requires planning and commitments in advance that wont necessarily line up with real-time physical phenomena that can significantly raise water levels above predicted tides as noted by the author.

In the main, my key concern is that the objectives of the WKT are not accurately described in the paper. The linkages to scientific assessment of the difference between the highest predicted tide in any year and the peak measured water level during daylight hours are almost incongruous to critiquing the WKT project? Some thoughts perhaps for the author to consider.

Thank you for the opportunity to review the work.

3.2 The Response

I thank Phil Watson for his comments. However, I feel that he has missed the main points of the manuscript, which are not to misrepresent the objectives of the Witness King Tides project by criticising its scientific output. Rather, I state that WKT has 'the aim of indicating the flooding that may occur routinely with sea-level rise' (page 1, lines 10-11) and my purpose is to 'indicate regions of the world where WKT should perform well ... and others where it would not' (Abstract, lines 2-3). I do not criticise WKT for any lack of rigorous or quantifiable scientific output.

As indicated in the Conclusions, I (a) show regions of the world where WKT may be successful 'in the sense that the day of highest predicted tide for the year ... would yield an observed level comparable with the maximum observed level for the year' (Page 16, lines 7-9), (b) suggest that local tide-gauge records should be analysed prior to initiating a WKT project in order to assess its likely success, and (c) suggest an alternative approach which is 'to photograph every high tide of the year and pick, in retrospect, the images which show the highest sea level ... using the camera of a smartphone, suitably programmed to take photos at the required times and to transmit them to a central repository' (Page 16, lines 13-15); this could form the basis of an alternative citizen-science project.

I agree with Phil that the primary motive of WKT is 'to raise public awareness ... about the prospect of predicted sea level rise from climate change and how that might impact local landscapes'. However, my manuscript hopefully serves as a warning that WKT should be planned with care and with due cognisance of a possible unintended consequence - namely, that a strong negative storm surge on the day of a WKT project could yield photos that are so underwhelming as to suggest to the general public that the impact of sea-level will be minimal. This is my biggest fear about WKT projects that are planned without a good understanding of the local regime of tides and storm surges.

4 Reviewer: Ben Hague

4.1 The Full Review

Overall, I believe that this study contains many useful insights into the causes of high sea levels and associated coastal inundation and their spatial variability around the world. In particular, the spatial distribution of where annual maximum sea levels is tide-dominated compared to surge-dominated helps to explain spatial variability in extreme sea level drivers and projections around the world. These are important findings and make this paper an important contribution to the coastal inundation literature. However, I feel that the definition of 'success' of Witness King Tides has been too narrowly defined, especially when viewed from the perspective as a mechanism to generate coastal inundation impact information.

This study has largely ignored one of the key motivations of Witness King Tides - to document coastal inundation impacts that will occur increasingly frequently with sea-level rise. Rather, it has rather narrowly considered the single question of whether high sea levels coincided with high predicted tides on some of the days that images were taken during the project. For example, the appropriateness of using a single 'WKT day' per year (as opposed to once-a-month or once-a-decade, for example) in the metrics defined has not been discussed. The existence or value of coastal assets that are impacted by king tides (e.g. Hanslow et al. 2018) also not been considered in the assessment of the suitability of sites for WKT locations. These are both important factors to consider when assessing the success of a coastal monitoring program. For example, recent research by Hague et al. (2019) used WKT and other sources (e.g. social media, online news) to show that there is large spatial variability in coastal inundation frequency across Australia. In some places coastal inundation was reported many times per year and in others it occurred less frequently than one year. The reasons for these spatial differences are likely many, but a lack of coastal infrastructure built close to the high tide marks was noted at some locations where coastal inundation occurred infrequently.

This leads into my key point - that just because the highest annual sea level didn't coincide with the highest predicted tide it doesn't make WKT 'not successful'. WKT is one of few coastal change monitoring programs - two other notable cases from Australia are Fluker Posts (Augar and Fluker 2015) and CoastSnap (Harley et al. 2019). The reduction in activity in WKT in the last 5 years has resulted in a large reduction of reports of coastal inundation impacts (e.g. refer Witness King Tides' Flickr page: https://www.flickr.com/photos/witnesskingtides/). To my knowledge this has not been replaced by an alternative publicly-available source - impact reports are now primarily confined to private or institutional repositories, portions of which are occasionally published in reports or research studies (e.g. Maddox 2018, Hague et al. 2019). Unlocking, collating, or generating, these sources of impacts information is vital to understand the physical impacts of coastal inundation and how the frequency and nature of these will change as sea-level rise continues and accelerates. The continuation and enhancements of programs such as WKT are of great scientific importance. Concerningly, the results of this study could be (mis)interpreted to suggest that we only need to monitor coastal impacts at locations where inundation is tide-dominated. This is a dangerous proposition when coastal inundation impact information is simultaneously becoming rarer but also more important as scientists consider the impacts of sea-level rise on coastal communities happening now and in the future.

The 'attractive alternative' offered by the author - to photograph every high tide and pick the ones associated with the highest sea level - is effectively advocating for CoastSnap or Fluker Posts to be extended to, or expanded in, areas where coastal inundation occurs. (CoastSnap is currently confined to open ocean environments where coastal erosion is being monitored.) This is an excellent idea, and one that would likely be successful, with enough financial or community support for the project. However, other new technologies such as flying of drones (Klemas 2015) or use of social media analytics (Hino et al. 2019) could also provide opportunities for citizen science coastal monitoring projects and should also be considered as alternatives. I would however suggest that the aim of future programs is to capture any day where coastal inundation occurs, rather than the highest annual sea level. This will ensure a focus on coastal inundation impacts, rather than simply extreme sea levels.

Finally, regarding the results discussed in Section 3.5 and shown in Figure 10 - that the ratio of variances of observed sea levels and predicted tides may be a simpler but suitable metric for assessing the relative proportions of tide-dominated and surge-dominated extreme sea level regimes. It would have been interesting to further explore whether tidal range is a key factor in this analysis. For example, are low ratios due to infrequent storm surges or because tidal range is large? This could be useful to investigate due to its implications in the changing predictability of coastal inundation and potentially highlight locations where increases in tide-dominated inundation are most pronounced, and hence help identify candidate locations for future monitoring efforts.

References

Augar, N. and Fluker, M. (2015) Towards Understanding User Perceptions of a Tourist-based Environmental Monitoring System: An Exploratory Case Study, Asia Pacific Journal of Tourism Research, 20, 10, 1081-1093, DOI: 10.1080/10941665.2014.962554

Hague, B. S, Murphy, B. F., Jones, D. A. and Taylor, A. J. (2019) Developing impact-based thresholds for coastal inundation from tide gauge observations. Journal of Southern Hemisphere Earth System Science. DOI: 10.22499/3.6902.006 [accepted: http://www.bom.gov.au/jshess/docs/2019/Hague2_early.pdf]

Hanslow, D. J., Morris, B. D., Foulsham, E. and Kinsela, M. A. (2018) A Regional Scale Approach to Assessing Current and Potential Future Exposure to Tidal Inundation in Different Types of Estuaries. Sci. Rep., 8, DOI:10.1038/s41598-018-25410-y.

Harley, M.D., Kinsela, M.A., Sanchez-Garcia, E. and Vos, K. (2019) Shoreline change mapping using crowd-sourced smartphone images, Coastal Engineering, 150, 175-189.

Hino, M., Belanger, S. T., Field, C. B., Davies, A. R. and Mach, K. J. (2019) High-tide flooding disrupts local economic activity. Sci. Adv., 5, DOI:eaau2736.

Klemas, V. V. (2015) Coastal and Environmental Remote Sensing from Unmanned Aerial Vehicles: An Overview. Journal of Coastal Research, 31, 5, 1260 - 1267.

Maddox, S. (2018) NSW Ocean and River Entrance Tidal Levels Annual Summary 2017-2018. Manly Hydraulics Laboratory Report MHL2618, State of New South Wales, Sydney.

4.2 The Response

I thank Ben Hague for his comments and am gratified that he feels that the manuscript is ‘an important contribution to the coastal inundation literature’. However, he claims that ‘the definition of “success” of Witness King Tides has been too narrowly defined, especially when viewed from the perspective as a mechanism to generate coastal inundation impact information’. I would argue that the manuscript does not attempt to define the ‘success’ of Witness King Tides (WKT) but rather to indicate places where the observed sea level on the ‘WKT Day’ is unlikely to be ‘unusually high’ (see below for my discussion of ‘unusually high’) with the result that none of the stated objectives could be properly met. I do not attempt to discuss any other attributes which could contribute to the ‘success’ of a WKT project, nor suggest any other ways in which a WKT project could be deemed ‘unsuccessful’.

There are two readily-accessible definitions of the purposes of Witness King Tides, firstly from the website `www.kingtides.net` :

'We are citizen scientists, capturing data and images showing what the future sea levels will be and what is at risk. The King Tides Project helps people all over the world understand how sea level rise will impact their lives.

King Tides photos are used several ways to help people:

1. Document current flood risk in coastal areas.
2. Visualize the impacts of future sea level rise in their community.
3. Ground-truth and validate climate change models by comparing model predictions with the high-tide reality.
4. Serve as a living record of change for future generations.'

Secondly, from the report of the first WKT project by Watson and Fraser (Watson and Fraser, 2009; reference in main manuscript), which defined the two 'primary objectives' as:

- 'identifying areas vulnerable to tidal inundation, capturing the tide level against revetments, seawalls, jetties and other marine infrastructure; and
- raising awareness throughout the wider community about the current projections for sea level rise to the end of the century (approximately 90 cm).'

It is clear from the above that the success of a single WKT project requires (among other things) that the maximum sea level on a 'WKT day' is unusually high. Given that WKT projects are generally only carried out once per year in any one location, I imply by 'unusually high' that the maximum sea level on a 'WKT day' is among the highest for the year. WKT makes the assumption that the day of highest predicted tide of the year is a good proxy for a day when the observed sea level is 'unusually high' - the manuscript questions this assumption and indicates places where it is probably valid and places where it is not. This is the primary aim of the paper.

The reviewer indicates numerous aspects of WKT that I do not discuss (or intend to discuss) in the manuscript, for example:

1. '...the appropriateness of using a single "WKT day" per year (as opposed to once-a-month or once-a-decade, for example) in the metrics defined has not been discussed.'

   This isn't discussed because the aim of the manuscript is not to redesign WKT. At least in Australia, this is the way in which WKT started out (in most location, there was one 'WKT Day' per year). Unfortunately, the history of WKT both in Australia and globally has been quite poorly documented, and it is difficult to get an overall picture of what projects have actually occurred, where and when.

2. 'The existence or value of coastal assets that are impacted by king tides (e.g. Hanslow et al. 2018) (have) also not been considered in the assessment of the suitability of sites for WKT locations.'

   Again, consideration of coastal assets was not an aim of the manuscript.

3. 'These are both important factors to consider when assessing the success of a coastal monitoring program.'

   The reviewer appears to believe that the main aim of the paper is to provide a comprehensive assessment of WKT. It is not. It is to investigate one critical requirement for a WKT to have some hope of success - as noted above, it is that the maximum sea level on a 'WKT day' is 'unusually high'. If this requirement is not met (and the manuscript indicates likely places where this might be so) then it can be reasonably argued that the WKT project will fail, in that the resultant images become no more useful than images of random high tides. Indeed, the manuscript warns that such cases could well negate the stated aims of WKT of 'raising awareness ... about the current projections for sea level rise' and to 'visualize the impacts of future sea level rise' (see above), by noting that 'a significant negative storm surge on a WKT Day may well give the unintended message that the impact of sea-level rise is likely to be unimportant' (page 1, lines 22-23).

4. 'Concerningly, the results of this study could be (mis)interpreted to suggest that we only need to monitor coastal impacts at locations where inundation is tide-dominated.'

   The manuscript indicates 'regions where a WKT project may be successful, in the sense that the day of highest predicted tide for the year (the WKT Day) would yield an observed level comparable with the maximum observed level for the year' (page 16, lines 7-9). Essentially, WKT works well in tide-dominated regions and poorly in regions not dominated by the tide. It seems a strange leap of logic to suggest that 'we only need to monitor coastal impacts at locations where inundation is tide-dominated' just because WKT only works well in these regions. The manuscript even suggests (page 16, lines 13-15) an alternative strategy to WKT for possible use in regions where WKT may not work well.

5. 'I would however suggest that the aim of future programs is to capture any day where coastal inundation occurs, rather than the highest annual sea level. This will ensure a focus on coastal inundation impacts, rather than simply extreme sea levels.'

   This is exactly what the suggested alternative strategy (page 16, lines 13-15) would do.

6. 'It would have been interesting to further explore whether tidal range is a key factor in this analysis. For example, are low ratios due to infrequent storm surges or because tidal range is large? This could be useful to investigate due to its implications in the changing predictability of coastal inundation and potentially highlight locations where increases in tide-dominated inundation are most pronounced, and hence help identify candidate locations for future monitoring efforts.'

   Yes - it could be useful but does not, alas, fall within the scope or aims of this manuscript.

John Hunter, 8 April 2020

Are tidal predictions a good guide to future extremes? - a critique of the Witness King Tides Project

John Hunter[1]

[1]Institute for Marine and Antarctic Studies, University of Tasmania, Hobart, Tasmania, Australia

Correspondence: John Hunter (jrh@johnroberthunter.org)

Abstract. An analysis of the viability of the *Witness King Tides Project* (hereafter called *WKT*) using data from the GESLA-2 database of quasi-global tide-gauge records is described. The results indicate regions of the world where *WKT* should perform well (e.g. the west coast of the USA) and others where it would not (e.g. the east coast of North America). Recommendations are made both for assessments that should be made prior to a *WKT* project, and also for an alternative to *WKT* projects.

1 Introduction

This work was originally stimulated by the *Witness King Tides Project* (hereafter called *WKT*), which originated in New South Wales, Australia (Watson and Frazer, 2009), and is now internationally active in a number of regions, especially the USA and Australia (King Tides Project: http://www.kingtides.net, accessed: 20 November 2019). *WKT* is a citizen-science project designed to collect ~~photos~~ photographs of the shoreline at the time of annual highest astronomical tide, with the aim of indicating the flooding that may occur routinely with sea-level rise (Moftakhari et al., 2015). Such flooding, if it is of low level and only causes minor rather than major disruption or property damage, is generally referred to as "nuisance flooding" (Moftakhari et al., 2018). Participants are informed of the annual highest astronomical tide in their region for a given year and are asked to photograph their local shoreline at this time (hereafter called a *WKT Day*). Unfortunately, the history of WKT both in Australia and globally has been quite poorly documented, and it is difficult to get an overall picture of when and where projects have actually occurred.

A critical assumption of *WKT* is that the annual highest astronomical tide is a good proxy for the actual highest water level during the year, both in timing and height. There are two potential problems with this approach: (a) that the water level on the *WKT Day* may be significantly modified~~by a storm surge~~ , particularly by storm surges and (b) a significantly higher water level may occur at a different time of the year from the *WKT Day* due to the coincidence of a large positive surge and an astronomical tide that is lower than the one on the *WKT Day* (so the opportunity of getting more dramatic ~~photos~~ photographs at this alternative time is lost). Regarding (a), during the first *WKT Day* on 12 January 2009 in New South Wales, Australia, the observed maximum water level was 0.09 metres *below* the maximum astronomical tide, presumably due to a negative storm surge (Watson and Frazer, 2009). By way of comparison, 0.09 metres is roughly the global-average sea-level rise from 1970 to 2009, raising the obvious question: ‘how well is *WKT* likely to demonstrate the impact of future climate change if the photographed water level may be lower than expected by an amount equivalent to about 40 years of sea-level rise?’. A significant negative storm surge on a *WKT Day* may well give the unintended message that the impact of sea-level rise is likely to be unimportant.

This study uses the Global Extreme Sea Level Analysis Version 2 (GESLA-2) database of quasi-global ‘high-frequency’ (i.e. sampled at least hourly) tide-gauge records (Woodworth et al., 2017) to compare the statistics of annual maxima in the astronomical tide and in ~~tidal~~ sea-level observations. The results indicate how well *WKT* should work at over 300 locations around the world.

It should be noted that, for some locations and some years, there are more than one astronomical tides of similar magnitude to the maximum. If the tides are predominantly semidiurnal, the largest maxima occur near the equinoxes (March and September) and, if the tides are predominantly diurnal, the largest maxima occur near the solstices (June and December); for example, see Ray and Merrifield (2019). In these cases, more than one *WKT Day* may be declared for that year. However, the analysis to be described here only considers the case of a single *WKT Day* during the year.

2 Methods

The GESLA-2 tide-gauge database contains 39,151 station-years of data from 1,355 stations (Woodworth et al., 2017). Most of this data was sampled hourly and the remainder more frequently. GESLA-2 data is composed of two data sets, one denoted ‘public’ (which contains data for most of the world) and the other denoted ‘private’ (which mainly contains data for Australia). For the present analysis, these data sets were combined and were downloaded on 11 March 2016 (for the ‘private’ data) and 19 March 2016 (for the ‘public’ data). Individual years from the tide-gauge records were selected as follows:

1. observed heights that departed by more than 10 standard deviations from the average were rejected (this is a simple check to remove extreme outliers; in the entire GESLA-2 data set of over 300 million data points, only 190 values were rejected in this way),
2. observed heights were ~~binned~~ averaged into bins to produce hourly values (this only affected the relatively few records that were sampled more frequently than hourly),
3. years with less than 80% of hourly values were rejected, and
4. years for which the two-year period centred on the the middle of the year had less than 80% of hourly values were rejected (this related to the tidal analysis – see later).

After this selection process, only tide-gauge records that contained at least 20 valid years were used for the results presented here. This represented a compromise between selecting long records and many records, and yielded data from 586 individual GESLA-2 *records*. Henceforth, a *record* (i.e. italicised) refers to an individual GESLA-2 record that contained at least 20 valid years. In some cases, more than one *record* occupied a given location. For example, data from the same location has sometimes been sourced from different data providers, in which case they generally cover different periods and are of different lengths; such *records* are therefore, to a certain extent, independent and were analysed individually. ~~Also~~However, a significant number of *records* are from distinct, but relatively close, locations; ~~for~~ this could be because the metadata from different providers may contain slightly different latitudes and longitudes for the same tide gauge, or could be due to genuinely different but nearby locations in the same port. For example, of the 171,405 separation distances between the 586 *records*, around 180 (0.1%) are less than 3 km. Consequently, for the maps produced in Figs. 1 to 6 and in Fig. 10, the results for some *records* would be obscured by the results for other nearby *records*. For this reason, the number of *records* was 'pruned' down from 586 to 311 using the 'neighbourhood' technique described in Appendix A. From each *neighbourhood*, the *record* with the most years of data was selected for display in Figs. 1 to 6 and in Fig. 10. It should be stressed that this process involves no averaging; it is simply a process of removing *records* that probably have less significant results (based on the fact that they are shorter) and that would otherwise obscure the results of their neighbours when plotted on a global map.

For each *record* (denoted by index k) and for each valid year (called here the *target year*; denoted by index j), the following analysis was performed:

1. A tidal analysis for 102 constituents was performed on the two-year period centred on the *target year*. A two-year analysis was performed because, for a few *records*, a one-year analysis failed using 102 constituents presumably because, for some constituent pairs, the Rayleigh criterion is only just satisfied. From this analysis, tidal predictions were performed for the times of all observations during the *target year*.

2. For each day, two periods were defined: a *civil day* (denoted by the subscript c), which is the full 24-hour day (defined in the local time zone, based on the longitude), and a *daylight day* (denoted by the subscript d), which represents the period over which a natural-light ~~photo~~ photograph may reasonably be taken and which is here (somewhat arbitrarily) defined as occupying 80% of the time between sunrise and sunset (therefore starting at 10% of the sunrise-to-sunset time after sunrise and ending at 10% of the sunrise-to-sunset time before sunset). Sunrise and sunset times were calculated using the *sunazimuth* program [1].

3. For each *record*, k, each valid year, j and for each 'day', i, the following were calculated for both *civil days* and *daylight days* (noting that, due to missing data, there are missing values of i and j):

   (a) the highest predicted tide for each 'day' (denoted $p_c(i,j,k)$ for *civil days* and denoted $p_d(i,j,k)$ for *daylight days*), and

   (b) the highest observed sea level for each 'day' (denoted $o_c(i,j,k)$ for *civil days* and denoted $o_d(i,j,k)$ for *daylight days*).

4. For each *record*, k, and each valid year, j the following were calculated for both *civil days* and *daylight days*:

[1] https://sidstation.loudet.org/sunazimuth-en.xhtml

   (a) the day of the highest predicted tide during each valid year (denoted $I_{pc}(j,k)$ for *civil days* and denoted $I_{pd}(j,k)$ for *daylight days*). The highest predicted tide during each valid year is therefore given by $p_c(I_{pc}(j,k),j,k)$ for *civil days* and $p_d(I_{pd}(j,k),j,k)$ for *daylight days*.
   (b) the day of the highest observed sea level during each valid year (denoted $I_{oc}(j,k)$ for *civil days* and denoted $I_{od}(j,k)$ for *daylight days*). The highest observed sea level during each valid year is therefore given by $o_c(I_{oc}(j,k),j,k)$ for *civil days* and $o_d(I_{od}(j,k),j,k)$ for *daylight days*.

5. The following three *annual metrics* were obtained for each kind of 'day' and for each valid year:
   (a) the *annual first metric*, which is the height of highest observed sea level above the observed maximum on the day of the highest predicted tide for the year, given by $o_c(I_{oc}(j,k),j,k) - o_c(I_{pc}(j,k),j,k)$ for *civil days* and $o_d(I_{od}(j,k),j,k) - o_d(I_{pd}(j,k),j,k)$ for *daylight days*.
   (b) the *annual second metric*, which is the number of days when the observed sea level ($o_c(i,j,k)$ for *civil days* and $o_d(i,j,k)$ for *daylight days*) was higher than the observed maximum on the day of the highest predicted tide for the year ($o_c(I_{pc}(j,k),j,k)$ for *civil days* and $o_d(I_{pd}(j,k),j,k)$ for *daylight days*), and
   (c) the *annual third metric*, which is the height of the highest observed sea level on the day of the highest predicted tide for the year above the highest predicted tide for the year, given by $o_c(I_{pc}(j,k),j,k) - p_c(I_{pc}(j,k),j,k)$ for *civil days* and $o_d(I_{pd}(j,k),j,k) - p_d(I_{pd}(j,k),j,k)$ for *daylight days*. The *third metric* is essentially a measure of the residual, or storm surge, on the day of the highest predicted tide for the year.

6. Finally, the three *annual metrics* (5(a) to 5(c), above) were averaged over all valid years for each *record* (these are here called *averaged metrics*) and presented on global maps in Figs 1 to 6. The spread of the first two *metrics* (5(a) and 5(b), above) over the valid years are presented as complementary cumulative distribution functions (CCDFs; otherwise called 'exceedance distributions') in Figs 7 to 9.

This resulted in three types of *annual* and *averaged metrics* for each *record*, and for each of the two kinds of 'day' (*civil days* and *daylight days*).

It should be noted that the results presented here are based on comparisons of the observed sea level with tidal predictions derived from a two-year period of observations which include the time of the observation. This removes signals of period longer than about two years, and most of the effects of any vertical datum shifts in the tide-gauge records. Therefore, the results are ~~only~~ mostly indicative of intra-annual (e.g. seasonal) deviations of observations from predictions, rather than of inter-annual deviations (e.g. those due to the El Niño-Southern Oscillation) or long-term trends (e.g~~,~~. sea-level rise). Inclusion of these latter effects would have required the selection of longer, and therefore fewer, tide-gauge records. Such effects would be expected to expand the regions where *WKT* would not perform well.

Tidal analysis and prediction broadly followed Cartwright (1985), with the tidal analysis using singular value decomposition (Press et al., 2007) for the least-squares solution. Astronomical arguments and tidal frequencies were generated by software provided by the (then) Proudman Oceanographic Laboratory (now the National Oceanography Centre, Liverpool, U.K.).

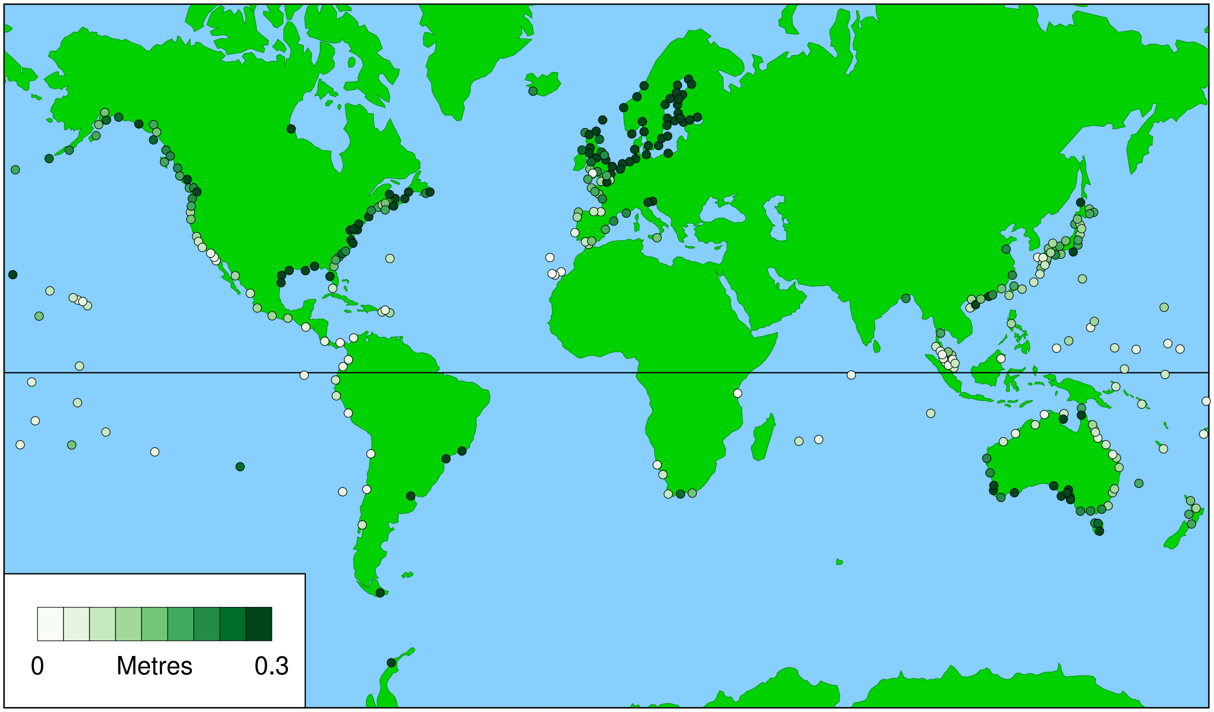

Figure 1. *Averaged first metric*, which is height of highest observed sea level above observed maximum on day of highest predicted tide for the year, for *civil days* ($o_c(I_{oc}(j,k),j,k) - o_c(I_{pc}(j,k),j,k)$), averaged over all valid years, j.

3 Results

3.1 The *averaged first metric*

Figs. 1 and 2 show the *averaged first metric* for *civil days* and *daylight days*, respectively. The Figures indicate how much higher, on average, the annual maximum observed sea level is above the maximum observed on the day of the highest predicted tide for the year (the *WKT Day*); in other words, how much better it would have been if the *WKT* photography had been done on the day of the annual maximum observed sea level rather than on the *WKT Day* (these days only rarely coincide, as discussed in Section 3.4 and shown in Figs. 7 to 9). As we might expect, Figs. 1 and 2 show that there is little obvious difference between the results for *civil days* and *daylight days*. The same is true for the other two *metrics* (Figs. 3 to 6) and, therefore, for Section 3.4 only the results for *daylight days* are shown.

Fig. 2 (for *daylight days*) provides a guide to where in the world *WKT* is likely to be successful (low values, light colour) and where it is not (high values, dark green). The large white and dark green circles show the locations of the *records* discussed in Section 3.4 and the white and dark green ellipses show the regions discussed in Section 4.

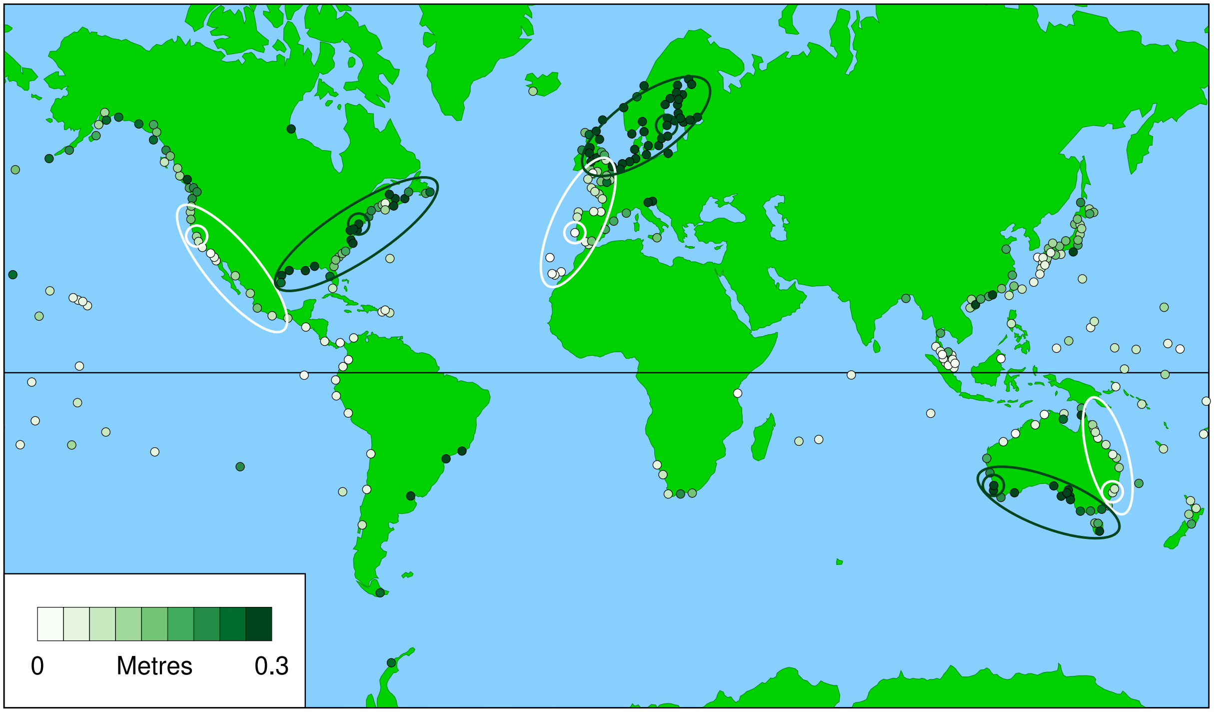

Figure 2. *Averaged first metric*, which is height of highest observed sea level above observed maximum on day of highest predicted tide for the year, for *daylight days* $(o_d(I_{od}(j,k),j,k) - o_d(I_{pd}(j,k),j,k))$, averaged over all valid years, j. The large white and dark green circles indicate the *records* for the results shown in Figs. 7, 8 and 9. The white and dark green ellipses indicate the regions discussed in Section 4.

3.2 The *averaged second metric*

Figs. 3 and 4 show the *averaged second metric* for *civil days* and *daylight days*, respectively. The Figures indicate the number of days during the year when the sea level was higher than it was on the day of the highest predicted tide for the year (the *WKT Day*); in other words, how many other better opportunities there were during the year for *WKT* photography than on the *WKT Day*.

Again, the results for *civil days* and *daylight days* are very similar. Figure 4 (for *daylight days*) provides another guide to where in the world *WKT* is likely to be successful (low values, light colour) and where it is not (high values, dark green).

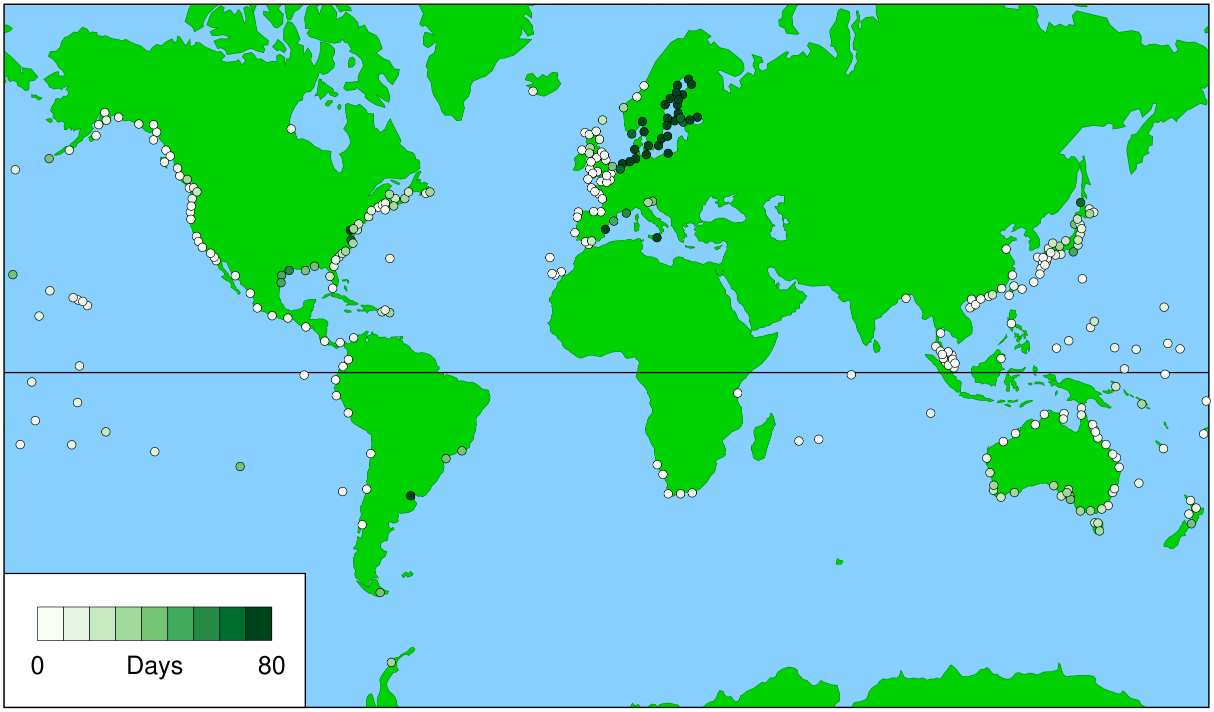

Figure 3. *Averaged second metric*, which is no. of days when observed sea level, $o_c(i, j, k)$, higher than observed maximum on day of highest predicted tide for the year, $o_c(I_{pc}(j, k), j, k)$, for *civil days*, averaged over all valid years, j.

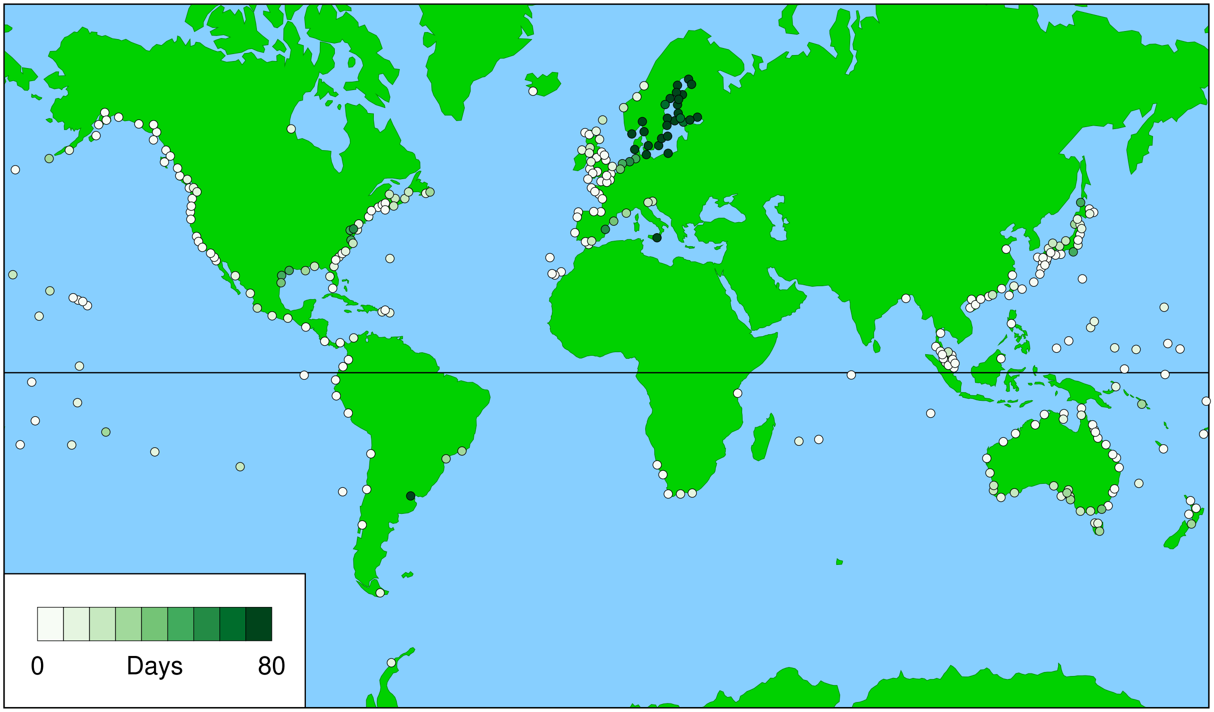

Figure 4. *Averaged second metric*, which is no. of days when observed sea level, $o_d(i,j,k)$, higher than observed maximum on day of highest predicted tide for the year, $o_d(I_{pd}(j,k),j,k)$, for *daylight days*, averaged over all valid years, j.

3.3 The *averaged third metric*

Figs. 5 and 6 show the *averaged third metric* for *civil days* and *daylight days*, respectively. The Figures show the difference between the highest observed and predicted sea levels on the day of the highest predicted tide for the year, which is essentially a measure of the residual, or storm surge, on that day. This *metric* can have either sign (for positive of negative surges).

Again, the results for *civil days* and *daylight days* are very similar. Fig. 6 (for *daylight days*) provides another guide to the usefulness of *WKT* in various parts of the world. However, in this case, the *metric* operates in the opposite direction to the other two. In cases where it is negative (light colour), the negative surge would clearly be problematic for *WKT* (it may well give the unintended message that the impact of sea-level rise is likely to be unimportant) whereas, in cases where it is positive (dark green), the positive surge ~~would~~ could be a bonus.

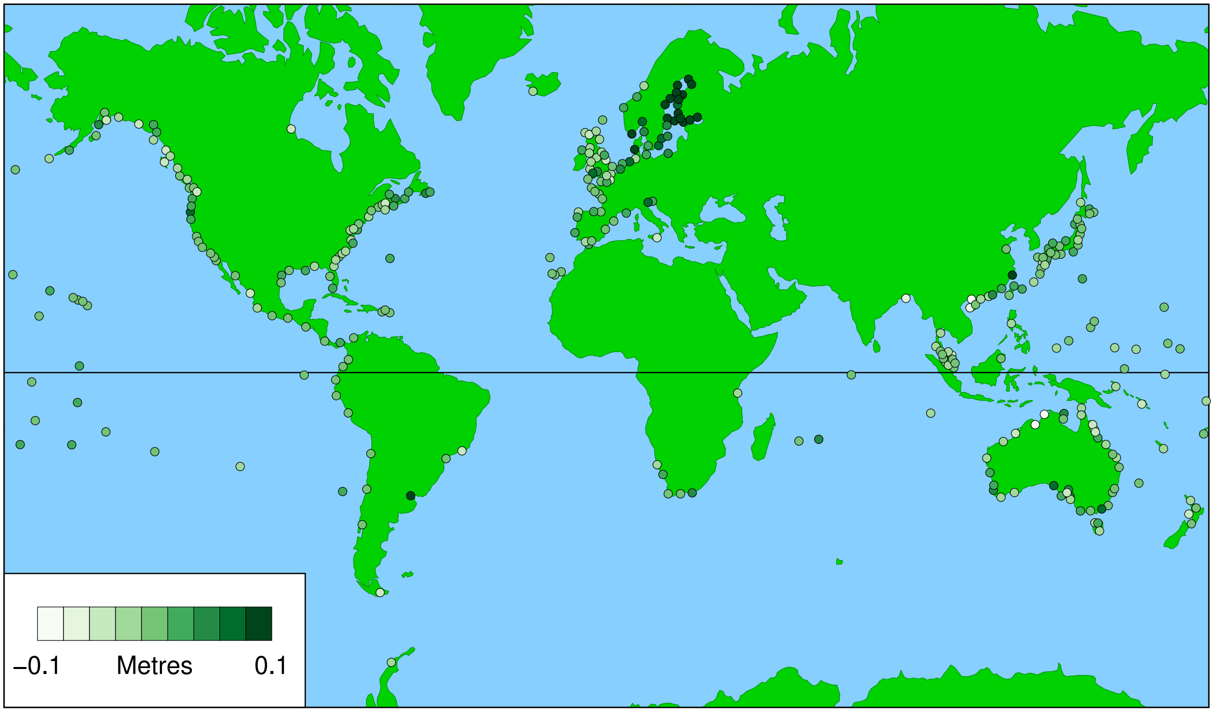

Figure 5. *Averaged third metric*, which is height of highest observed sea level on day of highest predicted tide for the year above highest predicted tide for the year, for *civil days* $(o_c(I_{pc}(j,k),j,k) - p_c(I_{pc}(j,k),j,k))$, averaged over all valid years, j.

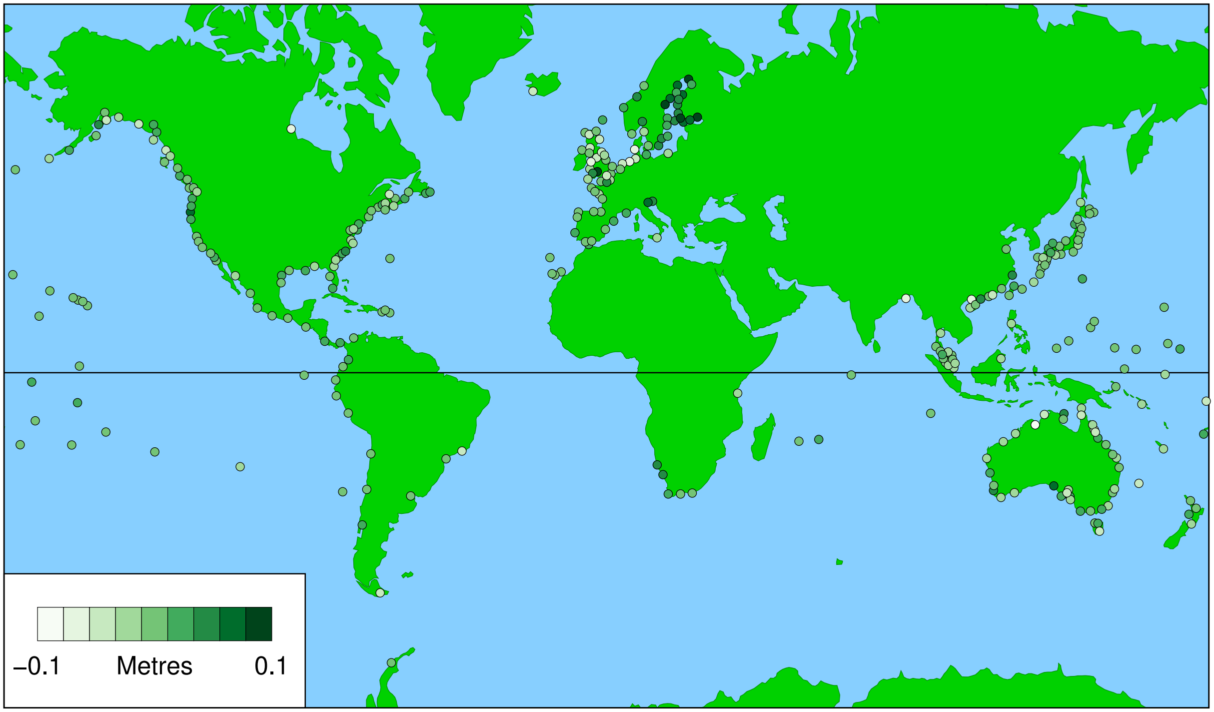

Figure 6. *Averaged third metric*, which is height of highest observed sea level on day of highest predicted tide for the year above highest predicted tide for the year, for *daylight days* $(o_d(I_{pd}(j,k),j,k) - p_d(I_{pd}(j,k),j,k))$, averaged over all valid years, j.

3.4 The distribution of the *annual first* and *second metrics* for six typical locations on three continents

Sections 3.1 to 3.3 discuss three *averaged metrics* derived from 311 *records* which have records that contained at least 20 valid years of data and which have been 'pruned' from the original 586 *records* for display on a global map. Here are presented the complementary cumulative distribution functions (CCDFs; otherwise called 'exceedance distributions') of the *annual first* and *second metrics* for *daylight days* for all valid years of data for six *records* on three continents (San Francisco and New York in ~~the USA~~North America; Cascais (near Lisbon) and Stockholm in Europe; Fremantle and Fort Denison (Sydney) in Australia). The locations have been selected because they illustrate, within each continent, very different fitness for *WKT*. The average and median values of these *annual metrics* for *daylight days* (i.e. those shown in Figs. 2 and 4) are shown in Table 1. The differences in fitness for *WKT* is evident from the significant differences of these values within each pair.

Two things should initially be noted about Figs. 7 to 9:

1. The intercepts on the vertical (CCDF) axes for any one location are the same for the *first* and *second metrics*. This is because years for which the *annual first metric* is zero are the same as the years for which the *annual second metric* is zero (i.e. when the highest sea-level of the year occurs on the *WKT Day*).

Table 1. First column: location. Second column: no. of valid years in analysis. Third and fourth columns: average and median of *annual first metric*, which is height of highest observed sea level above observed maximum on day of highest predicted tide for the year, for *daylight days* ($o_d(I_{od}(j,k),j,k) - o_d(I_{pd}(j,k),j,k)$), over all valid years, j. Fifth and sixth columns: average and median of *annual second metric*, which is no. of days when observed sea level, $o_d(i,j,k)$, higher than observed maximum on day of highest predicted tide for the year, $o_d(I_{pd}(j,k),j,k)$, for *daylight days*, over all valid years, j.

Location	Valid years	Annual first metric (metres)		Annual second metric (days)	
		Average	Median	Average	Median
San Francisco	114	0.11	0.09	4.1	2
New York	66	0.40	0.38	13.6	12
Cascais (near Lisbon)	33	0.03	0.00	1.4	0
Stockholm	119	0.35	0.35	84.2	57
Fremantle	93	0.30	0.30	21.5	17
Fort Denison (Sydney)	95	0.07	0.05	4.3	2

2. The pairs of CCDFs all overlap to a certain extent. Therefore, although one site may perform better on average than the other site, there are always some years at the first site that are worse than some years at the other site. A measure of this overlap may be provided by the proportion of *annual metric* values for one site that falls within the full range of *annual metric* values for the other site; this is discussed for each pair of sites in the following sections.

3.4.1 San Francisco and New York

Fig. 7 shows the CCDFs of the *annual first* and *second metrics* for *daylight days* for San Francisco (one of the large white circles in Fig. 2) and New York (one of the large green circles in Fig. 2) in the USA. The CCDFs for both *annual metrics* are significantly narrower for San Francisco (averages of 0.11 m and 4.1 days, respectively; see Table 1) than for New York (averages of 0.40 m and 13.6 days, respectively). On this basis, San Francisco seems a better candidate for *WKT* than New York.

However, there is considerable variability from year to year and considerable overlap of the CCDFs for the two sites. 51% of the *annual first metrics* at New York falls within the full range of the *annual first metrics* at San Francisco, while 86% of the *annual second metrics* at New York falls within the full range of the *annual second metrics* at San Francisco.

3.4.2 Cascais (near Lisbon) and Stockholm

Fig. 8 shows the CCDFs of the *annual first* and *second metrics* for *daylight days* for Cascais (near Lisbon; one of the large white circles in Fig. 2) and Stockholm (one of the large green circles in Fig. 2) in Europe. The CCDFs for both *annual metrics* are significantly narrower for Cascais (averages of 0.03 m and 1.4 days, respectively; see Table 1) than for Stockholm (averages of 0.35 m and 84.2 days, respectively). Cascais is clearly a better candidate for *WKT* than Stockholm.

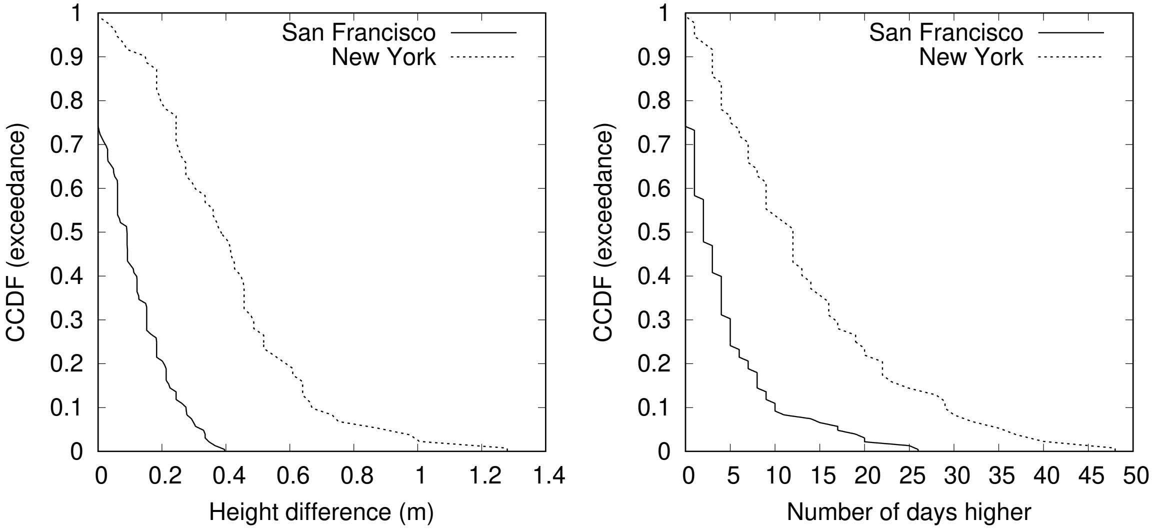

Figure 7. Complementary cumulative distribution functions (CCDFs) for San Francisco and New York. Left panel: *annual first metric*, which is height of highest observed sea level above observed maximum on day of highest predicted tide for the year, for *daylight days* ($o_d(I_{od}(j,k),j,k) - o_d(I_{pd}(j,k),j,k)$), estimated over all valid years, j. Right panel: *annual second metric*, which is no. of days when observed sea level, $o_d(i,j,k)$, higher than observed maximum on day of highest predicted tide for the year, $o_d(I_{pd}(j,k),j,k)$, for *daylight days*, estimated over all valid years, j.

The contrast between Cascais and Stockholm is more marked than for the other two pairs of *records*, Cascais showing very narrow CCDFs, with 50% of the *annual first* and *second metrics* being zero, meaning that the highest sea-level of the year occurred on the *WKT Day*. Only 13% of the *annual first metrics* at Stockholm falls within the full range of the *annual first metrics* at Cascais, while only 7% of the *annual second metrics* at Stockholm falls within the full range of the *annual second metrics* at Cascais. Cascais is clearly a good candidate for WKT.

3.4.3 Fremantle and Fort Denison (Sydney)

Fig. 9 shows the CCDFs of the *annual first* and *second metrics* for *daylight days* for Fremantle (one of the large green circles in Fig. 2) and Fort Denison (Sydney; one of the large white circles in Fig. 2) in Australia.

Qualitatively, the relationship between Fremantle and Fort Denison is similar to that between New York and San Francisco, Fort Denison and San Francisco being the better candidates for WKT. The CCDFs for both *annual metrics* are significantly narrower for Fort Denison (averages of 0.07 m and 4.3 days, respectively; see Table 1) than for Fremantle (averages of 0.30 m and 21.5 days, respectively).

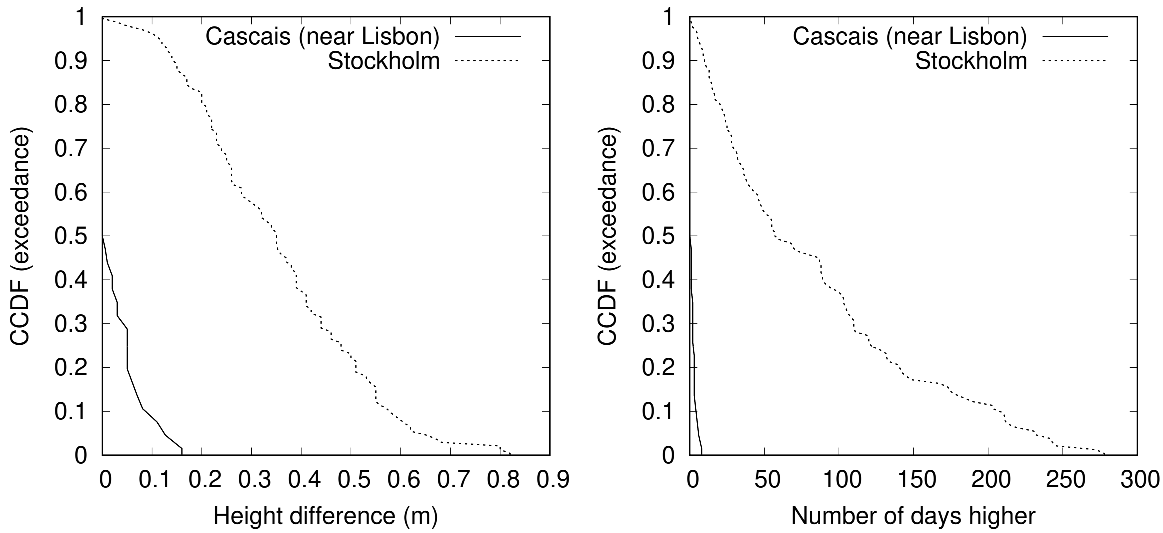

Figure 8. Complementary cumulative distribution functions (CCDFs) for Cascais (near Lisbon) and Stockholm. Left panel: *annual first metric*, which is height of highest observed sea level above observed maximum on day of highest predicted tide for the year, for *daylight days* ($o_d(I_{od}(j,k),j,k) - o_d(I_{pd}(j,k),j,k)$), estimated over all valid years, j. Right panel: *annual second metric*, which is no. of days when observed sea level, $o_d(i,j,k)$, higher than observed maximum on day of highest predicted tide for the year, $o_d(I_{pd}(j,k),j,k)$, for *daylight days*, estimated over all valid years, j.

Again, there is considerable variability from year to year and considerable overlap of the CCDFs for the two sites. 56% of the *annual first metrics* at Fremantle falls within the full range of the *annual first metrics* at Fort Denison. 58% of the *annual second metrics* at Fremantle falls within the full range of the *annual second metrics* at Fort Denison

3.5 The variances of the observed sea level and of the predicted tide

As noted in the Introduction, the success of *WKT* depends strongly on the size of the storm surge (which is indicated by the *third metric*, displayed in Figs. 5 and 6) relative to the tide; in general, strong storm surges confound attempts to predict the day when *WKT* would be successful while, if the storm surge were always zero, the *WKT Day* (i.e. the day with the highest predicted tide of the year) would always be the day of the highest sea level of the year. It is therefore possible that the relative magnitudes of storm surge and tide could provide a simple alternative to the *metrics* discussed earlier. Fig. 10 shows the ratio of the variance of the observed sea level to the variance of the predicted tide (both calculated in the same way as for the derivation of the *metrics*, as described in the Methods section). It provides another guide to where in the world *WKT* is likely to be successful (low values, light colour) and where it is not (high values, dark green).

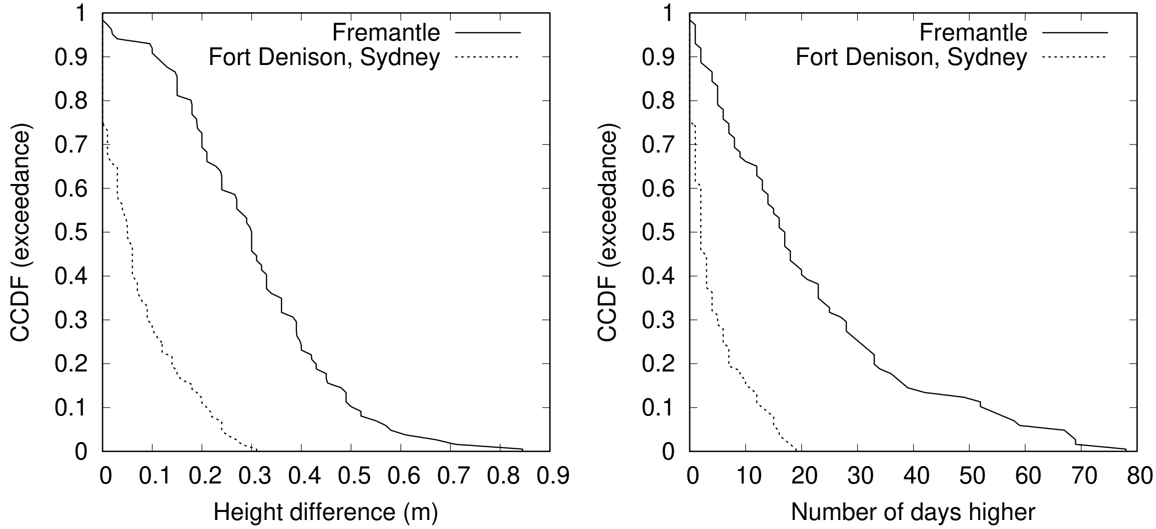

Figure 9. Complementary cumulative distribution functions (CCDFs) for Fremantle and Fort Denison (Sydney). Left panel: *annual first metric*, which is height of highest observed sea level above observed maximum on day of highest predicted tide for the year, for *daylight days* ($o_d(I_{od}(j,k),j,k) - o_d(I_{pd}(j,k),j,k)$), estimated over all valid years, j. Right panel: *annual second metric*, which is no. of days when observed sea level, $o_d(i,j,k)$, higher than observed maximum on day of highest predicted tide for the year, $o_d(I_{pd}(j,k),j,k)$, for *daylight days*, estimated over all valid years, j.

4 Discussion

Figs. 1 to 6 provide maps showing the three *metrics*, averaged over at least 20 valid years for 311 tide-gauge *records*. The best measures for suitability for *WKT* are the *averaged first* and *second metrics* (Figs. 1 to 4), as they are based on observations throughout each of the years analysed. Sites where it would be expected that *WKT* would perform well are indicated by low values (light colour), while high values (dark green) suggest poor performance.

Less useful, though nevertheless interesting, is the *third metric* (Figs. 5 to 6), which shows the storm surge averaged over all *WKT Days*; it is less useful than the other *metrics* because it is based solely on information from *WKT Days*. In cases where it is negative (light colour), the negative surge would clearly be problematic for *WKT* (it may well give the unintended message that the impact of sea-level rise is likely to be unimportant) whereas, in cases where it is positive (dark green), the positive surge ~~would~~ could be a bonus.

Figs. 1 to 6 are presented in two ways: for *civil days* (i.e. the normal 24-hour day) and *daylight days* (i.e. the periods over which a natural-light ~~photo~~ photograph may reasonably be taken). Inspection of the Figures indicates that there is little difference between the results for *civil days* and *daylight days*, and so the following discussion relates only to the results for *daylight days*.

Fig. 2 (the *averaged first metric* for *daylight days*) indicates three regions where *WKT* should perform well (white ellipses):

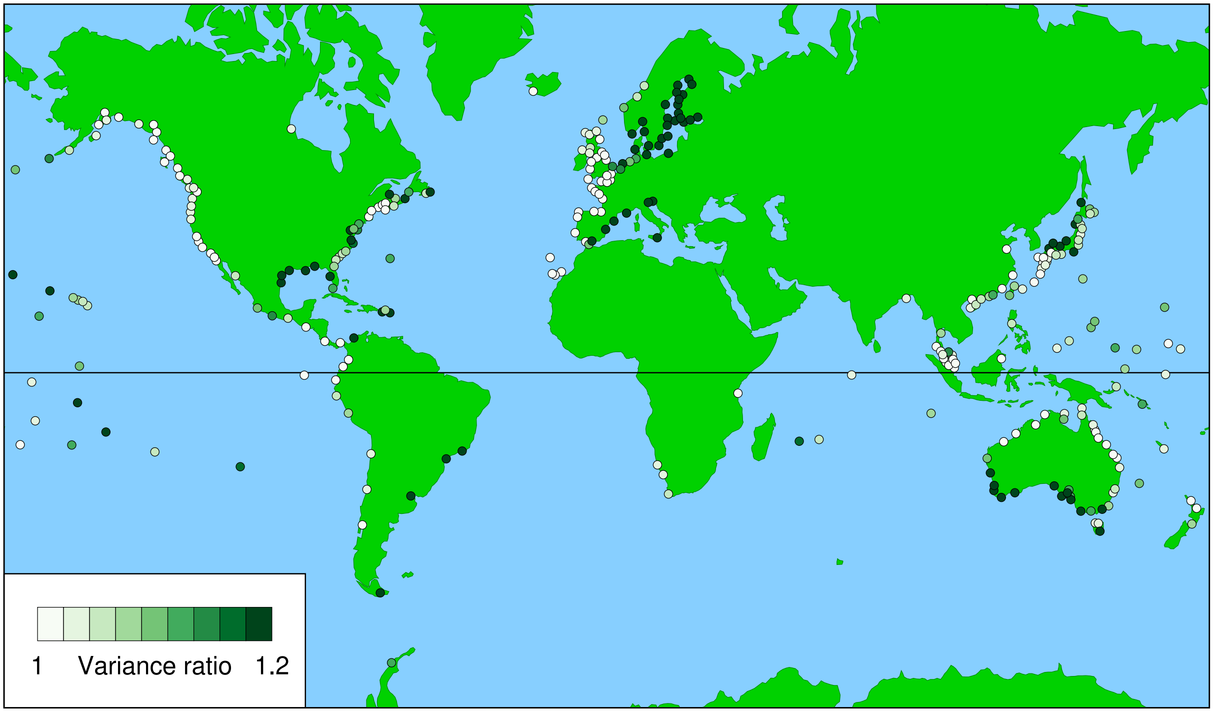

Figure 10. Ratio of variance of observed sea level to variance of predicted tide.

- the west coast of the USA,
- southwestern Europe and locations off northwestern Africa, and
- the east coast of the Australian mainland,

and three regions where *WKT* should perform poorly (dark green ellipses):

- the east coast of North America,
- northern Europe, and
- the south and southwest coast of the Australian mainland and Tasmania.

These regions coincide with the pairs of typical *records* shown in Figs. 7 to 9 and summarised in Table 1. It appears fortuitous that the first *WKT* project was conducted in New South Wales, which is the region around Fort Denison (Sydney), shown by the white circle in southeastern Australia in Fig. 2. The large values of the *averaged first metric* in northern Europe are related to a combination of weak tides (e.g. in the Baltic; Stigebrandt, 2001) and significant surges (e.g. in the North Sea; Huthnance, 1991).

Fig. 4 (the *averaged second metric* for *daylight days*) shows generally the same features as Fig. 2 but the contrasts are not so marked. Low values in southwestern Europe and locations off northwestern Africa, and high values in Northern Europe are clear, but the variations in North America and Australia are more subtle.

Figure 10 shows an alternative estimator of the viability of WKT, which is the ratio of the variance of the observed sea level to the variance of the predicted tide (again derived from *records* with at least 20 years of valid data); in this case, *WKT* is likely to be viable at sites with a low value (light colour). Figure 10 shows many of the features displayed by the *first metric* for *daylight days* (Fig 2), indicating that this simple estimator may be as useful as the *first metric* in determining regional variations in the the performance of *WKT*.

5 Conclusions

Figs. 2 and 10 provide useful preliminary indicators of regions where a *WKT* project may be successful, in the sense that the day of highest predicted tide for the year (the *WKT Day*) would yield an observed level comparable with the maximum observed level for the year. However, it is suggested that, prior to initiating a *WKT* project, local tide-gauge records that are longer than 20 years are analysed in ways similar to those described here (e.g. the production of figures similar to Figs. 7 to 9) to provide a more detailed assessment of the viability of *WKT*.

It is, however, unclear whether the *WKT* strategy (i.e. picking, in advance, the day when the coast is to be photographed) is the best one. An attractive alternative is to photograph every high tide of the year and pick, in retrospect, the images which show the highest sea level. This procedure could be quite easily performed using the camera of a smartphone, suitably programmed to take ~~photos~~ photographs at the required times and to transmit them to a central repository.

Data availability. Tide-gauge data used in these analyses was obtained from the database, Global Extreme Sea Level Analysis Version 2 (GESLA-2): https://gesla.org/, accessed: 11 March 2016 and 19 March 2016.

Appendix A: The method of pruning records into 'neighbourhoods'

In order to reduce the density of the locations of *records*, the locations were divided into groups which are here called *neighbourhoods*. A *neighbourhood* is a unique and objectively defined group of locations in which every location is within a prescribed distance, d, of at least one other location in that *neighbourhood*. In a similar way to houses in a neighbourhood, a house is close to one or more of its neighbours, but not necessarily close to all the other houses in the neighbourhood. The method proceeds as follows:

1. Calculate symmetric $n \times n$ matrix $A_{i,j}$ of spheroidal distances between all n locations.

2. For all (i,j), if $A_{i,j} > d$ set $A_{i,j} = 0$, otherwise set $A_{i,j} = 1$, where d is a prescribed distance. An entry of '1' in $A_{i,j}$ therefore indicates that the pair of locations are 'close'.

3. Matrix multiply $A_{i,j}$ with itself to yield another symmetric matrix, $B_{i,j}$ (i.e. ~~$B_{i,j} = A^2_{i,j}$~~ $B_{i,j} = A_{i,k}A_{k,j}$), and set all finite values of ~~B~~ $B_{i,j}$ to 1 (i.e. if $B_{i,j} > 0$ then $B_{i,j} = 1$).

4. If $A_{i,j} \neq B_{i,j}$, set $A_{i,j}$ to $B_{i,j}$ and go to 3, otherwise finish.

The resultant matrix, $B_{i,j}$, generally contains numerous repeated rows (and columns, because $B_{i,j}$ is symmetric). $B_{i,j}$ may be simplified by removing any rows that are repeated, yielding a non-symmetric $m \times n$ matrix, $C_{i,j}$ where m is the number of *neighbourhoods*. $C_{i,j}$ represents a table indicating in which *neighbourhood* a given location lies (the jth location lies in the ith *neighbourhood*, if $C_{i,j}$ = 1). Each column of $C_{i,j}$ ~~contain~~ contains a single ‘1’, because a location can only lie in one *neighbourhood*.

The above procedure converges quickly. For $d = 75km$, the locations of the 586 *records* yielded 311 *neighbourhoods* and required only 4 iterations of steps (3) and (4),

Competing interests. The author declares that he has no conflict of interest.

Acknowledgements. I am very grateful to Philip Woodworth for extensive discussions and collaborations concerning tides (~~e.g.~~ including the development of the GESLA-1 and GESLA-2 databases) over many years.

References

Cartwright, D. E.: Tidal prediction and modern time scales, International Hydrographic Review, 62(1), 127–138, 1985.

Huthnance, J.: Physical oceanography of the North Sea, Ocean and Shoreline Management, 16, 199–231, 1991.

Moftakhari, H. R., AghaKouchak, A., Sanders, B. F., Feldman, D. L., Sweet, W., Matthew, R. A., and Luke, A.: Increased nuisance flooding along the coasts of the United States due to sea level rise: Past and future, Geophysical Research Letters, 42, 9846–9852, https://doi.org/10.1002/2015GL066072, 2015.

Moftakhari, H. R., AghaKouchak, A., Sanders, B. F., Allaire, M., and Matthew, R.: What is nuisance flooding? Defining and monitoring an emerging challenge, Water Resources Research, 54, 4218–4227, https://doi.org/10.1029/2018WR022828, 2018.

Press, W. H., Teukolsky, S. A., Vetterling, W. T., and Flannery, B. P.: Numerical Recipes 3rd Edition: The Art of Scientific Computing, Cambridge University Press, New York, NY, USA, 3 edn., 2007.

Ray, R. D. and Merrifield, M. A.: The semiannual and 4.4-year modulations of extreme high tides, Journal of Geophysical Research: Oceans, 124, 5907–5922, https://doi.org/10.1029/2019JC015061, 2019.

Stigebrandt, A.: Physical oceanography of the Baltic Sea, in: A systems analysis of the Baltic Sea, edited by Wulff, F. V., Rahm, L. A., and Larsson, P., chapter 2, pp. 19–74, Springer, Berlin, Heidelberg, https://doi.org/10.1007/978-3-662-04453-7_2, 2001.

Watson, P. J. and Frazer, A.: A Snapshot of Future Sea Levels: Photographing the King Tide, 12 January 2009, Department of Environment, Climate Change and Water NSW, Australia, ISBN 978 1 74232 472 2, 2009.

Woodworth, P. L., Hunter, J. R., Marcos, M., Caldwell, P., Menéndez, M., and Haigh, I.: Towards a global higher-frequency sea level dataset, Geoscience Data Journal, 3, 50–59, https://doi.org/10.1002/gdj3.42, 2017.