1 Response to editor

Thank-you for your helpful comments.

1. At several points in the paper, you refer to the nodal tide (or node tide). I think most readers will take this to mean the near-equilibrium zonal tide of period 18.6 years. But surely you are instead referring to 18.6-y modulations of all lunar tides (especially the large ones like M2, O1, and K1). Yes? I think Phil, in informal comments, also thought you were referring to the 18.6-y tide; there is thus no reason to cite his 2012 paper on the topic, as its irrelevant (assuming Im right about what youve meant). So if you really mean nodal modulations of major tides, its best not to call that the node tide, even though all of this does arise from the moons nodal precession.

Yes, that's right, I should have referred to "nodal modulation". Now corrected throughout.

2. Both reviewers found the nomenclature problematic e.g. see Point (1) of Reviewer #1 and I also had to repeatedly read the relevant text because I kept getting confused about what was what. So please give some thought to making this clearer, possibly along the lines suggested by Reviewer #1, or some other way if you have a good idea.

See response to reviewers.

3. Many figures are difficult to see because they are so small, and their fonts are even smaller. Remember that most journals end up reducing figure sizes anyway, so give some care to figure legibility.

The figure fonts are now increased to be similar to the main text, and figures are enlarged.

As you know, we also received a review from Phil Woodworth. Most of his comments were on detailed presentation, and they have all been addressed, with the exception of the choice of named coastal locations. These were a compromise between even spacing and well known places, and hopefully the clearer reference to the map in the Appendix will make these figures easier to understand.

There was a discussion about the relative importance on the nodal tide in tidal range and the paragraph in section 4 now reads:

An approximate calculation of Range = $2(\mathbf{M}_2 + \mathbf{S}_2 + \mathbf{O}_1 + \mathbf{K}_1)$ is occasionally used [Yotsukuri 2017], but the error due to this can be over 1 metre (figure 6b). $\mathbf{N}_2$ is a significant contributor, at about 20% of $\mathbf{M}_2$ in many sites worldwide. A few tens of centimetres are accounted for by the omission of the nodal modulations, and there are also the shallow water constituents at the coast.

2 Response to reviewer 1

Thank-you for your helpful review.

The manuscript addresses current practices to predict water level changes for various operational marine applications. Such predictions need to include sea surface height changes due to all acting processes including atmospherically *induced surge and lu- nisolar ocean tides. Typically, information on tidal effects and the time evolution of the general ocean circulation are obtained from different sources and are added by means of linear superposition. This assumption of linearity can be, however, questioned in view of distinct periodicities in the atmospheric-induced circulation associated with the either the seasonal cycle or atmospheric tides. The present manuscript addresses this topic in a way I certainly believe worth to be published in Ocean Sciences. However, a number of points raised below might be addressed in order to increase clarity of the representation and expand the discussion to cover all relevant aspects of the topic:*

(1) The nomenclature applied is somewhat problematic: M obviously represents model- based sea surface heights, W apparently stands for observed water levels. H, however, is used for harmonic estimations/predictions for either models, observations, or final combined forecasts. This is difficult to comprehend, so I suggest to reserve capital letters to identifying the source of water level informations (i.e., model (M); tide gauge (G); water level forecasts (W)), and indicate the actual signal component by subscripts (time series of tides (t), harmonic estimates from a time series of tides (th); time series of surge and other meteorological forcings (s); harmonic estimates from a time series of tides and surge and other meteorological forcing (tsh), etc.).

Thank-you for the suggestion. All reviewers commented on the notation, and we've completely revised it. Rather than the double subscript, we've changed to an overhead tilde to indicate "time series derived from harmonics", as the shape is reminiscent of a sine wave. We also switch to F for "Forecast water level" and G for (gauge) observed total water level.

Then the forecast is given by $F = (M_s - M_t) + \tilde{G}$, the harmonic prediction derived from the tide-and-surge model is $\tilde{M}_s$, etc.

(2) W_g is apparently not properly introduced at all.

The observed total water level. Corrected alongside all notation.

(3) The example of Section 2.4 is only partially convincing. What is the usual base period taken to estimate H_g? Isnt it plausible to assume that surge event effects on H_g will cancel out over time? Are there recommendations available on the number of constituents to be considered? What about the treatment of minor tides?

Section 2.4 (on non-linearity, now 2.5) is about the effect on prediction of an individual surge event, given that there exists some discrepancy in phase between model tides M_t and the harmonic prediction from the gauge $\tilde{G}$.

If during such an event the surge causes an advancement of the tide, then $M_r = M_s - M_t$ is decreasing rapidly during High Water (the peak of M_t). The peak of $M_r + \tilde{G}$ is therefore dependent on the relative timing of the peak of $\tilde{G}$ and M_t.

Thank-you for the prompt to look at this again, as it turns out that for a simple tide it can be shown analytically thus (added to section 2.5):

We construct an example with model tide $M_t = A\cos(\sigma t)$, and a surge in which there is an additional uniform water level A_s and an advancement of the tide of $t = \delta$, so model surge is $M_s = A_s + A\cos(\sigma(t + \delta))$. The model residual is given by $M_r = M_s - M_t$.

Suppose the harmonic prediction at the gauge has the same amplitude but the tide is ϵ ahead of the tide-only model, $\tilde{G} = A\cos(\sigma(t+\epsilon))$.

The forecast water level is $F = M_r + \tilde{G}$ and the error in the skew surge forecast is $\max(F) - \max(M_s)$. Substituting in and assuming phase changes are small, the skew surge forecast error is

$$E = A\left(\cos(\sigma\epsilon) - \cos(\sigma(\delta+\epsilon)) + \cos(\sigma\delta) - 1\right).$$

Suppose for example that $A = 3$ m, $\sigma = 2\pi/12.42$, the difference between model and gauge tide is ϵ=0.083 (5 min for M2), and the surge advances the tide by 30 min ($\delta = 0.5$). Then $E = 0.03$ m. This is still below the level of other forecast errors at the moment, but may not be negligible in future.

Although in practice there are many more constituents than M2, a similar relationship will hold in a small window about high tide, with a changing amplitude each day. Indeed, the absence of a small constituent will often manifest as a small phase change in M2. If there are frequent surges, we would expect ϵ to have the same sign as δ, as the gauge would register water levels more like the surge+tide model than the tide-only model and the harmonic predictions would follow suit.

(4) The effects of the annual tide Sa and the semi-annual tide Ssa might be discussed in more detail, in particular in view of the fact that the ocean circulation might have also a distinct annual periodicity.

There are several contributions to annual cycles that we have omitted from this study, including steric effects, circulation changes, river input, ocean mass changes, gravitational changes... the larger of these are explicitly noted in the introduction. However since these are omitted from both model runs (other than very small effects via the atmosphere) they are not at risk of double counting.

We have added some notes on this in the introduction, and also expanded a little on the results seen for Sa. These in large part follow the local annual cycle in atmospheric pressure, an exception being in the wind-dominated Baltic.

(5) Changes in river discharge and their consequences on local water levels might be not relevant for the U.K. but can have a profound impact for estuaries in other parts of the world. A few comments about this process might be helpful.

Good point. It's a reason that using the tide gauge prediction rather than just model tides may be necessary. Added:

There are other contributors to water level, including steric effects and river flow, that will also create differences between the tide gauge and the forecast water levels, particularly seasonally. The problem of double-counting of periodic changes does not arise if they are omitted from the surge model entirely, but they may contribute to HAT and LAT calculations. These effects are not considered in this study.

A few rather minor points might be also addressed during the revision: (5) It could be mentioned somewhere in the text that M2 is also having a very weak atmospheric pressure signature (see 10.1002/2015JD024243).

Schindelegger 2016 was a very confusing paper till I spotted they were using L2 to mean M2 in the atmosphere, when L2 is used in tidal analysis for a subtle lunar elliptical effect at a different frequency! Note added in first paragraph of section 3.

"There is a very small atmospheric tide at $\mathbf{M}_2$, peaking at the equator at about 0.1 mbar [Schindelegger 2016] . "

(6) Figure 1 is difficult to read. Maybe enlarging the vertical extend of the figure would help?

Now enlarged as much as possible.

(7) The frequent change in units between cm and m in the text is rather unfortunate.

The figures all use metres. Text is now consistently cm except where refering to absolute tidal heights, HAT and water levels which are of the order of m.

3 Response to reviewer 2

Thank-you for your helpful review.

General Comments

The paper covers a topic that is interesting scientifically and important for storm surge modelling and forecasting, in particular for forecasts systems where the surge plus tidesurge interaction are added to tidal predictions. The paper describes the magnitude of errors that may arise from different processes omitted from some forecasting systems. The methodology is clear and valid. I recommend accepting the paper for publication following minor revisions, which are mostly structural and grammatical.

Specific Comments

The title implies the primary focus for the paper is the effect of radiational tides on surge forecasts, but the paper covers a number of considerations for storm surge forecasting and navigational chart datums (LAT, HAT). There are inconsistencies in the message, for example in the abstract and headings discussing HAT, when in fact a discussion of HAT and LAT is made. I recommend amending the title to cover the full content of the paper; for example Errors arising from the treatment of radiational tides in storm surge forecasting and tide-based datums.

We have amended the title to

"Radiational Tides: their double-counting in storm surge forecasts and contribution to the Highest Astronomical Tide."

Including LAT in the title as well felt a bit clumsy, but it is now explicitly in section headings.

Also, given the structure of the paper follows a report style, a walk through the paper structure at the end of the Introduction (Page 2, Ln 11) would be very useful.

Added some links to specific sections and a little more detail is given about the connection to HAT.

The numerical model is forced by ECMWF ERA-Interim wind fields with a resolution of 6 hours. It is my understanding that the storm surge numerical *model will therefore lack some of the peakiness in surge and high-frequency oscillations in the modelled tide+surge total water level (Ws) compared with tide gauge observations (at hourly or higher frequency sampling; Wg). Can the authors comment on the effective frequency of the surge signal by their use of a numerical model and can they quantify the effect on tide magnitude and phase estimation, e.g. quarter-diurnal shallow-water tidal constituents? I would imagine, since the numerical model will underestimate the total power in the signal, versus observations, that the double-counting of meteorological effects in the harmonic prediction are even larger than presented here. This extra work is not necessary for publication but would be interesting.*

There is more detail about the effect of the 6-hourly forcing on capturing surges in the model validation paper (Irazoqui et al 2018, in review). With the 6-hourly forcing there is some underprediction of surges due to tropical cyclones which is improved by the ERA-5 reanalysis (available too recently for the model runs carried out in this paper.) However, it should not contradict the main results a great deal, since tropical cyclones at any given location are sufficiently rare that the tidal coefficients fitted over a year should not be very different if the surges are slightly underestimated. A note on this has been added to the description of the model. "We make the assumption that tropical cyclones at any given location are sufficiently rare that the tidal coefficients fitted over a year should not be very different if the surges are slightly underestimated."

Pg 5 ln 8: Please explain what Byrne and Flowerdew were pointing out, and hence why this fortnightly periodic error is important.

They both observed a similar error in forecast high-water levels compared to observations. It is very clear in the Byrne report, but unfortunately that is only in the grey literature.

Minor typographical and grammatical notes

Please be consistent with tide gauge, storm surge or gauge, surge.

It is now consistently the longer form on first usage in a section and the shorter form is used for brevity where no confusion is likely.

Pg 2 Chapter 2: The notation is quite confusing. A notation table as an Appendix would be useful, clarifying what denotes total water level, tide and surge from what denotes numerical model or tide gauge observations and harmonic predictions.

The notation is now changed to be clearer (see response to review 1) and hopefully this is now not necessary.

For much of Chapter 2, the authors are clearly discussing the UK system. Can you make it clear we use is specifically referring to the operational system in the UK. Where a methodology is typically followed by the sea level community, make that clear; for example, on Page 2 Ln 29+, The choice and number of tidal constituents determined by harmonic analysis are typically chosen according to the length and frequency of data available Reworded. "Similar procedures are implemented elsewhere in the world, as noted above, so in this paper we replace the shelf model with GTSM to examine results globally."

All other minor notes are accepted and corrected accordingly.

4 Marked up manuscript

Follows. References are omitted, they seemed to break latexdiff!

~~Storm surge forecasting~~Radiational Tides: ~~quantifying errors arising from the~~ their double-counting ~~of radiational tides~~in storm surge forecasts and contribution to the Highest Astronomical Tide.

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Abstract. Tide predictions based on tide-gauge observations are not just the astronomical tides, they also contain radiational tides - periodic sea level changes due to atmospheric conditions and solar forcing. This poses a problem of double-counting for operational forecasts of total water level during storm surges. In some surge forecasting, a regional model is run ~~as~~ in two modes: tide-only, with astronomic forcing alone; and tide-and-surge, forced additionally by surface winds and pressure. The surge residual is defined to be the difference between these configurations and is added to the local harmonic predictions from gauges. Here we use the Global Tide and Surge Model based on Delft-FM to investigate this in the UK and elsewhere, quantifying the weather-related tides that may be double-counted in operational forecasts. We show that the global $\mathbf{S}_2$ atmospheric tide is captured by the ~~tide-surge~~ tide-and-surge model, and observe changes in other ~~key~~ major constituents, including $\mathbf{M}_2$. ~~We also quantify the extent to which the "Highest Astronomical Tide", which is~~ The Lowest and Highest Astronomical Tides levels, used in navigation datums and design heights, are derived from tide predictions based on observations~~,~~. We use our findings on radiational tides to quantify the extent to which these levels may contain weather-related components.

1 Introduction

The operational forecast in several countries of storm surge still-water levels is based on a combination of a harmonic tidal prediction and a ~~model derived~~ model-derived forecast of the meteorologically induced storm surge component. ~~In the UK, the~~ The forecast is based on the "non-tidal residual", the difference of two model runs with and without weather effects. This is linearly added to the "astronomical prediction" derived from local ~~tide gauge~~ tide-gauge harmonics (**?**). This approach is taken in the UK because the complexity and large range of the ~~UK~~ tides is such that it has historically been difficult to model them to sufficient accuracy. The same method was applied in the Netherlands until 2015 when improvements to the local surge model DCSM-v6 made it unnecessary (?). It is still in use operationally in the extra-tropical US, where results of the SLOSH surge model are added to local tidal predictions (**?**); similarly in Germany, using the BSHsmod model (**?**); and is also used in the new Aggregate Sea-level Forecasting under evaluation in Australia, which also incorporates sea-level anomalies from a global baroclinic model (**?**).

There are several possible sources of error in this procedure. The purpose of the combined tide-and-surge model is to capture the well-documented non-linear interactions of the tide and surge. (e.g. **?**). Yet the forecasting procedure assumes that the non-tidal residual may be added linearly to a gauge-based tide prediction. There is also an assumption that the tide-only model and the harmonic prediction from the ~~tide~~ gauge are equivalent. In fact, the harmonics at the gauge will also be affected by the weather~~. There is therefore~~ , so there is the potential for double-counting of radiational (weather-related) tidal constituents.

~~Specific radiational tides have been studied using response analysis, for example the solar-diurnal $\mathbf{S}_1$ by **?**, and semi-diurnal $\mathbf{S}_2$ by **?**. Here we use the Global Tide and Surge Model (GTSM) based on Delft-FM, to compare many constituents and their combined effect globally. We find~~ In section 2, we show that the double counting of radiational tides has a potential contribution to forecasting errror not just on long time scales (through $\mathbf{S}_{\mathrm{a}}$, $\mathbf{S}_{\mathrm{sa}}$) but also on a fortnightly cycle due to variations in $\mathbf{S}_2$ and in the phase of $\mathbf{M}_2$. We ~~demonstrate the atmospheric tide at $\mathbf{S}_2$ may be observed in the GTSM model. We~~ also show that the assumption of non-linearity may introduce errors if phase predictions disagree between model and observations.

Specific radiational tides have been studied using response analysis, for example the solar-diurnal $\mathbf{S}_1$ by **?**, and semi-diurnal $\mathbf{S}_2$ by **?**. In section 3 we look at more constituents, and demonstrate that the atmospheric tide at $\mathbf{S}_2$ may be observed in the GTSM model.

~~We also quantify the extent to which the~~

Highest and Lowest Astronomical Tide (HAT and LAT) are important datums used for navigation, and are calculated from tidal predictions. In section 4 we use the model predictions to quantify to what extent HAT and LAT are influenced by weather-related tides, and show that in many places several cm of what is reported as HAT is attributable to periodic weather patterns.

2 ~~Surge forecasting~~

~~The harmonic analysis function (**?**, Chapter 4) gives the tide prediction H as:~~

$$\cancel{H(t) = Z_0 + \sum_N A_n f_n \cos\left[\sigma_n t - g_n + (V_n + u_n)\right],}$$

~~where Z_0 is the mean of the gauge data and the amplitudes A_n and phases g_n are associated with the tidal constituents with astronomically-determined frequencies σ_n. $f_n(t)$~~ There are other contributors to water level, including steric effects and river flow, that will also create differences between the tide gauge and ~~$u_n(t)$ are nodal adjustments to amplitude and phase, applied in order to allow for the 18.61 year nodal cycle and 8.85 year longitude of lunar perigee cycle. V_n are~~ the ~~phases of the equilibrium tide, which we take as for Greenwich. We use UTC for all times to enable consistency between local gauges and global maps.~~ forecast water levels, particularly seasonally and which may be out of phase with the atmospheric contribution. The problem of double-counting of periodic changes does not arise if they are omitted from the surge model entirely, but they may contribute to HAT and LAT calculations. These effects are not included in this study.

2 Surge forecasting

The current procedure for forecasting total water level in the UK is as follows:

1. Run a barotropic shelf model (CS3X, currently transitioning to NEMO Surge (?)) in ~~surge-and-tide~~ tide-and-surge mode, forced by an ensemble of wind and pressure from the current weather forecast to give timeseries $M_s(\boldsymbol{x}, t)$ at each location $\boldsymbol{x}$. Also run the shelf model in tide-only mode, to get $M_t(\boldsymbol{x}, t)$. Get the residual from these models, $M_r = M_s - M_t$.

2. ~~Find the amplitude A_n and phases g_n of harmonics at each individual gauge location from past tide records. Derive a tide prediction $H_g(\boldsymbol{x}_g, t)$ from the gauge harmonics~~At individual tide-gauge locations, derive a tide harmonic prediction $\tilde{G}(\boldsymbol{x}_g, t)$ based on past records. This is assumed to be more accurate locally than the model tide.

3. Forecast the total water level ~~W_f~~ F at each location as model residual plus gauge harmonic prediction, ~~$W_f(\boldsymbol{x}_g, t) = M_r(\boldsymbol{x}_g, t) + H_g($~~

4. Finally, it has been proposed (?) that the forecast could apply various "empirical corrections" to nudge the forecast towards the observed level ~~W_g~~ G based on the mismatch of the peak tide over the last few days. However no formal correction schemes have been implemented.

2.1 ~~Selection of tidal constituentsThe choice of tidal constituents used for the harmonic analysis varies~~ Tide-and-surge model

Since similar procedures are implemented elsewhere in the world, in this paper we replace the shelf model with GTSM. This is the forward Global Tide and Surge Model developed at Deltares, on a base of Delft-FM (Flexible Mesh) (??). The version used in this paper has resolution from around 50 km in the open ocean to around 5 km at the coast. We ran the model in two modes, tide-only M_t and tide-and-surge M_s. The atmospheric forcing used was the ECMWF ERA-Interim 6-hourly reanalysis (?), downloaded at 0.25° resolution but from a spherical harmonic equivalent to $\sim 0.75°$. Validation of the major tidal coefficients has been favourable, and although the model under-predicts the effect of tropical cyclones, due to coarse temporal and spatial resolution in the weather reanalysis, most surge events are captured. We make the assumption that tropical cyclones at any given location are sufficiently rare that the tidal coefficients fitted over a year should not be very different if those surges are underestimated. Due to limitations of data storage and post-processing the output from the model was only saved at high frequency at all grid points for one month (Jan 2012) and a subset of coastal points for the year 2013. All runs were preceded by 11 days spin-up.

2.2 Harmonic analysis and selection of tidal constituents

Harmonic analysis (?, Chapter 4) gives a tidal prediction $\tilde{G}$ as:

$$\tilde{G}(t) = Z_0 + \sum_N A_n f_n \cos\left[\sigma_n t - g_n + (V_n + u_n)\right], \tag{1}$$

where Z_0 is the mean of the gauge data and the amplitudes A_n and phases g_n are associated with the tidal constituents with astronomically-determined frequencies σ_n. $f_n(t)$ and $u_n(t)$ are nodal modulations to amplitude and phase, applied in order to allow for the 18.61 year nodal cycle and 8.85 year longitude of lunar perigee cycle. V_n are the phases of the equilibrium tide, which we take as for Greenwich, using UTC for all times.

The choice and number of tidal constituents determined by harmonic analysis are typically chosen according to the length and frequency of data available. ~~We~~ In this paper we use 62 harmonics where there is one year's data, 115 for more than one year, as listed in table B1. To derive harmonics from the global model ~~(discussed below),~~ from only 1 month's data, we use 26 independent primary constituents, and a further 8 related constituents. We will use $\tilde{M}_s$ and $\tilde{M}_t$ to indicate harmonic prediction time series from the tide-and-surge model and tide model respectively.

2.3 Quantifying the effect on forecast of double-counting radiational tides

A significant source of error for this method is that a ~~gauge~~ tide-gauge is measuring the total water level, and hence the harmonic prediction ~~H_g~~ $\tilde{G}$ includes all wave, steric, river levels and surge effects. This is not therefore a prediction of the astronomical tide alone. Steric~~and wave~~, wave and river effects are omitted by the barotropic model, but M_s does include periodic radiational effects, which may be double-counted. We can test a minimum effect of this double-counting purely within the model by using ~~H_s~~ $\tilde{M}_s$, the harmonic prediction of the model *including surge*, as a proxy for the harmonics of the observations at gauges. Then the forecast procedure can be estimated as ~~$M_r + H_s$~~ $M_r + \tilde{M}_s$.

To estimate Δ, the error in this model forecast, we can once again use the model, assuming ~~$M_s \approx W_g$. Hence error $= M_s - (M_r + H_s) =$~~ $M_s \approx W$. Hence $\Delta = M_s - (M_r + \tilde{M}_s) = M_t - \tilde{M}_s$. That is, the minimum error from the current forecast procedure is equal to the error in the harmonic prediction from the model including surge at estimating the *tide-only* model, figure 1(top). There are several striking features here, annual cycles peaking around March in the Arctic, January in South-East Asia, and June in Europe. Fortnightly cycles occur almost everywhere, with amplitudes of several cm. We will examine the causes of these below.

If it were possible to avoid the double-counting, and provide astronomical tidal harmonics ~~H_t~~ for the observations, ~~this~~ the prediction would instead be equivalent to ~~$M_r + H_t$~~ $M_r + \tilde{M}_t$, and the error would become ~~$M_s - (M_r + H_t)$~~ $\Delta = M_s - (M_r + \tilde{M}_t)$=~~$M_t - H$~~ as shown in figure 1(bottom). Since we ~~'re~~ are using the model as proxy for observations, if the harmonic prediction ~~is~~ were an exact reproduction of the tide-only model then ~~this would be exact. It is less than 5~~ $\Delta = 0$. In practice $\Delta < 5$ cm at most UK sites and the monthly cycle has gone, but in the Bristol Channel there is still an error of ~~up to around 0.5~~ around 50 cm, indicating that the ~~selection of~~ 62 harmonic constituents are not capturing all of the model tide. This is consistent with ~~?~~ the conclusions of ?, who found an "average [across UK ports] rms error [in harmonic prediction of a tide-only run] of 7 cm with a maximum value of 29 cm at Newport, in the Bristol Channel", using 50 constituents on the ~~C3SX~~ CS3X model.

2.4 Fortnightly cycle arising from small changes to S_2 phase

M_2 has a period of 12.42 hours and S_2 exactly 12 hours. ~~Through a lunar month they gradually~~ They move in and out of phase with each other twice in a lunar month, resulting in ~~a~~ the spring-neap cycle. A small change in phase to S_2 harmonic would result in a change of which days it is in phase with $\mathbf{M}_2$, and hence a substantial change in total tidal amplitude at a given date. For example, ~~$\mathbf{S}_2$ in the GSTM model with/without surge~~ near Avonmouth in the Bristol channel $\mathbf{S}_2$ derived from M_s has an amplitude ~~change in the Bristol Channel of about 0.04 m~~3.5 cm greater than $\mathbf{S}_2$ derived from M_t, however there is a phase change of around ~~3° (~~3.5°, so the tide arrives 7 ~~min)~~minutes later. Figure 2 shows ~~the total change in amplitude at Avonmouth varies between the tide-only and surge models by~~ how this and smaller changes in $\mathbf{M}_2$ account for differences between $\tilde{M}_t$ and $\tilde{M}_s$ of up to 5–8 cm~~(~~, on a fortnightly cycle between these limits~~) from this effect alone. This cycle could account for that seen by **?**, and that in figure 2 of **?**~~. This can account for about half the error in forecasted high-water at Avonmouth, which varies between 5 and 20cm on a fortnightly cycle (**?**, figure 4). Similar variation in error of the forecast was seen by **?**.

2.5 Quantifying surge-forecasting error due to disregarding non-linearity

The forecasting approach of linear addition of ~~the harmonic prediction to the~~ a non-linear ~~residual, $W_f = M_r + H_g$, itself carries a risk of error, even if the harmonic prediction did not include any radiational forcing~~model residual to a harmonic prediction, $F = M_r + \tilde{G}$, can also cause errors. Disagreements in phase between the model tide M_t and harmonic prediction from the gauge $\tilde{G}$ affect the forecast of an individual surge event.

Consider ~~the following simplified example. Suppose the model tide has an $\mathbf{M}_2$ amplitude of 3 (ignore all other constituents), and~~ a simplified example, where the tide can be modelled by a single constituent, $M_t = A\cos(\sigma t)$. Suppose there is a ~~surge which has the effect of adding a constant amplitude 0.2 and advancing the tide by a constant 30 min. Suppose also that the harmonics of the observed tide have the same amplitude as~~ storm-surge in which there is an uniform additional water level A_s and an advancement of the tide of $t = \delta$, so the tide-and-surge model is $M_s = A_s + A\cos(\sigma(t+\delta))$. As before, the model residual is given by $M_r = M_s - M_t$.

Suppose the harmonic prediction at the gauge agrees in amplitude to the tide-only model, but ~~are out of phaseby 5 (equivalent to 2.4° phase change for $\mathbf{M}_2$). As~~ has slightly different phase: $\tilde{G} = A\cos(\sigma(t+\epsilon))$.

The skew surge is defined as the difference between the maximum water level, here $\max(M_s)$, and $\max(\tilde{G})$. The error in the skew surge forecast is $E = \max(M_r + \tilde{G}) - \max(M_s)$. Substituting in and assuming phase changes are small, we find A_s cancels out and can show analytically that

$$E \approx A\left(\cos(\sigma\epsilon) - \cos(\sigma(\delta+\epsilon)) + \cos(\sigma\delta) - 1\right).$$

This is illustrated in figure 3, ~~the~~ with $A = 3$ m, $\sigma = 2\pi/12.42\mathrm{hr}^{-1}$ ($\mathbf{M}_2$), and the surge advancing the tide by $\delta = 30$ min. The residual M_r is decreasing during High Water due to the advanced tide. So if the observed harmonics have High Water later than the model (ϵ=5 min), the forecast skew surge is underestimated by 3 cm. If the observed harmonics predict High Water earlier than the model (ϵ=-5 min), the forecast skew surge is overestimated by 3 cm.

~~This example illustrates the importance of accurate phase agreement between model and observations, as well as amplitude~~Although in practice there are more constituents, a similar relationship will still hold in a small window about each high tide. Where there are frequent surges with consistent effect on the tidal phase we would expect ϵ to have the same sign as δ, as the gauge registers water levels more like the tide-and-surge model than the tide-only model and the harmonic predictions would follow suit.

3 The difference of specific harmonics

Figure 4 shows the vector difference in individual constituents between ~~surge~~ tide-and-surge and tide-only models run for 2013, along the coast globally. With some exceptions in the Arctic and Antarctic, the effect on $\mathbf{S}_\mathrm{a}$ is around 5–20 cm, with around half that effect on $\mathbf{S}_\mathrm{sa}$, although ~~there is an annual effect onlyin South-East Asia.~~ in the Indian Ocean there is a change to $\mathbf{S}_\mathrm{a}$ only. Since the model was only run for one year, $\mathbf{S}_\mathrm{a}$ may not be representative of all years, but figure 4 indicates typical changes. In the Baltic, the seasonal change is wind-forced, but elsewhere it is consistent with the annual and semi-annual cycles in sea-level atmospheric pressure (**?**).

$\mathbf{MS}_\mathrm{f}$ is affected by the surge component, as a side effect of the interaction between $\mathbf{M}_2$ and $\mathbf{S}_2$. This is because $\mathbf{MS}_\mathrm{f}$ is the fortnightly constituent which arises from the combination of $\mathbf{M}_2$ and $\mathbf{S}_2$, with a speed equal to the difference of their speeds. $\mathbf{MS}_4$ is the counterpart to this, with a speed equal to the sum of the speeds of $\mathbf{M}_2$ and $\mathbf{S}_2$ (**?**). Less explicable is the effect on $\mathbf{M}_\mathrm{m}$ and $\mathbf{M}_\mathrm{f}$, but it may be due to insufficient separation with $\mathbf{MS}_\mathrm{f}$ over a relatively short record. The diurnal constituents $\mathbf{K}_1$ and $\mathbf{O}_1$ are affected by less than 5 cm, and are only changed regionally in the Antarctic. $\mathbf{S}_1$ however is everywhere less than ~~1 mm~~ 0.1 cm in the tide-only model, but with the surge model peaks at ~~5 mm~~ 0.5 cm in northern Australis, the broadest regional effect being has ~~2–3 mm~~0.2–0.3 cm, in South-East Asia, consistent with the findings of (**?**).

It may come as a surprise that constituents such as $\mathbf{M}_2$, which has a purely lunar frequency, could possibly be ~~effected~~ affected by the weather. ~~But this is where~~ There is a very small atmospheric tide at $\mathbf{M}_2$, peaking at the equator at about 0.1 mbar (**?**). But more significant is the non-linear interaction of surge and tide~~comes into play~~. The surge may consistently advance the phase of the tide during low pressure events and certain wind configurations. A high pressure system could delay the phase of the tide, but there is asymmetry between these events, so there is a net bias on the phase when the weather is included.

The effect on higher order constituents is everywhere less than 5 cm. The maximum difference in the UK and globally for each constituent is given in Appendix B. In the UK, the constituents affected the most by including the surge are $\mathbf{S}_2$, $\mathbf{S}_\mathrm{sa}$, $\mathbf{M}_2$, $\mathbf{S}_\mathrm{a}$, $\mathbf{M}_\mathrm{m}$, $\mathbf{MS}_4$, $\mathbf{MS}_\mathrm{f}$ and $\mathbf{M}_\mathrm{f}$, with a maximum change of > 2 cm, and a further 19 constituents change 1–2 cm~~somewhere on the UK coast~~. Globally, $\mathbf{S}_\mathrm{a}$ and $\mathbf{S}_\mathrm{sa}$ are far more significant, but $\mathbf{S}_2$, $\mathbf{M}_\mathrm{f}$, $\mathbf{M}_2$, $\mathbf{M}_\mathrm{m}$, $\mathbf{MS}_\mathrm{f}$, $\mathbf{S}_1$, $\mathbf{K}_1$, $\mathbf{K}_2$, $\mathbf{O}_1$, $\mathbf{M}_{A2}$, and $\mathbf{MS}_4$ all change more than 4 cm (somewhere on the global coast). ~~Vector differences~~ A vector difference of 13 cm in $\mathbf{S}_2$ is seen in north-west Australia.

These results are robust to the number of constituents fitted~~(~~, 115, 62 or 34~~) to within 2 mm~~, to within 0.2 cm.

3.1 $\mathbf{S}_2$ atmospheric tide

Some of the difference between harmonics of surge and tide-only models is directly attributable to the atmospheric tides. The ~~atmospheric pressure has~~ global atmospheric pressure field contains $\mathbf{S}_2$ variations with amplitude of about $1.25\cos^3\phi$

millibars, for latitude ϕ (**?**). ~~The~~ GSTM air pressure and wind forcing is taken from the ERA-Interim data set (Appendix A), and the ocean response to ~~the ERA-Interim~~ that forcing at $\mathbf{S}_2$ is contained in the difference between harmonic predictions of the ~~model runs with and without surge~~ M_s and M_t model runss (figure 5). It is consistent with response analysis based on the $\mathbf{S}_2$ tides seen in ECMWF reanalysis data (figure 2, **?**), and in a 2-layer model forced by 8 constituents (figure 1b, **?**).

4 Highest Astronomical Tide and Lowest Astronomical Tide

The Highest Astronomical Tide (HAT) is used internationally for flood-forecasting references levels and in navigation for clearance under bridges. HAT can be used in structural design ~~with~~ alongside skew surge as an independent variable for determining return period water levels. Lowest Astronomical Tide (LAT) is also an important parameter, recommended for use as the datum on navigation charts (**?**). Once the phases and amplitudes A_n and g_n are known, $H(t)$ is fully determined for all time by equation (1), and the future HAT and LAT are given by max$(H(t))$ and min$(H(t))$. But because of the overlap in phase of the forcing between the constituents, and the f_n and u_n nodal ~~adjustments~~modulations, it is not trivial to write HAT or LAT algebraically. They are therefore determined by inspection of the predicted tides, preferably over a 18.6 year nodal cycle. Figure 6a shows the range, HAT minus LAT, when we do this by synthesising a predicted tide at 15 minute intervals over 18.6 years, globally. Radiational effects are omitted from this figure, which is based on a tide-only run. Since this data was limited to 1 month, it uses only 34 constituents, therefore omitting $\mathbf{S}_1$ and the long-period contributions to HAT and LAT.

~~The quick~~ An approximate calculation of Range $= 2(\mathbf{M}_2 + \mathbf{S}_2 + \mathbf{O}_1 + \mathbf{K}_1)$ is occasionally used (e.g. **?**), but the error due to this can be over 1 metre (figure 6b)~~, and although in the open ocean most of this is due to~~. $\mathbf{N}_2$ is a significant contributor, at about 20% of $\mathbf{M}_2$ in many sites worldwide. A few tens of centimetres are accounted for by the omission of the nodal ~~tide, near the coast up to 0.5 m of the maximum range can be due to the~~ modulations, and there are also the shallow water constituents ~~. Radiational effects are omitted from figure 6a, which is based on a tide-only run. Also, this analysis was limited to 1 month, so uses only 34 constituents, therefore omitting $\mathbf{S}_1$ and the long-period contributions to HAT and LAT~~at the coast.

Figure 6c shows the effect on HAT and LAT using the constituents derived with surge in the GTSM. In many places round the world the HAT is higher when the tide-and-surge model is used. So the observation-based HAT has been raised by some radiational component. But in most of the UK, the HAT goes down when the ~~surge~~ tide-and-surge model is used to generate the tidal predictions~~, rather than going up~~. This is because the peak of the weather-related components does not coincide with the maximum astronomical effects alone.This implies that since the tide-gauge predictions include surge, the observation-based HAT in the UK is actually about 10 cm lower than true astronomical-only tidal height. ~~But in many places round the world the HAT is higher when the surge model is used. So the observation-based HAT actually has been raised by some radiational component.~~

LAT tends to move the opposite way, so in most places the maximum tidal range is increased by using the ~~tide+surge~~ tide-and-surge model. That is, the true astronomical-only tidal range is slightly less than that quoted from harmonics based on predictions. In Scotland, (just above Liverpool in figure 6c) both LAT and HAT go down when the surge model is used to generate the tidal predictions, so the quoted LAT and HAT ~~is actually about 10cm~~ are actually about 10 cm lower than astronomical only.

The most extreme changes shown in Figure 6c are in the Arctic and Antarctic, and should be interpreted with some caution as these areas are the least well ~~understood~~ represented in the model.

In places with small tide, seasonal signals may be dominant and they may be important to include for practical purposes. For example along the French/Italian coast from Mallorca to Sicily there ~~'s about a 7cm~~ is about a 7 cm increase in HAT and ~~3cm~~ 3 cm decrease in LAT using the surge rather than tide-only model, so a Highest "Astronomical" Tide based on predicted tide from observations actually contains about 7 cm due to seasonal winds.

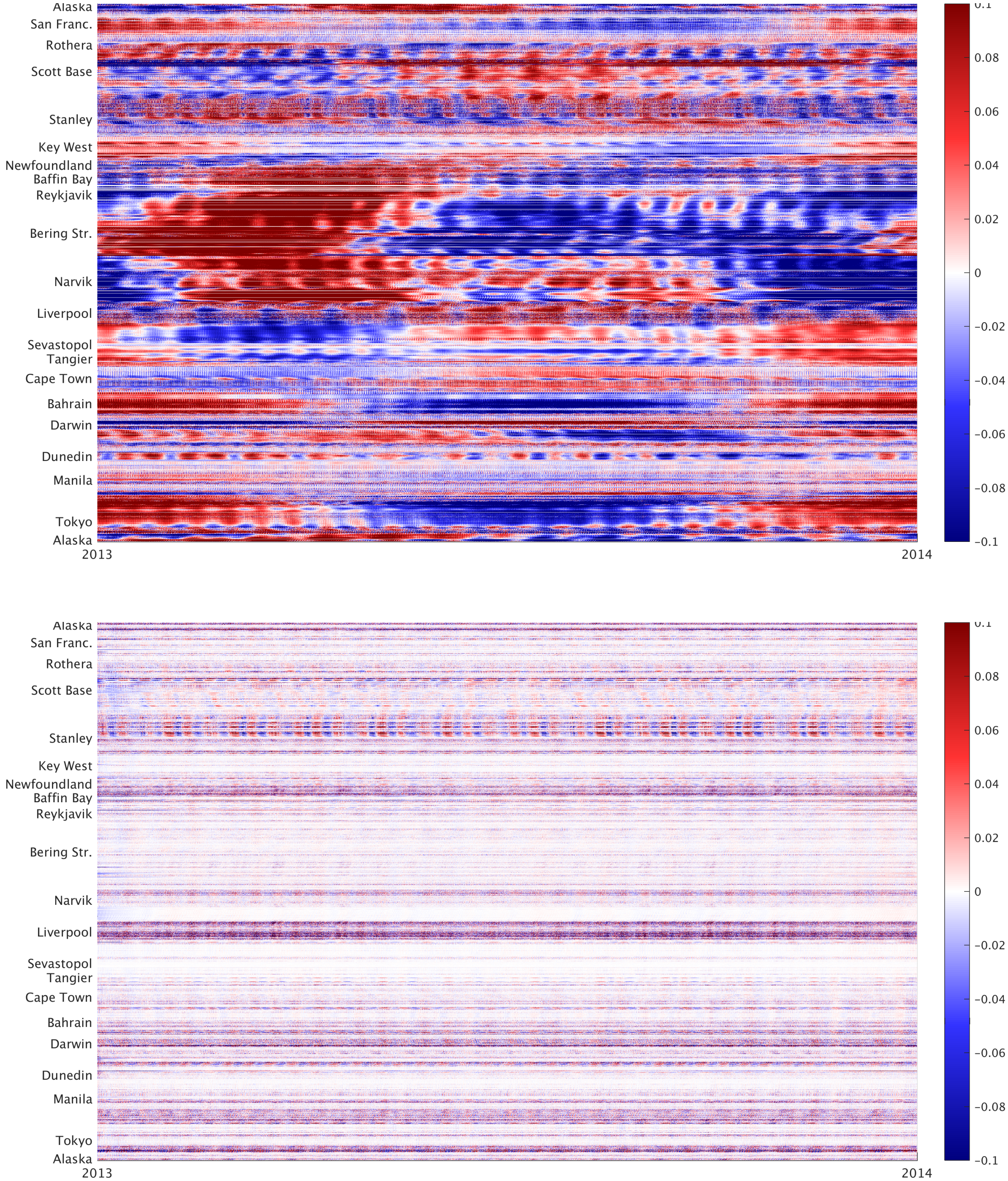

Figure 1. Time series (2013) of error (m) in 62-constituent harmonic prediction ~~with 62 constituents~~ from (top panel) ~~including surge~~tide-and-surge $\tilde{M}_s$ and (bottom panel) tide-only $\tilde{M}_t$ models at estimating the tide-only model M_t. The vertical axis is a continuous line around the world coastline, ~~GTSM 2013 only~~starting and ending at Alaska via East Pacific, Antarctica, West Atlantic, Arctic, East Atlantic, Indian Ocean, Australasia, and West Pacific. See appendix A for full explanation ~~of vertical coastal axis~~and a reference map.

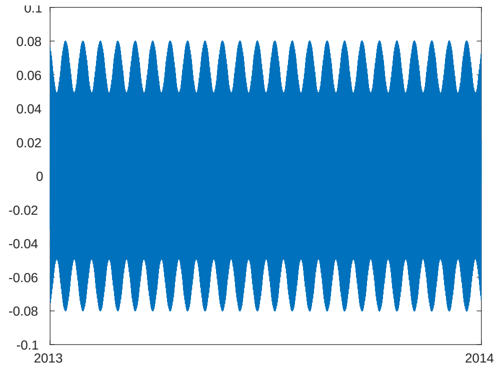

Figure 2. Fortnightly cycle of prediction change (metres) due to small changes in constituents $\mathbf{M_2}$+$\mathbf{S_2}$ alone, ~~between model with/without surge.~~ based on Avonmouth. $\mathbf{S_2}$ amplitude change = 3.5 cm, phase change $3.5°$, $\mathbf{M_2}$ amplitude change 1 cm, phase change $0.2°$.

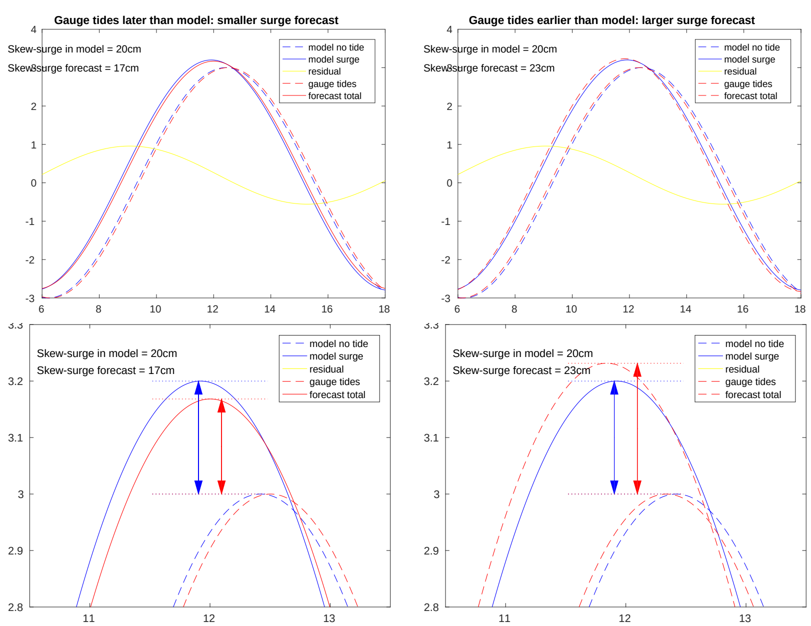

Figure 3. ~~A~~ Suppose a surge ~~is imposed which~~ adds a constant amplitude of 20 cm and advances the underlying 3 m amplitude $\mathbf{M_2}$ tide by a constant 30 min. If the harmonics of the observations differ in phase by 5 min from the model a forecast error of ± 3 cm will result as shown. Lower panels are magnified to show the ~~high water~~High Water.

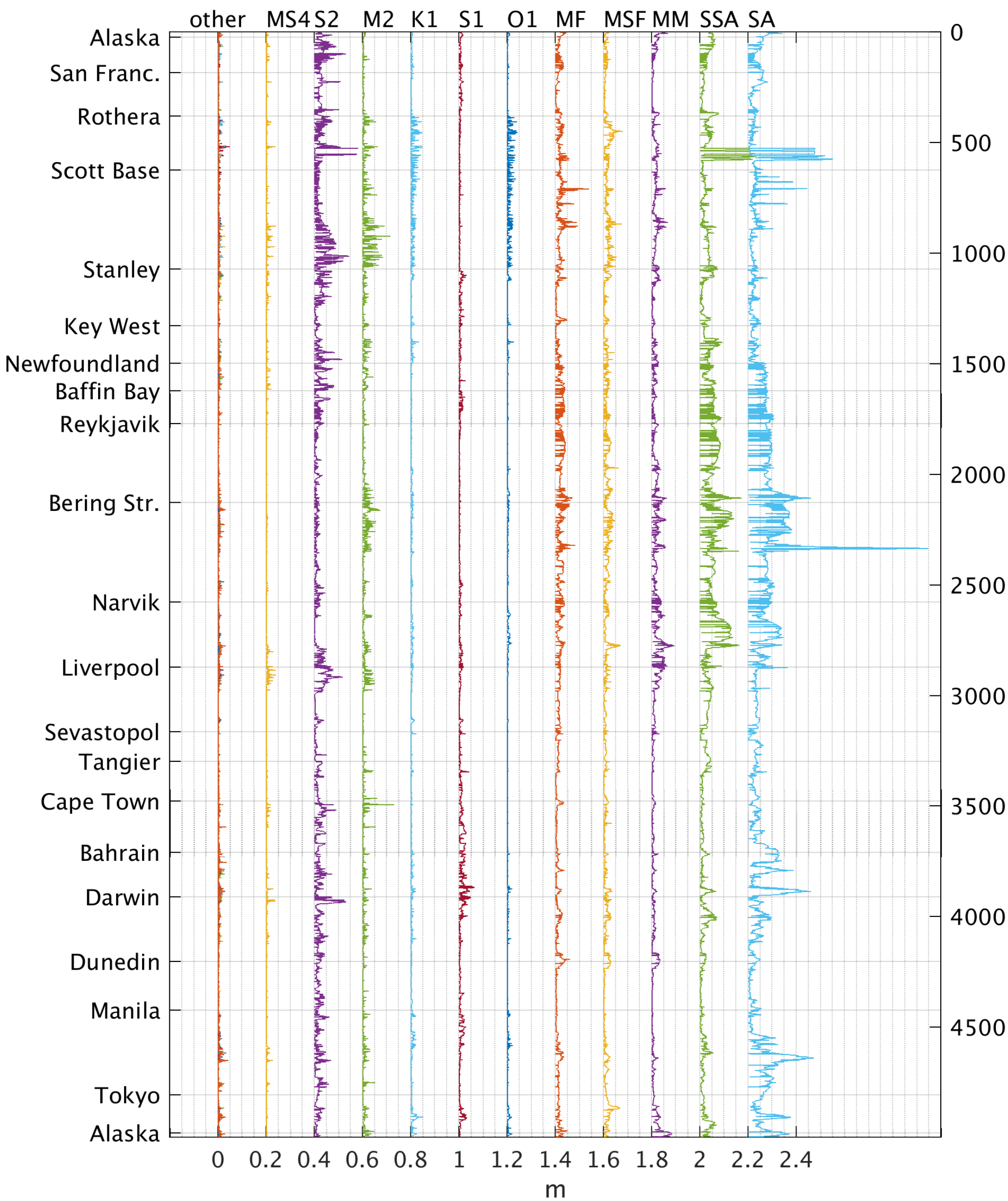

Figure 4. Vector difference (m, offset) between coefficients fitted to ~~model including surge or tide only,~~ GTSM ~~2013 only, 62 constituents fitted~~tide-and-surge (M_s) or tide-only (M_t) model. This is ~~is~~ the breakdown into constituents of the ~~the~~ difference between panels of figure 1. The maximum ~~effect~~ effects for these harmonics and others are given in table B1. See figure 1 and appendix A for explanation of coastal axis.

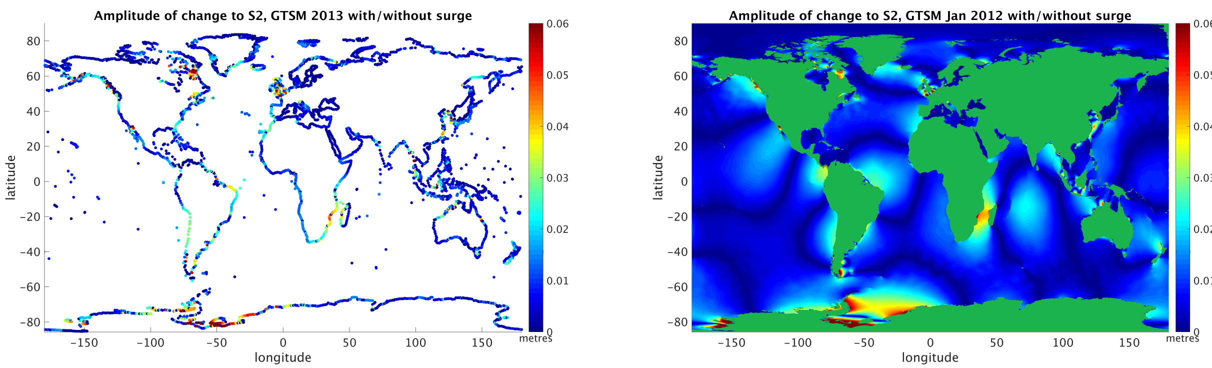

Figure 5. Amplitude (m) of $\mathbf{S}_2$ difference between ~~between~~ coefficients fitted to GTSM ~~model including surge~~ tide-and-surge (M_s) or ~~tide only~~tide-only (M_t) model. First panel: coastal data only, whole of 2013; second panel: 26 primary coefficients fitted to January 2012 only.

~~(a)(b)~~

5 Conclusions

There are substantial changes in tidal constituents fitted to tide-only and tide-and-surge model results. Even constituents with purely lunar frequencies, including $\mathbf{M}_2$, may be affected by the surge, perhaps owing to asymmetry in phase changes of the tide under high and low pressure weather systems.

Some effects of the weather on tides are double-counted in the forecast procedure used in the UK, where model residuals are added to gauge-based tide predictions. Even if the model were perfect, the minimum error from the current forecast procedure would be at least the error in the harmonic prediction including surge at estimating the tide-only model. If 62 constituents are fitted, this has a standard deviation of 20 cm at Avonmouth and 4–10 cm at most other UK gauges. 5–8 cm of the error at Avonmouth is due simply to a small change in phase of the $\mathbf{S}_2$ harmonic. Further errors in total water level and skew surge arise directly from the linear addition of the harmonic prediction to the non-linear residual, particularly where there is a phase difference between model and gauge tidal harmonics.

Understanding and quantifying these errors is extremely important for forecasters, who will often need to advise or intervene on the expected surge risk, often based on a direct comparison between observed residuals and the forecast non-tidal residual. Where, for example, such a comparison may lead to the observed residual falling outside the bounds of an ensemble of forecast non-tidal residuals, the forecaster may significantly (and potentially incorrectly) reduce their confidence in the model's estimate of surge if they are unaware of the additional errors associated with the harmonic tide and whether or not they have been addressed within the ensemble forecast's post processing system. For comparison, across the ~~UK-wide set of Class A ports~~ UK tide-gauge network, short range ensemble forecast RMS spread is of order 5–10 cm (**?**). It is noted that, in the UK, the majority of coastal flood events occur around peak spring tides (**?**), where the sensitivity to any errors in the $\mathbf{M}_2$–$\mathbf{S}_2$ phase relationship is arguably at its highest.

The atmospheric tide, at $\mathbf{S}_2$ is present in the ERA Interim forcing, and the ocean response to it, with amplitude about 1–5 cm, can be seen in the difference between the model results with and without surge. There is ~~therefore~~ hence an argument for including an atmospheric tide forcing in a "tide-only" model, and this is being explored by ~~(?)~~ **?**. In this case, care would need to be taken to omit the direct atmospheric tide forcing in the ~~tide+surge~~ tide-and-surge version, to avoid a different form of double-counting.

The estimates of Highest and Lowest Astronomical Tide are influenced by radiational tides. HAT and LAT are most readily calculated by inspecting long time series of predicted tides, and if observation-based, these predictions will include weather-related components. In most places globally this results in HAT being calculated as higher than the strictly astronomical component, and LAT being lower, however the opposite is true in the UK. The effects are of the order of $\tilde{1}0$ cm.

For many practical purposes it is correct to include predictable seasonal and daily weather-related cycles in the HAT and LAT. However the separate effects should be understood, as the radiational constituents may be subject to changing weather patterns due to climate change. It is also important not to double-count weather effects, if HAT or LAT are used in combinations with surge for estimating return-period water levels.

These considerations about HAT would also apply (proportionally less) to other key metrics such as mean high water.

Appendix A: ~~Global Tide and Surge Model~~

~~GTSM is the forward Global Tide and Surge Model developed at Deltares on a base of Delft-FM (Flexible Mesh) (??). The model is under active development, and the version used in this paper is has resolution from around 50 in the open ocean to around 5 at the coast. The atmospheric forcing is the ECMWF ERA-Interim 6-hourly reanalysis (?), downloaded at 0.25° resolution but from a spherical harmonic equivalent to $\tilde{0}.75°$. Validation of the major tidal coefficients has been favourable, and although the surge forecast under-predicts the effect of major hurricanes, due to lack of resolution in the weather forecast, most surge events are captured. For this report a 2013 run is used, with an 11 day spin-up period in December 2012. 62 tidal constituents are found by harmonic analysis of the 2013 results.~~

Appendix A: Ordering of model sites around the coast

~~Due to limitations of data storage the model is only output at high frequency at all grid points for one month (Jan 2012) and a selection of coastal points for the year 2013. These coastal points~~ The coastal points in the model output are spaced roughly every 80 km, and also wherever a tide gauge is situated, according to the GESLA data set. Due to automatic procedures to select output sites, a few may be incorrectly sited at model dry sites - these are clearly seen in plots as lacking sufficient high-frequency variability. The along-coast plots are ordered approximately ~~anti-clockwise around the UK including neighbouring coasts in Europe and Ireland.~~ from west to east around the world coastline, starting and ending at Alaska. The order is indicated in figure A1.

The algorithm for coastal order is as follows:

1) Define a single global coastline polygon.

This is done using the GSHHG (Global Self-consistent, Hierarchical, High-resolution Geography) data set (?), version gshhg2.3.6 (August 19, 2016, downloaded from www.ngdc.noaa.gov) . We use the coarse resolution, with only Level 1 (coastline) and Level 6 (Antarctic Ice Shelf), although consistent results for this technique can be obtained including enclosed lakes. To merge the separate landmasses and islands into a weakly simple polygon, topologically equivalent to a disc, we start with a single landmass and add others in turn using pairs of identical edges as "bridges". We start with the main landmass of Eurasia L_1, and find the closest vertex l to a vertex p from any of the remaining polygons $[P_2, ...P_N]$. Suppose p belongs to polygon P_j. Then we add P_j to L_1 using two new edges $\overrightarrow{lp}$ and $\overrightarrow{pl}$, to give a new merged polygon L_2. The vertices of L_2 are then $[L_1(1:l), P_j(p:end, 1:p-1), L_1(l:end)]$. Now repeat, searching for the nearest point in L_2 to any vertex in the remaining polygons $[P_2, ..., P_{j-1}, P_{j+1}, ...P_N]$. It is necessary for all initial polygons to be defined in the same sense (anticlockwise). If inland seas (Level 2) are included, they should be defined clockwise. The GSHHG data is consistent with this definition. Distance for nearest points are defined as arc-length on a sphere.

This technique has the benefit of tending to group island chains together in a consistent order. It cannot produce crossing edges. Because polygons are added in distance order, islands near continents are added to their neighbouring coast, and remote mid-ocean islands tend to be clustered, and attached to the nearest continent. The coasts of the Pacific, Atlantic and Indian and Arctic Oceans are all treated clockwise. Antarctica is attached across Drake Passage and ordered Westward. Nearby locations across narrow islands (particularly Sumatra), isthmuses (Panama), and straits (Gibraltar) may be widely separated in the order. But neighbouring points in the order can be expected to have fairly smoothly varying oceanography, with the "bridges" often, although not necessarily, approximating shoals.

As a final step we adjust the starting point of L_2 to be in Alaska, for convenience of mapping.

2) Rank the coastal points according to the nearest point on the global polygon.

Having defined this coastal order, we can apply it to any coastal data set, for example tide gauges. We number the vertices $[1,...,K]$. For each of the ~~tide~~ gauge locations T we find the nearest vertex k, and then rank the gauges according to T_k. In the event of gauges being much closer than the resolution of the vertices, a quick method for refinement is to linearly interpolate with extra vertices along polygon edges. Some problems may also occur with islands not in the coarse resolution data, which will tend to jump to the nearest coast.

A further advantage here is that having defined the coastal polygon, the same order can be applied to different data sets and models, leading to closely comparable along-coast plots.

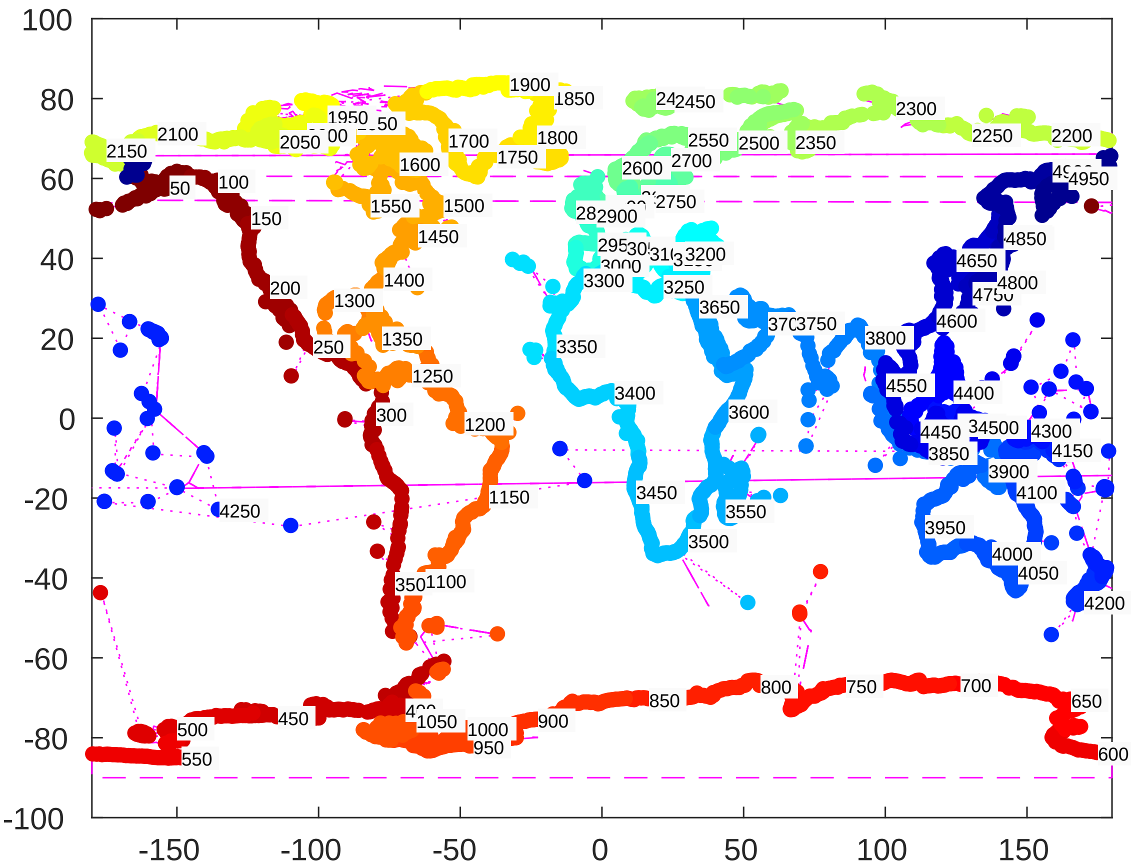

Figure A1. - Sites used for analysis ~~and~~ showing the order of coastal ~~ordering~~ points (Red to Blue ~~is~~ points shown above correspond to top-to-bottom ~~of other plots~~in Figures 1, 4 and 6)

Appendix B: Tidal constituents

Table B1 lists the constituents used in this paper. For short records, related constituents are used, and we fit 34 constituents with only 26 independent terms. ~~We follow the usual convention of a for annual, f fortnightly, 2 for approximately semi-diurnal etc., which are given as subscripts in the main text.~~

Table B1. Tidal Harmonic Constituents referred to in this paper, and the maximum change between ~~models run~~ GTSM tide-only (M_t) or with ~~surge~~ tide-and-surge forcing (M_s), at coastal locations, as from figure 4.

Name	Speed (deg/hour)	18yr list	1 year list	Max effect of surge in UK(cm)	Max effect of surge globally (cm)	1 month list Related	1 month list Primary
Total:		115	62			8	26
Sa	0.041 069	yes	yes	4.8	74.8	-	-
Ssa	0.082 137	yes	yes	5.6	23.4	-	-
Mm	0.544 375	yes	yes	4.2	9.3	-	yes
MSf	1.015 896	yes	yes	3.2	7.9	-	yes
Mf	1.098 033	yes	yes	2.1	14.0	-	-
2Q1	12.854 286	yes	yes	1.1	2.2	-	-
sigma1	12.927 140	yes	yes	1.1	1.3	-	-
Q1	13.398 661	yes	yes	0.7	1.6	-	yes
rho1	13.471 515	yes	yes	0.7	1.2	-	-
O1	13.943 036	yes	yes	0.7	4.3	-	yes
MP1	14.025 173	yes	yes	0.6	1.5	-	-
M1	14.496 694	yes	yes	0.5	1.4	-	yes
chi1	14.569 548	yes	yes	0.3	1.0	-	-
pi1	14.917 865	yes	yes	0.5	1.9	yes	-
P1	14.958 931	yes	yes	0.9	3.1	yes	-
S1	15.000 000	yes	yes	1.4	6.5	-	-
K1	15.041 069	yes	yes	1.0	5.1	-	yes
psi1	15.082 135	yes	yes	0.3	3.2	yes	-
phi1	15.123 206	yes	yes	0.6	1.3	yes	-
theta1	15.512 590	yes	yes	0.5	1.1	-	-
J1	15.585 443	yes	yes	1.0	1.2	-	yes
SO1	16.056 964	yes	yes	0.5	2.3	-	-
OO1	16.139 102	yes	yes	0.5	1.4	-	yes

Table B1. Continued.

Name	Speed (deg/hour)	18yr list	1 year list	Max effect of surge in UK(cm)	Max effect of surge globally (cm)	1 month list Related	1 month list Primary
Total:		115	62			8	26
2MN2S2	26.407 938	yes	-	-		-	-
3M(SK)2	26.870 175	yes	-	-		-	-
3M2S2	26.952 313	yes	-	-		-	-
OQ2	27.341 696	yes	yes	0.5	1.1	-	-
MNS2	27.423 834	yes	yes	0.8	1.1	-	-
MnuS2	27.496 687	yes	-	-		-	-
MNK2S2	27.505 971	yes	-	-		-	-
2MK2	27.886 071	yes	-	-		-	-
2N2	27.895 355	yes	yes	0.8	1.3	yes	-
mu2	27.968 208	yes	yes	1.7	2.7	-	yes
SNK2	28.357 592	yes	-	-		-	-
NA2	28.398 661	yes	-	-		-	-
N2	28.439 730	yes	yes	1.3	3.2	-	yes
NB2	28.480 796	yes	-	-		-	-
nu2	28.512 583	yes	yes	0.8	1.5	yes	-
OP2	28.901 967	yes	yes	1.2	2.8	-	-
MA2	28.943 036	yes	yes	0.8	4.3	-	-
M2	28.984 104	yes	yes	5.1	13.0	-	yes
MB2	29.025 173	yes	yes	1.3	3.9	-	-
MKS2	29.066 242	yes	yes	1.6	3.1	-	-
lambda2	29.455 625	yes	yes	1.3	1.6	-	-
L2	29.528 479	yes	yes	1.1	1.3	-	yes
2MN2	29.528 479	yes	-	-		-	-
2SK2	29.917 863	yes	-	-		-	-
T2	29.958 933	yes	yes	0.6	1.6	yes	-
S2	30.000 000	yes	yes	11.8	18.2	-	yes
R2	30.041 067	yes	yes	0.7	1.8	-	-
K2	30.082 137	yes	yes	1.1	5.0	yes	-
MSnu2	30.471 521	yes	-	-		-	-
MSN2	30.544 375	yes	yes	1.1	1.2	-	-
KJ2	30.626 512	yes	yes	0.6	1.0	-	-
2SM2	31.015 896	yes	yes	1.6	2.1	-	yes
2MS2N2	31.088 749	yes	-	-		-	-
SKM2	31.098 033	yes	-	-		-	-

Table B1. Continued.

Name	Speed (deg/hour)	18yr list	1 year list	Max effect of surge	Max effect of surge	1 month list Related	1 month list Primary
Total:		115	62	in UK(cm)	globally (cm)	8	26
MQ3	42.382 765	yes	-	-		-	-
NO3	42.382 765	yes	yes	0.5	1.6	-	yes
2MP3	43.009 277	yes	-	-		-	-
M3	43.476 156	yes	yes	0.1	0.7	-	yes
SO3	43.943 036	yes	yes	1.1	2.4	-	-
MK3	44.025 173	yes	yes	0.7	1.6	-	yes
2MQ3	44.569 548	yes	-	-		-	-
SK3	45.041 069	yes	yes	0.5	2.4	-	-
2MNS4	56.407 938	yes	-	-		-	-
3MK4	56.870 175	yes	-	-		-	-
3MS4	56.952 313	yes	-	-		-	-
MN4	57.423 834	yes	yes	0.7	1.3	-	yes
Mnu4	57.496 687	yes	-	-		-	-
2MSK4	57.886 071	yes	-	-		-	-
M4	57.968 208	yes	yes	1.7	3.0	-	yes
SN4	58.439 730	yes	yes	1.0	1.4	-	yes
3MN4	58.512 583	yes	-	-		-	-
MS4	58.984 104	yes	yes	3.2	4.1	-	yes
MK4	59.066 242	yes	yes	0.7	1.9	-	-
2MSN4	59.528 479	yes	-	-		-	-
S4	60.000 000	yes	yes	0.8	3.1	-	-
SK4	60.082 137	yes	yes	0.5	2.3	-	-
3MK5	71.911 244	yes	-	-		-	-
M5	72.460 261	yes	-	-		-	-
MSO5	72.927 140	yes	-	-		-	-
3MO5	73.009 277	yes	-	-		-	-
MSK5	74.025 173	yes	-	-		-	-
2(MN)S6	84.847 668	yes	-	-		-	-
3MNS6	85.392 042	yes	-	-		-	-
4MK6	85.854 280	yes	-	-		-	-
4MS6	85.936 417	yes	-	-		-	-
2MSNK6	86.325 801	yes	-	-		-	-

Table B1. Continued.

Name	Speed (deg/hour)	~~18yr~~ 18.6yr list	1 year list	Max effect of surge in UK(cm)	Max effect of surge globally (cm)	1 month list Related	1 month list Primary
Total:		115	62			8	26
2MN6	86.407 938	yes	yes	0.4	0.8	-	yes
2Mnu6	86.480 792	yes	-	-		-	-
3MSK6	86.870 175	yes	-	-		-	-
M6	86.952 313	yes	yes	0.7	1.2	-	yes
MSN6	87.423 834	yes	yes	0.6	1.1	-	yes
4MN6	87.496 687	yes	-	-		-	-
2MS6	87.968 208	yes	yes	1.4	2.6	-	yes
2MK6	88.050 346	yes	yes	0.3	0.9	-	-
3MSN6	88.512 583	yes	-	-		-	-
MKL6	88.594 720	yes	-	-		-	-
2SM6	88.984 104	yes	yes	0.6	1.4	-	yes
MSK6	89.066 242	yes	yes	0.4	1.5	-	-
2(MN)8	114.847 668	yes	-	-		-	-
3MN8	115.392 042	yes	-	-		-	-
M8	115.936 417	yes	-	-		-	-
2MSN8	116.407 938	yes	-	-		-	-
3MS8	116.952 313	yes	-	-		-	-
3MK8	117.034 450	yes	-	-		-	-
MSNK8	117.505 971	yes	-	-		-	-
2(MS)8	117.968 208	yes	-	-		-	-
2MSK8	118.050 346	yes	-	-		-	-
4MS10	145.936 417	yes	-	-		-	-
3M2S10	146.952 313	yes	-	-		-	-
4MSN12	174.376 146	yes	-	-		-	-
5MS12	174.920 521	yes	-	-		-	-
4M2S12	175.936 417	yes	-	-		-	-

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