**Response to R1:**

Thank you for the review and comments. We provide below our responses to the points raised, including details on the modifications made to the manuscript.

1. I want to bring up a possible systematic error which, if not addressed here, needs to be addressed at some point by this group as they continue to do these kinds of studies. I think it could cause errors of a few percent, which could be significant. Specifically, I'm beginning to think these very precise geodetic applications need to account for the variable density of seawater – that rho in Eqns (1-2) should stay inside the integral sign.

Thank you for pointing this out. The rho (density of seawater) stays inside the integral sign in Eqns (1-2), and the latest version of SPOTL accounts for the same variable density of surface seawater as before. In order to examine the effect of the variable density of the whole column seawater, we have computed the mean seawater density for each column on a 0.25x0.25° grid using the World Ocean Atlas (Boyer et al., 2013). The result is shown in the figure below.
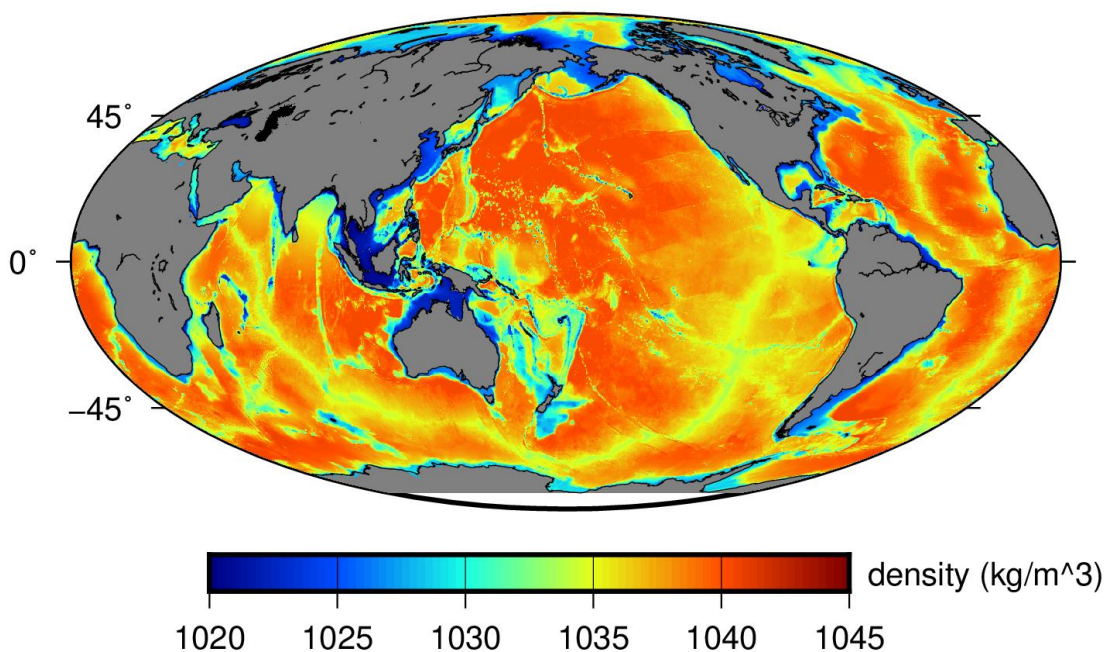
We have verified that this corresponds closely to Figure 6a of Ray et al. (2013) if $1/(g\rho_{mean})$ is plotted. For the loading computations we needed to extend some grid cells towards the coast to cover all water areas. The CARGA program was used (Bos, M S., and Baker, T. F.: An estimate of errors in gravity ocean tide loading computations, J. Geod., 79, 50-63, https://doi.org/10.1007/s00190-005-0442-5, 2005) to perform some sensitivity tests. First, a constant sea water density of 1030 kg m^{-3} was used (label=1030 in Table R1.1). Second, the spatially-varying mean sea water density was used in the OTL computations (label=spatial). Finally, we corrected the mean sea water density also for compressibility using the formula given in Ray (2013), with label 'compr'. Some statistics for the changes arising in M2 height displacement amplitude and phase-lag for the 102 GPS station locations in this study are presented in Table R1.1. The mean difference for the amplitude is around 0.11 mm if compressibility is also taken into account, and this is smaller than the 0.2-0.3 mm uncertainty of the GPS observations. The maximum difference reaches 0.37 mm, which is starting to be noticeable

and in future investigations this should be treated more carefully. Nevertheless, this is still much smaller than the observed discrepancies of over 1.5 mm and we have added a paragraph to the end of Section 5 which summarises these computations and comparisons.

Table R1.1 Influence of spatially-varying seawater density on M_2 vertical OTL displacement at the 102 GPS sites

Comparison	ΔAmplitude (mm)			ΔPhase-lag (º)		
	Min	Mean	Max	min	mean	max
spatial-1030	-0.13	0.03	0.16	-0.59	-0.22	0.38
compr-1030	-0.17	0.10	0.37	-0.99	-0.39	0.65

2. Abstract, line 13, recommend inserting "the regional model" before NAO99Jb, because many readers, even in the tide community, may see NAO99 and think it refers to Matsumoto's global altimeter-based model.

We have inserted "the regional model" as suggested.

3. Next line: "the most accurate." Well, this is risky because who knows if someone has developed another regional model here. I'd say "an accurate"– but it's up to the authors.

We have changed the part of the Abstract to now state, "By comparison with tide gauge observations, we establish that from nine selected ocean tide models (DTU10, EOT11a, FES2014b, GOT4.10c, HAMTIDE11a, NAO99b, NAO99Jb, OSU12, TPXO9-Atlas), the regional model NAO99Jb is the most accurate in this region".

4. In Abstract, and also page 15, bottom, authors quote 1.5 mm and 0.8 mm. I don't understand this. From Table 4, this looks to be "comparing apples and oranges." One is a maximum error and the other is RMS. Seems misleading, unless I'm just not following where they get these numbers.

0.8 mm was not in fact the RMS but the typical maximum error arising on applying the anelastic Green's functions, which we agree should have been made clear and used statistics consistent with Table 4. We have modified Table 4 to now incorporate minimum, maximum, 90th percentile and RMS values, and we now refer to these explicitly in the Abstract, the discussion in Section 5 and in Section 6 (Conclusions).

5. Page 13, line 5: Dahlen & Tromp is a massive book. I and many readers would appreciate your quoting the page number or even the Eqn number you're using when you cite this book.

We have inserted the equation number (9.66) to the text where Dahlen and Tromp (1998) is cited.

6. Page 2, line 36, where GPS is assigned an error of 0.3 mm. I don't accept this, because surely the errors in GPS are dependent on the length of the time series.

Penna et al. (2015) showed that with 2.5 years of GPS data, a semi-diurnal harmonic displacement could be estimated with an accuracy of around 0.2-0.4 mm. This led to our choice of 0.3 mm for the GPS observational error. To clarify, we have amended the text to state "the GPS observational error is assigned a STD of 0.3 mm following Penna et al. (2015), and which assumes that at least 2.5 years

of continuous GPS data will be available".

Response to R2:

Thank you for the review and comments. We provide below our responses to the points raised, including details on the modifications made to the manuscript.

1. The first part of the introduction gives a useful summary of previous work on using CGPS for tidal research. On page 2, line 9 it would be useful to mention that the GPS results from Yuan et al. (2013) were used by Lau, Mitrovica, ...(Nature September 2017) to look for lateral variations in body tide models of the lower mantle.
We have added a sentence on page 2 to incorporate this.

2. Page 3, line 16 (also page 7, line 5). It would be worth pointing out that Baker and Bos (2003, Fig. 9) used tidal gravity observations in Wuhan, China, to show that there are major problems with the earlier set of FES ocean tide models in that area.
We have added to Section 2 the sentence, "Such problems with the earlier set of FES ocean tide models were also seen from tidal gravity observations in Wuhan, China (Baker and Bos, 2003) near this sub-area".

3. Page 5, line 32. STDs of the phasor differences....should be STDs of the amplitudes of the phasor differences.
We used equation 2 of Stammer et al. (2014), which we now mention in the text, and which takes the form:

$$SD = \sqrt{\frac{1}{n}\sum_{n=1}^{n}\frac{1}{2}\left[\left(H_n\cos G_n - H_{mean}\cos G_{mean}\right)^2 + \left(H_n\sin G_n - H_{mean}\sin G_{mean}\right)^2\right]}$$

$$H_{mean}\cos G_{mean} = \frac{1}{n}\sum_{n=1}^{n}H_n\cos G_n$$

$$H_{mean}\sin G_{mean} = \frac{1}{n}\sum_{n=1}^{n}H_n\sin G_n$$

4. In Figures 4 and 5, it is very difficult to see all the phasors in Kyushu and the maps look very jumbled in that area. It is not easy to get round this problem. Maybe it would be better to reduce the number of sites/phasors and say that for clarity only 50% (or whatever) of the phasors are shown.
We have modified both Figures 4 and 5 such that they now comprise a part (a) showing the whole region and all phasors and a part (b) showing an enlargement of Kyushu and part of the Ryukyu Islands on an oblique Mercator plot. This enables us to still show the results from all GPS sites but with less clutter.

5. In Figure 5, the final (red) phasors still show some correlations along the Ryukyu islands. This

implies that there is still some information left in these residuals. The authors may want to comment on this.

We have included at the end of the first paragraph of the rewritten Section 5 a comment on the correlations between the residual phasors along the Ryukyu Islands, suggesting that they might be due to the tectonic setting of the subduction zone.

6. Page 15, line 32. It is stated that the discrepancies are less than 0.8 mm on the Ryukyu Islands. This is not consistent with Table 4 on the same page.

As per our response to Reviewer 1 point 4, we have modified Table 4 to now also include percentiles and we now refer to those in the Abstract, discussion in Section 5 and in Section 6 (Conclusions).

Response to R3:

Thank you for the review and comments. We provide below our responses to the points raised, including details on the modifications made to the manuscript.

1. To make a general point at the outset, using RMS as the sole measure of disagreement is hazardous. For example, in Figure 2, how do we know that the large RMS on the coast of China is not just one badly discrepant model rather than a Gaussian-like scatter? Or, alternatively, perhaps this RMS is large because the many global models used do not agree well: what I would want to know is how well the three most modern ones (FES2014b, TPXO9-Atlas, and GOT4.10c) agree.

We use the inter-model standard deviation (as shown in Figure 2) and then in Table 2 list the RMS agreement *per model* with respect to tide gauges in each defined sub-area. For the eastern China sub-area, the per model RMS values in Table 2 indicate that there are many models contributing to the sub-area's large scatter shown in Figure 2a, and that only NAO99Jb and FES2014b are accurate there, with RMS differences of 10-12 cm, whereas TPXO9-Atlas and GOT4.10c have RMS differences of 30-35 cm. To further confirm this, in Figure R3.1 we show, per pair, plots of the phasor differences among the three most modern models, namely FES2014b-GOT4.10c, FES2014b-(TPXO9-Atlas) and GOT4.10c-(TPXO9-Atlas). It can be seen that for all three pairs very similar patterns are obtained as for the standard deviations for all nine models shown in Figure 2, and we have added a couple of sentences to Section 2 (paragraph 3) to inform the reader. The only noticeable difference is that the older model differences tend to tail off slightly less rapidly on moving from the coast. These plots, together with the RMS differences with respect to the tide gauges listed in Table 2, do not suggest that the three most modern models should be chosen over the others in this region.
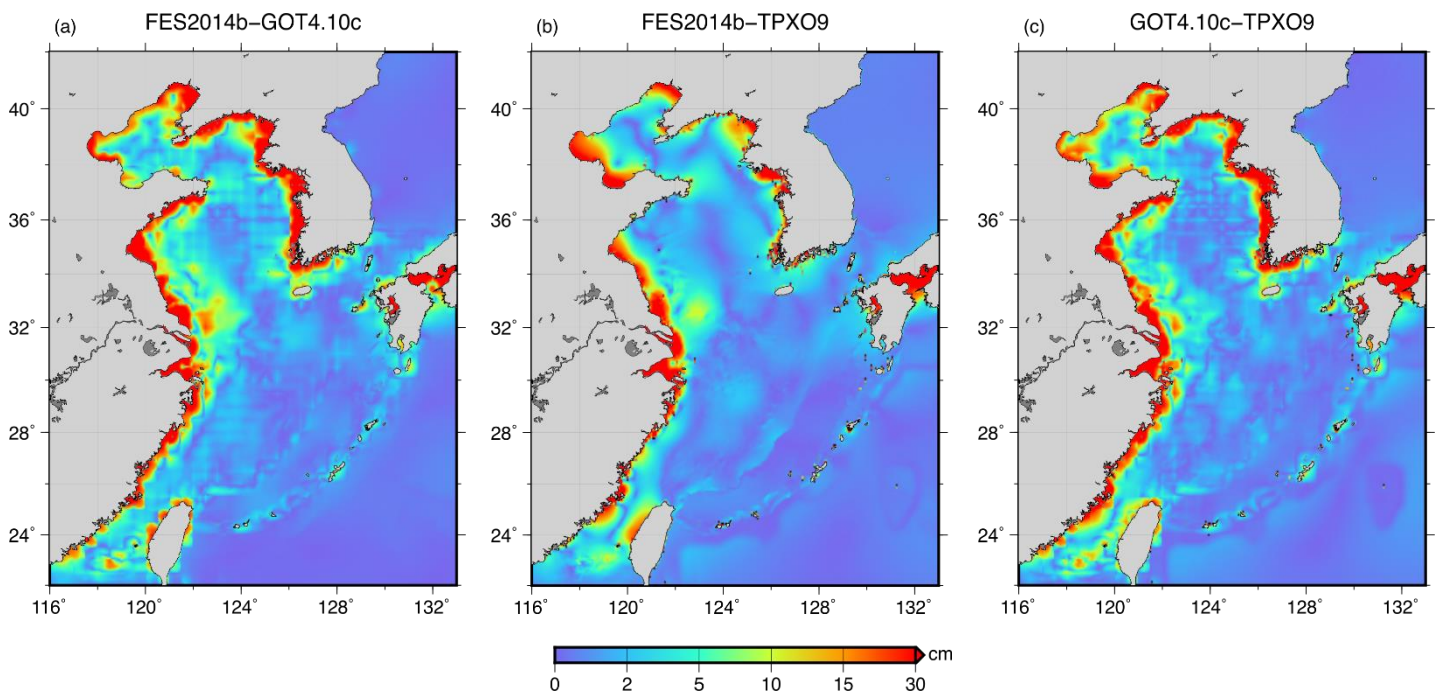

Figure R3.1 The M_2 phasor differences between each of the three most modern ocean tide models: FES2014b, GOT4.10c and TPXO9-Atlas.

2. Another general point is that the "East China Sea" in the title is misleading: the authors use data from the many GPS stations on Kyushu, a smaller number (but still quite a few) from the Ryukyu Islands, three in Korea, two in Taiwan, and one on the Chinese mainland. For tide gauges the same distribution is similar, except that there are six stations on the Chinese mainland and none on Korea. Any results, particularly any RMS values, will therefore be only about the first two areas, and especially Kyushu: for the GPS, the Pacific is likely to be as or more important than the East China Sea in producing almost all of the loads. I appreciate that the authors want to use as many stations as they can, but I think the paper would be much better if the few non-Japanese stations were omitted. This would also avoid a problem with Figures 4 and 5, which is that where most of the data is, it is impossible to see the results in any detail. Even if the authors do keep the few other stations, they should use a set of more focused maps, perhaps with the Kyushu-Ryukyu stations shown using an oblique Mercator.

We have changed the manuscript title to now state "around the East China Sea", not "in the East China Sea". To improve the presentation of Figures 4 and 5 (as also suggested by Reviewer 2), we now include an enlargement of Kyushu and most of the Ryukyu Islands on oblique Mercator plots. We consider the non-Japanese sites to still provide useful information as they are further from the local loads and hence provide a control on deeper mantle behaviour. Regarding the load contribution from the Pacific Ocean, we agree that a significant (but not dominant) proportion of the OTL is caused by this (as shown by Figure R3.2 below and in Table 3); but again the non-Japanese sites are useful in widening the aperture of our array to allow its effects to be distinguished from local loads. The Rest of NAO99Jb phasors in Figure R3.2 include the part of the Pacific Ocean contributing most to the loading, but inter-model variations are small, as they also are for the Central ECS contribution. The biggest impact on the loading and errors at the three sites considered comes from the very local sea areas, and where the importance of using NAO99Jb is shown.
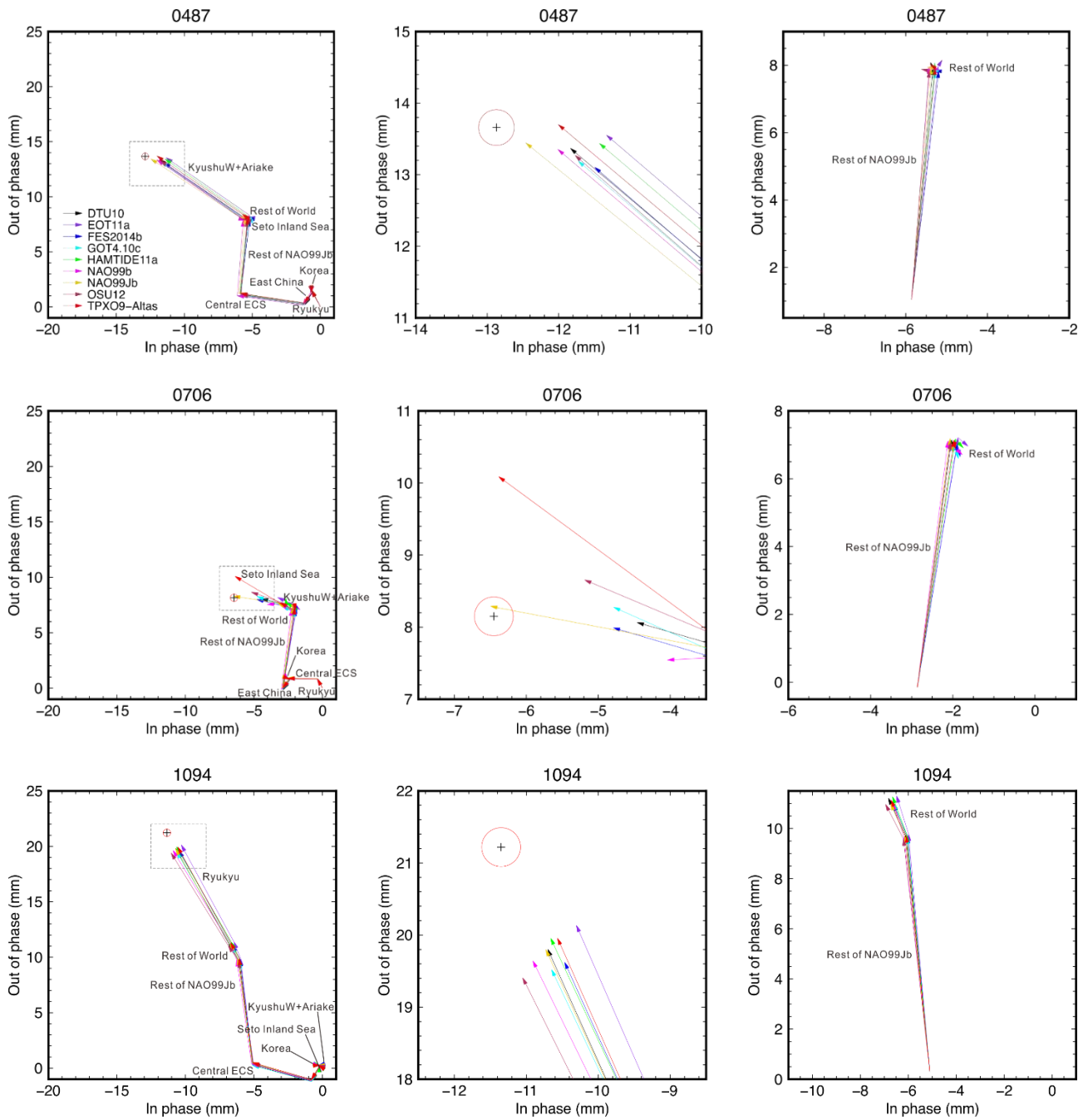
Figure R3.2 Phasor plot of the M$_2$ vertical OTL displacement contributions from the water sub-areas Eastern China, Korea, Central ECS, Seto Inland Sea (including the Kanmen Straits), Ryukyu Islands, Rest of NAO99Jb (comprises all the NAO99Jb coverage except the aforementioned sub-areas) and Rest of World.

3. This geographic imbalance leads to another problem, namely the authors' conclusion that the NAO99Jb model should be used, despite its age, because of its lower RMS compared to the tide gauges. But the authors' own Table 2 shows that for the most modern high-resolution global tide models (again, FES2014b, TPXO9-Atlas, and GOT4.10c) this lower RMS is confined to nearly-enclosed seas: for these NAO99Jb does much better. As the authors note, this is hardly surprising. The question is, how important are these enclosed seas in computing the loads?

I computed loads in two ways. A was to use all of the NAO99Jb model, and TPXO7.2atlas for the remaining global parts: close to the authors' procedure. B was to use the NAO99Jb model only inside the polygons and TPXO7.2atlas everywhere else. Figure 2 shows the results, as contours of the ratio of the M2 amplitude in vertical displacement for B, divided by the same thing for A. Two features of this plot are notable. First, the ratio is spatially smooth, which means that these enclosed seas only contribute to the estimated load for very nearby stations, so that NAO99Jb needs to be used only in these limited areas. The other is that there is, clearly, a systematic difference between loads that used NAO99Jb regionally and those that used it locally: this systematic difference might well make a difference in the authors' comparisons and conclusions. So I'd like to see the authors compute the loads using NAO99Jb only for limited areas, and more modern models (the three I've mentioned) for everywhere else.

We disagree that the lower RMS of NAO99Jb over FES2014b, GOT4.10c and TPXO9-Atlas (compared with tide gauge observations) is confined to the nearly-enclosed Ariake and Seto Inland seas: this is only the case for FES2014b. As shown in Table 2, the NAO99Jb M_2 RMS error with respect to tide gauges for the eastern China sub-area is 11.7 cm, whereas for GOT4.10c and TPXO9-Atlas the error is much larger at 30.1 cm and 34.5 cm respectively. Then for the Ryukyu Islands sub-area, TPXO9-Atlas has an RMS error of 11.0 cm compared with 2.4 cm for NAO99Jb, 3.1 cm for FES2014b and 3.9 cm for GOT4.10c. For the open sea areas where there are no tide gauges, Figure 2 suggests that all of FES2014b, GOT4.10c, TPXO9-Atlas and NAO99Jb agree to within 1-2 cm inter-model station deviation and so the choice of model here is immaterial.

To evaluate how important the regional improvements of NAO99Jb are in computing the load, we computed six sets of M_2 vertical OTL displacement for all 102 GPS sites, using two runs for each of the three most recent global models:

1. FES2014b:
    a. FES2014b augmented with all of NAO99Jb
    b. FES2014b augmented with NAO99Jb only for the Ariake and Seto Inland seas
2. GOT4.10c:
    a. GOT4.10c augmented with all of NAO99Jb
    b. GOT4.10c augmented with NAO99Jb only for the Ariake and Seto Inland seas
3. TPXO9-Atlas:
    a. TPXO9-Atlas augmented with all of NAO99Jb
    b. TPXO9-Atlas augmented with NAO99Jb only for the Ariake and Seto Inland seas

The PREM elastic Green's function was used and the minimum, maximum and RMS of the model M_2 vertical phasor residuals with respect to the GPS observations are shown in Table R3.1 for each ocean tide model combination. It can be seen that for all three models, the residuals when using all of NAO99Jb are smaller than when using it only for the Ariake and Seto Inland seas. The differences obtained among the global models when augmented with all of NAO99Jb are indistinguishable,

which confirms that our use of FES2014b (which was based on the accuracy tests with respect to the available tide gauges in the East China Sea region) for the Green's function comparisons is valid. This indistinguishability is also consistent with the small contributions and close model agreements for the areas outside the NAO99Jb extents shown in Figure R3.2. Whilst TPXO9-Atlas has a slightly lower RMS for the NAO99Jb augmentation with only the Ariake and Seto Inland seas compared with FES2014b and GOT4.10c, this is likely a result of improvements in areas with no tide gauges, but using all of NAO99Jb still gives lower RMS and maximum residual values.

Table R3.1 Phasor differences (in mm) between M_2 vertical OTL displacement and GPS observations at the 102 GPS sites using three different global ocean tide models and different augmentations of the regional NAO99Jb model, all with the PREM elastic Green's function

Model	(a) Use of all NAO99Jb			(b) NAO99Jb for Ariake and Seto Inland seas only		
	Min	Max	RMS	Min	Max	RMS
1. FES2014b	0.08	1.59	0.53	0.06	1.80	0.69
2. GOT4.10c	0.06	1.70	0.53	0.01	1.82	0.68
3. TPXO9-Atlas	0.09	1.64	0.50	0.02	1.76	0.58

4. Another major problem is that the conclusion about determining Earth structure seems inadequately supported by the evidence. Table 4 shows that once we adjust for anelastic attenuation, PREM gives RMS values that are basically indistinguishable from those for the regional model (which the authors more or less admit). Changing the model can reduce the RMS a bit more, but there is no demonstration that the reduction is significant given the added degrees of freedom: certainly the conclusion about asthenosphere depth (p. 13 lines 18-19) is not at all warranted.

The paper has first (to end of Section 4) demonstrated that the systematic M_2 residuals of about 1.3 mm amplitude arise from deficiencies in the elastic PREM Earth model. Our original intention with Section 5 was to explain these deficiencies by first obtaining the optimal model for the region. However, as the reviewer points out (and we had already noted), differences between anelastic global PREM, anelastic regional S362ANI and our modified regional S362ANI are relatively small. We have rewritten and reordered Section 5 to reflect this, whereby we first consider if the original elastic S362ANI regional model results in reductions in the residuals over elastic global PREM, and the effect is small (RMS for the whole region and the Ryukyu Islands alone both reduced by 0.08 mm). We then describe how accounting for anelasticity at the M_2 frequency for both PREM (globally) and S362ANI (in the ECS region) reduces the residuals (S362ANI_M2 results in slightly smaller RMS values than PREM_M2), but still residuals at the ~0.7 mm level for the Ryukyu Islands remain. Therefore we can only test optimality of the Green's function by computing a range of Green's functions based on different asthenosphere depths and values of Q. However, we did not find any significant improvement over S362ANI_M2 on doing this, and have therefore taken care to avoid any suggestion or claim that our observations *require* any change in the asthenosphere depth from S362ANI for this region. Instead, we have described our search tests to ascertain optimality, but that they result in similar reductions as S362ANI_M2 for the ECS region, and also how, for this region, using the global PREM_M2 model leads to residuals of almost comparable size. As well as rewriting Section 5, we have modified both the Abstract and the Conclusions to reflect this. For Figure 5, we now show the S362ANI_M2 residuals, not those of mod_S362ANI_M2.

The method presented is intended, to first order, to enable a further indication to be obtained that the large, systematic 1.3 mm M_2 residuals seen across the Ryukyu Islands and also on Kyushu are not caused by errors in the most accurate NAO99Jb model (as ascertained in Section 2). The inter-model standard deviations shown in Figure 3a for all nine ocean tide models are only around 0.3 mm across the Ryukyu Islands, suggesting that ocean tide model error contributions do not explain the discrepancies. However, around parts of Kyushu, namely the Seto Inland Sea and the Ariake Sea, the standard deviations increase to 2.5 mm, but in these regions we showed in Section 2 that the global models are erroneous. In terms of evaluating the contributions of the errors in each of the sub-area polygons to the total error at a specific location, in practice correlations are likely to exist among the polygons. For neighbouring regions, these correlations are likely to be positive, so equation 4 provides a very conservative (upper) bound on the expected level of model error. We have modified the text of Section 3 to emphasise this. For the Ryukyu Islands, the errors derived from equation 4 are about 0.5 mm, still much smaller than the 1.3 mm GPS observational residuals, and similarly across Kyushu, they are around 0.3 mm, indicating that the 2.5 mm inter-model standard deviations shown in Figure 3a are caused by models other than NAO99Jb. The errors within our defined eastern China sub-area polygon are around 1-2 mm and larger than the inter-model standard deviations, but this is because we have defined our eastern China polygon as considerably larger than the discrepant inter-model areas very close to the coast for both the ocean tides (Figure 2a) and OTL displacements (Figure 3a). Hence a conservative NAO99Jb error of 11.7 cm across all of the eastern China polygon has been applied, but which has been computed using eight tide gauges within the polygon, most of which are within the near coastal zone of much larger inter-model agreement than arises for much of the eastern China polygon. As well as mentioning in Section 3 that these large errors arise because of the fairly large 11.7 cm RMS error for NAO99Jb used, we have added an explanation that this is likely very conservative and results in errors which are too large for much of the area.

The GPS-estimated total vertical M_2 amplitudes and Greenwich phase lags and M_2 tide gauge estimates are included as a text file supplement. The Green's functions have also been moved from the appendices to this text file.

Response to Editor:

Thank you for the editorial summary and the additional comments on the manuscript itself. Our responses to each point raised, together with details of modifications made, are included below.

Title etc. I though geodesists insisted on GNSS and not GPS these days? Although I can see that most of the historical record must have come from GPS.
As we have used only GPS (not multi-GNSS) data in the processing and analysis, we consider GPS to be the appropriate and accurate term.

p2, 3 - what does 'positive trend of amplitude' mean?
We have rephrased this sentence to now read, "Ito et al. (2009) found the average amplitude ratios between GPS tidal displacement observations and an Earth tidal model (including OTL and Earth body tide) across Japan were greater than one, indicating observational agreement with inelastic Earth models".

40 - west coast of central America
We have inserted 'western' to clarify.

Figure 1 caption line 4 - move 'as triangles' to the end of the sentence. Also in the caption say that (b) has the same colour scale as (a) as there is no colour bar alongside it.
We have made these modifications.

p6, 17-18 - what does 'instead of .. values' mean? Obviously, if you have a record of 18.6 years you need nodal corrections to be time-dependent (with that period). I guess this is alluding to some software packages for which for short records one can assume a fixed 'f' and 'u'. But for what you are doing here it is obvious they have to be at the exact times.
We have simplified the sentence to now just state, "For time series shorter than 18.6 years, we applied nodal corrections during the harmonic tidal analysis (Foreman et al., 2009)."

Figure 2 - the absence of data from S. Korea in the UHSLC data set (and also GESLA-2) is a bit of a puzzle which hopefully will be corrected at some point. It that impacts on your analysis I would be grateful if you could stress the importance.
We have added a sentence to Section 2 to state that unfortunately no data are currently available within the Korea sub-area. However, it can be seen from Table 3 that the contribution of this water sub-area to the loading displacement at our sample sites shown is very small (<0.2 mm).

20 - the problematic coastal areas ..

'coastal' inserted.

"are" changed to "is".

Figure 3 - presumably the overflow white arrow in the colour bar is a GMT error? Could you make that red? Also, on paper anyway, I can hardly see the three GPS station numbers in (b). Also the caption should include mention of the numbers.
We have modified the colour bar in Figure 3 to be red, and also the caption to now mention the three GPS stations shown. We have also improved the readability of the three GPS station names on the figure by adding a white background box.

23 - Ryukyu Islands respectively (Figure 3b).
Change made.

p11, top - at this point I wondered if you had fully given credit to web sites or references of all data sources. Please check.
Here we state the data set / networks used. They have been mentioned in full in the Data Availability section, and also the providers thanked in the Acknowledgements section.

28 - I guess this 13.96 hour business is well known to GPS people but not to me. Could you have a sentence explaining more or a reference?
We introduce the concept of using an artificial harmonic displacement to quality control the GPS estimation of tidal displacement at the start of Section 4, but appreciate that we had not linked the last sentence of paragraph 1 of Section 4.2 sufficiently. We have therefore amended the last two sentences of this paragraph so that they now read, "In each daily solution, an artificial 13.96 hour harmonic signal of 3.0 mm amplitude was introduced in each of the east, north and vertical components, with the phase referenced to zero defined at GPS time frame epoch J2000, and hence the GPS harmonic estimation capability with the aforementioned GIPSY processing settings assessed. 13.96 hours was chosen as the period of this displacement following Penna et al. (2015), as it is approximately in the semi-diurnal band but is distinct from the main tidal harmonics so will not be contaminated by geophysical signals."

p12, 4 - change 'maps to only an error of' to 'has an error of only'
We consider the original form to be a clearer description, so have left this unchanged.

15 - an improvement
We have changed "the improvement" to "an improvement".

17 - isn't 'those' (i.e. the properties) of the asthenosphere part of the 'adopted Earth models' in the first part of the sentence? I think this needs rewording.

First sentence of Section 5 now changed to read, "As Green's functions essentially depend on the material properties of the adopted Earth models, an improvement of the agreement between GPS-observed and predicted OTL values (reduction in the observational residuals) could be expected by modifying the Earth models, and the representation of the asthenosphere has been demonstrated to be especially important (Bos et al., 2015)."

18 - especially important

Change made (incorporated within the response to the line 17 suggestion).

21 'was prepared'. Sounds like cookery. You mean computed or extracted?

Section 5 has been completely rewritten in response to .Reviewer 3's comments.

24 Q of 70. Is a reference needed here? Bos et al. (2015)?

Kustowski et al. (2008) reference added.

p13, 27 - 'has been validated'. Is this interpretation unique?

We have re-written Section 5 and no longer include a statement about asthenophere validation.

p16, 8 needs https://

We have added http://.

30 drop 'assumed'

This description has been moved into Section 5 and the 'assumed' dropped.

Asthenospheric anelasticity effects on ocean tide loading **around**~~in~~ the East China Sea ~~region~~ observed with GPS

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Abstract

Anelasticity may decrease the shear modulus of the asthenosphere by 8-10% at semi-diurnal tidal periods compared with the reference 1 s period of seismological Earth models. We show that such anelastic effects are likely to be significant for ocean tide loading displacement at the M_2 tidal period around the East China Sea. By comparison with tide gauge observations, we establish that from nine selected ocean tide models (DTU10, EOT11a, FES2014b, GOT4.10c, HAMTIDE11a, NAO99b, NAO99Jb, OSU12, TPXO9-Atlas), the regional model NAO99Jb is the most accurate ~~model among the nine selected latest numerical ocean tide models~~ in this region, and that related errors in the predicted M_2 vertical ocean tide loading displacements will be 0.2-0.5 mm. In contrast, GPS observations on the Ryukyu Islands (Japan), with uncertainty 0.2-0.3 mm, show 90th percentile discrepancies of ~~over~~ 1.3~~5~~ mm with respect to ocean tide loading displacements predicted using the purely elastic radial Preliminary Reference Earth Model. We show that the use of an anelastic PREM-based Earth model reduces these 90th percentile discrepancies to ~~no more than~~ 0.9~~8~~ mm. Use of an anelastic radial Earth model consisting of a regional average of the laterally-varying S362ANI model reduces the 90th percentile to 0.7 mm, ~~,~~ which is of the same order as the sum of the remaining errors due to uncertainties in the ocean tide model and the GPS observations. ~~Use of a regional Earth model based on the laterally-varying S362ANI, with or without further empirical tuning, results in minor additional improvements in fit.~~

1 Introduction

The periodic redistribution of ocean mass around the Earth's surface due to ocean tides deforms the solid Earth, a phenomenon known as ocean tide loading (OTL). The resulting OTL displacements can reach several centimetres in the vertical component and more than one centimetre in the horizontal components, with the Earth's response to the OTL depending strongly on the material properties within its interior (Farrell, 1972). In the past two decades, Global Positioning System (GPS) data analysis techniques have been developed to directly measure OTL displacements with millimetre accuracy, and even sub-millimetre accuracy at some frequencies (e.g., Allinson et al., 2004; Thomas et al., 2007; Yuan et al., 2009; Penna et al., 2015). With parallel substantial advancements in the accuracy of global ocean tide models (Stammer et al, 2014; Ray et al., 2019), comparisons of GPS-observed and predicted (modelled) OTL displacements have several times revealed the deficiencies

of using spherically symmetric, non-rotating, elastic and isotropic (SNREI) Earth models. One of the reasons for these deficiencies is that these models have been derived from seismic data and represent the Earth's elastic properties at a reference period of 1 s, but have typically been assumed to be directly applicable at tidal frequencies.

5

Ito et al. (2009) found~~analysed~~ the average amplitude ratio~~s~~ between GPS tidal displacement observations and an Earth tidal model (including OTL and Earth body tide) across Japan were greater than one, indicating observational agreement with inelastic Earth models ~~finding that the positive trend of amplitude agreed with predictions from inelastic Earth models~~. Ito and Simons (2011) further attempted to invert GPS-observed displacements for one-dimensional profiles of the elastic moduli and density beneath the western United States, demonstrating the limitations of the Preliminary Reference Earth Model (PREM) (Dziewonski and Anderson, 1981). Also, Yuan and Chao (2012) and Yuan et al. (2013) reported continental-scale spatially coherent differences between GPS-observed and predicted OTL displacements at sites located more than 150 km inland from the coastline, and attributed these differences to elastic and inelastic deficiencies in the a priori Earth body tide model. Subsequently, these GPS results were used by Lau et al. (2017) to look for lateral variations in body tide models of the lower mantle. ~~More recently, Bos et al. (2015) showed F~~for western Europe, Bos et al. (2015) showed that large discrepancies exist between GPS-observed and modelled OTL displacements, arising from disregarding anelastic dispersion in the asthenosphere that occurs when the elastic constants of the Earth model are modified to be applicable at tidal periods. Such an effect could bring about a reduction of around 8-10% of the shear modulus in the asthenosphere at tidal frequencies. In addition, Martens et al. (2016) observed spatial coherence among residual M_2 OTL displacements across South America, postulating deficiencies in the a priori SNREI Earth models.

Bos et al. (2015) showed the feasibility of representing the behaviour of the asthenosphere across an absorption band from seismic to tidal frequencies by a constant quality factor Q, which provides a rough transformation to account for the anelastic dispersion effect. Hence, it can be postulated that the asthenosphere should always produce ~8.5% OTL displacement discrepancies with respect to a purely elastic PREM-based Earth model, not only in western Europe where Bos et al. demonstrated this effect, but all over the world. However, these discrepancies will not be equally observable in all localities, either because ocean tide amplitudes are too small within the 50-250 km distance range from the analysis point that samples asthenospheric behaviour, or because regional uncertainties in ocean tide models are too large to be able to attribute any observed discrepancy to the Earth model. To identify regions where the findings of Bos et al. (2015) are testable, we have examined the global distribution of a 'detectability ratio'. This is defined as the ratio between the elastic-anelastic OTL displacement discrepancy (taken to be the difference between OTL predicted using a purely elastic PREM Green's function, as described in Section 3, and that using Bos et al.'s anelastic S362ANI(M_2) Green's function) as the numerator, and the combination of expected GPS observational and ocean tide model related errors as the denominator. For the latter, the ocean tide model related error is characterised as the standard deviation (STD) of the predicted elastic OTL displacements at each location, using each of the DTU10, EOT11a, FES2014b, GOT4.10c, HAMTIDE11a, NAO99b, OSU12, and TPXO9-Atlas numerical ocean tide models (see Table 1 for references). ~~, and t~~The GPS observational error is assigned a STD of 0.3 mm following Penna et al. (2015), which assumes that at least 2.5 years of continuous GPS data will be available.

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Figure 1a shows a global $1/8°$ grid of detectability ratio for the M_2 vertical OTL displacement, which is unfavourable (less than one) for most inland and deep ocean regions. Many of the areas where it exceeds one, such as off the coasts of southern Greenland, eastern Africa and western central America, are poorly sampled with continuously-operating GPS networks. However, the East China Sea (ECS) region exhibits a favourable combination of large OTL displacements and fairly consistent ocean tide models across much of it, so the detectability ratio here exceeds three across a wide area, and contains a healthy distribution of long-running GPS sites (Figure 1b shows the 102 GPS sites used). Accordingly, we have selected this as a suitable region for an independent test of Bos et al.'s (2015) conclusions. A further attraction of this region for the testing of Earth models is that its position overlying a subduction zone means that it represents a very different tectonic setting to the mature passive margin in western Europe studied by Bos et al.

Figure 1c shows the predicted M_2 vertical OTL displacements across the ECS region using the FES2014b ocean tide model (Carrère et al., 2016) and an elastic PREM Green's function. It can been seen that the M_2 vertical OTL displacement amplitudes are as large as 20-25 mm around the Ryukyu Islands and on the southeast coast of China, so the anelastic OTL displacement discrepancies would be expected to be about 2 mm and therefore detectable using GPS. Overall, the accuracy of recent ocean tide models is believed to be good, e.g. Stammer et al. (2014) show sub-centimetre M_2 root mean square (RMS) agreement between bottom pressure observations and seven recent models in the deep oceans globally and additionally, the FES2014b model has been suggested as providing a clear advancement in global ocean tide modelling (Ray et al., 2019). However, the fact that the tides in the ECS are large and complex owing to the irregular geometry of the basin (Lefèvre et al., 2000) implies that careful evaluation of the ocean tide models is still necessary in this region to ascertain the optimal model, and thus minimise the effect of errors in ocean tide models on the OTL predictions.

In this paper, we first assess the accuracy of a selection of up-to-date ocean tide models in the ECS, and quantify their contribution to the predicted OTL error budget. We then describe the kinematic GPS analysis approach for obtaining the observed OTL displacements. Finally, we examine the evidence of asthenospheric anelasticity effects in the ECS region based on the GPS-observed OTL displacements. We consider the M_2 constituent and the vertical component of OTL displacement, as these are dominant in the ECS region.
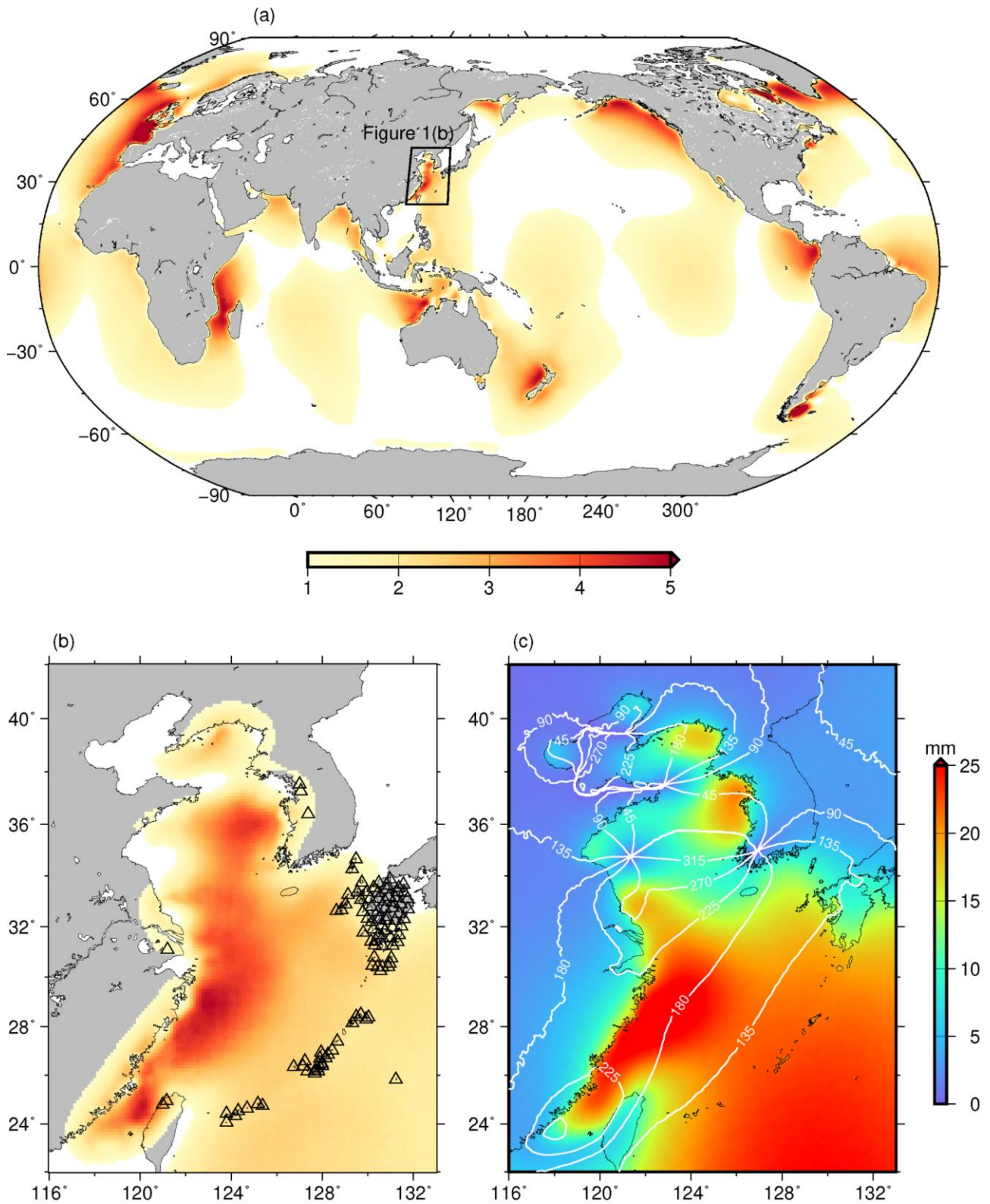
Figure 1 (a) Global distribution (1/8° grid) of M_2 'detectability ratio' of difference between vertical OTL displacements predicted using purely elastic and anelastic Green's functions to uncertainty in residual OTL displacements predicted using eight ocean tide models and the GPS observational error. **(b)** Detectability ratio in the East China Sea (ECS) region, showing ~~as triangles~~ the GPS sites used in this study as triangles. The colour scale is the same as in (a). **(c)** The M_2 vertical OTL displacement amplitudes and Greenwich phase lags for a 1/8° grid across the ECS region using the FES2014b ocean tide model and an elastic PREM Green's function.

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2 Ocean tide model accuracy assessment using tide gauges

A pre-requisite for using GPS measurements of OTL displacement for evaluating the Earth's interior material properties is that the impact of ocean tide model errors on the predicted OTL displacement is understood and found to be near negligible. Therefore, we first evaluate the quality of ocean tide models in the ECS region (considered throughout this paper as 116° to 133° east in longitude and 23° to 42° north in latitude) by assessing their consistency with each other and by comparing them with tide gauge observations.

To date, no single ocean tide model has been demonstrated as optimal in all regions of the world (Stammer et al., 2014; Ray et al., 2019), so we selected eight recent global (DTU10, EOT11a, FES2014b, GOT4.10c, HAMTIDE11a, NAO99b, OSU12, TPXO9-Atlas) models and one regional (NAO99Jb) model for the quality assessment. The key features of the models are listed in Table 1. All models, except for GOT4.10c, directly assimilate TOPEX/Poseidon (T/P) altimeter data plus, for some of the models, data from one or more of the ERS-1/2, Geosat Follow-on (GFO), Jason-1/2, Envisat and ICESat altimetry satellites, as well as tide gauge data. FES2014b, HAMTIDE11a, NAO99b and TPXO9 are barotropic data-assimilative models. DTU10 and EOT11a are both based on an empirical correction to the global hydrodynamic tide model FES2004 (Lyard et al., 2006), while the a priori model for GOT4.10c is a collection of global and regional models blended at mutual boundaries. OSU12 is a purely empirical model determined by analysis of multi-mission satellite altimeter measurements. TPXO9-Atlas is obtained by combining the base global TPXO9 and local solutions for all coastal areas including around Antarctica and the Arctic Ocean. The regional model, NAO99Jb, covers the area from 110° to 165° east in longitude and from 20° to 65° north in latitude, including the whole area of ~~our~~the considered ECS region, and assimilates more local tide gauge data than do the other models.

Table 1 Summary of the selected ocean tide models.

Model	Data assimilated[a]	Resolution	Type[b]	Author / Reference
DTU10	T/P, ERS-2, GFO, Jason-1/2, Envisat	1/8°	E	Cheng and Andersen (2011)
EOT11a	T/P, ERS-2, Jason-1/2, Envisat	1/8°	E	Savcenko and Bosch (2012)
FES2014b	T/P, ERS-1/2, Jason-1/2, Envisat, TG	1/16°	H	Carrère et al. (2016)
GOT4.10c	ERS-1/2, GFO, Jason-1/2, ICESat	1/2°	E	Ray (2013)
HAMTIDE11a	T/P, Jason-1	1/8°	H	Taguchi et al. (2014)
NAO99b	T/P	1/2°	H	Matsumoto et al. (2000)
NAO99Jb	T/P, TG	1/12°	H	Matsumoto et al. (2000)
OSU12	T/P, GFO, Jason-1, Envisat	1/4°	E	Fok (2012)
TPXO9-Atlas	T/P, ERS-1/2, Jason-1/2, Envisat, TG	1/30°	H	Egbert and Erofeeva (2002)

[a]T/P, TOPEX/Poseidon; GFO, Geosat Follow-on; TG, tide gauge.

[b]E, empirical adjustment to an adopted a priori model; H, assimilation into a barotropic hydrodynamic model.

To evaluate the consistency among the different ocean tide models for the dominant M_2 constituent, all models were bilinearly interpolated on to a common 1/16° grid across the ECS region and the STDs of the phasor differences from the mean were computed per grid point using equation 2 of Stammer et al. (2014), and ~~are~~as shown in Figure 2. It can be seen that away from the coastlines, all models are quite similar with the STD no more than 1-2 cm, which likely arises because they have

more or less assimilated the same altimeter data, albeit over different durations. However, closer to the coast large inter-model discrepancies arise, especially in the Seto Inland Sea, and near the coast of eastern China and western Korea, where the STD exceeds 30 cm in places. To check if the large discrepancies are caused by the older models, we considered the three most recent models (FES2014b, GOT4.10c and TPXO9-Atlas) and computed the differences per pair of FES2014b-GOT4.10c, FES2014b-(TPXO9-Atlas) and GOT4.10c-(TPXO9-Atlas). However, similar patterns and size of errors as in Figure 2 were obtained with the modern model difference pairs. The only changes were that the inter-model differences for the more modern models tend to tail off slightly more rapidly on moving away from the coast of eastern China.
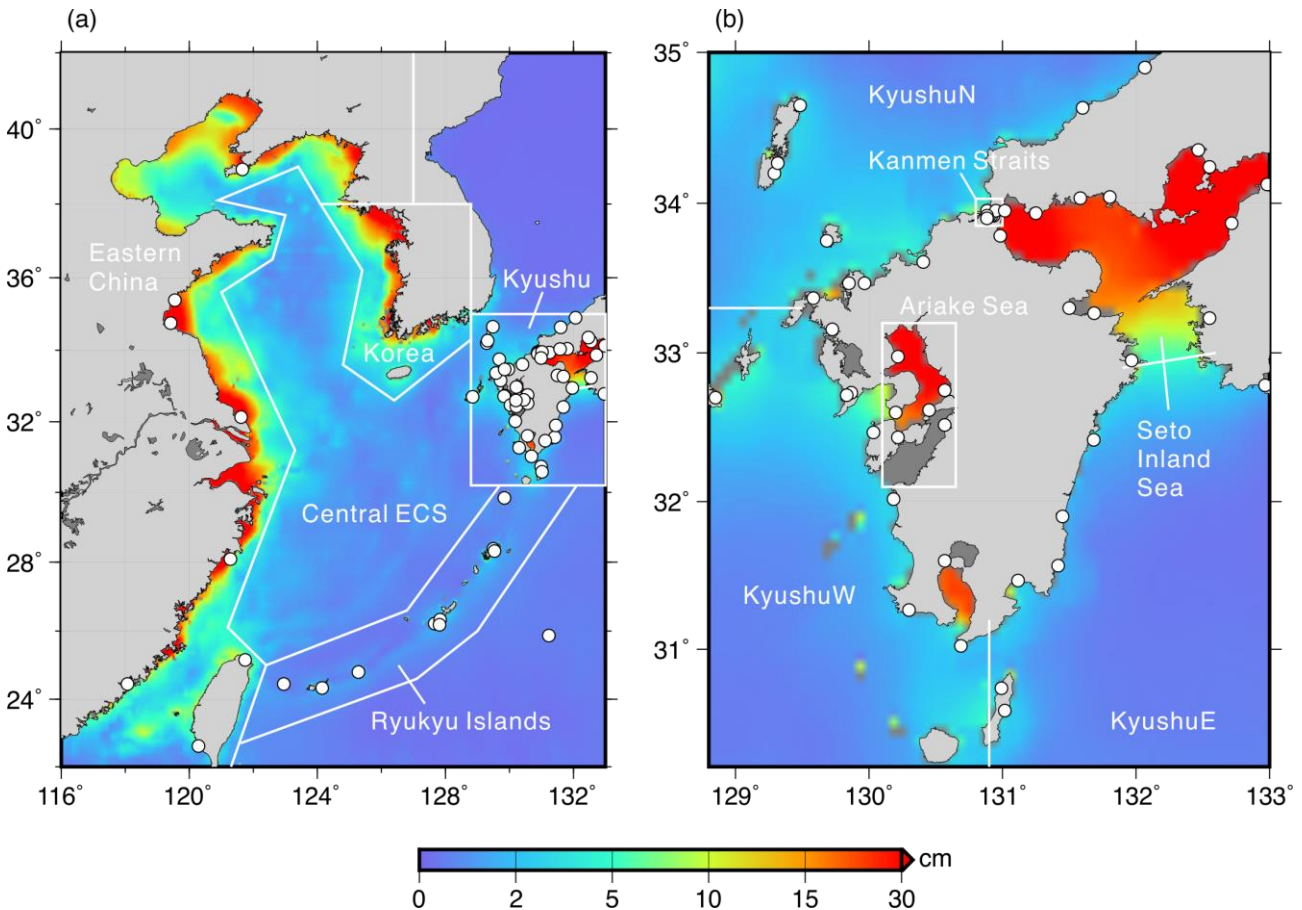

Figure 2 The M_2 standard deviations for nine ocean tide models (DTU10, EOT11a, FES2014b, GOT4.10c, HAMTIDE11a, NAO99Jb, NAO99b, OSU12 and TPXO9-Atlas). **(a)** shows the whole East China Sea (ECS) region, while **(b)** is an enlargement of the Kyushu sub-area of (a). The white labelled polygons define the sub-areas for which the quality of the ocean tide models has been evaluated, and the white dots represent the locations of coastal tide gauges.

To ascertain which models are the cause of the large STDs in some sub-areas, and to assess their accuracy, we compared each model with observations from 75 coastal tide gauges (58 from the Japan Oceanographic Data Centre and 17 from the University of Hawaii Sea Level Center) in the ECS region, as shown in Figure 2. Unfortunately no tide gauge data are currently available within the Korea sub-area. Using the UTide package (Codiga, 2011), the tidal constants observed at these locations were deduced from hourly sea level time series spanning 4 to 69 years, with a median time-series length of 26 years. For time series shorter than 18.6 years, we applied nodal corrections at exact times during the harmonic tidal analysis (Foreman et al., 2009), instead of regarding them as constant

~~values~~.

In order to investigate in detail the problematic <u>coastal</u> areas of eastern China, western Korea and the Seto Inland Sea, the region is divided into the separate sub-areas shown in Figure 2, basically in accordance with the zones of inter-model discrepancy. Moreover, for the sake of describing the ocean tide model errors as precisely as possible in the next section, the sub-area denoted as Kyushu is further divided. The M_2 phasor difference between each model and each tide gauge was computed, and the RMS of these differences per model for all tide gauges in each sub-area <u>is</u>~~are~~ listed in Table 2.

For eastern China, FES2014b and NAO99Jb perform quite well (RMS of 10-12 cm), whereas DTU10 and EOT11a are the worst models (RMS of 47-59 cm). This could be explained by the fact that the FES2004 model, on which DTU10 and EOT11a are both based, has several grossly incorrect tidal values in this area owing to insufficient satellite altimetry data available at the time. <u>Such problems with the earlier set of FES ocean tide models were also seen from tidal gravity observations in Wuhan, China (Baker and Bos, 2003) near this sub-area.</u> RMS agreements of better than 4 cm between tide gauge observations and each of the models are obtained for the Ryukyu Islands sub-area, except for TPXO9-Atlas. This is despite TPXO9-Atlas having the finest resolution among the models of 1/30°, whereas the coarser (1/2°) GOT4.10c and NAO99b models have better than 4 cm RMS agreement. Around the island of Kyushu, the observations compare consistently well with FES2014b and NAO99Jb (RMS lower than 4 cm), while the comparisons are poor for DTU10, EOT11a, HAMTIDE11a, OSU12 and TPXO9-Atlas along the west coast of Kyushu, and for GOT4.10c and NAO99b along the north coast of Kyushu. NAO99Jb exhibits the best agreement with the observations in the Ariake Sea and Seto Inland Sea, which is expected as it assimilates data from 219 local tide gauges (Matsumoto et al., 2000). This also results in NAO99Jb being more accurate than NAO99b in most parts of the ECS region. However, the agreement between NAO99Jb and the tide gauges is no better than the other models in the Kanmen Straits, because the tide gauges there were installed in 2011, after the release of NAO99Jb, and hence none of their data have been assimilated. Nonetheless, NAO99Jb is the most accurate ocean tide model in the ECS region as a whole.

Table 2 The root mean square (in cm) of the M_2 phasor differences between each of the nine ocean tide models and the tide gauge observations in each defined sub-area of the East China Sea region.

Area	DTU10	EOT11a	FES2014b	GOT4.10c	HAMTIDE11a	NAO99Jb	NAO99b	OSU12	TPXO9-Atlas
Eastern China	47.4	59.1	9.6	30.1	42.5	11.7	35.4	18.3	34.5
Ryukyu Islands	3.1	3.2	3.1	3.9	3.4	2.4	3.9	3.6	11.0
KyushuW	15.3	19.0	3.3	6.6	17.5	3.7	6.8	13.8	8.1
Ariake Sea	29.6	29.1	29.2	46.5	34.8	3.1	34.8	39.6	23.7
KyushuE	3.6	3.7	2.5	4.8	4.0	3.0	5.6	3.9	4.6
KyushuN	2.9	3.0	1.8	8.2	2.7	2.1	7.3	5.8	6.6
Seto Inland Sea	34.4	43.0	31.3	42.1	57.3	3.3	46.3	36.3	38.0
Kanmen Straits	15.6	17.6	14.5	12.9	16.8	16.2	16.8	11.8	11.9

3 Impact of ocean tide model errors on OTL displacement

In this section we assess the impact of ocean tide model errors on the predicted OTL displacements,

which is needed to ensure the confident geophysical interpretation of the GPS-observed OTL displacement residuals considered thereafter. For a particular tidal constituent, the OTL displacement u at a point $\boldsymbol{r}$ on the Earth's surface may be computed (predicted) with the following convolution integral (Farrell, 1972):

$$u(\boldsymbol{r}) = \int_{\Omega} \rho G(|\boldsymbol{r} - \boldsymbol{r}'|)Z(\boldsymbol{r}')d\Omega \tag{1}$$

where Ω represents the global water areas, ρ is the density of seawater, G is a Green's function that describes the displacement at $\boldsymbol{r}$ from a unit point load, and Z is the tide height at $\boldsymbol{r}'$, written as a complex number to include both the amplitude and varying phase-lag. Here, the convolution integral is determined by numerical integration, and may be written as:

$$u(\boldsymbol{r}) = \sum_{\Omega} \rho Z_i G_i \tag{2}$$

where G_i here is the integrated Green's function for the ith element of Ω, as per Agnew (1997), and the tidal heights Z_i are represented over Ω by inputting a global ocean tide model.

Bos et al. (2015) took the STD of predicted OTL displacements computed per point for a set of ocean tide models as the error contribution of the ocean tide models in western Europe, assuming that there were no systematic biases shared by the models. However, we have shown in Section 2 that for the ECS region, the STD among the models is not always a good indicator of their accuracy. To check this, M$_2$ vertical OTL displacements were computed for a 1/8° grid across the ECS region for each of the nine ocean tide models (NAO99Jb was augmented globally outside its boundary by FES2014b) using the SPOTL (NLOADF) software version 3.3.0.2 (Agnew, 1997). A Green's function computed based on the isotropic, purely elastic version of PREM was input (as for all elastic PREM-generated results in this paper) and is provided in the supplement~~Appendix A~~. As the GPS sites considered in this study are on land, the upper 3 km water layer in PREM was replaced with the density and elastic properties from the underlying rock layer. The OTL displacement STDs among the models per point are shown in Figure 3a, and it can be seen that the distribution of the STDs is similar to those shown for the ocean tide models in Figure 2, with large STDs of up to 2.5 mm arising around eastern China, western Korea and the Seto Inland Sea. However, as shown in Section 2, these large STDs arise from large errors in some (but not all) of the nine ocean tide models and NAO99Jb was shown to be the most accurate model across the ECS region. Therefore, it is unreasonable to use the inter-model STD as an indicator of OTL displacement accuracy for all of the ECS region. Instead, we now present an approach which allows us to quantify (to first order) the resulting OTL displacement prediction error individually for a particular ocean tide model.

Assuming the ocean is divided into k specified water areas Ω_k (e.g., as per Table 2), and that the ocean tide model error magnitude per area is δ_k, the corresponding OTL accuracy δu_k is:

$$\delta u_k(\boldsymbol{r}) = \sum_{\Omega_k} \rho \delta_k G_i \tag{3}$$

Then, assuming no correlation between each of the k areas, the total OTL displacement prediction error may be computed as:

$$\delta u(\boldsymbol{r}) = \sqrt{\sum \delta u_k^2(\boldsymbol{r})} \qquad (4)$$

Note that in practice there are likely to be positive correlations between adjacent water areas, which will result in the error estimates from equation 4 being too large (conservative).

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To evaluate the OTL error using equation 4 for NAO99Jb, the most accurate ocean tide model in the ECS region, we define the ocean tide model errors for the separate sub-areas (as per Figure 2) as the RMS difference between NAO99Jb and the tide gauge observations within the sub-area (Table 2). For the Korea sub-area, although no tide gauge data source is available, the error of NAO99Jb for 10 Korea can be estimated as the mean value of the RMS of the areas around Kyushu excluding the Kanmen Straits, considering the fact that NAO99Jb also assimilated the tide gauge data around Korea. The 'other water areas' (comprising the central ECS sub-area and all other global water areas not named in Figure 2) are either open oceans, or narrow coastal areas that are far from the ECS. To be conservative, a slightly larger value of 0.7 cm is chosen as the RMS error of NAO99Jb and its 15 complement of FES2014b for these areas, according to the largest RMS model differences of 0.66 cm for deep oceans inferred by Stammer et al. (2014).
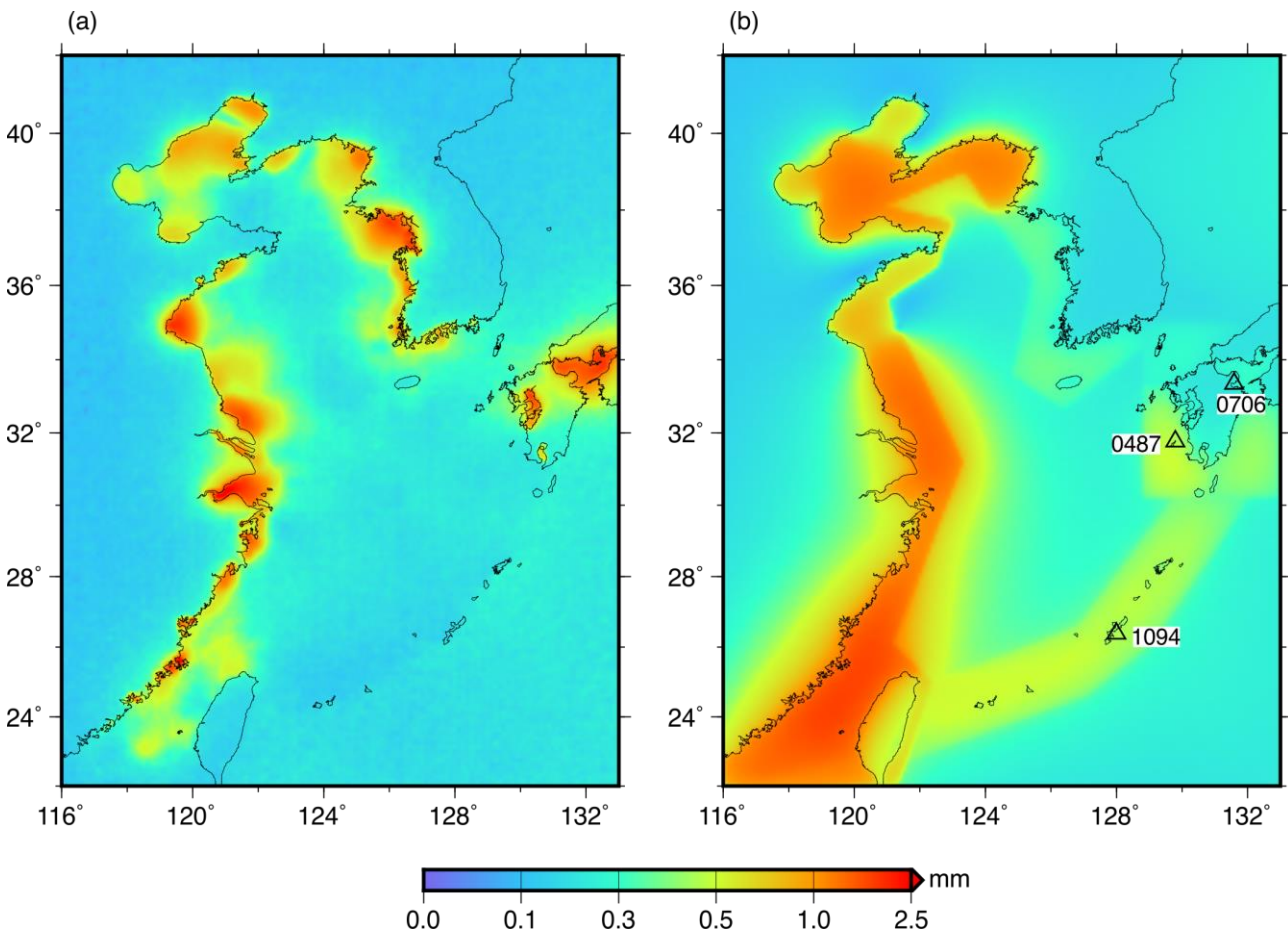

Figure 3 (a) The standard deviation of M_2 vertical OTL displacements, computed using the nine ocean tide models and 20 an elastic PREM Green's function. **(b)** The M_2 vertical OTL errors per grid point according to equation (4), using the RMS errors in NAO99Jb based on comparisons with tide gauges, and an elastic PREM Green's function. The triangles (and accompanying names) denote GPS sites which are considered for detailed OTL computation analysis.

Using equation 4 and inputting the NAO99Jb RMS errors per sub-area, the M_2 vertical OTL displacement errors at each point of a 1/8° grid were computed and are shown in Figure 3b. It can be seen that the largest errors of 1-2 mm are for the points falling within the eastern China sub-area, but these can be explained by the NAO99Jb model having a fairly large assumed RMS error of 11.7 cm for this sub-area, and this has the largest influence on the OTL displacement there. This is however likely very conservative and results in errors for much of the eastern China sub-area that are too large, because it can be seen from Figures 2 and 3 that it is only very close to the coast where large inter-model discrepancies arise. Away from the coast much of the inter-model ocean tide agreements for the eastern China sub-area are about 2 cm. For the rest of the ECS region, notably where most of the GPS sites are located, the OTL errors arising from NAO99Jb model RMS errors are no more than ~0.5 mm, even for sites on the east of Kyushu where the inter-model OTL STDs are large (~2.5 mm).

To provide a more detailed indication of the influence on the OTL of the NAO99Jb ocean tide model errors from each of the defined sub-areas, three GPS sites (0487, 0706 and 1094) are considered, located on the east and west of Kyushu and on the Ryukyu Islands respectively (Figure 3b). The contribution of each sub-area to both the OTL displacement and its accompanying error are shown in Table 3, which provides further clarification that the local ocean tides are the principal contributor to the OTL displacements, as well as the OTL errors. The large effect from the 'other water areas' is mainly due to their vast area, although most of this is far from our study area and will have no impact on regional comparison of Earth models. The Kanmen Straits and eastern China, where NAO99Jb performs relatively poorly, have little effect on the OTL displacements at these sites, with contributions to the OTL amplitude and error of only 1.0-1.5 mm and less than 0.1 mm, respectively. Furthermore, the effect of the ocean tide model errors from these two sub-areas is no more than 0.13 mm for all three sites. These computations were repeated for all the GPS sites, and only three of the 102 GPS sites had a total OTL prediction error greater than 0.5 mm. It can therefore be concluded that the OTL displacements computed using the NAO99Jb ocean model are suitable for investigating possible anelasticity effects in the ECS region.

Table 3 The contribution of the defined water sub-areas in Figure 2 to the M_2 vertical OTL displacement amplitudes and the resulting errors at GPS sites 0487, 0706 and 1094 according to equation 4 and using the NAO99Jb model and its RMS errors.

Area	M_2 vertical OTL amp (mm)			M_2 vertical OTL error (mm)		
	0487	0706	1094	0487	0706	1094
Eastern China	1.18	0.99	1.48	0.11	0.09	0.13
Ryukyu Islands	1.67	0.92	9.46	0.07	0.04	0.42
KyushuW	8.04	1.11	0.34	0.41	0.06	0.02
Ariake Sea	0.42	0.34	0.03	0.01	0.01	0.00
KyushuE	1.10	1.36	0.21	0.06	0.08	0.01
KyushuN	0.53	0.81	0.08	0.02	0.04	0.00
Seto Inland Sea	0.34	3.28	0.05	0.01	0.14	0.00
Kanmen Straits	0.00	0.01	0.00	0.00	0.00	0.00
Korea	0.18	0.15	0.13	0.02	0.01	0.00
Other Water Areas	7.78	5.81	13.47	0.13	0.17	0.13
Total	18.33	10.54	22.53	0.46	0.25	0.46

4 Kinematic GPS estimation of OTL displacement

Using the NASA GNSS-Inferred Positioning System (GIPSY) software in kinematic precise point positioning (PPP) mode, Penna et al. (2015) showed for sites in western Europe with at least 2.5 years of GPS data (4 years recommended), that vertical OTL displacements may be estimated with a precision of about 0.2-0.4 mm. We apply the same approach for GPS sites in the ECS region. In order to assess the accuracy and precision of the OTL displacements, particularly to check that the tuned coordinate and tropospheric delay process noise values for western Europe are applicable for the ECS region, we insert an artificial harmonic displacement per GPS site. We then assess how well it is recovered from the kinematic PPP GPS processing, as per Penna et al. (2015) but in the coordinate time series used for the final OTL displacement estimation rather than as a preliminary investigation step.

4.1 GPS data source

All available continuous GPS data in the ECS region were collated for the window 2013.0-2017.0, with the distribution of the 102 sites used shown in Figure 1. These comprised 96 sites from the GPS Earth Observation Network (GEONET), which all had at least 95% data availability throughout the 4-year window considered, and are located mainly on the Ryukyu Islands and Kyushu. We also collated data from six International GNSS Service (IGS) sites in China and Korea, although two sites (SHAO and YONS) only had 2.5 years of data. On the Ryukyu Islands and along the coast of Kyushu, the sites exhibit detectability ratios of greater than one, with the median value being 2.1, although close to the Seto Island Sea the ratio reduces to less than one. The data spans of at least 2.5 and typically 4 years are sufficient to separate the different major tidal constituents robustly according to the Rayleigh criterion.

4.2 Data analysis strategy

Full details of the GPS data processing strategy used are provided in Penna et al. (2015): in summary it is as follows. Daily, 30-hour, kinematic PPP GPS solutions were generated for each site using GIPSY version 6.4 software with Jet Propulsion Laboratory (JPL) reprocessed version 2.1 fiducial satellite orbits, Earth orientation parameters and 30 s satellite clocks held fixed in the IGb08 reference frame. A priori hydrostatic and wet zenith tropospheric delays from the European Centre for Medium-Range Weather Forecasts reanalysis product were used, with residual zenith tropospheric delays estimated every 5 min (applying a process noise of $0.1 \text{ mm}/\sqrt{s}$), together with north-south and east-west tropospheric gradients. The VMF1 gridded mapping function was used with an elevation cut-off angle of 10°, and corrections were applied for solid Earth and pole tides according to the IERS Conventions 2010 (Petit and Luzum, 2010), along with IGS satellite and receiver antenna phase centre variation corrections. Ambiguities were fixed to integers according to the approach of Bertiger et al. (2010). Receiver coordinates were estimated every 5 min, with a coordinate process noise of $3.2 \text{ mm}/\sqrt{s}$ applied. OTL displacement was modelled using the IERS Conventions (2010) hardisp routine, based on amplitudes and phase lags generated using the NLOADF software with the NAO99Jb model (augmented in the rest of the world with the FES2014b model) and a PREM elastic Green's function, computed in the centre of mass of the solid Earth and oceans (CM) frame to be compatible with the JPL orbits. In each daily solution, an artificial 13.96 hour harmonic signal of

3.0 mm amplitude was introduced in each of the east, north and vertical components, with the phase referenced to zero defined at GPS time frame epoch J2000, and hence the GPS harmonic estimation capability with the aforementioned GIPSY processing settings assessed. 13.96 hours was chosen as the period of this displacement following Penna et al. (2015), as it is approximately in the semi-diurnal band but is distinct from the main tidal harmonics so will not be contaminated by geophysical signals.

The estimated coordinates at 5 min resolution within the central 24 hours of the daily 30-hour kinematic PPP GPS solutions (which ran from 21:00 the previous day to 03:00 the next day) were averaged in non-overlapping, 30 min bins, then concatenated to form coordinate time series. Harmonic analysis was then undertaken using UTide to estimate the residual M_2 vertical OTL displacement signal per site, and also a 13.96 hour harmonic was estimated to assess how well the introduced 3.0 mm amplitude artificial signal could be recovered. The resulting UTide formal errors were 0.1-0.2 mm.

4.3 Results
The M_2 vertical OTL residual phasors extracted from the harmonic analysis are shown in Figure 4, as well as the artificial 13.96 hour harmonic signal residual phasors. It can be seen from Figure 4 that on the Ryukyu Islands and in the west coastal area of Kyushu the M_2 vertical OTL GPS-observed minus model discrepancies (residuals) can reach over 1.5 mm, corresponding to about 7% of the total loading signal. The typical magnitudes of phasor differences between the recovered and original artificial 13.96 hour harmonic signals are 0.2-0.3 mm, providing an indication of the accuracy level of our GPS-observed M_2 vertical OTL displacements, and indicating that the optimal process noise values found for western Europe by Penna et al. (2015) are also applicable to the ECS region. Since the ocean tide error of NAO99Jb maps to only an error of 0.2-0.5 mm for the predicted M_2 vertical OTL displacement values across the Ryukyu Islands and Kyushu (Figure 3b), it can be concluded that the 1.5 mm discrepancies must be dominated by errors in the elastic PREM Green's function.
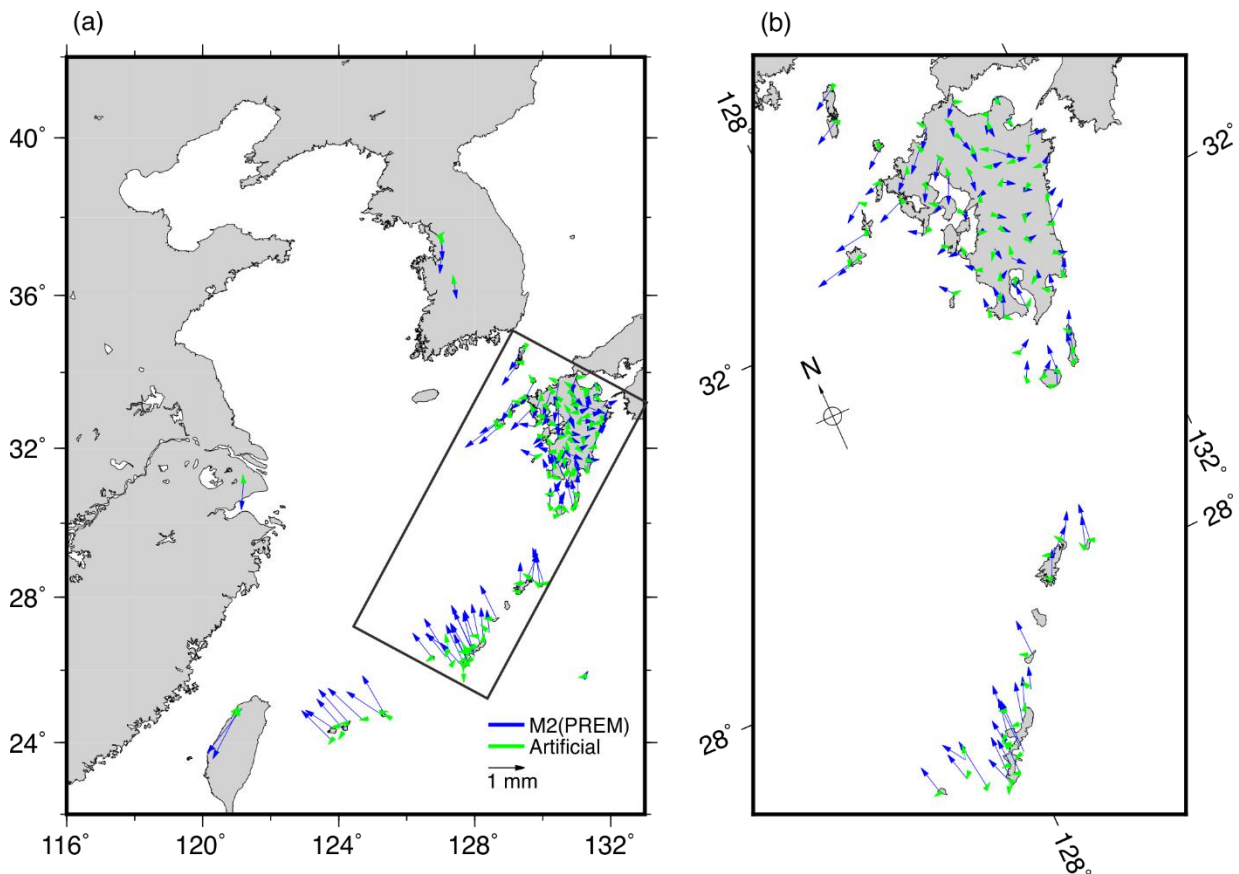
Figure 4 Phasor differences (in blue) between the GPS-observed M₂ vertical OTL displacements and the predictions computed using the NAO99Jb regional ocean tide model (augmented elsewhere globally with FES2014b) and an elastic PREM Green's function. Also shown (in green) are the phasor differences between the recovered and original artificial ~13.96 hour harmonic vertical displacement signal of 3.0 mm amplitude. **(a)** shows the whole ECS region, while **(b)** is an enlargement of Kyushu and part of the Ryukyu Islands, for the boxed region in (a).

5 Optimal Green's function for the East China Sea region

As Green's functions essentially depend on the material properties of the adopted Earth models, an~~the~~ improvement of the agreement between GPS-observed and predicted OTL values (reduction in the observational residuals) could be expected by modifying the Earth models~~se properties~~, and the representation ~~those~~ of the asthenosphere ha~~ve~~s been demonstrated to be especially important (Bos et al., 2015). So far we have used Green's functions computed from isotropic, purely elastic PREM, and we first consider whether the more recent elastic S362ANI Earth model (Kustowski et al., 2008), which is a transversely isotropic seismic tomographic model for the mantle, results in a reduction in the residuals. This model provides horizontal and vertical shear velocities (transversely isotropic) on a regular longitude/latitude grid for various depths. For each depth layer between longitudes 122° and 133° east and latitudes 23° and 35° north, we computed averaged shear velocities, which were used to compute the load Love numbers following Bos and Scherneck (2013), together with the density and compressional velocities of the STW105 model that was also developed by Kustowski et al. (2008). It can be seen from Table 4 that using the elastic S362ANI Green's function reduces the overall RMS of the residuals by about 0.1 mm compared to the elastic PREM Green's function (and similarly for the maximum and 90th percentile values), which could be explained by its use of the regional mean shear velocity.

We next considered whether using Green's functions with the anelastic dispersion effect in each of PREM and S362ANI results in reductions in the residuals. The elastic properties for these Earth models have been derived from seismic observations and are valid at the reference period of 1 s. To include the anelastic dispersion effect, the values of the shear modulus were converted from a period of 1 s to the period of the M_2 harmonic using the relation formula given by equation 9.66 in Dahlen and Tromp (1998) with a constant absorption band, as described by Bos et al. (2015). The bulk modulus has a much higher quality factor Q and is assumed not to be affected. After modifying the shear modulus, the load Love numbers were computed as described in Bos and Scherneck (2013), and the respective anelastic Green's functions will be hereafter referred to as PREM_M2 and S362ANI_M2. It can be seen from Table 4 that use of PREM_M2 and S362ANI_M2 reduces the overall RMS of the residuals from ~0.5 mm to ~0.4 mm. However, if only the GPS sites on the Ryukyu Islands are considered, the RMS residual is reduced from ~0.7 mm with elastic PREM and elastic S362ANI, to ~0.5 mm with PREM_M2 and to ~0.4 mm with S362ANI_M2. The respective 90th percentile residual values reduce from 1.3 mm with PREM to 0.9 mm with PREM_M2, and to ~0.7 mm with S362ANI_M2. This reduction across the Ryukyu Islands when using S362ANI_M2 instead of PREM can be clearly seen in Figure 5. However, one can observe that the residual phasors for S362ANI_M2 still show some correlations along the Ryukyu Islands, which might be due to the tectonic setting of the subduction zone.

As residuals at the ~0.7 mm level remain after accounting for anelasticity effects with the regional S362ANI_M2 model, we also test the optimality of the Green's function by computing a range of Green's functions based on different asthenosphere depths and values of Q. For the density and compressional velocity, S362ANI only provides global mean profiles. In our work, the asthenosphere is defined a priori to be between depths of 80 and 220 km with a Q of 70 as per Kustowski et al. (2008). Following a similar method to Bos et al. (2015), we vary the depths of the top (D1) and bottom (D2) of the asthenosphere of S362ANI, and the amount of anelastic dispersion (Q) in this layer. For each combination of these three parameters, a new Green's function was computed via the load Love number formulation. While computing the load Love numbers, we transformed the shear modulus from the reference period (1 s) to M_2 as described above. The Q value in the other layers is at least twice that of the asthenosphere so the frequency dependence will be smaller, but to be consistent the elastic properties were also transformed to the period of harmonic M_2. However, these Q values were not varied in our inversion. New Green's functions were then derived and used to predict the M_2 vertical OTL values using the NAO99Jb ocean tide model. This transformation produces complex-valued shear moduli and therefore complex-valued Green's functions but the imaginary part is less than 5% of the real part (Bos et al. 2015), and can be neglected. The optimal Green's function was considered to be that which minimised the sum of the squared misfits between the observed and predicted OTL phasor values using all the GPS sites. It was obtained when Q was 90 (corresponding to a reduction of the shear modulus of about 7.6% at the M_2 period), and the estimated values of D1 and D2 were 40 and 220 km, respectively, implying an asthenosphere extending to shallower depths than its original definition for this region in S362ANI. It can be seen from Table 4 that the residuals statistics with this mod_S362ANI_M2 Green's function are practically identical to that using S362ANI_M2 (and although not shown, very similar patterns for the residuals arise as in Figure 5), which confirms the large influence of the asthenosphere. In terms of practical usage for the region, S362ANI_M2 with its correction of S362ANI for anelastic dispersion provides a simple way to

improve predicted OTL displacements instead of performing the complex numerical optimisation scheme each time. As a further simple practical implementation for the region, the global PREM_M2 leads to almost comparable results as S362ANI_M2.

Table 4 Statistics (in mm) of the phasor differences between the GPS-observed and predicted M$_2$ vertical OTL displacements using the NAO99Jb regional ocean tide model (augmented elsewhere globally with FES2014b) and various Green's functions. 90th denotes the percentile.

Green's function	The whole ECS region				Ryukyu Islands			
	Min	Max	90th	RMS	Min	Max	90th	RMS
PREM	0.08	1.59	1.17	0.53	0.63	1.54	1.29	0.74
S362ANI	0.06	1.45	1.05	0.45	0.50	1.45	1.17	0.66
PREM_M2	0.10	1.12	0.86	0.41	0.25	1.12	0.89	0.47
S362ANI_M2	0.01	1.39	0.79	0.40	0.13	0.95	0.72	0.37
mod_S362ANI_M2	0.09	1.26	0.79	0.39	0.17	1.02	0.78	0.41
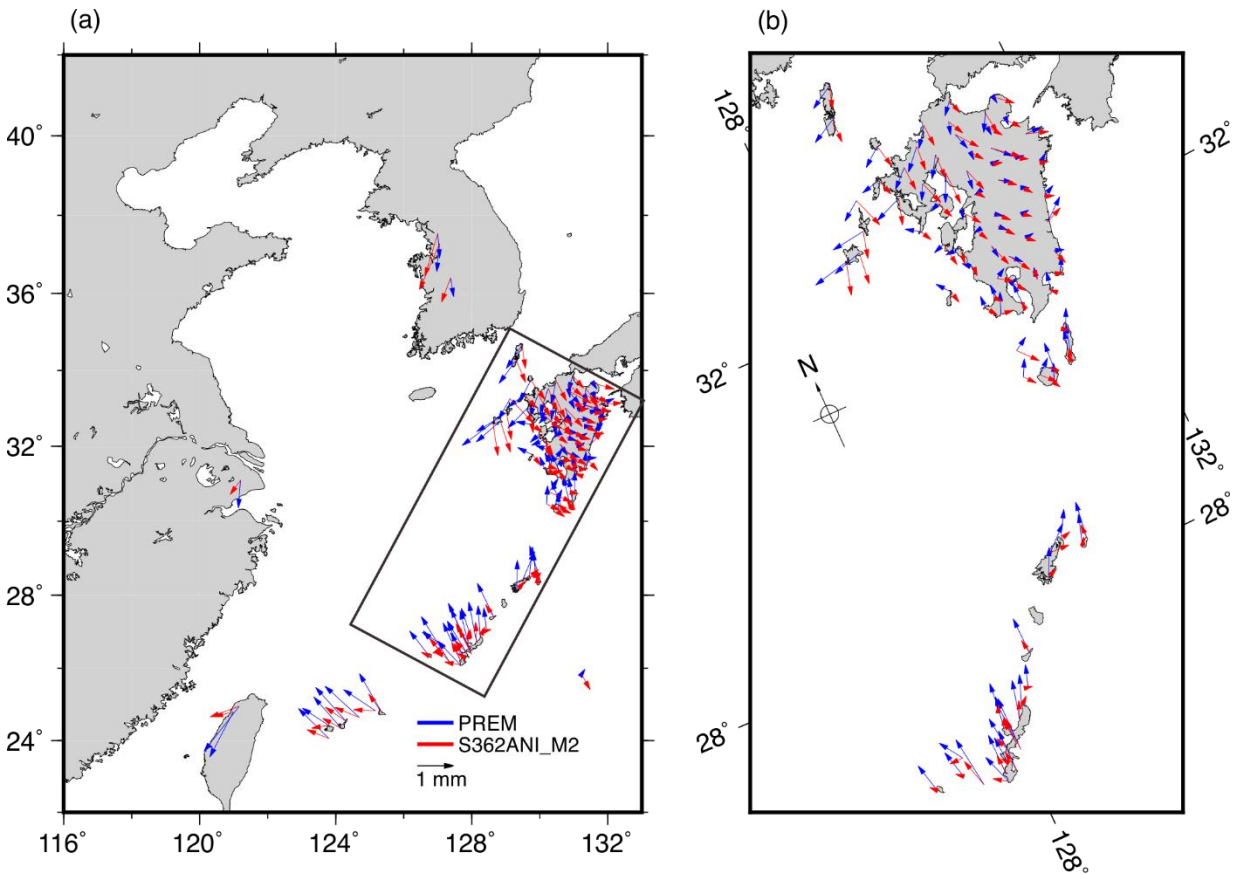
Figure 5 Phasor differences between our GPS-observed M$_2$ vertical OTL displacements and the predictions computed using the NAO99Jb regional ocean tide model (augmented elsewhere globally with FES2014b) and the elastic PREM (blue phasors) and ~~mod~~ S362ANI_M2 (red phasors) Green's functions. **(a)** shows the whole ECS region, while **(b)** is an enlargement of Kyushu and part of the Ryukyu Islands, for the boxed region in (a).

As a further check on the explanation of the observed and model discrepancies which we have attributed to asthenospheric anelasticity, we used the CARGA program (Bos and Baker, 2005) to compute the effect of varying sea water density on the M$_2$ vertical OTL displacements for the 102

GPS sites. First we computed the OTL displacements using a constant global density of sea water of 1030 kg m^{-3}. Then we recomputed the OTL displacements on inputting the spatially-varying (0.25°x0.25°) mean column sea water density from the World Ocean Atlas (Boyer et al., 2013), and found the mean change in M$_2$ vertical amplitude at our GPS sites was 0.03 mm (maximum difference of 0.16 mm). We then also corrected the mean sea water density per column for compressibility according to Ray (2013), and found that the mean change in M$_2$ vertical OTL displacement amplitude increased to 0.11 mm (maximum difference of 0.37 mm). Whilst such magnitude differences now have the potential to be detectable by geodetic observations, they are too small to explain our observed 1.5 mm discrepancies.

6 Conclusions

By introducing the detectability ratio for the asthenospheric anelasticity effects and considering the distribution of the available GPS sites, the ECS region was selected as a potential area to observe the anelastic dispersion in the asthenosphere. Using an inter-comparison of eight recent global (DTU10, EOT11a, FES2014b, GOT4.10c, HAMTIDE11a, NAO99b, OSU12, TPXO9-Atlas) and one regional (NAO99Jb) models and a validation with tide gauges, NAO99Jb has been demonstrated to be the most accurate tide model in the region. In the open sea areas NAO99Jb could be is slightly worse than the other ocean tide models, due to the assimilation of more satellite altimetry data in the latter, but this does not outweigh the benefits of forcing the NAO99Jb model to fit a large amount of tide gauge observations. We quantified the impact of the errors in NAO99Jb on the predicted OTL values, based on the RMS difference between NAO99Jb and the tide gauge observations. Compared to the approach of using the STD of predicted OTL displacements as the error contribution of the ocean tide models, this method can allow for systematic biases shared by the models, so the outputs are more conservativerealistic. For the GPS sites located in Japan, the errors in NAO99Jb result in M$_2$ vertical OTL displacement errors of 0.2-0.5 mm.

We then estimated the M$_2$ vertical OTL displacements for 102 sites around the ECS using GPS with typical accuracy of 0.2-0.3 mm. On the Ryukyu Islands and in the west coastal area of Kyushu, the discrepancies between GPS-observed and predicted values can reach over 1.5 mm (1.3 mm 90th percentile) when using the NAO99Jb tide model and the purely elastic PREM Green's function. However, tThe discrepancies cannot be explained by the sum of the remaining errors due to ocean tide models and the uncertainty in the GPS observations themselves, or by the small change in elastic parameters that results from using a regional average of the elastic S362ANI model in place of PREM. However, modelling of the anelastic dispersion effect using the Q values, which lowers the shear modulus by about 8% in the asthenosphere, reduces the 90th-percentile discrepancies to 0.9 mm and 0.7 mm for PREM and S362ANI respectively. Given that the observations are sensitive to the elastic properties of the asthenosphere, weWe estimated an regionally-optimal Green's function by varying the depth and thickness of the asthenosphere of the S362ANI Earth model and its Q values, but this resulted in essentially no further reduction in the discrepancies. which were used to model the anelastic dispersion effect during the computations. A reduction of about 7.6% of the shear modulus has been confirmed to produce the best agreement, which reduces the discrepancies to no more than 0.8 mm on the Ryukyu Islands, clearly demonstrating the importance of considering the anelastic properties of the asthenosphere.

This paper has confirmed the importance of considering the asthenospheric anelasticity effects observed by Bos et al. (2015). It is necessary to incorporate ~~the~~ dissipati~~on~~ve effects for the Green's functions based on seismic Earth models: use of elastic parameters at 1 s period is insufficient. The PREM_M2 Green's function is near-optimal for the ECS region and western Europe, and represents a sensible compromise with global applicability so is therefore a pragmatic choice for OTL prediction in geodetic analysis. For sites in areas where the detectability ratio exceeds one shown in Figure 1a, or where the highest accuracy is demanded, a regional anelastic Green's function calculated directly from a laterally-varying Earth model such as S362ANI should be considered.

Data availability. GPS data were obtained from the International GNSS Service (http://www.igs.org) and by request from the GPS Earth Observation Network (GEONET) of the Geospatial Information Authority of Japan (GSI) (http://datahouse1.gsi.go.jp/terras/terras_english.html). The ocean tide models used were those provided in the SPOTL software version 3.3.0.2 distribution (https://igppweb.ucsd.edu/~agnew/Spotl/spotlmain.html), except FES2014b was obtained from https://www.aviso.altimetry.fr/en/data/products/auxiliary-products/global-tide-fes.html, OSU12 from https://earthsciences.osu.edu/divisions/geodeticoceantides/OSU12v1.0/, TPXO9-Atlas from http://volkov.oce.orst.edu/tides/tpxo9_atlas.html, and GOT4.10c was provided by its author Richard Ray, NASA-Goddard Space Flight Center via personal communication. The Earth models were obtained from http://ds.iris.edu/ds/products/emc-referencemodels/, JPL orbits and clocks from ftp://sideshow.jpl.nasa.gov, tide gauge data from the Japan Oceanographic Data Centre (https://www.jodc.go.jp/jodcweb/) and the University of Hawaii Sea Level Center (https://uhslc.soest.hawaii.edu/).

Appendix A: Mass loading Green's function based on PREM

Here we list the Green's functions for the vertical (radial) and horizontal displacement based on the isotropic version of the Preliminary Reference Earth Model (PREM) used in this study. This is still one of the most-used Earth models for loading computations. The elastic properties have been derived from seismic observations and are valid at the reference period of 1 s. More details of the computations of the load Love numbers are presented by Bos and Scherneck (2013). To include the anelastic dispersion effect, the values of the shear modulus were converted to the period of M_2 with a constant absorption band assumed as described by Bos et al. (2015). The bulk modulus has a much higher quality factor Q and is assumed not to be affected. After modifying the shear modulus, the load Love numbers were computed in the same manner. The first column contains the angular distance between the point load and the station under interest. The second and third columns contain the scaled Green's functions for the vertical and horizontal displacement respectively for the purely elastic PREM. Columns four and five are the same as the previous two but for the one with the anelastic dispersion effect corrected (PREM_M2). Due to the smallness of the imaginary part of the Green's function of PREM_M2, we only list the real part. All the Green's functions are computed in the CM frame which has its origin at the centre of mass of the solid Earth plus ocean tides. To obtain Green's functions in the CE frame (origin at the centre of mass of the solid Earth alone), the quantity $a \cos\theta / m_E$ should be added to the radial Green's function u_r and $a \sin\theta / m_E$ subtracted from

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the horizontal Green's function u_θ, where a and m_E are respectively the mean radius and mass of the Earth.

5 **Table A1** Green's function per kilogram of mass load for the radial and horizontal displacements based on PREM with units of m/kg

θ (deg)	PREM		PREM_M2	
	$u_r \times 10^{12} (a\theta)$	$u_\theta \times 10^{12} (a\theta)$	$u_r \times 10^{12} (a\theta)$	$u_\theta \times 10^{12} (a\theta)$
0.0001	-42.174	-12.844	-42.532	-12.866
0.0010	-41.982	-12.844	-42.340	-12.866
0.0100	-40.081	-12.808	-40.432	-12.829
0.0200	-37.998	-12.699	-38.343	-12.720
0.0300	-35.965	-12.521	-36.303	-12.540
0.0400	-33.999	-12.280	-34.332	-12.297
0.0600	-30.335	-11.640	-30.661	-11.652
0.0800	-27.111	-10.853	-27.434	-10.860
0.1000	-24.375	-10.000	-24.700	-10.001
0.1600	-18.950	-7.662	-19.310	-7.655
0.2000	-17.100	-6.596	-17.499	-6.593
0.2500	-15.919	-5.832	-16.373	-5.843
0.3000	-15.379	-5.511	-15.889	-5.543
0.4000	-14.949	-5.483	-15.556	-5.566
0.5000	-14.676	-5.660	-15.351	-5.797
0.6000	-14.375	-5.798	-15.091	-5.981
0.8000	-13.691	-5.854	-14.420	-6.102
1.0000	-12.984	-5.729	-13.660	-5.997
1.2000	-12.298	-5.527	-12.890	-5.780
1.6000	-11.045	-5.065	-11.455	-5.229
2.0000	-9.967	-4.609	-10.229	-4.671
2.5000	-8.851	-4.088	-8.989	-4.050
3.0000	-7.959	-3.633	-8.025	-3.531
4.0000	-6.689	-2.905	-6.689	-2.748
5.0000	-5.895	-2.375	-5.874	-2.210
6.0000	-5.407	-1.991	-5.379	-1.832
7.0000	-5.115	-1.715	-5.084	-1.564
8.0000	-4.946	-1.515	-4.916	-1.375
9.0000	-4.854	-1.369	-4.826	-1.239
10.0000	-4.809	-1.258	-4.784	-1.138
12.0000	-4.791	-1.094	-4.772	-0.992
16.0000	-4.833	-0.820	-4.823	-0.749
20.0000	-4.851	-0.497	-4.844	-0.448
25.0000	-4.779	0.015	-4.771	0.049
30.0000	-4.587	0.645	-4.577	0.672
40.0000	-3.890	2.214	-3.875	2.235
50.0000	-2.928	4.049	-2.910	4.069

60.0000	-1.860	5.931	-1.840	5.951
70.0000	-0.753	7.661	-0.734	7.681
80.0000	0.395	9.103	0.411	9.120
90.0000	1.617	10.174	1.629	10.187
100.0000	2.949	10.831	2.955	10.837
110.0000	4.405	11.049	4.405	11.049
120.0000	5.977	10.816	5.970	10.811
130.0000	7.630	10.125	7.615	10.117
140.0000	9.306	8.974	9.284	8.964
150.0000	10.933	7.367	10.904	7.357
160.0000	12.428	5.318	12.394	5.310
170.0000	13.709	2.851	13.669	2.846
180.0000	14.696	0.000	14.653	0.000

Appendix B: Mass loading S362ANI Green's functions for the East China Sea

Here we list the Green's functions of the vertical (radial) and horizontal displacement based on the S362ANI Earth model of Kustowski et al. (2008). This model provides horizontal and vertical shear velocities (transversely isotropic) on a regular longitude/latitude grid for various depths. For each depth layer between longitudes 122° and 133° east and latitudes 23° and 35° north, we computed averaged shear velocities. Together with the density and compressional velocities of the STW105 model (Kustowski et al., 2008), this provides us enough information to compute load Love numbers. These load Love numbers were computed in the same manner as those for PREM in Appendix A. Columns 2 and 3 contain the Green's functions based on the elastic properties valid at 1 s. Columns 4 and 5 are based on the elastic properties converted to the period of harmonic M_2. For the Green's functions listed in columns 6 and 7 the depths of the top and bottom of the asthenosphere have also been changed to 40 and 220 km respectively while the quality factor Q has been increased to 90. Due to the smallness of the imaginary part of the Green's function, we only list the real part. Again, the Green's functions are given for the CM frame.

Table B1 Green's function per kilogram of mass load for the radial and horizontal displacements based on S362ANI, S362ANI_M2 and mod_S362ANI_M2 with units of m/kg

θ (deg)	S362ANI		S362ANI_M2		mod_S362ANI_M2	
	$u_r \times 10^{12}(a\theta)$	$u_\theta \times 10^{12}(a\theta)$	$u_r \times 10^{12}(a\theta)$	$u_\theta \times 10^{12}(a\theta)$	$u_r \times 10^{12}(a\theta)$	$u_\theta \times 10^{12}(a\theta)$
0.0001	-42.198	-12.851	-42.923	-12.894	-42.933	-12.897
0.0010	-42.013	-12.851	-42.736	-12.894	-42.748	-12.897
0.0100	-40.183	-12.818	-40.888	-12.860	-40.913	-12.863
0.0200	-38.182	-12.714	-38.868	-12.755	-38.907	-12.759
0.0300	-36.228	-12.543	-36.898	-12.582	-36.950	-12.588
0.0400	-34.341	-12.312	-34.995	-12.348	-35.060	-12.355
0.0600	-30.831	-11.699	-31.458	-11.726	-31.548	-11.739
0.0800	-27.748	-10.947	-28.356	-10.965	-28.469	-10.986
0.1000	-25.141	-10.134	-25.739	-10.144	-25.871	-10.173
0.1600	-20.004	-7.934	-20.615	-7.932	-20.782	-7.990
0.2000	-18.263	-6.955	-18.906	-6.959	-19.074	-7.036

0.2500	-17.141	-6.278	-17.830	-6.302	-17.977	-6.395
0.3000	-16.596	-6.014	-17.329	-6.065	-17.435	-6.162
0.4000	-16.053	-6.016	-16.852	-6.122	-16.846	-6.196
0.5000	-15.620	-6.155	-16.455	-6.311	-16.330	-6.327
0.6000	-15.158	-6.225	-16.002	-6.420	-15.780	-6.364
0.8000	-14.190	-6.126	-14.993	-6.367	-14.665	-6.178
1.0000	-13.259	-5.855	-13.967	-6.099	-13.630	-5.834
1.2000	-12.406	-5.529	-12.999	-5.746	-12.706	-5.460
1.6000	-10.952	-4.892	-11.319	-5.002	-11.157	-4.773
2.0000	-9.787	-4.343	-9.984	-4.337	-9.928	-4.202
2.5000	-8.643	-3.777	-8.708	-3.663	-8.727	-3.621
3.0000	-7.761	-3.318	-7.759	-3.140	-7.807	-3.152
4.0000	-6.547	-2.630	-6.502	-2.411	-6.551	-2.460
5.0000	-5.814	-2.158	-5.768	-1.949	-5.800	-1.993
6.0000	-5.375	-1.833	-5.335	-1.646	-5.354	-1.678
7.0000	-5.117	-1.609	-5.082	-1.443	-5.093	-1.465
8.0000	-4.970	-1.452	-4.939	-1.304	-4.946	-1.319
9.0000	-4.889	-1.338	-4.862	-1.207	-4.866	-1.216
10.0000	-4.848	-1.251	-4.825	-1.133	-4.828	-1.140
12.0000	-4.827	-1.114	-4.810	-1.019	-4.812	-1.022
16.0000	-4.854	-0.852	-4.845	-0.789	-4.845	-0.790
20.0000	-4.861	-0.523	-4.854	-0.481	-4.854	-0.481
25.0000	-4.782	-0.002	-4.775	0.027	-4.775	0.027
30.0000	-4.588	0.634	-4.579	0.656	-4.579	0.656
40.0000	-3.891	2.206	-3.879	2.224	-3.878	2.223
50.0000	-2.931	4.041	-2.916	4.059	-2.915	4.058
60.0000	-1.863	5.922	-1.847	5.942	-1.846	5.939
70.0000	-0.756	7.653	-0.741	7.672	-0.740	7.669
80.0000	0.392	9.095	0.405	9.112	0.406	9.108
90.0000	1.614	10.167	1.624	10.180	1.624	10.176
100.0000	2.945	10.824	2.950	10.831	2.950	10.827
110.0000	4.401	11.043	4.401	11.045	4.400	11.041
120.0000	5.973	10.811	5.967	10.808	5.965	10.804
130.0000	7.625	10.121	7.613	10.114	7.610	10.110
140.0000	9.301	8.970	9.283	8.962	9.279	8.959
150.0000	10.927	7.365	10.903	7.356	10.899	7.353
160.0000	12.422	5.316	12.393	5.310	12.388	5.308
170.0000	13.702	2.850	13.669	2.846	13.663	2.845
180.0000	14.688	0.000	14.653	0.000	14.646	0.000

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