Answers to reviews of paper "Brief Communication: The global signature of post-1900 land ice wastage on vertical land motion" by Riva et al. (2016), doi:10.5194/tc-2016-274.

We wish to thank the referees for their feedback on our manuscript.
Below we respond to each individual comments, where text by the referees is in bold.

On behalf of all authors,
Riccardo Riva

Referee #1 (Alvaro Santamaría-Gómez)

L21: "the century-long trend" in ice-mass loss . . . Also, a reference to the Fig. 1 (right) would be appropriate.

Done.
We have added "in ice-mass loss" and a reference to Fig.1

L26: "what is often not realized" by who? I believe is quite common to deal with solid Earth deformation due to loading at global scale.

We have changed the sentence into "what those communities often do not realize".
From experience, we have the feeling that outside the geodetic community, to which Reviewer 1 belongs and which routinely deals with loading effects, scientists are mostly aware of the near field effects.

L56: while the secular or mean VLM trends are probably indistinguishable in a CM or CE/CF frame, the interdecadal vertical deformation may be different depending on the chosen frame, which, in turn, may have an impact on the short-term trends shown in figs. 2 and 3. This is what happens with other loadings (atm, ocean and hydro) at the interannual variations leaving the long-term trend unchanged. Maybe it does not happen with the spatial pattern of the ice-mass unloading, so I suggest adding a sentence explaining why the CM frame was chosen and whether it has any impact on the results.

We carefully considered whether to present vertical deformation in the Centre-of-Mass of the Earth System (CM) of Centre-of-Figure of the Solid Earth (CF) frame, after having computing both.
What we found is actually the opposite of what has been sketched by the reviewer: secular VLM trends are largely affected by the choice in reference frame, especially in the far-field, while the difference between secular and decadal trends is mostly significant in the near field, which means it is roughly reference-frame independent.
From the point of GPS observations, it would have made sense to use the CF frame, since CM-CF motion is accounted for by the underlying global reference frame (albeit the reference frame realization introduces uncertainties of its own).
However, from the point of sea level research, we believe that it makes more sense to look at vertical land motion in the CM frame, since that is the most natural reference (the sea surface at rest follows the geoid, which is centered at the CM).
We have added an explanatory sentence to the text about why we chose the CM, but we deem the discussion of the impact of the reference frame choice on the modelled signal to be too technical, hence possibly confusing, for the broader TC audience.

Fig. 2: if the format of the communication allows it, I would suggest to add two more maps showing the rate differences between the maps a) and c) and a) and d). This would support the discussion of the results and also fig. 3.

We agree with the suggestion and we have added two panels to Fig.2, showing differences between the secular and the decadal trends. The practical need to use the same colour scale for all panels mostly highlights near-field differences, but it is luckily enough to highlight the larger mid-latitude trends in the last decade. This indeed supports the discussion of the time-variable trends in Fig.3, especially for New York, London and Sidney which experience a considerable acceleration in recent times.
We have added a brief discussion of the new panels while describing Fig.2 and a reference to them while discussing the right panel of Fig.3.

<u>Note: from this point on there seems to be an offset of 5 lines between the numbering used by the reviewer and the online version of the manuscript (e.g., L66 below should be line 71).</u>

L66: accuracy of both, the melt distribution and the regional mass loss values.

Agree, added "and the regional mass loss values".

L71:"most of Australia has been subsiding at rates larger than 0.4 mm/yr" this has been observed by GPS estimates since long ago without any plausible explanation thus far (see for instance Altamimi et al 2016). I suggest emphasizing this point.

We have added a sentence to highlight this issue, but we cannot accommodate the suggested reference due to limitations of the Bref Communication format.

L71: This is a very interesting spatial pattern in which northern TGs are uplifted faster in the last decade (captured by the GPS VLM corrections) compared to the last century, while southern TGs have subsided faster. This could partially explain the hemispheric difference in sea-level rise found by Wöppelamn et al. 2014. At the time that paper was published, this ice-mass loss fingerprint was unknown and it seems to me from your Fig. 2 that the average difference between the northern and southern TGs used by Wöppelman et al. 2014 could accommodate part of the hemispheric difference that was not explained by the uncertainties.

Wöppelmann et al. (2014) indeed found a hemispheric difference of about 0.9 mm/yr in sea level rise at GPS-corrected tide gauge stations, with larger values in the Northern Hemisphere. From the new panels of Figure 2 (e and f) it can be seen that GPS trends in the last 1-2 decades might overestimate the secular hemispheric difference by more than 0.4 mm/yr (e.g., by comparing New York with Hobart, which in the cited paper show trends close to the corresponding hemispheric means). Indeed, this could potentially explain a large part of the hemispheric difference discussed by Wöppelmann et al. (2014).
However, an exact estimate of this effect would require repeating their experiment by making use of all the 76 tide gauges used in that study. Hence, we have added a comment and the suggested reference in the discussion section (after line 122 in the original manuscript), but not given any hard number on the size of the bias potentially induced by non-linear VLM (simply referred to as "up to a few tenths of mm/yr").

L71: In relation to my comments above. Similar to the GIA effect on the deepening of the ocean basins and the resulting global mean sea-level change (of about 0.3 mm/yr), is there any ocean basin effect due to recent ice-mass loss to be accounted for in the sea-level trend?

This point is actually already discussed in the discussion section, at lines 123-126. The effect is about -0.1 mm/yr: noticeable, but within the uncertainty of global mean trends based on, e.g., satellite altimetry.

L89: The estimated changes in VLM rates appear to induce a periodic-like oscillation close to 60 years, especially in northern TGs close to the areas of ice-mass loss. Many of these TGs have very long records and were used to assess a global 60-year oscillation in sea-level by Chambers et al. 2012. I wonder how much of the observed 60-year oscillation is due to the ice-mass loss fingerprints shown here. A detailed analysis would be worth pursuing. A priori, the oscillation phase shown by Chambers et al. 2012 (Fig. 1) is consistent with your results.

We thank the reviewer for another suggestion about potential implications of our results. However, we find it difficult to assess the impact of the VLM variability on the results by Chambers et al. (2012), for at least two reasons: first of all, it is not possible to quantitatively compare VLM with relative sea level changes, since the latter also include the effect of ocean mass changes and geoid changes; secondly, the oscillation found by Chambers et al. (2012) is centered around a zero mean, while our rates remain positive or negative (depending on the hemisphere), since the net cryospheric contribution never changes sign.
Hence, while glacial fingerprints might have modulated long-term oscillations in regional sea level, we prefer not to comment on the issue, considering the impossibility to assess the size of this effect on the basis of VLM fingerprints alone.

L99-101: Note that we didn't correct or encouraged correcting for continental water mass loading due to the significant differences amongst the model outputs in terms of secular, as you mention in the next sentence, but also interannual deformation.

We have added that models outputs are also uncertain in terms of interannual signals.

L113: "those approaches are limited by the fact that space geodetic observations are only available since the 1990's". Note that there exist alternative approaches in combining satellite altimetry and tide gauge observations that benefit from the longer TG series, thus reducing this limitation (see for instance Kuo et al., 2004 and Santamaría-Gómez et al. 2014).

Thank you for those references, we have added a reference to Santamaría-Gómez et al. (2014) at line 117. Considering that, to our knowledge, those alternative techniques are not yet widely used, we have further edited the sentence at line 118 by writing "the majority of those approaches", instead of "those approaches".

L115-117: This is probably the biggest limitation of using GPS for correcting long TG records (together with the lack of nearby GPS observations), especially when very short GPS series are used. However, it is not a limitation exclusive of the GPS VLM corrections, but also when using GIA corrections which neglect any non-linear VLM in addition to any other linear VLM that is not GIA.

True. The fact that using GIA models to correct of VLM does not solve all problems has already been mentioned earlier in the same section. The fact that several processes can induce non-linear VLM has not been mentioned explicitly, simply because those processes are not the object of this study.

L117: In relation to my comment above. The average VLM for the last 10 years for the 6 TGs shown in Fig. 3, does not seem to lie far from the average VLM over the last century. It would be interesting to have some statistics of the VLM deviation during the GPS era or the additional maps I suggested above.

We have decided to add two panel to Figure 2, as earlier suggested by the same reviewer. The new plots show that the non-linearity effect in the far-field, where all 6 cities are located, is mostly visible during the last decade.
At line 122 we have added "especially if the observations have been collected during the last decade".

L140: This is an interesting perspective, but one also needs to consider the uncertainties in the ice-mass loss fingerprints, which were not discussed in this brief communication. In addition, even after correcting for this effect, the VLM corrections (from GPS or GIA) will still be considered linear as a working hypothesis even if we have clues that they may not be (due to pole motion deformation, hydrologic loading, long-memory noise, etc.).

Indeed, we have not directly assessed uncertainties in the ice mass loss fingerprints, even though those are part of the previous study by Frederikse et al. (2016), on which the fingerprints are based. It is also true that many other unmodelled processes might induce non-linear motions. Nonetheless, it seems reasonable to assume that VLM induced by ice melt currently represents the largest signal at regional scales, and as such should be modelled as well as possible.
We have rephrased the last sentence, which now reads: "In particular, due to the recent acceleration in land ice melt, which represents one of the largest drivers of regional vertical land motion, the estimation of secular rates from GPS observations should account for the effect of glacial mass change".

Technical corrections:
L28: "position of every other point on the Earth's surface" with respect to the Earth's center of mass.

Actually, changes in surface load will always change the 3D position of every other point at the Earth's surface, while fixing a certain reference frame will determine the size and direction of that change. Considering that our statement is only qualitative, we don't see the need for specifying a reference frame. We have considered adding "with respect to their initial position", but that seemed implicit in the wording "change the position".

L48: "cumulative mass loss" should be "equivalent sea-level change" or "barystatic sea-level change".

Agree, we now write "equivalent sea-level change".

L121: "induce" I would suggest "reveal" here

We agree that "induce a bias" is possibly not the best phrasing and decided to change it into "cause a bias".

Referee #2

Abstract. “Deformation” should be replaced by “vertical displacement” here and in the rest of the paper. They are used as synonyms but they are not, in my opinion.

We agree that the two words are not synonyms, with “displacement” being a purely kinematic concept especially valid when talking pointwise (displacement is a change in the position of a point or of all points of a rigid object), while “deformation” better refers to the relative motion between sets of points (with the more general meaning of “change of shape”). Hence, we argue that it is appropriate to talk about “GPS measuring displacement” and “ice melt causing deformation”. As such, we would rather keep using both words, though we have made an additional effort to use each of them consistently through the paper.

Line 23. Another less obvious effect that could be mentioned is the variation of gravitational potential \Phi that together with U give relative sea-level change according to the sea-level equation S=\Phi/\gamma + c -U where c is the notorious c-constant.

True, but maybe confusing, since the paper expressly only deals with vertical land motion.

L26. I think this is realised, indeed, also in the cryospheric community.

We are not sure whether the reviewer expects us to remove the sentence, or agrees with our viewpoint. In any case, we admit that it is difficult to quantify which portion of a community is aware of a specific concept. That is why we have originally opted for the wording “what is often not realised”, which we believe we can defend based on our personal experience.

L28. Actually the SLE is more general and can also deal with the viscoelastic Earth’s response.

True. Even though this paper only deals with elastic deformation, it is a good idea to have statements of more general validity in the introduction. We have changed “elastic” into “viscoelastic”.

L30. In this brief communication. . . From what I have understood, the novelty here is the long time window considered (1900-now) for the computation of the elastic displacement, and the use of realistic ice sources.

Indeed. We now mention the long time window and of the use of realistic ice sources as an additional innovation of this study.

L40. Quantification is not so problematic if the melting histories are well constrained.

We did mean an accurate quantification of the melting histories. We now specify it.

L58. Adding the individual responses to obtain the total response is OK if you assume linearity. An indeed the SLE is linear as long as you do not allow for shoreline migration. But I guess that here the shorelines do not move.

Indeed. We have added a sentence explaining that our superimposition approach is allowed by the fact that the SLE is linear since we make use of fixed coastlines.

L58. Compressible is OK. But I imagine also layered and consistent with the seismic travel times.

Indeed. We now write “compressible and spherically layered”. Consistency with seismic travel times is, to our knowledge, standard practice.

L59. ‘period of interest’ is vague. From the figures I see different rates at different times, that appears to contradict the use of a unique linear trend.

We meant to refer to the various time windows shown in Fig.2. We now say “over each time window under study”.

L65ff. It can be worth to recall that these fingerprints have a vanishing global average.

We are afraid that such a statement will be obvious to people familiar with spherical harmonics, but confusing to many other potential readers. In addition, when sampled at discrete points (e.g., GPS stations or tide gauges) these fingerprints will probably still lead to non-zero global mean values due network geometry issues. Hence, we prefer not to add the suggested comment.

L68. I am not sure that ‘pole tide’ is appropriate. From e.g., http://www.navipedia.net/index.php/Pole_Tide I understand that the pole tide is related with the 14-months Chandler Wobble, which I am sure the authors have filtered out from their equations. What causes the lobes in the far field in the vertical displacements maps is the (non-oscillatory) secular component of polar motion.

We are sure that the terminology “solid earth pole tide” is appropriate. In the given link, the Chandler Wobble is only provided as an example. The term is mostly used within the geodetic community, that’s why we had only mentioned it within brackets.
Nonetheless, we have removed the word “pole tide”, since we reckon that the terminology may be misleading (the pole tide is not a “regular” tide, in the sense that it originates from Earth’s rotation instead of from gravitational attraction by external bodies).
As a consequence, at line 112 we now write “earth rotational effects” instead of “pole tide”.

L68ff. Where are these max values met?

These max values are met over Greenland, we now specify this in the manuscript.

L76. . . Has been subsiding. . . well, the actual subsidence stems from this component plus GIA, etc. etc

True. We thought this was implicit, but it may be better to specify it once more. We have added “because of contemporary ice mass change”.

L85. Ditto. See L76. These subsidences are virtual, they only represent one component of total subsidence, and probably not the largest one.

Same as above. We now specify “due to continental ice mass loss, cities...”.

L84. Vertical displacement has certainly an effect on tide gauge. But also N =\Phi/\gamma + c has one. Is this negligible? Has this been computed? In a more in-depth study I recommend to show both S and N along with U, for the same sources considered in this study.

We acknowledge that, especially in the far-field, geoid changes and global mean mass changes can be as important as vertical land motion. However, those signals are a part of the tide gauge observations that researchers want to preserve. It is vertical land motion that often represents a nuisance signal, which is the reason why we have decided to make it the object of the current study.

L111. The coseismic displacement can be also modelled globally (see http://onlinelibrary.wiley.com/doi/10.1029/2003GL019347/full).

We have added the suggested reference to Melini et al. (2004).

L112. What is the signal identified therein? Unclear. Is the rate of solar motion driven by the ice sources considered? What is its amplitude and direction?

Indeed, we do not specifically quantify the size and direction of the pole tide (now "earth rotational effects") driven by ice mass loss, because it is beyond the scope of this study.
We have clarified the sentence, which now reads "meaning that the decadal and secular signals contributing to vertical land motion as identified in this study are not considered".

L130. I do not understand why the 'far field signature' is mentioned here. Viscosity also controls deformation in the near field.

The far-field signature is the main object of this study. Instead of "controlled by bulk viscosity values" we now say "controlled by viscoelastic relaxation mostly taking place deep in the mantle". We agree that also the near field is controlled by viscosity, but near field relaxation is more sensitive to shallow mantle regions, where viscosity values could be much lower and provide significant responses even at decadal scales.

See http://journals.fcla.edu/jcr/article/view/80095/77355 for advice on how hyphenate "sea level".

Thank you for the reference, we have harmonized hyphenation of "sea level".

Brief Communication: The global signature of post-1900 land ice wastage on vertical land motion

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Abstract. Melting glaciers, ice caps and ice sheets have made an important contribution to sea-level rise through the last century. Self-attraction and loading effects driven by shrinking ice masses cause a spatially-varying redistribution of ocean waters that affects reconstructions of past sea level from sparse observations. We model the solid Earth response to ice mass changes and find significant vertical deformation signals over large continental areas. We show how deformation rates have been strongly varying through the last century, which implies that they should be properly modelled before interpreting and extrapolating recent observations of vertical land motion and sea-level change.

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1 Introduction

The amount of ice stored on land has strongly declined during the 20th century, and melt rates showed a significant acceleration over the last two decades. Land ice wastage is well known to be one of the main drivers of global mean sea-level rise, as widely discussed in the literature and reflected in the last assessment report of the IPCC (Church et al., 2013). They show that the century-long trend in ice-mass loss is mainly due to melting mountain glaciers (Fig.1, right panel), while the recent acceleration is mostly driven by increased mass loss from the Greenland and the Antarctic ice sheets.

A less obvious effect of melting land ice is the response of the solid Earth to mass redistribution on its surface, which, in the first approximation, results in land uplift where the load reduces (e.g., close to the meltwater sources) and land subsidence where the load increases (e.g., under the rising oceans). This effect is nowadays well known within the cryospheric and sea-level communities (Watson et al., 2015). However, what those communities often do not realize is that the solid Earth response is a truly global effect: a localized mass change does cause a large deformation signal in its proximity, but also causes a change of the position of every other point on the Earth's surface. The theory of the Earth's visco-elastic response to changing surface loads forms the basis of the 'sea-level equation' (Farrell and Clark, 1976), which allows sea-level fingerprints of continental mass change to be computed.

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In this brief communication, we provide the first dedicated analysis of century-long global vertical land motion driven by land ice wastage and based on realistic ice sources. By means of established techniques to compute the solid Earth elastic response to surface load changes and the most recent datasets of glacier and ice sheet mass change, we show that land ice loss currently leads to vertical deformation rates of several tenths of mm per year at mid-latitudes, especially over the Northern Hemisphere where most sources are located. In combination with the improved accuracy of space geodetic techniques (e.g., Global Navigation Satellite Systems), this means that the effect of ice melt is non-negligible over a large part of the continents. In particular, we show how the recent acceleration in melt rates affects estimates of secular vertical land motion, and therewith has an impact on various geodetic applications, including estimates of long-term sea-level rise at tide gauges. While elastic deformation of the Earth has been widely considered due to especially atmospheric loading changes, the effects of ice loading changes have been largely ignored, due to the difficulty of an accurate quantification of the melting histories (Santamaria-Gomez and Memin, 2015).

2 Datasets and methods

As in Frederikse et al. (2016), we consider yearly mass losses from glaciers and ice caps and the Greenland and Antarctic ice sheets. For glacier mass loss, the recent estimate of Marzeion et al. (2015) is used. For the Greenland ice sheet during the period 1902-1992 we use data from Kjeldsen et al. (2016). Between years 1993-2014, we use an input-output approach for both Greenland and Antarctica: input is based on the modelled RACMO2.3 surface mass balance (Van den Broeke et al., 2016); Greenland ice discharge is also based on van den Broeke et al. (2016). For Antarctica, the ice discharge is parametrized as a constant acceleration of 2.0 Gt/y^2, starting from equilibrium between 1979-1992, which gives a good fit with IMBIE estimates (Shepherd et al., 2012). Figure 1 shows the location of the glaciers and ice sheets on which our mass balance estimates are based, together with the equivalent sea-level change of the individual iced regions. The glacier mass loss is regionalized following the regions described in Pfeffer et al. (2014). For both ice sheets, the spatial distribution of the mass change is based on linear trends obtained from GRACE JPL mascon solutions (Watkins et al., 2015), scaled to match the estimated total mass loss (Frederikse et al., 2016). Note that this approach will bias the resulting fingerprints towards post-2002 values (e.g., the signal over the Antarctic Peninsula contains the signature of the glacier acceleration following the 2002 Larsen B ice shelf breakup), but with a limited effect on the far-field signal.

We determine the solid Earth elastic response by solving the sea-level equation (Farrell and Clark, 1976) for each load at each year and add them together to obtain the total response, where superimposition is allowed by the linearity of the sea-level equation under the assumption of fixed coastlines. We follow a pseudo-spectral approach (Tamisiea et al., 2010) in the centre-of-mass of the Earth sytem (CM), solved up to spherical harmonic degree 360 for a compressible and spherically-layered earth, including the effect of induced changes in the Earth's rotation. We then estimate a linear trend through the resulting vertical land motion time series, over each time-window under study, by means of ordinary least squares. We have chosen to solve the sea-level equation in the centre-of-mass of the Earth sytem (CM) frame, since this is the natural reference for sea-level observations (the sea surface at rest follows the geoid, which is centred at the CM).

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3 Results

Global maps of vertical deformation rates are shown in Figure 2 for different time spans. In all panels, the largest values are reached at the location of the melt sources, while the far-field negative deformation is shaped by the change in the position of the Earth rotation axis.

The near-field deformation rates are dominated by the direct effect of the individual melt sources. The maximum uplift rates are reached over Greenland and range from about 4 mm/yr (panel a) to 11 mm/yr (panel d), though the exact values are dependent on the model resolution (0.5 degrees), and by the accuracy of the melt distribution and of the regional mass loss values.

In the far field, here loosely defined as regions located several hundred kilometers away from any region of ice mass loss and characterized by small gradients in vertical deformation rates, maximum uplift rates have increased from less than 0.6 mm/yr over the last century to about 1.0 mm/yr during the last decade. Larger rates are combined with a southward shift of the 0.4 mm/yr contour, which has moved over North America from South of Hudson Bay to about Washington D.C., and over Europe from Denmark to Northern Italy. During the last decade, most of Australia has been subsiding because of contemporary ice mass change at rates larger than 0.4 mm/yr, consistent with GPS estimates. Interestingly, the far-field deformation pattern in Central Asia is not very different through the century, being dominated by the relatively constant effect of glacier mass loss on and around the Tibetan Plateau. The increased deformation rates during the satellite era are highlighted in the bottom panels of Figure 2, showing the difference between the last decades and the long-term average: as already pointed out about Figure 1, most of the differences originate from the two ice sheets.

In order to better show the temporal evolution of vertical land motion through the last century, in Figure 3 we display time series of the signal and of its time derivative for six major cities worldwide. Note that deformation rates have been computed after using a 15-year moving average. We have specifically chosen coastal cities because they are representative of the far-field deformation over large portions of the continents, due to the smoothness of the signal, but also because vertical land motion has a direct effect on sea-level change and on tide gauge measurements of that change.

In the course of the 113 years covered by this study, due to continental ice mass loss alone, cities in the Northern Hemisphere have accumulated several centimeters of uplift (2.8 cm for New York, 3.9 cm for London, and 5.0 cm for Seattle), while cities in the Southern Hemisphere have subsided (Rio by 1.0 cm, Sydney by 3.4 cm). At lower latitudes the signal is smaller, e.g. Shanghai has been uplifted by 1.0 cm. These changes are in addition to vertical land motion due to other processes.

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The vertical motion has not been constant in time, following temporal variations in ice mass loss rates. In particular, rates were lower at the beginning of the last century and in the 1970's, while a clear acceleration can be seen during the last 20 years, when the ice sheets contribution has increased (bottom panels of Figure 2). Interestingly, the recent high rates are not exceptional at all locations, depending on the relative distance from specific glaciers and the two ice sheets. For example, in Seattle rates above 0.6 mm/yr have already been reached in the 1930's, while in London the recent rates of about 0.5 mm/yr are lower than those experienced in the 1930's. The increased contribution of the ice sheets can also lead to a reduction in the local deformation rates; this is the case for Shanghai, which is currently experiencing very little vertical motion associated with ice melt, due to its location on the transition line between uplift driven by northern sources and subsidence enhanced by the small recent mass gain in East Antarctica.

4 Discussion

Long-term vertical land motion in the near-field is dominated by the effect of ice loss, which allows geodetic observations to be used to quantify ice mass change (e.g., Bevis et al., 2012) or to separate the effect of present-day mass loss from the signature of glacial isostatic adjustment (GIA) (e.g., Kahn et al., 2016).

In the far field, several competing processes can lead to inter-annual vertical deformation rates at the millimeter-per-year level. For this reason, geodetic observations are usually corrected for the effect of a number of loading processes related to water mass redistribution, such as changes in atmospheric pressure, land hydrology and ocean mass (Santamaria-Gomez and Memin, 2015). This approach is problematic when studying the effect of climate change, since current models of the water cycle are not accurate in terms of inter-annual and secular variations, which are orders of magnitude smaller than those driven by the seasonal cycle.

The remaining signal is usually attributed to geodynamic processes (e.g., GIA, earthquakes, volcanoes, landslides) or to local effects, either of natural (e.g., ground compaction, sediment transport) or of anthropogenic origin (e.g., groundwater and hydrocarbons extraction, dam building). Of all those processes, only GIA (e.g., Peltier et al., 2015) and coseismic deformation (Melini et al., 2004) can currently be modeled globally, albeit with large uncertainties. While Earth rotational effects are modelled in geodetic data analysis, those are entirely limited to quasi-annual variations (King and Watson, 2014) meaning that the decadal and secular signals contributing to vertical land motion as identified in this study are not considered.

The general approach in sea-level studies until early 2000's has been to neglect any non-GIA signal, meaning that sea-level estimates based on tide gauges have been potentially biased by several tenths of a millimeter per year, as recently discussed by Hamlington et al. (2016). More recently, estimates of vertical land motion have been obtained by the combination of observations from satellite altimetry and tide gauges (Nerem and Mitchum, 2002) or by direct observations by means of GPS (e.g., Santamaría-Gómez et al., 2014; Woppelmann and Marcos, 2016). However, the majority of those approaches are limited by the fact that space geodetic observations are only available since the 1990's, when the effect of ice wastage has been considerably larger than during the rest of the 20th century (Fig. 2c vs. Fig. 2b). The assumption of constant rates

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throughout the century means that significant errors in sea-level reconstructions based on tide gauge records will still be present, even after correcting for vertical land motion as observed by GPS, especially if the observations have been collected during the last decade. For example, the dominantly positive rates in the Northern Hemisphere could explain up to a few tenths of mm/yr of the hemispheric difference in sea-level rise found by Wöppelmann et al. (2014).

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Global vertical land motion is also changing the shape of the ocean basins (Fig.2), which causes a bias in sea-level change estimates based on satellite altimetry. However, during 1993-2014, this effect is less than -0.11 mm/yr over the global ocean (-0.07 mm/yr between +/- 66 degrees latitude), largely within the uncertainty of space-based estimates of global mean sea-level change. Additionally, the vertical land motion discussed in the GPS context could induce an additional bias in altimetry estimates, due to the use of tide gauges to determine altimeter drift (Watson et al., 2015).

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It is worth noticing that we have modelled the Earth's elastic deformation, but neglected the viscoelastic response of the mantle (Farrell and Clark, 1976; Peltier et al., 2015); however, the far-field signature of relaxation is controlled by viscoelastic relaxation mostly taking place deep in the mantle, which is expected to provide a significant response at time scales much longer than those covered by this study.

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Considering the recent improvement in mass loss reconstructions of glaciers and ice caps (Marzeion et al., 2015) and ice sheet (Shepherd et al., 2012) mass loss, even though the 20th century contribution of Antarctica is still poorly understood, we advocate direct modelling of the effect of time-varying ice wastage as a way to improve the accuracy of sea-level change estimates (Frederikse et al., 2016).

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5 Conclusions

We have shown how land ice wastage through the last century has caused vertical land motion in the order of several tenths of mm per year over large parts of the continents. Deformation rates are highly non-linear and location dependent, with larger values between 1930-1950, minima around 1970 and a clear acceleration during the last two decades.

This effect is particularly important in the context of sea-level studies, since several of the longest tide gauge records are at mid-latitudes in the Northern Hemisphere, where the effect of melt of Arctic glaciers and the Greenland ice sheet is large, as also discussed by Thompson et al. (2016).

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In particular, due to the recent acceleration in land ice melt, which represents one of the largest drivers of regional vertical land motion, the estimation of secular rates from GPS observations should account for the effect of glacial mass change.

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Data policy

The data used to generate Fig.2 and Fig.3, in the form of NetCDF files containing gridded values of annual vertical deformation, are freely available through the 4TU.Centre for Research Data at https://data.4tu.nl/repository/uuid:fb667e7a-52f3-4876-8cab-ae7a2ddaf0db. For the data used to generate Fig.1, we refer to the original papers.

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Author contribution

REMR and TF designed the study; TF performed the computations and produced the figures; REMR wrote the paper; MAK contributed to the analysis of the results; BM provided glacier mass balance data; MvdB provided ice sheet SMB data; all authors commented on the manuscript.

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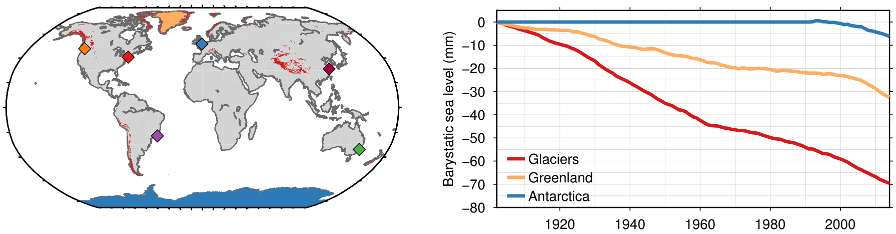

Figure 1: Left: Land ice regions considered in this study (red, glaciers; orange, Greenland; blue, Antarctica), with colored diamonds representing the coastal cities of Fig.3. Right: global mean sea level contribution of ice wastage between years 1902-2014.

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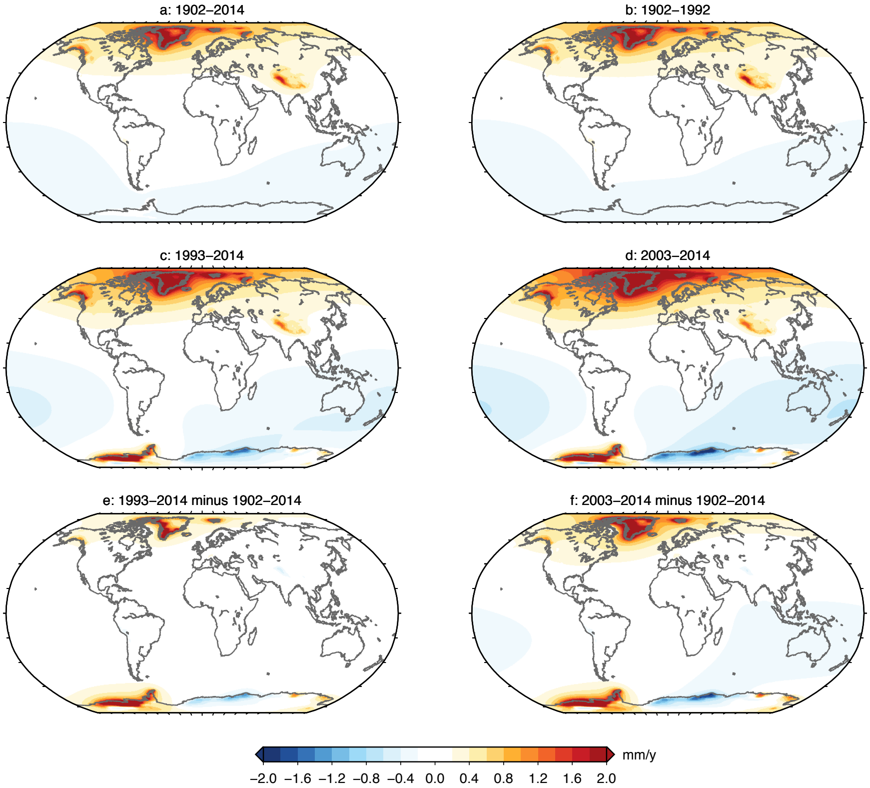

Figure 2: Maps of average vertical deformation rates over different time spans. a: full time span covered by this study; b: pre-satellite era; c: the GPS era; d: the GRACE era; e: panels c - a; f: panels d - a.

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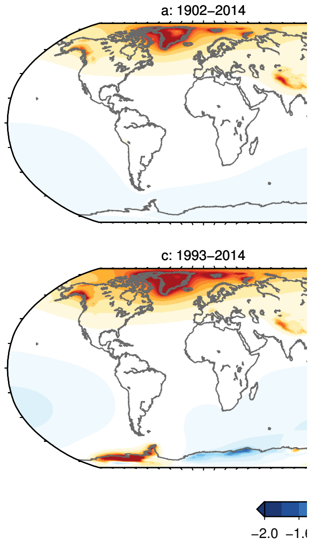

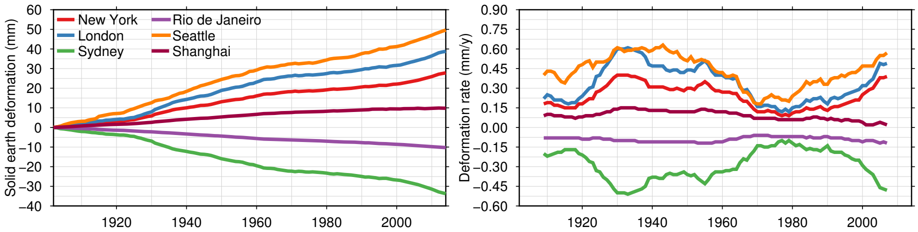

Figure 3: Time series of vertical deformation (left panel) and 15-year-average rates (right panel) at selected coastal cities due to global ice mass changes. The locations of the cities are indicated by diamonds in Fig.1a, following the same color-coding.