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EXPRESS LETTER

Geodetic vertical velocities affected by recent rapid changes in polar motion

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SUMMARY

Secular motion of Earth's rotation pole results in large-scale secular deformation of Earth. Here, we investigate the magnitude of the deformation that has resulted from the rapid motion of the rotation pole to the east since ∼2005. We show that geodetic (GNSS, DORIS, VLBI and SLR) estimates of vertical velocity since ∼2005 have been biased by up to ±0.38 mm yr^{-1} relative to the longer-term deformation pattern. The largest signals occur within regions that include the U.S. Pacific Coast, Europe and South Pacific islands where geodetic measurements provide essential measurements of tide-gauge vertical movement and important constraints on models of glacial isostatic adjustment. Consequently, geodetic vertical velocities based on recent data should not be interpreted as being identical to centennial or longer term vertical land movement. Since 2010 the effect is further amplified by the overprediction of the IERS polar motion model relative to the ongoing secular change in pole position—during this time geodetic vertical velocities based on the IERS pole tide model are not just biased relative to the long-term rates but also from actual post-2010 Earth deformation. For geophysical or reference frame studies seeking geodetic vertical velocities that are representative of decadal timescales, where interannual variation is considered noise, the correction for this non-linear effect is straightforward, requiring an elastic computation using a reference rate of polar motion that is linear over the timescales of interest.

Key words: Reference systems; Sea level change; Space geodetic surveys; Earth rotation variations; Dynamics of lithosphere and mantle.

1 INTRODUCTION

Geodetic data sets are now routinely used to determine site velocities which are commonly interpreted as representing deformation over much longer time periods than covered by the data. This is particularly the case with vertical land movement, where inferences of vertical velocities from data as short as a few years are used to either test or constrain geophysical models that capture processes occurring over centuries or longer. For instance, geodetic vertical velocities are now widely used to test or constrain models of the ongoing deformation of Earth associated with the demise of the Late Pleistocene ice sheets (e.g. Milne *et al.* 2001; Argus & Peltier 2010; Whitehouse *et al.* 2012; Ivins *et al.* 2013). Other examples include the extrapolation of vertical land movement at tide gauges to centennial timescales (e.g. Wöppelmann *et al.* 2009; Santamaria-Gomez *et al.* 2012) or separation of multiple superimposed long-term geophysical signals, including those of tectonic origin (e.g. Serpelloni *et al.* 2013). In all cases, the study of these processes assumes geodetic velocities are not substantially affected by measurement error or geophysical signal operating over shorter timescales. To facilitate such measurements, the Global Geodetic Observing System has a goal of a global reference frame accurate to 0.1 mm yr^{-1} (Gross *et al.* 2009).

One source of deformation that could exceed this magnitude over interannual or longer timescales is deformation driven by shifts in Earth's rotation pole relative to the mean lithosphere (see also Argus & Gross 2004). Such movement occurs at periods ranging from subdaily to millennial, including the well-known tidal, annual and Chandler (∼433 d) signals (Gross 2007) and results in deformation of Earth that has a dominant spatial pattern well characterized by a spherical harmonic expansion of degree 2, order 1 (Wahr 1985).

Within geodetic analyses, deformation related to short-term polar motion is corrected using the International Earth Rotation Service's (IERS) elastic 'pole tide' model (Petit & Luzum 2010), based on the theory of Wahr (1985), with the aim of attenuating high-frequency (>∼0.5 cycles yr^{-1}) signal and leaving lower-frequency Earth deformation within the geodetic position time-series.

Recently, Chen *et al.* (2013) reported that the direction of motion of Earth's rotation pole began to shift rapidly towards the east around 2005 (more precisely, drifting along the 16°W meridian instead of the 82°W meridian, as was the case before ∼2005), largely as a result of increased ice sheet melting in Greenland. Smaller deviations have also been reported to have occurred in the early 1990s (Roy & Peltier 2011). By convention, the deformation associated with such deviations in polar motion from its longer-term path is not corrected through the pole tide model which addresses only periodic deviation away from a time variable reference pole position. Here we show that this recent anomalous polar motion has occurred sufficiently quickly to non-negligibly bias vertical velocities from longer-term values, influence reference frame parameters and add time-correlated noise to time-series of vertical coordinates.

2 DATA AND MODELLING

The daily International Earth Rotation Service (IERS) C04 polar motion time-series is shown in grey in Figs 1(a) and (b) for the x- and y-poles respectively, for the period 1980 to early 2014. We adopt the C04 product as it is presently a few months more up-to-date than C01 at http://datacenter.iers.org; over their common period, the two differ by negligible amounts for our purposes (1–2 mas *SD* with no trend). Polar motion time-series, as seen in Fig. 1, are dominated by signal at annual and Chandler periods. Changes in polar motion over long timescales result in viscoelastic deformation (Han & Wahr 1989), although over years to decades the viscous component is negligible and elastic deformation dominates (Wahr 1985). These deformations may be measured through geodetic GNSS, DORIS, VLBI and SLR observations, with the IERS 2010 Conventions (Petit & Luzum 2010) giving the radial deformation component (S_{r}) as:

$$S_r = -33 \sin(2 * \mathrm{lat}) * [m_1 \cos(\mathrm{lon}) + m_2 \sin(\mathrm{lon})] \qquad (1)$$

in units of mm, where m_1 and m_2 are the observed pole positions x_p, y_p (in units of arcsec), respectively, relative to a reference pole time-series ($\bar{x}_p$, $\bar{y}_p$), such that:

$$m_1 = x_p - \bar{x}_p, \quad m_2 = -(y_p - \bar{y}_p). \qquad (2)$$

The radial component of deformation is two to three times larger than the horizontal deformations, and here we focus only on the radial component.

It is important to note that this pole tide modelling requires the definition of $\bar{x}_p$, $\bar{y}_p$, and it is only the anomalies to this reference pole time-series that are included within the elastic model. As such, the choice of $\bar{x}_p$, $\bar{y}_p$ influences the deformation patterns that remain within the coordinate time-series after the elastic model is subtracted.

Today, $\bar{x}_p$, $\bar{y}_p$ of the IERS 2010 Conventions are universally adopted in geodetic positioning. These are based on a composite cubic+linear fit to the IERS C01 time-series after filtering them to remove the signal at annual and Chandler periods. The composite polynomial is comprised of a cubic over 1976.0–2010.0 and a linear extrapolation from 2010.0 (Petit & Luzum 2010). This cubic+linear fit is shown as a black line in Figs 1(a) and (b); the elastic deformation associated with the difference between the grey and black lines is what is modelled within geodetic analysis software using eq. (1) when IERS 2010 Conventions are adopted. Deformations associated with any longer-period variations remain in the coordinate time-series and their further treatment is the focus of this paper.

To examine how well the cubic+linear fit represents inter-annual to decadal polar motion, we filtered the C04 series as follows. We implemented a Kalman Filter/Smoother, estimating constant and linear terms in addition to sine and cosine terms related to the dominant semi-annual, annual and Chandler (433 d) periodic terms. A well-known characteristic of polar motion time-series is time-variable amplitude and phase of annual and Chandler terms (Gross 2007); an advantage of a Kalman Filter approach is that all parameters are able to vary over time, according to the adopted parameter process noise. The x- and y-poles were treated independently and their motions were modelled as random walk processes. Initial estimates of the constant and linear terms were obtained by robust linear regression, with the harmonic parameters set to zero but with high initial variances (100^2 mas^2 with the constant term variance set to 10^2 mas^2). Parameter process noise variances were 1^{-10} (constant term), 0.075^2 (linear term), 1^2 (annual, semi-annual terms) and 5^2 (Chandler terms), each with units of mas^2 yr^{-1}. These values were empirically chosen based on maximizing the fit to the data whilst ensuring the parameter estimates varied relatively smoothly over

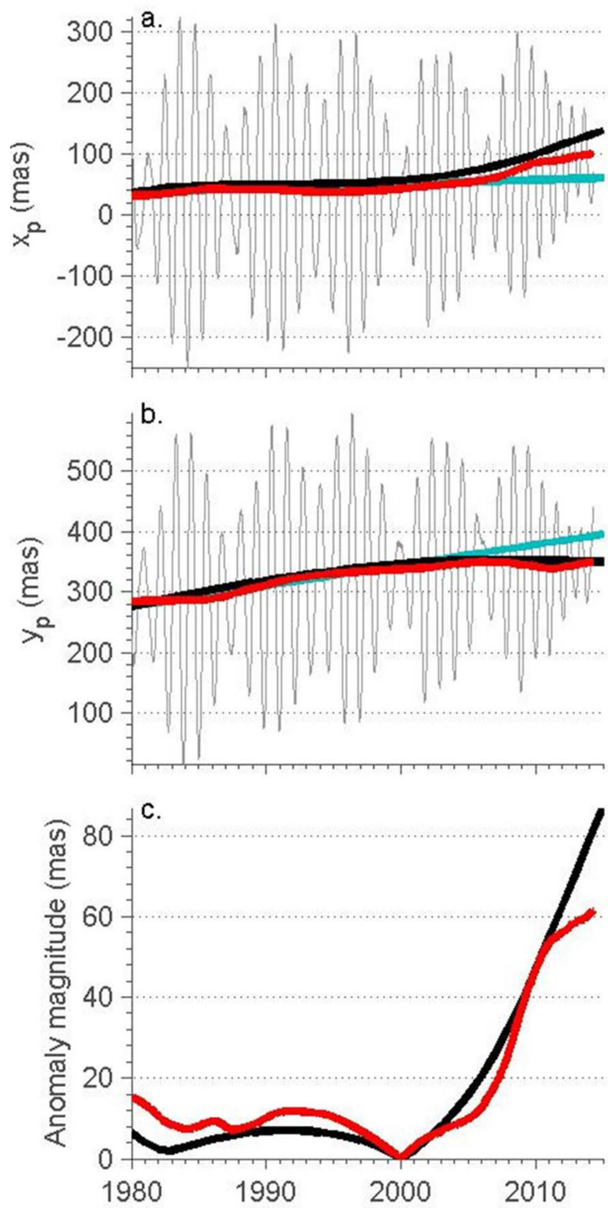

Figure 1. (a) and (b) Time-series of Earth's polar motion showing for the x and y components, respectively of the unfiltered (grey) IERS C01 time-series (x_p, y_p), (black) IERS2010 cubic+linear model ($\bar{x}_p$, $\bar{y}_p$) and (red) our filtered IERS C04 time-series. The cyan line is a continuation of the estimated mean rate over 1900–1990 (Gross & Vondrák 1999). (c) Polar motion anomaly to the 20th century mean rate described in the main text, with magnitude computed relative to 2000.0, for the IERS2010 cubic+linear model (black) and our filtered C04 time-series (red).

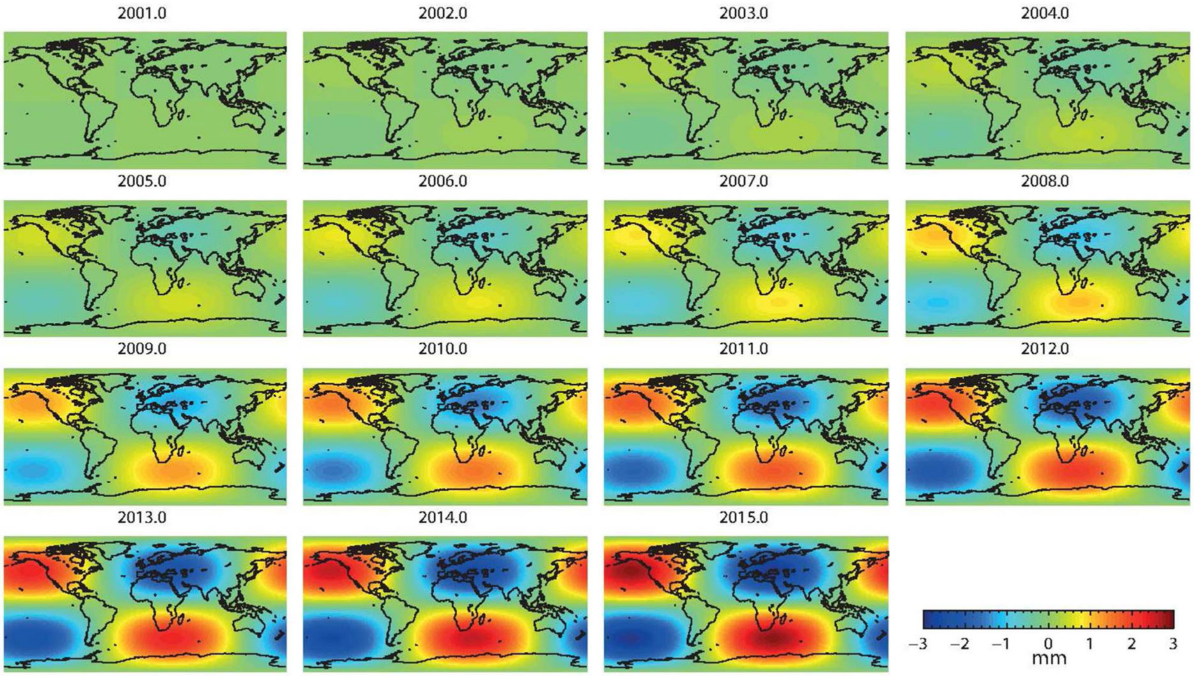

Figure 2. Modelled deformation patterns for 2001 January 1 to 2015 January 1 expressed as anomalies to the average pattern (related to polar motion) over the 20th century.

time. The residual to the modelled positions had a standard deviation of ∼3 mas for each component.

The filtered time-series are shown in Figs 1(a) and (b), with differences to the cubic+linear model evident. To highlight this anomaly, we first remove a linear background rate from the cubic+linear model and our filtered series, with the background rate chosen somewhat arbitrarily to be an estimate of the 20th century (1900–1990) mean polar motion rate (3.51 mas yr^{-1} @ 79.2°W; Gross & Vondrák 1999). We then compute the magnitude of the long-term polar motion relative to its position at 2000.0. The resulting time-series (Fig. 1c) show that while the cubic+linear model (black line) provides a reasonable fit to the filtered observations (red line), deviations from the actual mean pole location have been greater than 10 mas for several years at a time. (We note that the IERS 2010 Conventions state that for the most accurate results deviations should be <10 mas.) The anomalous polar motion commencing around 2005 (Chen *et al.* 2013) is not particular evident in the cubic+linear model, whereas it is clear in our filtered time-series. The most prominent difference is the substantial deviation of the actual mean pole from the cubic+linear model since 2010 when the cubic+linear model over-predicts the polar motion. This is the period within the cubic+linear model that is represented by a linear extrapolation.

The importance of Fig. 1(c) to the accuracy of geodetic time-series is as follows. First, the rapid deviation of the pole since around 2005 results in a deformation pattern of Earth which is inconsistent with that experienced over longer periods. For example, post-2005 geodetic site velocities are not representative of 20th century deformation rates, or even those of the full space geodetic period (∼1980–present). Second, because the pole tide model ensures the deformation pattern reported in geodetic time-series is fully consistent with the polar motion described by the cubic+linear model, geodetic velocities do not represent actual Earth deformation during periods of deviation of the pole from the cubic+linear model (e.g. post-2010).

To quantify this effect we first assume that the pole tide has been applied in the Conventional manner, thus removing signal at annual and Chandler periods away from the reference pole position as determined using the cubic+linear terms. We then revisit eq. (2) with the view of making a second elastic correction to geodetic position time-series in order to improve time-series linearity. In this case, the x_p, y_p is now the cubic+linear model. Reflecting a desire in many studies for long-term linear time-series $\bar{x}_p$, $\bar{y}_p$ is now a purely linear representation of polar motion, representative of an appropriate period. For example, $\bar{x}_p$, $\bar{y}_p$ could be composed of just the mean polar motion rate over either the geodetic period or the 20th Century. For the sake of illustration, we use here an estimate of the 20th Century linear rate of motion (3.51 mas yr^{-1} @ 79.2°W, Gross & Vondrák 1999; Gross 2007). We compute polar motion anomalies as the difference between this linear rate and the IERS cubic+linear model, and evaluate eq. (1). The resulting quantification of the anomalous deformation patterns associated with the recent rapid polar motion is shown in Fig. 2.

The minima of the degree-2 order-1 pattern are located over Europe and the South Pacific, with the maxima located in the North Pacific near Alaska and south of Africa. This pattern is ∼90° rotated in longitude from the pattern of deformation driven by glacial isostatic adjustment (GIA; Mitrovica *et al.* 2001) as a result of the most recent deviation of the pole being nearly orthogonal to its longer-term direction of motion. The spatial pattern of anomalous deformation is such that Europe has decreased in elevation by up to 3 mm since ∼2000, or ∼−0.5 parts-per-billion of scale. In the same period, South Pacific islands have subsided by up to 3 mm.

The time-evolution of the radial deformation and deformation rate are shown as black lines in Fig. 3 for locations of the signal maxima; the pattern of the signal minima is a mirror image. Fig. 3(b) reveals acceleration in radial deformation that reaches 0.27 mm yr^{-1} in 2010 and, due to the linear extrapolation of the IERS 2010 model, remains constant thereafter.

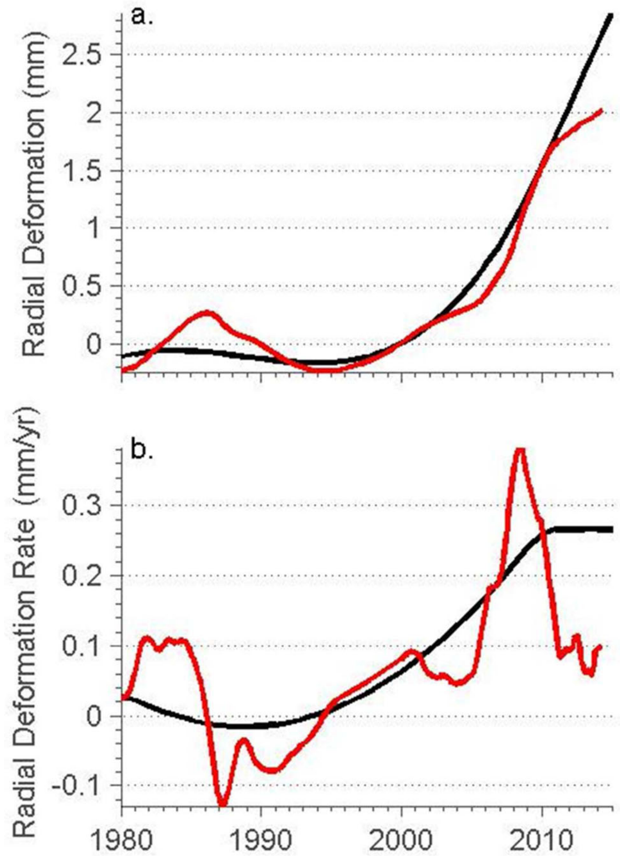

Figure 3. (a) Radial deformation at maxima; (b) radial deformation rate at the maxima. Deformation patterns at the minima are identical but of opposite sign. The black lines are computed using the IERS 2010 model, the red lines using our filtered C04 time-series.

The actual Earth deformation will differ from that governed by the cubic+linear model especially since around 2010 (Fig. 1c). To quantify this difference, we used our filtered C04 polar motion time-series and repeated the elastic modelling. In computing deformation rates, short-term variability is enhanced and we first apply further smoothing to our filtered C04 time-series to reduce this effect. The results of re-evaluating eq. (1) are shown in Fig. 3 (red lines) showing larger fluctuations in deformation rate compared with the cubic+linear model, reaching a maximum deformation rate of ±0.38 mm yr^{-1} in 2009 before reducing to ±0.10 mm yr^{-1} in 2010. The implication is that the inferred change in shape of Earth using geodetic time-series produced using the IERS2010 model will differ substantially from the actual changing shape of the Earth. The magnitude of the difference is largest commencing in 2010, and is ongoing since, with differences cumulating at a rate of up to ±0.18 mm yr^{-1}. More importantly for most geophysical studies, though, the correction of all non-linear deviations, and notably those since around 2005, is required in order to obtain vertical velocities that are reflective of vertical motion over much longer timescales than covered by the data.

3 DISCUSSION

The importance of this effect falls into two end-member scenarios. First, geodetic measurements that have commenced since around 2005 will result in velocities and positions biased relative to measurements conducted over earlier periods according to the pattern shown in Fig. 2. These post-2005 velocities will contrast to those based on earlier periods given they were made under polar motion conditions more similar to the long-term average. Geodetic velocities are commonly extrapolated for the purpose of correcting 20th century sea level measurements (Wöppelmann *et al.* 2009; King *et al.* 2012); the effect described here reaches ∼±15 per cent of the global-mean 20th century sea level trend. Given the large-scale spatial coherence of the signal, it may also have some bearing on geodetic constraints on models of GIA (e.g. Argus & Peltier 2010; Lidberg *et al.* 2010), particularly in Europe and the U.S. Pacific Coast (on a related note, when comparing GIA models to geodetic positions such models should include the effects of long-term migration of Earth's rotation pole, often referred to as 'rotational feedback'). The change around 2005 is especially important given the dramatic increase in GNSS site densities since this time, including the establishment of large-scale scientific and national geodetic networks in USA, Europe and Australia. We note that the deformation in Fig. 2 does not have the right spatial pattern or sufficiently large amplitude to explain the regionally-correlated differences recently identified between models of glacial isostatic adjustment and GPS vertical velocities (King *et al.* 2012), and that large-scale deformation at the millimetres per year level remains unexplained.

The other end-member is long-term geodetic measurements, where the non-linear deformations discussed here effectively represent time-series noise as well as bias. Since all geodetic data is sensitive to these short-term variations, the construction of terrestrial reference frames will be degraded by time-series determined using an inadequate treatment of the deformation considered here. A displacement of much of Europe, where many of the VLBI and SLR telescopes are located, by up to 3 mm or 0.5 part-per-billion since around 2005 is larger than the expected and target uncertainties of the International Terrestrial Reference Frame (Gross *et al.* 2009; Altamimi *et al.* 2011). Some of this deformation may be absorbed into SLR estimates of geocentre motion, with the amount depending strongly on the particular SLR network geometry. Computing the spectra of the time-series in Fig. 3(a) in log–log space, reveals a spectra with a slope close to –2, suggesting this signal will increase the random-walk component of geodetic time-series noise unless appropriately modelled.

Implementing a correction for this deformation is, fortunately, trivial as all the theory is in place. The only necessary development is adoption of $\bar{x}_p$, $\bar{y}_p$ that are consistent with the chosen reference frame—for instance, the ITRF2008 origin is defined over the period 1983.0–2009.0 with our estimate of the C04 polar motion over this period being 2.58 mas yr^{-1} @ 69.7°W. Adopting this reference rate only changes the results of Fig. 3 by 0.03 mm yr^{-1} but shifting the pattern in Fig. 2 in longitude a few tens of degrees west. Removal of site motion anomalies over this period will increase the consistency of the station positioning with respect to the ITRF2008 origin and scale that are defined as being constant over the modern geodetic period. Accounting for this non-secular deformation will also yield instantaneous improvements in the accuracy and uncertainty of terrestrial reference frames, which are constructed from time-series that exhibit incompletely understood non-linearities (Altamimi *et al.* 2011; Argus 2012). Further investigation is required to determine if the modelling of the kind discussed here must be performed at the technique observation-level or can be undertaken at the post-processing stage; given the size of the signals to date our expectation is that the latter will be sufficient but the former is preferable.

The rapid changes in polar motion observed since around 2005 are driven largely by changes in the Greenland and Antarctic ice sheets (Chen *et al.* 2013). While this rate of mass loss has subsequently reduced, predictions for both ice sheets are for substantially increased mass loss through the coming decades (Church *et al.* 2013). As such, Earth's pole will be expected to deviate even more strongly from its recent longer-term average motion. For ongoing observations, therefore, the post-2010 linear component of the IERS 2010 cubic+linear polar motion model will be insufficiently accurate for geophysical studies interested in small vertical deformations. Adoption of a second elastic correction with linear $\bar{x}_p, \bar{y}_p$ would ensure that all geodetic time-series accurately reflect the real changing shape of Earth at timescales of at least decades, although at the expense of any studies wishing to study very short-term variations in Earth's shape.

Until this is resolved, measurements since 2010 are forced to comply with the IERS 2010 cubic+linear polar motion model, meaning the deformation pattern since 2010 shown in Fig. 2 will be embedded within such measurements into the future, regardless of the actual polar motion rate and its related deformation.

4 CONCLUSIONS

Rapid polar motion observed since around 2005 has resulted in large-scale elastic radial deformation of Earth that reached ±0.38 mm yr^{-1} around 2009. Best expressed as a spherical harmonic degree-2, order-1 signal, this effect reaches its maxima over the U.S. Pacific Coast and South Africa and its minima over Europe and south Pacific islands, producing up to 3 mm of uplift/subsidence. Measurements of Earth deformation since ∼2005 will, therefore, differ from the rate of deformation prior to, and likely after, this period at up to this magnitude. As a consequence, studies that have adopted geodetically derived radial velocities using data exclusively since 2005 may have had their conclusions influenced by velocities biased compared to longer periods (e.g. the 20th century mean). With present GPS precisions and the magnitude of measured geophysical signals, this is particularly relevant for GPS measurements of tide gauge vertical movement. The presence of these unmodelled signals represents a combination of bias and noise that degrades individual time-series, site velocities and the terrestrial reference frame.

For such applications of geodetic measurements, with their interest in multidecadal rates of deformation, this signal may be entirely attenuated through an elastic correction that is additional to the IERS pole tide model; this correction is based on the adoption of a linear reference rate, such as the mean rate over the geodetic period, together with existing theory of elastic deformation due to polar motion (Wahr 1985; Petit & Luzum 2010). In some geodetic analysis it may be preferable to combine the pole tide correction with this additional correction.

Since an increase in melting of the ice sheets is expected in the future, more rapid polar motion will result and produce even larger deformations than those considered here; revision to existing analysis approaches is consequently required.

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