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Geocentric sea level trend using GPS and >100-year tide gauge record on a postglacial rebound nodal line

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Abstract. For studies of global sea level change, 103 years of tide gauge data were analyzed from North Shields on the North Sea coast of Great Britain, near a predicted nodal line of postglacial rebound (PGR). Simultaneous estimation of statistically significant tidal components gives a relative sea level rate of 1.8 ± 0.1 mm/yr with no significant acceleration. Analysis of a Global Positioning System (GPS) station, which we installed directly on the tide gauge structure, shows the tide gauge rising at 1.4 ± 1.5 mm/yr relative to the international terrestrial reference frame (ITRF96). Leveling shows the tide gauge rising with statistical significance at 0.8 ± 0.2 mm/yr relative to a nearby lighthouse (0.5 km away) situated on bedrock. Thus our geodetic estimate of geocentric crustal rise is 0.6 ± 1.5 mm/yr, which is consistent with the PGR nodal hypothesis. Our estimate of geocentric sea level rise using local leveling and assuming the PGR nodal hypothesis (i.e., zero crustal rise with no model uncertainty) is therefore 2.6 ± 0.2 mm/yr. Introducing an upper bound error based on observational evidence and PGR model differences modifies this to 2.6 ± 1.0 mm/yr. This is to be compared with our model-independent GPS-based estimate of 3.2 ± 1.5 mm/yr. We conclude that PGR and geodesy corroborate a geocentric sea level rise of 2.6 ± 1.0 mm/yr (upper bound), which is larger than the tide gauge records alone (1.8 mm/yr) would indicate.

1. Introduction

Global warming would create thermal expansion of the oceans and could induce a net transfer of water between ocean and land. Quantifying the trend in sea level over the last century should therefore be useful to test the predictions of global change models [*Carter et al.*, 1989].

Tide gauges measure sea level relative to a bench mark on the ground; however, if the ground moves vertically, the sea level obtained from a tide gauge will be biased. Vertical land movement at tide gauges might occur owing to tectonic activity, postglacial rebound (PGR) due to Pleistocene deglaciation, or local instability [*Baker*, 1993]. In general, the vertical motion of the land cannot be ignored because it is of the same order of magnitude (mm/yr) as the trend in sea level.

There have been attempts to model and remove the PGR effect from the sea level record [e.g., *Douglas*, 1995; *Mitrovica and Davis*, 1995]. However, this approach does not account for bias due to local instability, which we show here can be as large as crustal motion and is unlikely to have a zero mean global average. A more subtle problem is the degree to which the rheological and ice sheet parameters in PGR models have been influenced by knowledge of long-term sea level trends.

An alternative model-independent approach is to determine the vertical motion of the tide gauges using modern geodetic methods [*Carter*, 1994]. The Global Positioning System (GPS) has become the most favored geodetic technique for measuring tide gauge motions since completing the full satellite constellation in 1994 and the establishment of the International GPS Service (IGS) [*Neilan et al.*, 1997]. The secular variation of relative sea level can be determined by at least 50 years of sea level data with 0.3–0.5 mm/yr error levels [*Neilan et al.*, 1997]. Therefore the geodetic measurement of vertical tide gauge motion is currently the limiting error source for geocentric sea level rates at tide gauges with long records.

2. Experiment Design

While *Douglas* [1991] performed a general analysis, applying PGR corrections to many tide gauges, we have taken a complementary approach. Our investigation focuses on a single tide gauge that (1) has a long >100-year history, (2) lies near a predicted nodal line of PGR in a tectonically inactive region, and (3) lies near bedrock and is otherwise suitable for direct geodetic measurement of vertical motion.

The tide gauge selected is at North Shields, situated at the mouth of the River Tyne, in the Newcastle upon Tyne conurbation on the North Sea coast of England. The North Shields tide gauge has a 103-year history, with data available from ~90% of that time span. *Lambeck and Johnston* [1995] model PGR for the British Isles and predict a nodal line that intersects the North Sea coast of Britain in the region of Newcas-

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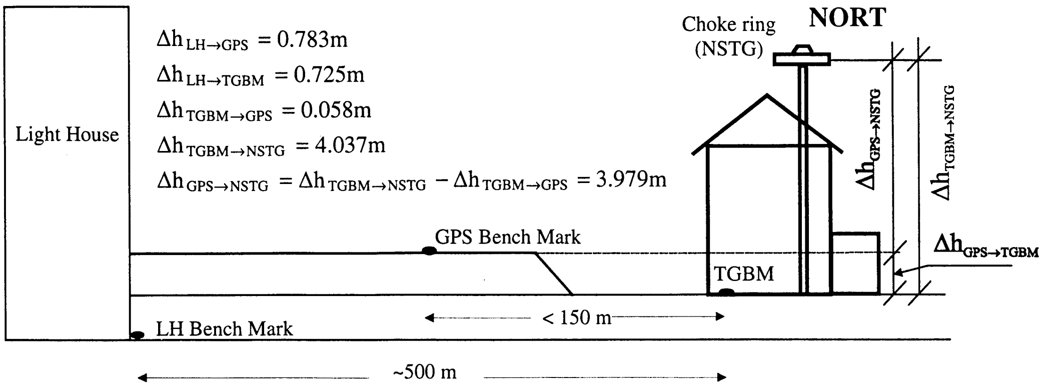

Figure 1. Height relationships between the lighthouse bedrock bench mark (LH), tide gauge bench mark (TGBM), an adjacent GPS bench mark used intially for epoch campaigns, and a permanent mast-mounted GPS choke ring antenna (NSTG).

tle. Their ice sheet model was based on *Lambeck* [1993], which was constrained by evidence from geomorphology and sea level observations [*Johnston and Lambeck*, 1998].

Uncertainty in PGR estimates is somewhat reduced by choosing a location that is predicted to have small PGR [*Mitrovica and Davis*, 1995]. For example, the quite different PGR models of *Peltier* [1994, 1996] for Laurentia and Fennoscandia show as much as 4 mm/yr disagreement in vertical rates; however the predicted difference around the nodal line is typically 1 mm/yr. However, the British ice sheet (radius ~300 km) had a relatively small load in comparison to that of Fennoscandia (~1000 km) and Laurentia (~2000 km), leading to modeled PGR magnitudes in the north of Britain that are a factor of 2–8 less than in Fennoscandia or Laurentia [*Lambeck and Johnston*, 1995]. As a further observational constraint, *Zong and Tooley* [1996] used coastal stratigraphy to reconstruct Holocene sea level history in the northwest of England, which should be much more affected by the Irish Sea Glacier and ice in the Lake District and southwest Scotland [*Lambeck*, 1993]. Holocene sea level in this active region shows exponential decay, which, extrapolated to today, shows a magnitude <2 mm/yr PGR [*Zong and Tooley*, 1996]. Taking all this evidence into account, we suggest that ±1 mm/yr represents a conservative upper bound for PGR at North Shields.

We obtained permission from the Port of Tyne Authority to install a GPS station (NORT) directly on the North Shields tide gauge structure. The station is located with water to the south, which provides good satellite visibility for a station at midlatitude in the Northern Hemisphere. A lighthouse founded on bedrock at 0.5 km from the tide gauge provided a leveling bench mark, which allowed us to separate local tide

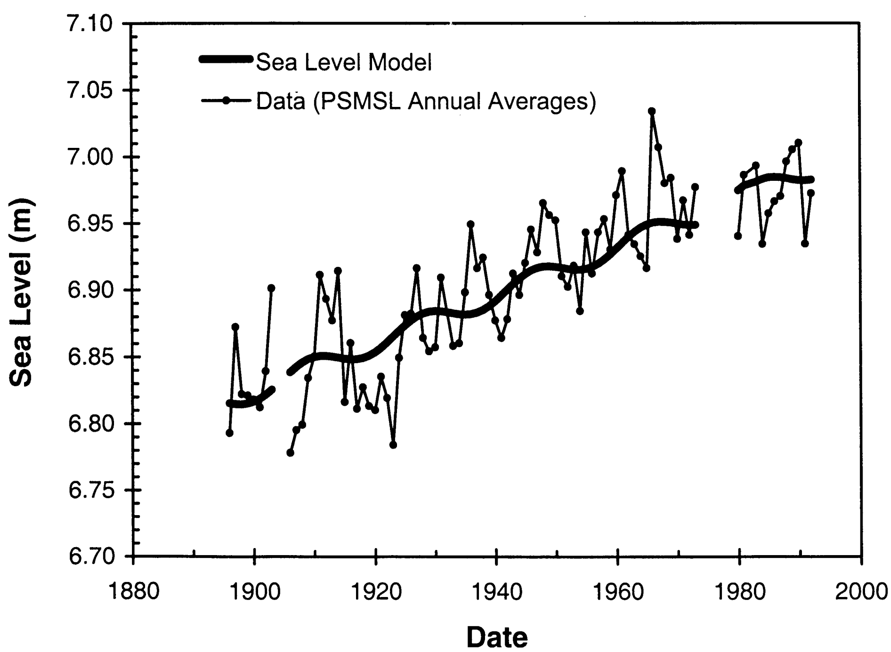

Figure 2. The North Shields tide gauge data regressed to our sea level model. Although monthly averaged data from PSMSL were actually used for the regression, only annual averages are shown for clarity.

gauge instability from regional crustal motion. Figure 1 shows schematically the height relationships between the lighthouse bedrock bench mark (LH), tide gauge bench mark (TGBM), an adjacent GPS bench mark used intially for epoch campaigns, and a permanent mast-mounted GPS choke ring antenna (NSTG).

Three possible methods to correct for vertical motion of the tide gauge were considered:

1. Conduct precise leveling to the tide gauge bench mark from the lighthouse bedrock bench mark (LH→TGBM), then assume that LH moves according to PGR models.

2. As above, but determine the motion of LH using space geodesy.

3. Determine the tide gauge motion relative to the Earth's center directly, using a GPS station installed on the tide gauge structure.

In this paper, we apply methods 1 and 3, which provide completely independent corrections to relative sea level. Method 2 is obviously correlated with method 1 as they have leveling in common. Moreover, it is not independent of method 3 due to spatial correlations in geocentric GPS estimates arising from tropospheric refraction, GPS satellite orbit error, and reference frame error.

Initially the GPS data were collected from 1996.9 to 1998.1 every 2 weeks with 6 hours of observation window in "epoch campaign mode," using a tripod-mounted antenna over a GPS bench mark located <150 m from the tide gauge, on the same wooden structure. After encountering practical difficulties collecting data at the GPS bench mark in a busy environment, a permanent GPS antenna was installed directly on the tide gauge structure (NSTG). A braced, marine-grade aluminum pole (~4 m) was installed into the floor of the tide gauge hut, with a choke ring antenna mounted on top, clear above the roof. An Ashtech Z12 receiver with choke-ring antenna acquired GPS carrier phase and pseudorange data at 30-s intervals, using a 15° elevation cutoff angle.

To tie the permanent GPS time series with the epoch GPS time series, the height difference between the GPS bench mark and the permanent GPS antenna (GPS→NSTG) was measured several times using an electronic level and, as an independent check, using GPS (in single-frequency mode to reduce noise). The result was 3.979 m using both methods: thus the tie was considered an insignificant source of error (< 1 mm) in connecting the time series.

Owing to resource constraints beyond our control, the permanent station ceased operation at 1998.7. Our initial analysis of data from 1996.9 to 1998.7 was subsequently augmented to include 18 extra sets of 24-hour observations around 1999.5 to provide significantly improved leverage in height trend estimation for relatively little additional cost. The conclusions of this paper were unchanged by inclusion of these extra data, except for improved statistical significance.

3. Analysis

3.1. Analysis of North Shields Tide Gauge Record

North Shields sea level data were obtained from the Permanent Service for Mean Sea Level (PSMSL), and analysis was performed on monthly averaged data (Figure 2). The linear regression model for monthly analysis was constructed as follows:

$$L(t) = a + \dot{a}t + C_{0.5}(t) + C_1(t) + C_{8.8}(t) + C_{18.6}(t)\,, \qquad (1)$$

where a denotes mean sea level at reference time $t = 0$, $\dot{a}$ is the linear trend, $C_{0.5}$ solar semiannual tide, C_1 solar annual tide, $C_{8.8}$ lunar perigee tide (of period 8.8 years), and $C_{18.6}$ lunar node tide (of period 18.6 years). The tidal constituents were chosen following the recommendations by *Hannah* [1990] and *Vanicek* [1978].

The coefficients of the regression model were solved by least squares estimation. Each coefficient was tested for significance using Student's **t** test. For instance, a tidal component is incorporated in the linear model by

$$C_p(t) = b_1 \sin\left(\frac{2\pi t}{p}\right) + b_2 \cos\left(\frac{2\pi t}{p}\right), \qquad (2)$$

where p is tidal period, t is time, b_1 and b_2 are amplitude constituents estimated by least squares. The nonzero significance of b_1 and b_2 can be tested by forming the following alternative hypotheses [*Walpole and Myers*, 1993]:

$$\begin{aligned} H_0 &: \beta_1 = \beta_2 = 0 \\ H_1 &: \beta_1 \neq 0, \beta_2 \neq 0. \end{aligned} \qquad (3)$$

The **t** test statistics for the null hypothesis can be calculated by forming the ratio

$$\mathbf{t}_i = \frac{b_i - \beta_i}{s_i}\,, \qquad (4)$$

where s_i is the standard error of the estimated coefficient b_i. If for both amplitude constituents $-T_{\alpha/2} < \mathbf{t}_i < T_{\alpha/2}$, then H_0 is accepted; that is, the tidal constituent is not significant and can be removed from the model. Values of $T_{\alpha/2}$ are tabulated value with α significance level and υ degrees of freedom. As a result of these tests, the polar tide (with the Chandler wobble period) was found to be insignificant ($\alpha < 0.05$) and therefore does not appear in equation (1).

The coefficients can also be tested to see if they make a significant improvement to the post-fit residuals by Fisher's F test. The F test is applied if one can not make a decision by **t** test (i.e., one of the amplitude constituent is significant, the other one is not). To apply the F test, parameters to be tested are removed from the linear model, and least squares is repeated. The reduced sum of squares is computed:

$$S_{\text{red}} = \sum_{i=1}^{n} (\hat{y}_i - \bar{y})^2\,, \qquad (5)$$

where $\hat{y}_i$ is the sea level value from estimated model, $\bar{y}$ is mean sea level value calculated from the original data, and n is number of data. The previous hypothesis statement is also valid for the F test, and the test statistics is given by

$$f = \frac{(S - S_{\text{red}})/2}{s^2}\,, \qquad (6)$$

where S is the sum of residual squares (defined as above, except using the complete model instead of the reduced model) and s^2 is the variance of the data minus the complete linear model. Since we test two coefficients at a time for tidal components, ($S - S_{\text{red}}$) is divided by 2. If f is smaller than the tabulated critical value of the F distribution for (2, $n-u$) degree of freedom (u is number of unknowns) and α significance level, then the hypothesis is accepted.

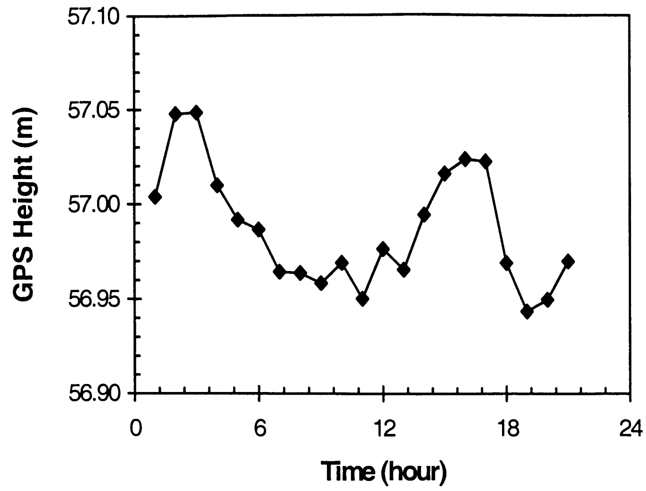

Figure 3. Height estimates derived from 3-hour (overlapping) sessions of GPS measurements.

With simultaneous estimation of significant tidal components, relative sea level was determined to be 1.82 ± 0.06 mm/yr from the record of North Shields tide gauge. The quoted one standard deviation error has been scaled by the unit variance to account for unmodeled variance in the data. The monthly sea level analysis model developed here explains 60% of the sea level variance if one refers to the coefficient of multiple determination given by

$$R^2 = \frac{\sum_{i=1}^{n}\left(\hat{y}_i - \bar{y}\right)^2}{\sum_{i=1}^{n}\left(y_i - \bar{y}\right)^2}. \qquad (7)$$

Fitting a linear trend to the sea level data explains only 31% of the variance. Interestingly, a major improvement can be achieved by adding the annual tide into the linear regression model, which explains an additional 27% of the variance. (This would include seasonal variation not necessarily driven by solar gravity). The remaining tidal terms (solar semiannual, lunar perigee, and lunar node) account for only 2% of the variance.

3.2. Analysis of GPS Data

Jet Propulsion Laboratory's GIPSY/OASIS II software was used to process the GPS data, using the "precise point positioning" method (PPP) by *Zumberge et al.* [1997]. PPP results were computed using the International Earth Rotation Service's reference system ITRS [*McCarthy*, 1996], as realized through the reference frame ITRF96 [*Boucher et al.*, 1998], which has an inner geometry dominated by the global GPS network.

Our use of the term "geocentric" to describe sea level rates requires a subtle but important qualification. Contrary to the description of ITRS [*McCarthy*, 1996], the origin of ITRF96 is not actually constrained to move with Earth center of mass (as realized through satellite dynamics). Rather its kinematic evolution with respect to the rigid plate model NUVEL-1A is defined to have no net translational rate (Z. Altamimi and D. Argus, personal communication, 2000). To obtain sea level wirh respect to the Earth center of mass awaits more definitive results from ongoing research into reference frames [*Argus et al.*, 1996]. Our objective here is to quote results in a kinematically defined "geocentric frame" that can in future be converted to dynamically defined center of mass frames as such research develops.

To improve GPS vertical positioning accuracy, various tropospheric modeling strategies were studied, and the effect of ocean loading was investigated on PPP-derived height estimates. GIPSY allows for stochastic troposphere estimation using random walk process noise for the wet zenith delay bias. The precision of height estimates can be improved by tuning random walk process noise [*Gregorius and Blewitt*, 1999]. We determined that a value of 10 mm/h$^{-1/2}$ minimizes the long-term repeatability of station height at NORT.

Baker et al. [1995] and *Curtis* [1996] previously showed that relative GPS positioning can reveal the effect of ocean loading during timescales of a few hours. In this study, a large ocean loading effect has been determined on PPP height estimates. For example, Figures 3, 4, and 5 examine the effect over 3-hour (overlapping) data spans of GPS observation for April 4, 1998. It can be seen from Figure 5 that the sequence of GPS height estimates (Figure 3) is highly anticorrelated with the tide gauge record (Figure 4), giving a correlation coefficient $r = -0.8$. This can be explained in terms of the rising tide increasing pressure on the Earth's crust, which must bend downward to balance the loading force, thus lowering station (and tide gauge) height.

Further examination has shown that ocean loading effect on height estimation varies with respect to the span of GPS observations. Standard deviations of station height time series for varying data spans (up to 24 hours) were computed from continuous GPS data (spanning about 6 months) and are given in Figure 6. We would expect shorter data spans to have a greater systematic bias from ocean loading, which tends to average down with time. The semidiurnal tide M_2 (principle lunar) has the biggest effect on GPS-derived height estimates [*Baker et al.*, 1995], which can be significantly biased (~20 mm at NORT) for data spans <12 hours. The bias reduces to a few millimeters for data spans of 12–24 hours.

Ocean loading is particularly difficult to model accurately in Britain, which has some of steepest tidal gradients in the

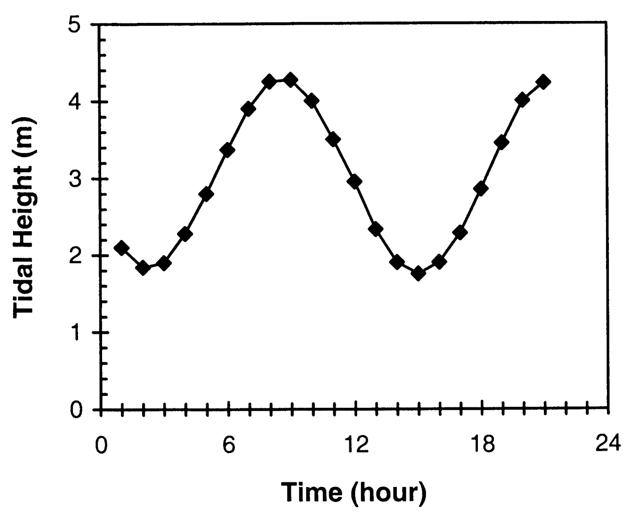

Figure 4. Digitized tide gauge record over the same time period as Figure 3.

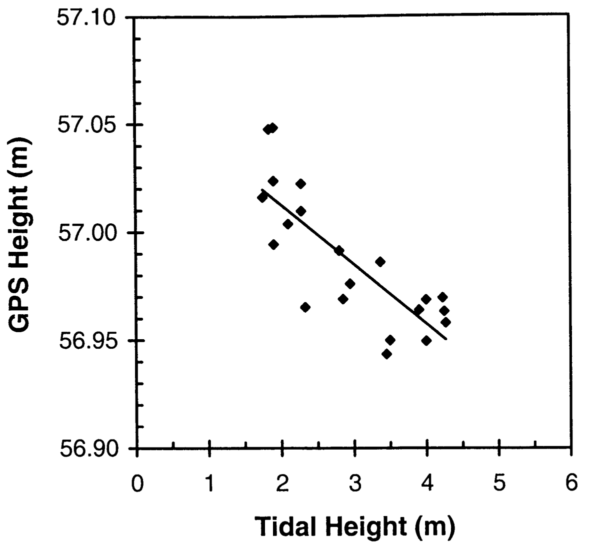

Figure 5. GPS-derived height for each 3-hour session (in Figure 3) plotted against tidal height (in Figure 4), with linear regression. The correlation between GPS and tidal height is $r = -0.8$.

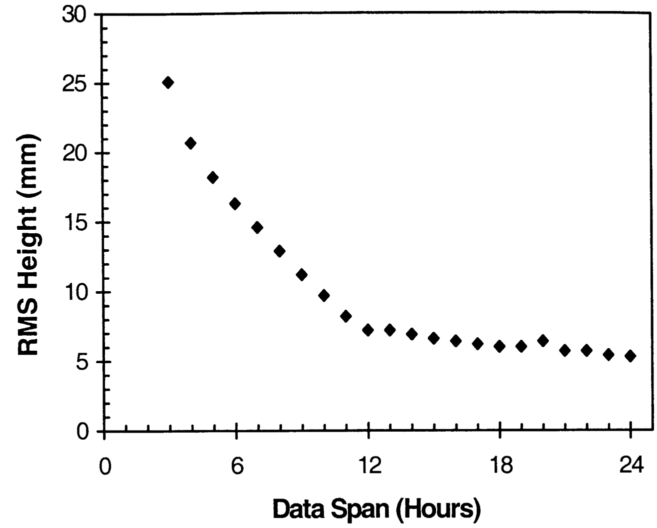

Figure 6. RMS variation in GPS height time series of various data spans (using a total of 6 months of data, spliced a different way for each data point). Note the significant reduction in RMS height beyond 12 hours of data. This, together with Figure 5, provides strong evidence that ocean loading bias is significant for shorter time spans.

world, has a complex coastline, and has tidal currents moving in opposite directions that can superimpose constructively or destructively [*Curtis*, 1996]. Therefore, instead of attempting to correct for ocean loading, the following procedure was adopted for computing realistic error bars that account for the increasing ocean loading bias for shorter data spans. The formal error of each GPS height estimate (from the computed covariance matrix) was "coupled" (i.e., added in quadrature) with the RMS deviation of Figure 6, appropriate to its data span. The weights of the GPS height estimates were then computed as the inverse square of these coupled errors. Generally, this procedure has the desirable effect of decreasing the relative weight of epoch solutions relative to the 24-hour permanent solutions (which are less biased by ocean loading).

Figure 7 shows the GPS height estimates for epoch and permanent solutions, together with their error bars, and the weighted least squares estimation of height trend computed according to this procedure. The heights shown were also corrected for thermal expansion of the aluminum pole holding the permanent GPS antenna using temperature data (an effect which contributes 0.2 mm/yr to the trend). Regression of the thermally corrected heights shows that NORT is rising 1.4 ± 1.5 mm/yr relative to the WGS-84 ellipsoid (attached to the ITRF96 origin).

3.3. Analysis of Leveling Measurements

Using a Wild NA2002 electronic level, 6 leveling campaigns were carried out during the same time period as for GPS measurements, between the tide gauge bench mark and

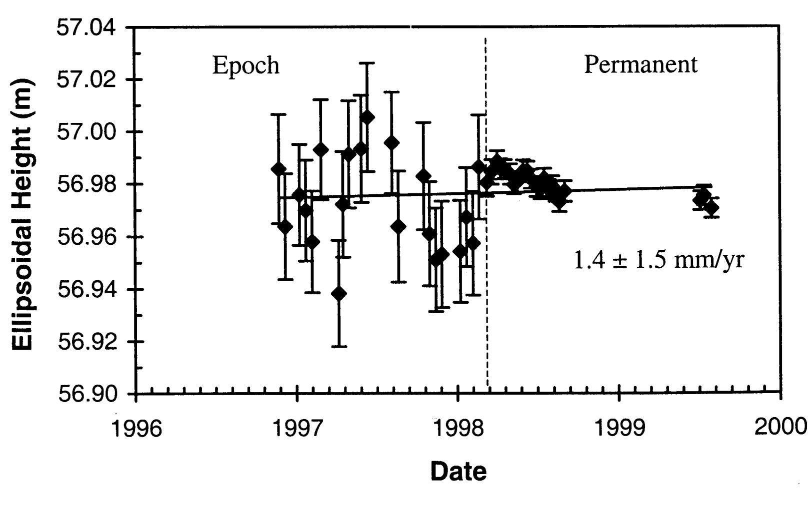

Figure 7. Time series of GPS height estimates at NORT with linear regression. For permanent station data, 24-hour height estimates were used for the regression, but only weekly averages are shown here for clarity. Heights are referenced to the WGS-84 ellipsoid.

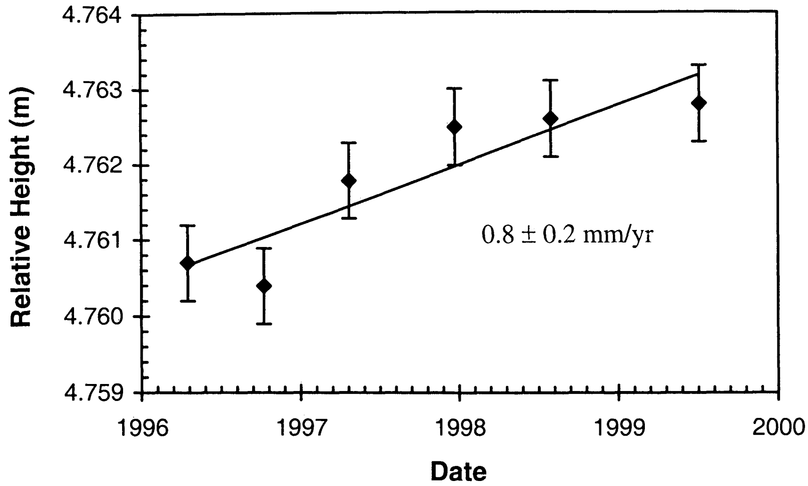

Figure 8. Leveling results of the height of the NORT tide gauge bench mark relative to local bedrock, with linear regression.

the lighthouse bedrock bench mark (LH→TGBM). Measurement precision was estimated at 0.5 mm from forward and return runs over the ~500 m leveling line. The time series of leveling results (Figure 8) shows that the tide gauge is rising at a statistically significant 0.8 ± 0.2 mm/yr relative to the lighthouse bedrock.

4. Discussion

The 103-year tide gauge at North Shields has been found to be moving upward by two independent methods, which indicates that the tide gauge measurements and resulting sea level trend (1.8 ± 0.1 mm/yr) are negatively biased and should be corrected upward. The magnitude of the tide gauge movement is 1.4 ± 1.5 mm/yr vertically relative to ITRF96 using GPS and 0.8 ± 0.2 mm/yr by leveling relative to local bedrock.

Note that the local instability of the tide gauge (0.8 ± 0.2 mm/yr) is significant both statistically and in comparison to the magnitude of sea level rise and has not been accounted for in recent PGR-based studies of tide gauge records. This is presumably due to the general lack of precise local stability measurements at tide gauges, despite recent recommendations on this point [e.g., *Baker*, 1993; *Carter*, 1994; *Neilan et al.*, 1997]. Little, in any consideration, has been given in the literature to the possibility that tide gauges could rise (as opposed to subside) from local instability. We speculate that the local rise of the tide gauge might be related to warping of the wooden pier structure upon which it is founded. The remaining 1.4 − 0.8 = 0.6 ± 1.5 mm/yr global contribution is consistent with zero geocentric motion of the Earth's crust but does not exclude a small component of PGR. These results are consistent with the PGR model of *Lambeck and Johnston* [1995],which predicts a nodal line in the region of North Shields. If we assume the nodal hypothesis for PGR, then leveling provides our geocentric estimate for sea level rise at 2.6 ± 0.2 mm/yr. Including our upper bound on PGR at North Shields modifies this result to 2.6 ± 1.0 mm/yr. GPS provides a model-independent estimate of geocentric sea level rise of 3.2 ± 1.5 mm/yr.

The one standard deviation error bar for the GPS-based estimate includes both formal errors and an estimate of systematic error induced by ocean loading. While including ocean loading errors accounts more realistically for the relative weight between GPS sessions of different data spans, it is likely to contribute to an overestimate of the error in the trend. This is because our procedure of adding the formal height error in quadrature with an empirical standard deviation is, to some extent, accounting for data precision twice. However, the error bar on the GPS-based trend does not account for colored noise [*Mao et al.*, 1999], which may account for some of systematic variation apparent in Figure 7. To some degree, these two factors will tend to cancel. The good agreement (0.6 mm/yr) between GPS and PGR (plus leveling) results provides an independent indication of both GPS and PGR model accuracy, which is less than the quoted GPS standard error (±1.5 mm/yr), and less than the upper bound on PGR model error (±1 mm/yr). We therefore see no reason to modify our quoted error.

Both methods of producing geocentric sea level rise estimates use the same tide gauge data for relative sea level. The one standard deviation error in relative sea level is estimated to be ±0.1 mm/yr, which is negligible. The autocorrelation function of the residuals shows that there is a short-term correlation between monthly sea level data. This correlation can be induced from interannual and interdecadal variation of sea level and should be incorporated in the stochastic model for weighted least squares estimation. Accounting for this changes the error estimate to ±0.2 mm/yr, which is still negligible compared to geodetic error. Sources of systematic error on relative sea level might include meteorological effects (air pressure, temperature, and wind stress) and river discharge. Strong correlation between the North Shields tide gauge measurements and those taken from a tide gauge at Blyth, 12 km up the coast, indicates that river discharge is unlikely to be a significant component. It is also difficult to construct a scenario such that local meteorological effects could create a secular variation of >100 mm per century.

5. Conclusions

Careful analysis of individual tide gauges using modern geodetic techniques can provide an alternative method to reliance on PGR models, while having the advantage of directly accounting for local instability as well as crustal motion. Our methodology shows the utility of using local leveling as well as GPS directly on the tide gauge bench mark to provide independent estimates of sea level change. Using GPS to account for biases in sea level at North Shields provides us with an estimate of geocentric rise in sea level of 3.2 ± 1.5 mm/yr. Assuming all tide gauge motion to be local (as measured by leveling), with zero PGR, gives 2.6 ± 0.2 mm/yr. Introducing an upper bound error based on published observational evidence and PGR model differences modifies this to 2.6 ± 1.0 mm/yr. The difference of the GPS-based and PGR-based estimates (0.6 mm/yr) indicates the accuracy of both the PGR model (plus leveling) and the GPS-based estimate. We conclude that PGR and geodesy corroborate a geocentric sea level rise of 2.6 ± 1.0 mm/yr (where the error is an upper bound), which is larger than the tide gauge records alone (1.8 mm/yr) would indicate.

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