Crustal motion and sea level changes along the Arctic coasts (CRUSLAC)

Hans-Peter Plag*, Surija Tatevian†, Oleg Zilberstein‡

Abstract

The combination of tide gauges with high-precision (space-geodetic) measurements of vertical displacements of the crust and associated absolute gravity changes provide valuable constraints for observations and models of changes in nearby ice loads. In particular, geodetic observations at tide gauges in the Arctic are of high potential value for global change studies. A preliminary analysis of the available Arctic tide gauge data indicates a spatial pattern in sea level consistent with significant changes in the ice cover on Greenland and the larger ones of the Arctic islands. However, due to lack of data on crustal motion, ambiguities remain in the separation of geocentric crustal motion and geocentric sea levels as well as the attribution of the observed trends to past or present changes in the ice loads.

It is proposed to co-located several long-operating Arctic tide gauges with continuously recording GPS, to perform absolute gravity measurements at these selected tide gauges, and to connect all Arctic tide gauges to a geocentric datum. It is expected that these observations will allow to reduce the uncertainty of the geocentric crustal motion and thus provide a better estimate of the geocentric sea-level trends at these tide gauges. The resulting trends will constitute valuable constraints for changes in the Arctic cryosphere. Moreover, the proposed measurements will also provide new constraints on the present-day tectonical motion of the Arctic crust.

1 Introduction

As discussed in the recent assessement of the Intergovernmental Panel on Climate Change (IPCC), the contribution of the two large ice shields on Greenland and Antarctica remains one of the largest uncertainties in explaining the global change in sea level (Warrick *et al.*, 1996). Estimates for the contribution to sea level change from the Greenland and Antarctic ice sheets are ± 0.4 mm/yr and ± 1.4mm/yr, respectively (Table 1). These uncertainties are due to several circumstances. (1) The accuracy of satellite altimetry over ice is still not sufficient particularly over areas with step topography to determine the change in the large ice sheets accurately enough to reduce the uncertainties. (2) The response of glaciers and ice sheets to climate change involves long time scales of up to several centuries. Climate variability (i.e. the input forcing function) is not well enough determined both in space and time to successfully force ice mass balance models. Additionally, the available ground observations are insufficient to constrain these ice models. (3) Observations of global ocean mass and volume (GOMV) changes could help to constrain the overall mass balance of the cryosphere, however, the determination of GOMV changes from relative sea level (RSL) observations at tide gauges is uncertain in itself due to the temporal and spatial structure of the global data set as well as the complex physical relation between GOMV and RSL. Moreover, RSL is strongly affected by other factors than GOMV changes. (4) The determination of GOMV changes from satellite altimetry is still not possible with sufficient accuracy due to the short interval of observation and problems in the separation of steric (volume) and mass effects.

Table 1: **Major contributions to global sea level changes.** Contributions are converted into equivalent rates of a globally uniform sea level change in mm/yr. Rates taken from Warrick *et al.* (1996).

Source	Estimated rate of sea level change (mm/yr)
Steric effects	0.2 to 0.7
Antarctica	-1.4 to 1.4
Greenland	-0.4 to 0.4
Glaciers	0.2 to 0.5
Continental ground waters	-0.5 to 0.7

In many recent sea-level studies based on the tide gauge data set, the aim has been to determine a global sea level rise. This approach suffers from inherent problems as summarized, for example, by Warrick *et al.* (1996) and discussed in details in Zerbini *et al.* (1996). However, local RSL trends at tide gauges close to ice loads may be used to infer information about changes in these loads, particularly, if interpreted together with other geophysical signals induced by ice load changes.

*Norwegian Mapping Authority, Kartverksveien, N-3500 Hønefoss, Norway, phone: +47-32118100, fax: +47-32118101, Email: plag@gdiv.statkart.no

†Institute of Astronomy of the Russian Academy of Science (INASAN), Moscow, Russia

‡ROSHYDROMET, Moscow, Russia

2 Geophysical signals of ice load changes

Changing ice loads induce significant viscoelastic deformations of the Earth's crust and mantle as is documented by a wealth of observations related to the postglacial rebound induced by the last ice age. The present-day deformations are the results of a convolution of the Green's function (i.e., the impuls response of the Earth to surface loading) with the complete time history of the combined ice and water load. Therefore, these deformations are also affected by recent changes in both the present-day ice sheets and the ocean waters. The effect of the present-day forcing potentially is large enough to use the induced deformations to constrain, for example, concurrent changes in the volume of the Antarctic and Greenland ice sheets (e.g. Conrad and Hager, 1995; James and Ivins, 1995; Wahr and Han, 1997).

Relative sea level (RSL) changes due to mass exchange between cryosphere and ocean are not globally uniform (Farrell and Clark, 1976). Due to the combined effect of the viscoelastic response of the Earth to ice deloading and ocean loading and the change in the gravitational potential, RSL will fall close to a melting ice sheet, while at intermediate distances there will be nearly no changes. A rise in RSL will only be observed in the far-field. Consequently, melting/growing Antarctic ice will have a sea-level signature distinctively different from melting/growing Greenland ice. Therefore, the pattern of RSL changes, in principle, can be used as a constraint for the origin of the mass added to or extracted from the ocean due to melting or growing ice sheets, respectively. Tide gauges should record the "foot-print" in RSL due to present-day changes in the large ice sheets. Tide gauges in the near-field are particularly important for this detection. Therefore, the combination of Arctic tide gauge data with space-geodetically observed crustal motion at the gauges would be an important contribution to the monitoring of the current pattern in relative sea level changes particularly in the Arctic ocean.

However, the post-glacial signal in these deformations is of the same order as the deformations induced by present-day ice changes. Any interpretation therefore requires the separation of the two effects. This separation may be achieved by combining observations of vertical motion and gravity changes (Wahr *et al.*, 1995).

Gravity changes δg due to surface loads measured by an observer on the Earth surface have two contributions: (1) due to the direct gravitational attraction, gravity changes at a given fixed point whenever mass movements take place. Thus, changes in the cryosphere and the induced deformations of the Earth result in gravity changes δg_m (Bouguer); (2) moving the observation point with respect to the (inhomogeneous) gravity field changes gravity at the observation point. Therefore, the vertical displacement of the measuring point due to glacially induced viscoelastic deformations results in gravity changes δg_v (free air). Thus, $\delta g = \delta g_v + \delta g_m$. If the vertical displacement v is known, then the free air contribution easily can be computed from $\delta g_v = -2\frac{g}{a}v \approx -\alpha v$ with a the Earth radius, g the gravitational acceleration, and $\alpha = -0.3$ μgals/mm. Both, the Bouguer contribution and the vertical displacement can be split into an elastic part due to the instantaneous response to current mass movements and a purely viscous part resulting from past mass changes, that is

$$\delta g_m = \delta g_m^e + \delta g_m^v \quad (1)$$

$$v = v^e + v^v. \quad (2)$$

In an extensive numerical study, Wahr *et al.* (1995) showed that

$$v^v \approx A\delta g_m^v \quad (3)$$

with $A \approx 6.5$ mm/μgal. Therefore,

$$\Delta = v - A\delta g_m \approx v^e - A\delta g_m^e \quad (4)$$

is a quantity decontaminated from the viscous part due to past mass changes resulting from surface loads. Moreover, it is likely that eq. 3 also holds approximately for tectonically induced deformations. Therefore, Δ can also be considered to be free of tectonic effects. Δ can be compared to geophysical forward computations using models of recent ice history as input. In this way, Δ can be used in the validation of ice mass balance models as well as ground-truth for changes in the ice cover determined from satellite altimetry.

Similarly, the sea-level equation derived by Farrell and Clark (1976) can be used to compute the RSL foot-print for a given ice history, which can be compared to tide gauge observations. However, to isolate the foot-print of present-day changes in the cryosphere, the RSL signal of disturbing factors have to be eliminated from the observations. Most prominent, these are (1) vertical crustal motion due to tectonics, (2) RSL changes due to postglacial rebound, and (3) decadal to interdecadal RSL variability due to atmosphere-ocean interactions.

For a discussion of how to correct for (3) see e.g. Zerbini *et al.* (1996). In many coastal areas, long-term changes in RSL are strongly dominated by crustal motion due to tectonic processes. In the Arctic, however, most of the coasts are passive margins (see e.g. Johnson *et al.*, 1979; Kearey and Vine, 1990). Tectonically induced vertical motions therefore should be small except for areas close to large rivers and their sedimentary domain.

The postglacial rebound signal (pgs) in RSL can be computed from geophysical models based on reconstructions of the ice history during the last 20000 years. However, models with slightly different viscosity structure in the mantle predict significantly different pgs (see below).

3 Arctic tide gauges

In Figure 1 the monthly mean values for the Arctic tide gauge records found in the global database of the *Permanent Service for Mean Sea Level* (PSMSL) are shown after an annual and semi-annual harmonic constituent and a linear trend has been removed. The PSMSL data set contains more than 1700 quality-controlled records (Spencer and Woodworth, 1993). In the Figure, we have compiled all Arctic records available in the PSMSL database with more than 5 years of data.

In some cases, the national authorities responsible for maintaining the tide gauges have far more data available than stored in the PSMSL data base. It should, however, be mentioned that the number of tide gauges operated in the Arctic is constantly decreasing. Thus, in recent years, Canada has closed down all Arctic tide gauges due to budgetary reasons. Denmark is considering to close down tide gauges in Greenland. During the last years, the quality of tide gauge observations in Russia has dramatically decreased due to a general reduction of the observational system, low payment of the observers, and staff shortages particularly at remote observing sites.

A change in sea level measured relative to a benchmark on land is the difference between geocentric sea surface changes and geocentric vertical motion of the tide gauge benchmark (ideally this is identical to the vertical motion of the crust). For linear trends, we therefore can write

$$r = t + v \quad (5)$$

where r is the geocentric sea level trend, t the RSL trend (positive for rise), and v the geocentric vertical crustal motion (positive for uplift). The determination of the geocentric sea-level changes thus requires knowledge of the vertical crustal motion v. At most tide gauges, this is currently not available.

As mentioned above, the pgs is a major contribution to RSL changes. To decontaminate RSL trends from the pgs, Peltier and Tushingham (1989) used a model to compute the pgs in RSL p and computed a decontaminated geocentric sea level

$$\hat{r} = t - p. \quad (6)$$

In another approach, Zerbini *et al.* (1996) used

$$v_o = -(t - p - r'); \quad (7)$$

with $r' = 1.8$ mm/yr to determine crustal vertical motion in the Mediterranean and found small (of the order of ± 1 mm/yr) and spatially consistent values for the crustal motion. In Table 2, $\hat{r}$ and v_o are given for the Arctic stations of Figure 1 using two different postglacial rebound models provided by Mitrovica (1996, personal communication). Model 1 has an elastic lithosphere of 120 km, and upper and lower mantle viscosities of 1×10^{21} Pas and 2×10^{21} Pas, respectively. Model 2 is identical to Model 1 except for a lower mantle viscosity of 4.75×10^{21} Pas. The ice model used is ICE-3G (Tushingham and Peltier, 1991).

Under the assumption that the pgs predicted by the two models is close to the actual pgs, then $\hat{r}$ can be interpreted as the difference between any vertical crustal motion and geocentric sea level change others than postglacial rebound. A value of $\hat{r}$ close to zero indicates that these two

Table 3: **Vertical crustal motion at Ny-Ålesund.** Velocities are in mm/yr. NUVEL1-A (NUV.) rates and VLBI results are from Ma (1998, personal communication). GPS results are from Heflin (1998).

Component	NUV.	VLBI	GPS
Radial	0.00	$1.16 \pm .54$	5.51 ± 0.39
Latitude	13.60	$13.50 \pm .17$	13.47 ± 0.08
Longitude	12.95	$11.75 \pm .17$	10.93 ± 0.11

contributions nearly compensate each other while a positive/negative value indicates a geocentric sea level change larger/smaller than vertical crustal mition. For the Norwegian stations souths of 68.6 °N, there is a tendence for uplift larger than the geocentric sea level trend while further north and east, the gsl appears to be larger than uplift. Only for those sites with short records, this pattern is disturbed. At all other stations except for Tuktoyaktuk (with a short record), $\hat{r}$ is close to zero.

Assuming a global sea-level rise of 1.8 mm/yr (Douglas, 1997), v_o tends to be positive except for Murmansk, Russkaya Gavan, Tuktoyaktuk (short record), and Honnigsvåg (with possible problems in the geodetic control). This pattern is consistent with an overall deloading due to a decrease of the Arctic land-based cryosphere, particularly the Greenland ice sheet. However, problems in the predictions of the pgs may bias the v_o. Moreover, the values for v_o may also partly be due to tectonics.

At Ny-Ålesund, the tide gauge is regularly connected to the space-geodetic benchmarks by precise leveling, and VLBI and GPS are providing information on the three-dimensional movement of the crust. Unfortunately, the precision currently achievable for the VLBI and GPS analyses is not sufficient to provide a reliable estimate of v (see Table 3).

Ny-Ålesund is in the vicinity of the active ridge and transform fault area west of Svalbard, and here tectonically induced vertical crustal motion cannot be excluded. It is interesting to note that both the VLBI and GPS results are in close agreement with the rates expected from the global plate tectonic model NUVEL1-A (DeMets *et al.*, 1994). This indicates that the location is still on the stable plate and not in the marginal deformation area. Moreover, a vertical motion v_o of 2 mm/yr appear to be too large to be fully attributed to tectonic causes. However, without additional observations it is impossible to support the notion of a decreasing ice load in the Arctic.

4 Objective of CRUSLAC

The proposed project has the objective to enhance our knowledge concerning vertical crustal movement and sea level changes along the Arctic coast on intra-seasonal to decadal time scales in order to contribute to a better understanding of the effects of climate changes on the Arctic and in order to detect such effects at the earliest possible stage.

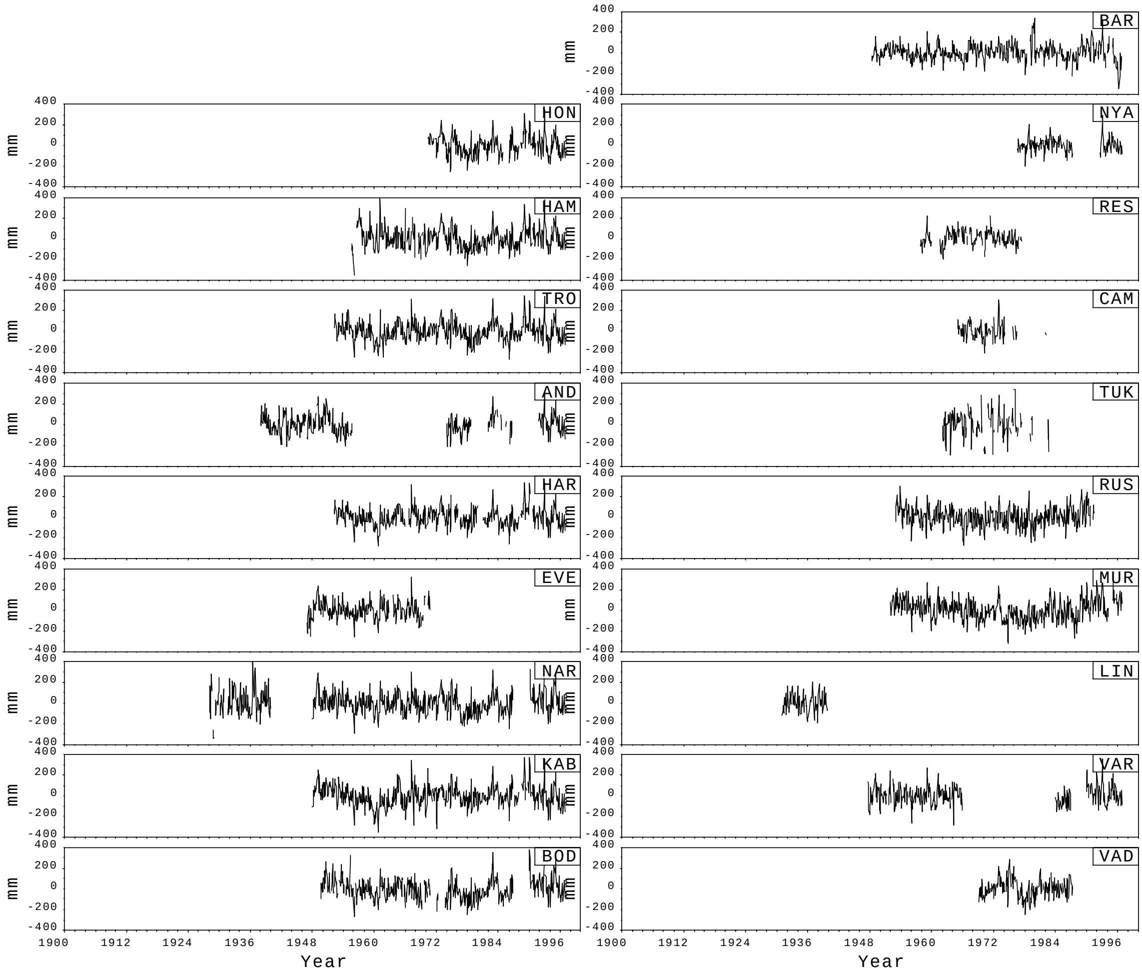

Figure 1: **PSMSL's Arctic tide gauges records.**

For the full names of the sites, see Table 2. Displayed are the residual monthly means after a model consisting of a seasonal cycle and a linear trend has been removed. The model is fitted to the time series in a least squares fit. The seasonal cycle is represented by an annual and a semiannual harmonic constituent. Thus, the full model $m(t) = A_{\mathrm{Sa}} \sin(\omega_{\mathrm{Sa}} t + \varphi_{\mathrm{Sa}}) + A_{\mathrm{Ssa}} \sin(\omega_{\mathrm{Ssa}} t + \varphi_{\mathrm{Ssa}}) + a + bt$ with t being the time, A the amplitude, ω the angular frequency, φ the phase of the constituent, and Sa and Ssa denoting the annual and semi-annual constituents, respectively. The trends resulting from the fits are compiled in Table 2 together with other relevant parameters of the two time series.

Note the non-linear behaviour at both Russkaya Gavan and Murmansk. Unfortunately, the tide gauge at Russkaya Gavan was closed in 1991. Some neigbouring tide gauges display some large differences indicating problems in the maintenance or the data. For example, compare Barentsburg and Ny-Ålesund around 1980 and 1994. These features become more elaborated by considering the differences between neigbouring tide gauges (see Plag, 1998).

At all sites, the original monthly means are dominated by the annual and semiannual harmonic constituents with amplitudes of the order of 100 mm and 20 mm, respectively. Only at Cambridge Bay is the semiannual constituent with almost 70 mm much larger than the average. Along the Norwegian Coast and up to Svalbard and along the Siberian Coast maximum sea levels occur late in autumn while at the North American sites the maximum occurs in summer, a pattern that may be attribute to the presence and absence of the gulf stream, respectively. Non-seasonal variations are generally of the order of $\pm$150 mm with a few exceptional sea levels exceeding $\pm$ 200 mm.

Table 2: **Trends at Arctic tide gauges**

N is the number of monthly values in the record. t is the linear term and δt the standard error resulting from the fit of the model equation given in Figure 1 to the time series. $\hat{r}$ is computed from eq. 6, while v_o results from eq. 7 assuming $r = 1.8$ mm/yr (Douglas, 1997). The indices 1 and 2 refer to the two models for the pgs (see text). All rates in mm/yr.

Station	Long.	Lat.	Beg.	End	N	t	δt	p_1	p_2	r'_1	r'_2	v_{o1}	v_{o2}
Bodø	14°23'E	67°17'N	1949	1996	482	-3.049	0.5	-2.5	-3.6	-0.5	+0.6	2.3	1.2
Kabelvåg	14°29'E	68°13'N	1880	1996	572	-0.962	0.3	-0.5	-1.6	-0.5	0.6	2.3	1.2
Narvik	17°25'E	68°26'N	1928	1996	685	-3.245	0.2	-2.2	-3.5	-1.0	0.3	2.8	1.5
Evenskjær	16°33'E	68°35'N	1947	1970	267	-4.000	0.7	-1.3	-2.5	-2.7	-1.5	4.5	3.3
Harstad	16°33'E	68°48'N	1952	1996	497	-0.053	0.4	-0.9	-2.1	0.8	2.0	1.0	-0.2
Andenes	16°09'E	69°19'N	1938	1996	362	1.538	0.5	0.2	-0.9	1.3	2.4	0.5	-0.6
Tromsø	18°58'E	69°39'N	1952	1996	533	0.034	0.3	-0.8	-2.1	0.8	2.1	1.0	-0.3
Hammerfest	23°40'E	70°40'N	1955	1996	471	-0.137	0.4	-1.2	-2.7	1.1	2.6	0.7	-0.8
Honningsvåg	25°59'E	70°59'N	1970	1996	292	2.705	0.5	-1.3	-2.9	4.0	5.6	-2.2	-3.8
Vadsø	29°45'E	70°04'N	1969	1987	206	-2.318	0.6	-2.1	-3.9	-0.2	1.6	2.0	0.2
Vardø	31°06'E	70°20'N	1947	1996	322	-0.755	0.5	-1.6	-3.4	0.8	2.6	1.0	-0.8
Linakhamari	31°22'E	69°39'N	1931	1939	107	-4.377	1.2	-2.2	-4.0	-2.2	-0.4	4.0	2.2
Murmansk	33°03'E	68°58'N	1952	1996	530	1.581	0.3	-2.4	-4.1	4.0	5.7	-2.2	-3.9
Russkaya Gavan	62°35'E	76°12'N	1953	1991	457	-0.851	0.4	-2.8	-4.5	1.9	3.6	-0.1	-1.8
Tuktoyaktuk	132°58'W	69°25'N	1962	1982	156	7.134	1.1	3.0	2.7	4.1	4.4	-2.3	-2.6
Cambridge Bay	105°04'W	69°07'N	1965	1982	121	-3.991	1.0	-3.5	-5.8	-0.5	1.8	2.3	0.0
Resolute	94°53'W	74°41'N	1957	1977	206	-2.883	0.9	-3.2	-4.3	-0.3	1.4	2.1	0.4
Ny-Ålesund	11°56'E	78°56'N	1976	1996	175	-1.373	0.8	-0.9	-1.3	-0.5	-0.1	2.3	1.9
Barentsburg	14°15'E	78°04'N	1948	1996	560	-2.253	0.3	-2.0	-2.6	-0.3	0.3	2.1	1.5

To achieve the objective, it is proposed

- to co-locate at least five existing, equally distributed operational tide gauges in the Arctic with continuously recording GPS receivers (CGPS);
- to perform zero-epoch absolute gravity measurements at these tide gauge;
- to connect all operational Arctic tide gauges in a zero-epoch GPS campaign.

The tide gauges selected for potential co-location with CGPS and absolute gravity are Honningsvåg in Norway, Tiksi in Russia, Alert in Canada, Danmarkshavn in Greenland, and Prudhoe Bay in Alaska.

It should be mentioned here, however, that Canada has closed down all Arctic tide gauges. This is a loss for the proposed project and it would be an important step towards a sea level monitoring in the Arctic, if at least some of the GLOSS gauges could be reinstalled. Denmark is also considering to close down gauges in Greenland, and the proposed project may contribute to prevent this to happen.

The tide gauge at Ny Aalesund, Svalbard is already connected to a CGPS site. Absolute gravity measurements will be carried out at the site in July 1998. A co-location of the tide gauge at Barentsburg with one of the longest Arctic record available in the database of the PSMSL is currently discussed.

The project will involve the responsible agencies from Norway (Norwegian Mapping Authority), Russia (ROSHYDROMET and Institute of Astronomy, Russian Accademy of Science (INASAN), Moscow), USA (NOAA), Canada (Canadian Hydrographic Service) and Denmark (KMS and Meteorological Institute). The project will be partly financed out from the available resources of the participating institutes. Additional funding will be requested from different founding sources both on national and international level. On international level, the EU and the Global Environment Facility (GEF) are considered to be appropriate sources for founding.

Depending on available funding and internal resources, it is planned to establish the CGPS sites in the period June to September 1999. Absolute gravity measurements at the five co-located tide gauges as well as the GPS traverse are envisaged to be carried out in the year 2000.

Acknowledgements

The postglacial rebound signal was computed from data sets provided by J.X. Mitrovica.

References

Conrad, C. P. and Hager, B. H. (1995). The elastic response of the Earth to interannual variations in Antarctic precipitation. *Geophys. Res. Lett.*, **22**, 3183–3186.

DeMets, C., Gordon, R. G., Argus, D. F., and Stein, S. (1994). Effect of recent revisions to the geomagnetic reversal time scale on estimates of current plate motions. *Geophys. Res. Lett.*, **21**, 2191–2194.

Douglas, B. C. (1997). Global sea level rise: a redetermination. *Surveys Geophys.*, **18**, 279–292.

Farrell, W. E. and Clark, J. A. (1976). On postglacial sea level. *Geophys. J. R. Astron. Soc.*, **46**, 647–667.

Heflin, M. B. (1998). GPS time series. http://sideshow.jpl.nasa.gov/mbh/series.html.

James, T. S. and Ivins, E. R. (1995). Present-day Antarctic ice mass changes and crustal motion. *Geophys. Res. Lett.*, **22**, 973–976.

Johnson, G. L., taylor, P. T., Vogt, P. R., and Sweeney, J. F. (1979). Arctic basin morphology. *Polarforschung*, **48**, 20–30.

Kearey, P. and Vine, F. J. (1990). *Global Tectonics*. Geoscience Texts. Blackwell Scientific Publications, Oxford. 302 pp.

Peltier, W. R. and Tushingham, A. M. (1989). Global sea level rise and the Greenhouse effect: Might they be connected? *Science*, **244**, 806–810.

Plag, H.-P. (1998). Space-geodetic contributions to global-change research at ny-ålesund. In *Proceedings for the 27-th Int. Symp. on Remote Sensing of Environment: Information for Sustainability, June 8-12, 1998, Tromsø, Norway*, pages 227–231. Norwegian Space Centre.

Spencer, N. E. and Woodworth, P. L. (1993). Data holdings of the Permanent Service for Mean Sea Level. Technical report, Permanent Service for Mean Sea Level, Bidston, UK. 81pp.

Tushingham, A. M. and Peltier, W. R. (1991). Ice-3G: a new global model of late pleistocene deglaciation based upon geophysical predictions of post-glacial relative sea level change. *J. Geophys. Res.*, **96**, 4497–4523.

Wahr, J. and Han, D. (1997). Predictions of crustal deformation caused by changing polar ice on a viscoelastic Earth. *Surveys Geophys.*, **18**, 303–312.

Wahr, J. M., DaZhong, H., and Trupin, A. (1995). Prediction of vertical uplift caused by changing polar ice volumes on visco-elastic earth. *Geophys. Res. Lett.*, **22**, 977–980.

Warrick, R. A., Provost, C. l., Meier, M. F., Oerlemans, J., and Woodworth, P. L. (1996). Changes in sea level. In J. T. Houghton, L. G. Meira Filho, B. A. Callander, N. Harris, A. Kattenberg, and K. Maskell, editors, *Climate Change 1995–The science of climate change*, pages 359–405. Cambridge University Press, Cambridge, UK.

Zerbini, S., Plag, H.-P., Baker, T., Becker, M., Billiris, H., Bürki, B., Kahle, H.-G., Marson, I., Pezzoli, L., Richter, B., Romangoli, C., Sztobryn, M., Tomasi, P., Tsimplis, M., Veis, G., and Verrone, G. (1996). Sea level in the Mediterranean: a first step towards separation of crustal movements and absolute sea-level variations. *Global and Planetary Change*, **14**, 1–48.