# Sea level and ice sheets: what can tide gauges tell us?

Hans-Peter Plag*

## Abstract

**The global data set of monthly mean sea levels obtained from coastal tide gauge may provide valuable constraints on the present-day mass balance of the large ice sheets. However, this requires a full account for the physical relationship describing changes in relative sea level induced by the exchange of mass between ocean and cryosphere. In addition, a careful processing of the tide gauge data is required to obtain local relative sea-level trends decontaminated for tectonic crustal motion, postglacial rebound and decadal sea level variability.**

## 1 introduction

One of the impacts of the predicted global warming is the anticipated global sea-level rise. Estimates of a global sea level rise over the last 100 years have been utilized in the climate change discussion as an indication of changes in the ocean volume. Particularly for the assessment of future impacts of climate change and the planning of actions to mitigate these, a knowledge of future relative sea-level changes is required. Considering that most of the coasts and low-lying areas are heavily populated and often with a well developed infrastructure, there is a great potential for damage due to a regional sea-level rise. Consequently, the possibility of a significant sea-level rise over the next 50 to 100 years as projected by the IPCC assessments (Warrick *et al.*, 1996) has invoked considerable public interest.

Considerable attempts have been made to identify a ”climate signal” in global sea level (see Warrick *et al.*, 1996, for a summary), which can be expected for two reasons: (1) the ocean volume changes whenever a change in the heat content of the ocean's water takes place; and (2) the ocean mass changes due to exchanges between ocean and other reservoirs in the global hydrological cycle. The ocean is the largest reservoir in the global hydrological cycle. Moreover, the flows between the ocean and the other reservoirs are generally larger then the flows between any of the other reservoirs. This clearly illustrates the dominant role of the ocean for the hydrological cycle. Therefore, changes in the ocean's volume or mass are directly related to changes in the global hydrological cycle and therefore to climate change.

As illustrated by any picture of the Earth from space, it is obvious that the Earth is a wet planet where water vapor, fluid or frozen water participate, dominate or control all processes at the Earth's surface. The energy available for the hydrological cycle crucially determines the state and the processes in the system. Hydrology could therefore be considered as Earth system science (O'Kane, 1996, personal communication). From this point of view, our degree of knowledge of the hydrological cycle is equivalent to the degree to which we understand the basic processes.

Over the last decades, estimates of flows and reservoir sizes in the hydrological cycle have changed considerable, indicating also the degree to which we know these numbers. Today, important reservoirs such as the water stored in soil and in the ground are rather uncertain with some estimates indicating uncertainties larger than 20 %. Flows between the reservoirs are equally uncertain with particularly flows into the ground and exchanges of the terrestrial hydrosphere with the ocean being uncertain. For the present mass exchange with the cryosphere, even the sign is uncertain (see Warrick *et al.*, 1996; Plag *et al.*, 1998).

A knowledge of the mass and/or volume of the global ocean water as function of time constitutes a crucial constraint for the reconstruction of past climates, as well as the validation of models used to predict future changes in these quantities. In an attempt to determine the recent changes in these quantities, sea-level curves for the last 100 to 150 years as well as global trends have been constructed in several studies (for a review, see Warrick *et al.*, 1996; Zerbini *et al.*, 1996). However, all of them used basically the same global data set of monthly (or annual) mean sea-level records obtained by coastal tide gauges. Despite the common data base, the results display a considerable scatter of 1 to 2.5 mm/yr indicating the degree of freedom in data preparation, selection, and corrections inherent both in the data set and the complex relation between relative coastal sea level at a single tide gauge and the global mass and volume. Moreover, the uncertainties given for the global trends determined in the various studies are of the order of less than 1 mm/a, but these uncertainties are pure statistical quantities. The uncertainties due to the complexity of the physical problem may in fact be much larger than the numbers given. The complex relation between changes of the ocean's global mass and volume and relative sea level changes has only been accounted for in the correction of the postglacial rebound effect due to the last deglaciation. A few authors have criticized the approach used to determine a global sea level rise from tide gauge (Pirazzoli, 1989; Gröger and Plag, 1993; Plag, 1993). Plag (1993) even claimed that it is not possible to determine a global sea level

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

change from tide gauge data due to the poor spatial sampling.

## 2 Basic concepts

For the discussion of the relation between sea level changes and changes in the ocean's mass forced by changes in the cryosphere, it is important to distinguish between the global ocean mass and volume (GOMV) and relative sea level (RSL).

On the one hand, the GOMV are two quantities characterizing the ocean as a reservoir in the global hydrological cycle. It is important to note that these quantities are absolute numbers. The GOMV are functions of ocean mass, salinity and heat content. On climatological time scales, the cryosphere has the greatest potential to contribute to mass changes, and this ability has been well documented during the ice ages. Volume changes (for constant mass) are due to density changes which, on climatological time scales, result primarily from heat exchange with the atmosphere.

On the other hand, sea level is always a relative quantity given with respect to a coordinate system (e.g. a geocentric coordinate system) or a reference plane (e.g. a geoid model or the reference ellipsoid). Sea level describes how the GOMV is distributed in a given topography of the Earth surface. RSL at any given tide gauge may be affected by many causes operating on different spatial and temporal scales which separate into two broad classes, namely those changing the sea level (with respect to a fixed reference surface) and those resulting in vertical land movements. Thus, the distribution of GOMV on the Earth's surface depends on many different factors, such as the topography, the geoid, Earth rotation, atmospheric and oceanic circulation, heat distribution in the ocean, viscoelastic properties of the solid Earth, past and present mass movements including changes in ice sheets and sedimentation, and even crustal subsidence of anthropogenic origin.

GOMV is a global parameter indicating changes in the hydrological cycle and thus is an indicator for climate change or climate variability. Coastal RSL is a parameter relevant for coastal development with both, the sea level itself and the rate of changes influencing the coastal development. For an integrated and sustainable development of coastal areas, the knowledge of sea level and sea level trends therefore is of basic interest. RSL is thus an indicator for local impact of climate change.

Whenever mass is transferred between the ocean and other reservoirs, sea level is changed in a complex way. Due to the fact that the Earth is a deformable, gravitating body, there is no simple relation between sea level observed at any point on the Earth's surface and the GOMV. In fact, a mass movement from or to the ocean changes all planes relevant to sea level, i.e., ocean bottom, the reference ellipsoid, the geoid and the sea surface. In particular, the combined gravitational and elastic response of the Earth to changes in the ice sheets lets sea level fall in the vicinity of a decreasing ice sheet and rise in the far-field. The complex relation between GOMV and RSL has to be taken into account both in predicting future RSL changes at a given location and in inverting past RSL observations for GOMV changes.

## 3 Outline of a rigorous determination of GOMV from RSL observations

A linear description of the relation between changes in the Earth's ice cover and RSL was given first by Farrell and Clark (1976) as the hydrostatic RSL equation on a viscoelastic Earth:

$$
\begin{aligned}
\xi(\vartheta,\lambda,t) \;=\; & c(t) + \qquad (1)\\
& O(\vartheta,\lambda,t)\int_{-\infty}^{t}\int_{0}^{\pi}\int_{0}^{2\pi} G(\vartheta,\lambda,\vartheta',\lambda',t-t') \\
& \frac{\mathrm{d}}{\mathrm{d}t'}\left\{O(\vartheta',\lambda',t')\rho_{\mathrm{W}}\xi(\vartheta',\lambda,t')\right. \\
& \left. +\left[1-O(\vartheta',\lambda',t')\right]\rho_{\mathrm{I}}\eta(\vartheta',\lambda,t')\right\} \\
& \sin\vartheta'\mathrm{d}\lambda'\mathrm{d}\vartheta' dt'.
\end{aligned}
$$

Here, $\xi$ is the sea level change relative to the (deformable) solid Earth surface. For $t = 0$ we have $\xi(t = 0) = 0$. $G$ is the Green's function for sea level, $O$ is the ocean function, defined as

$$
O(\vartheta,\lambda,t) = \begin{cases} 1 & \text{on oceans} \\ 0 & \text{on continents} \end{cases}, \qquad (2)
$$

and $\eta$ the cumulated ice load change due to mass added or removed from land. $\rho_{\mathrm{W}}$ and $\rho_{\mathrm{I}}$ are the densities of the ocean water and the ice, respectively. $c(t)$ is determined such that mass is conserved, i.e.

$$
\left\langle \xi(t) \right\rangle_{O} = \frac{\rho_{\mathrm{I}} \left\langle \eta \right\rangle_{E}}{\rho_{\mathrm{W}} \left\langle O(t) \right\rangle_{E}} (= \text{eustatic change;}) \,. \qquad (3)
$$

$\left\langle \cdot \right\rangle_{O}$ and $\left\langle \cdot \right\rangle_{E}$ denote an average over the oceans and total Earth surface, respectively.

Equation (1) does not consider any dynamic effects in the ocean due to the mass movements, i.e., it is assumed that all processes are slow enough for the ocean to respond hydrostatically to the changes. Dickman (1997, personal communication) estimated dynamics effects due to seasonal melting and growth of the Antarctic ice sheets and found these effects to be of the order of a few mm. Thus, for considerations of trends in the ice sheets, these effects can be safely neglected.

Based on a Maxwell rheology and a simple Earth model, Farrell and Clark (1976) showed that the viscous contribution 1000 years after a significant mass change still is below a few percent of the instantaneous elasto-gravitative effect. Moreover, the spatial pattern of the sea-level changes is not significantly changed by the viscous contribution. Gasperini *et al.* (1986) considered present-day cryogenic forcing of perturbations in the Earth's rotation and found that a transient rheology may be important in the modeling of the response due to such a forcing on time scales of centuries. However, over time scales of up to centuries, the viscoelastic contribution can be consider small compared to the elasto-gravitative one.

As discussed in Farrell (1972) and Peltier (1974) for the elastic and viscoelastic case, respectively, the Green's function $G$ can be computed for a given spherically symmetric elastic (viscoelastic) isotropic Earth model. Thus, for a known load history, the sea-level variations can be computed for such a simplified Earth model.

It is well known that the disintegration of the last great ice sheets produced a distinct spatial pattern, a footprint, in RSL, with rather different temporal characteristics of the RSL in the near-, the intermediate and the far field of the load changes (see, e.g., Quinlan and Beaumont, 1982; Lambeck, 1993). The elastic response of the Earth to present-day changes in the cryosphere can be expected to produce a similar footprint, which should be present in the tide gauge data. In principle, this footprint should be detectable in the tide gauge data. Thus, the tide gauge data should provide information on recent changes in the cryosphere. However, to identify this footprint, the local trends at the tide gauges have to be determined with utmost care.

# 4 Determination of RSL trends at tide gauges

The global tide gauge data set provided by the PSMSL (Spencer and Woodworth, 1993) contains more than 1700 records of monthly mean sea levels. These time series are of variable quality and length. The PSMSL separates the total data set into a so-called metric and Reviced-Local-Reverence data set, with the latter one comprising all the records with a well-recorded history of the tide gauge benchmark. For trend determinations, only records in the RLR subset can be used. In this RLR data set, there are about 1000 records with sufficient lengths to determine reliable local trends.

To improve the quality of the trend data set, it is necessary to account for as many influences as possible. Basically, the local trends determined from tide gauges are significantly affected by (1) tectonic movements, (2) postglacial rebound, and (3) decadal to interdecadal variability. We will discuss these effects one by one.

(1) Large parts of the ocean's coasts are in deformation areas associated with plate tectonics (see, e.g. Fig. 6 in Stein, 1993). In most of these regions, the tectonically caused vertical crustal movements are dominated by short spatial scales of the order of 30 to 100 km (see e.g. Emery and Aubrey, 1991). Thus, the ice mass footprint is distinctively different from the tectonic signal in sea level and a contamination should be small. With respect to the long-wavelength ice signal, the tectonic signal can be considered as noise. Moreover, in many tectonic regions the vertical motion is of the order of less than $\pm 1$ mm/yr and thus smaller than the expected local signal due to ice mass changes. Therefore, except for a few regions with extremely large tectonic vertical motion, the local tide gauge trends need not be corrected for tectonic vertical crustal motion.

(2) The postglacial signal in sea level may be highly correlated with the present-day footprint. Fortunately, elaborated models exist for the postglacial signal in RSL and these models can be used to decontaminate the tide gauge trends for the postglacial signal. Inter-model differences are still considerable. Therefore, a suite of models should be used to study the sensitivity of the results to uncertainties in the postglacial rebound model.

(3) The interannual to multidecadal variations in RSL are of the order of several cm, and thus bias trends significantly. To determined a local trend from an individual tide gauge with an accuracy of 0.5 mm/yr, records of 60 years are required in most coastal regions (e.g. Zerbini *et al.*, 1996). Both, tide gauge studies (e.g. Sturges, 1987; Gröger and Plag, 1993) and satellite altimetry observations (e.g. Nerem *et al.*, 1997) have shown that the interannual to multi-decadal sea level variations are spatially coherent over large regions. Therefore, based on a high-quality long record in a given region, shorter records can be decontaminated for the interannual to multidecadal variability. Monthly differences between the two records are nearly free of the interannual to multidecadal variability. The trend of these differences plus the long-term trend at the base station thus is a decontaminated long-term trend at the station with the shorter record (see, e.g., Plag, 1988).

# 5 Conclusions

Up to now, establishing past variations in the GOMV based on RSL data has been hampered by the complexity of this relation, and the available global curves and trends are insufficient. Only a rigorous analysis of the global tide gauge data set making use of all available information concerning local effects at the tide gauge location can determine reliable uncertainty bounds for the global signal. Up to now, no such rigorous but urgently required analysis is available. In fact, most of the studies of sea level changes were motivated more by the impact than the cycle aspect.

Utilizing the full physical relationship between sea level and GOMV changes, the tide gauges could well be sufficient to constrain the mass movement having contributed to the observed trends in local RSL.

Based on the sea-level equation describing the response of sea level to mass exchange between ocean and cryosphere, the global tide gauge data collected over the last 200 years should be sufficient to provide important constraints for the mass balance of the major ice sheets.

## References


Emery, K. O. and Aubrey, D. G. (1991). *Sea Levels, Land Levels, and Tide Gauges*. Springer, Berlin.

Farrell, W. E. (1972). Deformation of the Earth by surface loads. *Rev. Geophys. Space Phys.*, **10**, 761–797.

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

Gasperini, P., Sabadini, R., and Yuen, D. A. (1986). Excitation of the earth's rotational axis by recent glacial discharges. *Geophys. Res. Lett.*, **13(6)**, 533–536.

Gröger, M. and Plag, H.-P. (1993). Estimations of a global sea level trend: Limitations from the structure of the PSMSL global sea level data set. *Global and Planetary Change*, **8**, 161–179.

Lambeck, K. (1993). Glacial rebound of the British Isles - I. Preliminary model results,II. A high-resolution, high precision model. *Geophys. J. Int.*, **115**, 941–990.

Nerem, S. M., Rachlin, K. E., and Beckley, B. D. (1997). Characterization of global mean sea level variations observed by TOPEX/POSEIDON using empirical orthogonal functions. *Surveys Geophys.*, **18**, 293–302.

Peltier, W. R. (1974). The impulse response of a Maxwell Earth. *Rev. Geophys. Space Phys.*, **12**, 649–669.

Pirazzoli, P. A. (1989). Present and near-future global sea-level changes. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **75**, 241–258.

Plag, H.-P. (1988). A regional study of Norwegian coastal long-period sea-level variations and their causes with special emphasis on the Pole Tide. *Berl. Geowiss. Abhandl. Reihe A*, **14**, 1–175.

Plag, H.-P. (1993). The "sea level rise" problem: An assessment of methods and data. In *Proceedings of the International Coastal Congress, Kiel 1992*, pages 714–732. P. Lang Verlag, Frankfurt.

Plag, H.-P., Tatevian, S., and Zilberstein, O. (1998). Crustal motion and sea level changes along the Arctic coasts (CRUSLAC). In H.-P. Plag, editor, *The Ninth General Assembly of the Working group of European Geoscientists for the Establishment of Networks for Earth-science Research, WEGENER98*, pages 98–103. Norwegian Mapping Authority, Norway.

Quinlan, G. and Beaumont, C. (1982). The deglaciation of Atlantic Canada as reconstructed from the post glacial relative sea-level record. *Can. J. Earth Sci.*, **19**, 2232–2246.

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.

Stein, S. (1993). Space geodesy and plate motion. In D. E. Smith and D. L. Turcotte, editors, *Contributions of Space Geodesy in Geodynamics: Crustal Dynamics*, volume 23 of *AGU Geodynamics Series*, pages 5–20. AGU.

Sturges, W. (1987). Large-scale coherence of sea level at very low frequencies. *J. Phys. Oceanogr.*, **17**, 2084–2094.

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.