
Time-Varying Mean Sea Level

Luciana Fenoglio-Marc and Erwin Groten

Contents

1	Introduction	520
2	Theoretical Considerations	522
3	Scientific Relevance	524
4	Data and Methodology of Numerical Treatment	526
4.1	Fundamental Results	527
5	Future Directions	534
5.1	Accuracy of Sea-Level Observation	534
5.2	Observation at the Coast and in Open Ocean	535
5.3	Attribution of Sea-Level Rise	536
5.4	Reconstruction of Past Sea Level	537
5.5	Prediction of Sea-Level Evolution	537
5.6	Mathematical Representation of Time-Varying Sea Level	538
6	Conclusions	540
	References	541

Abstract

After a general theoretical consideration of basic mathematical aspects, we give numerical and physical details for the last two decades, where global and reliable data are available. The concept of a “mean sea level” is in itself rather artificial, because sea level varies at various temporal and spatial scales. This is because the sea is in constant motion, affected by the high- and low-pressure zones above

L. Fenoglio-Marc (✉)

Institute of Geodesy, Technical University Darmstadt, Darmstadt, Germany

e-mail: fenoglio@ipg.tu-darmstadt.de

E. Groten

Institute of Physical Geodesy, Technical University Darmstadt, Darmstadt, Germany

e-mail: erwingroten@yahoo.de

it, the tides, local gravitational differences, and so forth. What is possible to do is to calculate the mean sea level at that point and use it as a reference datum.

Traditionally, coastal tide gauges measure sea-level variability. Since 1993 satellite altimetry provides near-global maps of sea-level change with high spatial and temporal resolution. Sea-level change has therefore in altimetry its primary global source of information.

Coastal and global sea-level variability is here considered. The coastal variability is estimated from tide gauges, from altimeter data colocated to the tide gauges and from altimeter data along the world coasts. The global variability is derived from altimeter data. We show that the sea level has in the interval 1993–2012 an average positive trend of 3.2 ± 0.4 mm/year, which is higher than the average trend of 1.8 ± 0.5 mm/year derived from tide gauge data over the twentieth century. The trends are not spatially uniform but regionally dependent. The variability at interannual time scale appears to be related to the variability of climatic indices, like Northern Atlantic (NAO) and the El Niño-Southern Atlantic Oscillation (ENSO).

At certain coastal locations, non-climatic components of relative sea-level change, mainly subsidence, are locally appreciable. The relative sea-level rise there is up to three to four times larger than the global mean sea-level rise.

1 Introduction

The study of transient phenomena differs essentially from usual geodetic investigations where in the past stationary solutions prevailed. Whenever time-dependent boundary value problems (BVPs) are considered, harmonic function solutions have to be carefully selected, because nonstationary potentials are often nonharmonic and, therefore, cannot be handled by geodetic techniques deduced from classical potential theory. Consequently, the investigation of global vertical reference frames in connection with rising sea level, global warming, and coastal deformations for Earth models affected by plate tectonics does not lead to straightforward classical solutions but rather to stepwise and similar approaches where redundant data sets involving a large number of various types of observations can yield reliable results. Applications of that kind are not totally uncommon in geodesy, as geodetic systems had always been evaluated for models of the Earth perturbed by tides and other temporal variations where, however, appropriate reduction schemes had to be applied. The study of time-varying mean sea level is a rather complex topic in that connection which benefits from modern satellite techniques. They make precise solutions possible. In so far geodetic approaches are typically approximation approaches.

Sea-level rise is an important aspect of climate change. At least 50-year records are needed to separate secular, decadal, and interannual variations (Douglas 2001). Over this long time interval, only few tide gauge stations along the world coastlines are available for the analysis (Church et al. 2008); the corresponding data indicate over the twentieth century a mean sea-level rise in the range of 1–2 mm/year (Cazenave and Nerem 2004; Church et al. 2004; Church and White 2006; Holgate

2007; Domingues et al. 2008). The spatial distribution of the tide gauge stations as well as the existence of interannual and low-frequency signals affects the recovery of secular trends in short records. Thus, it is important to develop techniques for the estimation of sea-level trends “cleaned” from decadal variability.

The analysis based on tide gauge data alone reflects only the coastal sea level, while the global sea-level change is derived from the satellite altimeter missions, which provide since 1993 an uninterrupted global record of sea-level changes. Another fundamental difference between tide gauge and altimeter-derived sea level consists in the fact that while the first is relative to land, the second is relative to the Earth’s center.

Estimates for the rate of the global sea level from altimetry, without accounting for the effect of glacial isostatic adjustment (GIA), are around 2.8 ± 0.4 mm/year over 1993–2003 (Lombard et al. 2005; Bindoff et al. 2007), 3.1 ± 0.4 in 1993–2006 (Beckley et al. 2007), and 3.1 ± 0.1 mm/year in 1993–2007 (Prandi et al. 2009).

Holgate and Woodworth (2004) suggest that the coastal sea level is rising faster than the global mean and give in 1993–2002 a rate of 4 mm/year for the coastal sea level. Following White et al. (2005) however, the difference between the rates derived from global altimetry and from coastal tide gauges is due to the different sampling. Finally Prandi et al. (2009) show that the differences observed are mainly an artifact due to the interannual variability.

In addition to the uncertainty of the rate due to the fitting procedure, measurement errors and omission error are involved. The calibration of altimeter data using colocated altimetry and tide gauge stations gives an error of 0.4 mm/year for the altimetric sea-level change (Mitchum 2000; Leuliette et al. 2004). Jevrejeva et al. (2006) assign an error of 1 mm/year to the global sea-level change derived from tide gauges, due to the nonuniform data distribution.

The tide gauge stations used in the various studies are different, from more than 1,000 stations in Jevrejeva et al. (2006) to 91 stations in Prandi et al. (2009). The filling of the incomplete time series reduces the effective number of stations.

Fenoglio-Marc and Tel (2010) investigate if the coastal sea level observed by tide gauges conveniently represents the global sea level obtained using both altimetry and tide gauge stations. The study differs from Prandi et al. (2009) in the selected tide gauge stations and in considering the sea-level averages both globally and regionally. Distinction is made between (a) global sea-level change derived from altimetry (GSL), (b) costal sea-level change derived from altimetry (CGSL), and (c) costal sea-level change derived from tide gauges (CGTG). First, the global and regional basin averages of sea level are considered and long-term trends are identified, and then the relationship between climatic indices and the main components of the interannual and interdecadal variability is investigated. Similar results are obtained over the extended interval 1993–2012 (Nerem et al. 2010).

Regional analysis on the impact of sea-level rise in coastal zone shows that at certain locations, non-climatic components of relative sea-level change, mainly subsidence, are locally appreciable and the relative sea-level rise there is found to be up to three to four times larger than the global mean sea-level rise (Cazenave and Llovel 2010; Fenoglio-Marc et al. 2012).

2 Theoretical Considerations

One of the key problems related to mean sea level is the global unification of vertical datums. Regionally, e.g., in Europe, the various national leveling systems have in the past been interconnected by different geodetic techniques. One of the pilot products was the UELN (Unified European Levelling Network) or REUN (Reseau Européen Unifié de Nivellement). In crossing smaller oceanic areas, hydrostatic leveling had been applied, e.g., between Denmark and Northern Germany. With the advent of the Global Positioning System (GPS) technique, satellite methods played a significant role, e.g., in the construction of the railway tunnel between France and Great Britain. For precise navigation purposes, the connection of vertical data between continents gained increasing interest. In this context, satellite altimetry together with recent precise Earth Gravity Models (EGM), e.g. EGM 2008, played a major role. With data from the gravimetric satellites GRACE and GOCE at hand, the previous obstacles in creating a global vertical datum are substantially diminished. The traditional argument that there is no unique solution of the third “mixed” (in the sense Dirichlet (first) plus Neumannian (second) BVP) boundary value problem of potential theory in terms of altimetric data at sea and gravity data on land is long-time obsolete. With GPS available all over the Earth, the BVP is considered to be a “fixed” problem. Meanwhile, satellite altimetry and gravity space techniques allow the measurement of both time and space variability of sea level and of a global absolute geoid. The transition from “observed instantaneous” to “mean sea-level” data is a rather complex and numerically complicated process which depends on the validity of involved modeling processes and on the availability and accuracy of related data sets. The exact determination of the $N(\text{zero})$ -term in geoid evaluation, i.e., its scale constant, and the estimation of time-varying sea tide contributions have meanwhile been solved by appropriate modeling procedures. Also temporal changes in tide gauge positions along the coasts where sea-level variations are of utmost practical importance are accurately monitored by GPS. In summary, the space-based positioning, altimetric and gravimetric techniques (see chapter ► [Gauss' and Weber's "Atlas of Geomagnetism" \(1840\) Was Not the First: The History of the Geomagnetic Atlases](#)) render traditional arguments obsolete. Their main innovation is the use of a same accurate and global reference frame ensuring long-term precise monitoring and integration in a Global Geodetic Observing System (GGOS) which is crucial for many practical applications.

In this way geodesy can substantially contribute to the discussion and analysis of rising mean sea level and related ecological questions. Without highly precise monitoring of global mean sea level and its combination with reliable information on time-varying global gravity, there is no solution.

Not only secular changes of mean sea surface in terms of steric and circulation variations, which vary significantly between oceanic regions, can be investigated but also periodic and aperiodic effects. In analyses of secular effects, these different types of time-varying contributions can be separated only over relatively long time spans. A typical example is the El Niño and La Niña effects in the Pacific between

Peru and Australia affecting climate perturbations almost all over the globe. To what extent frequency and amplitude variations of such effects are really interdependent (global warming affects frequency and amplitudes and vice versa) has not yet been answered.

M. Bursa (Bursa et al. 2001) is one of the pioneers in investigating the global vertical datum. His first attempts led to accuracy estimates of about a decimeter or so, as far as the intercontinental connection of vertical datums is concerned. His various publications since 1997 reveal clearly that the determination of an absolute global geoid is basically a question of uniform global, i.e., unified scaling including time scales. This is obvious, because today the length scale is defined via the time scale given by an interval of travel time of a photon in vacuo. Moreover, atomic time is directly related to a specific value of the geopotential and thus to the dimension of the Earth. Consequently, the definition and implementation of a global vertical datum is a topic of broad practical and theoretical implications. Formally, the atomic time scale is related to “mean sea-level geopotential,” but this is just one of the different possible definitions. At present, this quantity is identified with the (constant) geoidal potential W^o (Bursa et al. 2007). It is a consequence of the classical definition of the geoid as the global approximation of mean sea level in least-squares sense. In a transient system, it needs a revision. This revision gains importance both with the increasing precision, i.e., relative accuracy, of time standards, e.g., “cold fountains,” which is of the order of $10 \text{ (exp} - 18)$, and with the significant secular changes of global gravity and mean sea level. In (Bursa et al. 2007) also space-based gravity measurements have been used. These are superior to both shipborne and airborne gravity observations in detecting the time-varying gravity, thanks to their global coverage and repeated period. Still crucial is the coastal zone where altimeter data are less reliable. This is also the boundary between land and sea in the aforementioned “mixed” boundary value problem.

Of primary importance is the establishment of a global geocentric vertical reference system. Intercontinental air and sea traffic will strongly benefit from new improved determinations of such a global vertical datum. Open questions such as the melting processes of glaciers, particularly in Arctic and Antarctic regions, will benefit as well. There is no precise solution of such questions without dependable information about the time-varying Earth’s gravity field. The key to these solutions is the transition from steady-state to transitional solutions. Therefore, besides oceanography, glaciology, and precise measuring techniques, geodesy plays a dominant role for exact solutions of related problems by providing the precise global reference systems. The existing results on sea-level rise (secular and periodic) as well as the investigations of underlying processes leading to reliable prediction methods are promising but still controversial. This is not surprising, because GOCE was basically designed as a tool for investigation of steady-state phenomena, whereas GRACE’s aim is primarily the study of temporal changes at larger spatial scales. Due to the short duration of the space mission, the secular gravity changes are difficult to be detected by stand alone methods. Consequently, (numerically) ill-posed and (physically) improperly posed procedures are involved in the hybrid

data processes, such as analytical downward continuation of gradiometric satellite results to sea level. Whereas the conversion of accelerations, i.e., gravity, to geopotential differences is stable, in general, the opposite procedure in converting altimetric results into sea surface gravity anomalies is not well posed. Only skilful combinations of the available data sets can, e.g., lead to useful results on secular variations. The final (stationary) product of a unified global vertical datum would be a value of the geopotential $W^{\circ}(x)$ associated with a set of geocentric coordinates (x) related to the equatorial terrestrial system at epoch (t). With present data at hand, the accuracy of the numerical values is assumed to be of the order of 10^{-9} . The transition to a time-dependent transient geoid $W^{\circ}(x, t)$ including secular temporal changes is a challenging goal. A more exact definition of the geoid would be necessary in that case, as is seen from $W^{\circ}(x, t)$ because also $W^{\circ}(x(t))$ would make sense by keeping W° constant. The decision in that case depends on the coupling between volume and potential of the Earth. It is easily seen that, for instance, steric mean sea-level changes can lead to significant changes of the Earth's volume without affecting the geopotential seriously. Therefore, only modeling processes based on gravity and geometric information, for instance, satellite altimetry, yield satisfying results.

The analysis and separation of the different components of sea-level variation are now investigated by several authors. They were first initiated in areas where GPS-controlled tide gauge data of high data density were available, due to the particular interest in coastal areas. Also here the application of space techniques appears superior to terrestrial approaches.

3 Scientific Relevance

Sea level is a very sensitive indicator of climate change and variability. It responds to change of several components of the climate system. Sea level rises due to global warming, as sea waters expand and fresh water comes from melted mountain glaciers. Variations in the mass balance of the ice sheets in response to global warming has also direct effect on sea level. The modification of the land hydrological cycle due to climate variability and anthropogenic forcing leads to change in runoff in river basins, hence ultimately to sea-level change. Even solid Earth affects sea level through small changes of the shape of ocean basins. Coupled atmosphere-ocean perturbations, like El Nino-Southern Oscillation (ENSO) and North Atlantic Oscillation (NAO), also affect sea level in a rather complex manner and contribute to sea-level variability.

While sea level remained almost stable during the last two millennia, subsequently to the last deglaciation that started $\sim 18,000$ years ago, tide gauge measurements available since the late nineteenth century have indicated significant sea-level rise during the twentieth century, at a mean rate of about 1.7 mm/year (e.g., Church et al. 2004; Church and White 2006; Holgate 2007).

Since early 1993, sea-level variations are accurately measured by satellite altimetry from Topex/Poseidon, Jason-1, and Jason-2 missions (Cazenave and Nerem 2004; Leuliette et al. 2004; Beckley et al. 2007). This 15-yearlong data set shows that, in terms of global mean, sea level is presently rising at a rate of 3.5 ± 0.4 mm/year, with the GIA correction applied (Peltier 2004, 2009). The altimetry-based rate of sea-level rise is therefore significantly higher than the mean rate recorded by tide gauges over the previous decades, suggesting that sea-level rise is currently accelerating in response to global warming. Owing to its global coverage, altimetry also reveals considerable regional variability in the rates of sea-level change. In some regions, such as the Western Pacific or North Atlantic around Greenland, sea-level rates are several times faster than the global mean, while in other regions, e.g., Eastern Pacific, sea level has been falling during the past 20 years. It is expected that regional sea-level rise will strongly affect particular regions with direct impacts including submergence of coastal regions, rising water tables, and salt intrusion into groundwaters. It can possibly also exacerbate other factors as floodings, associated to storms and hurricanes, as well as ground subsidence of anthropogenic nature.

There is an urgent need to understand the causes for the observed sea-level rise and its possible development. Over the 1993–2003 time span, sea-level rise was about equally caused by two main contributions: $\sim 50\%$ from warming of the oceans (through thermal expansion) and $\sim 50\%$ from glaciers melting and ice mass loss from Greenland and Antarctica (Bindoff et al. 2007). Since 2003 thermal expansion has negligibly contributed to sea level (e.g., Willis et al. 2008) although meanwhile satellite altimetry-based sea level has continued to rise. Accelerated ice mass loss from the Greenland and West Antarctica ice sheets (evidenced from various remote-sensing techniques such as radar and laser altimetry, INSAR and GRACE space gravimetry) and increase in glacier melting (e.g., Meier et al. 2007; Rignot et al. 2008) appear to account alone for the last 5 years sea-level rise (Cazenave et al. 2009).

Changes in each component of the climate system, in ocean, land, and ice sheets, have a sensible effect on sea level. At global scale the sum of the observed contribution to sea-level rise has been compared to the observed sea-level rise over multi-decadal period. An improved closure of the sea-level global budget has been obtained both in trends and in mean trend variability (Cazenave and Llovel 2010; Church and White 2011; Moore et al. 2011). Key uncertainties include the role of the Greenland and West Antarctic ice sheets and the amplitude of regional changes in sea level, caused by both climatic and non-climatic components (Becker et al. 2012; Henry et al. 2012).

Regional analysis on the impact of sea-level rise in coastal zone shows that at certain locations, non-climatic components of relative sea-level change, mainly subsidence, are locally appreciable, and the relative sea-level rise there is found to be up to three to four times larger than the global mean sea-level rise (Cazenave and Llovel 2010).

4 Data and Methodology of Numerical Treatment

We use altimeter data from January 1993 to December 2008 of the Topex/Poseidon, Jason-1, and Envisat altimeter missions. Standard corrections are applied to the altimetry data with exception of the inverse barometric correction, for consistency with the monthly tide gauge data that are not corrected either. This correction, given by the MOG2D model, is applied for the comparison between global and coastal sea-level change derived from altimeter data only. Monthly 1° grids are constructed by using a simple Gaussian weighted average method (half-weight equal to 1 and search radius equal to 1.5°).

Tide gauge data are available from the Permanent Service for Mean Sea-Level (PSMSL, <http://www.pol.ac.uk/psmsl/>) database. We correct the sea level at the tide gauge station for the GIA using the SELEN software (Spada and Stocchi 2007) forced with the ICE5-G glaciation history and a viscoelastic Maxwell Earth derived from VM2 (Paulson et al. 2007). Also sea-level change derived from the altimeter is corrected for the GIA effect, and this correction increases the satellite estimates of global sea surface rates by 0.3 mm/year (Church et al. 2004).

Selection criteria of the tide gauges are based on the time length of the time series and on the data gaps. The stations available in each of the three intervals 1900–2001, 1950–2001, and 1993–2001 are 1,158, 1,103, and 738, respectively. A station is used if it is available over 90 % of the interval with gaps shorter than 2 years (availability criteria); stations fulfilling these criteria are 15, 117, and 365, respectively, and mostly located in the northern hemisphere along the European and North American coasts.

A further criterion for the selection of tide gauge is based on proximity and agreement with satellite altimetry. The chosen stations will represent the large-scale open sea-level variability, and stations describing the local sea-level variability are eliminated (Fenoglio-Marc et al. 2004). A station is eliminated if the minimum distance from a point of the altimeter grid is greater than 2° . For each tide gauge station, we consider the nearest node of the altimeter grid within 2° radius and four parameters: (1) correlation, (2) the trend of the difference, (3) the standard error of the trend of the difference, and (4) the standard deviation of the difference are used as indicators of the agreement between altimetry and tide gauge data. The criteria are correlation >0.5 , the trend and standard error of the trend <5 mm/year, and the standard deviation of the differences <80 mm. Not fulfillment of the selection criteria can arise from a jump in the record or from local variability (location in an harbor or near to an estuary). In this last case, the station, also if correctly recorded, will not be used for sea-level change analysis.

Only complete time series are then used to estimate the empirical models. To increase the number of tide gauge stations, the gaps in the records are filled by linear regression with the highest correlated time series. For each of the time series of anomalies, the trend and seasonal signal are subtracted and the correlation matrix of the residuals computed. For each of the time series with gaps, the gaps are filled by linear regression of the residuals with the complete time series that realizes the highest correlation. The process is repeated until all the gaps are filled. The filling is

not done for a time series if the correlation coefficient with any of the complete tide gauges is lower than 0.5. The time series are then reconstructed by adding trends and seasonal cycles.

For the analysis of the sea-level trend, the monthly time series are deseasoned and the trend is evaluated by linear regression. The probable uncertainty of the linear term of the regression is estimated, accounting for the temporal correlation of the residuals. The effective degree of freedom and the probable uncertainty of the linear term are derived from the lag-1 autocorrelation of the detrended time series and the standard error obtained from the linear regression (Fenoglio-Marc et al. 2004; Wilks 1995).

For the analysis of the long-term trends, we compute monthly spatial averages over the complete globe and over selected basins. The seasonal variation is removed and a linear regression model is fitted to the residuals after application of a moving average with a window of 12 months.

For the analysis of interannual and interdecadal signals, the trend and seasonal component are removed from each time series, and the residual time series are low-pass filtered. For interannual analysis, the filtering consists in averaging the deseasoned monthly time series over 1 year of data with a time spacing of 0.5. For interdecadal analysis, the filtering consists in averaging monthly data over 5 years with a time sampling of 2.5 years.

The statistical method of principal component analysis (PCA) (Preisendorfer 1988) is applied to the interannual and interdecadal anomaly fields to detect the principal modes of variability. A significance test based on a Monte Carlo technique (Overland and Preisendorfer 1982) is applied to find the number, of principal components, k , to be retained.

The statistical method of canonical correlation analysis (CCA) in the PCA basis (PCA-CCA) is used to analyze the coupled variability of altimetric and tide gauge data; the decomposition is obtained maximizing the correlation between the temporal patterns.

The interannual variability is reconstructed in the past from altimetry and tide gauge data using the climatic indices (Trenberth 1984; Trenberth and Hurrell 1994; Woolf et al. 2005). The method consists in first applying separately the PCA method to the standardized anomaly fields of altimetry and of tide gauges. The modes maximizing the temporal correlation with the same climatic index are selected to build the empirical model of the sea-level variability by using the corresponding spatial patterns from altimetry and the temporal coefficients from tide gauges.

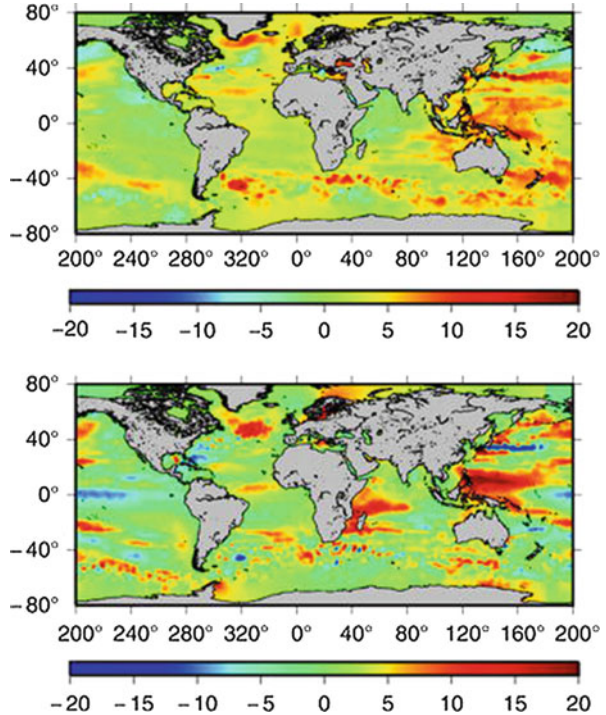
In conclusion, relatively simple mathematical procedures have been used, namely, gridding, interpolation, filtering, and trend estimation.

4.1 Fundamental Results

The trend of sea level is regional and has time-dependent characteristics (Fig. 1).

Tide gauge stations suitable for large-scale sea-level change analysis are reduced to 365 by the “time-length” condition, to 339 by the “proximity” condition, and finally to 290 by the comparison to the nearest altimeter point (Fig. 2).

Fig. 1 Sea surface height trends from Topex-Poseidon in 1993–2005 (*above*) and from Jason-1 in 2002–2008 (*below*)



The variability of the averaged coastal sea level measured by tide gauge and altimetry at a colocated altimetric point are in good agreement with a correlation of 0.96, RMS of 3.4 mm between the smoothed time series. The difference in the trends is within the errors.

The interannual and interdecadal variability of global sea-level change derived from altimetry, coastal sea-level change derived from altimetry, and coastal sea-level change derived from colocated altimetry at tide gauge locations have slightly different characteristics and similar positive trends (Fig. 3).

Trends are evaluated from January 1993. For intervals longer than 8 years, all trends are positive and in the range 2–5 mm/year. The trend of global sea level is almost constant over the last 10 years (3.0 ± 0.4 mm/year from January 1993 to December 2007). The trend of coastal global sea level is monotonic decreasing (2.28 ± 0.59 mm/year in 1993–2007), while the trend of global sea level at tide locations is more variable (2.68 ± 0.64 mm/year in 1993–2007). The best agreement between all trends is reached in 2002–2004 (Fig. 4).

The omission error of the coastal sea level trend from tide gauges σ_{miss} , due to the incomplete coastal coverage, is evaluated to be 0.3 mm/year from the difference in trends of coastal altimetry and coastal altimetry at the tide gauges. The error σ_{miss} is smaller than the adopted measurement error σ_{meas} of 0.4 mm/year (Mitsum 2000).

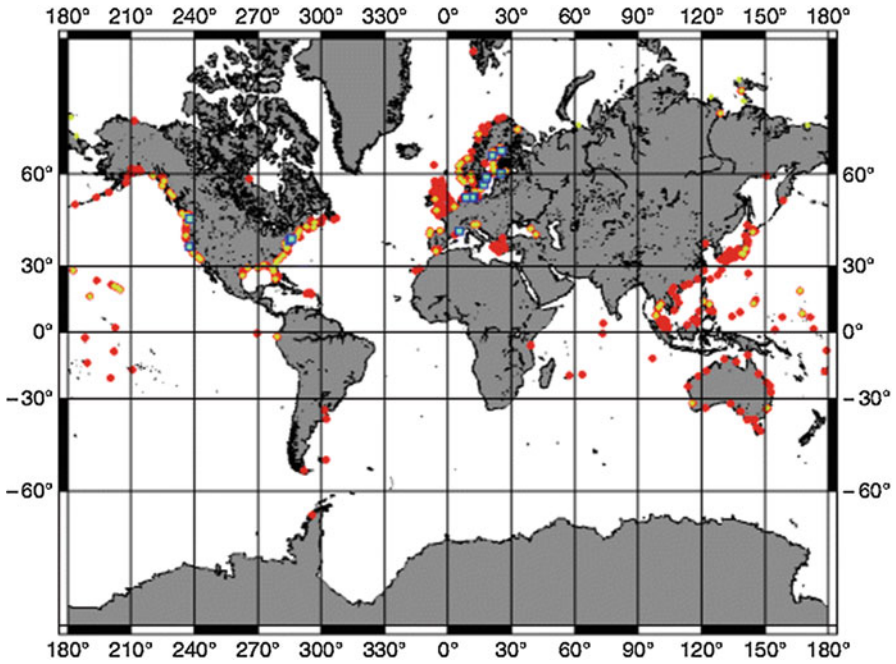


Fig. 2 Tide gauge stations of the PSMSL data set satisfying availability criteria. A number of stations are 365 in 1993–2001 (red), 117 in 1950–2001 (yellow), and 15 in 1900–2001 (blue)

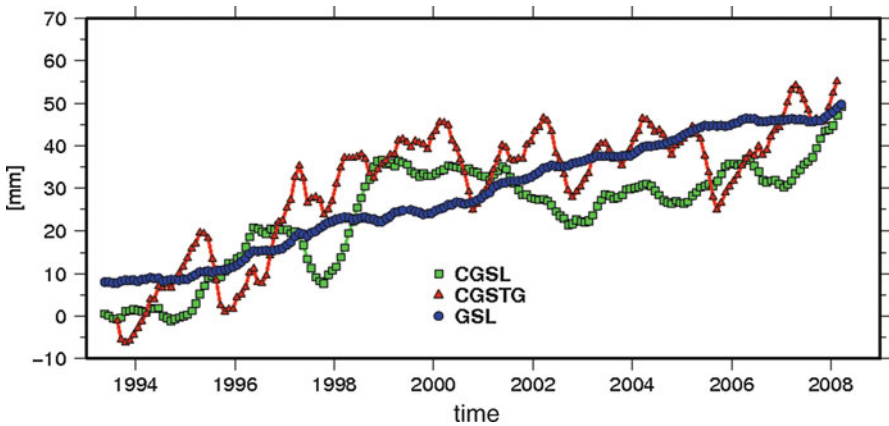


Fig. 3 Trends and error bars of global sea level (*square*), coastal sea level (*triangle*), and coastal sea level at 290 tide gauge stations (*circle*) computed over different time intervals starting from 1994

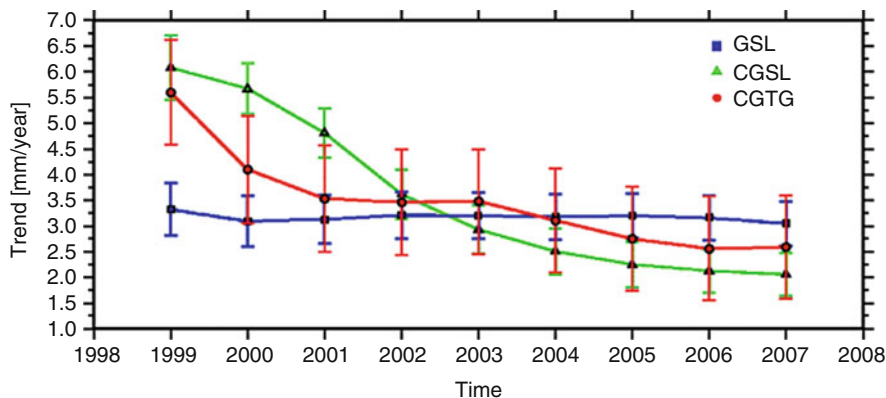


Fig. 4 Average sea-level change from Topex/Poseidon and Jason-1 altimeter data: global sea level (*circle*), coastal sea level at 100 km from coast (*square*), and near 290 selected tide gauges (*triangle*)

The interannual variability is stronger in the coastal averaged time series. Regionally there is a good agreement between coastal and open-ocean sea-level variability; trends are positive in the main world basins. The location, number, and distribution of the tide gauge stations and the extension of the coasts explain part of the differences observed. The Tropical Pacific dominates the global variability; the highest agreement between the coastal sea-level variability from altimetry and tide gauge is found there.

There is a strong correlation between the climatic indices and the patterns of interannual variability. The first four dominant modes of the PCA altimeter decomposition account for more than 60 % of the total variability. The Southern Ocean Index (SOI) and the Northern Atlantic Index (NAO) are significantly correlated to the dominant modes over 1993–2001 (Fig. 5). The variability of the tide gauge data sets is biased to the North Hemisphere coasts (Fig. 6), as most of the tide gauges are located along the European and North American coasts. This explains the different order of the dominant modes obtained from the tide gauge and from the altimeter data sets.

The empirical model based on NAO and SOI for the period 1993–2001 reproduces about 50 % of the global averaged interannual variability observed by altimetry. The corresponding average time series of global interannual mean sea level is estimated to have an accuracy of 2–3 mm. Over 1950–2001, the correlation between the SOI and NAO climatic indices and the temporal patterns of the interannual and interdecadal models is conserved. We conclude that the variability of the trends is related to the time-scales of the NAO and SOI indices.

The spatial analysis (Figs. 1, 5, and 6) shows the regional characteristics of sea-level variability. Being the signal of large scale, the results do not considerably change using suitable subsets of the original selected set.

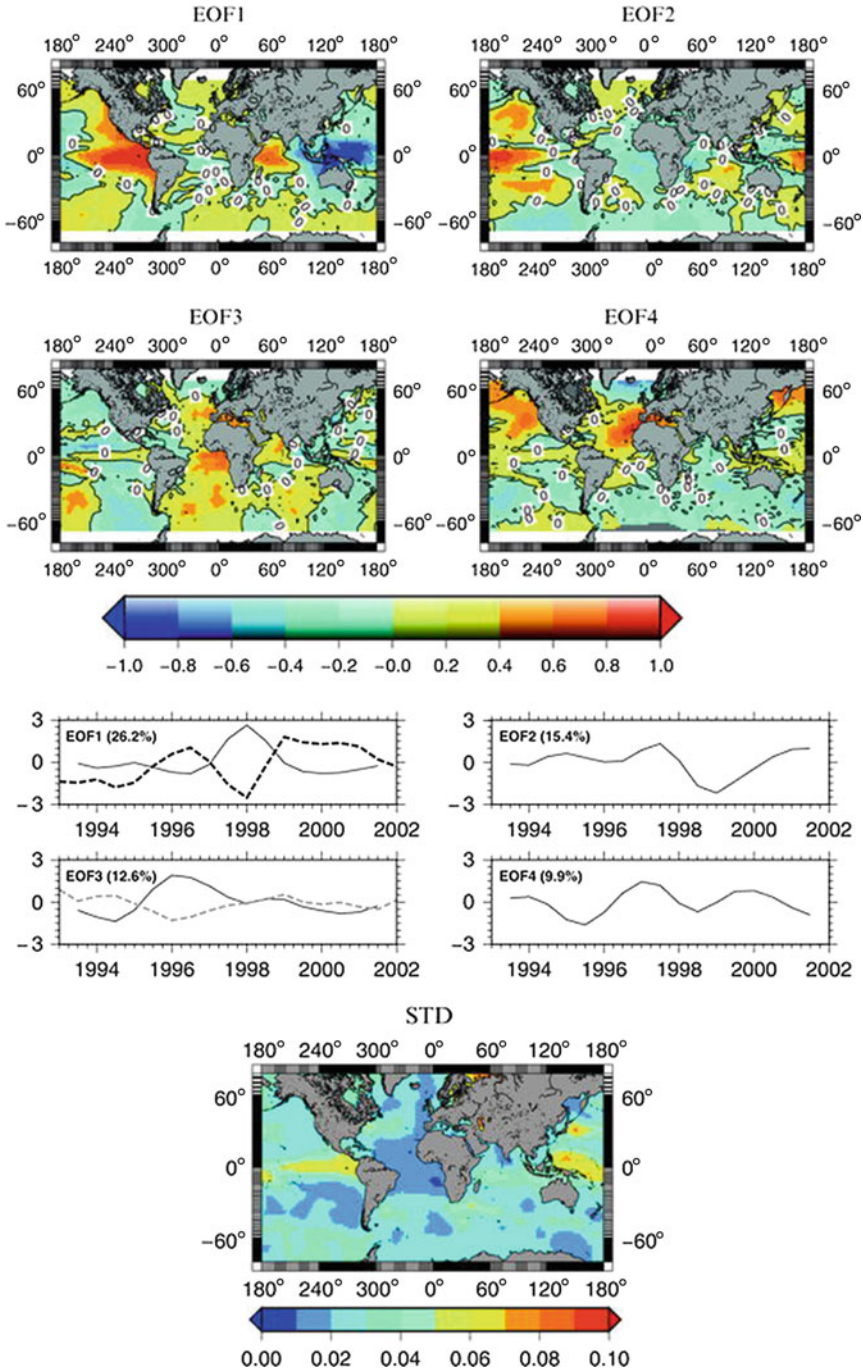


Fig. 5 Dominant spatial patterns (*top*), temporal EOF coefficients and cumulative percentage of variance (*center*), standard deviation (*bottom*) of interannual variability from altimetry in 1993–2002. Interannual time series of SOI (*dashed black*) and NAO (*dashed gray*) are plotted with the correlated temporal coefficients

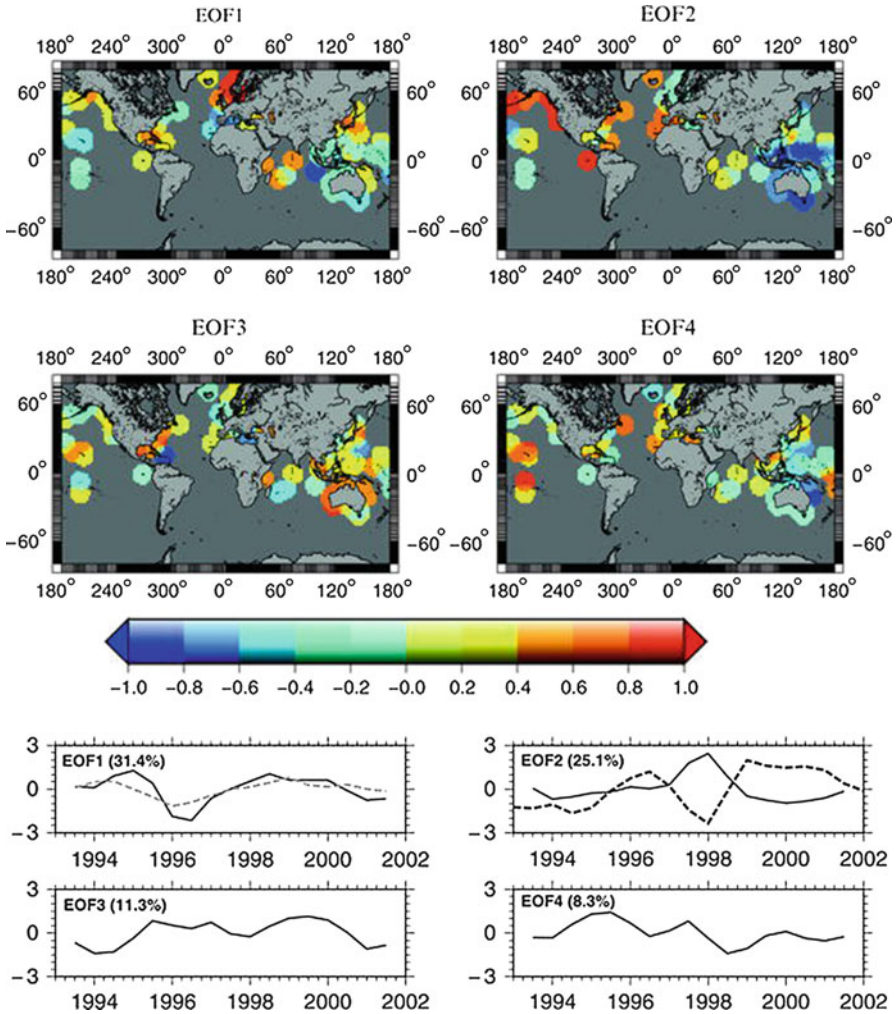


Fig. 6 Dominant spatial patterns (*top*) and temporal EOF coefficients and cumulative percentage of variance (*bottom*) of interannual variability from 197 tide gauge stations in 1993–2001. Interannual time series of SOI (*dashed black*) and NAO (*dashed gray*) are plotted with the correlated temporal coefficients

The sea-level trends have positive average of 3.1 ± 0.4 mm/year in the time interval 1993–2008, and the average remains almost constant by extending the analysis to the whole period 1993–2013 (Fig. 7). Satellite altimetry-based global mean sea-level trend from different processing groups agrees well over the whole altimetry period and shows differences over shorter time span. The causes for the differences are in particular due to different processing methodologies adopted by the different groups. The largest differences result from using gridded versus

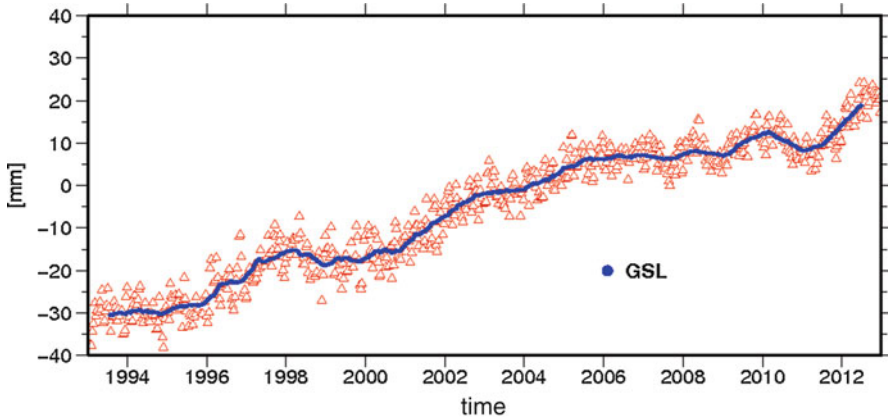


Fig. 7 Global sea-level change over 1993–2013 from Topex/Poseidon, Jason-1, and Jason-2 altimeter data. Annual variability has been eliminated and running average applied

non-gridded sea surface heights anomalies when calculating the mean (Masters et al. 2012).

It is expected that the regional sea-level rise will strongly affect particular regions with direct impacts including submergence of coastal zones, rising water tables, and salt intrusion into groundwaters. It can possibly also exacerbate other factors as floodings, associated to storms and hurricanes, as well as ground subsidence of anthropogenic nature. The regional sea-level change has been analyzed in Thailand and Indonesia region during the period 1993–2011 using satellite altimetry, tide gauge data, and GPS (Trisirisatayawong et al. 2011; Fenoglio-Marc et al. 2012). The sea-level change is closely linked to the ENSO mode of variability and is spatially homogeneous at both interannual and decadal scales. The rates of absolute eustatic sea-level rise derived from satellite altimetry through 19-yearlong precise altimeter observations are in average higher than the global mean rate. Several tide gauge records indicate an even higher sea-level rise relative to land (Fig. 8). We have determined the vertical crustal motion at a given tide gauge location by differencing the tide gauge sea-level time series with an equivalent time series derived from satellite altimetry and by computing the trend of the differences. This method, which assumes that both instruments measure an identical ocean signal, represents an interesting alternative to the use of collocated GPS at the tide gauge stations when GPS is not available. The land vertical rates correspond to GPS-derived rates. In this way we have find subsidence in Jakarta, already known from previous studies, and in three other tide gauge stations.

It appears that the impact of fast-rising sea-level combined with high rates of post-seismic downward crustal motions makes coastal areas and river estuaries along the Gulf of Thailand and in Indonesia highly vulnerable to flooding, particularly the low-lying city of Bangkok and Jakarta. We conclude that the climate-related sea-level trend is reinforced by vertical land movements of a similar

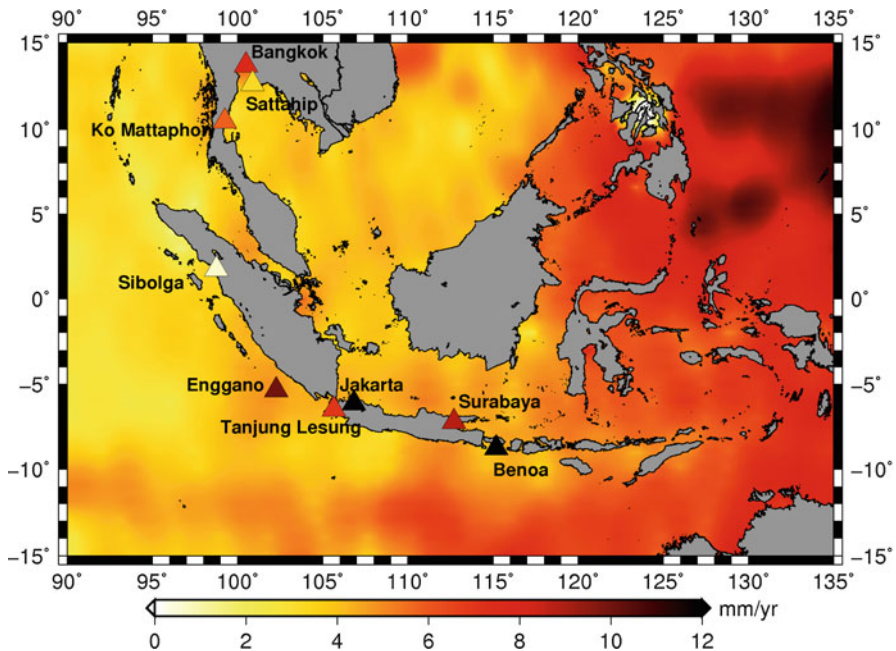


Fig. 8 Sea-level rise (SLR) from satellite altimetry in 1993–2011 and corresponding relative sea-level rise (RSLR) from tide-gauge stations (*triangle*) in Indonesia-Thailand region

or even larger magnitude and that the impact on coastal areas needs to be seriously considered.

5 Future Directions

The space technologies allow the estimation of sea-level change at global scale. For the past century, estimates of sea-level variations have been based on tide gauges data that suffer from some limitations, as incomplete coverage and contamination by vertical motions of the ground from GIA, tectonics, volcanism, and local subsidence. Satellite altimetry gives new challenges.

5.1 Accuracy of Sea-Level Observation

Since the early 1990s, satellite altimetry has become the major tool for precisely measuring sea level with quasi-global coverage and short revisit time. This objective has pushed the altimetry systems toward their ultimate performance limit. To measure global mean sea-level rise with 5% uncertainty, a precision at the 0.1 mm/yr level or better is needed.

Errors affecting altimetry-derived sea-level estimates fall into two main categories: (1) orbit errors (through force model and reference frame errors) and (2) errors in geophysical corrections applied to sea surface height measurements. The latter result either from drifts and bias of the instruments used to measure these corrections, e.g., onboard radiometers used to measure atmospheric water content, or from model errors. The precision of a single sea surface height measurement from Topex/Poseidon (1 s along track average) is estimated to be 4 cm (Chelton et al. 2001). Recent progress in data processing has decreased this error level to 2 cm for both Topex/Poseidon and Jason-1; averaging over a 10-day interval over the oceanic domain leads to a global mean sea-level precision of about 4 mm that translates into 0.1 mm/year uncertainty on the global mean sea-level rate. Differences up to 0.5 mm/year in altimetry-based rates of sea-level rise, commonly seen between investigators, result from differences in data processing and geophysical corrections used.

A robust procedure to assess the precision/accuracy of altimetry-derived sea level change consists in an external calibration using high-quality tide gauges records (Mitchum 2000). The tide gauge data need to be corrected for vertical crustal motions using GPS, and so far, errors on the global mean sea-level rate of rise based on tide gauge calibration are about 0.4 mm/year, because of uncertainty in crustal motions at the tide-gauge sites.

5.2 Observation at the Coast and in Open Ocean

A key issue is if the coastal sea level observed by tide gauges conveniently represents the global sea level using both altimetry and tide gauge stations.

Global mean sea level rises by an estimated 3 mm/year. But how important is the global figure if we only see the impact at the coast line? It is hence prudent to ask: What is the sea level rise near the coast? Is it different from the global number, and if so, why?

Preliminary analyses show that the sea level in a 200 km radius from the coast is actually rising faster, about 4 mm/year, but this value is dominated by the large 5 mm/year rise in the Indonesian Sea, in which value is largely influenced by El Niño-Southern Oscillation (ENSO) variability. Some other contributors to increased coastal sea-level rise would include warming of the coastal waters.

It is now accepted that the difference between the rates from global altimetry and coastal tide gauges is due to the different sampling and to interannual variability (Prandi et al. 2009). Geographical patterns of sea level change are far from being uniform as revealed by altimeter satellites (Cazenave and Llovel 2010). When considering coastal security issues, it is especially the regional and local sea level (relative to the coast line) and not just the global mean that is relevant.

Another analysis that can shed some light on what components are currently the largest contributors to sea-level change is the separation of the regional time series into empirical orthogonal functions (EOFs). The largest EOFs show the predominant features: seasonal heating, ENSO, PDO, and North Atlantic

Oscillation (NAO) and very little power that is purely coastal. That makes us conclude that eustatic and steric sea-level rise, outside the aforementioned contributors, is actually largely a homogeneous global phenomenon.

5.3 Attribution of Sea-Level Rise

Understanding ongoing and predicting future sea-level changes requires an understanding of the contributing processes at the regional and local levels.

We distinguish between five components of sea-level change, namely, the mass, steric, meteorological, circulation, and anthropological components. The first four components are part of the internal variability of the climate system, and the last component, e.g., greenhouse gases and water extraction, is an external forcing factor.

When dealing with slow processes, the major forcings for global sea level are water mass addition/removal from the oceans due to the melting/growing of continental ice, referred to as the mass component (Becker et al. 2012; Henry et al. 2012) and changes in the volume of the water column, mainly attributed to thermal expansion/contraction and referred to as the steric component (Levitus et al. 2000). The salinity changes at global level are considered as of less importance. At regional scale, however, and in the Mediterranean Sea in particular, salinity plays an important role as it affects both the mass component and the density of the sea water and hence its volume (Fenoglio-Marc et al. 2013). The thermosteric spatial patterns are not stationary but fluctuate in time and space in response to driving mechanisms such as ENSO (El Niño-Southern Oscillation), AO (North Atlantic Oscillation), and PDO (Pacific Decadal Oscillation) (Lombard et al. 2005) and result from the redistribution of heat and fresh water through air-sea fluxes and changes.

The effect of atmospheric pressure and wind, referred to as the meteorological component of sea level, and changes in the circulation also contributes to regional long-term sea-level variability and to its mass change. Surface wind stress has been identified as the driving mechanism of circulation-based heat and salt redistribution over the past few decades (Timmermann et al. 2010). Surface fluxes and buoyancy fluxes may have played an increasing role over the past two decades (Kohl and Stammer 2008).

Interdisciplinary studies are necessary to interpret the observations and analyze the causes of the sea-level observations in view of climate change. The advanced remote-sensing capabilities provide unprecedented opportunities for monitoring, studying, and forecasting the ocean environment. Altimetry gives the total sea-level variability; it does not distinguish between volume (steric) and mass (non-steric) sea-level change. Once measured the mass component from GRACE, the steric component of sea level can be derived as difference of the two fields.

A good agreement has been found at both global and regional scale between the GRACE-based ocean mass change and the steric-corrected altimetry (Willis et al. 2008; Fenoglio-Marc et al. 2012). In semi-enclosed basins the mass flux through the straits could be determined from the GRACE-derived mass balance (Fenoglio-Marc et al. 2013). Other studies used GRACE data to separate altimetrically observed

sea-level variations into the mass and steric components (Rietbroek et al. 2012). Integration of altimetry, GRACE and ARGO data may also allow for quantification of steric contributions within the deep ocean.

Present-day regional sea-level changes appear to be primarily caused by natural climate variability (Meyssignac et al. 2012a). However, the imprint of anthropogenic effects on regional sea level will grow with time as climate change progresses, and toward the end of the century, regional sea-level pattern will be a superposition of climate variability modes and natural and anthropogenically induced static sea-level pattern, with the anthropogenic contributions becoming more prominent toward the end of the twenty-first century.

Satellite altimetry together with GRACE and GOCE data allows the separation of the different components of sea level. With GRACE the volume (steric) and mass changes are separated at large spatial scales of about 300 km; with GOCE, the mean sea level can be separated in its two components, the geoid and the mean dynamic topography.

5.4 Reconstruction of Past Sea Level

Estimates of sea-level variations for the past century are based on tide gauges data or on reconstruction methods that combine tide gauge records with regional sea-level variability derived from either satellite altimetry (Church et al. 2004) or general ocean circulation model outputs (Berge-Nguyen et al. 2008).

The aim of the reconstruction is to combine short 2-D signal (with good spatial sampling) with long 1-D signal (with good temporal sampling) in order to reconstruct long-term, 2-D sea level. The general approach uses EOF decomposition of the 2-D time series to extract the dominant modes of spatial variability of the signal. Then, the spatial modes are fitted to 1-D records to provide reconstructed multidecadal 2-D sea-level fields. Such an approach makes two important assumptions: (1) the temporal length of the 2-D fields is high enough to capture the dominant modes of interannual/decadal variability and (2) errors are Gaussian. Assumption (1) is crucial for past sea-level reconstruction.

The attempts to reconstruct past-decade sea level combining sparse and long Tide gauge records with sea-level time series of limited temporal coverage have shown that the results are very sensitive to the input spatial information (e.g., Church and White 2011, Meyssignac et al. 2012b for global scales and Calafat and Gomis 2009, Meyssignac et al. 2011 for regional scales).

The ultimate goal of those reconstructions is to constrain coupled climate models used by the IPCC, to predict SLR over the twenty-first century.

5.5 Prediction of Sea-Level Evolution

The Intergovernmental Panel on Climate Change (IPCC) projections (Bindoff et al. 2007) indicate that sea level should be higher than today by about 40 cm on average by 2100 (within a ± 20 cm range).

Considerable uncertainty is associated with these projections, which essentially account for future thermal expansion of the oceans and glaciers melting. The major source of uncertainty is the future behavior of the ice sheets which is almost unknown. Recent observations of the mass balance of the Greenland and West Antarctica ice sheets indicate that a large proportion of ice mass loss observed during the past decade is due to rapid coastal glacier flow into the ocean, with incredible acceleration in the recent years. Such processes, due to complex ice dynamics, are not yet fully understood and thus not taken into account in sea-level projection models.

5.6 Mathematical Representation of Time-Varying Sea Level

The sea-level variability is due to the interaction of traveling waves of different spatial scales and temporal frequencies; the different components are superposed to a noise component and exhibit stationarity or nonstationarity in their statistics.

In the analysis of sea-level change, the main components of the sea-level height variability are to be identified and a model that is best suitable to represent the sea-level variability constructed.

For its nature, sea level is not completely defined over the sphere. Global and local representations are of interest. The selection depends on the goals.

Fitting a mathematical model to data is usually accomplished by expanding the model as an infinite series of appropriate basis functions. These functions are the solution to the relevant differential equations, subject to relevant boundary conditions. It is generally required that the basis functions form an infinite and complete set and that, for fixed boundary, they are mutually orthogonal over the interval of expansion.

We distinguish between parametric and nonparametric methods. In parametric method the model is chosen a priori and the coefficients are determined accordingly, while in nonparametric method a data-adaptive basis set is used. Between the nonparametric methods are the multivariate statistical analysis methods, as the singular spectrum analysis (SAS) based on the lag-covariance matrix of the data (Allen and Smith 1994), and the principal component analysis (PCA) in the time domain (TD-PCA) and in the frequency domain (FD-PCA), which perform an optimal decomposition of the data variance, respectively, in the time and in the frequency domain.

The PCA is a second-order statistical method, which maximizes the variance of principle components realizing their decorrelation (second-order independency). In time-domain approach, the base functions are space-dependent functions, generally called empirical orthogonal functions (EOF), and the coefficients, called principal components (PC), are time-dependent functions (Preisendorfer 1988). The PCA method has no phase information; therefore, it can detect standing oscillations but not traveling waves. The complex PCA (CPCA) investigates propagating phenomena. Complex time series are formed from the original time series and from their Hilbert transform, and complex eigenvectors are determined from the

cross-covariance or cross-correlation matrices derived from the complex time series (Horel 1984). The extension of PCA to two fields is the Canonical Correlation Analysis (CCA) statistical method, which identifies pairs of patterns in two fields which fulfill an optimality criterion: we find the linear combination of variables in each set that have maximum correlation (Bretherton et al. 1992). For each field, we have therefore a representation in terms of spatial and temporal functions. However, while in the PCA, the patterns are orthogonal and therefore appear in both the synthesis and analysis formula; in CCA the spatial functions are not orthogonal, and therefore, the spatial vector of the analysis equation does not necessarily coincide with the spatial patterns of the synthesis equation (Fenoglio-Marc 2001). An alternative to PCA is the VARIMAX-rotated PCA, based on a rotation criterion which maximizes the variance of the principal components. The second-order statistical methods present a “mixing problem,” consisting in the clustering of the long-term and periodical components of the signal in several modes.

The Independent Component Analysis Method uses a higher-order statistical criterion to separate multivariate data sets into independent data-adjusted base functions (Hyvarinen et al. 2001). The ICA algorithm based on diagonalization of fourth order cumulants (Cardoso and Souloumiac 1993) can better separate a mixture of deterministic sinusoidal signals in the presence of a trend and improves the separation compared to PCA analysis.

Commonly used in geodesy is the spherical harmonic set of base functions, where the spherical harmonics can be considered as eigenfunctions of invariant pseudodifferential operators (such as the Beltrami operator) and are expressed in terms of Legendre polynomials in colatitude, while the coefficients are trigonometric functions in latitude. In case of an area of investigation limited to a portion of the Earth’s surface, other Legendre polynomials and trigonometric functions are the most appropriate base functions. The method of modeling data over a spherical cap is referred to as spherical cap harmonic analysis (Haines 1985). Whereas the associated Legendre functions for the all sphere have integer degree, those for the spherical cap have noninteger degree.

Propagating phenomena are investigated by the complex PCA (CPCA) in the time domain, where complex time series are formed from the original time series and from their Hilbert transform and complex eigenvectors are determined from the cross-covariance or cross-correlation matrices derived from the complex time series (Horel 1984). This method is therefore used in the study of the El-Nino region.

The extension of PCA to two fields is the CCA statistical method, which identifies pairs of patterns in two fields which fulfill an optimality criterion; we find the linear combination of variables in each set that have maximum correlation (Bretherton et al. 1992). For each field, we have therefore a representation in terms of spatial and temporal functions, but while in the PCA, the patterns are orthogonal and therefore appear in both the synthesis and analysis formula; in CCA the spatial functions are not orthogonal, and therefore, the spatial vector of the analysis equation does not necessarily coincide with the spatial patterns of the synthesis equation (Fenoglio-Marc 2001). The independent component analysis method (Hyvarinen et al. 2001) aims at the separation of the components of a signal.

With increasing impact to transient phenomena in geodetic applications, alternative representatives deserve more interest. As a first step, the equivalence of multipole with harmonic representations is seen to find various applications in modeling the Earth's interior phenomena. Meanwhile, a large number of highly flexible trial functions serve local and global modeling processes which are basically superior to standard procedures (Groten 2003). With increasing numbers of data sources, such as tide gauge, altimetric, gravimetric observations, the optimum estimation based on biased redundant data sets of quite different kind and origin is at stake.

Another common tool for analyzing localized variations of power within a time series is the wavelet method. By breaking down a time series into time-frequency space, it allows to determine both the dominant modes of variability and how those modes vary in time.

6 Conclusions

The mean level is variable in time and in space. As sea-level rise is a very important component of climate change, it is important to develop techniques for the estimation of sea-level trends "cleaned" from decadal variability.

At least 50-year records are needed to separate secular, decadal, and interannual variations, and over this long time interval, only few tide gauges along the world coastlines are available for the analysis. Moreover, the spatial distribution of tide gauges as well as the existence of interannual and low-frequency signals affects the recovery of secular trends in short records.

Satellite altimetry provides high-precision, high-resolution measurements of sea surface height with global coverage and a revisit time of a few days starting from 1992, i.e., over the last 20 years.

During this time interval, the agreement between altimeter and tide gauge data is good. Global mean sea level rises by an about 3.1 ± 0.4 mm/year between January 1993 and December 2008. Coastal sea level rises at the same rate in the long term, but with higher interannual variability. Tide gauges conveniently represent the global sea level over the long term. Regionally there is a good agreement between coastal and open-ocean sea-level variability from altimeter data, and trends are positive in the main world basins.

The sea-level rise is not uniform, and it is expected that regional sea-level rise will strongly affect particular regions with direct impacts for the population. When considering coastal security issues, it is especially the regional and local sea level (relative to the coast line) and not just the global mean that is relevant. Regionally, the global sea-level rise in response to ocean warming and ice melting has important implications, such as beach erosion, inundation of land, increasing salination of coastal aquifers, increasing food, storm damage, and loss of the coastal ecosystem. The climate-related sea-level rise may be reinforced by land subsidence due to natural (e.g., tectonics and volcanism) and anthropogenic (e.g., groundwater extraction) causes.

Using altimeter data together with space gravity data, we can analyze the reason for sea-level change and the corresponding components. At global scale, the sea-level rise derived from altimetry and the sum of the observed contribution to sea-level rise show an improved closure of the sea-level global budget both in trends and in mean trend variability.

At the present time, we are still apart from exact global solutions. Recent data from GOCE and other satellite projects may, however, soon lead to more homogeneously distributed data sets of different kind and of substantially higher accuracy. Consequently, the rigorous treatment in terms of global boundary value problem, as described at the beginning of the chapter, is still far apart. Only with more numerous and redundant data sets unique solutions can be attempted. The approach described in the present chapter will be further applied to the extended data.

References

- Allen M, Smith L (1994) Investigating the origins and significance of low frequency modes of climate variability. *Geophys Res Lett* 21:883–886
- Becker M, Meyssignac B, Leletré C, Llovel W, Cazenave A, Delcroix T (2012) Sea level variations at tropical Pacific islands since 1950. *Global Planet Change* 80–81:85–98. doi:10.1016/j.gloplacha.2011.09.004
- Beckley BD, Lemoine FG, Luthcke SB, Ray RD, Zelensky NP (2007) A reassessment of global and regional mean sea level trends from TOPEX and Jason-1 altimetry based on revised reference frame and orbits. *Geophys Res Lett* 34:L14608. doi:10.1029/2007GL030002
- Berge-Nguyen M, Cazenave A, Lombard A, Llovel W, Viarre J, Cretaux JF (2008) Reconstruction of past decades sea level using thermosteric sea level, tide gauge, satellite altimetry and ocean reanalysis data. *Global Planet Change* 62: 1–13
- Bindoff N, Willebrand J, Artale V, Cazenave A, Gregory J, Gulev S, Hanawa K, Le Quéré C, Levitus S, Nojiri Y, Shum CK, Talley L, Unnikrishnan A (2007) Observations: oceanic climate and sea level. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) *Climate change 2007: the physical science basis. Contribution of working group I to the fourth assessment report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, pp 385–428
- Bretherton C, Smith C, Wallace J (1992) An intercomparison of methods for finding coupled patterns in climate data change. *J Clim* 5:541–560
- Bursa M, Groten E, Kenyon S, Kuba J, Radey K, Vatrt V, Vojtiskova M (2001) Earth dimension specified by geoid potential. *Studia Geophys Geodetica* 46:1–8
- Bursa M, Kenyon S, Kouba J, Sima Z, Vatrt V, Vitek V, Vojtiskova M (2007) The geopotential value W^0 for specifying the relativistic atomic time scale and a global vertical reference system. *J Geodesy* 81:103–110
- Calafat F, Gomis D (2009) Reconstruction of Mediterranean Sea level fields for the period 1945–2000. *Global Planet Change* 66:225–234. doi:10.1016/j.gloplacha.2008.12.015
- Cardoso JF (1999) High-order contrasts for independent component analysis. *Neural Comput* 11:157–192. doi:10.1162/089976699300016863
- Cardoso JF and Souloumiac A (1993) Blind beamforming for non Gaussian signals. *IEE Proc* 140:362–370
- Cardoso J-F, Souloumiac A (1993) An efficient technique for blind separation of complex sources. In: *Proceedings of the IEEE SP workshop on higher-order statistics, Lake Tahoe*, pp 275–279

- Cazenave A, Llovel W (2010) Contemporary sea level rise. *Annu Rev Mar Sci* 2:145–173. doi:10.1146/annurev-marine-120308–081105
- Cazenave A, Nerem RS (2004) Present-day sea level change observations and causes. *Rev Geophys* 42:RG3001. doi:10.1029/2003RG000139
- Cazenave A, Dominh K, Guinehut S, Berthier E, Llovel W, Ramillien G, Ablain M, Larnicol G (2009) Sea level budget over 2003–2008: a reevaluation from GRACE space gravimetry, satellite altimetry and Argo. *Global Planet Change* 65(1–2):83–88
- Chelton DB, Ries JC, Haines BJ, Fu LL, Callahan P (2001) Satellite altimetry. In: Fu LL, Cazenave A (eds) *Satellite altimetry and earth sciences*. Academic, New York, pp 57–64
- Church JA, White NJ (2006) A 20th century acceleration in global sea-level rise. *Geophys Res Lett* 33:L01602. doi:10.1029/2005GL024826
- Church D, White N (2011) Sea-level rise from the late 19th to the early 21st century. *Surv Geophys*. doi:10.1007/s10712-011-9119-1
- Church JA, White NJ, Coleman R, Lambeck K, Mitrovica JX (2004) Estimates of the regional distribution of sea level rise over the 1950–2000 period. *J Climate* 17(13):2609–2625
- Church J, White NJ, Arrup T, Wilson WS, Woodworth PL, Domingues CM, Hunter JR, Lambeck K (2008) Understanding global sea levels: past, present and future. *Sustain Sci* 3:9–22. doi:10.1007/s11625-008-0042-4
- Domingues CM, Church J, White NJ, Gleckler PJ, Wijffels SE, Barker PM, Dunn JR (2008) Improved estimates of upper-ocean warming and multi-decadal sea level rise. *Nat Lett* 453. doi:10.1038/nature07080
- Douglas BC (2001) Sea level change in the era of the recording tide gauge. In: *Sea level rise, history and consequences*. International geophysics series, vol 75. Academic, London
- Fenoglio-Marc L (2001) Analysis and representation of regional sea level variability from altimetry and atmospheric data. *Geophys J Int* 145:1–18
- Fenoglio-Marc L, Tel E (2010) Coastal and global sea level change. *J Geodyn* 49(3–4):151–160. doi:10.1016/j.jog.2009.12.003
- Fenoglio-Marc L, Groten E, Dietz C (2004) Vertical land motion in the mediterranean Sea from altimetry and tide gauge stations. *Marine Geodesy* 27:683–701
- Fenoglio-Marc L, Schoene T, Illigner J, Becker M, Manurung P, Khaid (2012). Sea level change and vertical motion from satellite altimetry, tide gauges and GPS in the Indonesian region. *Marine Geodesy* 35(sup1):137–150. doi:<http://dx.doi.org/10.1080/-01490419.2012.718682>
- Fenoglio-Marc L, Mariotti A, Sannino G, Meyssignac B, Carillo A, Struglia M (2013) Decadal variability of the net water ux at the Mediterranean Gibraltar Strait. *Global Planet Change* 100: 1–10
- Groten E (2003) Ist die Modellbildung in der Geodäsie hinreichend zukunftstauglich? *Zeitschr f Vermessungsw* 3:192–195
- Haines G (1985) Spherical cap harmonic analysis. *J Geophys Res* 90:2583–2591
- Henry O, Prandi P, Llovel W, Cazenave A, Jevrejeva S, Stammer D, Meyssignac B, Koldunov N (2012) Tide gauge based sea level variations since 1950 along the Norwegian and Russian coasts of the Arctic Ocean: contribution of the steric and mass components. *J Geophys Res* 117:C09,023. doi:10.1029/2011JC007706
- Holgate SJ (2007) On the decadal rates of sea level change during the twentieth century. *Geophys Res Lett* 34:L01602. doi:10.1029/2006GL028492
- Holgate SJ, Woodworth PL (2004) Evidence for enhanced coastal sea level rise during the 1990s. *Geophys Res Lett* 31:L07305. doi:10.1029/2004GL019626
- Horel JD (1984) Complex principal component analysis: theory and examples. *J Climate Appl Meteor* 23:1661–1673
- Hyvarinen A, Karhunen J, Oja E (2001) *Independent component analysis*. Wiley, New York
- Jevrejeva S, Grinsted A, Moore JC, Holgate S (2006) Non linear trends and multiyear cycles in sea level records. *J Geophys Res* 111:C09012. doi:10.1029/2005JC003299
- Kohl A, Stammer D (2008) Decadal sea level changes in the 50-year GECCO ocean synthesis. *J Climate* 21:1876–1890. <http://dx.doi.org/10.1175/2007JCLI2081.1>

- Leuliette E, Nerem RS, Mitchum G (2004) Calibration of Topex/Poseidon and Jason altimeter data to construct a continuous record of mean sea level change. *Marine Geodesy* 27:79–94. doi:10.1080/01490410490465193
- Levitus S, Antonov JI, Boyler T, Stephens C (2000) Warming of the world ocean. *Science* 287:2225–2229
- Lombard A, Cazenave A, Le Traon P-Y, Ishii M (2005) Contribution of thermal expansion to present-day sea-level change revisited. *Global Planet Change* 47(1):1–16
- Masters D, Nerem S, Choe C, Beckley B, Leuliette E, White N, Ablain M (2012) Comparison of global mean sea level time series from TOPEX/Poseidon, Jason-1, and Jason-2. *Marine Geodesy* 35(1):20–41
- Meier F, Dyurgerov MB, Rick UK, O’Neel S, Pfeffer W, Anderson RS, Anderson SP, Glazovsky AF (2007) Glaciers dominate Eustatic sea level rise in the 21st century. *Science* 317(5841):1064–1067. doi: 10.1126/science. 1143906
- Meysignac B, Calafat F, Somot S, Rupolo V, Stocchi P, Llovel W, Cazenave A (2011) Two-dimensional reconstruction of the Mediterranean sea level over 1970–2006 from tide gage data and regional ocean circulation model outputs. *Global Planet Change* 77:49–61. doi:<http://dx.doi.org/10.1016/j.gloplacha.2011.03.002>
- Meysignac B, Salas y Melia D, Becker M, Llovel W, Cazenave A (2012a) Tropical Pacific spatial trend patterns in observed sea level: internal variability and/or anthropogenic signature? *Climate Past* 8:787–802. doi:10.5194/cp-8-787-2012
- Meysignac B, Becker M, Llovel W, Cazenave A (2012b) An assessment of two-dimensional past sea level reconstructions over 1950–2009 based on Tide-Gauge data and different input sea level grids. *Surv Geophys* 33(5):945–972
- Mitchum G (2000) An improved calibration of satellite altimetric heights using tide gauge sea level with adjustment for land motion. *Marine Geodesy* 23:145–166
- Moore J, Jevrejeva S, Grinsted A (2011) The historical global sea-level budget. *Ann Glaciol* 52(59):8–14
- Nerem RS, Chambers D, Choe C, Mitchum GT (2010) Estimating mean sea level change from the TOPEX and Jason altimeter missions. *Marine Geodesy* 33(1 supp 1):435
- Overland JE, Preisendorfer RW (1982) A significance test for principal components applied to a cyclone climatology. *Mon Weather Rev* 110(1):1–4
- Paulson A, Zhong S, Wahr J (2007) Inference of mantle viscosity from GRACE and relative sea level data. *Geophys J Int* 171:497–508. doi:10.1111/j.1365-246X.2007.03556.x
- Peltier WR (2004) Global glacial isostasy and the surface of the ice-age earth: the ICE-5G (VM2) model and GRACE. *Ann Rev Earth Planet Sci* 32:111–149
- Peltier R (2009) Closure of the budget of global sea level rise over the GRACE era: the importance and magnitudes of the required corrections for global glacial isostatic adjustment. *Quat Sci Rev* 28(17–18):1658–1674. doi:10.1016/j.quascirev.2009.04.004
- Prandi P, Cazenave A, Becker M (2009) Is coastal mean sea level rising faster than the global mean? A comparison between tide gauges and satellite altimetry over 1993–2007. *Geophys Res Lett* 36:L05602. doi:10.1029/2008GL036564
- Preisendorfer RW (1988) Principal component analysis in meteorology and oceanography. In: *Developments in atmospheric science*, Vol 17. Elsevier, Amsterdam
- Rietbroek R, Fritsche M, Brunnabend S-E, Daras I, Kusche J, Schröter J, Flechtner F, Dietrich R (2012) Global surface mass from a new combination of GRACE, modelled OBP and reprocessed GPS data. *J Geodyn* 59–60:64–71
- Rignot E, Box JE, Burgess E, Hanna E (2008) Mass balance of the Greenland ice sheet from 1958 to 2007. *Geophys Res Lett* 35:L20502. doi:10.1029/2008GL035417
- Spada G, Stocchi P (2007) Selen: a Fortran 90 program for solving the sea-level equation. *Comput Geosci* 33:538–562
- Timmerman A, McGregor S, Jin F-F (2010) Wind effects on past and future regional sea level trends in the southern Indo-Pacific. *J Climate* 23:4429–4443. doi:<http://dx.doi.org/10.1175/2010JCLI3519.1>

- Trenberth KE (1984) Signal versus noise in the southern oscillation. *Mon Weather Rev* 112: 326–332
- Trenberth KE, Hurrell JW (1994) Decadal atmosphere-ocean variations in the Pacific. *Climate Dyn* 9:303–319
- Trisirisatayawong I, Naeije M, Simons W, Fenoglio-Marc L (2011) Sea level change in the Gulf of Thailand from GPS-corrected tide gauge data and multi-satellite altimetry. *Global Planet Change* 76:137–151. doi:10.1016/j.gloplacha.2010.12.010
- White NJ, Church JA, Gregory JM (2005) Coastal and global averaged sea level rise for 1950 to 2000. *Geophys Res Lett* 32:L01601. doi:10.1029/2004GL021391
- Wilks D (1995) *Statistical methods in the atmospheric sciences*. Academic, San Diego
- Willis JK, Chambers DP, Nerem S (2008) Assessing the global averaged sea level budget on seasonal and interannual timescales. *J Geophys Res* 113:C06015. doi:10.1029/2007JC004517
- Woolf DK, Shaw A, Tsimplis MN (2005) The influence of the North Atlantic oscillation on sea-level variability in the North Atlantic region. *Global Atmos Ocean Syst* 9:145–167. doi:10.1080/10236730310001633803