Global and Planetary Change 116 (2014) 54–67

Contents lists available at ScienceDirect

Global and Planetary Change

journal homepage: www.elsevier.com/locate/gloplacha

Regional sea level variability, total relative sea level rise and its impacts on islands and coastal zones of Indian Ocean over the last sixty years

H. Palanisamy [a,*], A. Cazenave [a], B. Meyssignac [a], L. Soudarin [b], G. Wöppelmann [c], M. Becker [d]

[a] LEGOS/CNES, Toulouse, France
[b] CLS, Ramonville Saint-Agne, France
[c] LIENSs, UMR7266, CNRS, University of La Rochelle, France
[d] UAG, UMR ESPACE-DEV (IRD, UM2, UAG, UR), Cayenne, France

ARTICLE INFO

Article history:
Received 2 June 2013
Received in revised form 31 January 2014
Accepted 1 February 2014
Available online 8 February 2014

Keywords:
Regional sea level variability
Mean Reconstructed Sea Level
Altimetry
Tide gauge
Vertical land motion
Indian Ocean
Indian Ocean Dipole

ABSTRACT

Indian Ocean is the home to many tropical low lying islands and highly populated coastal zones. Since a few recent decades, many of these zones have been gaining a lot of international attention due to fears of sea level rise and possible submersions of islands. In this study we estimate sea level rise and regional sea level variability in Indian Ocean (20°E–140°E, 30°N–35°S) over a period of 60 years from 1950 until 2009. We determine the climatic factors that influence the sea level change and variability in this region. We find that the changes in the Indian Ocean sea level are of steric origin and are also driven by short-term Indian Ocean Dipole events. The trend in this region over 60 years amounts to 1.5 mm/yr, a value lesser (although not statistically different) than the global mean sea level rise over the same period. There is also an east–west increase in sea level trend pattern below 15°S latitude which is more amplified since the two recent decades. Climate-related sea level changes are also studied at different sites in the Indian ocean corresponding to the existence of tide gauge records and has been found that over the long term period (60 years), the sea level trend at most of the individual locations are well within the global mean sea level rise. Total relative sea level change which is the sum of climate-related sea level change and vertical land motion is also estimated at 5 locations with the help of GPS and DORIS measures.

1. Introduction

High precision satellite altimetry available since the early 1990s has for the first time provided sea level time series over the whole oceanic domain. This invaluable data set has confirmed that in terms of global mean, the rate of sea level rise during the last 20 years is twice larger than during the previous longer multidecadal time period (e.g., Nerem et al., 2010; Church and White, 2011). It also revealed high regional variability in the rates of sea level change (e.g., Cazenave and Llovel, 2010). Sea level trend patterns over the past 20 years show high sea level rates in the western tropical Pacific (up to 3 times the global mean), in the northern Atlantic and Austral oceans. While the main cause of last 20 years global mean sea level rise (GMSLR) is land ice melt (~55%), followed by ocean thermal expansion (~30%) (Church et al., 2011; Meyssignac and Cazenave, 2012; Hanna et al., 2013), the regional sea level trends mostly result from non-uniform ocean thermal expansion and salinity variations (Lombard et al., 2005; Levitus et al., 2012) related to ocean circulation changes (e.g., Bindoff et al., 2007; Stammer et al., 2013). There are other processes causing regional variability in sea level rates, among these are deformations of ocean basins and self-gravitational changes due to glacial isostatic adjustment (GIA) resulting from the last deglaciation and due to present-day land ice melt, respectively (e.g., Milne et al., 2009; Stammer et al., 2013). However so far, their contribution is small compared to ocean temperature and salinity changes. In the recent years, growing attention has been given in the literature to the regional variability in sea level rates (see Stammer et al., 2013 for a review). In fact this regional sea level variability superimposes on the GMSLR, either amplifying or reducing it. When studying the impacts of sea level rise, what does matter locally is indeed the sum of the GMSLR plus the regional variability (and including the effect of vertical land motions, see below). There are also raising concerns whether the shoreline erosion reported today in many coastal regions of the world is mostly due to sea level rise (e.g., Bruun, 1962; Bird, 1996; Zhang et al., 2004) or whether it also results from other factors, including urbanization, coastal management, reduced sediment transport, etc. To answer these questions, the estimate of the 'total relative' sea level change at local scale is needed (e.g., Le Cozannet et al., 2013). The term 'total relative' here means total 'climatic' sea level change, i.e., GMSLR plus the regional trend in sea level, plus eventual vertical

* Corresponding author at: 18. Avenue Edouard Belin, 31400 Toulouse, France. Tel.: +33 5 61 33 29 72.
E-mail address: hindumathi.palanisamy@legos.obs-mip.fr (H. Palanisamy).

http://dx.doi.org/10.1016/j.gloplacha.2014.02.001
0921-8181/

land motion. In order to estimate the total climatic sea level change and its coastal impacts, knowledge on past regional sea level trend patterns is important. In fact, several studies have shown that spatial trend patterns in sea level are not stationary but evolve in space and time in response to the main modes of internal variability of the ocean–atmosphere system (Lombard et al., 2005; Bindoff et al., 2007; Meyssignac et al., 2012a; Stammer et al., 2013). For example, in the tropical Pacific, sea level oscillates west–east in responses to ENSO (El Nino-Southern Oscillation) events (Wyrtki, 1984; Busalacchi and Cane, 1985; Zebiak and Cane, 1987; Chao et al., 1993; Hendricks et al., 1996; Zhang and Levitus, 1996; Delcroix, 1998;Becker et al., 2012). In addition, studies have shown that in the Pacific, the spatial trend patterns have a life time of 20–30 years (Meyssignac et al., 2012a) and that associated fluctuations are driven by the Pacific Decadal Oscillation (PDO) (Meyssignac et al., 2012a; Hamlington et al., 2013).

The regional variability is measured by satellite altimetry over the last two decades only. To determine the spatial trend patterns prior to the altimetry era, several approaches have been developed: (1) numerical ocean modeling from OGCMs (Ocean General Circulation Models) forced by meteorological data, either assimilating ocean data (e.g., ocean temperature and salinity data) or not; (2) past sea level reconstructions combining long, good quality tide gauge records of limited distribution with short records of global gridded sea level time series from satellite altimetry or OGCMs (Church et al., 2004; Llovel et al., 2009; Hamlington et al., 2011; Ray and Douglas, 2011; Meyssignac et al., 2012b). These two-dimensional sea level reconstructions allow mapping sea level trend patterns over a time span about 3 times longer than the altimetry period. In three previous studies, we estimated the total 'climatic' sea level changes since 1950 at several sites from three different regions: the western tropical Pacific (Becker et al., 2012), the Caribbean region (Palanisamy et al., 2012) and the South China Sea (Peng et al., 2013).

In these studies, we used the most recent reconstruction from Meyssignac et al. (2012b) to estimate the total 'climatic' sea level (i.e., global mean sea level plus regional variability) at different sites of the studied regions. The present study uses a similar approach to those three studies in order to determine the total 'climatic' sea level change since 1950 at several coastal sites of East Asia, India and Western Australia in the Indian Ocean, as well as at several Indian Ocean islands. When available, precise positioning data from GPS (Global Positioning System) or DORIS (Doppler Orbitography and Radiopositioning Integrated by Satellite) are used to estimate vertical land motion allowing us to estimate the total relative sea level change.

Section 2 describes the data sets used in the study. In addition to the reconstructed sea level data, we also analyze available tide gauge records in the Indian Ocean region as well as satellite altimetry data and steric sea level data. Altimetry data are used to validate the sea level reconstruction over their overlapping time span while steric data spanning over the whole studied period (1950–2009) allow us to discuss the regional variability of the Indian Ocean sea level. In Section 3 we show the few tide gauge records available along the Indian Ocean coastlines and islands. Section 4 presents the sea level reconstruction and its validation. In Section 5 we analyze the regional variability over the whole Indian Ocean over the past 20 years and 60-year long time span using Empirical Orthogonal Function (EOF) decomposition of the altimetry-based, reconstructed and steric sea level grids to highlight the dominant modes of natural/internal variability in this region. Section 6 provides the best estimates of total climate-related sea level trends at individual locations in the coastal and island regions of the Indian Ocean. In Section 7, we discuss the rate of vertical land motion at locations with GPS and DORIS data whereas in Section 8 we deal with the estimation of total relative sea level change at selected locations by making use of climatic-related sea level change and vertical land motion. Section 9 is the summary and general conclusion on the contribution of the regional variability and land motions to the local sea level changes.

2. Data

This section presents the five datasets used in studying the climate-related sea level changes and variability: (1) the 2-D past sea level reconstruction from Meyssignac et al. (2012b), (2) satellite altimetry data, (3) steric data (representing effects of ocean temperature and salinity on sea level), (4) tide gauges and (5) GPS/DORIS vertical land motion measures.

2.1. Ensemble 2D past sea level reconstruction

Many studies have been developed to perform two dimensional past sea level reconstruction on time spans longer than the altimetry era (starting in 1993) (Church et al., 2004; Llovel et al., 2009; Hamlington et al., 2011; Ray and Douglas, 2011; Meyssignac et al., 2012b). The main advantage of past sea level reconstructions is that they provide estimates of regional and global variations of sea level, as well as time series of estimated sea level at any location over a period longer than the 2-D altimetry record and many individual tide gauge records (Church et al., 2004). The general approach consists of computing spatial modes from the gridded fields using an Empirical Orthogonal Function decomposition and computing new EOF temporal amplitudes through a least-squares optimal interpolation that minimize the difference between reconstructed fields and tide gauge records at tide gauge locations. In this study, we make use of an ensemble two dimensional past sea level reconstruction over the period 1950 to 2009 at yearly interval with a resolution of 0.5° × 0.5° developed by Meyssignac et al. (2012b). The sea level reconstruction is based on 91 long (up to 60 years) but sparsely distributed tide gauge records as described in Meyssignac et al. (2012b). It also uses gridded sea level data from two numerical ocean models, the DRAKKAR/NEMO model (Penduff et al., 2010) without data assimilation and the SODA ocean reanalysis (Carton and Giese, 2008) over 1958–2009, and satellite altimetry data over 1993–2009. It is the mean of the three different global reconstructions derived from the three above mentioned sea level grids. (See Section 4 for a detailed presentation of the reconstruction).

2.2. Satellite altimetry

DT-MSLA "Ref" altimetry data provided by Collecte Localisation Satellite (CLS) has been used in this study. It is a 0.25° × 0.25° Mercator projection grid at weekly interval. The data is used over a time span from January 1993 to December 2009. Even though the available data set extends into April 2012, the gridded dataset only until December 2009 has been used in most of this study in order to be compared with the 2D sea level reconstruction grid. However in cases where the altimetry data is superimposed to reconstructed sea level and tide gauge records at several individual locations in order to study the total climate related sea level change (Section 6), the time period is extended. The DT-MSLA "Ref" global grid is a merge of several altimetry missions, namely TOPEX/Poseidon, Jason-1 and Jason-2, Envisat and ERS-1 and 2. It is a global, homogenous, intercalibrated dataset based on global crossover adjustment (Le Traon and Ogor, 1998) using TOPEX/Poseidon and followed by Jason 1 as reference missions. Geophysical corrections like the solid Earth, ocean and pole tides, wet and dry troposphere, and ionosphere (updates from Ablain et al., 2009) have been performed. An advanced dynamic atmospheric correction (DAC) using the MOG2D model has also been applied (Volkov et al., 2007). In the altimetry data, the annual and semi-annual signals have been removed through a least square fit of 12 month and 6 month period. In order to be consistent with the temporal resolution of the 2-D past sea level reconstruction data, the weekly altimetry data has been averaged to obtain the annual temporal resolution.