Continental Shelf Research 30 (2010) 1680–1691

Contents lists available at ScienceDirect

Continental Shelf Research

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

A survey of recent changes in the main components of the ocean tide

P.L. Woodworth

National Oceanography Centre, Joseph Proudman Building, 6 Brownlow Street, Liverpool L3 5DA, United Kingdom

ARTICLE INFO

Article history:
Received 27 February 2010
Received in revised form
15 June 2010
Accepted 2 July 2010
Available online 3 August 2010

Keywords:
Ocean tides
Sea level variations
Decadal ocean variability

ABSTRACT

Changes in the ocean tide during the 20th century have been reported for several parts of the world by different authors. However, it has not always been clear whether the observed changes have been local or regional in scale. This paper reports on a survey of tidal changes in recent decades using a quasi-global data set of tide gauge information. Little evidence has been found in Europe or the Far East (including Australasia and Asia) for the extensive regional changes to the main tidal constituents reported recently for N America. However, evidence for change in smaller regions can be identified wherever the density of tide gauge information allows. Therefore, it seems that tidal changes may be commonplace around the world, although not necessarily with large spatial scales. All of the reported changes have been difficult to explain. However, it is hoped that quasi-global surveys such as the present one may eventually provide further insights.

1. Introduction

Changes in mean sea level have been the subject of much recent research owing to their association with climate change (Bindoff et al., 2007). Changes in extreme sea levels, and the consequent changes in flood risk, have also been investigated in some detail (Lowe et al., 2010). In most of these studies, the ocean tide is regarded as having undergone little change and, it is assumed, will not change significantly over the next few decades.

However, it seems that there were indeed measurable changes in the ocean tide during the 20th and early 21st centuries, which at some locations were comparable to those in the mean level. The observed changes have not been confined to particular stations, or localised estuaries or bays, but have occurred over large sections of the world coastline. In most cases, the changes are not understood and require further investigation. Amongst recent papers, Ray (2006, 2009) has pointed to increases in the amplitude of the M_2 tide in the near-resonant Gulf of Maine and along most of the NE American coast, and also to considerably larger (in percentage terms) decreases in S_2 amplitude. At certain American Atlantic stations the S_2 amplitude has exhibited a negative trend exceeding 10% per century (0.1% per year). Jay (2009) described changes along the Pacific coasts of N and S America with increases in amplitude of order 2% per century (0.02% per year) in both semi-diurnal and diurnal bands for stations north of 18°N. These recent regional studies have presented a more comprehensive overview of tidal change than most made previously that tended to concentrate on records from individual countries or locations (e.g. Woodworth et al. (1991) for the UK, and references therein relating to neighbouring European countries; Flick et al. (2003) for the USA; Hollebrandse (2005) for the Netherlands).

The purpose of the present paper is to present a survey of the extent of recent tidal changes by making use of a quasi-global sea level data set, with the aim of the tidal community deriving further insights from them. The Global Extreme Sea Level Analysis (GESLA) data set was compiled through a collaborative activity of the Antarctic Climate and Ecosystems Cooperative Research Centre (ACE CRC), Australia and the National Oceanography Centre (NOC), Liverpool, UK in order to study variations in extreme sea levels (e.g. Menéndez and Woodworth, in press). However, it also provides what is probably at the present time the best source of information on regional and large-scale tidal changes.

The GESLA data set consists of 675 separate sea level records, with many duplicates, obtained from the archives of the University of Hawaii Sea Level Center (UHSLC, uhslc.soest.hawaii.edu), the Global Sea Level Observing System (GLOSS) Delayed Mode centre (www.gloss-sealevel.org), and a number of national data centres. Its focus is on providing information on extreme sea levels in recent decades. As a consequence, while it has useful spatial coverage for the 1970s onwards, it contains only a small number of records that span most of the 20th century. It is our intention that future versions of the data set will contain a larger number of long records. However, in the meantime, the analysis presented below demonstrates how the shorter records may be used to provide insight into century-timescale tidal changes, on at least a data set-average, if not an individual station, basis.

2. Methods

In this study, we concentrate on the 2 main semi-diurnal (M_2 and S_2) and diurnal (K_1 and O_1) components of the ocean tide. S_2 differs from the other constituents in being 'radiational' as well

E-mail address: plw@pol.ac.uk

0278-4343/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.csr.2010.07.002

as gravitational in origin (Cartwright, 1977; Pugh, 1987). The amplitudes and phase lags of each constituent were obtained from analysis of separate calendar years of data using the NOC Tidal Analysis Software Kit (TASK, Bell et al., 1996), selecting only those years of data for which tidal measurements were at least 75% complete. For a one-year analysis, TASK assumes equilibrium tide relationships between a tidal harmonic and its nodal (18.61 year) sidebands. That is to say, it assumes an approximately 3.7%, 0.0%, 12% and 19% variation in amplitude (this is usually referred to as the nodal factor '*f*'), and approximately 2.1, 0.0, 9 and 11 degrees variation in phase lag (nodal factor '*u*'), over 18.61 years for M_2, S_2, K_1 and O_1, respectively (Doodson and Warburg, 1941). Consequently, any real non-equilibrium relationship will result in an apparent 18.61 years variation in harmonic 'constants' (amplitudes and phase lags) due to the imperfect nodal parameterization, and that apparent variation (which we denote as 'residual variation' below) could be misinterpreted in a short record as a secular trend in the tidal constants.

Each time series of amplitude or phase lag derived from the annual analyses of each tide gauge record was parameterized in terms of an 18.61 year sinusoidal cycle plus a secular trend, the former to account for any residual (non-equilibrium) nodal component. Four parameters were obtained from these linear regressions:

1. The rate of change of the amplitude of the constituent expressed as a percentage change per year (RPA).
2. The rate of change of the phase lag of the constituent expressed in degrees per year (RPL).
3. The amplitude of the residual nodal variation expressed as a percentage of the mean amplitude (PNOD).
4. An integer (NSIGN) which flags whether the residual nodal variation peaks closer to *N* (the mean longitude of the lunar ascending node) equal to 0° rather than to *N* equal to 180° (i.e. whether any residual nodal variation peaks closer to $1950.62 \pm n$ 18.61 rather than in between); NSIGN is defined as -1 and $+1$, respectively.

As a check on the method, parameterizations were made to time series for stations reported by Woodworth et al. (1991), Araújo and Pugh (2008), Ray (2006, 2009) and Jay (2009) using the same spans of data employed by those authors. In each case, almost identical findings were obtained for trends in tidal constants and, in the case of Ray (2006), for the amplitude of nodal variations.

(A reviewer has pointed out correctly that an alternative approach would be to conduct first a tidal analysis of all the data in each record, thereby determining empirical average nodal '*f*' and '*u*' factors which can be applied subsequently to each separate annual tidal analysis cf. Foreman and Neufeld (1991). Such an approach should lead to similar conclusions on trends in amplitudes and phase lags.)

In order to obtain an optimum spatial coverage of observations of tidal change from the GESLA data set, it was necessary to make use of many of the records which span only the last few decades. Findings based on these shorter records were validated with the use of the long records in the data set, by performing one analysis over the entire record length and a second analysis over a shorter period. In this way, notwithstanding the undoubtedly valid observations of Ray (2009) that trends in tidal constants can themselves have a temporal dependence, the suitability of the shorter records to provide information relevant to century-timescale trends can be tested. In addition, the ability of the shorter records to determine reliable nodal (18.61 year) parameters from as little as 30 years of data can be determined.

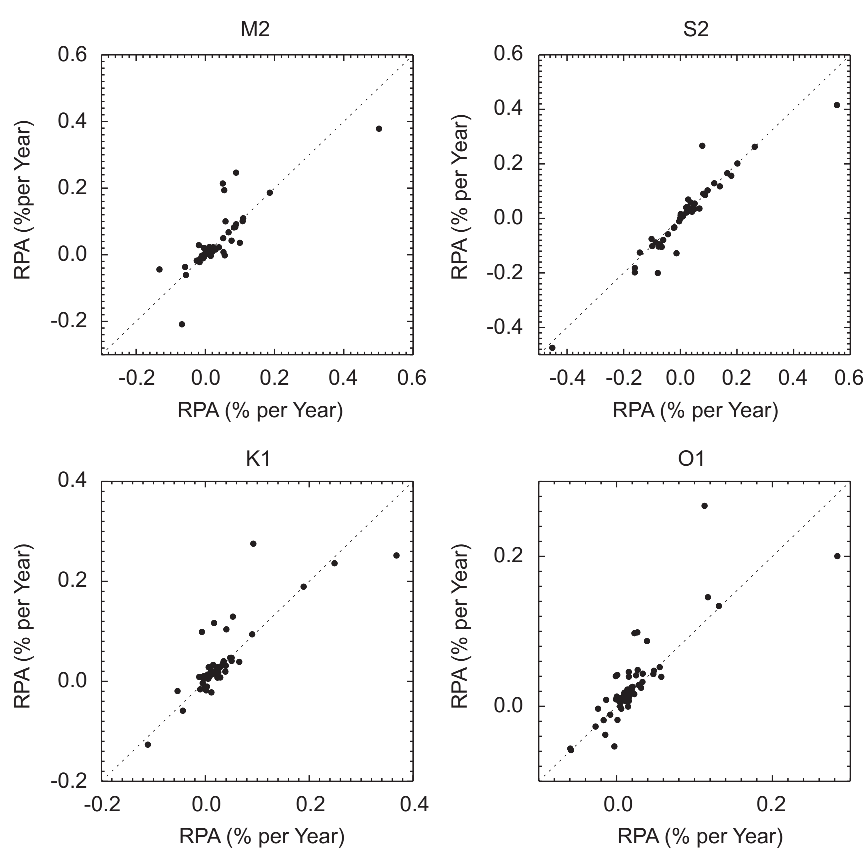

Fig. 1. Values of RPA obtained using subset A (abscissa) and subset B (ordinate) selection criteria for M_2, S_2, K_1 and O_1. The dotted line corresponds to equal values.