Sea-Level Changes

David T. Pugh and Yasser Abualnaja

Abstract
Sea levels are always changing, for many reasons. Some changes are rapid, while others take place very slowly. The changes can be local, or extend globally. Sea levels, particularly extremes, are important for coastal flooding and coral reef development, both of which may be impacted by climate change. In this chapter, we review Red Sea sea-level changes, before looking at the various processes involved in more detail and relating them to basin development and dynamics. There is no systematic review of Red Sea levels: most scientific studies have been local and piecemeal; measurements are few and limited to widely spaced harbour facilities. This chapter is a brief overview of sea-level changes and a source of references for further studies. On increasing timescales, we review tidal, weekly, seasonal and long-term changes. Finally, we link to changes of sea level in the recent geological record.

Introduction

Sea levels are always changing, for many reasons. Some changes are rapid, while others take place very slowly. The changes can be local, or extend globally. Sea levels, particularly extremes, are important for coastal flooding and coral reef development, both of which may be impacted by, for example, climate change. In this chapter, we review Red Sea sea-level changes, over timescales from hours to thousands of years, and in doing so make links with several other chapters in this book, from physical oceanography and circulation to geologically recent postglacial reviews. We look at several processes involved in more detail, relating them to basin development and dynamics. This overview makes extensive references to published work and as such will be a useful guide for those planning more specific studies.

There is no published systematic review of Red Sea levels; most scientific studies have been local and piecemeal. Direct sea-level measurements in the region are extremely limited and restricted to a few widely spaced harbour facilities. However, there are other useful sources of information, including shoreline features and, more recently, satellite altimetry measurements.

The time and space scales of sea-level variability are summarized in Fig. 1 (from Pugh and Woodworth 2014). For the Red Sea, the changes due to meteorological effects and those due to tides are roughly of equal magnitude, some tens of centimetres. The longer-term geological timescale changes are many tens of metres and more. In this chapter, on increasing timescales, we review tidal, weekly, seasonal and long-term mean sea-level changes. Finally, we link to changes of sea level in the recent geological record and comment on tsunami generation.

Tides

Red Sea tidal amplitudes are relatively small compared with those of the open ocean and with those generally experienced along coasts near continental shelves. The semidiurnal oscillations predominate with maximum ranges on spring

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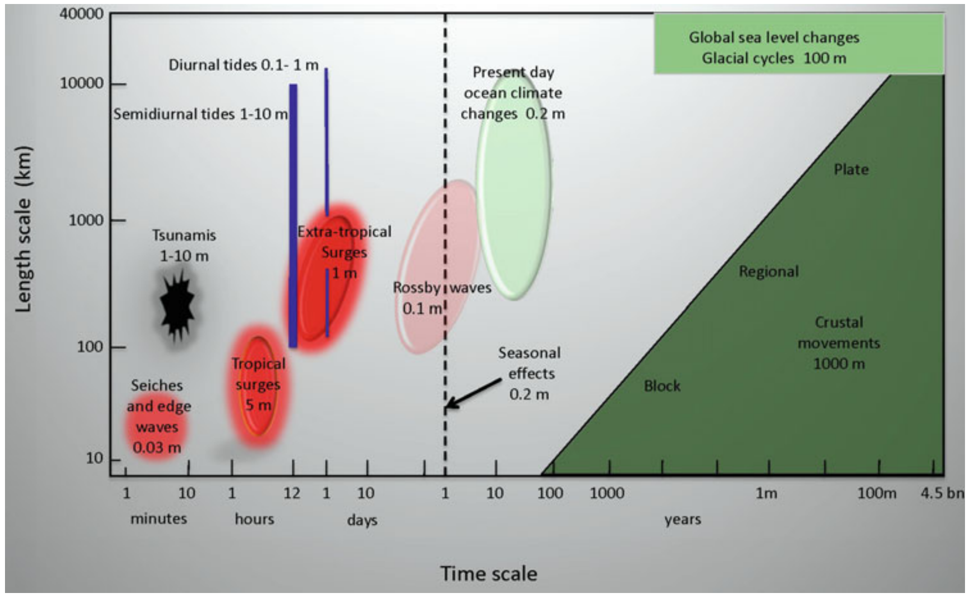

Fig. 1 A conceptual time–space map of reasons for sea-level changes. The effects vary from wind waves over a few seconds, to geological movements over millions of years (from Pugh and Woodworth 2014, with permission)

tides of about one metre in the far north at Suez and in the south near Perim. The length and depth of the Red Sea give half-wavelength dynamics for the semidiurnal tide, which on a rotating Earth results in a wave progression around the amphidrome (a point with zero tidal amplitude) roughly located between Jeddah and Port Sudan, as shown in Fig. 2. The diurnal tides are only a few centimetres in range throughout the Red Sea, being most evident in the records from around Port Sudan, where the semidiurnal ranges are very small due to the local amphidrome. Figure 3a shows a month of sea-level variability (February 1991) at Port Sudan, near the amphidrome, where diurnal tides sometimes dominate, but where the lower-frequency meteorological effects discussed below are equally or more important.

Table 1 shows tidal analyses of a recent 6-month period of sea-level data (actually sub-sea-surface bottom pressures) at three sites, as part of an experiment to investigate Red Sea tides: Port Sudan, Arkylai, some 67 km north of Port Sudan, and Swakin, 55 km to the south. The very low semidiurnal amplitudes show the proximity of an amphidrome, and the north-to-south phase progression shows that the amphidrome is offshore. The diurnal phases are almost identical at all three places. The exact location and movement of this amphidrome are not well known: loss of energy in a reflected south-going Kelvin wave could explain the displacement from the centre towards the coast of Sudan (Pugh 1981), but there are complicating factors, as discussed below.

Despite the small range, the Red Sea has been of interest in the development of scientific ideas about the tides, as discussed by Defant (1961). Because of its long narrow shape and deep sides, the Red Sea was used as an early application of numerical computations of tides, before

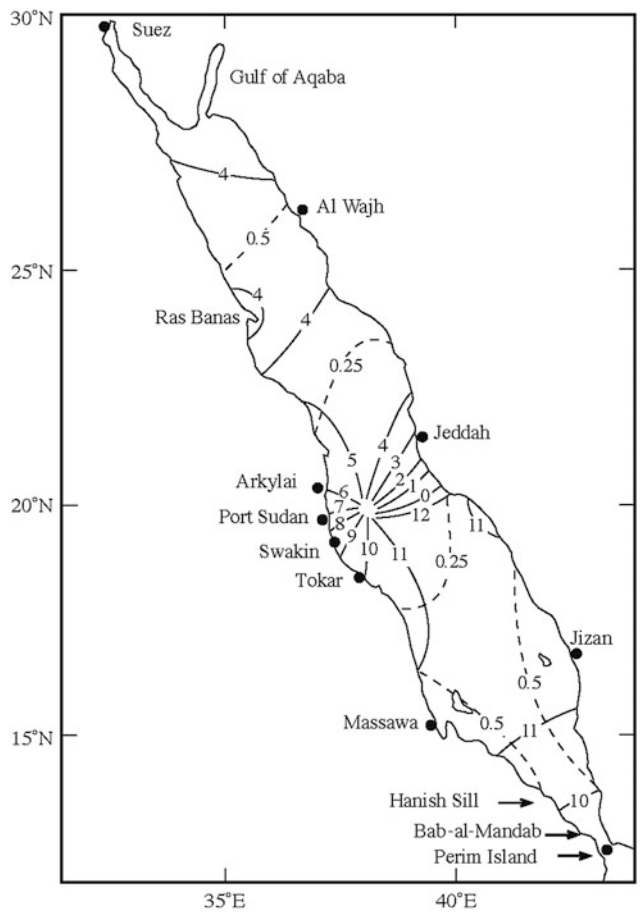

Fig. 2 Map of the principal lunar semidiurnal tide for the Red Sea showing the approximate amphidrome position near Port Sudan. *Solid lines* are Greenwich phase in hours. The *broken lines* are the amplitudes in metres. Maximum amplitudes are at the extreme north and south ends of the Sea

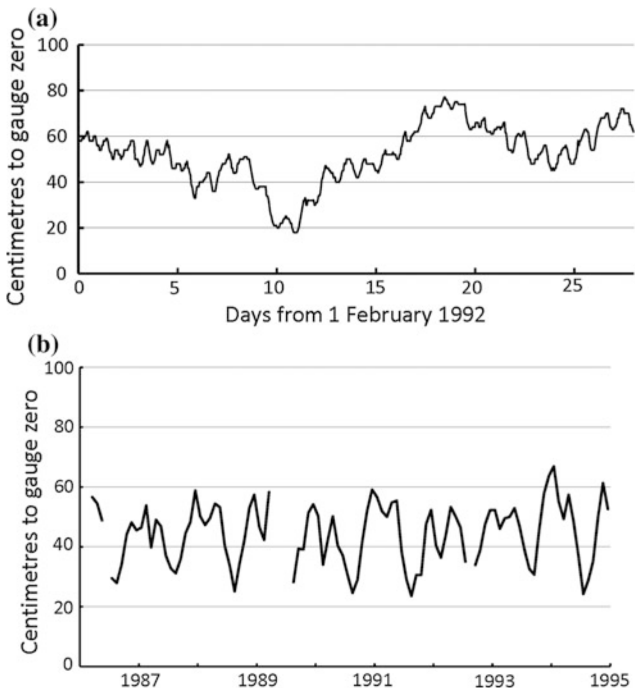

Fig. 3 **a** One month (February 1992) of sea levels at Port Sudan. Note that, because the tides are small, the lower-frequency meteorological effects are very important and **b** monthly mean sea levels at Port Sudan, 1985–1992

modern computer power made it easy and routine (Grace 1930). Proudman (1953) by modelling 39 sections along the axis derived the behaviour of Red Sea tides as seiches in a one-dimensional basin and also studied the influence of direct gravitational forcing within the sea, in both cases without Earth rotation. The relative importance of tidal forcing through the Strait of Bab-al-Mandab, compared with direct gravitational forcing within the Red Sea itself, remained unclear. Defant (1961) called these the *co-oscillating* and *independent* tides respectively; he suggested they are equally important, but also recommended consideration of the frictional energy losses.

Further evidence to understand the Red Sea tides comes from detailed surveys of levels and currents at the southern end of the Red Sea (Jarosz et al. 2005). These show a complicated system of tides with an amphidrome for M_2 between the Perim Narrows and the Hanish Sill. Tides to the south, in the Perim Narrows, are similar to those in the Gulf of Aden. Amplitudes become very small near Assab and then increase northwards to the co-oscillating amplitudes shown in Fig. 2. Using both current and sea-level measurements, Jaroz et al. calculated the tidal energy fluxes. For both K_1 and M_2, there is a flow of tidal energy from the Gulf of Aden into the Strait of Bab-al-Mandab region (300 ± 150 MW and 460 ± 16 MW, respectively). There is probably a small flow of K_1 energy from the Strait into the Red Sea (8 ± 8 MW), but for the semidiurnal tides, the net energy is from the Red Sea into the Gulf (320 ± 200 MW). The Strait is a region of relatively high semidiurnal energy dissipation, with tidal energy flowing in from the Red Sea to the north and from the Gulf of Aden to the south.

The significance of this net outward semidiurnal tidal net energy for the process of overall tide generation in the Red Sea, as discussed by Defant and Proudman, is an interesting scientific question, but it suggests that the tides generated by gravitational forces within the Red Sea are dominant and that the Red Sea is a net exporter of tidal energy. This in turn opens the question of why the central amphidrome is displaced to the Sudanese side and invites examination of the role of energy dissipation in the shallow Gulf of Suez. More detailed analyses are underway to investigate the amphidrome and possible movements, symptomatic, and related to regional tidal dynamics.

To the north, where the Red Sea divides into the Gulf of Aqaba and the Gulf of Suez, the two marginal gulfs have very different tidal regimes. The Gulf of Suez is shallow and interspersed with small islands. It has a mean depth of 36 m and a natural period of 6.7 h; the Gulf of Aqaba has a mean depth of 650 m and a natural period of about 0.9 h (Defant 1961). There is a further amphidrome in the Gulf of Suez, with strong currents and high local tidal energy dissipation.

The Gulf of Aqaba tides oscillate in a similar way to the adjacent Red Sea with a 35-min lag from the entrance at the Strait of Tiran, to the head of the Gulf, a typical standing wave (Monismith and Genin 2004). Tidal currents in the Gulf of Aqaba appear to be associated with internal wave generation, as tidal currents flow through the Strait of Tiran, driving internal tidal waves on the internal density interface; their strength varies considerably throughout the year, associated with varying density stratification.

Table 1 Tidal analyses of sub-sea-surface pressures, 25 February 2013 to 7 September 2013 (noon to noon)

	Latitude (N)	Longitude (E)	stdev	Residual	Ssa		O_1		K_1		M_2		S_2	
					h	g	h	g	h	g	h	g	h	g
Arkylai	20.232	37.204	0.151	0.081	0.173	57	0.018	160	0.031	170	0.027	131	0.013	214
Port Sudan	19.625	37.223	0.160	0.106	0.168	48	0.020	159	0.032	166	0.017	142	0.013	230
Swakin	19.116	37.342	0.156	0.101	0.160	55	0.021	159	0.034	168	0.010	176	0.013	245

Weather Effects

At periods longer than semidiurnal and diurnal tides, the Red Sea levels are influenced by air pressures, winds, evaporation and changes in surface currents. General changes in water circulation are discussed elsewhere in this volume, and sea-level changes are closely linked to these. Here, we discuss only the sea-level changes. The general patterns of winds are different in the north and south of the Sea. The wind direction north of roughly 19°N is persistently from the northwest throughout the year, while the southern region is affected by the seasonally reversing Arabian monsoon system; the prevailing wind in the summer is northerly, whereas in the wintertime, the wind blows from the south to the north (Clifford et al. 1997; Sofianos and Johns 2003).

There are also several local controls acting on the winds on the Red Sea. The surrounding mountain chains of various altitudes greatly influence surface winds; the mountains orographically force the winds to blow approximately parallel to the longitudinal axis of the Red Sea (Patzert 1974). Additionally, the coastal areas are also usually affected by the diurnal sea/land temperature difference, which produces sea breeze in the day and land breeze in the night almost all the year around (Pedgley 1974).

It is useful to look in detail at the variations measured at a mid-located buoy and bottom pressure recorder. The data from a marine buoy, deployed 64 km off the King Abdullah University of Science and Technology (KAUST) shoreline for 26 months (October 2008 to December 2010) along the central Red Sea, show the computed wind stresses. The wind was primarily from the northwest, characteristic of the northern (here 21.5°N) part of the Red Sea (Fig. 4). The wind speed often increased during the day and decreased during the night. Faster wind speeds occur with variations over periods between 2 and 14 days.

A bottom pressure/temperature/conductivity (PTC) instrument was deployed at the same time. In Fig. 5, the power spectra of wind speeds (red) and sea bed pressure (blue) show significant wind energy in the band from 3 to 100 days, with corresponding but generally not obviously matching increases in the energy of sea bed pressure (sea level) variations. There is a possible matching energy peak in both spectra near to 35 days. The bottom pressure and scaled wind speed show that the bottom pressure diurnal variability was smaller than the semidiurnal variability and that the wind speed diurnal variability was larger than the semidiurnal variability. A broad band of pressure and wind power was observed at timescales of 3–14 days. Significant coherence was found between bottom pressure and the alongshore component of the wind stress for periods of less than 14 days with the wind stress leading to the bottom pressure fluctuations. This suggests that the on/offshore component of the Ekman transport (the alongshore wind stress) contributes to bottom pressure variability. The dominant southeastward wind stress had an offshore transport in the Ekman layer (10–30 m) and a set down at the coast. Large-scale wind variability over the Red Sea may generate Kelvin waves that contribute to some of the sea-level variations. Over longer periods, steric effects (salinity changes) and large-scale wind stress will be involved. Limeburner et al. (2012) suggest that the low-frequency variability of 14–43-day fluctuations could be related to the coastal trapped waves propagating along the coast or could be due to inflow to the Red Sea of relatively low salinity water in the south, or variability in the large-scale wind stress. The authors explain that the 14-day bottom pressure variability was due to wind-driven Ekman transport with setup and set down of up to 30 cm due to the local wind stress (Fig. 6).

As another example, further south, sea-level variations at Jizan were strongly affected by the two wind stress components, that is, long-shore (north–south) and cross-shore (east–west) directions considering the orientation of the

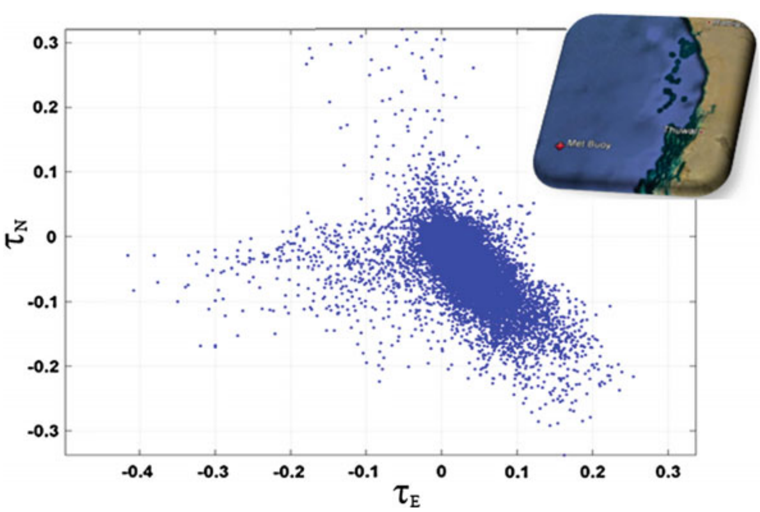

Fig. 4 Scatter plot of hourly wind stress (N/m^2) over two years from a buoy located in the Red Sea 64 km WSW from KAUST (Limeburner et al. 2012)

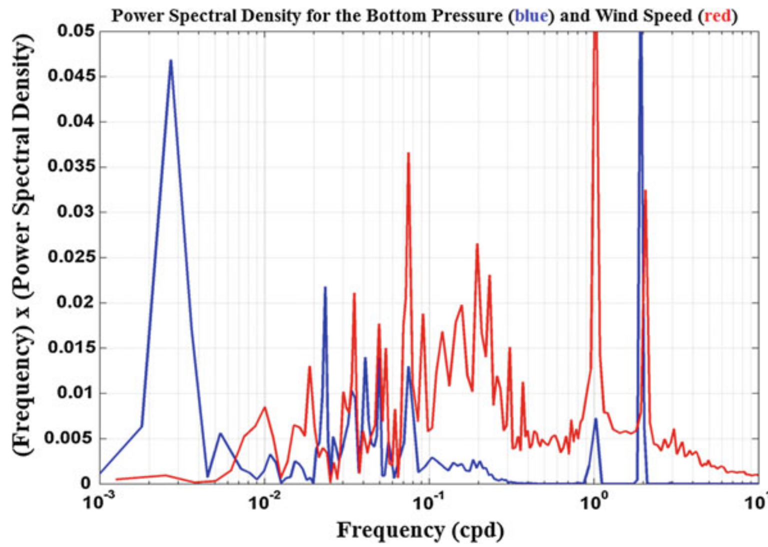

Fig. 5 Bottom pressure and scaled wind speed power spectra. Annual, coastal trapped wave (>14 days), wind (1–14 days) and tidal variability are observed (Limeburner et al. 2012)

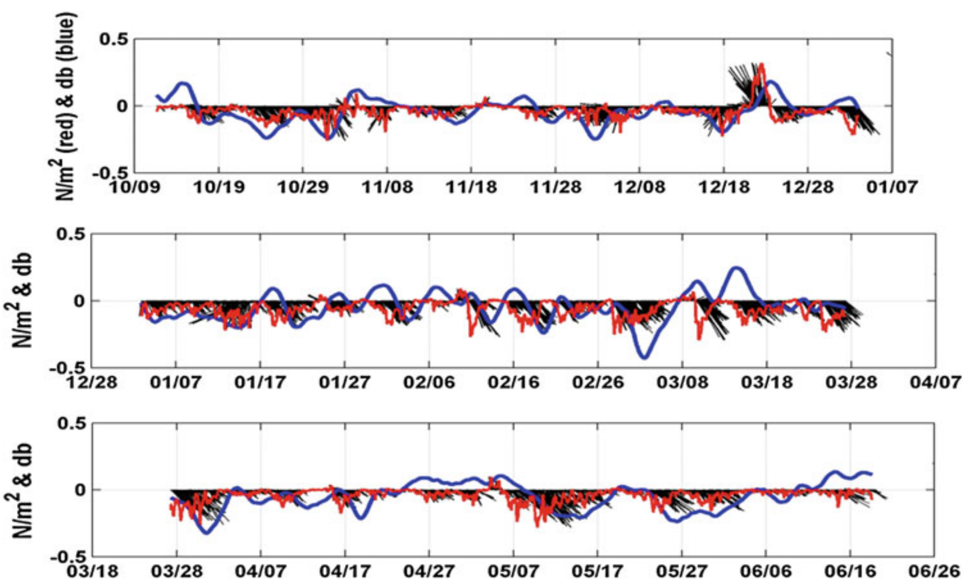

Fig. 6 Buoy wind data stick plot; low-pass-filtered alongshore wind stress leads to "Ekman transport" (*red*), and the *blue line* represents the bottom pressure (Limeburner et al. 2012)

coastline (Abdelrahman 1997; Eltaib 2010). The cross-shore component is directed towards the east causing an increase in sea level all the year around. The minimum value occurs during July when the long-shore component is dominant and directed southward causing a sea-level decrease during summer time. On the other hand, the maximum value occurs during December and January when the long-shore wind stress reverses from the SSE, driving surface currents from the Gulf of Aden into the Red Sea. Patzert (1974) computed the steric effect at Perim in Bab-al-Mandab and showed positive steric effect and high sea level during the winter season.

Sea-level changes associated with eddies can be detected. Satellite-tracked surface drifters, released during the spring of 2010, detected a well-defined anticyclonic eddy around 23°N. Chen et al. (2014) used a finite-volume community ocean model (FVCOM) to investigate the formation of the eddy. The model was driven by the meteorological forcing at the sea surface together with a given tidal elevation at the open boundary and was capable of reproducing the observed anticyclonic eddy with the same location and size. The examination of the anticyclonic eddy shows that wind forcing did not play a critical role in the eddy formation; however, it may significantly impact the structure and intensity of the eddy. South of this eddy, around 19°N, the Tokar Wind Jet, some 150 km south of Port Sudan, during summer season plays a major rule in the formation of a dipolar eddy during the summer season (Figs. 7 and 8). The cyclonic and anticyclonic eddies are highly influenced by the strength of the Jet (Zhai and Bower 2013).

Regionally coherent sea-level changes may be driven by changes outside the Red Sea. These longer-period changes are coherent over a wide area, including Port Sudan on the

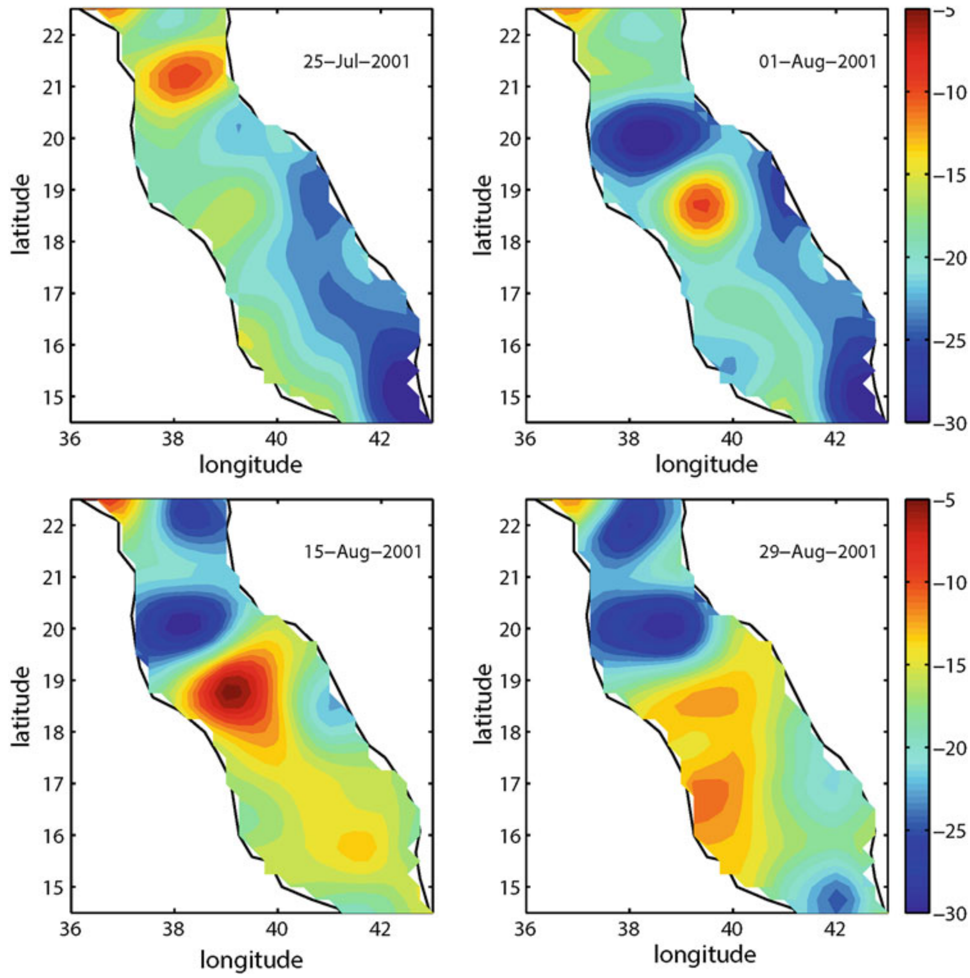

Fig. 7 The sequence development of sea-level anomaly (SLA) during 25 July to 29 August 2001, by the Tokar Wind Jet and the formation of cyclonic and anticyclonic eddies (Zhai and Bower 2013)

west coast (Sultan et al. 1996; Sultan and Elghribi 2003; Pugh et al. 2001); more simultaneous and widespread measurements are needed to investigate this coherence.

Seasonal and Longer Changes

As discussed above, the sea level in the Red Sea has annual and semiannual variations (see Fig. 5 for the dominant annual blue peak and the smaller semiannual peak) due to the seasonal variations in atmospheric parameters, in the evaporation rate and in the seasonal water mass exchange with the Gulf of Aden. These seasonal variations of the sea level account for more than half the total variance in the central and southern parts of the Red Sea (Sultan and Elghribi 2003; Cromwell and Smeed 1998; see also Sultan et al. 1995a).

The annual variability timescale in the central region at KAUST, where the bottom pressure showed approximately 40-cm difference between a high in winter (January–February) and a low in summer (July–August), can be related to wind stress. The semiannual variation is possibly related to the evaporation (Sofianos and Johns 2003; Sultan and Elghribi 2003; Cromwell and Smeed 1998; Sultan et al. 1995a, b, 1996). The amplitudes of the annual variations at Jeddah and Port Sudan are about 20–13 cm, respectively, while the semiannual components are about 10–8 cm. The variations at Jeddah are related to the long-shore wind component only. At Port Sudan, the long-shore and cross-shore components are significantly affecting the sea-level seasonal variations (Sultan et al. 1995b), with the maximum levels occurring in December–February and the lowest levels in June–August.

Normally, in the Northern Hemisphere, the seasonal cycle of sea levels peaks in late summer, as the sea warms, and expands causing steric levels to rise. In the Red Sea, the reverse is true, as is also the case for the Black Sea, where excess of winter freshwater inflow from rivers gives winter highs and dominates over any steric summer expansion. In the case of the Black Sea, there is a long adjustment time for the river inflow to reach a balance with the Mediterranean connection. Similarly, the Red Sea seasonal sea-level changes are dominated by the evaporation/precipitation balance and regional winds, complicated by the narrow

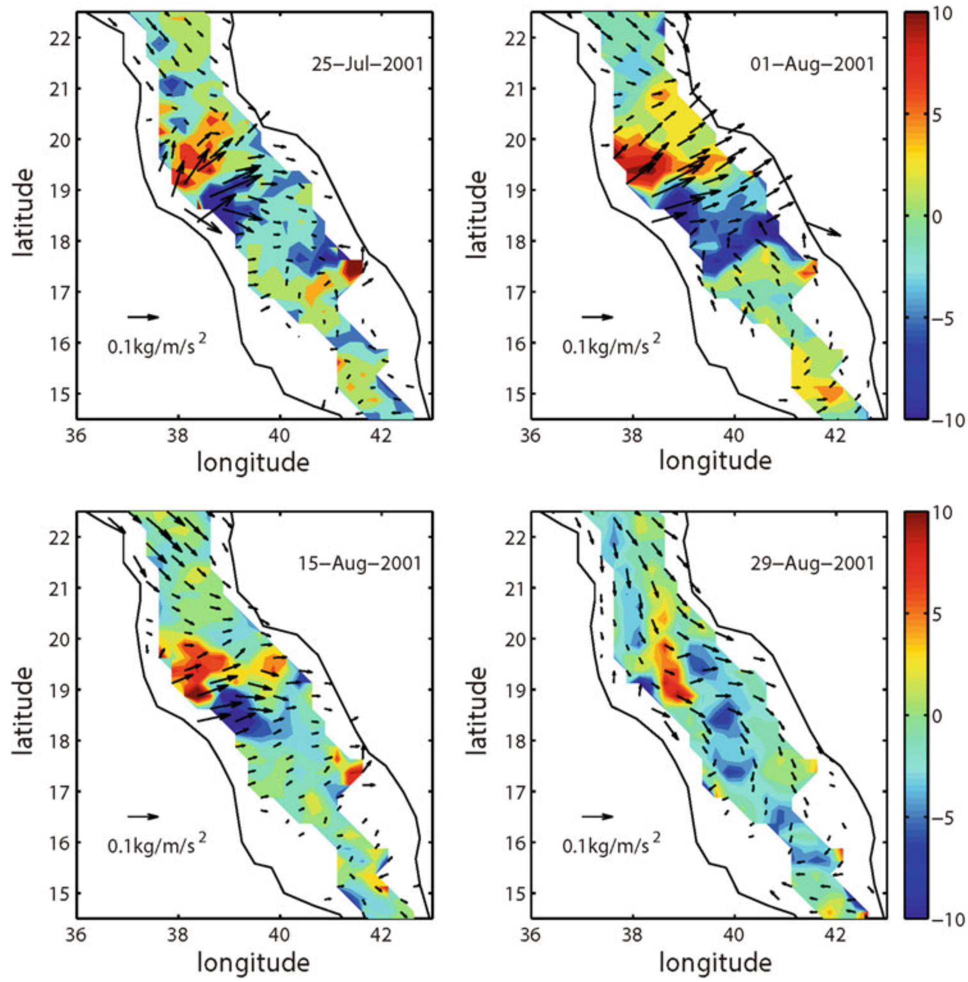

Fig. 8 The sequence development of the QuickSCAT wind stress and the wind stress curl (unit 10^{-7} N/m^3) to the same period in Fig. 4; cyclonic eddy develops with (−) SLA, and anticyclonic eddy develops with (+) SLA (Zhai and Bower 2013)

connection to the Gulf of Aden. This reversal of phase is also opposed to the seasonal cycle of air pressures and dominates over a normal ocean inverted barometer pressure effect on sea level (Osman 1984). Annual evaporation in the central Red Sea was estimated at around 2 m per annum (Morcos 1970; Ahmad and Sultan 1989), while there is very little precipitation or river inflow. Sofianos and Johns (2001) with altimeter data demonstrated that the annual cycle of sea level in the central and northern Red Sea can be explained as a balance between sea surface elevations and wind stress.

These sea-level variations are well reproduced in the data assimilation program SODA (http://www.atmos.umd.edu/~ocean; Carton and Giese 2008). SODA ocean modelling assimilates data from many sources including temperature/salinity profiles and altimetry data. Manasrah et al. (2009) have analysed the Red Sea SODA data output from 1958 to 2001. They verified the outputs by comparing them with the sea-level records for Port Sudan for 1986–1994. Sea-level data from three different parts (north, central, and south) for 43 years showed, compared to the other parts, that the sea level in the northern part of the Red Sea is permanently lower by about 7–8 cm. Overall, the sea levels in the three regions are significantly higher in the winter and spring compared with the summer and autumn. Furthermore, the mean sea level during the summer is significantly lower than that in the winter by about 10–12 cm. The increasing sea level from the north to the south and from summer to winter is related to the water mass exchanges with the Gulf of Aden during both seasons. Therefore, the coherent Red Sea response is due to the influx of water from the Gulf of Aden at the surface during winter with less salinity and warmer temperature which produces positive steric effect compared with the summer season when the Red Sea overflow water (RSOW) exits to the Gulf of Aden. A quasi 2.5–2.7-year oscillation was identified in these analyses, with varying amplitudes and without any identified forcing function. Mohamad (2012) has also analysed Red Sea levels as encapsulated in the SODA data. Some information on long-term changes in deep-water steric effects is included in Alraddadi (2013).

Long-Term Mean Sea-Level Trends

Mean sea levels in the Red Sea averaged over long periods of decades will closely follow the changes in the global ocean, as on these timescales the Bab-al-Mandab connection is very open. The Intergovernmental Panel on Climate Change reports that it is very likely that the mean rate of globally averaged mean sea levels rose by 0.19 ± 0.02 m over the period 1901–2010 (IPCC 2013). The changes of the Red Sea level should be similar.

The international Permanent Service for Mean Sea Level (PSMSL), which maintains the global archive of monthly and annual sea levels, holds very little data from the Red Sea. Table 2 shows that the only long-term record in the region is from Aden, outside the Red Sea in the Gulf of Aden. Figure 9 shows the annual mean sea-level record for Aden, where the gauge has recently been reactivated. At Aden, the latest data are from 2012. Over the period from 1880, the average rate of sea-level rise has been 2.88 mm/yr.

Table 2 shows that PSMSL holds data from 1986 to 1994 for Port Sudan. Although this is a short period, further investigation has found four separate periods of observation at Port Sudan: 1925–1928, 1962–1968, 1986–1994, and briefly for 6 months in 2013. In the context of this chapter, it is appropriate to consider these collectively in more detail.

1925–1928: Measurements of sea levels at Port Sudan are reported by Vercelli (1931). Unfortunately, no copy of this paper could be obtained. However, Osman (1984) says that his values are "21.8 cm higher than the value listed by Vercelli". Osman's mean value was 58.8 cm above the zero of the Port Sudan tide gauge, so that Vercelli's mean level would be 37 cm. However, without reading the earlier papers, we cannot be certain whether the same datum level applies.

1962–1968: Osman (1984) gives a detailed analysis of these data. The annual means are given in Table 3a. The overall mean is 58.6 cm.

1986–1994: These levels have been analysed in detail (Eltaib 2010). The monthly means are plotted in Fig. 3b. The vertical axis is the mean sea level, presumably to the tide staff zero, which is also Chart Datum. Table 3b summarizes the annual mean levels tabulated by the PSMSL. The average over these 7 years is 44.4 cm.

Table 2 Permanent Service for Mean Sea Level data holdings for Red Sea region monthly and annual mean sea levels. Metric quality means unconfirmed datum continuity. RLR is to a standard datum defined by PSMSL and has a more robust datum history

Station	Latitude (°E)	Longitude (°N)	Period	Completeness (%)	Quality
Suez (Port Taufiq)	29.93	32.57	1925–1986	32	Metric
Eilat	29.55	34.95	1962–1971	90	Metric
New gauges installed at Eilat North and Eilat South, 2010					RLR
Port Sudan	19.63	37.12	1986–1994	95	RLR
Aden	12.78	45.00	1879–2012	51	RLR
Djibouti	11.58	43.15	1970–2012	15	Metric

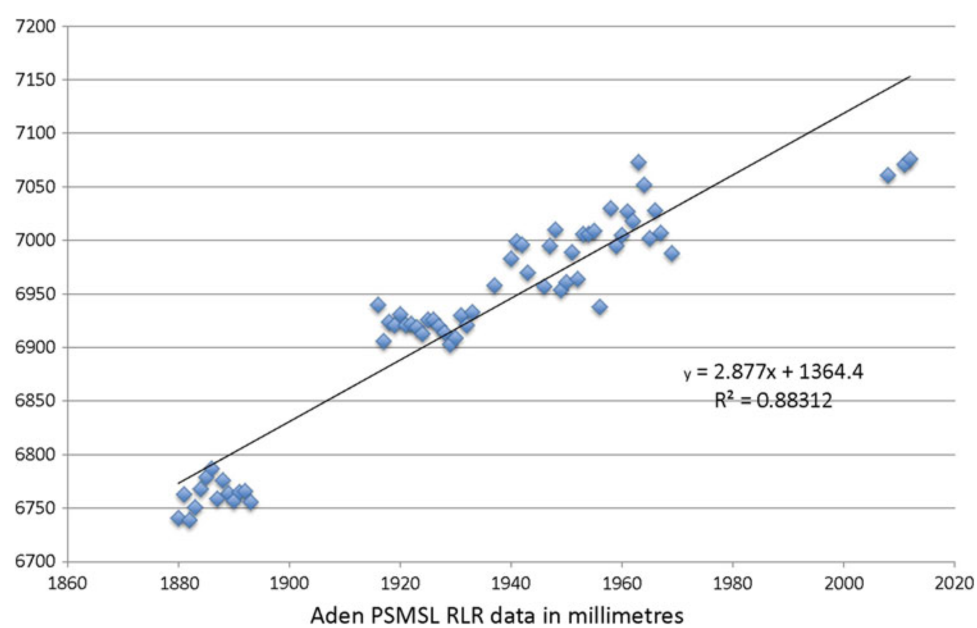

Fig. 9 The long-term sea-level record from Aden

Table 3 Annual (a) 1962–1968 and (b) 1987–1994 mean sea levels at Port Sudan

(a)	1962	1963	1964	1965	1966	1967	1968	
Annual mean (cm)	60.3	62.7	56.0	57.8	59.6	54.9	58.8	
(b)	1987	1988	1989	1990	1991	1992	1993	1994
Annual mean (cm)	45.2	45.7	44.9	42.4	45.7	38.2	45.8	50.2

Table 4 Summary of mean sea levels for all four measurement periods at Port Sudan

	1925–1928	1962–1968	1987–1994	2013 (part, adjusted)
Mean (cm)	37	58.8	44.4	48

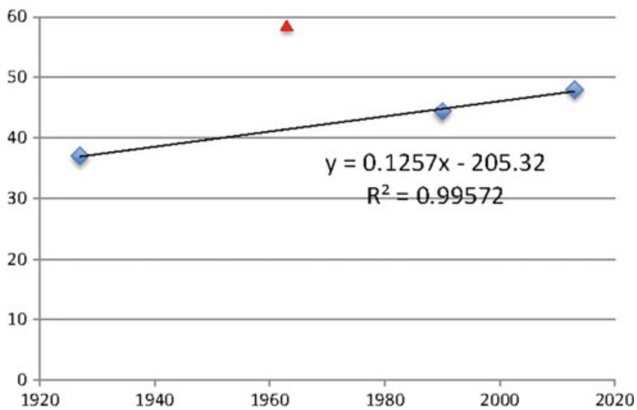

Fig. 10 Plot of sea-level annual means at Port Sudan, assuming the same datum for different epochs

2013: Measurements taken in 2013 were part of a study of amphidrome development in the vicinity of Port Sudan. The RBR-manufactured gauge measured sea bed pressures at a jetty adjacent to the permanent tide gauge location, from February to September. These seabed pressures are converted to readings from the permanent tide staff adjacent to the tidal building, using a series of staff readings taken at 0900 (L) every morning from 22 April to 31 July by Elfatih Bakry Ahmed Eltaib, the physical oceanographer on the staff of the adjacent Institute of Marine Research. Having only 6 months of 2013 data makes it impossible to draw conclusions about recent trends. Speculatively, we can adjust our half-year period over which the measurements were taken, to an average annual cycle of sea level, using the curve of average monthly mean sea levels at Port Sudan, in Osman (1984). On average, over these 6 months, the mean sea level is about 4 cm lower than the annual average level, so we might adjust our 43.71 cm upwards for an estimated annual mean of 48 cm. It would be valuable to continue these recent readings.

The mean sea levels of the four periods are summarized in Table 4 and plotted in Fig. 10.

In conclusion, the 2013 levels look reasonable in comparison with earlier data. However, the 1962–1968 levels seem 10–15 cm too high, beyond any statistically acceptable variability.

Tentatively ignoring the 1960s' data, and assuming the same datum (Chart Datum) for the other periods, gives a trend over the other measurements of 1.26 mm/yr from 1925 to 2013, equivalent to 12.6 cm per century, which agrees favourably with global trends over the same period. Local vertical land movement also affects measured trends.

The Geological Record

Mean sea-level changes are measured locally relative to some fixed land datums. Only with the advent of satellite altimetry has it been possible to measure sea levels in absolute geocentric terms. Of course, these sea-level measurements relative to the land include both the vertical sea surface and vertical land movements. Generally, over a few decades, sea levels change more rapidly than land levels, but over centuries and millennia, the land movements are increasingly important and eventually dominant. Apart from plate and crustal tectonic movements, by far the major influence on land levels is the adjustment to crustal loading that occurs during global glacial cycles, where polar ice mass becomes a globally distributed mass of sea water. The additional local water mass can depress local coastal areas substantially. Lambeck et al. (2011) have applied global ice load and crustal models to evaluate how the glacial cycles affect the Red Sea and land levels. They have looked in detail at relative sea levels in the Red Sea during the Holocene, during the last glacial maximum and during the last interglacial period (see also Bailey, this volume).

During the Holocene, that is, roughly the past 10,000 years, levels were perhaps a few metres lower than today, but not evenly so along the whole Red Sea, because of the different land loading effects. Figure 11a, b shows a section from Port Said to Socotra and the relative sea levels

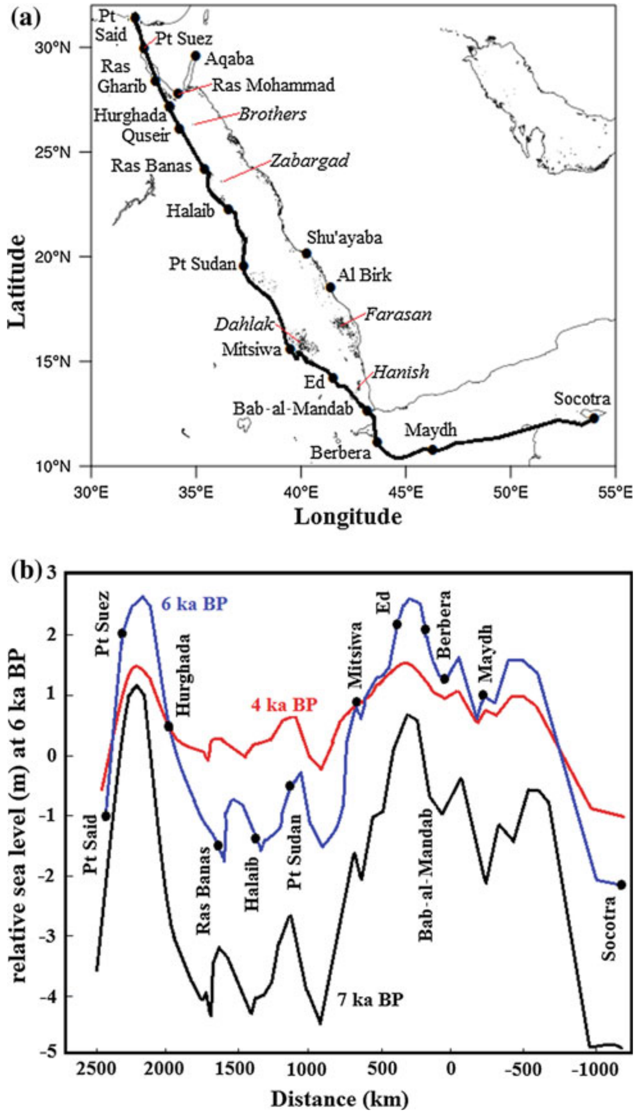

Fig. 11 **a** Location of selected sites and the section corresponding to the profiles in Fig. 11b (Reprinted from Lambeck et al. 2011, with permission from Elsevier) and **b** representative predictions for mid-Holocene sea-level change along the section in Fig. 11a (Reprinted from Lambeck et al. 2011, with permission from Elsevier)

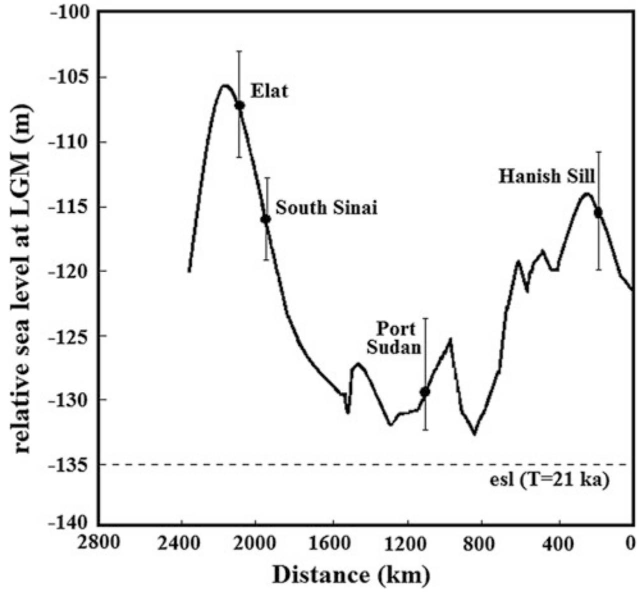

Fig. 12 Predicted LGM sea levels along the section in Fig. 11a. The *dashed horizontal line* is the model level at 21 ka BP (Reprinted from Lambeck et al. 2011, with permission from Elsevier)

along the section some 7,000 years ago (7 ka BP), 6,000 years ago and 4,000 years ago. There was a strong rise between 7,000 and 6,000 years ago and then a slower rise or fall, depending on location, to today's levels. There is observational evidence in the form of raised coral platforms to support this.

During the last glacial maximum, some 20,000 years ago, globally the water locked in the polar ice caps reduced sea levels by about 125 m. In the Red Sea, allowing for the regionally variable crustal response to reduced sea mass loading locally as isostatic loading adjustments, levels ranged from −110 m in south Sinai, to −128 m south of Port Sudan, relative to the present day. Figure 12 shows the relative curve, but note that the Gulf of Suez (shaded) was dry at these lower levels. Direct observational evidence for these much lower sea levels is now submerged and so difficult to find, though some submerged terraces have been tentatively identified, which may be interpreted as supplying evidence.

The last interglacial extreme maximum, some 125,000 years ago, when the polar ice caps were at their minimum extent, probably produced Red Sea levels some 5–7 m above today's mean sea levels, also with regional vertical land movement differences. This is confirmed by field evidence for reefs some 5–8 m above the present coast level, certainly in the northern and central Red Sea.

There is no evidence through the period of these studies that the Red Sea has been cut off from the Gulf of Aden. If this happened, given the very high local evaporation rates (about 2 m/year), and low precipitation, the Red Sea levels would fall relatively rapidly, with very high salinities as a result. However, the corresponding sediments have not been found. Nevertheless, levels at the southern entrance, the Hanish Sill, at the last glacial maximum some 20,000 years ago, were much reduced. Lambeck et al. (2011) estimate that the depth maximum at the sill may have been 25 ± 4 m and that the cross-sectional area of the much reduced connecting channel could have been only about 2 % of the cross-sectional area today.

As global sea levels have risen and fallen by many tens of metres over the geological Quaternary Period, the hydraulic connection between the Red Sea and the Gulf of Aden has increased and reduced accordingly. More limited water exchange at times when sea levels were lower, that is, at times of maximum glaciation, resulted in higher Red Sea salinities and changes in the oxygen isotope composition (Siddall et al. 2004). By relating the oxygen ^{16}O to ^{18}O isotope ratio in the foraminifera in Red Sea sediment cores, it has been possible to indirectly estimate the water depths at the Hanish Sill, which was the controlling factor for water exchange through this Gulf of Aden connection. These depths in turn may be considered to represent global sea levels. Hence, Red Sea sediments contain a valuable record of *global* sea-level changes through a succession of glacial cycles over the past 550,000 years (Siddall et al. 2003).

Tsunamis

The major tsunami disasters in the adjacent Indian Ocean make it a little surprising that very few tsunamis have been reported for the Red Sea. This is despite the region being one of the frequent seismic activities, as the central Red Sea axis is an opening mid-ocean ridge, with associated activity. The few records of actual tsunami generation in the region are summarized in Jordan (2008). They include the inundation at El Tor, Egypt, on the Sinai Peninsula in the Gulf of Suez on 11 July 1879. A landslide is a possible source for this tsunami. The second reported incident was at Mitsiwa, Eritrea, on 20 July 1884, when an earthquake occurred at sea offshore. Reportedly, sea waves built up in the Massawa harbour, mostly between the localities known as Taulud and Edaga Barai. The waves swept over a causeway, and ships in the harbour were seen swaying violently. Multiple flooding from the sea over land left dead fish onshore (Ambraseys et al. 1994). From this evidence, it appears that generally the magnitude and character of local earthquakes are not favourable for frequent tsunami generation.

Summary

Red Sea tides are relatively small but scientifically challenging. Weather effects are at least as important as tidal changes. Seasonal sea levels are out of phase with the general Northern Hemisphere pattern of maximum levels in late summer. Instead, seasonal changes are dominated by weather and water exchange processes. Despite an acute sparsity of sea-level observations, records from Port Sudan hint at increases over the past century compatible with global increases, but only if a continuous datum is assumed. Over geological periods, the effects of glacial cycles have raised levels by up to 7 m and lowered them by as much as 128 m, from today's levels.

Looking ahead, global mean sea level will continue to rise during the twenty-first century, and the Red Sea will follow this trend (IPCC 2013). The rate of rise will very likely exceed that observed globally during 1971–2010 (2.0 mm/yr), due to continuing global warming and loss of ice from glaciers and ice sheets. The impacts of these changes on local flooding risks are not easily determined because of the limited availability of sea-level data.

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