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Interpreting and analyzing King Tide in Tuvalu

C.-C. Lin, C.-R. Ho, and Y.-H. Cheng

Department of Marine Environmental Informatics, National Taiwan Ocean University, Keelung, Taiwan

Correspondence to: C.-R. Ho (b0211@mail.ntou.edu.tw)

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Abstract. The spatial and temporal distribution of sea-level rise has the potential to cause regional flooding in certain areas, and low-lying island countries are severely at risk. Tuvalu, an atoll country located in the southwest Pacific Ocean, has been inundated by this regional flooding for decades. Tuvaluans call this regional flooding phenomenon *King Tide*, a term not clearly defined, blaming it for loss of life and property in announcing their intention to migrate. In this study, we clarified and interpreted King Tide, and analyzed the factors of King Tide in Tuvalu. Using tide gauge and topographical data, we estimated that 3.2 m could be considered the threshold of King Tide, which implied half of the island of Tuvalu was flooded with seawater. This threshold is consistent with the finding of the National Oceanic and Atmospheric Administration that King Tide events occur once or twice a year. We surveyed 28 King Tide events to analyze the factors of regional flooding. Tide gauge and satellite altimeter data from 1993 to 2012 were cross-validated and indicated that the King Tide phenomenon is significantly related to the warm-water effect. Warm water contributed to the King Tide phenomenon by an average of 5.1 % and a maximum of 7.8 %. The height of King Tide is affected by the combined factors of spring tide, storm surge, climate variability, and, significantly, by the warm-water effect.

1 Introduction

Inundation and flooding have become common threats to island countries in tropical regions because of the impact of global warming and climate change (Mimura et al., 2007). At its highest elevation, Tuvalu is less than 5 m above sea level and is considered among the island countries most threatened by sea-level rise (Church et al., 2006; Mimura et al., 2007; Webb and Kench, 2010; Wong, 2011). Because of its low-lying setting and vulnerability as an island composed of coral, any change in the ocean, whether man-made or natural, can cause damage. The people of Tuvalu have already experienced the effects of flooding. Regional flooding has washed over the coastline, and seawater has seeped through the porous atoll ground, killing crops, contaminating freshwater, increasing the risk of disease, and decreasing agricultural productivity (Mortreux and Barnett, 2009). Tuvaluans call this flooding that threatens their lives and property "King Tide". In Tuvalu, King Tide events correspond to spring tide fluctuations and can last for hours or days, leaving a trail of disaster (EPA, 2011). According to tide gauge data, the highest recorded sea level was 3.44 m on 28 February 2006. The Australian Bureau of Meteorology interpreted this as the result of a combination of the highest astronomical tide and regional climactic activity (AusAID, 2007).

Sea-level rise is one of the first effects to be considered when people talk about global warming. In the context of global warming, sea-level rise typically refers to the global average. This obscures the fact that sea levels are not rising in all areas. By contrast, our use of the term "flooding" does not refer to global sea-level rise. Limited by the lack and inaccuracy of data, historical and projected sea levels are a subject of considerable controversy in Tuvalu. Previous studies (Becker et al., 2012; Cazenave and Llovel, 2010; Nerem et al., 2006) have indicated that sea-level fluctuations in the western tropical Pacific are 3 to 4 times larger than the global average. Hunter (2002) cautiously estimated present long-term sea-level rises in Tuvalu at a rate of −1.1 to 2.7 mm yr^{-1} relative to the land, accounting for the effect of El Niño–Southern Oscillation (ENSO) events. This is of the same magnitude as the global average sea-level rise estimate of the Intergovernmental Panel on Climate Change (IPCC), 1–2 mm yr^{-1} (Church et al., 2001). Eschenbach (2004a, b) estimated the rate of sea-level rise to be 0.07 mm yr^{-1} based

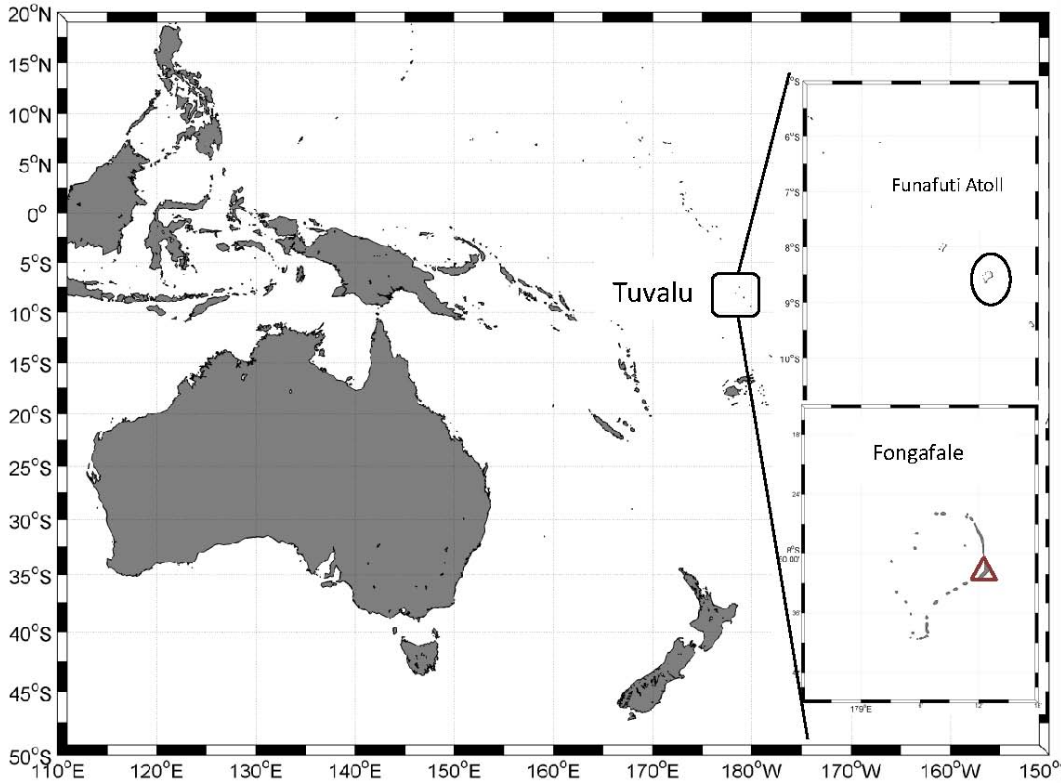

Fig. 1. The relative position of Australia and Tuvalu (left map). The upper right map is the relative position of nine Tuvalu atolls. Fongafale (bottom of right corner), the study site, is shown by red triangle.

on an analysis of Mitchell et al. (2001) for the period 1977–1998. Cabanes et al. (2001) used tide gauge data for the period of 1955–1996 but found that the mean sea level in Tuvalu had fallen. Residents noted that there had been no flooding in the previous decade, but in recent years flooding has occurred once or twice per year. By analyzing sea-level data, it is clear that global warming is not the only factor contributing to Tuvalu's present problem of inundation; oceanic factors must be also considered.

Ocean mechanisms cannot facilitate estimating the basic foundation of regional sea levels, but can assist in precisely understanding sea-level variability. The variability of the sea level in the tropical Pacific has been connected with ENSO (Trenberth and Hurrell, 1994; Chambers et al., 2002; Church et al., 2006), the Asian–Australian monsoon, and the Pacific Decadal Oscillation (PDO) (Mantua et al., 1997). Cabanes et al. (2001) revealed that the dominant contribution to regional sea-level variability results from non-uniform changes in ocean thermal expansion. Cazenave and Llovel (2010) indicated that about 30 % of the observed rate of sea-level rise between 1993 and 2007 was caused by oceanic thermal expansion. Houghton et al. (1996) estimated that half of the rate of sea-level rise was because of steric heating. Merrifield (2011) noted that the sea-level trend in the western tropical Pacific was linked to remote wind forcing. In the tropics between 20° N and 20° S, trade winds drive currents westward along the equatorial region and feed and maintain high water levels on the western side of the Pacific, which contributes slightly to regional sea-level rise.

We adjusted the tide gauge measurements to account for the barometric effect and performed harmonic analysis; there were unknown residuals of about 20 cm. Many factors are connected to changes in sea level, and certain mechanisms that drive the sea level are analyzed. In this study, we scientifically defined King Tide, investigated the unknown residuals with oceanic mechanisms that intensify regional flooding, and discussed the King Tide events between 1993 and 2012.

2 Regional setting

Tuvalu, an island country located in the southwest Pacific (Fig. 1), consists of four reef islands and five atolls between 6° and 11° S latitude and 176° and 180° E longitude. Because of the particular characteristics of coral atolls, flooding in Tuvalu occurs both on the shoreline and inland. At the center of the town of Fongafale, built on extensive swampland and mangroves, seawater oozes from the ground, and pond water flows in and out through the lower part of the storm ridge during spring tide (Webb, 2006; Yamano et al., 2007). When extreme spring tides hit the island, the water surges

Table 1. A check list of possible influential factors of the 28 King Tide events.

Event	Date	Sea level (m)	Duration (days)	Highest astron. tide	Spring tide	Warm water	Tsunami	Tropical cycle
1	26 Feb 1994	3.241	2	X	+	+ (5.9 %)	X	X
2	21 Jan 1996	3.255	3	+	+	+ (2.2 %)	X	X
3	18 Feb 1996	3.312	4	X	+	+ (5.7 %)	+ (2.5 %)	X
4	18 Mar 1996	3.200	1	X	+	+ (4.5 %)	X	X
5	8 Feb 1997	3.255	2	+	+	+ (1.7 %)	X	X
6	9 Mar 1997	3.304	4	X	+	+ (3.5 %)	X	X
7	1 Feb 1999	3.207	1	X	+	+ (6.6 %)	X	X
8	21 Jan 2000	3.236	2	X	+	+ (3.5 %)	X	X
9	9 Feb 2001	3.322	4	+	+	+ (5.5 %)	X	X
10	9 Mar 2001	3.347	4	X	+	+ (7.7 %)	X	X
11	30 Jan 2002	3.226	1	X	+	+ (4.8 %)	X	X
12	28 Feb 2002	3.309	3	+	+	+ (4.3 %)	X	X
13	28 Mar 2002	3.303	3	X	+	+ (5.4 %)	X	X
14	16 Apr 2003	3.253	2	X	+	+ (5.0 %)	X	X
15	15 May 2003	3.246	3	X	+	+ (5.8 %)	X	X
16	30 Jan 2006	3.358	4	X	+	+ (6.9 %)	X	X
17	28 Feb 2006	3.415	5	+	+	+ (7.8 %)	X	X
18	29 Mar 2006	3.236	2	X	+	+ (4.0 %)	X	X
19	18 Mar 2007	3.241	2	+	+	+ (4.3 %)	X	X
20	17 Apr 2007	3.262	3	X	+	+ (7.3 %)	X	X
21	22 Jan 2008	3.218	1	X	+	+ (5.6 %)	X	X
22	12 Jan 2009	3.234	2	X	+	+ (5.1 %)	X	X
23	10 Feb 2009	3.271	2	+	+	+ (5.6 %)	X	X
24	30 Jan 2010	3.210	1	X	+	X	X	X
25	20 Jan 2011	3.286	3	X	+	+ (5.5 %)	X	X
26	19 Feb 2011	3.223	2	+	+	+ (4.3 %)	X	X
27	20 Mar 2011	3.206	2	X	+	+ (4.2 %)	X	X
28	9 Mar 2012	3.200	2	X	+	+ (6.1 %)	X	X

Note: + = means the positive influence; X = means non-influence; the value inside quotation marks indicates the percentage effect on sea level variation.

from underground through the coral, and then submerges the main road and nearby houses. Because of the mean sea-level elevation of approximately 2 m, the low-lying atoll island is vulnerable to oceanic fluctuation of any type. Referring to sea-level rise impacts in Fongafale, both natural and anthropogenic factors should be accounted for.

Morphologically, the island eroded and was reshaped. The establishment of a US Army base during World War II intensified these natural effects (Lewis, 1989; Eschenbach, 2004a). The US Army also built a straight airport runway in Fongafale, excavating a wide channel, which increased erosion. A high population density of approximately 1600 people per km^2 (Secretariat of the Pacific Community, 2005), limited resources of fresh water and food, vulnerability to natural hazards, and threatened biodiversity (Wong, 2011) all increased Tuvalu's vulnerability.

3 Data

Estimates of regional short-term sea-level variation are primarily based on historical tide gauge data. Raw data from 1993 to 2012 were acquired from the South Pacific Sea Level and Climate Monitoring Project (SPSLCMP) (http://www.bom.gov.au/oceanography/projects/spslcmp/spslcmp.shtml), sponsored by the Australian Agency for International Development (AusAID). The Sea-level Fine Resolution Acoustic Measuring Equipment (SEAFRAME) gauge was installed in Tuvalu in 1993. Sea-level data were revised using a continuous global positioning system network and the Tide Gauge Benchmark for vertical movement.

Sea surface height anomaly data derived from satellite altimetry are employed in this study. They were acquired from Archiving Validation and Interpretation of Satellite Data in Oceanography (AVISO). The merged data from the TOPEX/Poseidon, Jason-1/2, ERS-1/2, and Envisat satellites have a $1/4°$ spatial resolution and 7-day temporal intervals. The along-track sea surface height data of Pass 173, the track

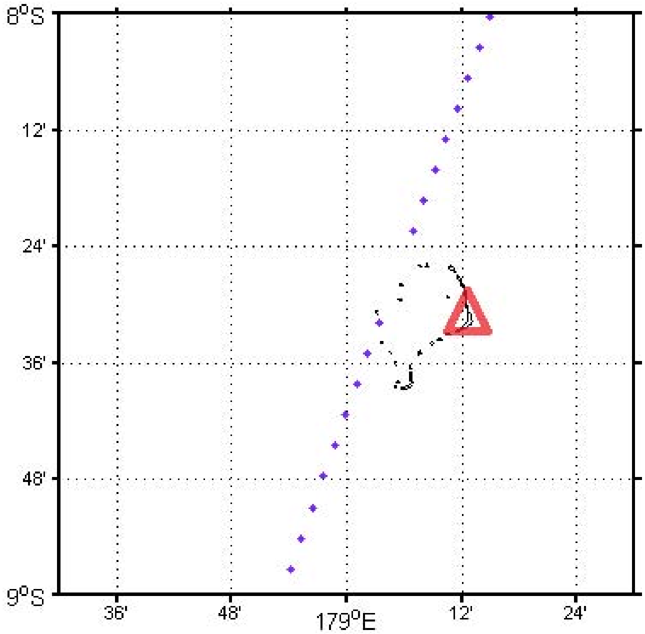

Fig. 2. Sampling points of satellite altimeter along-track Pass 173: data points are marked with purple dots, and the location of tide gauge is shown by the red triangle.

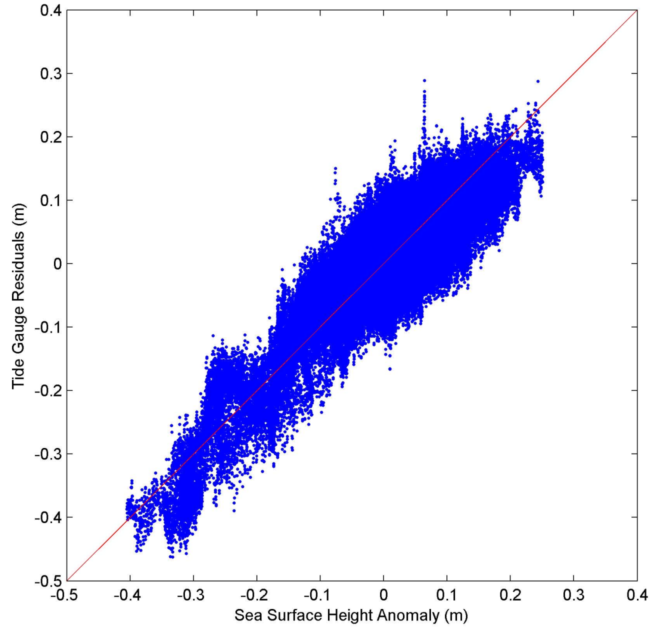

Fig. 3. The root-mean-square error of tide gauge and altimeter data for 19 years (March 1993 to July 2012) reaches a value of 4.37 cm.

nearest to the tide gauge station at Fongafale (Fig. 2), are also used and are interpolated to one datum each hour to match with the tide gauge data. There are 714 matched-up data available from March 1993 to July 2012.

Elevation is one interrelated factor that determines the vulnerability of land to the effects of sea-level rise. Evaluating coastal vulnerability requires accurate spatial analyses of horizontal and vertical resolutions on the extent and timing of coastal flooding. The digital elevation of Fongafale in this study is based on a static GPS survey by Yamano et al. (2007).

4 Analyzing methods

Atmospheric pressure is one parameter potentially influencing local sea-level rise. Variations in barometric pressure affect the shifting of weather patterns, which in turn affects sea-level rise or fall. A 1 hPa decrease sustained over a day could cause a 1 cm increase in relative sea level (AusAID, 2010), or an inverted barometer response of 0.995 cm mbar^{-1} decrease (increase) in atmospheric pressure (Fu and Pihos, 1994). In this study, inverted barometer responses were calculated using Eq. (1) mentioned by Jeffreys (1916). $\eta(t)$ is the oceanic sea-level change; $p'_{\mathrm{a}}(t)$ is an atmospheric pressure change measured in millibars; g is the gravitational acceleration; and ρ_0 indicates the water density ($\sim 1.02\,\mathrm{g\,cm^{-3}}$).

$$\eta(t) = -\frac{p'_a(t)}{\rho_0 g}. \tag{1}$$

To determine the factors that contributed to regional flooding, we first accounted for barometric effects. Harmonic analysis was then used to calculate the amplitudes and phases of the tides. The tidal level $Y(t)$ can be described by the linear functions of cosine and sine as

$$Y(t) = a_0 + \sum_{i=1}^{M} (a_i \cos\omega_i t + b_i \sin\omega_i t), \tag{2}$$

where a_0 is the mean sea level, a_i, b_i ($i = 1,2, \ldots, M$) the amplitude of the ith constituent, ω_i the frequency of the ith constituent, and t time.

Harmonic analysis showed 186 tidal constituents with a 95 % confidence interval. Tide gauge data and satellite altimeter data were then compared to examine reliability. The root-mean-square error of both data sets reached 4.37 cm (Fig. 3), which conforms to the uncertainty of satellite altimeter data (Dibarboure et al., 2011).

5 Results

5.1 Clarification of King Tide and high tide

King Tide, a layman's term used in the Pacific, could easily be simplified as merely the highest spring tide. It is always related to regional flooding in the Pacific. The US Environmental Protection Agency (EPA, 2011) defines King Tide as the highest predicted high tide of the year at a coastal location. The government of Queensland, Australia (http://www.msq.qld.gov.au/Tides/King-tides.aspx) defines it as any high

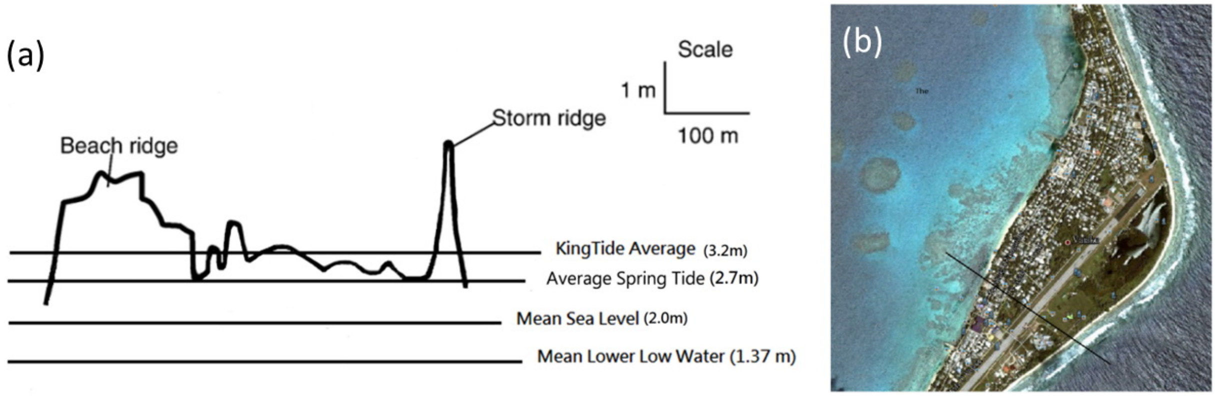

Fig. 4. A terrain profile of Fongafale, Tuvalu. Left map is drawn by the profile of black line in right image. The framework **(a)** was accessed from Yamano et al. (2007), while the image of Fongafale **(b)** was accessed from Google Maps.

tide well above average height, or the higher high waters that occur approximately near the end of each calendar year. Green Cross International (http://www.witnesskingtides.org/what-are-king-tides.aspx) regards it as an especially high tide event occurring twice a year, and the NOAA similarly defines it as normally occurring once or twice a year. All of these definitions indicate that a significant relationship between highest astronomical tide and King Tide. If gravitational force were adequate for explaining King Tide, a year's highest astronomical tide would correspond to the most severe floods of that year. However, on the highest astronomical tide days of 1998 and 2010, the sea surface heights were respectively 38 cm and 23 cm lower than expected. As shown in Table 1, less than half of the King Tide events occurred during the highest tide period.

5.2 Definition of King Tide in Tuvalu

Generally, mean lower low water indicates the average height of the lowest tide recorded every day at a tide station during a recording period. This depth is relative to a chart datum, which is typically the water level at the lowest possible astronomical tide and is therefore the minimum possible water depth during the tidal cycle. The mean lower low water represents the intersection of the land with the water surface at the elevation of mean lower low water. In Fongafale, the 19 yr (1993–2012) mean lower low water was 1.37 m relative to the chart datum. The local average altitude of 1.83 m reported by United Nations (2008) was measured based on the mean lower low water. The sum of these two reaches the value of 3.2 m, which is the average elevation of Fongafale, and is also assumed to be a reasonable threshold for defining King Tide.

Figure 4 shows the terrain profile of Tuvalu to illustrate the relative elevation of mean lower low water, the regular spring tide elevation, and the King Tide threshold. Over 19 yr (1993–2012), the average regular spring tide was only 2.7 m, 0.5 m lower than the King Tide threshold. This difference of 0.5 m in sea-level variation demonstrates the significant effects of King Tide on sea-level fluctuation. In the years the tide gauge data have been recorded, there were 108 instances exceeding 3.2 m. In this study, continuous records during the same spring tide were considered to be one King Tide event; therefore, the total number is approximately 28 events. This means that, on average, there are approximately 1.5 King Tide events every year, which corresponds both to local knowledge in Tuvalu and to the NOAA definition of King Tide as a normal occurrence once or twice a year in coastal areas. Figure 5 displays an exceptional case in which the King Tide event continuously occurred three times. The time series of sea-level variation shows three King Tide events and one usual spring tide from January to April 2011.

5.3 Effect of warm water

Maps of sea surface height anomaly with data derived from satellite altimetry have demonstrated that Tuvalu is surrounded by warm water during King Tide periods. Figure 6 is a sample map of warm water accompanying a King Tide event. Anomalous high water is diagrammed in red, passing from east to west, the motion of water within the ocean driven by Rossby waves or the equatorial current. The sea surface height ascends when warm water passing Tuvalu runs into the spring tide. Warm water has induced a maximum rise in sea surface height of 26 cm during 28 King Tide events. Except for the King Tide event of 2010, all King Tide events have been accompanied by warm water, and have raised the sea surface height by an average of 17 cm. King Tide events occurring on 1 February 1999, 9 March 2001, and 17 April 2007 (Fig. 7) did not occur during the highest astronomical tide period of that year, but warm water induced anomalous sea surface height rising by 21, 25, and 23 cm, respectively. This implies that warm-water effect is significant to sea-level rise.

We quantified the warm-water effect described in Table 1. The percent of the sea level height contributed by warm water

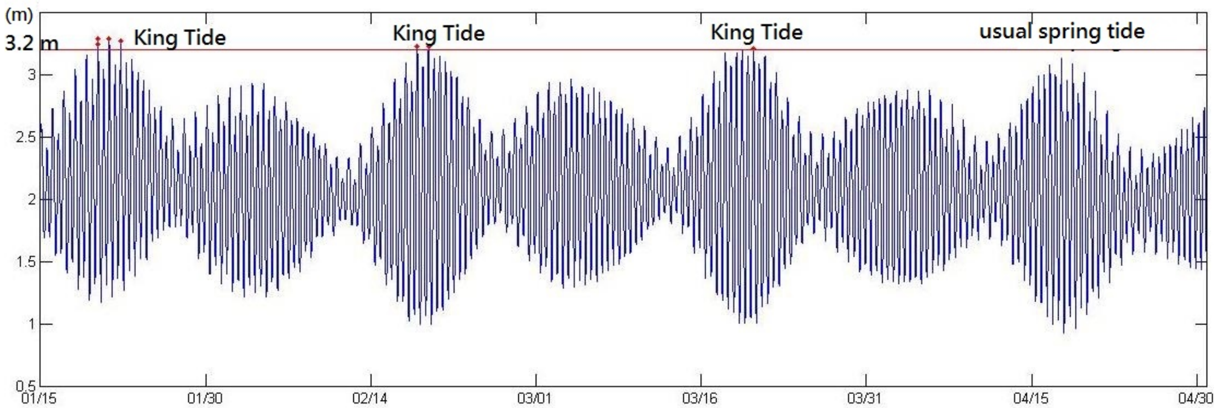

Fig. 5. Time series of sea level variation includes three King Tide events and the usual spring tide. Red line is the threshold of King Tide. There are three King Tide events and one usual spring tide from 15 January to 30 April 2011.

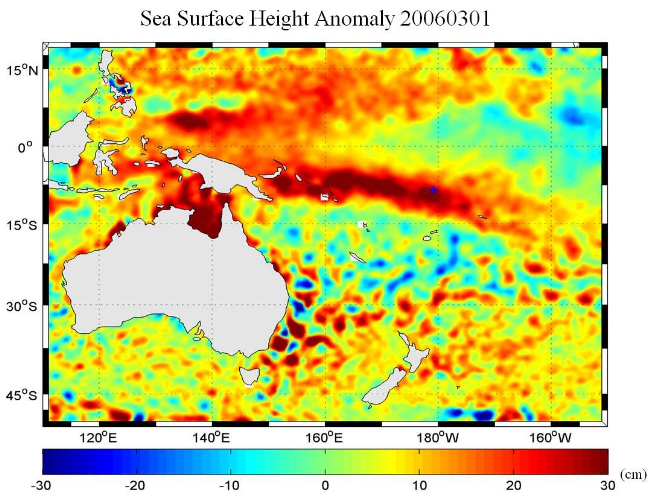

Fig. 6. A map of sea surface height anomaly during a King Tide event. The blue star indicates the position of Tuvalu. Color bar shows the sea surface height anomaly by centimeter. Red color presents the warm-water effect, while blue presents the cold-water effect. The image is a 7-day average datum. The date on the image is the middle date of the 7 days.

is 5.1 % on average and 7.8 % at maximum. The warm-water effect is not as crucial as other factors in spring tide, but for an island with average elevation of 3.2 m, a rise of 26 cm caused by warm water cannot be ignored.

5.4 Other factors to King Tide

The 28 King Tide events and the possible factors on regional flooding are shown in Table 1. Besides tide and the warm-water effect, oceanic factors must be discussed. Because of Tuvalu's location in the tropical Pacific, it is definitely affected by the interannual variability of barometric pressure (Aung et al., 2009). Due to the influence of barometric effects filtered out, the ENSO effect has already been taken into account. By considering El Niño, the sea level is anomalously high in the eastern tropical Pacific and low in the western tropical Pacific. In this area, the easterly surface wind that extends across the entire equatorial Pacific begins to weaken, and seawater flows back toward the eastern Pacific. Simultaneously, it decreases in the western Pacific where Tuvalu is located. ENSO seems to exert a fundamental influence on sea-level fluctuation in this area. As shown in Table 1, a King Tide event did not occur in the El Niño years of 1997–1998. Maps of sea surface height anomaly indicated that cold water was sustained for 10 months instead. By contrast, Tuvalu experienced more floods in La Niña years than usual – for example, in the La Niña years of 1999–2001.

Tuvalu, at latitude 6°–11° S, is a producer rather than a victim of tropical cyclones. Since the installation of the SEAFRAME tide gauge in 1993, the only tropical cyclone detected was Cyclone Gavin. The storm surge was not sufficient for producing a King Tide event because it did not occur in spring tide period, but reached a peak height of 0.3 m.

Regarding the short-term effects of tsunamis, 17 separate tsunami events have been detected since SEAFRAME was installed. The highest surge record was 10 cm caused by an earthquake of magnitude Mw 8.8 that occurred off the coast of Chile on 27 February 2010 (AusAID, 2010). Figure 8a shows that, at that time, Tuvalu was surrounded by cold water. The energy of ocean dynamics reduced the sea surface height and diminished the effects of the tsunami; rather than rising, sea levels fell 10–20 cm. By contrast, an earthquake of magnitude Mw 8.2 near Irian Jaya on 17 February 1996 (Fig. 8b) occurred during a warm-water spring tide. Combined with the slight effects of La Niña, this contributed to the production of a King Tide event.

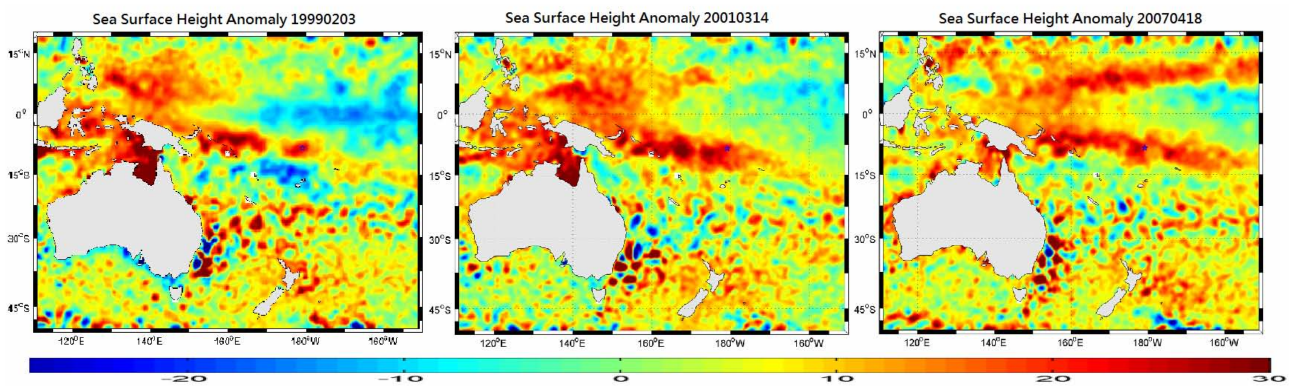

Fig. 7. The example images of sea surface height anomaly affected by warm water during non-highest astronomical tide period, and caused sea-surface rise of 21, 25, and 23 cm, respectively.

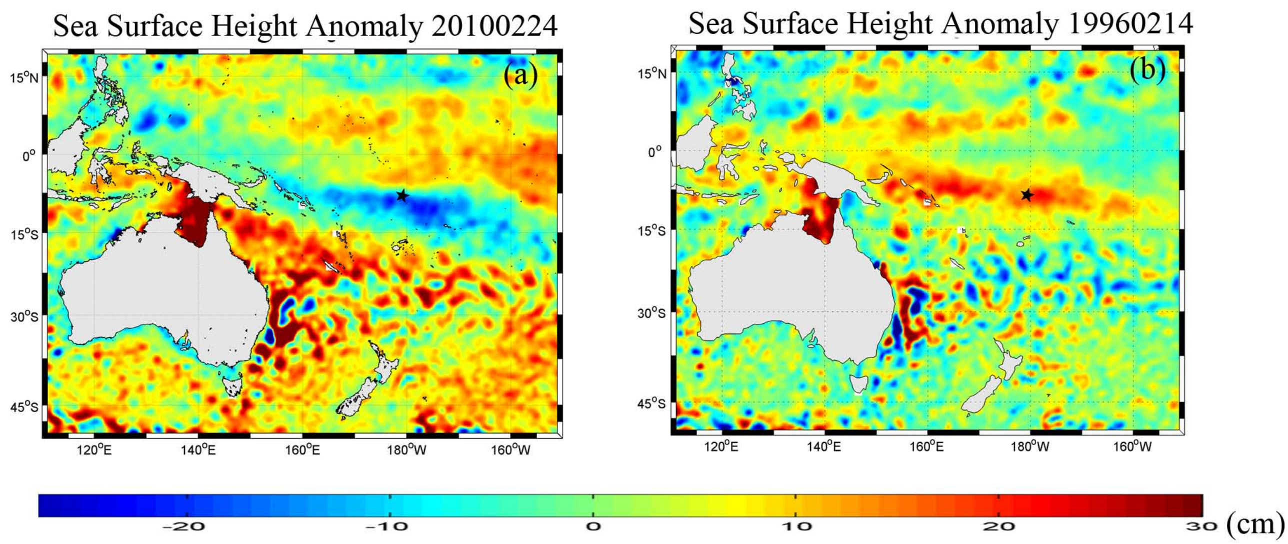

Fig. 8. (a) The image of sea surface height interprets that Chile earthquake did not cause severe regional flooding in Tuvalu under the background of cold water mass. **(b)** The image displays Tuvalu was flooded under the combination of tsunami surge and warm-water effect. The date on the image of sea surface height anomaly indicated the middle date of the 7 days.

6 Discussion and conclusion

Ninety percent of King Tide events occurred between January and March (i.e., in austral summer). They are all consistent with the characteristic of sea water expanding with heat. In other words, warm water was a significant factor contributing to King Tide events. One-hundred percent of King Tide events occurred during the spring tide period, but only 29 % occurred during the highest astronomical tide. Twenty-seven of 28 (96 %) events were accompanied by a warm-water mass. Warm water contributed to sea level variation by an average of 5.1 %, but tsunamis contributed to sea level variation only by an average of 2.5 %. No King Tide event was caused by the combination of tropical cycle surge.

As with sea-level rise, an isolated flooding event on a given day in a given place is not proof of a global trend, but regional sea-level variation implying sea-level fluctuation is practical information. Regional sea-level change may be caused by many factors, such as isostatic rebound, climate variability (Merrifield, 2011; Timmermann et al., 2010), non-uniform changes in ocean thermal expansion (Cabanes et al., 2001; Cazenave and Nerem, 2004), and the warm-water effect. Nevertheless, not all of these factors will play key roles in low-lying island countries, nor can they be effectively predicted or prevented. This study defines King Tide and recommends applying that definition to Tuvalu. The definition of King Tide used in this study is consistent with the NOAA and Tuvaluans local knowledge. The results indicate the relationship between King Tide and the possible mechanisms raising the sea level. Spring tide is largely responsible for King Tides, but the warm-water effect is a key factor in raising sea surface height and should not be underestimated. Potential

King Tides that occurred in conjunction with warm water but had sea levels beneath the threshold were not included in this study. The formation, duration, and diminishment of warm-water periods are highly relevant subjects for future research.

Supplementary material related to this article is available online at http://www.nat-hazards-earth-syst-sci.net/14/209/2014/nhess-14-209-2014-supplement.pdf.

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