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King Tide floods in Tuvalu

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Abstract

The spatial and temporal distributions of sea level rise present regional floods in some certain areas. The low-lying island countries are obviously the spots affected severely. Tuvalu, an atoll island country located in the south-west Pacific Ocean, is suffering the devastating effects of losing life, property, and intending migration caused by floods. They blame the regional flooding to King Tide, a term used but not clearly identified by Pacific islanders. In this study, we clarify what King Tide is first. By the tide gauge and topography data, we estimated the reasonable value of 3.2 m as the threshold of King Tide. This definition also fits to the statement by National Oceanic and Atmospheric Administration (NOAA) of King Tide occurring once or twice a year. In addition, We cross validate the 19 yr data of tide gauge and satellite altimeter (1993–2012), the correlation coefficient indicates King Tide phenomenon is considerable connected to warm water mass. The 28 King Tide events revealed the fact that flooding can be referenced against spring tide levels, so can it be turned up by warm water mass. The warm water mass pushes up sea level; once spring tide, storm surge, or other climate variability overlaps it, the rising sea level might overflow and so has been called "King Tide" for the floods in Tuvalu. This study provides more understanding of the signals of King Tide and an island country case study of regional sea level rise.

1 Introduction

As with the impacts of global warming and climate change, inundation and flooding have become the common threats to island countries in the tropical oceans (Mimura et al., 2007). Tuvalu with the highest point less than 5 m up to sea level, is broadly considered to be one of the island country most threatened by sea level rise (Church et al., 2006; Mimura et al., 2007; Webb and Kench, 2010; Wong, 2011). Because of the low-lying setting and the vulnerable characteristic of coral islands, any oceanic influential factors which were made worse by the effects of human and nature, can cause damages. The people in Tuvalu are already experiencing flooding in places. They call those floods pulling the Pacific Ocean farther ashore than normal "King Tide", a term connected to threaten their lives and properties. Not only wash over the coastline, it also seeps through small holes in the porous atoll ground which may wash away soils, kill crops, contaminate freshwater, increase risk of disease, and decline agricultural productivity (Mortreux and Barnett, 2009). Originally, King Tide refers to any high tide well above average height, or the highest spring tide in every year occurring in summer or winter (http://www.msq.qld.gov.au/Tides/King-tides.aspx). The popular concept is that the King Tide is simply the very highest tide that usually occurs around the full moon or new moon. Back to the phenomenon of King Tide here, it is neither a high water phenomenon existing always, nor a series of continuous events, it happens mostly on the specific days of a year with regular tidal fluctuation. The duration can last for hours to days, but it leaves behind a trail of unforgettable disaster (EPA, 2011). There has been estimated the highest astronomical tide in Tuvalu should occur on 28 February 2006 over the period of 1990–2016 (AusAID, 2006). That day was as expected of occurring King Tide, bringing the severest floods with the record of sea level 3.44 m. Though adjusted of barometric and harmonic analysis, there still has been 20 cm unknown residuals left (AusAID, 2007). We regarded the combination of astronomical tide and regional climate activities can mainly be explained to the inundation of Tuvalu, but what cause the unknown residuals need to be explained.

Sea level rise is normally the first impression connected to global warming. Of many things about global warming misunderstood by the public when sea level rise is mentioned, it typically refers to the global average, but this obscures the fact that not all areas are rising. On the opposite, when we mentioned about flooding, it does not refer to sea level rise globally. Limited by the length and accuracy of data, the historical and projected sea level is always a subject of considerable and controversial in Tuvalu. Some previous studies (Becker et al., 2012; Cazenave and Llovel, 2010; Nerem et al., 2006) indicated that sea level in the western tropical Pacific is 3–4 times larger than the global average. A comment by Hunter (2002) noted a cautious estimate of

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present long-term sea level change at Tuvalu was a rate of rise between −1.1 and 2.7 mm yr^{-1} relative to the land, concerning the data affected by El Niño/Southern Oscillation (ENSO) events. It's of very similar magnitudes to the Intergovernmental Panel on Climate Change (IPCC) estimate of global average sea level rise during the 20th century, 1–2 mm yr^{-1} (Church et al., 2001). Eschenbach (2004a, b) estimated the rate of rise of 0.07 mm yr^{-1} based on an analysis of Mitchell et al. (2001) for the period 1977–1998. Cabanes et al. (2001) used the sea level data from tide gauge for the period 1955–1996 but found out mean sea level has fallen in Tuvalu. Somehow, a consensus view unveils sea level rise is a trend and will be an unpreventable issue. The United States Environmental Protection Agency called the world that sea level rise will make today's King Tides become the future's everyday tides (EPA, 2011). The regional flooding or King Tide flooding will be more frequent and more severe. By the analysis of tide gauge and satellite altimeter data, Tuvalu's present problem of inundation seems not simply being contributed by long trend of sea level rise by global warming. Some oceanic factors need to be concerned.

Except for estimating the basic foundation of regional sea level, examining the mechanisms of ocean can help to understand sea level variability precisely. The sea level in tropical Pacific variability has been regarded with the association of ENSO (Trenberth and Hurrell, 1994; Chambers et al., 2002; Church et al., 2006), the Asian–Australian monsoon or 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 about 30 % of the observed rate of rise during 1993–2007 was caused by ocean thermal expansion. Houghton et al. (1996) estimated that half of rising was due to steric heating. Merrifield (2011) pointed out the sea level trend in the western tropical Pacific has linked to remote wind forcing. In tropical area of 10° N–10° S, the trade wind drives currents westward along the equator, feeds and maintains the high water on the western side of the Pacific, which contributes to regional sea level rise a bit.

Many factors and components are connected to the change of sea level, and some of the mechanisms of driving sea level have been analyzed. This study differs from the usual attempts to determine how much sea level rises in Tuvalu or how many centimeters response driven by variable factors. We focus on the definition of King Tide, the possible mechanisms intensify King Tide events, and the discussion of King Tide events during 1993–2012. First, a threshold of King Tide was identified to confine our discussion of flooding events. Then we discussed the oceanic factors of King Tide events. We took tide gauge data and satellite altimeter data as basic data, removed the barometric pressure effect, used harmonic method to filter out the tidal influence, then the correlation coefficient and unknown residuals unveiled the true factors of regional flooding. By the snap shoot and discussion of King Tide, we sincerely hope offering a different view to understand the signals of King Tide and temporary regional sea level rise in tropical islands.

2 Regional setting

Tuvalu, a Pacific island country, located in the south-west Pacific (Fig. 1) between 6 and 10° S latitude, and from 176 to 180° E longitude, comprising four reef islands and five atolls. Owning to the characteristic of coral atoll, the inland is at increased risk of flooding as well as the shoreline in Tuvalu. The central part of Fongafale is formed by extensive swampland and mangroves, sea water always oozes out of the ground, and pond water can also go in and out through the lower part of the storm ridge during spring tide (Webb, 2006; Yamano et al., 2007). Once the extreme spring tide hits the island, the water surges up from underground through the coral, the main road and nearby houses are also submerged. With the mean sea level elevation around 2 m, the low-lying atoll island is vulnerable to any oceanic fluctuation. Referring to sea level rise impact in Fongafale, the capital island of Tuvalu, nature and anthropogenic sides are supposed to be described. Morphologically, the island was eroded and reshaped. The historic combination of being a base of American army during World War II (WWII)

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strengthened the natural effects (Lewis, 1989; Eschenbach, 2004a). US army building a straight airport runway in Fongafale, and excavating a wide channel during WWII broadened the erosion. On the other side, high population density of about 1600 per km^2 (Secretariat of the Pacific Community, 2005), limited land resources of fresh water and food, vulnerability to natural hazards, threatened biodiversity (Wong, 2011), all above made Tuvalu more vulnerable. The last shoot of psychological awareness came on one response of Kyoto conference in 1997. The United States and Australia governments failed on promising CO_2 emission reduction, which provoked Tuvaluans call the international of being the less contributors to global warming, but the first climate refugees. So far, the spotlight of the global warming and Tuvalu seems connected tightly.

3 Data sets and methods

Sea level records show variability over a wide range of different time scales, including ranging from hours to years of tidal oscillations, hours to weeks of weather scale phenomena, seasonal variation, interanual variations, or over periods of ten years to geological times scale. Estimates of regional short-term sea level variation are primarily based on the historical tide gauge data. The raw data from 1993 to 2012 are accessed from South Pacific Sea Level and Climate Monitoring Project (SPSLCMP) (http://www.bom.gov.au/oceanography/projects/spslcmp/spslcmp.shtml), sponsored by Australian Agency for International Development (AusAID). The Sea Level Fine Resolution Acoustic Measuring Equipment (SEAFRAME) gauge in Tuvalu was installed in 1993, offering accurate data of sea level measurement, air and water temperatures, wind speed, wind direction and atmospheric pressure. All parameters are collected for 2 min record of every 6 min and averaged to each hour. Sea level readings are taken every 3 min record of each 6 min by calculating the traveling time of a sound pulse from and back between acoustic head and sea surface to one hour one datum. The sea surface height

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is revised by the assistance of Continuous Global Positioning System (CGPS) network and Tide Gauge Bench Mark (TGBM) for vertical movement.

Sea Surface Height (SSH) data are accessed from Archiving Validation and Interpretation of Satellite Data in Oceanography (AVISO). It is a merged product derived from TOPEX/Poseidon, Jason-1/2, ERS-1/2, and ENVISAT satellites with a 1/4° spatial resolution and 7 day temporal intervals. The along track sea level data based on three satellites (Topex/Poseidon, Jason-1, and Jason-2) is used to interpolate one datum each hour to match with tide gauge data. Cycle 173 of along track (Fig. 2), the nearest track to the tide gauge at Fongafale was used. There are about 714 points valid data matched up to the middle of 2012.

Atmospheric pressure is one parameter potentially influencing local measurements of relative sea level rise. Variations in barometric pressure do not cause changes in global ocean volume, but they affect sea level to rise or fall by the shifting weather patterns. 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). The inverted barometer response was calculated as Eq. (1) mentioned by Jeffreys (1916). $\eta(t)$ is the oceanic sea level change; $p'_a(t)$ is an atmospheric pressure change measured in millibars; while g is the gravitational acceleration and ρ_0 indicates the water density ($\sim 1.02\,\mathrm{g\,cm^{-3}}$)

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

After barometric influence removed, we took harmonic analysis as the method to calculate the amplitudes and phases of tidal characteristics. The tidal signal, modeled as the sum of a finite set of sinusoids at specific frequencies, was related to astronomical parameters. These frequencies are specified by various combinations of sums and differences of 6 fundamental frequencies arising from planetary motions (Godin, 1972), which includes the rotation of the earth, the orbit of the moon around the earth, the earth around the sun, the lunar perigee, the lunar orbital tilt, and the perihelion

(Pawlowicz et al., 2002). Harmonic analysis displayed the tidal constituents of 186 constituents, with 95 % confidence interval.

4 Results

King Tide, a layman's term in Pacific, has been identified by United States of Environmental Protection Agency (EPA, 2011) as the highest predicted high tide of the year at a coastal location. The Queensland Government of Australia (http://www.msq.qld.gov.au/Tides/King-tides.aspx) takes any high tide well above average height, or the higher high waters which occur around Christmas time as King Tide. Green Cross (http://www.witnesskingtides.org/what-are-king-tides.aspx) regards it as an especially high tide event occurring twice a year, similar to the definition as National Oceanic and Atmospheric Administration (NOAA) of a normal occurrence once or twice a year. Therefore, King Tide is clearly explained to the gravitational forces exerted by the Moon and the Sun and the rotation of the Earth. All above indicate the significant relation of highest tide and King Tide. If gravitational force can simplify the happening of King Tide, the highest astronomical tide (HAT) of every year should occur the severest floods in every year. But the fact displayed sea surface height (SSH) in the highest astronomical tide of 1998 had 38 cm fall than expected; and same to the case in 2010 of 23 cm fall. King Tide definition cannot be simplified to the highest predicted high tide only, there must have some other conditions need to be concerned. In this study, the previous studies and the tide gauge data which reflects regional sea level, the real flooding situation, and the pains people suffering are taken to estimate a reasonable threshold of the King Tide.

Generally, mean lower low water (MLLW) is the average height of the lowest tide recorded at a tide station during the recording period. The line on a chart 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) MLLW was 1.37 m relative to the chart datum, which is the lowest expected tidal level at a particular location and can be considered as

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the level relative to the depths on nautical charts and tidal levels. The average altitude of Tuvalu was reported 1.83 m (United Nations, 2008) relative to MLLW. The addition of both comes to the value of 3.2 m which we assumed to be a reasonable threshold of King Tide. Under the definition, once sea level measures over 3.2 m, we definitely consider sea water rises up to the average height of Fongafale land, half of the island land could be flooded by sea water. During the record years of tide gauge station set, there are 108 records of one datum each hour over than 3.2 m. The continuous records at the same spring tide are generalized to one King Tide event, therefore, the total amount brings about 28 events. The average amount of each year comes to 1.5 events, which satisfies with the introduction by Tuvaluans, also fits with the identification by NOAA: a normal occurrence once or twice every year in coastal areas.

The total amount of 28 King Tide events are shown in Table 1. Every King Tide event happened during spring tide period, but less than half of them occurred at the HAT period. The events happened in 1993–1995, 1998–2000, 2003–2005, 2008, 2010, and 2012 are out of HAT period. NOAA defined King Tide as the highest predicted high tide of the year; however, the fact of King Tide events in Tuvalu seems not accommodated. Although the gravitational force contributes sea level, without the other factors involved, the King Tide threshold will not be achieved. HAT is one optional component of King Tide, not essential.

Besides, Queensland Government defines King Tide as any high tide well above average height, or the higher high waters which occur around Christmas time. This identification cannot be imitated by Tuvalu of the fact that the higher high tide average is 2.7 m. If it is taken as the threshold of King Tide, then King Tide is every month tide. On the other side, 90 % of King Tide events happened on the month of January–March. From the point of the gravitational force, the theory of celestial cycle is acceptable. The perihelion, the point earth comes closest to the sun, is on 2 January at present.

In order to expose the unknown residuals of sea level rise, we examined and compared the data of tide gauge and satellite altimeter. The root-mean-square error of both data reaches a value of 4.37 cm (Fig. 3) which meets the uncertainty of satellite

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altimeter data (Dibarboure et al., 2011). Interest in the King Tide phenomenon has been strengthened with the recognition of warm water mass, which is described as the motion of water within the ocean driven by the Rossby waves or the equatorial current. Maps of sea surace height anomaly (SSHA) with data derived from satellite altimetry demonstrated that Tuvalu is surrounded by the warm water mass most of the flooding time. Figure 4 shows the fact that King Tide events are accompanied with warm water masses. The anomaly high water is diagramed by red colour, passing through from east to west. Once the warm water mass passing Tuvalu runs into the spring tide, SSH turns out an effective action. The impact of warm water mass brings 26 cm maximum of SSH for the King Tide events. Except the event occurred in 2010, all the others happened with warm water masses company, and pushed up SSH a 17 cm in average. The King Tide events occurred on 1 February 1999, 9 March 2001, and 17 April 2007 (Fig. 4) were not occurring in the HAT period of that year; but warm water masses made SSHA rise 21, 25, and 23 cm, respectively. The latter condition piled up the sea level high enough to be concerned with King Tide.

5 Discussion

As the display of Table 1 shows, the duration of King Tide (1–5 days) matches well with tidal period. Definitely, gravitation of moon pulling up sea level is one of the most important factors. Every King Tide event happening on full moon or new moon period clearly demonstrates that tidal fluctuation is the very first basic foundation of flooding. Warm water mass brought by the oceanic dynamic piling up the sea water is also one significant factor cannot be ignored. The duration of warm water mass formation, pass, and diminishing will be the future study to predict the duration of flooding. For the detail understanding of King Tide events, we discuss the influential impacts depending on the time and the amplitude of running into the spring tide. Some other components as below which are last but not least factors, need to be considered further.

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Regarding to the impact of El Niño and La Niñ a events, Tuvalu located in the tropical Pacific, is definitely affected by the interannual sea surface temperature and barometric pressure variations. Since we had filtered out the influence of barometric in data processing, the ENSO effect should be out of discussion here. But taking a quick view of El Niño, sea level is anomalously high in the eastern tropical Pacific and low in the western tropical Pacific. The easterly surface wind, that usually extending all the way across the equatorial Pacific, begins to weaken, sea water flows back to the east Pacific. Simultaneously, it drops down in the western Pacific where Tuvalu locates. As we check the King Tide events list out in Table 1, no King Tide record showed in 1998. Maps of SSHA indicating the cold water feature instead. On the contrary, Tuvalu experienced floods in La Niña periods than usual.

Referring to tropical cyclones effects, Tuvalu, situated in latitude 5.3–11° S, a site produces tropical cyclones instead of being attacked. Since the installation of SEAFRAME tide gauge in 1993, tropical Cyclone Gavin was the only one detected Tuvalu. The storm surge did not make King Tide event due to no support of spring time, though reached a peak of 0.3 m by the surge.

As for the short term effects of tsunami, there were 17 separate tsunami events detected since its installation. The highest surge record was 10 cm caused by the earthquake of magnitude $M_w = 8.8$ that occurred of Chile on 27 February 2010 (AusAID, 2010). SSHA (Fig. 5a) unveils of fact of time that Tuvalu was surrounded by cold water. The energy of ocean dynamic cuts down the SSH foundation and diminished the effects of tsunami. Instead of sea level rising, a fall of 10–20 cm was recorded at that time. But the other earthquake of magnitude $M_w = 8.2$ near Irian Jaya happened on 17 February 1996 (Fig. 5b) was not as lucky as the last one. The occurrence on spring tide with warm water mass, and the slight effects of La Niña contributed to the flooding of King Tide event.

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6 Conclusions

As with sea level rise, the state of an individual flooding happened on a given day or a given place is not proof of global trend, but regional sea level variation implying sea level fluctuation is obviously complicated. Regional sea level change may be re-acted by many factors, such as: isostatic rebound; climate variability (Merrifield, 2011; Timmermann et al., 2010); interannual influence; non-uniform changes in ocean thermal expansion (Cabanes et al., 2001; Cazenave and Nerem, 2004); or the warm water mass. Nevertheless, not all above will play key roles in the low-lying island countries; neither can they be well predicted or prevented by local government. In this study, a definition of King Tide is recommended to be introduced and applied in Tuvalu area, a reasonable threshold to examine the floods inducing by King Tide, which could satisfy the needs of local people. We make the term King Tide proper to the fact of occurring once or twice a year; also can it represent the Tuvaluans' deeper fear of losing their land and life. The results indicate the straight relationship of King Tide and the possible mechanisms raising sea level. The warm water mass, one of the key factors but easily be ignored, arises the SSH should not be underestimated. Some of the potential King Tides, occurring with the contributions of warm water mass but in low tide period of SSH under the threshold, are not included in this research.

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References

AusAID: Pacific country report on sea level and climate: their present state, Australian Agency for International Development, Tuvalu, 2006.

AusAID: Pacific country report on sea level and climate: their present state, Australian Agency for International Development, Tuvalu, 2007.

AusAID: Pacific country report on sea level and climate: their present state, Australian Agency for International Development, Tuvalu, 2010.

Becker, M., Meyssignac, B., Letetrel, C., Llovel, W., Cazenave, A., and Delcroix, T.: Sea level variations at tropical Pacific islands since 1950, Global Planet. Change, 80–81, 85–98, doi:10.1016/j.gloplacha.2011.09.004, 2012.

Cabanes, C., Cazenave, A., and Le Provost, C.: Sea level rise during past 40 years determined from satellite and in situ observations, Science, 294, 840–842, doi:10.1126/science.1063556, 2001.

Cazenave, A. and Llovel, W.: Contemporary sea level rise, Annu. Rev. Mar. Sci., 2, 145–173, doi:10.1146/annurev-marine-120308-081105, 2010.

Cazenave, A. and Nerem, R. S.: Present-day sea level change: observations and causes, J. Geophys. Res., 42, RG3001, doi:10.1029/2003RG000139, 2004.

Chambers, D. P., Melhaff, C. A., Urban, T. J., Fuji, D., and Nerem, R. S.: Low-frequency variations in global mean sea level: 1950–2000, J. Geophys. Res., 107, 1–10, doi:10.1029/2001JC001089, 2002.

Church, J. A., Gregory, J. M., Huybrechts, P., Kuhn, M., Lambeck, K., Nhuan, M. T., Qin, D., and Woodworth, P. L.: Changes in sea level, in: Climate Change 2001: The Scientific Basis, Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Houghton, J. T., Ding, Y., Griggs, D. J., Noguer, M., van der Linden, P. J., Dai, X., Maskell, K., and Johnson, C. A., Cambridge University Press, Cambridge, UK and NY, USA, 639–693, 2001.

Church, J. A., White, N. J., and Hunter, J. R.: Sea level rise at tropical Pacific and Indian Ocean islands, Global Planet. Change, 53, 155–168, doi:10.1016/j.gloplacha.2006.04.001, 2006.

Dibarboure, G., Pujol, M.-I., Briol, F., Le Traon, P. Y., Larnicol, G., Picot, N., Mertz, F., and Ablain, M.: Jason-2 in DUACS: updated system description, first tandem results and impact on processing and products, Mar. Geod., 34, 214–241, doi:10.1080/01490419.2011.584826, 2011.

EPA (United States of Environmental Protection Agency): King Tides Facts Sheet, EPA-842-F-11-010, available at: http://water.epa.gov/type/oceb/cre/upload/king_tides_factsheet.pdf, last access: 1 February 2013, 2011.

Eschenbach, W.: Tuvalu not experiencing increased sea level rise, Energy & Environment, 15, 527–543, 2004a.

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Eschenbach, W.: Response to John Hunter's review, Energy & Environment, 15, 931–935, 2004b.

Fu, L. L. and Pihos, G.: Determining the response of sea level to atmospheric pressure forcing using TOPEX/POSEIDON data, J. Geophys. Res., 99, 24633–24642, doi:10.1029/94JC01647, 1994.

Godin, G.: The Analysis of Tides, University of Toronto Press, Toronto, 285 pp., 1972.

Houghton, J. T., MeiraFilho, L. G., Callander, B. A., Harris, N., Kattenberg, A., and Maskell, K.: Climate Change 1995: The Science of Climate Change, Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, 572 pp., 1996.

Hunter, J. R.: A note on relative sea level change at Funafuti, Tuvalu, Antarctic Cooperative Research Center, Hobart, Australia, 2002.

Jeffreys, H.: Causes contributory to the annual variation in latitude, Mon. Not. R. Astron. Soc., 76, 499–525, 1916.

Lewis, J.: Sea level rise: some implications for Tuvalu, Environmentalist, 9, 269–275, doi:10.1007/BF02241827, 1989.

Mantua, N. J., Hare, S. R., Zhang, Y., Wallace, J. M., and Francis, R. C.: A Pacific interdecadal climate oscillation with impacts on salmon production, B. Am. Meteorol. Soc., 78, 1069–1079, doi:10.1175/1520-0477(1997)078<1069:APICOW>2.0.CO;2, 1997.

Merrifield, M. A.: A shift in western tropical Pacific sea level trends during the 1990s, J. Climate, 24, 4126–4138, doi:10.1175/2011JCLI3932.1, 2011.

Mimura, N., Nurse, L., McLean, R., Agard, J., Briguglio, L., Lefale, P., Payet, R., and Sem, G.: Small islands, in: Climate Change 2007: Impacts, Adaptation and Vulnerability, Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Parry, M., Canziani, O., Palutikof, J., van der Linden, P., and Hanson, C., Cambridge University Press, Cambridge, 687–716, 2007.

Mitchell, W., Chittleborough, J., Ronai, B., and Lennon, G. W.: Sea Level Rise in Australia and the Pacific, The South Pacific Sea Level and Climate Change Newsletter, Q. Newsl., 5, 10–19, 2000.

Mortreux, C. and Barnett, J.: Climate change, migration, and adaptation in Funafuti, Tuvalu, Global Environ. Change, 19, 105–112, 2009.

Nerem, R., Leuliette, E., and Cazenave, A.: Present-day sea level change: a review, C. R. Geosci., 338, 1077–1083, doi:10.1016/j.crte.2006.09.001, 2006.

Pawlowicz, R., Beardsley, R., and Lentz, S.: Classical tidal harmonic analysis include error estimates in MATLAB using T_TIDE, Comput. Geosci., 28, 929–937, doi:10.1016/S0098-3004(02)00013-4, 2002.

Queensland Government, Maritime Safety Queensland: available at: http://www.msq.qld.gov.au/Tides/King-tides.aspx/, last access: 1 February 2013.

Secretariat of the Pacific Community: Tuvalu 2002 Population and Housing Census: Volume 1, Analytical Report, Secretariat of the Pacific Community, Nouméa, 2005.

Trenberth, K. E. and Hurrell, J. W.: Decadal atmosphere-ocean variations in the Pacific, Clim. Dynam., 9, 303–319, 1994.

Timmermann, A., McGregor, S., and Jin, F. F.: Wind effects on past and future regional sea level trends in the southern Indo-Pacific, J. Clim. Change, 23, 4429–4437, doi:10.1175/2010JCLI3519.1, 2010.

United Nations: Effects of Climate Change on Indigenous Peoples: a Pacific Presentation, available at: http://www.un.org/esa/socdev/unpfii/documents/EGM_cs08_Elisara.doc, last access: 1 February 2013.

Webb, A.: Tuvalu technical report – coastal change analysis using multi-temporal image comparisons – Funafuti Atoll, EU EDF 8, SOPAC Project Report 54, 2006.

Webb, A. P. and Kench, P. S.: The dynamic response of reef islands to sea level rise: evidence from multi-decadal analysis of island change in the Central Pacific, Global Planet. Change, 72, 234–246, doi:10.1016/j.gloplacha.2010.05.003, 2010.

Wong, P. P.: Small island developing states, WIREs Clim Change, 2, 1–6, doi:10.1002/wcc.84, 2011.

Yamano, H., Kayanne, H., Yamaguchi, T., Kuwahara, Y., Yokoki, H., Shimazaki, H., and Chikamori, M.: Atoll island vulnerability to flooding and inundation revealed by historical reconstruction: Fongafale Islet, Funafuti Atoll, Tuvalu, Global Planet. Change, 57, 407–416, doi:10.1016/j.gloplacha.2007.02.007, 2007.

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

Event	Date	Sea level (m)	Duration (days)	HAT	Spring tide	Warm water mass	Tsunami	Tropical cycle
1	26 Feb 1994	3.241	2	×	+	+	×	×
2	21 Jan 1996	3.255	3	+	+	+	×	×
3	18 Feb 1996	3.312	4	×	+	+	+	×
4	18 Mar 1996	3.200	1	×	+	+	×	×
5	8 Feb 1997	3.255	2	+	+	+	×	×
6	9 Mar 1997	3.304	4	×	+	+	×	×
7	1 Feb 1999	3.207	1	×	+	+	×	×
8	21 Jan 2000	3.236	2	×	+	+	×	×
9	9 Feb 2001	3.322	4	+	+	+	×	×
10	9 Mar 2001	3.347	4	×	+	+	×	×
11	30 Jan 2002	3.226	1	×	+	+	×	×
12	28 Feb 2002	3.309	3	+	+	+	×	×
13	28 Mar 2002	3.303	3	×	+	+	×	×
14	16 Apr 2003	3.253	2	×	+	+	×	×
15	15 May 2003	3.246	3	×	+	+	×	×
16	30 Jan 2006	3.358	4	×	+	+	×	×
17	28 Feb 2006	3.415	5	+	+	+	×	×
18	29 Mar 2006	3.236	2	×	+	+	×	×
19	18 Mar 2007	3.241	2	+	+	+	×	×
20	17 Apr 2007	3.262	3	×	+	+	×	×
21	22 Jan 2008	3.218	1	×	+	+	×	×
22	12 Jan 2009	3.234	2	×	+	+	×	×
23	10 Feb 2009	3.271	2	+	+	+	×	×
24	30 Jan 2010	3.210	1	×	+	×	×	×
25	20 Jan 2011	3.286	3	×	+	+	×	×
26	19 Feb 2011	3.223	2	+	+	+	×	×
27	20 Mar 2011	3.206	2	×	+	+	×	×
28	9 Mar 2012	3.200	2	×	+	+	×	×

Note: + means the positive influence; × means non-influence.

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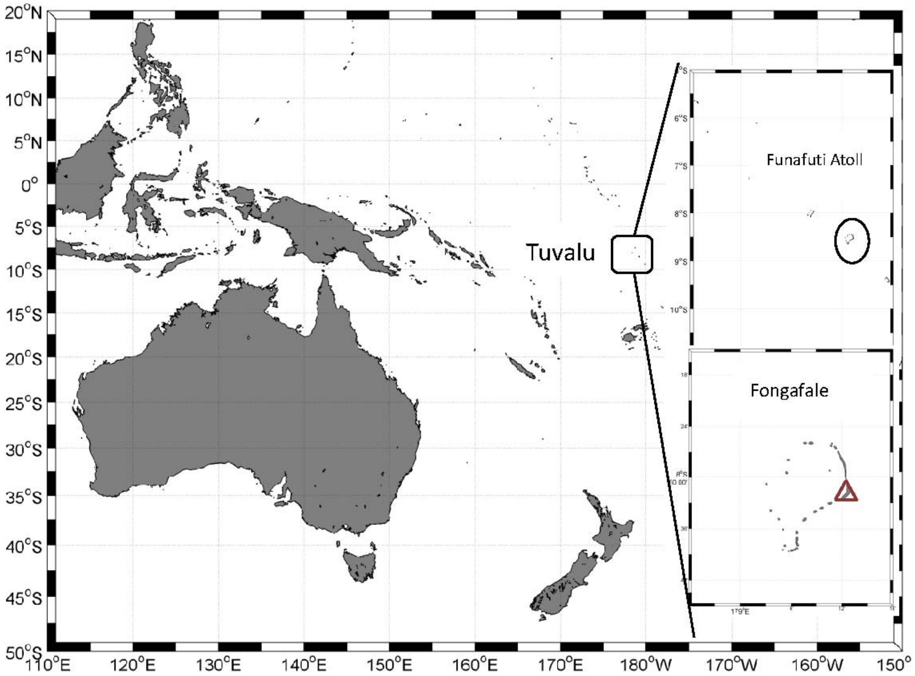

Fig. 1. Location of Tuvalu and the relative position of Australia (left map). The upper right map is the relative position of Tuvalu nine atolls, Funafuti atoll is the main atoll of Tuvalu. And Fongafale (bottom of right corner), the capital of Tuvalu referred to in the text, is shown by red triangle.

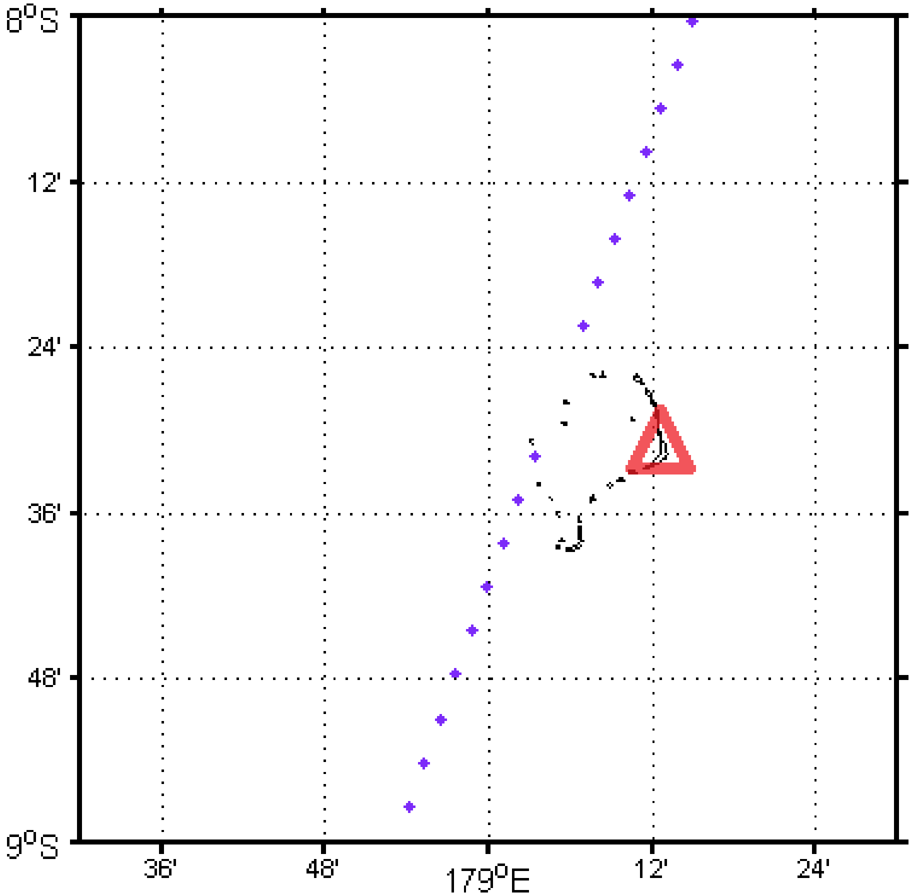

Fig. 2. Sampling points of satellite altimeter along track 173 are marked in purple dots, and the location of tide gauge is shown by the red triangle.

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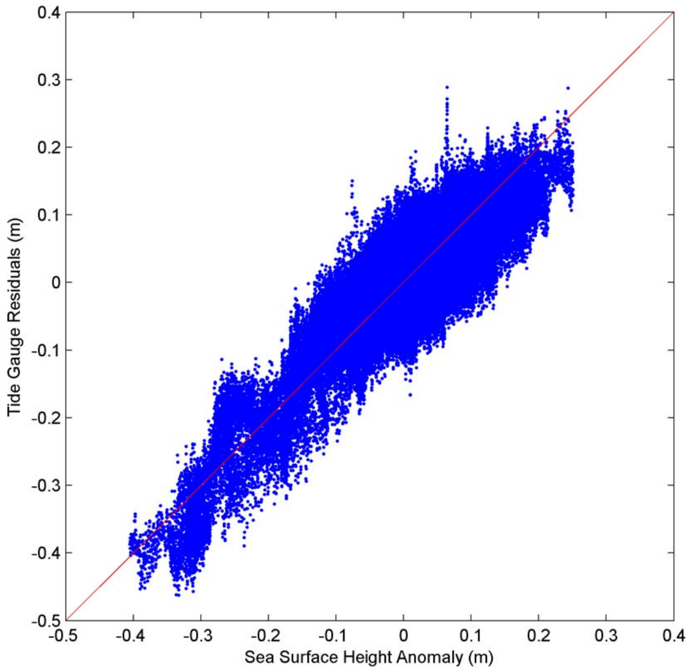

Fig. 3. The root-mean-square error of tide gauge and altimeter data for 19 yr (March 1993–November 2012) reaches a value of 4.37 cm.

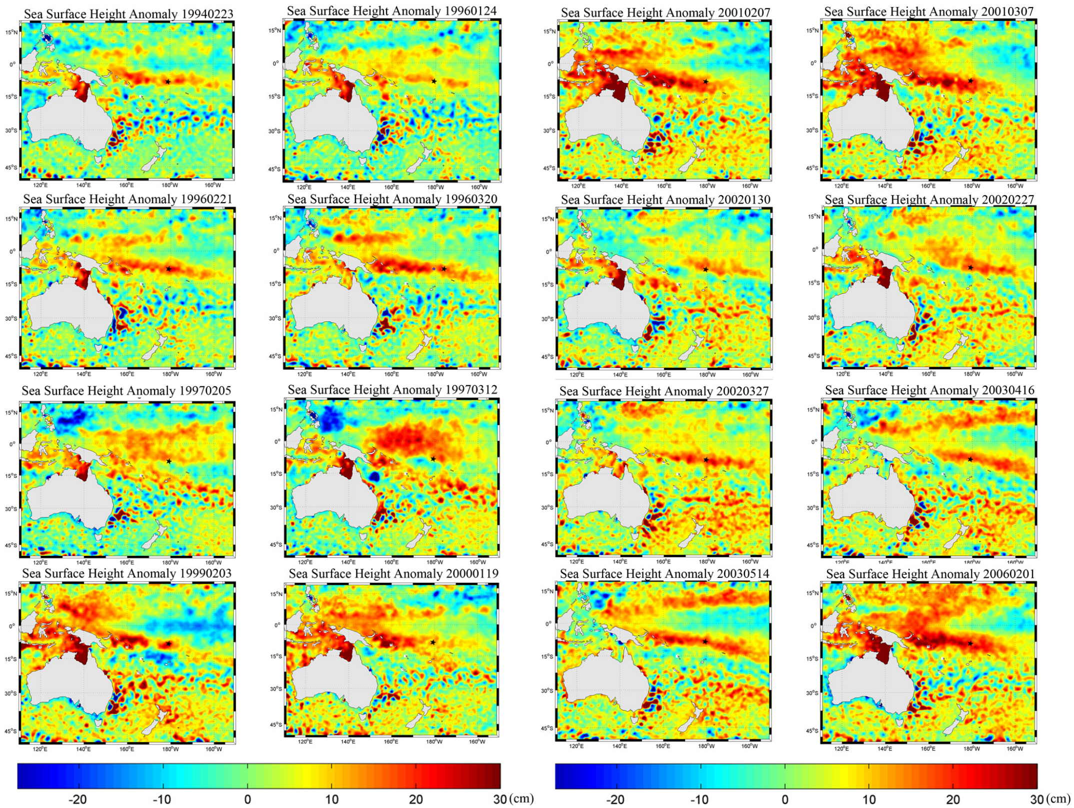

Fig. 4. Maps of SSHA during King Tide events. Star indicates the position of Tuvalu. The colour bar shows the SSHA by cm. Red colour presents the warm water mass; while blue presents the cold water mass. The image is a 7 day average datum. The date indicated on the image is the middle date of the 7 days.

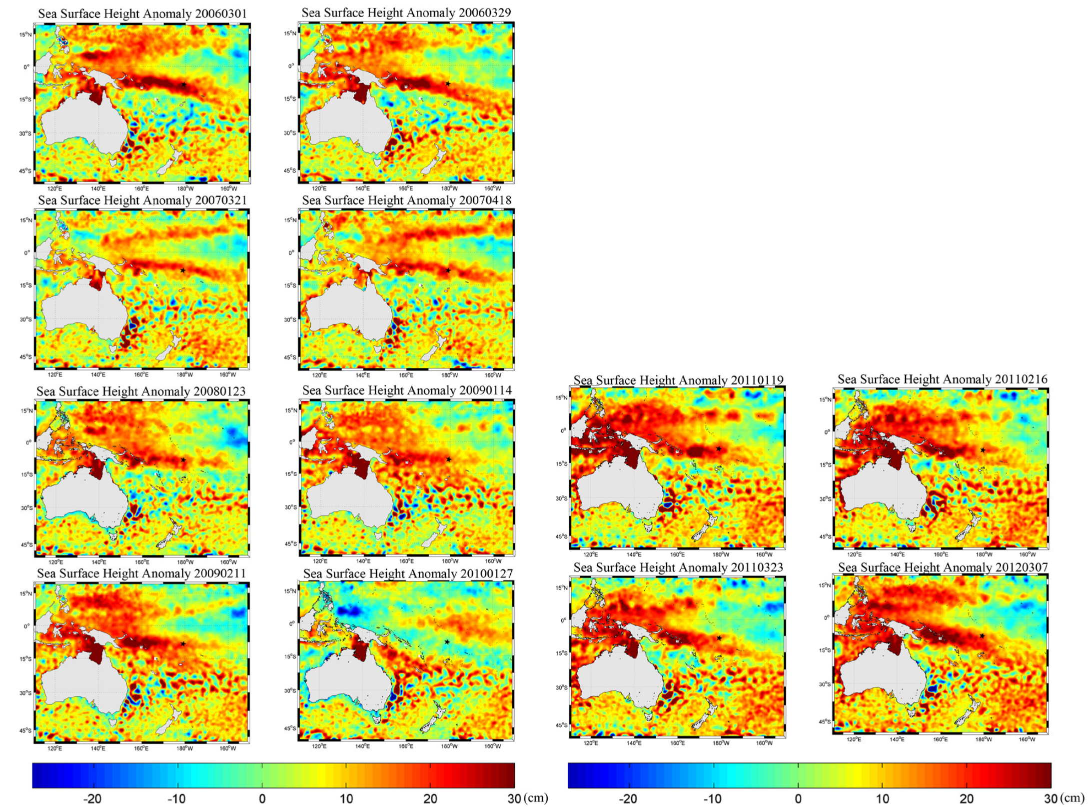

Fig. 4. Continued.

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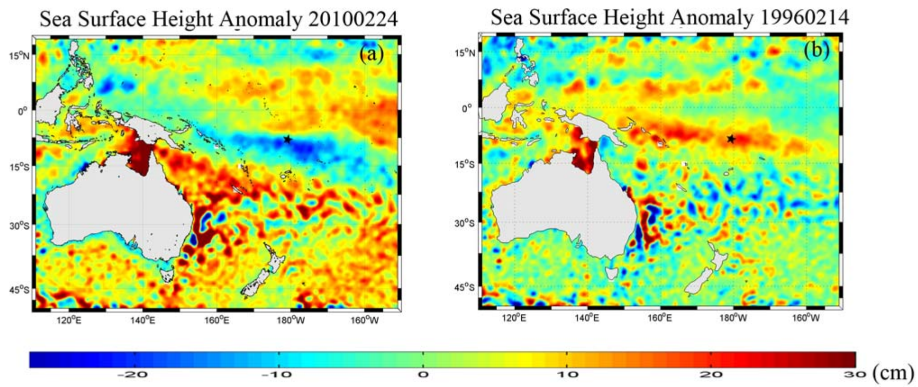

Fig. 5. (a) SSHA in the week of 24 Feb 2010 indicated that Tuvalu was under the background of cold water when surge caused by Chile earthquake occurred on 27 February 2010. No King Tide occurred at this moment. **(b)** SSHA in the week of 14 February 1996 presented the King Tide event response by the combination of spring tide, warm water mass, and tsunami surge on 17 February 1996. The date indicated on the image is the middle date of the 7 days.

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