Estimation of Relative Mean Sea Level Rise from Fort Denison Tide Gauge Data

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ABSTRACT

The tide gauge data collected at Fort Denison in Sydney Harbour, one of the longest tide gauge data sets in the world, are briefly described and analyzed to estimate the average rate Θ of relative mean sea level rise. The 122-year tide gauge data consist of three types of data sets: the 29-year monthly mean tide level data analyzed from the Tide Register for 1886 to 1914, the 73-year hourly tide level data digitized manually from the tide gauge paper charts from 1914 to 1996, and the 12-year hourly tide level data digitally recorded at 0.5 Hz for 6 minutes every hour from 1996 to 2007. Based solely on the Fort Denison original tide gauge data, the 122-year annual mean tide level data in time series were used to fit a linear regression line to give Θ=0.63±0.14mm/yr from 1886 to 2007. A higher estimate of Θ=0.93±0.20mm/yr from 1914 to 2007 is found and includes a sharp increase in water level shown in the record around 1950. Based on the more reliable data collected from 1950 to 2007, Θ is estimated as 0.58±0.38mm/yr. A new approach is also developed in this paper for estimation of Θ. With this newly developed method, meteorological and oceanographic fluctuations with timescales of days to decades can be averaged out to reduce data scatter and increase the fitting correlation coefficient for Θ. The effects of averaging timescale, missing data points and seasonality on Θ are also investigated.

1. INTRODUCTION

Global sea level rise is caused by thermal expansion of ocean water and melting of global land-based ice due to global warming. Global mean sea level is projected to rise by at least 18~79cm by the year 2100 according to the 2007 IPCC report. Most recently, scientists at the 2009 International Scientific Congress on Climate Change in Copenhagen postulated revising the upper range of sea level rise to 100cm or possibly more based on new research findings that rapid ice loss in Greenland and Antarctica has contributed more to global mean sea level rise than initially expected. Rising sea level can cause coastal inundation, coastline retreat, loss of coastal properties and infrastructure, acceleration of beach erosion, and modification of coastal ecosystems such as wetlands and mangroves. Therefore, it is of enormous economic, social, ecological and engineering importance to accurately project mean sea level rise.

Conventionally, tide gauge data have been used to estimate mean sea level rise. For a given location, a tide gauge records sea level with respect to a land-based benchmark. The measured sea level is affected by many factors, e.g. astronomical tides, ocean waves, barometric pressure, wind speed, ocean currents, seasonal variations, and climate variability such as ENSO (You and Lord, 2008). Thus, the local meteorological and oceanographic fluctuations with timescales of days to decades may affect the estimate of relative mean sea level rise from tide gauge data. On the other hand, a tide gauge that is located on a land-based structure may also move vertically with the land as a result of post-glacial rebound, tectonic uplift or crustal subsidence. The rate of relative mean sea level rise estimated from tide gauge data will contain the vertical movement of the land. It is this relative change that is important in assessing the impacts at or near the shoreline. For example, if the land on which a tide gauge is located subsides, the tide gauge will record an increase in mean sea level relative to the land-based benchmark even though there is no change in global mean sea level. A global rate of absolute mean sea level rise between 1950 and 2000 was estimated by Church *et al* (2004) to be 1.8±0.3 mm/yr from global tide gauge data collected around the world. This estimated rate of 1.8mm/yr is consistent with the lower limit cited in the 2007 IPCC report for the next 100 years.

Recently, satellite altimetry is applied to record absolute sea levels by measuring the distance between an earth-orbiting satellite and the surface of the ocean. Since 1992, satellite altimeters have been measuring sea level on a global basis with high accuracy. The TOPEX/POSEIDON (T/P) satellite measured sea level changes from 1992 to 2005. The Jason-1 satellite, launched in late 2001 as the successor to T/P, continues to measure sea level changes and provides an estimate of global mean sea level every 10 days with an uncertainty of 3~4 mm. The major setback of this technique is that a large number of tide gauge stations, which span the majority of both the T/P and Jason missions, are required to calibrate the altimetry data in order to remove the altimeter drift. The vertical movement of the land at each tide gauge station also needs to be known for this calibration, but this information is lacking for many of the tide gauge stations around the world. Leuliette *et al* (2004) found that the errors from the vertical movement of the land at the tide gauge locations are apparently larger than the altimeter drift in estimating global sea level change from the T/P altimetry data. The rate of global mean sea level rise is estimated from the T/P and Jason-1 altimetry data from 1993 to 2008 to be 3.2±0.4mm/yr as shown on the website: http://sealevel.colorado.edu/.

In this study, the long-term tide gauge data collected at Fort Denison will be briefly discussed and used to estimate relative mean sea level rise with two different approaches based solely on that original data set. The effects of averaging timescale, missing data points and seasonality on estimates of relative mean sea level rise are also investigated quantitatively.

2. TIDE GAUGE DATA

2.1 Fort Denison

Fort Denison, a Martello Tower (see Fig.1), was built between 1841 and 1857 on a rocky island in Sydney Harbour, Australia. The rocky island was then called Pinchgut by convicts marooned there as punishment for serious breaches of the peace after European settlement in 1788. Fort Denison was designed in 1839 by George Barney, the civil engineer for NSW, and it was constructed from 8,000 tons of sandstone quarried near Kurraba Point in Neutral Bay, and was named after Sir William Denison, the then Governor of NSW.

Fig.1. Location of Fort Denison in Sydney Harbour.

2.2 Tide Gauges

Three different analogue tide gauges have been used to collect tide data at Fort Denison since 1886. A first self-recording tide gauge was made by Smalley to record the tide data at Fort Denison from 1866 to 1870. The collected tide data may be of no use because a hempen cord was used between float and instrument (Hamon, 1987). In 1872, Russell had a new tide gauge made. This gauge went into service in June 1872 and continued until June 1914. Since 1908, three Harrison tide gauges were purchased and used to collect the tide data at Fort Denison, Camp Cove and Goat Island within Sydney Harbour. A brief description of Russell's and Harrison's gauges was given by Hamon (1987). The archived tide gauge paper charts are available for Fort Denison from 1905 to 1999 and are held in the NSW Sate Archives.

In 1996, a digital tide gauge was installed at Fort Denison by Sydney Ports Corporation to replace the analogue tide gauge and automatically collect the tide level data. The tide level data have been recorded at 0.5Hz for 6min every hour since 1996. There are 180 level readings recorded over 6min every hour. The hourly tide level is then averaged from the 180 level readings. The digital tide gauge has enabled the collected tide level data to be sent electronically to the National Tidal Centre in South Australia. The old analogue tide gauge was still used as a backup at Fort Denison until 1999.

2.3 Tide Gauge Zero and Datum

The tide gauge zero is the level at which the tide gauge records zero sea level or the zero level of the graduated staff used for dipping the tide stilling well. The tide gauge zero at Fort Denison has been altered only once and it was lowered 12.7cm relative to the previous zero level on 1 January 1954.

The standard datum for levels in NSW, which was adopted in 1897, was mean sea level (MSL), the value of which was found to be 2.525 feet (0.77m) on the Fort Denison tide gauge and computed from the tide records over a period of 13 years to 1885. On 1 January 1954, the NSW Maritime Services Board decided to change the MSL datum to the new uniform datum known as Indian Spring Low Water (ISLW), the value of which was determined from the tide records over a period of 31 years to 1927. The ISLW datum is 0.897m lower than the MSL datum and 0.925m lower than Australian Height Datum (AHD).

2.4 Tide Gauge Data

Since 1886, the times and heights of daily high and low waters were entered in the Tide Register that consists of several ledger-sized volumes and was kept by the Survey Branch of the Maritime Services Board. The Tide Register was set out with one page for each month, and columns for heights of daily high and low waters, and for corresponding times. The monthly and yearly mean tide levels from 1886 to 1914 were given in Table-2 of Hamon (1987).

From 1914 to 1996, the hourly tide levels and times were digitized from the archived tide gauge paper charts by different researchers. The hourly tide level data from 1914 to 1940 were digitized manually by Hamon (1987), from 1941 to 1970 by CSIRO with D-MAC chart reader (Greig, 1977), and from 1970 to 1996 manually by Flinders University.

Since 1996, the digital tide gauge has replaced the analogue tide gauge to collect tide levels at 0.5 Hz for 6min every hour at Fort Denison. The hourly tide level is averaged from 180 level readings recorded over 6 minutes every hour, while the hourly tide level data digitized from the tide gauge paper charts prior to 1996 are instantaneous tide levels. The difference between the 6min averaged and digitized instantaneous tide levels is generally small and can be omitted.

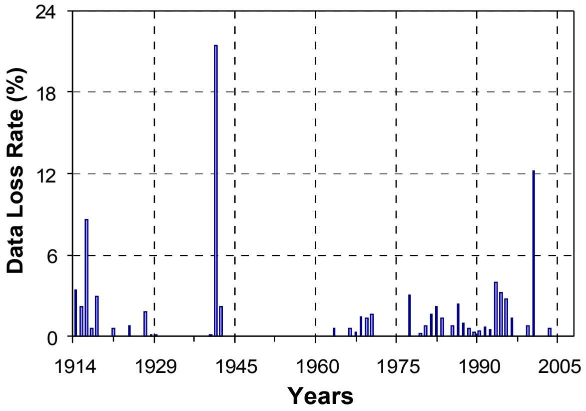

Fig.2. Annual data loss rate recorded at Fort Denison.

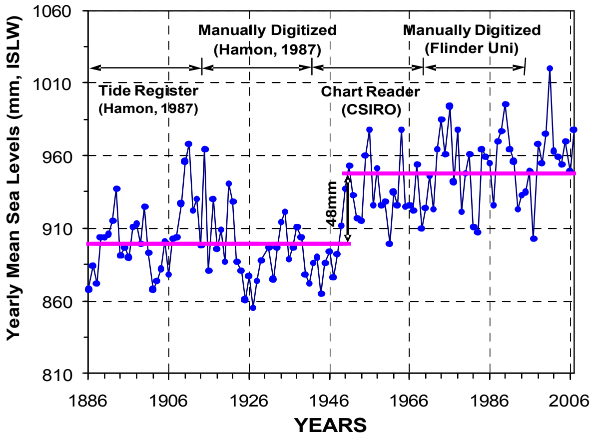

Fig.3. Annual mean sea levels measured at Fort Denison.

Fig.2 shows the annual data loss rate from 1914 to 2007, and there is no data collected in 1930. The data loss may affect Θ and this will be investigated in this study. Fig.3 also plots the annual mean sea levels that are averaged annually from daily low and high water levels. The zero-up crossing method is used to analyze the hourly tide level data to obtain daily low and high water levels. It is evident from the record that there is a distinct "saw-tooth" in the data record prior to about 1950, which is not readily explained or contemplated in the literature to date. It is noted that the data record indicates a relatively sharp rise in the annual average mean sea level around 1950. The tide gauge zero at Fort Denison has been altered only once and it was lowered by 12.7cm on 1 January 1954 when the MSL datum was changed to the ISLW datum. A plausible explanation for this datum shift has not been found at this stage. No correction has been made for the datum shift in this study.

3. METHODOLOGY

3.1 *x*-Year Mean Method

This method is to fit a linear regression line through *x*-year mean tide level data (t, y) to estimate Θ under the assumption of a linear increase in mean sea level. The slope of the fitted regression line is equal to Θ and the 95% confidence interval for Θ can be also calculated accordingly. The *x*-year mean sea level y is averaged over x years that is long enough to filter out periodic components of waves and tides. In Fig.4, the yearly means of daily low and high waters are used to estimate Θ. The yearly means of daily low and high waters from 1886 to 1940 are from Table-2 of Hamon (1987), while the yearly means of daily low and high waters from 1914 to 2007 are analyzed from the hourly tide level data with the zero-crossing method. It can be seen from Fig.4 that the estimates of Θ are made for three distinct time periods: Θ=0.62mm/yr from 1886 to 2007, Θ=0.89mm/yr from 1914 to 2007 and Θ=0.55mm/yr from 1950 to 2007. The first time period has the longest data length for the estimation of Θ. The data collected during the second time period have been most used to estimate Θ by researchers (e.g BoM, 2003; Church, et al, 2006). The data collected during the last time period are expected to be more reliable than those collected before 1950.

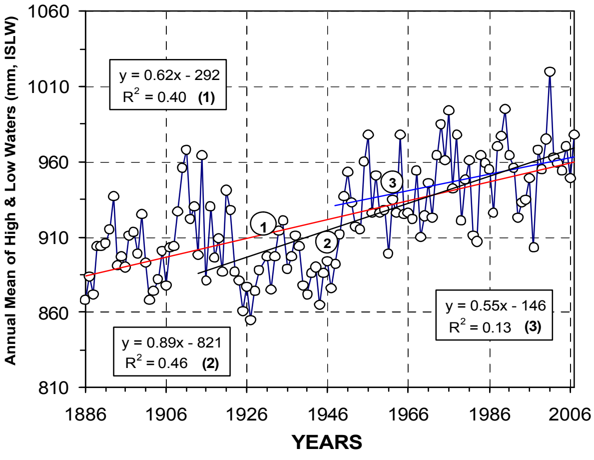

Fig.4. Values of Θ estimated from the annual means of low and high waters : (1) 1886-07, (2) 1914-07 and (3) 1950-07.

Fig.5 also shows estimates of relative mean sea level rise made from the yearly means of hourly tide levels. The yearly means of hourly tide levels from 1886 to 1940 are approximated by the yearly means of daily low and high waters because there are no hourly tide level data available. It can be seen that over the three different time periods, $\Theta=0.63$mm/yr in 1886-2007, $\Theta=0.93$mm/yr in 1914-2007 and $\Theta=0.58$mm/yr in 1950-2007. The values of Θ estimated from the yearly means of hourly tide levels are shown to be almost equal to those from the yearly means of daily low and high waters. Thus, the annual means of hourly tide levels are preferred to the annual means of low and high waters for the estimation of Θ as they are easier to compute.

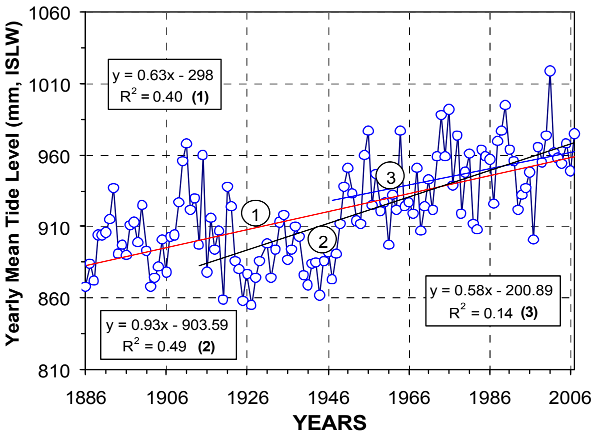

Fig.5. Estimates of Θ made from the yearly means of hourly tide levels : (1) 1886-07, (2) 1914-07 and (3) 1950-07.

Different averaging timescales x are also used to study the effect of x on Θ in Table-1 (Code-1). The hourly, annual, 4-year and 18.6-year mean tide level data sets are used to estimate Θ. The averaging time length of $x=18.6$ years is equal to the period of the lunar nodal tide. It can be seen from Table-1 that the values of Θ estimated from different averaging timescales are quite similar. The correlation coefficient R^2 is shown to increase with increasing x as the number of data points is significantly reduced with increasing x. Therefore, the annual timescale is preferred to the hourly, monthly or other timescales for the estimation of Θ.

In Table-1 (Code-2), the yearly means of full cycle tide levels are also used to study the effect of missing data on Θ. Fig.2 shows the data loss rates from 1914 to 2007. If the data loss rate is zero, sea level fluctuations caused by tides can be averaged out to eliminate the effect of tides on the yearly mean sea level. However, since the data loss rate is not always zero as shown in Fig.2, the missing data in individual tidal cycles will over or under-estimate the yearly mean of hourly tide levels and finally affect Θ. Based on the hourly tide level data, the zero-up crossing method is used to identify individual full tidal cycles with no missing data. This approach is based on the assumption that the average of periodic tide levels from individual full tidal cycles is approximately equal. It can be seen from Table-1 that the estimate of $\Theta=0.88$mm/yr made without missing data from 1914 to 2007 is generally close to that of $\Theta=0.93$mm/yr predicted with missing data in the same time period. Thus, the effect of missing data on Θ is found to be insignificant in this study.

Table-1. Estimates of Θ made from different data sets are used to study the effects of timescale (Code-1), missing data (Code-2), tide level (Code-3) and seasonality (Code-4) on Θ.

Code	Data Type	Starting Date	Q (mm/yr)	R^2
1	Hourly tide levels	1914 1950	0.93 0.57	0.00 0.00
1	1-year mean of hourly tide levels	1886 1914 1950	0.63 0.93 0.58	0.40 0.49 0.14
1	1-year mean of high & low water levels	1886 1914 1950	0.62 0.89 0.55	0.40 0.46 0.13
1	4-yr mean of high & low water levels	1886	0.62	0.54
1	18.6-yr mean of high & low water levels	1886	0.64	0.75
2	Annual mean of full cycle tide levels	1914 1950	0.88 0.63	0.41 0.16
3	Annual mean of slack water levels	1914 1950	0.93 0.56	0.50 0.16
3	Annual mean of low water levels	1914 1950	1.19 0.84	0.53 0.21
3	Annual mean of high water levels	1914 1950	0.59 0.26	0.27 0.03
3	Annual mean of highest tide levels	1914 1950	0.90 0.21	0.10 0.00
4	Seasonal mean of autumn tide levels	1914 1950	1.10 0.43	0.38 0.05
4	Seasonal mean of winter tide levels	1914 1950	0.93 0.65	0.33 0.33
4	Seasonal mean of spring tide levels	1914 1950	0.70 0.72	0.24 0.11
4	Seasonal mean of summer tide levels	1914 1950	0.77 0.52	0.23 0.07

The yearly means of high tides, slack tides, low tides and annual maximum tides are also used to estimate Θ in Table.1 (Code-3), respectively. The zero-crossing water level is used to define the slack tide that occurs when the direction of the tidal current reverses. The estimates of Θ made at different tide levels are used to study the effect of tide height on Θ. It is shown in Table-1 (Code-3) that the value of Θ estimated from the hourly tide levels is quite close to that from the slack tides, but smaller than from the low tides and larger than from the high tides. This may be because the slack tides do not fluctuate as much as do the low or the high waters. The annual maximum tide level data give $\Theta=0.90$mm/yr from 1914 to 2007, which is quite close to that from the hourly tide level data. Thus, the annual maximum tide level data are preferred to the slack, low or high tide level data for the estimation of Θ because it is much easier to analyze the annual maximum tide level data than the other three.

In Table-1 (Code-4), the seasonal means of the winter, spring, summer and autumn hourly tide level data sets are also used to estimate Θ. The estimates of Θ are found generally larger in winter and autumn than in spring and summer. The seasonal mean sea levels are also found to be different and they are ranked as the spring, the summer, the autumn and the winter mean sea level in ascending order. Based on the Bruun rule (1962), beaches may be more susceptible to erosion in winter and autumn than in spring and summer because of these relatively higher seasonal sea levels.

3.2. Cumulative Moving Average Method

This method is to fit a linear or non-linear regression curve through the cumulative moving mean tide level data for the estimation of Θ. It is derived as follows. Assume that sea level y increases linearly with time t

$$y(t) = \Theta t + y_0\,, \tag{1}$$

where Θ is the mean rate of sea level rise, and y_0 is the sea level at t=0. A more general polynomial expression of y(t) may be also used in Eq.(1). With respect to t, Eq.(1) is integrated from t_1 to t_2 to compute the T-year mean sea level $\bar{y}$

$$\bar{y} = \frac{1}{T}\int_{t_1}^{t_2}(\Theta t + y_0)dt = \frac{1}{T}\int_{0}^{T}[\Theta t' + \Theta t_1 + y_0]dt' \\ = \frac{1}{2}\Theta T + Y_0 \tag{2}$$

where t_1 is a fixed initial time, t_2 is an arbitrary time, Y_0 is constant and $Y_o = (\Theta t_1 + y_o)$, $t' = (t - t_1)$ is a new variable, and $T = (t_2 - t_1)$ is an averaging time scale. In statistics, $\bar{y}$ is also called the cumulative moving average, which is different from the moving average. The t_1 and t_2 values of the moving average are moving at the same speed and (t_2-t_1) is always constant, while the t_1 value of the cumulative moving average is fixed and only t_2 is allowed to move forward by one time step each time and (t_2-t_1) increases with increasing the data points to be calculated.

On the other hand, the cumulative moving average $\bar{y}$ can be also computed directly from the tide gauge data. When y(t) is taken as the yearly mean tide level, for example, $\bar{y}$ can be then computed as

$$\bar{y} = \frac{1}{m}\sum_{i=1}^{m} y_i\,, \quad m=1, 2, 3, \cdots N, \tag{3}$$

where each value of $\bar{y}$ is the average of all previous data points plus one current data point in the full data set, and the size of the subset being averaged grows by only one when each new value of $\bar{y}$ is calculated.

After individual data points ($\bar{y}$, T) are generated from the yearly mean tide levels of N years, a linear regression line is then fitted to the N data points to obtain Θ=2k as indicated in Eq.(2), where k is the slope of the linear regression line. With this method, the cumulative moving averages of the annual mean tide levels are plotted in Fig.6 for the same three time periods, 1886-2007, 1914-2007 and 1950-2007, respectively. A linear regression line is fitted to only the data points that follow a linear distribution under the assumption of a linear increase in mean sea level. The estimates of 0.80mm/yr, 1.02mm/yr and 0.50mm/yr are then made for the three time periods. The values of Θ estimated in Fig.6 are shown generally close to those in Fig.5, but with much higher value of R^2. The tide levels collected from 1950 to 2007 are also shown to be shifted upwards by about 25mm relative to the tide levels collected from 1886 to 2007. This indicates there is a relatively abrupt change in the data around 1950.

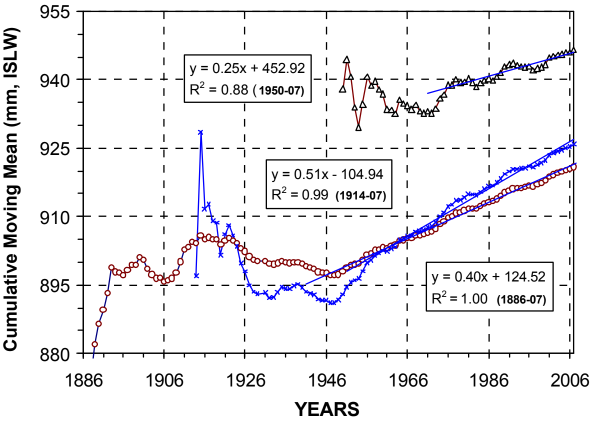

Fig.6. Estimates of Θ are made with the cumulative moving mean method: Θ=0.80mm/yr in 1886-07, Θ=1.02mm/yr in 1914-07 and Θ=0.50mm/yr in 1950-07.

It can be also seen from Fig.6 that the cumulative moving mean varies irregularly and does not follow any obvious trends when T<25-60yr for the three different time periods. This may be because when the averaging time length T is not long enough, long-term meteorological and oceanographic fluctuations and climate variability with period of up to decades could be not filtered out and thus cause the cumulative means to fluctuate. This implies that the length of tide gauge data for estimation of Θ should be long enough, e.g. longer than the period of the lunar nodal tide

4. CONCLUSION

The tide gauge data collected at Fort Denison have been briefly discussed and analyzed to estimate the average rate Θ of relative mean sea level rise. Based on the 122-year tide gauge data available at this location, Θ=0.63±0.14mm/yr is estimated from the annual mean tide level data with the *x*-year mean method. A rate of 0.58±0.38mm/yr is also estimated from the more reliable tide level data collected after 1950. The rate of rise is similar over the two time scales and, importantly, shows no sign of accelerating at the present time based on the data from this single gauge. This needs to be examined further using reliable data sets for gauges at other locations

The effect of averaging timescale on Θ has been found to be insignificant. The averaging timescale of x=1 year is preferred for the estimation of Θ. The effect of missing data on Θ is also found to be minor in this study. The estimates of Θ made from the seasonal mean tide level data sets are found generally to be larger in autumn and winter than in spring and summer, and the seasonal mean sea levels are higher in autumn and winter than in spring and summer.

The new approach, Eq.(2), is also presented for the estimation of Θ. With this method, mean sea level is clearly found to rise linearly with time relative to the land. Long-term meteorological and oceanographic fluctuations and climate variability can be averaged out with this method to reduce data scatter and increase the fitting correlation coefficient R^2.

DISCLAIMER

The views expressed in this paper are those of the authors and not necessarily those of the Department of Environment, Climate Change and Water (DECCW).

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