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Historical Sea Level in the South Pacific from Rescued Archives, Geodetic Measurements, and Satellite Altimetry

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Abstract—Automatic sea-level measurements in Nouméa, South Pacific, started in 1957 for the International Geophysical year. Data from this location exist in paper record for the 1957–1967 period, and in two distinct electronic records for the 1967–2005 and 2005–2015 period. In this study, we digitize the early record, and established a link between the two electronic records to create a unique, nearly 60 year-long instrumental sea-level record. This work creates one of the longest instrumental sea-level records in the Pacific Islands. These data are critical for the study of regional and interannual variations of sea level. This new data set is then used to infer rates of vertical movements by comparing it to (1) the entire satellite altimetric record (1993–2013) and (2) a global sea-level reconstruction (1957–2010). These inferred rates show an uplift of 1.3–1.4 mm/year, opposite to the currently accepted values of subsidence found in the geological and geodetic literature, and underlie the importance of systematic geodetic measurements at, over very near tide gauges.

Key words: Sea level, archives, tide gauges, altimetry, geodesy.

1. Introduction

Accurate sea-level measurements are necessary for navigation, and to monitor and study sea level globally, locally, and over different time scales. Relative sea level measured by the tide gauge (hereafter TG) is a critical variable for land planning, extreme event prevention, warning against tsunamis, etc...Absolute sea level measured by satellite altimetry since 1993 has a more global relevance and is used to study regional and global sea-level variations over the decades starting at the beginning of the altimetry era in 1993 (Chambers et al. 2017).

Theoretically, the difference between the absolute sea level measured by satellite altimetry and the relative sea level measured by the TGs is equal to the vertical land movement (VLM) at the TG location. Comparison between TG data and satellite altimetry has been used to evaluate vertical land motion (Nerem and Mitchum 2002; Fenoglio-Marc et al. 2012; Ray et al. 2010; Santamaria-Gomez et al. 2014; Pfeffer and Allemand 2016). When the VLM is known or inferred, the average difference between TG and altimeter data can be used to detect global drifts in successive altimetry missions (Ablain et al. 2009; Valladeau et al. 2012; Watson et al. 2015). In return, the difference between a particular TG and calibrated altimeter data can be used to detect instrumental problems at individual TGs (Ablain et al. 2009).

Prior to 1993, TGs are the primary source of data for the study of global mean sea level over several decades (Hay et al. 2015; Ray and Douglas 2011; Church and White 2011). TGs have also been used to study regional patterns of sea-level variations in the Pacific where data from several TG are available (Thompson and Merrifield 2014). Both the length of each data set and the repartition of the TGs used can have an impact on the result of the analysis (Hamlington and Thompson 2015; Thompson et al. 2016).

Before the use of digital TGs starting in the 1960s, analog TGs were recording sea level on paper records. The digitization of these paper records, along with earlier hand-written records, can lead to the creation of century long time series of sea level after a laborious data rescue effort (Pouvreau 2008; Marcos et al. 2011). Old indications of mean sea level

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can also be reattached to modern day measurement to obtain century long trends of mean sea-level variations (Testut et al. 2010).

The city of Nouméa, New Caledonia is located in the Tropical Southwest Pacific where only a few other TGs exist and where rates of sea-level rise often exceed the global rate (Fig. 1). In 2003, the Nouméa TG was moved a few kilometers to follow the change of location of the local hydrographic services headquarter. As a result of this change of location, there are two distinct Nouméa sea-level electronic data sets: a Chaleix data set covering the 1967–2005 period and a Numbo data set starting in 2005. Data from Chaleix and Numbo have been used as part of the global TG data set to calibrate the altimetry missions TOPEX-Poseidon (TP) (Mitchum 2000) and Jason-2 (Valladeau et al. 2012), respectively. However, different data for these two data sets prevented until now a straightforward concatenation of the data, so no Nouméa sea level data set exists for the entire altimetry period 1993–present, and more recent studies do not include Nouméa TG data (Watson et al. 2015).

In this paper, we describe the creation of a unified, instrumental, sea-level data set for Nouméa from 1957 to present, by combining the pre-1967 paper record and data sets from the two nearby Nouméa tide gauges (Table 1; Sect. 4). We then analyze the quality and stability over time of this created data set, by combining the analysis of satellite altimetry, nearby tide gauges, and measured or inferred vertical land movement (Sect. 5). The different existing data sets and their repositories are given in Sect. 3.

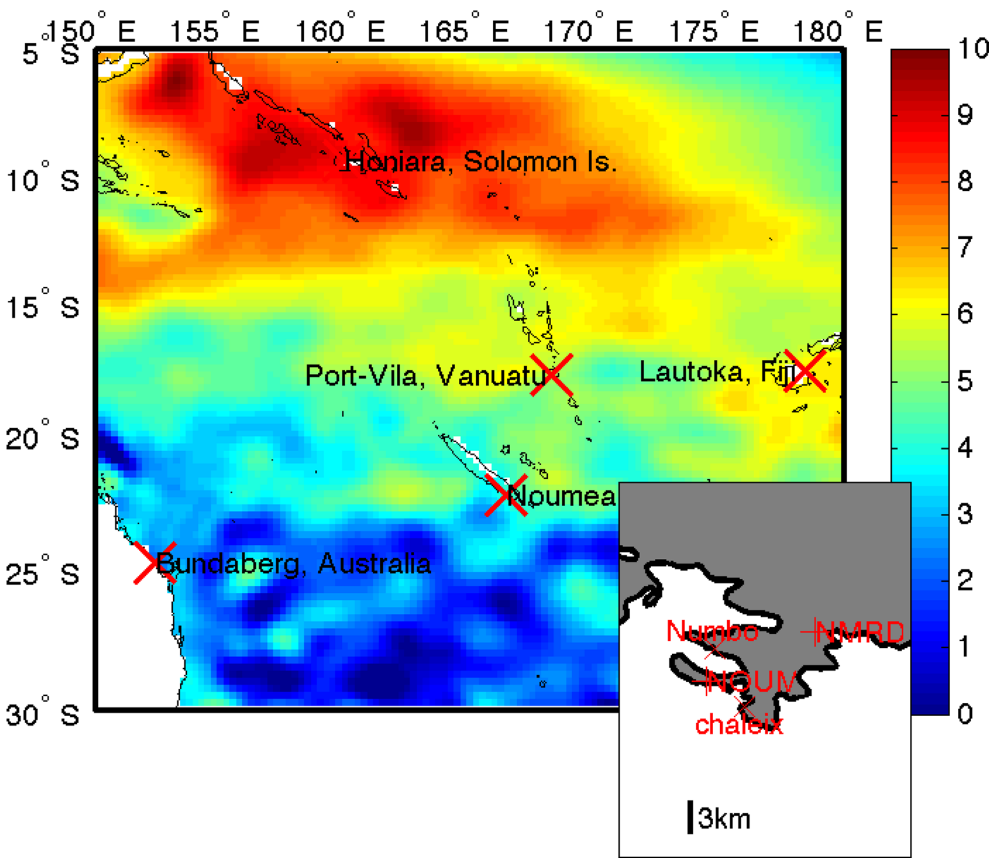


Figure 1
South pacific map of absolute sea-level trend (1993–2013) from altimetry (in mm/year), and location of nearby tide gauges with long data sets (2 decades or more). *Inset* Location map of Nouméa indicating the locations of the two tide gauges Chaleix and Numbo, the NOUM, NRMD, and NMEA GPS stations. The DORIS stations NOUA, NOUB and NOWB, and NOWB are collocated with GPS stations NOUM and NRMD, respectively

Table 1

Summary of tide gauge measurements in Nouméa

Location	Institution	Instrumentation	Period covered	Data type
Chaleix	SHOM	N/A	1957–1958	Paper
Chaleix	SHOM	Saint-Chamond Granat	1958–1966	Paper
Chaleix	SHOM	OTT R16	1967–2005	Electronic
Chaleix	UHSLC	Fischer and Porter	1967–2005	Electronic
Numbo	SHOM	Khrone BM100 radar	2005–present	Electronic

2. *History of Tide Gauge Measurements in Nouméa*

The first automatic tide observatory in Nouméa, New Caledonia, was established by the French Navy Oceanographic and Hydrographic Service (SHOM) in 1957 for the International Geophysical year, and was based at the Pointe de Chaleix (hereafter "Chaleix" site). It was destroyed by a tropical cyclone in June 1958, replaced by a Saint-Chamond Granat tide recorder installed in July 1959 and decommissioned in 1966. Data for this 1957–1966 period were only available on paper records and daily data were not available in digital format until now. Paper records from an even earlier period (1930–1937) could be found, but they were essentially used to produce tide calendars. As a consequence, these early records are actually quite short (a few weeks every year) and did not provide sufficient information on their vertical datum to be attached to the later records.

A new wharf was built in 1966–1967, and a new tide gauge station was installed. It consisted of one American (Fischer and Porter Analog-to-Digital Recorder) and one French tide gauge (an OTT R16 mechanical tide gauge). The UHSLC (University of Hawaii Sea Level Center) managed the American tide gauge for the GLOSS (Global Sea Level Observing System) and the PTWC (Pacific Tsunami Warning Centre) programs. This tide gauge was maintained locally by the New Caledonia hydrographic base (SHOM/BHNC) and the IRD (Institut de Recherche pour le Developpement). The installation of floating switches on the pier on which the Chaleix TG was installed ensures any instrumental drift of the data would have been captured. Sea-level observations at the Chaleix site were discontinued in July 2005. Since January 2005, sea-level observations in Nouméa are made by the New Caledonia hydrographic base (SHOM/BHNC) in the Numbo Bay (hereafter the "Numbo" site), ~6 km from the Chaleix TG (Fig. 1). The contemporary Numbo TG consists of a Khrone BM100 radar and a Marelta acquisition unit.

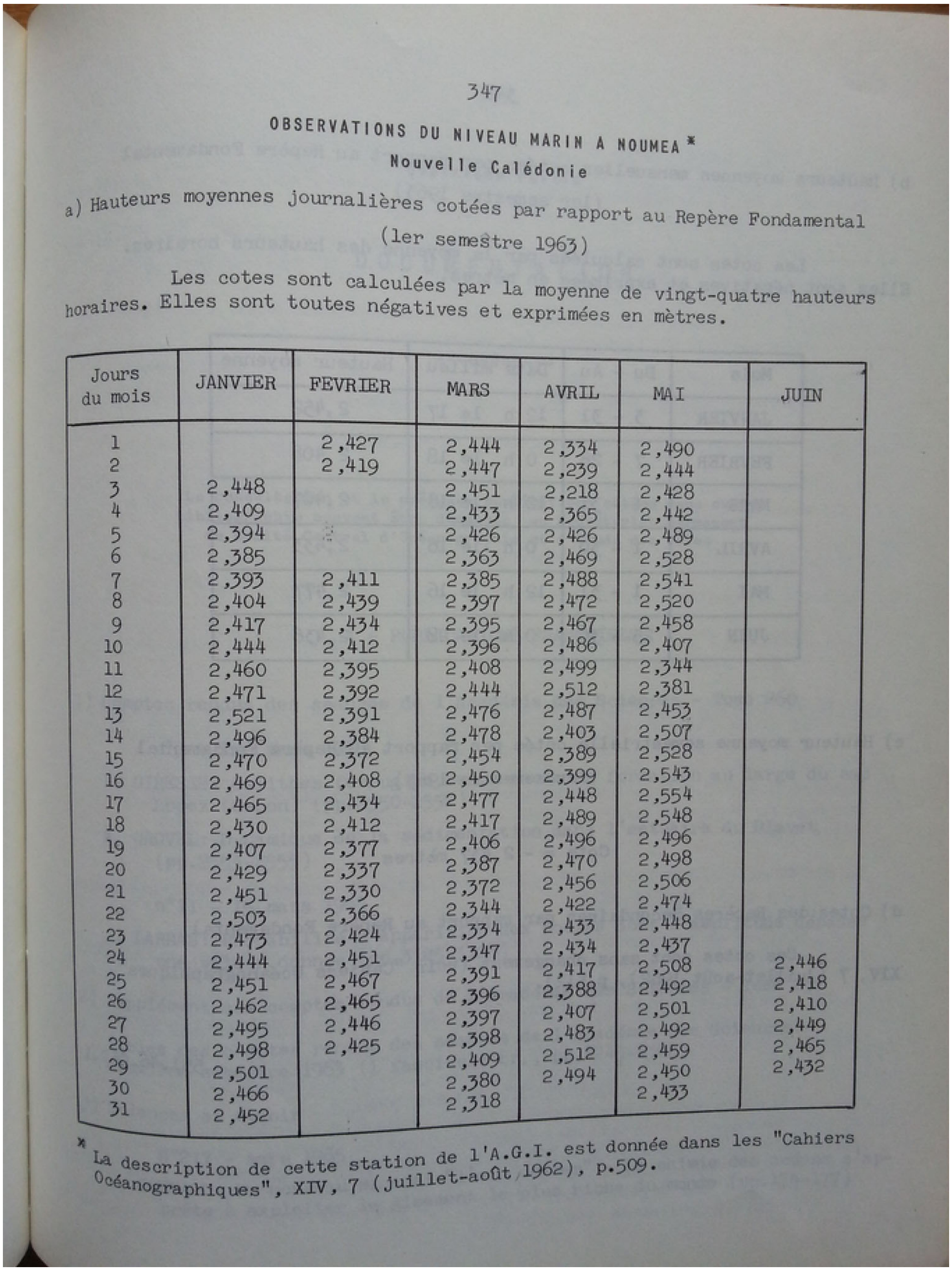
3. *Data Sets and Methods*

For the 1957–1967 period at the Chaleix site, two types of paper records are available: Raw instrumental paper rolls and typed, calculated daily values. The paper rolls from the instruments represent a total of 2975 m of paper data (4 cm for 1 h of observation), and no human or financial resources are currently available to scan and digitize this entire archive. However, these data were used over the years by SHOM hydrographic officer to calculate daily values, which were typed, organized by semesters, and published by SHOM in the *Cahiers Oceanographiques* (Oceanographic Notes), see Table 2 and example on Fig. 2. These daily values obtained from the SHOM for the 1957–1967 period are averages of the 24 h values for each day. A continuous monitoring throughout the period by SHOM of the benchmarks at and around the Chaleix site is available and allows the calculation of a common vertical datum for the different Chaleix data set (described in

Table 2

Publication year of daily values in Cahiers Oceanographiques

Publication year	Page	Period
1961	194	1957(2)
1962	509	1959(2)
1963	75	1960(1)
1963	500	1960(2)
1964	163	1961(1)
1964	408	1961(2)
1964	895	1962(1)
1965	272	1962(2)
1965	347	1963(1)
1965	730	1963(2)
1966	727	1964(1)
1966	816	1964(2)
1967	433	1965(1)
1967	510	1965(2)
1968	418	1966(1)



347

OBSERVATIONS DU NIVEAU MARIN A NOUMEA *

Nouvelle Calédonie

a) Hauteurs moyennes journalières cotées par rapport au Repère Fondamental

(1er semestre 1963)

Les cotes sont calculées par la moyenne de vingt-quatre hauteurs horaires. Elles sont toutes négatives et exprimées en mètres.

Jours du mois	JANVIER	FEVRIER	MARS	AVRIL	MAI	JUIN
1		2,427	2,444	2,334	2,490	
2		2,419	2,447	2,239	2,444	
3	2,448		2,451	2,218	2,428	
4	2,409		2,433	2,365	2,442	
5	2,394		2,426	2,426	2,489	
6	2,385		2,363	2,469	2,528	
7	2,393	2,411	2,385	2,488	2,541	
8	2,404	2,439	2,397	2,472	2,520	
9	2,417	2,434	2,395	2,467	2,458	
10	2,444	2,412	2,396	2,486	2,407	
11	2,460	2,395	2,408	2,499	2,344	
12	2,471	2,392	2,444	2,512	2,381	
13	2,521	2,391	2,476	2,487	2,453	
14	2,496	2,384	2,478	2,403	2,507	
15	2,470	2,372	2,454	2,389	2,528	
16	2,469	2,408	2,450	2,399	2,543	
17	2,465	2,434	2,477	2,448	2,554	
18	2,430	2,412	2,417	2,489	2,548	
19	2,407	2,377	2,406	2,496	2,496	
20	2,429	2,337	2,387	2,470	2,498	
21	2,451	2,330	2,372	2,456	2,506	
22	2,503	2,366	2,344	2,422	2,474	
23	2,473	2,424	2,334	2,433	2,448	
24	2,444	2,451	2,347	2,434	2,437	2,446
25	2,451	2,467	2,391	2,417	2,508	2,418
26	2,462	2,465	2,396	2,388	2,492	2,410
27	2,495	2,446	2,397	2,407	2,501	2,449
28	2,498	2,425	2,398	2,483	2,492	2,465
29	2,501		2,409	2,512	2,459	2,432
30	2,466		2,380	2,494	2,450	
31	2,452		2,318		2,433	

* La description de cette station de l'A.G.I. est donnée dans les "Cahiers Océanographiques", XIV, 7 (juillet-août 1962), p.509.

Figure 2
Example of paper data in *Cahiers Océanographiques*

Sect. 4. The daily values are used here to extend the existing data set back to 1957. For the more modern Chaleix TG, over the 1967–2005 period, two independent numerical data sets of "Research Quality" hourly sea level are available. The first one is from UHSLC (http://uhslc.soest.hawaii.edu/data/rqh, or file: rqh0019a.csv), and the second is from the SHOM Refmar website (http://refmar.shom.fr/fr/chaleix_noumea). Identical trends for the period 1967–2003 calculated from the two independent data sets at the Chaleix site further confirm the absence of instrumental drift at either of the Chaleix TG.

The Numbo TG officially entered service on 27 January 2005 and is currently active. Hourly data for the Numbo site were obtained on the Refmar website (http://refmar.shom.fr/fr/numbo_noumea). As a reference TG maintained by SHOM, it is regularly controlled and we are also confident about the absence of instrumental drift at this TG. While earlier data for the Numbo TG (back to 2001) can be found, we only use the quality-controlled Numbo TG data collected after its official commissioning in 2005.

Vertical and horizontal land movements around Nouméa are measured by a nearby permanent GPS stations and one DORIS station. Data and rates are available on the SONEL website (http://www.sonel.org) and the International DORIS service website (http://ids-doris.org/network/sitelogs/station.html?code=NOUMEA). The site of the DORIS and GPS measurement also changed in 2007 (Fig. 1): The current DORIS stations (nowb and noxb) are now collocated with the NRMD and NRMG GPS stations at the NOUMEA–NORMANDY site (Fig. 1). The NOUM GPS station, collocated with the DORIS stations noua and noub, was decommissioned in 2007, and was located about halfway between the Chaleix and Numbo TGs (Fig. 1). The different vertical land movement values measured in Nouméa are discussed in Sect. 5.

To compare the relative sea level measured at the TG, we use the absolute sea-level product from AVISO (http://www.aviso.altimetry.fr). For the period 1993–2013, we use the Ssalto/Duacs Gridded Absolute Dynamic Topography on 1/4 degree grid (data set-duacs-dt-global-allsat-madt-h), which merges data from all satellites available. All corrections except for the GIA correction were applied in this product. The inverse barometer effect was removed for the altimetry product. To be consistent with the TG data, it was re-included using the mean sea-level pressure field from the ECMWF ERA-Interim reanalysis product. To compare satellite altimetry and TG data, we first interpolate the altimetry product and the TG data on the same monthly time steps between Jan 1 1993 and Dec 31 2013, and we calculate the correlation between the tide gauge time series and the altimetry time series at neighboring grid points. We extract the altimetry time series at the point with the highest correlation (0.86), which found for a grid point 95 km from the tide gauge. At this point, when calculated over 1993–2013, the altimetry and the tide gauge time series have a rms difference of 2.8 cm.

We also used Church and White (2011) reconstruction of global sea level to compare our entire data set starting in 1957. All linear trends uncertainties provided in this paper are based on a bootstrap method, and do not take into account the uncertainties of the data used to calculate the trend.

4. *Unified Sea-Level Construction*

We first digitized the daily values at Chaleix found in the SHOM *Cahiers Hydrographiques* by manually typing them into a spreadsheet. These data were reported in meters, composed of negative values relative to a fixed, reference vertical datum. Between 1957 and 1959, the vertical datum was changed by 65.3 cm, and the 1957 data were corrected accordingly. Data for the remaining period 1959–1966 are referenced to the datum of benchmark “A1”, located 2.572 m above the geodetic zero. The more modern Chaleix values (1967–2005) were referenced to the hydrographic zero, chosen at 0.835 m below the geodetic zero. We, therefore, can refer the entire Chaleix data set to the hydrographic zero.

We then bridge the Chaleix and Numbo data set over the gauge relocation of 2005. Individually, the relative sea-level data from these two TGs are of the highest quality: Both TGs were or are GLOSS reference stations and underwent research quality QA/QC, and local ground movement was regularly checked by optical leveling around each TG. There are $\sim$154 days of overlap between the Chaleix and Numbo data sets (27-Jan-2005 04:00:00 to 30-Jun-2005 23:00:00). The mean difference between the 2 hourly data sets is 2.616 cm with a standard deviation of 0.99 cm, where Numbo is higher than Chaleix (Fig. 3, bottom). Correlation is very high at 0.9997. Over this 5 month overlap period in 2005, a tidal analysis shows that the amplitude difference of the high-frequency tidal components (<48h) between the two TGs is smaller than the confidence interval of the tidal analysis. This gives us confidence that these two nearby TG are measuring the same relative sea-level signal at tidal and lower frequencies. Over long

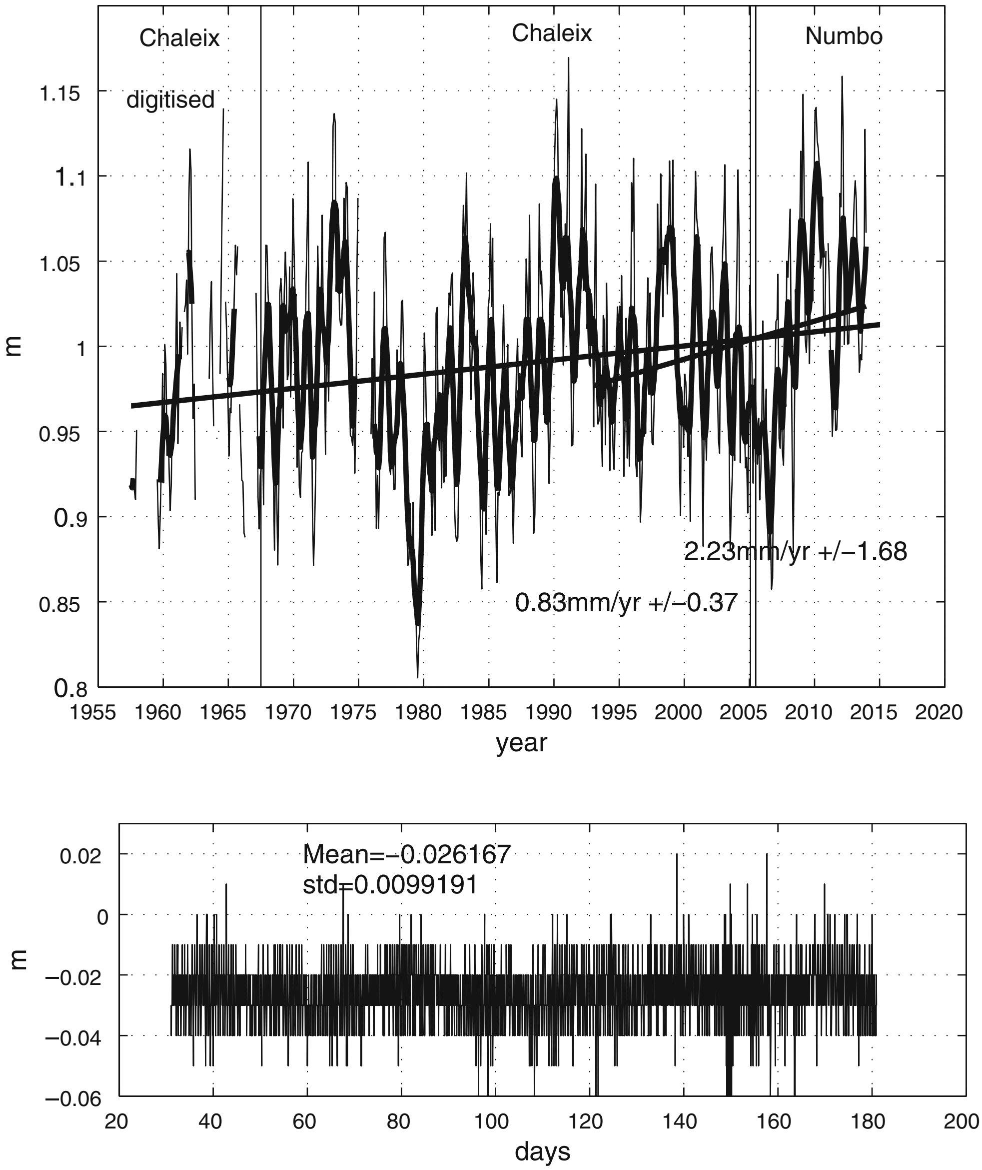


Figure 3

Top unified time series of sea level in Nouméa, between 1957 and 2015, from the two tide gauges. *Thin black vertical lines* indicate the overlap period over which the common datum is calculated. *Linear trends* indicated are calculated over the entire period (*left*), and for the altimetry period (*right*). *Bottom*, difference between tide gauges during the overlap period in 2005

periods, we find that a change in offset of 1 mm would induce a change in the trend of 0.07 mm/year when calculated over the 1993–2013 period, which is small compared to the calculated trend of 2.2 ± 1.6 mm/year (Fig. 3, top).

We, therefore, use the calculated offset of 2.6 cm to correct the Chaleix data set and to create a unified hourly continuous sea-level time series from 1967 to 2014. We apply a 71-point Demerliac filter to calculate daily means, centered at noon (UTC), for the 1967–2013 data set, to which we concatenate the 1957–1967 daily data set. We then calculate monthly means, centered on the 15th of each month, with an arithmetic mean of the daily means, if 15 days or more are present for each monthly value (Fig. 3).

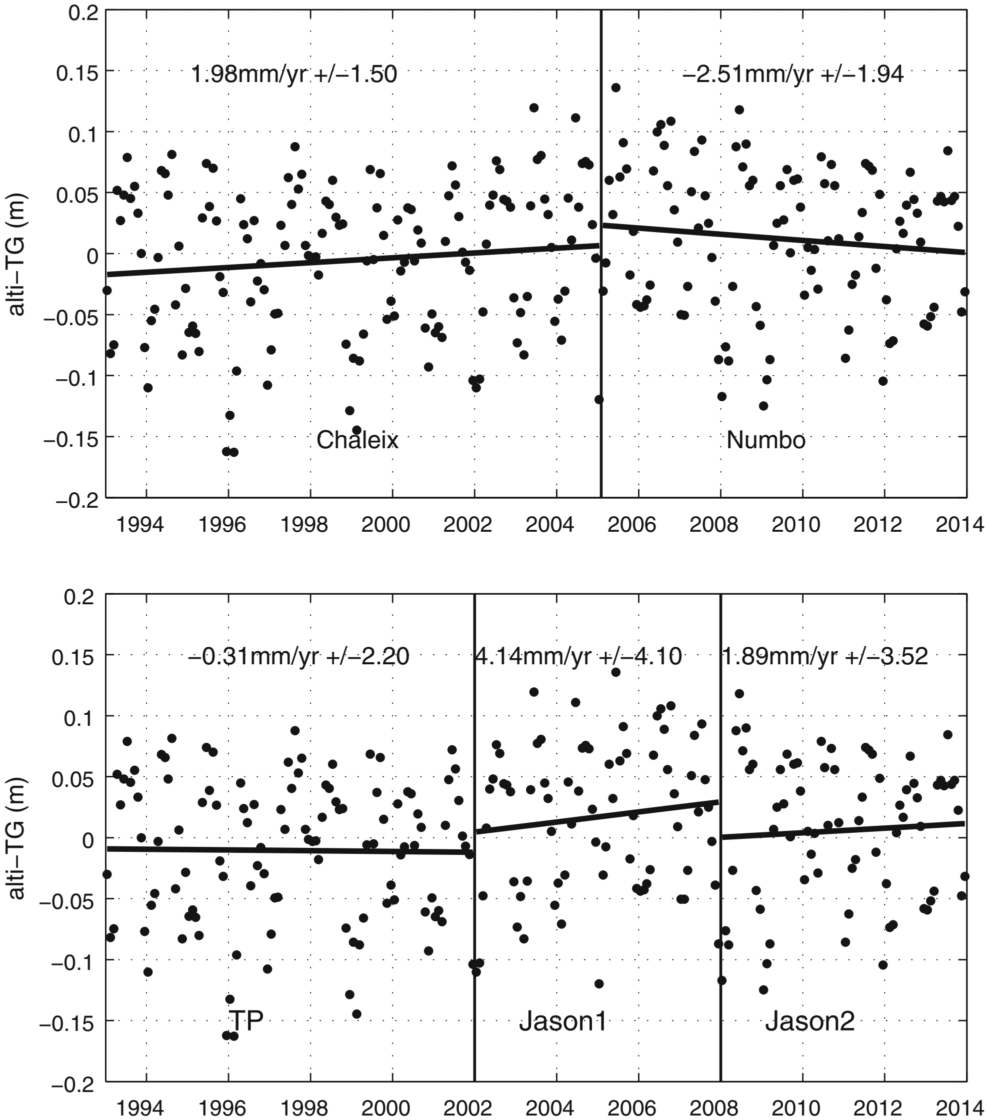


Figure 4
Difference between altimetry and tide gauges at Nouméa (*both panels*). Indicated linear trends are calculated piecewise for each tide gauge period, before and after 02/2005 (*top*) and for each altimetry mission period (*bottom*). The linear trend over the entire period is 1.41 ± 0.67 mm/year

5. Vertical Land Movements

Different rates of VLM at the sites of the 2 Nouméa TGs would prevent joining the two time series to look at long-term absolute and relative sea-level trends. If we infer VLM rates from the difference between altimetry and TG data, we find different rates of VLM for the periods separated by the TG site change (Fig. 4, top), where the inferred VLM rates for the Chaleix site are 1.98 ± 1.55 mm/year (1993–2005) and the inferred VLM rates for the NUMBO site are -2.46 ± 1.94 mm/year (2005–2013). We note here that the removal of an 18.6 year tidal cycle in the TG following Slangen et al. (2014) leads to a different set of VLM rates (-1.04 ± 1.50 mm/year for 1993–2005) and 1.95 ± 1.18 mm/year for 2005–2013). We also note that a drift in the altimetric product could also produce such

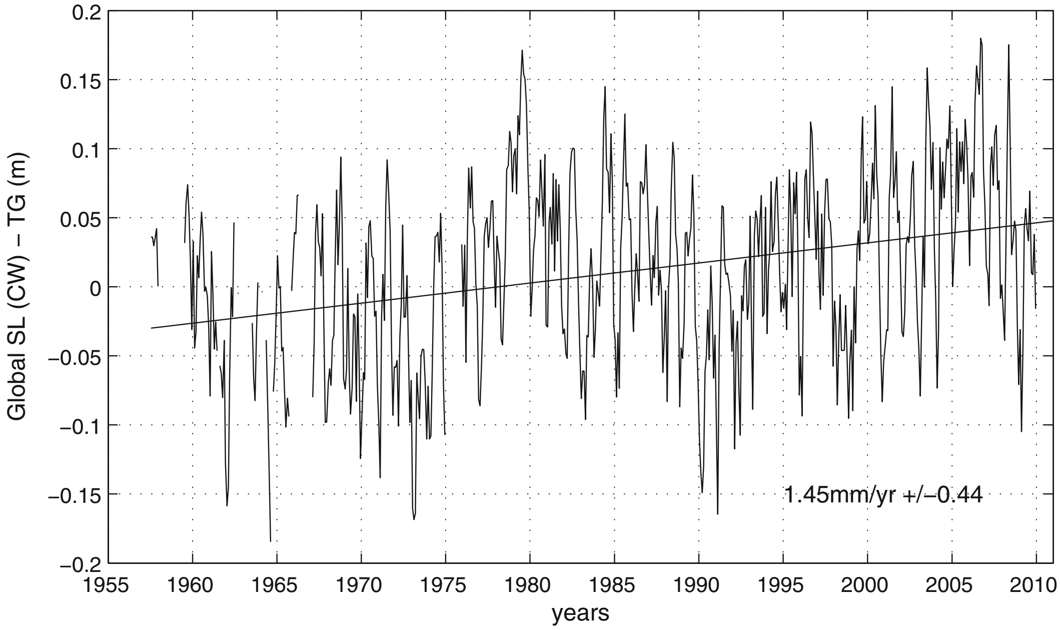


Figure 5
Difference between global sea level and tide gauges at Nouméa. Indicated linear trend is calculated for the 1957–2010 period

different rates of inferred VLM (Ablain et al. 2009; Watson et al. 2015). The altimetry product we used here is primarily based on data from three successive satellites' mission (Topex-Poseidon, Jason 1 and Jason 2), which transition periods are 2002 and 2008. When we calculate rates of inferred VLM for the periods separated by the satellite used in the altimetry product (Fig. 4, bottom), we find yet a different set of inferred VLM rates, inconsistent again with the previous ones. Furthermore, using a similar method, Nerem and Mitchum (2002) found an "uplift" of 2.5 ± 1.5 mm/year in Nouméa for the 1993–2001 Topex-Posseidon (and Chaleix TG) period. All these inferred rates of VLM which we found for individual tide gauges and/or satellite missions are lower than the uncertainty stated by Santamaria-Gomez et al. (2014) and well within the range of values found for a global set of tide gauges (Nerem and Mitchum 2002).

We can, however, expect that the precision of the method improves when we calculate these rates over longer periods (Nerem and Mitchum 2002; Ray et al. 2010), and this is one of the motivations behind this concatenation work. If we calculate the inferred VLM rate for the entire altimetry period 1993–2013, we find an "uplift" of 1.41 ± 0.67 mm/year. Another method to derive VLM from the tide gauges with several decades of data is to assume that when calculated over several decades, the rates at one tide gauge should be equal to the global rate (Mitchum 2000; Nerem and Mitchum 2002). To calculate this "internal VLM rate", we use the GMSL reconstruction from Church and White (2011) and find an uplift of 1.45 ± 0.44 mm/year (Fig. 5) for the 1957–2010 period, surprisingly close to the inferred VLM rate for the altimetry period 1993–2013.

Rates of measured VLM near Nouméa can also be obtained from two different nearby GPS and DORIS sites, and compared to our VLM estimates (Table 3). The rates vary by several mm/year, and can show either uplift or subsidence (Table 3). The reason for discrepancy among these measurements and with our estimates is unclear. Differences in VLM can exist even over several kilometers in such urban areas (Raucoules et al. 2013), and can be caused by hydrological processes or localized ground movements. Also no rate is calculated over periods longer than 10 years. Current efforts are underway to assess the long-term stability of the NRMD GPS, NOWB, and NOXB DORIS stations as this station is suspected of localized subsidence, which could explain

Table 3

Measured or inferred rates of vertical land movements in Nouméa

Station name	Source	Time frame	Rate
GPS station NOUM	Sonel ULR4	1997–2007	-1.61 ± 0.29 mm/year
GPS station NOUM	Sonel ULR5	1997–2007	$+0.64 \pm 0.47$ mm/year
GPS station NOUM	Sonel ULR6	1997–2007	-1.4 ± 0.28 mm/year
GPS station NRMD	Sonel ULR4	2006–2009	-1.55 ± 1.15 mm/year
GPS station NRMD	Sonel ULR5	2006–2013	-1.49 ± 0.51 mm/year
GPS station NRMD	Sonel ULR6	2006–2013	-1.86 ± 0.23 mm/year
DORIS station (NOUA)	DORIS website	1993–2000	-0.73 ± 0.71 mm/year
DORIS station (NOWB)	DORIS website	2005–2011	-1.39 ± 0.3 mm/year
DORIS station (NOXB)	DORIS website	2011–2013	-2.93 ± 1.92 mm/year
DORIS station (NOUA, NOWB)	From Ray et al. (2010)	Unknown	$+1.2 \pm 0.6$ mm/year
GPS station NOUM	From Becker et al. (2012)	Unknown	-2.1 ± 0.2 mm/year
Diff Alti-TG	From Nerem and Mitchum (2002)	1993–2001	$+2.5 \pm 1.5$ mm/year
Diff Alti-TG	This study	1993–2013	$+1.41 \pm 0.67$ mm/year
Diff global SL-TG	This study	1957–2010	$+1.45 \pm 0.44$ mm/year

the negative VLM rates at these stations. In April 2015, a permanent GNSS (global navigation satellite system) station was installed at the Numbo TG site, providing collocated high-quality relative sea level and VLM measurements (station NBTG). Over longer time scales, VLM caused by the glacial isostatic adjustment (GIA) over the last few thousand years has low geographical variability (King et al. 2012; Slangen et al. 2014). In the Nouméa region, GIA-related VLM is modeled to be a small uplift of 0.21 mm/year for versions 1.2 and 1.3 of the ICE-5G model of Peltier (2004). Finally, over longer geological time scales, geomorphological features, such as paleo reef terraces, can provide rates of VLM in the Nouméa region due to tectonic factors and the proximity to the New Hebrides trench. Cabioch et al. (1996) estimates a small average rate of subsidence of −0.07 mm/year over the past 125,000 years.

6. *Data Availability in International Repositories*

The Chaleix–Nouméa (1967–2005) data set is available in the following databases with the following ID:

GLOSS: 123 (http://www.gloss-sealevel.org/station_handbook/stations/123/).

UHSLC/JASL: 019A (http://uhslc.soest.hawaii.edu/data/?rq).

PSMSL: 852 (http://www.psmsl.org/data/obtaining/stations/852.php).

SHOM: 701 (http://refmar.shom.fr/fr/chaleix_noumea).

SONEL: 1814 (http://www.sonel.org/spip.php?page=maregraphe&idStation=1814.php).

The Numbo–Nouméa (2005–present) data set is available in the following databases with the following ID:

GLOSS: 123 (http://www.gloss-sealevel.org/station_handbook/stations/123/).

UHSLC/JASL ID: 019B (http://uhslc.soest.hawaii.edu/data/?rq).

PSMSL ID: 2134 (http://www.psmsl.org/data/obtaining/stations/2134.php).

SHOM: 702 (http://refmar.shom.fr/fr/chaleix_noumea).

SONEL ID: 1863 (http://www.sonel.org/spip.php?page=maregraphe&idStation=1863.php).

The daily and the hourly (1967–present) data sets constructed in this study are now available in the UHSLC/JASL repository under a unique ID 019.

7. *Conclusion*

In this paper, we present the construction and verification of a unique instrumental sea-level record for Nouméa by (1) rescuing and digitizing paper data, and (2) concatenating data from the 2 nearby tide gauges of Chaleix and Numbo. This new data set provides daily sea-level values from 1957 to present, and hourly values from 1967 to present. This makes this new time series one of the longest high-quality sea-level time series in the tropical South Pacific. Complete information on the continuity of vertical datum used throughout the different 1957–2005 ensures the homogeneity of the Chaleix data. The data overlap (154 days) between Chaleix and Numbo ensure the continuity of the relative sea-level measurements and allowed us to reference the two data sets to a single vertical datum.

For the calculation of absolute sea level, both relative sea level and VLM need to be known or estimated. Over short periods (<5 to 10 years) during the altimetry period, we cannot identify any statistically significant difference in the rates of inferred VLM (TG-altimetry) at the two sites, that would prohibit the joining of our two sea-level data sets.

From this new long data set, we could also calculate inferred rates of VLM over longer periods. Over the altimetry period (1993–2013), the inferred rates of VLM from the TG-altimetry difference and the "internal VLM rate" over 1967–2010 are close and show an uplift of 1.3–1.4 mm/year. Over the past centuries, the rate of VLM Nouméa region due to GIA is modeled to be a small uplift of 0.21 mm/year, while over longer geological time scales, VLM rates in the Nouméa region based on tectonic considerations indicate a subsidence. We, therefore, cannot conclude with certainty the sign nor the amplitude of contemporary VLM in Nouméa. This study underlies again the importance of having GNSS stations exactly collocated with the reference tide gauges.

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