

Bali 13th January 2017

Dear Editor

We thank the two reviewers for their comments. Both reviewers appear to be positive. Their comments aimed to clarify some aspects of the context of the work, and some aspects of the methods. We have tried to comply with all the requests. We provide hereafter explanations and additional information, that have been used for the revised version, or that can remain available in the Discussion archive.

Specifically,

Reviewer 1 requested:

1. a clarification of the relationship between Mean Low Water (MLW), which indicates the upper level of coral survival, and the ADT anomaly (Figure 3 of the initial manuscript). The reviewer said “*However, the upper level of coral survival before this event is not quantitatively discussed, but only described as Mean Low Water (MLW). MLW which limit the coral survival before the event should be quantitatively shown in the time series ADT in Figure 3, and then the mortality of the upper 15cm of corals should be defined in sea level changes*”.

Response: The request can not be fulfilled since we do not have precise measurements of Mean Low Water level for Bunaken. For this, data from a pressure sensor are ideally needed. Instead, tide gauge data could be used, but tide-gauge data are scarce in Indonesia. Fortunately there are two tide-gauges in the north of Sulawesi in the city of Bitung, east of Bunaken, by latitude 1.430N and longitude 125.200E on the other side of Sulawesi compared to Bunaken, our study site. Thus, while tide-gauge data are available in the region, they are not exactly on Bunaken, but can help visualize the range of conditions found in Bunaken.

Bitung data can be retrieved from the Sea Level Center in Hawaii (SLCH), specifically at http://uhslc.soest.hawaii.edu/thredds/uhslc_quality_daily.html?dataset=RQD033A. The Sea Surface Height (SSH) provided is referenced, for Bitung, against a GPS station located at Bako (http://www.igs.org/igsnetwork/network_by_site.php?site=bako) which is itself referenced against the WGS84 ellipsoid. Hence, raw Bitung SSH do not represent absolute depth above the Bitung seafloor. SLCH provides high quality data (available till early 2015) that have been controlled for most outliers and errors, and lower quality data that includes the most recent coverage, included our period of interest (2015-2016).

We include below and in the revised version (new Figure 3) a graph showing from the available Bitung data the daily mean sea level (that can be compared to sea level as provided by altimetry), and the daily lowest level (not directly measured by altimetry) (Fig. 1 below). This graph only aims to show what was likely happening in Bunaken before El Niño in terms of range of sea level variations due to normal tide fluctuations. The daily lower value exhibits a ~40-cm variation from neap tide to spring tide. The limit of coral survival is species dependent, but close to the mean of the daily lowest level (blue curve). If this mean is changing through time, the limit of mortality also changes dynamically. In 2014, and 2015, we witnessed during spring tide conditions *Porites* corals that had the upper part of the colonies well above the sea level, and without signs of mortality (see Picture 1). Hence, the upper limit of coral survival is somewhere around 20 cm above the spring tide lowest level for the end of the period shown on the graph below.

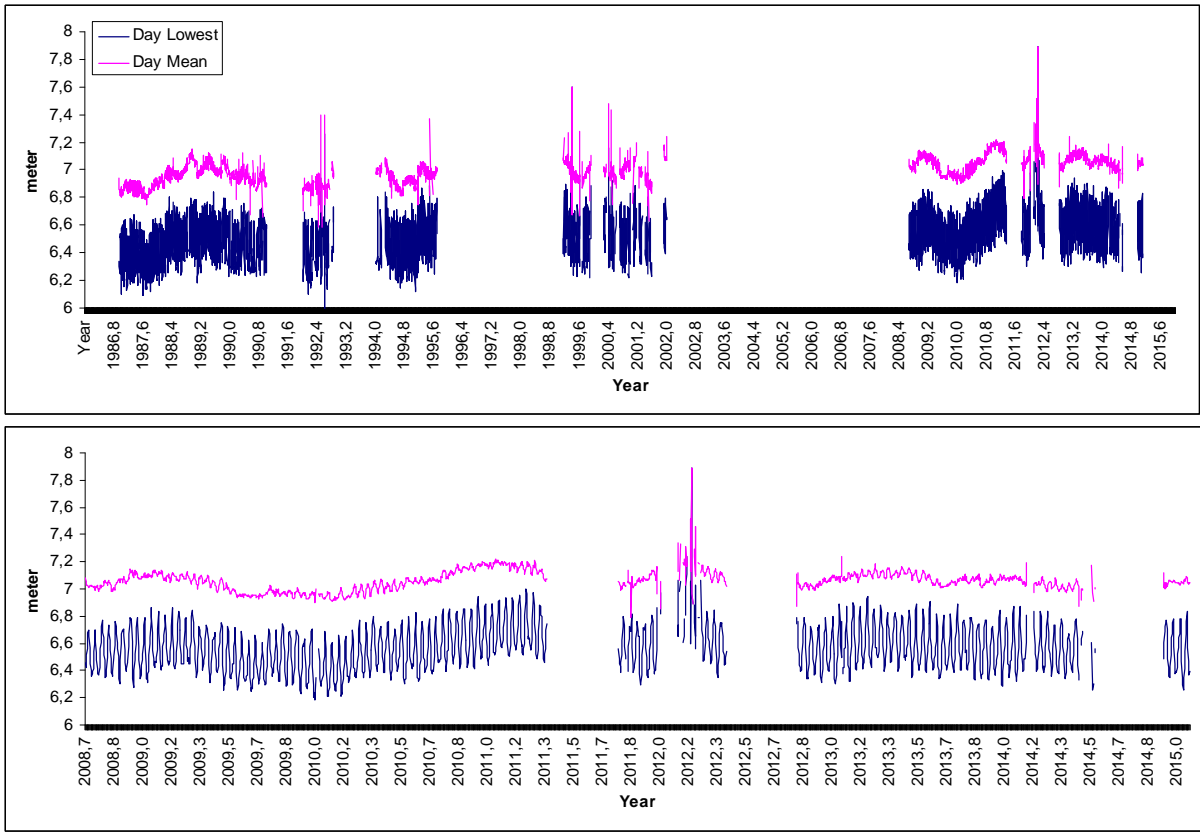


Figure 1 : Available data from the Bitung (east North Sulawesi) tide-gauge referenced against Bako GPS station. On top, the entire available data, from 1986 till 2015. Bottom, a close-up of the 2008-2015 period.



Picture 1: Reef flat close to lowest spring tide the 15th May 2014. The upper part of *Porites* colonies are fine and can obviously accommodate these conditions for few hours per month. The limit of growth is higher (~20 cm) than the lowest spring tide limit. This picture is from the same location as the Figure 1 on the manuscript, taken from a lower angle.

Therefore, the ~15cm fall that we observed on altimetry data around Bunaken and on most of east Indonesia changed for a short time (of several weeks) the lowest levels, and these changes lasted long enough so that coral tissues were damaged by too much UV and air

exposure. This fall shifted during few weeks in August-September 2015 the mean low level close to the pre-El Niño lowest levels shown in the Figure 1 above.

The request “*the mortality of the upper 15cm of corals should be defined in sea level changes*” is unclear. Not all corals have a 15cm band of tissue mortality, as it depends on the depth of the coral. See the new photographs that we have added in response to Reviewer 2 (Picture 2). We hope that the above graph and discussion replies to this comment.

2. an explanation on how the extent of the mortality was mapped. Reviewer 1 said: “*Figure 2 shows coral mortality area spatially. To obtain spatial distribution of coral mortality, the authors states that "reef flats were visually surveyed and recent mortality was recorded. Geographic coordinates of the presence of mortality were compiled to map its extent". However, it seems to me the area was not only mapped by field survey, but also by remote sensing. If so, the authors should describe how remote sensing was applied to map the mortality area.*”

Response: Indeed, the map of mortality (Figure 2, middle, of the submitted paper) is created using a pre-existing habitat map from remote sensing (described in Ampou 2016, a PhD thesis recently defended 6th December 2016). Our survey was done for all coral habitats along the reef. If we recorded mortality for that habitat, we flagged the corresponding polygon in the map as a mortality area. Hence, the yellow mask in Figure 2 is the mask corresponding to all mapped habitats where mortality was found, but mortality itself is not inferred from remote sensing.

We have clarified this in the new Material and Methods section.

3. further discussion related to reconstruction of sea level using micro-atolls. The reviewer said “*Further discussion of this point referring to reconstruction of tectonic sea level change by coral microatolls would extend viewpoint of this paper.* »

Response: Indeed, there is a common ground between our observations and the use of coral to reconstruct sea level. Reconstructions of paleo-sea level, whether it is induced by tectonic relative sea level change or not, is a science that takes advantage of the shape of modern or fossil micro-atolls. We now briefly point out this aspect in the beginning of the Discussion. However, we stress out that our study is clearly not about reconstructing sea levels using dead corals. Rather, we explain coral mortality using sea level data.

4. comparison of tide gauge data and altimetry sea level data. The reviewer said: “*The authors reconstruct sea level changes by satellite remote sensing. Reliable sea level history is obtained by tidal gauge. The remote sensing reconstruction should be compared with tide gauge data in this area.*”

Response: We show below and in the revised Results section publicly available sea level data from the aforementioned Bitung tide-gauge (low quality data to include the end of 2015 and 2016 period) to show the agreement between altimetry data and tide gauges (Fig. 2). The Bitung SSH data and the Sea Level altimetry data are comparable because we show the anomalies relative to the mean for the same period of concurrent measurement.

Altimetry data are extracted from the AVISO server: <http://misgw-sltac.vlandata.cls.fr:45080/thredds/dodsC/dataset-duacs-rep-global-merged-allsat-msla-14>

These are interpolated data, from various altimetry missions. The selected retrieved location is the closest available from Bitung (1.375N and longitude 125.125E). Data are available without interruption since 1993.

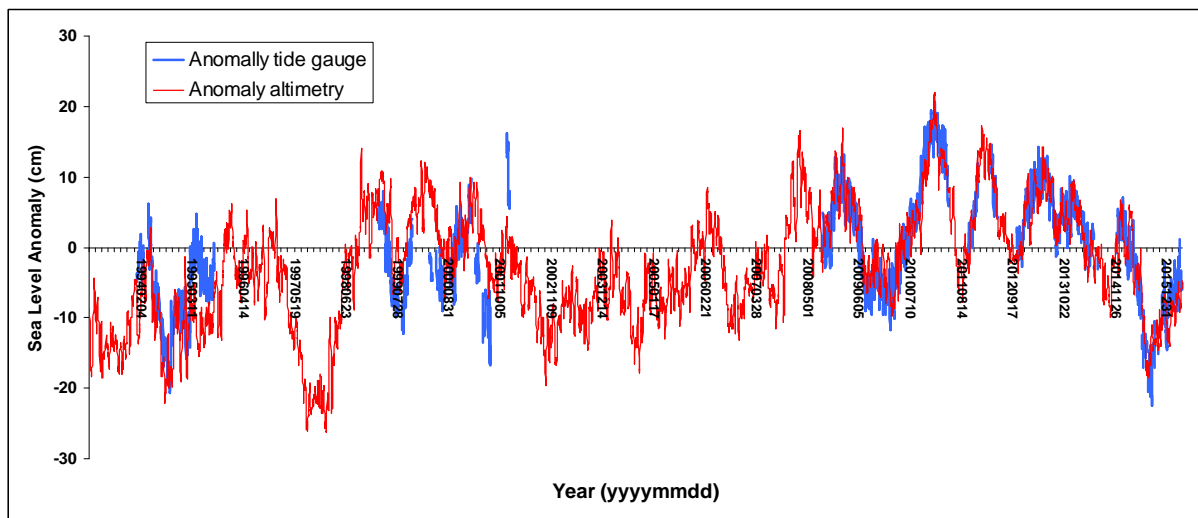


Figure 2: Sea level anomalies measured by the Bitung tide gauge station, and by altimetry (AVISO data server). Note the gaps in the tide gauge time-series. The anomaly was computed for both data sets by taking into account only the periods concurrently monitored by both types of measurements.

The good correlation (Pearson $r=0.83$) and the agreement in anomalies confirm that altimetry data are perfectly suitable to monitor sea level variation close to a coast. This confirms the value of using altimetry observations even without other local source of sea level data, as in Bunaken, to identify the cause of coral mortality (sea level fall).

This information is provided in the new Figure 3, in the revised Material and Methods, and in the revised Results sections

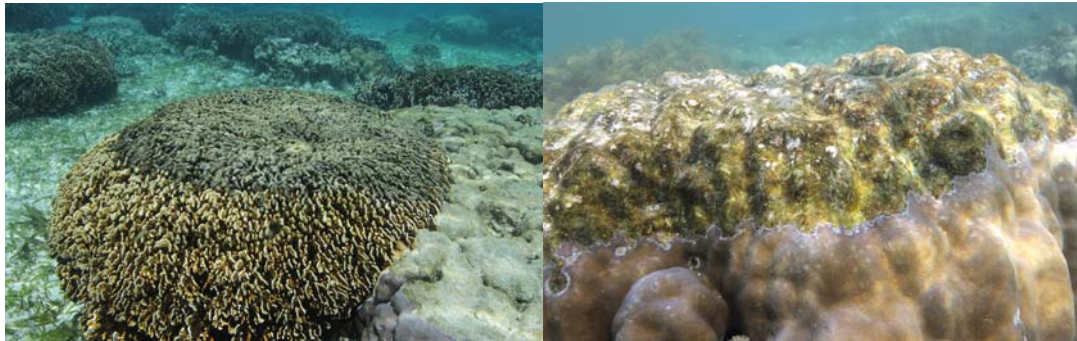
Reviewer 2 suggests:

5. to emphasize the paradox between our observations and the fact that one of the three main climate change threats for coral reefs is sea level rise.

Response: this can be now done at the beginning of the new Discussion. The following sentence has been added: “Interestingly, we found that sea level fall appeared to be responsible of coral mortality, while most recent climate change literature is generally focused on the present and future effects of sea level rise (Hopley, 2011). Geological records and present-time observation have already demonstrated that sea level variation is a driver of coral community changes. Sea level rise can have antagonistic effects: on the one hand, it can provide new growing space for corals. On the other hand, higher depth may enhance wave propagation and increase physical breakage in areas that were previously sheltered. If sea level rise is fast, corals may not keep up and the reef may be drowning relative to the new sea level. As such, sea level rise is seen as one of the three main climate change threats for coral reefs. This study reminds that the processes can be much more variable at ecological time-scale.”

6. enhancing the color plate with close-up of mortality on colonies.

Response: we have modified the color plate Figure 1 to include the two following close-up pictures with clear banding due to tissue mortality, for a *Heliopora* colony (Picture 2, left) and for a *Porites* colony (right). More information has also been provided on the Figure 1 caption. The Picture 1 above was also included in the new figure.



Picture 2: Bands of dead tissue as seen in February 2016. Left: *Heliopora coerulea* colony; right: A *Porites lutea* colony.

7. adding the number of colonies surveyed for each transect and station

Response: The information we have provided is the percentage of mortality found on all colonies on the transects, but unfortunately we did not keep the information on how many colonies were measured. Photographs of the transects are available but they do not cover the entire transects. The number of colonies on 20m long transect is however high since coral cover was high. We estimate the number of colonies ranged between 10 and 30 per transect, depending on the size of the colonies. This estimation has been provided in the new caption of the Figure 2.

8. reorganize the map. The reviewer said: “*Figure 2 could do with a line drawing of that bit of the N Sulawesi coast to better present the geographic setting for the false colour map of the Bunaken reef. Make the present map of all Indonesia an inset to the N Sulawesi map.* »

Response: The Figure 2 has not been re-organized as suggested. We tried, but in fact, inserting the Indonesian map into the Bunaken frame resulted in a cluttered figure without much visible. The location of Bunaken map is now a dark point, highlighted by the arrow, on the Indonesia map. We believe this is enough to locate Bunaken.

9. suggest some additional references

Response: while we did not cite the 2 references provided by the Reviewer, we have previously included similar references to illustrate the same facts, including references by Brown et al. on Phuket reefs. However, we have now added the 2 suggested references.

In addition, Reviewer 2 provided edits on the draft itself, for English corrections that were all kept, if the initial text was not removed to accommodate the comments above.

END.

1 **Coral mortality induced by the 2015-2016 El-Niño in Indonesia:**
2 **the effect of rapid sea level fall**

3
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20 **Abstract:** The 2015-2016 El-Niño and related ocean warming has generated significant coral bleaching and mortality
21 worldwide. In Indonesia, first signs of bleaching were reported in April 2016. However, this El Niño has impacted
22 Indonesian coral reefs since 2015 through a different process than temperature-induced bleaching. In September 2015,
23 altimetry data shows that sea level was at its lowest in the past 12 years, affecting corals living in the bathymetric range
24 exposed to unusual emersion. In March 2016, Bunaken Island (North Sulawesi) displayed up to 85% mortality on reef
25 flats dominated by *Porites*, *Heliopora* and *Goniastrea* corals with differential mortality rates by coral genus. Almost all
26 reef flats showed evidence of mortality, representing 30% of Bunaken reefs. For reef flat communities which were living
27 at a depth close to the pre-El Niño mean low sea level, the fall induced substantial mortality likely by higher daily aerial
28 exposure a least during low tide periods. Altimetry data was used to map sea level fall throughout Indonesia, suggesting
29 that similar mortality could be widespread for shallow reef flat communities, which accounts for a vast percent of the
30 total extent of coral reefs in Indonesia. The altimetry historical records also suggest that such event was not unique in the
31 past two decades, therefore rapid sea level fall could be more important in the dynamics and resilience of Indonesian reef
32 flat communities than previously thought. The clear link between mortality and sea level fall also calls for a refinement
33 of the hierarchy of El Niño impacts and their consequences on coral reefs.

34

35 **Key-words:** ENSO; Absolute Dynamic Topography; Sea Level Anomaly; Coral reef; Indonesia; Coral Triangle

36

37 **1. Introduction**

38 El Niño-Southern Oscillation (ENSO) is the most important coupled ocean-atmosphere phenomenon impacting climate
39 variability at global and inter annual time scales (McPhaden, 2007). The consequences on coral reefs have been well
40 documented, especially since the 1997-1998 massive coral bleaching event, which reached planetary dimension (Hoegh-
41 Guldberg, 1999). In short, El Niño increases temperature in several coral reef regions and induces zooxanthellae
42 expulsion from the coral polyp, resulting in coral colony looking white, hence “bleaching”. If the situation persists the
43 coral colony eventually dies. Coral bleaching intensity has been related to different temperature thresholds, other
44 environmental factors and stressors, and type of zooxanthellae and corals (Baker et al., 2008). Bleaching episodes due to
45 ocean warming were recorded during the strong 1982-83 El Niño in Australia (Glynn, 2000) and have since been
46 reported worldwide in several instances (Guest et al., 2012; Wouthuyzen et al., 2015). The last bleaching episode has
47 occurred in 2015-2016 during what occurs to be the strongest El Niño event on record (Schiermeier, 2015). Bleaching
48 events were often global in the past, including Indonesia (Suharsono, 1990; Guest et al., 2012; Wouthuyzen et al., 2015).
49 Last reports for Indonesia in 2016 are still under analysis, and Reef Check survey locations are presented at
50 <http://reefcheck.or.id/bleaching-indonesia-peringatan/>. It is thus assumed that coral bleaching induced by ocean warming
51 will be the main culprit if post-El Niño surveys report coral mortalities.

52

53 While in Bunaken National Park in February 23rd – March 5th 2016 for a biodiversity survey, we noticed recent
54 mortalities on the upper part of many massive colonies on several reef flats. This prompted a systematic investigation of
55 the phenomenon’s spatial distribution. We report here observations on what appears to be the first significant impact of
56 the 2015-2016 El Niño on Indonesia reefs. Unlike what is expected during such a strong event, the mortality was not

57 related to warm water induced-bleaching, but could be tracked to rapid sea level variations. Coral mortality data around
58 Bunaken Island are provided, and we investigate various altimetry and sea level anomaly data sets to explain mortality.
59 The clear link between mortality and sea level fall calls for a refinement of the hierarchy of El Niño impacts and their
60 sequences on coral reefs.
61

62 2. Material and Methods

63 Bunaken National Park (BNP) is located at the northwest tip of Sulawesi, Indonesia. The location is at the core of the
64 epicenter of marine biodiversity, the so-called Coral Triangle, a vast area spanning Malaysia to Solomon Island, where
65 the number of marine species is maximum (Hoeksema, 2007). BNP includes several islands with Bunaken Island
66 (1.62379°N, 124.76114°E) one of the most studied Indonesian reef site. Bunaken Island is surrounded by a simple
67 fringing reef system, comprising reef flats, several small enclosed lagoons and forereefs. The tide regime is semi-diurnal,
68 but with marked diurnal inequalities (Ray et al. 2005), with a maximum spring tidal range that can reach 2.52 m.
69 Bunaken Island is generally exposed to southwest wind from May to October, resulting in calm seas due to the short
70 fetch between mainland and the island, and to northwest wind from November to February, which can be strong at time
71 and generate large waves breaking on the west and north shores.
72

73 Two previous BNP surveys for habitat mapping, in May-June 2014 and May-June 2015, did not show any significant
74 signs of widespread mortalities on reef flats. Different species of corals were frequently exposed above water level at
75 low spring tide, yet they were entirely alive (Fig. 1). Microatolls were present. They have not been studied in Bunaken
76 NP, but by similarity with other sites, their growth is likely constrained by a Mean Low Water (MLW), between Mean
77 Low Water Neaps (MLWN) and Mean Low Water Springs (MLWS) (Smithers and Woodroffe, 2000; Goodwin and
78 Harvey, 2008). Several reef flats were characterized by compact communities of massive and semi-massive colonies that
79 could be described as keep-up communities limited in their vertical growth by the MLW (by analogy with the
80 terminology of Holocene reefs provided by Neumann and Macintyre, 1985).
81

82 In contrast with the 2015 observations, in late February 2016, during a coral biodiversity census survey, we noticed the
83 widespread occurrences of dead massive corals and we performed a systematic investigation on the spatial distribution of
84 the phenomenon. ~~Using the habitat map created by Ampou (2016), all coral habitat polygons present on reef flats around~~
85 Bunaken Island were visually surveyed and recent mortality was recorded (presence/absence). Geographic coordinates of
86 the presence of mortality were compiled to map its extent. ~~In practice, when mortality was observed on a habitat~~
87 ~~polygon, the entire polygon was flagged as positive.~~ Then, in different locations around the island, mortality was
88 measured on six reef flat locations characterized by high coral cover and different dominant massive coral species,
89 principally *Porites lutea* and the octocoral *Heliopora coerulea*, using six 10-meter long Line Intercept Transect (LIT)
90 (English et al., 1997). We recorded the percent cover of live and dead tissue for each coral ~~and summed the total. We~~
91 ~~also recorded~~ the species/genus for each coral, and substrate categories between colonies. ~~We did not keep track of the~~
92 ~~number of colonies present on each transect.~~
93

94 A clear sharp horizontal limit of tissue mortality was present in impacted colonies. The distribution of dead tissue
95 between colonies and among colonies (Fig. 1) suggested that mortality was related to sea level variations, with increased

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96 aerial exposure time during the last few months. In order to test this hypothesis, we needed to identify sea level variation
97 data. For this, long term data from a tide gauge or a pressure sensor are ideal but these were not available for Bunaken.
98 Tide-gauge data are scarce in Indonesia but fortunately there are two tide-gauges in the north of Sulawesi in the city of
99 Bitung, east of Bunaken, by latitude 1.430N and longitude 125.200E on the other side of Sulawesi compared to Bunaken.
100 Thus, while tide-gauge data are available in the region, they are not exactly on Bunaken, but can help visualize the range
101 of conditions found in Bunaken. Bitung data was retrieved from the Sea Level Center in Hawaii (SLCH), specifically at
102 http://uhslc.soest.hawaii.edu/thredds/uhslc_quality_daily.html?dataset=RQD033A. The Sea Surface Height (SSH)
103 provided is referenced, for Bitung, against a GPS station located at Bako
104 (http://www.igs.org/igsnetwork/network_by_site.php?site=bako) which is itself referenced against the WGS84 ellipsoid.
105 Hence, raw Bitung SSH do not represent absolute depth above the Bitung seafloor. SLCH provides high quality data
106 (available till early 2015) that have been controlled for most outliers and errors, and lower quality data that includes the
107 most recent coverage, included our period of interest (2015-2016). The Bitung tide gauge stopped recording in many
108 instances for raisons unknown to us, hence the records present many, irregularly-spaced, gaps.

109
110 In addition to the Bitung tide gauge data, different sea level anomaly products were investigated, based on their temporal
111 coverage and spatial resolution. First, we used gridded altimetry data in terms of Absolute Dynamic Topography (ADT),
112 from the Archiving, Validation and Interpretation of Satellite Oceanographic Data center (AVISO) at the spatial
113 resolution of $\frac{1}{4}^{\circ}$. ADT provides the sea level with respect to the geoid. Data is available from 1993 to 2016, allowing a
114 long-term comparison of the sea level trends. The mean ADT over the period were extracted for a small box next to
115 Bunaken Island (1.5-1.7° N; 124.5-124.8° E), a larger box (3 by 3 degrees around the smaller box) centered on Bunaken
116 Island and including the north of Sulawesi and Tomini Bay in the south, and for the entire Indonesia (-14.9-10.0°S, 94.9-
117 140.0°E). The difference between the minimum value (observed in September 2015) and the 2005-2014 mean or the
118 1993-2016 mean periods were also computed. In addition, we also retrieved ADT data corresponding to the Bitung tide
119 gauge location to compare altimetry sea level anomalies with *in situ* data. The selected retrieved location is the closest
120 available from Bitung (1.375N and longitude 125.125E). To compute sea level anomalies, we considered only the
121 periods of time covered by both data sets in order to use a common baseline.

122
123 Second, to extract geophysical information from higher spatial resolution altimeter data, we used the along-track
124 measurements from SARAL/AltiKa Geophysical Data Records (GDRs) distributed by the AVISO service
125 (<http://www.aviso.altimetry.fr/fr/>). This data set was chosen because the new Ka-band instrument from SARAL has a
126 finer spatial resolution and enables a better observation of coastal zones (Verron et al., 2015). Data extends from March
127 2013 (cycle 1 of the satellite mission) to May 2016 (cycle 33), with a repeat period of 35 days. Over this period, we use
128 all altimeter observations located between 10°S-10°N and 105°E-140°E. Two tracks (#535 and #578) intersect the north
129 of Sulawesi Island and contain sampling points just off Bunaken Island. The data analysis is done in terms of sea level
130 anomalies (SLA) computed from the 1-Hz altimeter measurements and geophysical corrections provided in GDRs
131 products. The SLA data processing and editing are described in details in Birol and Niño (2015). The 1-Hz SLA data
132 have a spatial resolution of ~ 7 km along the satellite tracks. In order to quantify the spatial variations of the regional sea
133 level change in March 2013-May 2016, a linear trend model is applied (using a simple linear regression) to the individual
134 SLA time series observed at the different points along the altimeter tracks crossing the area of interest. The trend is the
135 slope of the regression (in cm.y^{-1}). The resulting 3-year sea level trend values can be represented on a map.

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137 3. Results

138 3.1 Mortality rates per dominant coral genus

139 For all colonies found on the six stations, dead tissues were found on the top and upper-flank of the colonies, with the
 140 lower part of the colonies remaining healthy (Fig. 1). Mortality was not limited to microatoll-shaped colonies only.
 141 Round massive colonies were also impacted. On microatolls and other colonies that may have lived close to MLW, the
 142 width of dead tissue appeared to be around a maximum of 15 cm. Dead tissues were systematically covered by turf algae,
 143 with cyanobacteria in some cases, suggesting that the stressor responsible for the mortality occurred few months earlier.
 144 There were no obvious preferential directions in tissue damage at colony surface as it has been previously reported for
 145 intertidal reef flat corals in Thailand (Brown et al. 1994).

146

147 The six surveyed reef flat locations were dominated by *H. coerulea* and *P. lutea*, while other genus and species occurred
 148 less frequently (Table 1). When taking into account all genus, up to 85% of the colonies were dead (Site 5). The average
 149 mortality was around 58% all sites included (Fig. 2). When it was present *Goniastrea minuta* colonies were the most
 150 impacted, with a 82% mortality on average (Fig. 2). Highest mortalities were found on keep-up communities relative to
 151 sea level (Fig. 1).

152

153 3.2 Map of occurrences of mortality

154 The survey around the island revealed presence of mortality all around the island except the north reef flats where corals
 155 were scarce and encrusting (Fig. 2). The same coral genus as listed in Table 1 were impacted, but mortality levels
 156 differed depending on colony heights. When colonies were clearly below the present minimum sea level, they remained
 157 healthy (Fig. 1). Locations of positive observations show that mortality has occurred mostly along the crest, which is
 158 expected to be the most vulnerable during sea level fall (Fig. 2). The spatial envelop of mortality occurrences is shown
 159 on Figure 2's Bunaken map. The survey and generalization through the habitat map suggests that nearly 163 hectares, or
 160 30% of the entire reef system, has been impacted by some mortality. However, this does not mean that 30% of the reef
 161 has died.

162

163 3.3 Comparison between tide gauge and altimetry data

164 We found a good correlation (Pearson $r=0.83$) between sea level anomalies from altimetry (ADT) and from tide-gauge.
 165 The two time series are compared Figure 3 to confirm the agreement. The Bitung sea-level data reveal the type of sea-
 166 level variations that likely occurred around Bunaken, although patterns may not be exactly the same considering the
 167 distances between sites. Figure 3 shows from the available Bitung data the daily mean sea level (that can be compared to
 168 sea level as provided by altimetry), and the daily lowest level (which can not be directly measured by altimetry). This
 169 graph suggests what was likely the range of sea level variations happening in Bunaken before El Niño, due to normal
 170 tide fluctuations. The daily lowest value (blue curve in middle and lower panels in Fig. 3) exhibited a ~40-cm variation

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171 from neap tide to spring tide. In 2014, and 2015, we witnessed during spring tide conditions *Porites* corals that had the
172 upper part of the colonies well above the sea level, and without signs of mortality (Fig. 1). Hence, the upper limit of coral
173 survival is somewhere around 20 cm above the spring tide lowest level for the end of the period shown on Figure 3. In
174 other words, the limit of coral survival is close to the mean of the daily lowest level curve. If this mean value is changing
175 through time, the limit of mortality also changes dynamically. The ~15cm fall that we observed on altimetry data around
176 Bunaken and on most of east Indonesia changed for a short time (of several weeks) the lowest levels, and these changes
177 lasted long enough so that coral tissues were damaged by excessive UV and air exposure. During few weeks in August-
178 September 2015, this fall resulted in a shift of the mean low level towards the pre-El Niño lowest levels shown Figure 3
179 (lower panel).

180

181 **3.4 Absolute Dynamic Topography time series**

182 The ADT time-series (Fig. 4) shows a significant sea level fall congruent with El Niño periods, at all spatial scales,
183 although the pattern is not as pronounced at Indonesia-scale (Fig. 4). The 1997-1998 and the 2015-2016 years display the
184 highest falls. The September 2015 value is the local minima, considering the last ten years (Fig. 4). The 8 cm fall in
185 September 2015 compared to the previous 4 years, and the 15 cm fall compared to the 1993-2016 mean (Fig. 4) is
186 consistent with the pattern of mortality following a maximum of ~15 cm width on the top of the impacted micro-atolls
187 and colonies that were living close to the mean low sea-level before the event (Fig. 1).

188

189 **3.5 Sea Level Anomaly trends**

190 SARAL/AltiKa data in March 2013-May 2016 are shown in Figure 5 for a small area that includes Bunaken Island (top)
191 and a larger box (bottom) covering part of the western equatorial Pacific Ocean and Coral Triangle. A substantial sea
192 level fall is observed around Bunaken Island, with values ranging from 4 to 8 cm/year (12 to 24 cm accumulated over 3
193 years, Fig. 5). Further analysis of the individual sea level time series indicates that the overall trend is explained, and
194 accelerated, by the fall due to El Niño (not shown). This result agrees with findings from *Luu et al.* (2015) around
195 Malaysia and can be extended to much of the Coral Triangle. The Figure 5 shows that this phenomenon is consistent
196 over a large part of Indonesia and the warm water pool, with strong differences in sea level variations (up to -15 cm/year
197 are observed between Asia and Micronesia, north of 5°N and east of 130°E).

198

199 **4. Discussion**

200 A common ground exists between this study and the use of massive corals to reconstruct sea level. Reconstructions of
201 paleo-sea levels, whether it is induced by tectonic events or not, is a science that takes advantage of the shape of modern
202 or fossil micro-atolls (Meltzner et al. 2006). However, we stress out that this study is not about reconstructing sea levels
203 using dead corals. Rather, we explained coral mortality using sea level data, primarily from altimetry data. The
204 agreement between altimetry and tide gauge data (Fig. 3) confirms that altimetry data are suitable to monitor sea level

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205 variation close to a coast. More specifically, this confirms the value of using altimetry observations to help identifying
206 the cause of shallow coral mortality, even without any other local *in situ* source of sea level data, as in Bunaken.

207

208 Interestingly, we found that sea level fall appeared to be responsible of coral mortality, while most recent climate change
209 literature is generally focused on the present and future effects of sea level rise (Hopley, 2011). Geological records and
210 present-time observation have already demonstrated that sea level variation is a driver of coral community changes. Sea
211 level rise can have antagonistic effects: on the one hand, it can provide new growing space for corals. On the other hand,
212 higher depth may enhance wave propagation and increase physical breakage in areas that were previously sheltered. If
213 sea level rise is fast, corals may not keep up and the reef may be drowning relative to the new sea level. As such, sea
214 level rise is seen as one of the three main climate change threats for coral reefs. This study reminds that the processes can
215 be much more variable at ecological time-scale.

216

217 We aimed here to document the spatial scale and the cause of an ecological event that could be easily overlooked when
218 documenting the 2016 El Niño impact on Indonesian coral reefs. Many studies have emphasized the role of
219 hydrodynamics and sea level on the status and mortality of coral communities growing on reef flats (e.g., Anthony and
220 Kerswell, 2007; Hopley, 2011; Lowe et al., 2016). Here we emphasize, with altimetry data for one the first time for a
221 reef flat study (see Tartinville and Rancher 1997), that the 2015-2016 El Niño has generated such mortality, well before
222 any ocean warming-induced bleaching. The exact time of the mortality remains unknown, but it is likely congruent to the
223 lowest level in September 2015. The aspect of the colonies in February 2016, with algal turf covering the dead part (Fig.
224 1), is also consistent with a lowest sea level occurring few months earlier. The Figure 1 shows corals that were fine in
225 May 2015 even when exposed to aerial exposure during low spring tide, without wave or wind, for several hours, during
226 several days of spring tide. Thus, we assume the mortality was due to several weeks of lower water, including spring tide
227 periods, which is compatible with the temporal resolution of the altimetry observations. The aerial exposure could have
228 led to tissue heating, desiccation, photosystem or other cell functions damage (Brown, 1997). It is possible that colonies
229 could have look bleached during that period (Brown et al. 1994). Lack of wind-induced wave in the September period
230 also prevented wave washing and water mixing which could have limited the damage (Anthony and Kerswell, 2007).

231

232 The various satellite Sea Surface Temperature (SST) products for coral bleaching warning available at
233 <http://coralreefwatch.noaa.gov/> do not suggest any bleaching risk in the Bunaken region before June 2016, hence the
234 wide mortality we observed can not be simply explained by ocean warming due to El Niño. We also verified on
235 <http://earthquake.usgs.gov/> that between the May 2015 habitat mapping survey and the February 2016 coral survey, no
236 tectonic movement could generate such a 15 cm–uplift, with an upward shift of coral colonies relative to sea level as it
237 has been reported in different places in the past, including in Sumatra, Indonesia after the 2004 Sumatra Earthquake
238 (Meltzner et al. 2006). An uplift of that magnitude would be related to a significant event, but there are no reports higher
239 than a 6.3 magnitude earthquake (16th September 2015, origin 1.884°N 126.429°E) in the north Sulawesi area for that
240 period.

241

242 Altimetry data have been seldom used to study coral reef processes, even in a sea level rise era that may affect coral reef
243 communities and islands. They have been useful to assess the physical environment (wave, tide, circulation, lagoon
244 water renewal) around islands and reefs (e.g., Tartinville and Rancher, 1997; Andréfouët et al., 2001; Burradge et al.,
245 2003; Andréfouët et al., 2012; Gallop et al., 2014), or explain larval connectivity and offshore physical transport between
246 reefs (e.g., Christie et al., 2010), but this is the first time to our knowledge that altimetry data, including the new
247 SARAL/AltiKa data, are related to a coral ecology event. Different measures of sea level and sea level anomalies
248 confirmed an anomalous situation following the development of the 2015-2016 El Niño, resulting in lower sea level
249 regionally averaging 8 cm in the north of Sulawesi compared to the previous 4 years (Figs. 3-6). Mortality patterns on
250 coral colonies strongly suggests that sea level fall is responsible of the coral die-off that could reach 80% of reef flat
251 colonies that were in a keep-up position relative to, usually, rising sea-level in this region (Fenoglio-Marc et al; 2012).

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253 While mortality due to sea level fall was characterized opportunistically in Bunaken NP, the impact remains unquantified
254 elsewhere. However, we speculate that similar events have occurred throughout the Indonesian seas when considering
255 ADT values for this region (Fig. 6). Particularly impacted by sea level fall could have been the stretch of reefs and
256 islands between South Sumatra, South Java, the Flores Sea and Timor, and the domain centered by Seram island and
257 comprised between East Sulawesi, West Papua and the Banda Sea. These areas have substantial reef flat presence (e.g.,
258 for the Lesser Sunda region comprised between Bali, Maluku and Timor islands, see maps in Torres-Pulliza et al., 2013).

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260 Specifically for Bunaken NP, the event we have witnessed helps explaining long term observations of reef flat dynamics
261 and resilience. Indeed, our surveys and historical very high resolution satellite imagery show around Bunaken Island the
262 fast colonization of reef flats by *Heliopora coerulea* and by carpets of branching *Montipora* in the years 2004-2012, a
263 period congruent to substantial rising sea level (Fig. 3) (Fenoglio-Marc et al. 2012). Rising seas has allowed these corals,
264 especially fast growing and opportunistic like *H. coerulea* (Babcock, 1990; Yasuda et al., 2012) to cover previously bare
265 reef flats by taking advantage of the additional accommodation space. A similar process occurred in Heron Island reef
266 flats in Australia, with an artificially-induced sea level rise due to local engineering work (Scopélitis et al., 2011). In
267 Bunaken, and probably elsewhere in Indonesia and the Coral Triangle, the 2015-2016 El Niño event counter-balances
268 this period of coral growth with rising seas.

269

270 The ADT time-series (Fig. 4) suggests that similar low level situations have probably previously occurred, and almost
271 certainly at least in 1997-1998, the highest anomaly on altimetry record. Reef flat coral mortality reported in the Coral
272 Triangle as the consequences of bleaching in these years is thus most likely also the consequences of sea level fall. The
273 discrimination between thermal and sea level fall-induced mortality could be difficult to pinpoint on reef flats, if surveys
274 had occurred several months after the thermally-induced bleaching. In Bunaken NP, mortality due to sea level fall
275 preceded by nearly 7 months the first occurrences of bleaching in Indonesia, reported in April 2016. The real impact of
276 sea level fall could have been largely underestimated during all El Niño episodes and especially in Asia. The
277 implications for coral reef monitoring in the Coral Triangle are substantial. Surveys that may have started in April 2016
278 may be confused and assigned reef flat mortalities to coral bleaching. In future years, monitoring SLA may be as
279 important as monitoring SST. While there are several SST-indices specifically used as early-warning signals for potential

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280 coral bleaching (Teneva et al., 2012), there are no sea level indices specific for coral reef flats. However, several ENSO
281 indices can help tracking the likelihood of similar events for Indonesia. The high correlation between the NINO3_4
282 index and ADT over the 1993-2016 period (monthly mean minus seasonal baseline, Fig. 6) shows this potential. Other
283 indices, such as the Southern Oscillation Index (SOI, computed as the pressure difference between Darwin and Tahiti),
284 or the Equatorial SOI (defined by the pressure difference between the Indonesia-SLP, standardized anomalies of sea
285 level, and the Equatorial Eastern Pacific SLP) appears to be even more suitable over Indonesia and the Coral Triangle to
286 develop suitable early-warning signals related to sea level variations.

287

288 5. Conclusion

289 This study reports coral mortality in Indonesia after a El Niño-induced sea level fall. The fact that sea level fall, or
290 extremely low tides, induces coral mortality is not new, but this study demonstrates that through rapid sea level fall, the
291 2015-2016 El Niño has impacted Indonesian shallow coral reefs well before that high sea surface temperature could
292 trigger any coral bleaching. Sea level fall appear as a major mortality factor for Bunaken Island in North Sulawesi, and
293 altimetry suggests similar impact throughout Indonesia. Our findings confirm that El Niño impacts are multiple and the
294 different processes need to be understood for an accurate diagnostic of the vulnerability of Indonesian coral reefs to
295 climate disturbances. This study also illustrates how to monitor local sea level to interpret changes in a particular coastal
296 location. For Indonesia coral reefs, in addition to sea level fall depending on the ENSO situation, further changes can be
297 expected, due to coral bleaching, diseases, predator outbreaks, storms and sea level rise (Baird et al., 2013; Johan et al.,
298 2014). Considering the level of services that shallow coral reefs offer, in coastal protection, food security and tourism,
299 the tools presented here offer valuable information to infer the proper diagnostic after climate-induced disturbances.

300

301 Competing interests

302 The authors declare that they have no conflict of interest.

303 Acknowledgements

304 This study was possible with the support of the INfrastructure DEvelopment of Space Oceanography (INDES0) project
305 in Indonesia, and its Coral Reef Monitoring Application. Fieldwork on Bunaken Island was authorized by the research
306 permit 4B/TKPIPA/E5/Dit.KI/IV/2016 delivered by the Ministry of Research, Technology and Higher Education of the
307 Republic of Indonesia to SA. [This is ENTROPIE contribution 178.](#)

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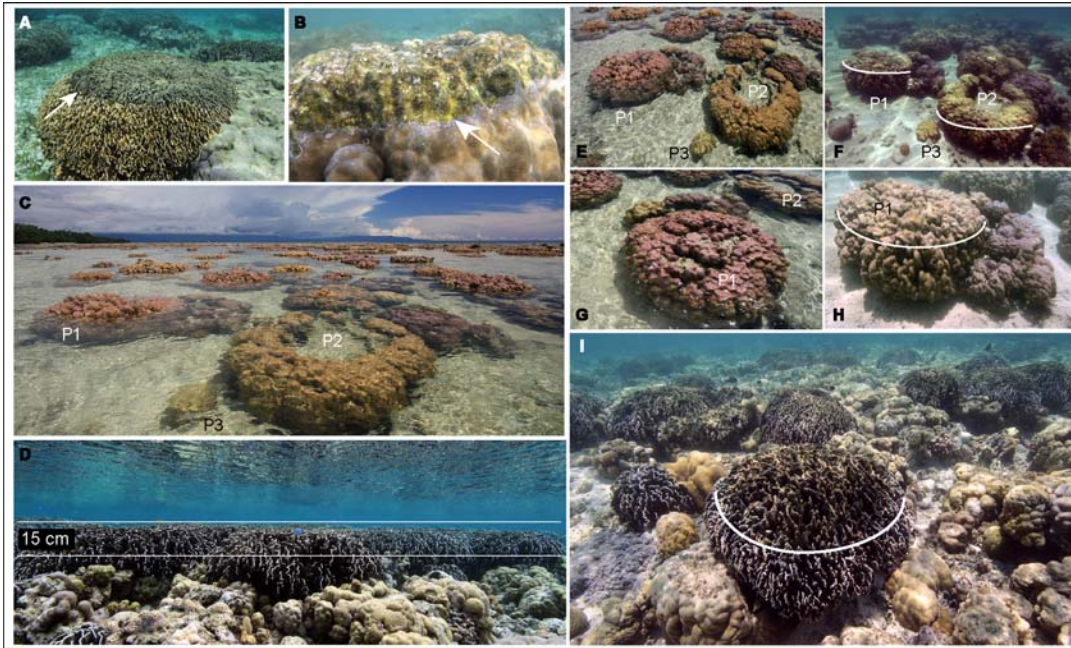
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390 Table 1: Mortality rates (mean \pm standard deviation, n=6) of all corals for the 6 reef flat sites. The three dominant species were *Porites lutea*, *Heliopora*
 391 *coerulea*, and *Goniastrea minuta*. Several species and genus were found only once. Standard deviation is not shown when only one measurement per type of
 392 coral could be achieved (i.e., one colony per site).

393

		Coral										
		<i>Porites lutea</i>	<i>Heliopora</i>	<i>Goniastrea</i>	<i>Acropora</i>	<i>Galaxea</i>	<i>Cyphastrea</i>	<i>Montipora</i>	<i>Porites cylindrica</i>	<i>Lobophyllia</i>	<i>Pocillopora</i>	<i>Mean</i>
Site	1	44 \pm 36	52 \pm 24						42 \pm 40			46
	2	39 \pm 16	18 \pm 8	100 \pm 0							100	57
	3	54 \pm 5		100 \pm 0	100 \pm 0	100	100					58
	4	20 \pm 17		100	25					100		55
	5	61 \pm 13	29 \pm 18			67		100 \pm 0				85
	6	52 \pm 23	70 \pm 8	46 \pm 51		100						47
	<i>Mean</i>	44	42	82	45	89	100	100	42	100	100	58

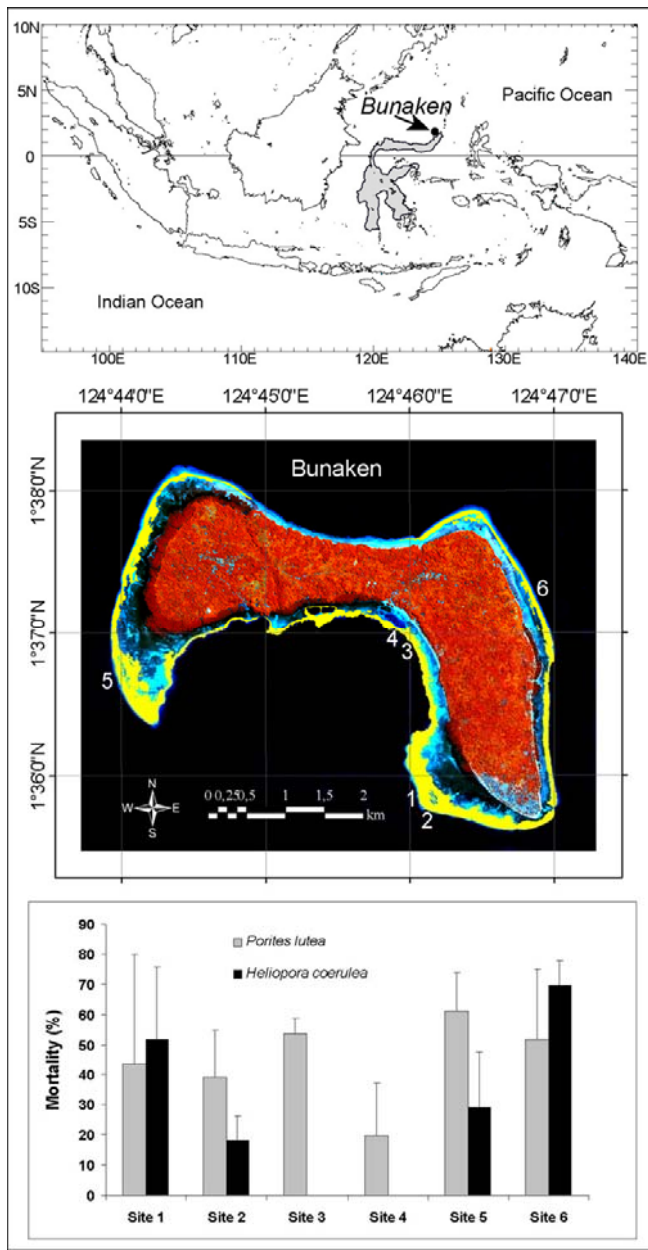
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396 Figure 1: Bunaken reef flats. A: close-up of one *Heliopora coerulea* colony with clear tissue mortality
 397 on the upper part of the colonies. B: same for a *Porites lutea* colony. C: reef flat *Porites* colonies
 398 observed at low spring tide in May 2014. Even partially above water few hours per month in similar
 399 conditions, the entire colonies were alive. D: a living *Heliopora coerulea* (blue coral) community in
 400 2015 in a keep-up position relative to mean low sea level, with almost all the space occupied by
 401 corals. In that case, a 15-cm sea level fall will impact most of the reef flat. E-H: before-after
 402 comparaison of coral status for colonies visible in C. In E, healthy *Porites lutea* (yellow and pink
 403 massive corals) reef flat colonies in May 2014 observed at low spring tide. The upper part of
 404 colonies is above water, yet healthy. F: Same colonies in February 2016. The white line visualizes
 405 tissue mortality limit. Large *Porites* colonies (P1, P2) at low tide levels in 2014 are affected, while
 406 lower colonies (P3) are not. G: P1 colony in 2014. H: viewed from another angle, the P1 colony in
 407 February 2016. I: Reef flat community with scattered *Heliopora* colonies in February 2016, with
 408 tissue mortality and algal turf overgrowth.

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410 Figure 2: Top: Bunaken location in the north of Sulawesi, the large island in grey. Middle: Close-up
 411 of Bunaken Island. The yellow area shows where coral mortality occurred around Bunaken reef flats,
 412 with the position of six sampling stations. Dark areas between the yellow mask and the land are
 413 seagrass beds. Blue-cyan areas are slopes and reef flats without mortality. Bottom: Mortality rates
 414 for the 6 sites for two dominant species *Porites lutea* and *Heliopora coerulea*. The latter is not found
 415 on Sites 3 and 4. The number of colonies ranged between 10 and 30 per transect, depending on the
 416 size of the colonies.

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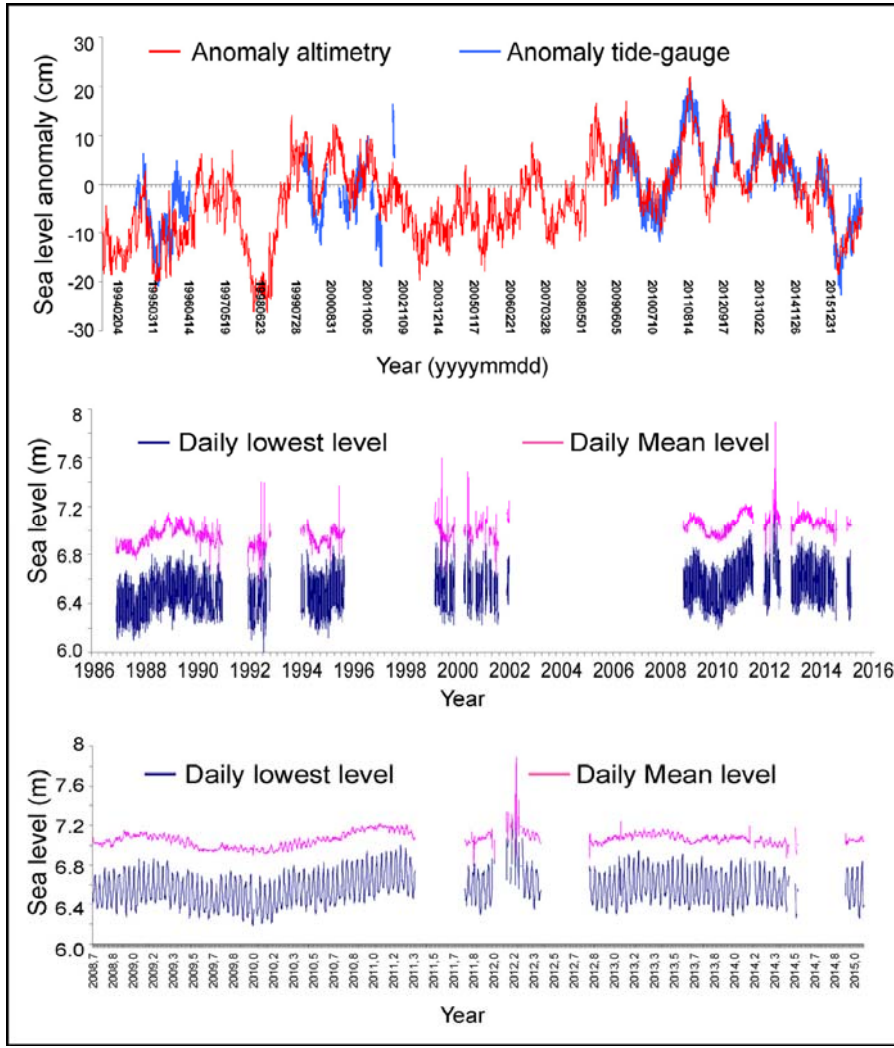
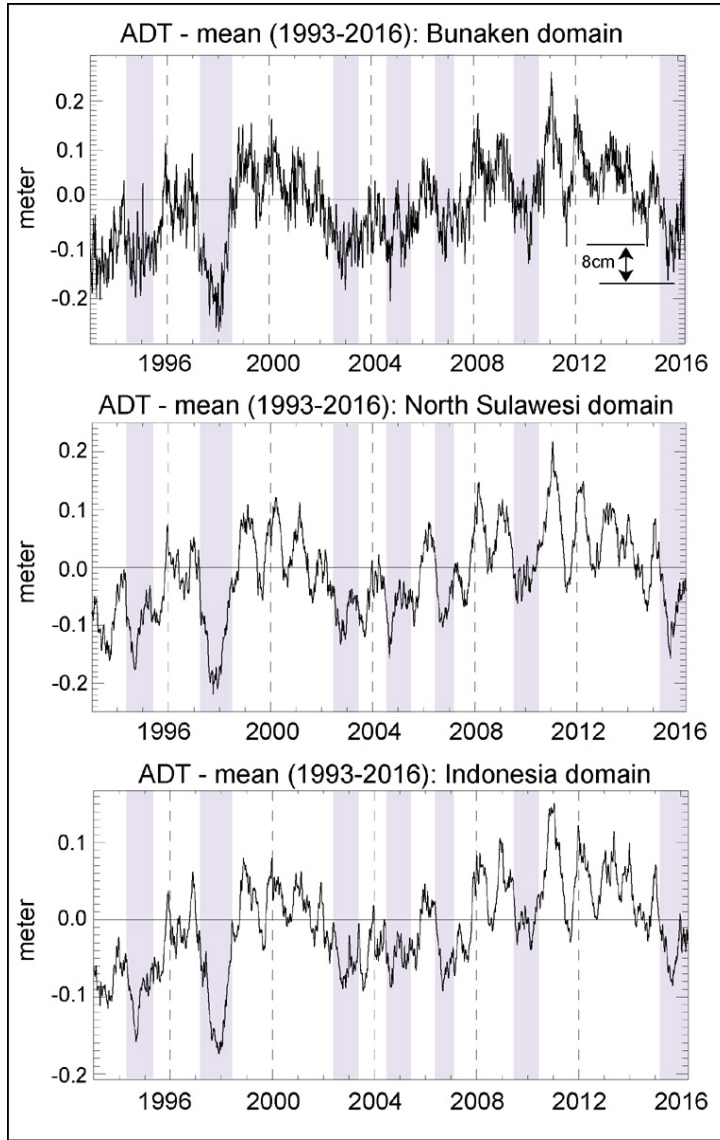


Figure 3: Sea-level data from the Bitung (east North Sulawesi) tide gauge, referenced against Bako GPS station. On top, sea level anomalies measured by the Bitung tide gauge station (low-quality data), and overlaid on altimetry ADT anomaly data for the 1993-2016 period. Note the gaps in the tide gauge time-series. Middle: Bitung tide gauge seal level variations (high-quality data, shown here from 1986 till early 2015) with daily mean and daily lowest values. Bottom, a close-up for the 2008-2015 period.

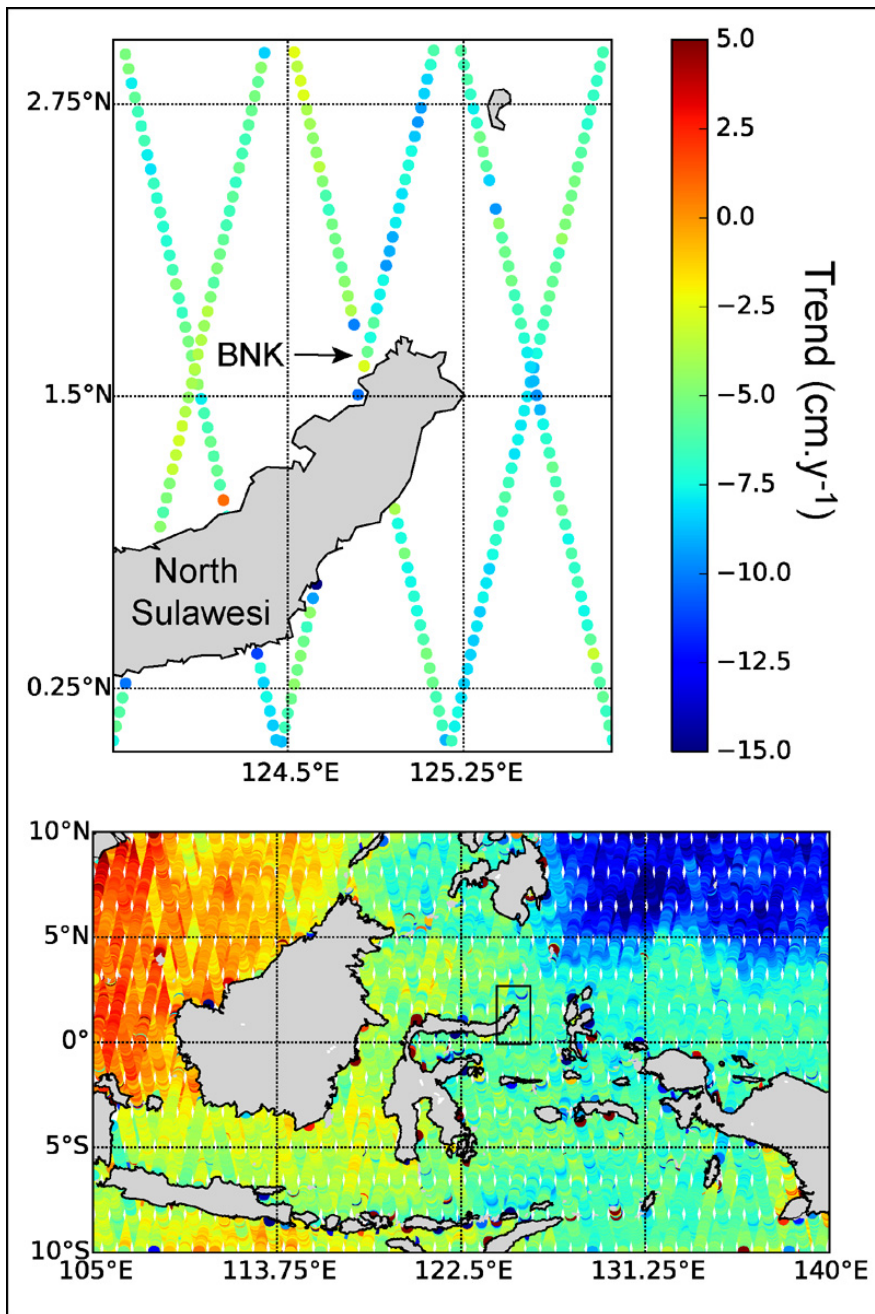
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426

427 | Figure 4: Time series of ADT, minus the mean over the 1993-2016 period, for Bunaken Island (top), North
428 | Sulawesi (middle), and Indonesia (bottom). The corresponding spatial domains are shown Figure 6. El Niño
429 | periods (http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml) are depicted
430 | with light shadings. The September 2015 minimum corresponds to a 8 cm fall compared to the minima the
431 | four previous years, and a 14 cm fall compared to the 1993-2016 mean. The 1998 El Niño displays the largest
432 | sea level fall.

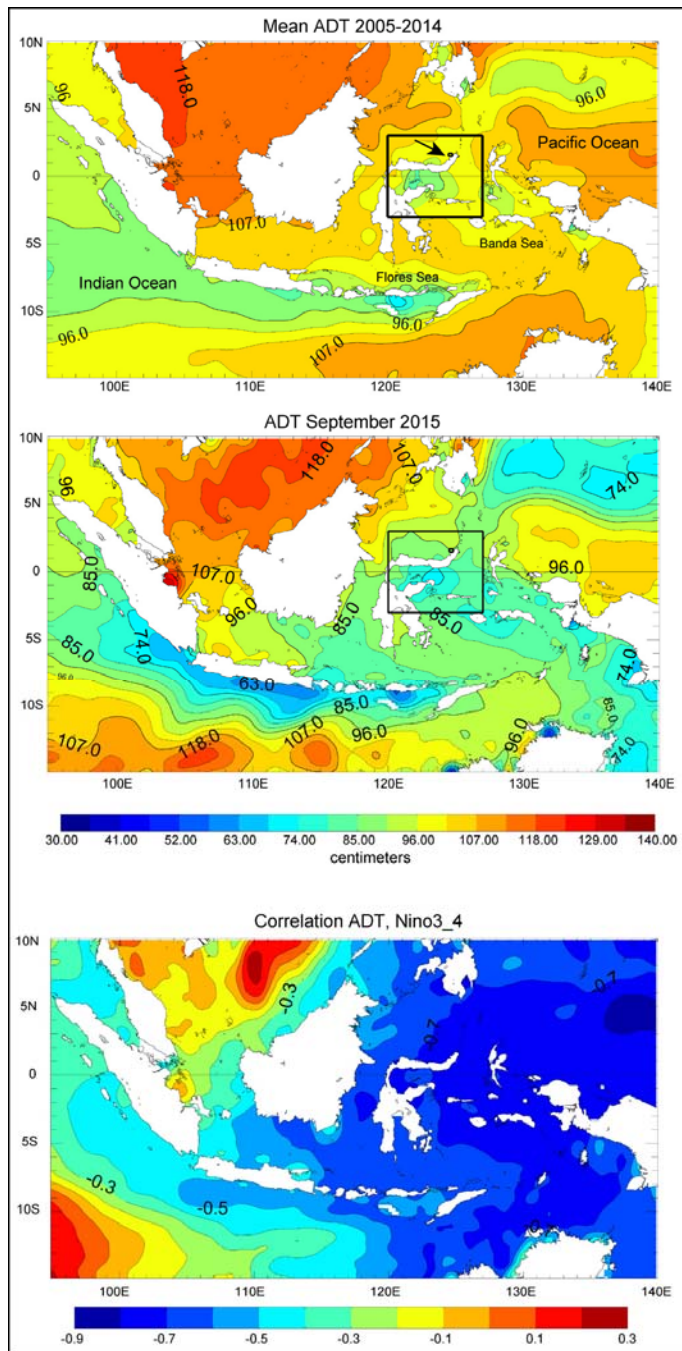
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434 | Figure 5: Top: Map of along-track SLA trend (in $\text{cm}\cdot\text{year}^{-1}$), 2013-2016, for the north Sulawesi area.
 435 The position of Bunaken Island is shown (BNK). Bottom: Map of along-track SLA trend (1-Hz),
 436 2013-2016, for Indonesia. The domain on the top panel is the rectangle in the Indonesia map.

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437

438 | Figure 6: Top: Map of the 2005-2014 Absolute Dynamic Topography (ADT, in centimeters) average
 439 | over Indonesia. Middle: Map of the September 2015 ADT mean value over Indonesia. The two
 440 | squares indicate the domain just around Bunaken Island (arrow on top panel) and the north Sulawesi
 441 | domain used for the ADT time-series presented in Figure 4. Bottom: Map of correlation between
 442 | ADT and the Nino3-4 index (1993-2016, monthly average minus seasonal cycle).

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