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SUPPORTING INFORMATION

ENSO-driven extreme oscillations in mean sea level destabilise critical shoreline mangroves – an emerging threat

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1. Sea level influences on tidal mangroves

Mangrove vegetation notably dominant tidal wetlands bordering sub-tropical and tropical shorelines worldwide [2]. For this study, we focused on mangroves in northern Australia’s Gulf of Carpentaria (GOC) where there had been an unexplained instance of mass dieback [4, 11, 14, 15]; Fig 2). Forested mangrove habitats occupy distinct elevation zones across tropical tidal profiles, depending on sea level, tidal range and soft sediments [11]. The following definitions emphasise these distributional constraints on the combined vegetative composition of tidal wetlands consisting of mangroves plus tidal saltmarsh and microphyte-carpeted saltpans [3]. This tidal wetland zone has been defined broadly as the shoreline upper intertidal niche across the elevational range between mean sea level (MSL) and the highest astronomical tides (HAT).
The relative proportions and positioning of these three dominant vegetated components across this tidal wetland zone appear largely dependent on prevailing longer-term rainfall conditions [3]. As such, mangroves typically were located along the seaward foreshore edge, and considerably less along the landward edge. This profile distribution is displayed in the schematic (Fig A) of GOC shorelines for a seemingly compressed profile (occasionally up to 1-2 kilometres wide), comprised of a narrow landward edge of mangrove trees, a wide span of diminutive saltmarsh-saltpan vegetation, and a moderately wide zone of seaward mangroves. The 2015 dieback occurred at the upper ecotone edge of this seaward zone (see Fig B).

Fig A depicts three dominant processes influencing sea levels, including: A) longer-term oscillations in MSL (mentioned in the article); B) tidal cycles; and C) sea level rise.

![Schematic depiction of tidal zone and common positioning of vegetation zones along southern shorelines of Australia’s Gulf of Carpentaria. Vegetation consisted of a narrow landward mangrove zone, a wide expanse of saltpan flats with saltmarsh, and a mangrove seaward zone. These vegetation types occupy elevations between mean sea level (MSL) and highest astronomical tide (HAT) levels. Dieback in 2015 was notably present at the upper (rear) edge of the seaward mangrove fringe. Oscillations in MSL (A) were one of three dominant sea level change processes also including daily tidal influences (B) and the pervasive pressures of rapidly rising sea levels (C). Each have differing impacts regards changes to vegetation across the zone, and these responses are uniquely indicative of the dominant processes responsible (Image source: illustration by NCD).](image-url)

**A. Sea level influences – multi-decadal and annual oscillations in mean sea level.** While mangrove shorelines have been shaped and characterised by tidal cycles (see B) and rising sea levels (see C), it was further evident that fluctuations in MSL had also been influential
In 2015, when mass dieback of mangroves (see Fig B) occurred in Australia’s GOC, a particularly severe El Niño had caused an abrupt and extreme drop of >20 cm in MSL across the western Pacific region – a feature quantified initially in satellite altimetry [4, 57] and later in port sea level gauge records in this study. In the GOC, port gauges recorded much lower drops in MSL of >40 cm. These data were investigated for the GOC area to discover patterns in sea level fluctuations and their influences on events of mass dieback plus the seasonal growth of mangroves generally.

B. Sea level influences - the daily ebb and flow of tidal cycles. The daily period and range of tidal cycles define the upper and lower boundaries for the tidal wetland niche occupied by mangroves (shrubs and trees), saltmarsh (succulents and sedges) and saltpan (microphytobenthos). These vegetation types together occupy tidally-inundated upper portions of shoreline slopes comprised of largely unconsolidated sediments between upper landward tidal limits marked by the HAT level and lower seaward limits around MSL. The extent, location and combination of vegetation types between these firm boundary limits appear related to the net moisture limitations from key factors like tidal inundation frequency and range, groundwater flows, landscape runoff and rainfall [3, 11]. There are often also distinct mangrove zones [2] especially at landward and seaward fringes. For the GOC, while changes in rainfall and temperature had significantly shaped the pre-impact zonation [3, 13], these influences were notably independent of the process that caused the widespread mass dieback in 2015 (see A above).

C. Sea level influences - rising of sea levels. Sea levels have been rising progressively as a direct consequence of global warming. And, rises in the GOC reportedly had been unusually rapid (>8 mm/yr) [50] driven by unusual biogeographic and topographic features of the GOC [56]. Furthermore, observations of rising sea levels were also consistent with anecdotal accounts of saline intrusion across the region. However, these impacts on mangrove condition caused by rising sea levels were also independent of the processes responsible for the 2015 mass dieback in northern Australia (see A above).

It has been instructive to distinguish between these sea level processes, where each expresses different constraints on landward and seaward zone ecotones, and ultimately where their combination gives rise to the characteristic zonation observed amongst tidal wetland vegetation. And, as such, this usefully demonstrates how zonation ultimately appears dependent on their combined influences of moisture availability – especially where this relates to the particular environmental drivers responsible. So, our focus on the 2015 mangrove dieback has allowed us to discriminate between the key sea level influences occurring across the inter tidal zone (Fig A).

Accordingly, the upper ecotone of the landward zone appears mostly influenced by infrequent seawater wetting at the tidal limit of HAT plus seasonal groundwater flows (fed by catchment rainfall). The key determining factors for this ecotone include all three processes influencing MSL (Fig A) plus rainfall. Changes to the landward ecotone include ‘terrestrial retreat’ (= dead supratidal vegetation, bank erosion and undercutting [11]) and ‘mangrove
encroachment’ (= mangrove seedlings amongst dead and dying supratidal vegetation [11]).
By contrast, the lower ecotone of the landward zone is mostly influenced by longer-term
rainfall, with the indicator of ‘ecotone shift’ (either = negative, with patches of mangrove
dieback, or = positive, with patches of mangrove seedlings, spread along the ecotone [3, 11]).
This combination of influences explains why the landward zone is often quite narrow or
absent in particularly arid areas of very low rainfall, like the GOC.

Between the lower mangrove ecotone of the landward mangrove zone and the upper ecotone
of the seaward mangrove zone, there is another indicator of rising sea levels (Fig A) with
‘saltpan scouring’ (= sheet erosion, channelling drainage erosion, loss of saltmarsh and
saltpan vegetation [11]) of often very wide flat areas of saltpan and saltmarsh vegetation. It is
expected that these influences contribute to respective upper and lower ecotones with each of
the two bordering mangrove zones.

Also influenced by ecotone shift, is the upper ecotone of the seaward edge. But, in areas of
relatively low rainfall like the GOC, this ecotone appears to exist at or near some minimal
position dependent on mostly moderate annual oscillations in MSL (Fig A) for regular
seawater inundation with normal tidal cycles. This feature explains why healthy closed-

11. Two types of mangrove dieback attributed to extremes in sea level
Two previously unrecognised types of mangrove dieback have been identified in this article.
These are the direct consequence of either unusually low or high sea levels. These two types
of mangrove dieback add to the range of indicative processes observed influencing coastal
shorelines and mangrove-lined waterways [14, 41, 42], and depicted in Fig 9.6 in Duke et al.
[11] as a graphical schematic showing the range of response indicators observed influencing
intertidal shorelines. The two newly identified types of mangrove dieback are described as
follows.

‘Desiccation dieback’ or ‘Taimasa dieback’ (Fig B)
**Indicator.** Broad, abrupt and widespread dieback of mangroves at and below the upland ecotone of the shoreline mangrove zone (Fig A). This differs from rainfall influenced ‘ecotone shift’ which is relatively moderate and progressive in response to longer-term trends in climate [3]. Trees killed by both these kinds of dieback noticeably die standing without any physical damage.

**Fig B.** ‘Desiccation dieback’, similar to ‘ecotone shift negative’ [3], notably varied in severity from extreme (A), to moderate (B), to minor (C). This was quantified, as indicated, by the proportional loss of the shoreline mangrove zone (hatched green area) down from the upper ecotone (also see Fig A). The map (D) also represents the location of the green fraction timeseries site for Karumba (GOC6; see Table A), noting this location marks the upland ecotone (Image sources: photographs and illustration by NCD).

**Impact.** Damage to the shoreline zone can be particularly severe where most, if not all, of the shoreline zone trees are killed. Impacted shorelines become highly vulnerable to shoreline erosion from other factors including severe cyclones and the progressive pressure of rising sea levels. Where more than 20% of the shoreline zone mangroves remain, the longer-term impacts are significantly reduced with recovery notably more likely.
Cause. Mangroves trees die from ‘desiccation dieback’ during periods of unusually low MSL resulting from very strong El Nino conditions. The low sea levels responsible have been estimated to be less than -40 cm over six months during the dry season. Trees die from severe moisture deficit in the absence of seawater inundation, or moisture from any other source, like rainfall.
‘Drowning dieback’ or ‘Inner Fringe Collapse’ (Fig C)

Indicator. Patches of dieback, dead trees, regrowth and forest gaps close to the seaward edge of mangroves of the shoreline mangrove zone (Fig A). This differs from ‘storm damage’ which tends to be associated with ‘shoreline erosion’ plus broken branches and uprooted trees. Trees killed by ‘drowning dieback’ noticeably die standing without physical damage.

Fig C. ‘Drowning dieback’, also called ‘inner fringe collapse’, is characterised by patches of dead trees or gaps close to, and along, the seaward edge of the shoreline mangrove zone (also see Fig A). For A, ‘inner fringe collapse’ was described from shoreline surveys of Boigu Island in Torres Strait [42]. For B, the map represents the location of the green fractional timeseries site for Carnarvon in this study (W1; see Table A). Note, the location was positioned close to the seaward ecotone amongst the fringing dieback patches (Image sources: photograph and illustration by NCD).

Impact. Damage to the seaward edge of mangroves reduces their resilience to the pressures of rising sea levels. So, this damage can often be associated with erosion of exposed trees along
the seaward edge. Shorelines in such a damaged state are further vulnerable to large waves and gale-force winds from occasional severe tropical cyclones, and severe flood events.

Cause. Mangroves trees die from ‘drowning dieback’ during periods of unusually high MSL resulting from very strong La Nina conditions. Trees die from excessive inundation when sea levels fail to retreat for more than 50% of the time. This kind of dieback is also likely associated with rising sea levels, especially where such impacts occur during periods of periodically high sea levels.

2. Study site additional information – Tables A & B

Table A. Specific locations as comparisons for the presence or absence of 2015 mass mangrove dieback across northern Australia, specifically in north western Australia (W), the Gulf of Carpentaria (GOC), and north eastern Australia (E) referred to in these investigations (see Fig 2). Unlike the other sites, field transect sites in the GOC – marked with asterisks – each had lost substantive portions (>50%) of their seaward fringing mangroves.

| #  | Site Code | Location                      | Latitude S   | Longitude E   |
|----|----------|-------------------------------|--------------|---------------|
| 1  | W1       | Carnarvon, WA                 | -24.969945   | 113.663849    |
| 2  | W2       | Mangrove Bay, near Exmouth, WA| -21.958355   | 113.947217    |
| 3  | W3       | Joseph Bonaparte Gulf, NT, near Wyndham, WA | -14.866115 | 128.927841    |
| 4  | GOC1     | Blue Mud Bay, Roper , NT – GOC| -13.684102   | 135.891294    |
| 5  | GOC2     | Groote Is., Roper, NT – GOC   | -13.831171   | 136.458774    |
| 6  | GOC3*    | Limmen Bight R. – Roper, NT – GOC | -15.146215 | 135.788778    |
| 7  | GOC4*    | Mule Ck. – Roper, NT – GOC    | -15.650919   | 136.441971    |
| 8  | GOC5     | Nicholson R., QLD – Southern – GOC | -17.484300 | 139.588160    |
| 9  | GOC6*    | Karumba, QLD – South East – GOC | -17.422561 | 140.853576    |
| 10 | GOC7*    | North Mitchell R., QLD, West Cape – GOC | -15.027324 | 141.665424    |
| 11 | GOC8     | Weipa, QLD, West Cape – GOC  | -12.691041   | 141.825381    |
| 12 | E1       | Cairns & Trinity Inlet, QLD  | -16.882779   | 145.762058    |
| 13 | E2       | Port Curtis & Gladstone, QLD | -23.839073   | 151.197393    |
| 14 | E3       | Moreton Bay & Brisbane, QLD  | -27.334663   | 153.240527    |
Table B. Mangrove monitoring sites with both nearby Bureau of Meteorology (BOM) and Permanent Service for Mean Sea Level (PSMSL) monitoring sites used in multivariate regression analyses. Locations of recording stations across northern Australia, specifically relate to multivariate regression analyses applied in this study (see Table A; Fig 2). Source: BOM (http://www.bom.gov.au/) and PSMSL (https://www.psmsl.org/). Sites in bold are those located in Australia’s Gulf of Carpentaria (GOC).

| Site | BOM monitoring site                        | PSMSL monitoring site                        |
|------|--------------------------------------------|----------------------------------------------|
| W1   | Carnarvon Airport: 006011                  | Carnarvon: 1115                              |
| W2   | Exmouth Town: 005051                       | Exmouth: 1762                                |
| W3   | Wyndham: 001013                            | Wyndham: 1116                                |
| GOC1 | Groote Eylandt Airport: 014518             | Milner Bay (Groote Eylandt): 1160            |
| GOC2 | Groote Eylandt Airport: 014518             | Milner Bay (Groote Eylandt): 1160            |
| GOC6 | Normanton Airport: 029063                  | Karumba: 835                                 |
| GOC8 | Weipa Aero: 027045                         | Weipa: 1157                                  |
| E1   | Cairns Aero: 031011                        | Cairns: 953                                  |
| E2   | Gladstone Airport: 039326                  | Gladstone: 825                               |
| E3   | Brisbane: 040913                           | Brisbane (West Inner Bar): 822               |
3. Post impact assessments of mangrove canopy recovery - Table C

Table C. Instances of pulse (abrupt) mangrove canopy decline in the 14 sites across northern Australia (Fig 2; Table A between 1987 and 2020 observed in green fraction (GF) timeseries plots (Fig 3). The comparison of percent canopy loss and years to recovery displayed in Fig 6).

| #  | Site Code | Pulse Canopy Decline # | Date of Canopy Decline | % Loss of Canopy GF | Recovery Time (Years) | Apparent Cause of Pulse Setback | Prior and Post Observed Storm Events |
|----|-----------|------------------------|------------------------|---------------------|----------------------|-------------------------------|-------------------------------------|
| 1  | W1        | 1                      | Nov-2002               | 8                   | 1                    | Drowning                      | Post TC Alistair (Cat. 1) Apr-2001 |
| 2  |           | 2                      | May-2000               | 15                  | 1.5                  | Drowning                      | Post TC Steve (Cat. 2) Mar-2000     |
| 3  |           | 3                      | Sep-1997               | 25                  | 1                    | Desiccation                   | Post TC Olwyn (Cat. 3) Mar-2015     |
| 4  |           | 4                      | Jul-2010               | 30                  | 4.5                  | Drowning                      | Post TC Olwyn (Cat. 4) Mar-2015     |
| 5  |           | 5                      | Aug-2015               | 48                  | 10                   | Desiccation                   |                                     |
| 6  |           | 6                      | Dec-2002               | 55                  | 9                    | Desiccation                   |                                     |
| 7  | W3        | 1                      | Apr-2011               | 8                   | 0.5                  | Drowning                      | Post AU291314_09U (Cat. 1) Feb-2014 |
| 2  |           | 2                      | Nov-2002               | 20                  | 1                    | Desiccation                   | Post TC Raymond (Cat. 1) Jan-2005   |
| 3  |           | 3                      | Aug-2015               | 25                  | 5                    | Desiccation                   |                                     |
| 4  | GOC1      | 1                      | Apr-2011               | 10                  | 1.5                  | Drowning                      | Post TC Alessia (Cat. 1) Nov-2013   |
| 2  |           | 2                      | Apr-2008               | 15                  | 1                    | Drowning                      | Post TC Paul (Cat. 2) Mar-2010      |
| 3  |           | 3                      | Apr-1995               | 21                  | 7                    | Drowning                      |                                     |
| 4  |           | 4                      | Aug-2015               | 25                  | 5                    | Desiccation                   |                                     |
| 5  | GOC2      | 1                      | May-1999               | 15                  | 2                    | Drowning                      | Post TC Winsome (Cat. 2) Feb-2001   |
| 2  |           | 2                      | Nov-2002               | 30                  | 3                    | Desiccation                   | Prior TC Winsome (Cat. 2) Feb-2001  |
| 3  |           | 3                      | Aug-2015               | 58                  | 8                    | Desiccation                   |                                     |
| 6  | GOC3      | 1                      | Apr-2009               | 10                  | 1                    | Drowning                      |                                     |
| 2  |           | 2                      | Aug-2015               | 50                  | 12                   | Desiccation                   | Post TC Owen (Cat. 3) Dec-2018      |
| 7  | GOC4      | 1                      | Apr-2009               | 10                  | 1                    | Drowning                      | Post TC Oswald (Cat. 1) Jan-2013    |
| 2  |           | 2                      | Sep-1994               | 39                  | 7                    | Storm Flooding                | Prior flood Feb-1994; Post TC Jacob (Cat. 1) Feb-1996 |
| 3  |           | 3                      | Aug-2015               | 45                  | 8                    | Desiccation                   | Post TC Trevor (Cat. 4) Mar-2019    |
| 8  | GOC5      | 1                      | Aug-2015               | 10                  | 2                    | Desiccation                   |                                     |
| 2  |           | 2                      | Apr-2009               | 12                  | 1                    | Drowning                      | Post TC Olga (Cat. 1) Jan-2010      |
| 3  |           | 3                      | Aug-2015               | 15                  | 6.5                  | Desiccation                   |                                     |
| 9  | GOC6      | 1                      | Apr-2009               | 10                  | 3                    | Drowning                      | Post TC Olga (Cat. 1) Jan-2010      |
|   |   |   |   |   |
|---|---|---|---|---|
| 2 | Sep-1995 | 25 | 2 | Desiccation | Post TC Steve (Cat. 1) Feb-2000 |
| 3 | Aug-2015 | 66 | 14.5 | Desiccation |
| 10 | GOC7 | 1 | Apr-2009 | 2 | 0.5 | Drowning | Post TC Jasmine (Cat. 1) Feb-2012 |
| 2 | Apr-2009 | 8 | 1 | Drowning | Post TC Jasmine (Cat. 1) Feb-2012 |
| 3 | Jun-2011 | 45 | 10.5 | Storm Flooding | Prior flood Mar-2011; Post TC Jasmine (Cat. 1) Feb-2012 |
| 4 | Aug-2015 | 55 | 10 | Desiccation |
| 11 | GOC8 | 1 | Mar-2008 | 40 | 3 | Drowning |
| 2 | Oct-2015 | 42 | 10 | Desiccation |
| 3 | Jul-1993 | 60 | 8 | Desiccation | Prior TC Nina (Cat. 3) Dec-1992; Post TC Ethel (Cat. 2) Mar-1996 |
| 12 | E1 | 1 | Oct-1990 | 8 | 0.5 | Desiccation |
| 2 | Sep-1991 | 12 | 0.5 | Desiccation |
| 3 | Oct-2015 | 13 | 0.5 | Desiccation |
| 13 | E2 | 1 | May-2011 | 4 | 0.5 | Drowning | Post TC Marcia (Cat. 2) Feb-2015 |
| 2 | Nov-1994 | 30 | 4 | Storm Hail | Concurrent hail storm Nov-1994 |
| 14 | E3 | 1 | Jun-1999 | 2 | 0.5 | Drowning |
| 2 | Nov-1992 | 11 | 1 | Desiccation |
4. Timeseries plots for the sea level stress index - Fig D

**Fig D.** Sea level stress index (SLSI) timeseries for the 10 sites across northern Australia display fluctuations in sea level between 1987 and 2021, notably followed annual and longer-term oscillations. Note that the extreme low threshold of -400 mm in SLSI was only lower in the Karumba (GOC6) site (see Fig 3, and Table 3), the site with the most catastrophic loss of shoreline mangroves of these sites (Image source: illustration by ADC).
5. **Comparisons between green fraction indices and sea level stress index (SLSI)** - Fig E

| Site | W1 | W2 | W3 | GOC1 | GOC2 | GOC3 | GCC8 | E1 | E2 | E3 |
|------|----|----|----|------|------|------|------|----|----|----|
|      | ![Anomaly](anomaly.png) | ![Percentage](percentage.png) | ![Anomaly](anomaly.png) | ![Percentage](percentage.png) | ![Anomaly](anomaly.png) | ![Percentage](percentage.png) | ![Anomaly](anomaly.png) | ![Percentage](percentage.png) | ![Anomaly](anomaly.png) | ![Percentage](percentage.png) |

**Fig E.** Green fractional indices (anomaly and percentage) versus the sea level stress index (SLSI) in the 10 sites across northern Australia between 1987 and 2021. Right-side plots (for each site) display the relationship between the SLSI and canopy condition with lowest levels during 2015-2016 (red arrow line). Further depicted is the impact on mangrove canopies in Carnarvon (W1) during 2010-2011 (blue arrow line). Left-side plots display the significant linear relationships (P<0.001) between the SLSI and green fractional anomaly data. Monthly averages follow a common, repeated cyclical pattern (bold line) with the same calendar months each year (circled 1-12) having high (months 3-4 = March-April; orange circles) and low (months 10-11 = October-November; yellow circles) canopy densities in tropical sites from Exmouth to Weipa (Image source: illustration by NCD).
6. Timeseries plots for climate data - Figs F & G

**Fig F.** Mean temperature anomaly timeseries for the 10 sites across northern Australia display fluctuations in the monthly rainfall between 1987 and 2021. These followed annual and longer-term oscillations (Image source: illustration by ADC).
Fig G. Rainfall anomaly timeseries for the 10 sites across northern Australia display fluctuations in the monthly rainfall between 1987 and 2021. These followed annual and longer-term oscillations (Image source: illustration by ADC).
7. Comparative assessment of sea level and southern oscillation data - Table D

Table D. Statistics for multivariate regressions with autocorrelated errors predicting the sea level anomaly from the SOI anomaly and time at ten coastal sites across northern Australia (Table A). Fit statistics include: the coefficients, its standard error (Coef SE), the t value, P value, Akaike Information Criterion (AIC), Bayesian Information Criterion (BIC), Log-likelihood (loglik), residual standard error (RSE), degrees of freedom (DF) and residuals.

| Site | Component  | Coefficient | Coef SE | t value | P value | AIC   | BIC   | loglik | RSE | DF | Residuals |
|------|------------|-------------|---------|---------|---------|-------|-------|--------|-----|----|-----------|
| W1   | Intercept  | -8.09       | 313.69  | -0.03   | 0.979   | 1779.67 | 1795.64 | -884.84 | 102.54 | 180 | 177       |
|      | SOI anomaly| 1.84        | 1.16    | 1.58    | 0.116   |        |       |        |      |    |           |
|      | Time       | 0.00        | 0.02    | 0.10    | 0.921   |        |       |        |      |    |           |
| W2   | Intercept  | -84.00      | 204.17  | -0.41   | 0.681   | 1758.72 | 1774.69 | -874.36 | 77.11  | 180 | 177       |
|      | SOI anomaly| 2.81        | 1.08    | 2.60    | <0.001  |        |       |        |      |    |           |
|      | Time       | 0.01        | 0.01    | 0.40    | 0.693   |        |       |        |      |    |           |
| W3   | Intercept  | 49.51       | 182.12  | 0.27    | 0.786   | 1842.03 | 1858.00 | -916.02 | 80.32  | 180 | 177       |
|      | SOI anomaly| 8.15        | 1.32    | 6.20    | <0.001  |        |       |        |      |    |           |
|      | Time       | 0.00        | 0.01    | -0.23   | 0.820   |        |       |        |      |    |           |
| GOC1 | Intercept  | 65.58       | 276.88  | 0.24    | 0.813   | 1987.33 | 2003.24 | -988.66 | 124.36 | 178 | 175       |
|      | SOI anomaly| 11.81       | 2.08    | 5.68    | 0.000   |        |       |        |      |    |           |
|      | Time       | 0.00        | 0.02    | -0.22   | 0.830   |        |       |        |      |    |           |
| GOC2 | Intercept  | 65.58       | 276.88  | 0.24    | 0.813   | 1987.33 | 2003.24 | -988.66 | 124.36 | 178 | 175       |
|      | SOI anomaly| 11.81       | 2.08    | 5.68    | <0.001  |        |       |        |      |    |           |
|      | Time       | 0.00        | 0.02    | -0.22   | 0.830   |        |       |        |      |    |           |
| GOC6 | Intercept  | 92.94       | 419.83  | 0.22    | 0.825   | 2119.36 | 2135.24 | -1054.68 | 187.41 | 177 | 174       |
|      | SOI anomaly| 17.39       | 3.13    | 5.56    | <0.001  |        |       |        |      |    |           |
|      | Time       | -0.01       | 0.03    | -0.24   | 0.813   |        |       |        |      |    |           |
| GOC8 | Intercept  | 33.21       | 323.50  | 0.10    | 0.918   | 2065.40 | 2081.37 | -1027.70 | 145.82 | 180 | 177       |
|      | SOI anomaly| 13.63       | 2.43    | 5.61    | <0.001  |        |       |        |      |    |           |
|      | Time       | 0.00        | 0.02    | -0.09   | 0.929   |        |       |        |      |    |           |
| E1   | Intercept  | -33.66      | 286.22  | -0.12   | 0.907   | 2023.97 | 2039.94 | -1006.99 | 129.47 | 180 | 177       |
|      | SOI anomaly| 12.34       | 2.16    | 5.71    | <0.001  |        |       |        |      |    |           |
|      | Time       | 0.00        | 0.02    | 0.10    | 0.918   |        |       |        |      |    |           |
| E2   | Intercept  | -101.95     | 113.10  | -0.90   | 0.369   | 1567.37 | 1583.14 | -778.69  | 45.86  | 173 | 170       |
|      | SOI anomaly| 1.97        | 0.75    | 2.63    | 0.009   |        |       |        |      |    |           |
|      | Time       | 0.01        | 0.01    | 0.97    | 0.335   |        |       |        |      |    |           |
| E3   | Intercept  | -7.19       | 69.40   | -0.10   | 0.918   | 1496.57 | 1512.50 | -743.28  | 30.95  | 179 | 176       |
|      | SOI anomaly| 0.82        | 0.51    | 1.59    | 0.113   |        |       |        |      |    |           |
|      | Time       | 0.00        | 0.01    | 0.28    | 0.780   |        |       |        |      |    |           |
**8. Comparative assessment of green fraction with climate and sea level - Table E**

**Table E.** Statistics for multivariate regressions with autocorrelated errors predicting the fractional canopy cover anomaly from the sea level anomaly, rainfall anomaly, temperature anomaly and time at ten coastal sites across northern Australia (see Table A). Fit statistics include: the coefficients, its standard error (Coef SE), the t value, P value, Akaike Information Criterion (AIC), Bayesian Information Criterion (BIC), Log-likelihood (loglik), residual standard error (RSE), degrees of freedom (DF) and residuals.

| Site | Component          | Coefficients | t value | P value | AIC     | BIC     | loglik   | RSE     | DF | Residuals |
|------|--------------------|--------------|---------|---------|---------|---------|----------|---------|----|-----------|
| W1   | Intercept          | 5.83         | 0.15    | 0.880   | 433.86  | 453.43  | -209.93  | 7.04    | 121| 116       |
|      | Sea level anomaly  | 0.03         | 0.01    | 5.08    | 0.000   |         |          |         |    |           |
|      | Rainfall anomaly   | -0.04        | 0.02    | -2.03   | 0.045   |         |          |         |    |           |
|      | Temperature anomaly| -0.84        | 0.14    | -5.94   | 0.000   |         |          |         |    |           |
|      | Time               | 0.00         | 0.00    | -0.23   | 0.819   |         |          |         |    |           |
| W2   | Intercept          | -99.09       | -1.92   | 0.058   | 439.48  | 459.05  | -212.74  | 11.62   | 121| 116       |
|      | Sea level anomaly  | 0.02         | 0.00    | 3.65    | 0.000   |         |          |         |    |           |
|      | Rainfall anomaly   | 0.01         | 0.01    | 0.60    | 0.547   |         |          |         |    |           |
|      | Temperature anomaly| 0.03         | 0.08    | 0.36    | 0.723   |         |          |         |    |           |
|      | Time               | 0.01         | 0.00    | 1.88    | 0.063   |         |          |         |    |           |
| W3   | Intercept          | -4.84        | -0.18   | 0.855   | 466.25  | 485.82  | -226.12  | 4.94    | 121| 116       |
|      | Sea level anomaly  | 0.04         | 0.01    | 7.22    | 0.000   |         |          |         |    |           |
|      | Rainfall anomaly   | -0.01        | 0.01    | -1.09   | 0.278   |         |          |         |    |           |
|      | Temperature anomaly| -1.49        | 0.19    | -7.79   | 0.000   |         |          |         |    |           |
|      | Time               | 0.00         | 0.00    | 0.11    | 0.909   |         |          |         |    |           |
| GOC1 | Intercept          | 10.04        | 0.26    | 0.798   | 617.43  | 636.88  | -301.71  | 7.94    | 119| 114       |
|      | Sea level anomaly  | 0.05         | 0.01    | 5.62    | <0.001  |         |          |         |    |           |
|      | Rainfall anomaly   | -0.01        | 0.02    | -0.38   | 0.706   |         |          |         |    |           |
|      | Temperature anomaly| -3.88        | 0.60    | -6.42   | <0.001  |         |          |         |    |           |
|      | Time               | 0.00         | 0.00    | -0.25   | 0.803   |         |          |         |    |           |
| GOC2 | Intercept          | 33.02        | 0.96    | 0.340   | 561.68  | 581.13  | -273.84  | 6.76    | 119| 114       |
|      | Sea level anomaly  | 0.03         | 0.01    | 4.41    | <0.001  |         |          |         |    |           |
|      | Rainfall anomaly   | 0.01         | 0.01    | 0.62    | 0.536   |         |          |         |    |           |
|      | Temperature anomaly| -3.99        | 0.46    | -8.74   | <0.001  |         |          |         |    |           |
|      | Time               | 0.00         | 0.00    | -0.89   | 0.377   |         |          |         |    |           |
| GOC6 | Intercept          | 5.16         | 0.18    | 0.860   | 501.26  | 520.83  | -243.63  | 5.53    | 121| 116       |
|      | Sea level anomaly  | 0.02         | 0.00    | 4.09    | <0.001  |         |          |         |    |           |
|      | Rainfall anomaly   | -0.02        | 0.01    | -1.84   | 0.068   |         |          |         |    |           |
|      | Temperature anomaly| -3.18        | 0.30    | -10.78  | <0.001  |         |          |         |    |           |
|      | Time               | 0.00         | 0.00    | -0.22   | 0.826   |         |          |         |    |           |
| GOC8 | Intercept          | 12.08        | 0.19    | 0.850   | 596.39  | 615.96  | -291.19  | 11.39   | 121| 116       |
|                   | E1        | E2        | E3        |
|-------------------|-----------|-----------|-----------|
| Intercept         | -2.35     | 13.84     | -18.07    |
| Sea level anomaly | 0.03      | 0.05      | 0.04      |
| Rainfall anomaly  | 0.00      | -0.01     | -0.03     |
| Temperature       | -4.13     | -0.38     | -0.03     |
| anomaly           | 0.41      | 0.11      | 0.21      |
| Time              | 0.00      | 0.00      | 0.00      |

9. **Green fraction data used to quantify mangrove condition**

Relevant data used in this article are listed for 14 sites across northern Australia (see Table A) for the period 1987 to 2021. For a description of the variables used, see the Methods. The variables include: ‘FCC_anomaly’; ‘SL_anomaly’; ‘SOI_anomaly’; ‘Rainfall_anomaly’ and ‘Temp_anomaly’. Refer to the spreadsheet titled ‘S1 Data’.