**Supplementary materials**

Application of earth observation data and Google Earth Engine for monitoring coral reef exposure to environmental stressors

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**This supplementary material contains:**

Table S1: Accuracy and uncertainty of environmental variables from GG products used for the CRSEI. Global; error estimates for each product were not always available. In lieu of these regional error estimates from the literature are given. Note that no units for mean absolute error values and annual mean correlations are given as these are multiplicative metrics opposed to linear metrics of accuracy [1].

Table S2: Region, sites and reef names used for calculating Coral Reef Stress Exposure Score (CRSEI). Latitude and longitude in decimal degrees is included.

Table S3: Variables used for the assessment of coral reef stress. Positive and negative thresholds obtained from the literature, are provided with variable units and threshold references. Whether a threshold is Chagos specific or a global threshold is indicated. Health stressors and stress reinforcers were given values of 0 and 1 for positive (+) and negative (-) thresholds respectively. Stress reducers were given 1 for + thresholds and 0 for – thresholds.

Table S4: Summary statistics for CRSEI scores per region by non-El Niño period (April 2012) and strong El Niño period (April 2016).

Figure S1: Scree plot of PCA of CRSEI stress variables.

Figure S2: Comparison of CRSEI scores using global and local thresholds for the Chagos Archipelago. Mean Quarterly CRSEI scores from all sites (January, April, July and October) from the Chagos Archipelago, from 01/01/2003 – 31/12/2016 are presented. Solid lines indicate CRSEI scores using global thresholds, and dashed line indicating CSEI scores using regional thresholds. El Niño are highlighted by strength; yellow = weak; moderate = orange; and strong = red. Asterisks note El Niño years where bleaching events occurred during this period.

Table S1: Accuracy and uncertainty of environmental variables from GEE products used for the CRSEI. Global error estimates for each product were not always available. In lieu of these, regional error estimates from the literature are given. Note that no units for mean absolute error values and annual mean correlations are given as these are multiplicative metrics opposed to linear metrics of accuracy [1].

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Variable** | **Data source** | **Scale** | **Accuracy** | **Unit** | **Reference** |
| cloud cover | NOAA CDR PATMOSX | Regional -Tibetan plateau | 0.93 | annual mean correlations | [2] |
| current | HYCOM: Water Velocity | Regional - Agulhas | 0.35 m s-1 | Root mean square deviation (RMSE) | [3] |
| depth | Automated Global Shallow Water Bathymetry | Global | 1.26 - 1.92 m | Root mean square deviation (RMSE) | [4] |
| salinity | HYCOM: Water Temperature and Salinity | Regional – western Pacific | 0.05 – 0.3 ppt | Root mean square deviation (RMSE) | [5] |
| SST | MODIS: Aqua | Global | 0.350 °C at Eq-20N | Robust standard deviation | https://oceancolor.gsfc.nasa.gov/atbd/sst4/#sec\_4 |
| wind | NOAA CDR | Global | 0.39 m s-1 | Mean wind speed uncertainty | https://www1.ncdc.noaa.gov/pub/data/sds/cdr/CDRs/Ocean%20Near-surface%20Atmospheric%20Properties/AlgorithmDescription\_01B-27b.pdf |

Table S2: Region, sites and reef names used for calculating Coral Reef Stress Exposure Score (CRSEI). Latitude and longitude in decimal degrees is included. Those sites removed from the final CRSEI dataset for the PCA analysis are highlighted in yellow. Bikenibeu, highlighted in red, was permanently removed from the analysis as it had no data for multiple variables (current, depth and salinity)

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **The British Indian Ocean territory** | | | | |  |
| **Site** | **Reef** | **ID** | **Latitude** | **Longitude** | **Data missing** |
| Egmont | Egmont Mid | EG01 | -6.6434 | 71.3581 | NA |
|  | Egmont South-east | EG02 | -6.6782 | 71.3967 | NA |
| Grand Chagos Bank | Brothers Middle | GCB01 | -6.1637 | 71.5230 | NA |
|  | Brothers South | GCB02 | -6.1733 | 71.5372 | NA |
| Peros Banhos | Ile Diamant | PB01 | -5.2479 | 71.7620 | NA |
|  | Ile Diamant Lagoon | PB02 | -5.2552 | 71.7682 | NA |
|  | Ile Fouquet | PB03 | -5.4609 | 71.8185 | NA |
|  | Moresby | PB04 | -5.2400 | 71.8358 | NA |
|  | Ile Petit Coquillage | PB05 | -5.3394 | 71.9791 | NA |
|  | Ile Poule | PB06 | -5.4110 | 71.7459 | depth |
| Saloman | Ile Fouquet | SA01 | -5.3451 | 72.2727 | NA |
|  | Ile Jacoby | SA02 | -5.3539 | 72.2478 | NA |
|  | | | | |  |
| **The Gilbert Islands of the Republic of Kiribati** | | | | |  |
| **Site** | **Reef** | **ID** | **Latitude** | **Longitude** | **Data missing** |
| Abaiang | Confusion | ABG001 | 1.8577 | 172.8796 | NA |
|  | Western reef | ABG002 | 1.8820 | 172.8180 | depth |
|  | Tebontike | ABG003 | 1.7143 | 172.9865 | NA |
| Butaritari | SW Tip | BUT002 | 3.0429 | 172.7580 | NA |
|  | SW Outer Reef | BUT003 | 3.0731 | 172.7468 | depth |
|  | NW Tip | BUT004 | 3.2708 | 172.6801 | NA |
|  | NW Outer Reef | BUT005 | 3.2107 | 172.7013 | NA |
| South Tarawa | Teaoraereke | TRW002 | 1.3332 | 173.0217 | NA |
|  | Bikenibeu | TRW008 | 1.3579 | 173.1458 | current, depth salinity |
|  | Causeway | TRW010 | 1.3302 | 172.9634 | NA |
|  | Eita | TRW011 | 1.3570 | 173.0790 | NA |
|  | | | | |  |
| **The central Saudi Arabian Red Sea** | | | | |  |
| Inshore Reef | Tahla | IS1 | 22.2750 | 39.0497 | NA |
|  | Fsar | IS2 | 22.2358 | 39.0303 | current |
|  | Abu Shosha | IS3 | 22.3036 | 39.0408 | NA |
|  | Shaab | IS4 | 22.2012 | 38.9992 | NA |
| Midshelf Reef | Al Fahal | MS1 | 22.2518 | 38.9564 | NA |
|  | Qita Al-Kirsh | MS2 | 22.4257 | 38.9960 | NA |
|  | Umm Al Kiethl | MS3 | 22.1686 | 38.9408 | NA |
|  | Umm Albalam | MS4 | 22.1961 | 38.9489 | NA |
| Offshore Reef | Shi’b Nazar | OS1 | 22.3409 | 38.8521 | NA |
|  | Abu Madafi | OS2 | 22.0766 | 38.7751 | NA |
|  | Al-Mashpah | OS3 | 22.1117 | 38.8425 | NA |

Table S3: Variables used for the assessment of coral reef stress. Positive and negative thresholds obtained from the literature, are provided with variable units and threshold references. Whether a threshold is Chagos specific or a global threshold is indicated. Health stressors and stress reinforcers were given values of 0 and 1 for positive (+) and negative (-) thresholds respectively. Stress reducers were given 1 for + thresholds and 0 for – thresholds.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Stress variable** | **Unit** | **Global or Chagos specific** | **Lower threshold** | **Upper threshold** | **Reference** |
| cloud cover | oktas | Global | 3.0 | 7.0 | [6] |
| current | m/s1 | Global | 0.13 | 0.15 | [7] |
| depth | m1 | Chagos | < 5 or ≥ 30 | ≥ 5 - < 15 | [8] |
| salinity | ppt | Global | 32.0 – 38.0 | < 26.0 or > 45.0 | [9] |
| SST | °C | Chagos | 24.0 | 29.5 | [8] |
| SST anomaly | °C | Chagos | 0.4 | 0.8 | [10] |
| SST DHW | weeks | Chagos | 4.0 | 6.0 | [11] |
| SST variability | °C | Global | 4.0 | 10.0 | [7] |
| wind | m/s1 | Global | 8.0 – 28.0 | < 5.0 or > 33.0 | [7,12] |

Table S4: Summary statistics for CRSEI scores per region by non-El Niño period (April 2012) and strong El Niño period (April 2016)

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Region** | **Year** | **Month** | **Mean CRSEI** | **Min CRSEI** | **Max CRSEI** | **sd** |
| Brazilian province | 2012 | Apr | 0.17 | 0.00 | 0.22 | 0.06 |
| Brazilian province | 2016 | Apr | 0.14 | 0.00 | 0.21 | 0.06 |
| Caribbean | 2012 | Apr | 0.14 | 0.00 | 0.35 | 0.07 |
| Caribbean | 2016 | Apr | 0.17 | 0.00 | 0.38 | 0.08 |
| Central Indian Ocean | 2012 | Apr | 0.15 | 0.02 | 0.24 | 0.04 |
| Central Indian Ocean | 2016 | Apr | 0.23 | 0.06 | 0.44 | 0.08 |
| Central Pacific | 2012 | Apr | 0.02 | 0.00 | 0.08 | 0.03 |
| Central Pacific | 2016 | Apr | 0.10 | 0.00 | 0.33 | 0.09 |
| Eastern Pacific | 2012 | Apr | 0.19 | 0.00 | 0.49 | 0.11 |
| Eastern Pacific | 2016 | Apr | 0.18 | 0.00 | 0.49 | 0.09 |
| Great Barrier Reef | 2012 | Apr | 0.14 | 0.00 | 0.35 | 0.06 |
| Great Barrier Reef | 2016 | Apr | 0.19 | 0.00 | 0.50 | 0.09 |
| Micronesia | 2012 | Apr | 0.19 | 0.00 | 0.35 | 0.09 |
| Micronesia | 2016 | Apr | 0.22 | 0.00 | 0.38 | 0.10 |
| Middle East | 2012 | Apr | 0.11 | 0.00 | 0.28 | 0.08 |
| Middle East | 2016 | Apr | 0.15 | 0.00 | 0.44 | 0.10 |
| Polynesia | 2012 | Apr | 0.13 | 0.00 | 0.31 | 0.08 |
| Polynesia | 2016 | Apr | 0.12 | 0.00 | 0.35 | 0.09 |
| South East Asia | 2012 | Apr | 0.16 | 0.00 | 0.32 | 0.08 |
| South East Asia | 2016 | Apr | 0.20 | 0.00 | 0.34 | 0.07 |
| Western Australia | 2012 | Apr | 0.22 | 0.09 | 0.33 | 0.08 |
| Western Australia | 2016 | Apr | 0.30 | 0.13 | 0.53 | 0.08 |
| Western Indian Ocean | 2012 | Apr | 0.12 | 0.00 | 0.30 | 0.07 |
| Western Indian Ocean | 2016 | Apr | 0.18 | 0.00 | 0.48 | 0.11 |

Fig. S1: Scree plot of PCA of CRSEI stress variables.

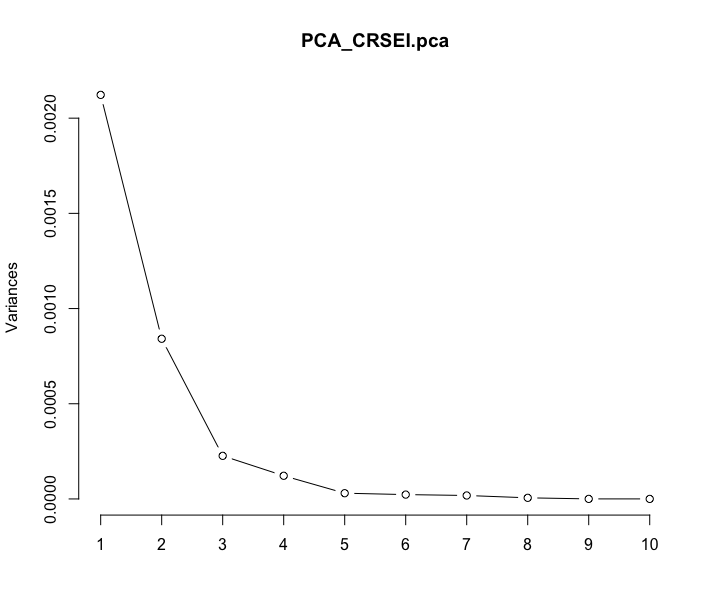




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References

1. Seegers, B.N.; Stumpf, R.P.; Schaeffer, B.A.; Loftin, K.A.; Werdell, P.J. Performance metrics for the assessment of satellite data products: an ocean color case study. *Opt. Express* **2018**, *26*, 7404-7422, doi:10.1364/OE.26.007404.

2. Liu, J. *Comparing three satellite retrieval cloud fraction data over Tibet Plateau*; SPIE: 2019; Volume 11152.

3. Savage, J.A.; Tokmakian, R.T.; Batteen, M.L. Assessment of the HYCOM velocity fields during Agulhas Return Current Cruise 2012. *J. Oper. Oceanogr.* **2015**, *8*, 11-24, doi:10.1080/1755876X.2015.1014637.

4. Li, J.; Knapp, D.E.; Lyons, M.; Roelfsema, C.; Phinn, S.; Schill, S.R.; Asner, G.P. Automated global shallow water bathymetry mapping using Google Earth Engine. *Remote Sens.* **2021**, *13*, 1469, doi:10.3390/rs13081469.

5. Wan, L.; Zhu, J.; Bertino, L.; Wang, H. Initial ensemble generation and validation for ocean data assimilation using HYCOM in the Pacific. *Ocean Dynamics* **2008**, *58*, 81, doi:10.1007/s10236-008-0133-x.

6. Mumby, P.; Chisholm, J.; Edwards, A.; Clark, C.; Roark, E.; Andrefouet, S.; Jaubert, J. Unprecedented bleaching-induced mortality in *Porites* spp. at Rangiroa Atoll, French Polynesia. *Mar. Biol.* **2001**, *139*, 183-189, doi:10.1007/s002270100575.

7. Maina, J.; Venus, V.; McClanahan, T.R.; Ateweberhan, M. Modelling susceptibility of coral reefs to environmental stress using remote sensing data and GIS models. *Ecol. Modell.* **2008**, *212*, 180-199, doi:10.1016/j.ecolmodel.2007.10.033.

8. Sheppard, C.; Sheppard, A.; Mogg, A.; Bayley, D.; Dempsey, A.; Roche, R.; Turner, J.; Purkis, S. Coral bleaching and mortality in the Chagos Archipelago to 2017. *Atoll Res. Bull.* **2017**, *613*, 1-25, doi:10.5479/si.0077-5630.613.

9. Li, X.; Huang, H.; Lian, J.; Huang, L.; Dong, J. Effects of the multiple stressors high temperature and reduced salinity on the photosynthesis of the hermatypic coral *Galaxea fascicularis*. *Acta Ecol. Sin.* **2009**, *29*, 155-159, doi:10.1016/j.chnaes.2009.07.002.

10. Sheppard, C.R.C.; Harris, A.; Sheppard, A.L.S. Archipelago-wide coral recovery patterns since 1998 in the Chagos Archipelago, central Indian Ocean. *Mar. Ecol. Prog. Ser.* **2008**, *362*, 109-117, doi:10.3354/meps07436.

11. Head, C.E.I.; Bayley, D.T.I.; Rowlands, G.; Roche, R.C.; Tickler, D.M.; Rogers, A.D.; Koldewey, H.; Turner, J.R.; Andradi-Brown, D.A. Coral bleaching impacts from back-to-back 2015–2016 thermal anomalies in the remote central Indian Ocean. *Coral Reefs* **2019**, doi:10.1007/s00338-019-01821-9.

12. Fabricius, K.E.; De'ath, G.; Puotinen, M.L.; Done, T.; Cooper, T.F.; Burgess, S.C. Disturbance gradients on inshore and offshore coral reefs caused by a severe tropical cyclone. *Limnol. Oceanogr.* **2008**, *53*, 690-704, doi:10.4319/lo.2008.53.2.0690.