

# <sup>1</sup> eo-tides: Tide modelling tools for large-scale satellite Earth observation analysis

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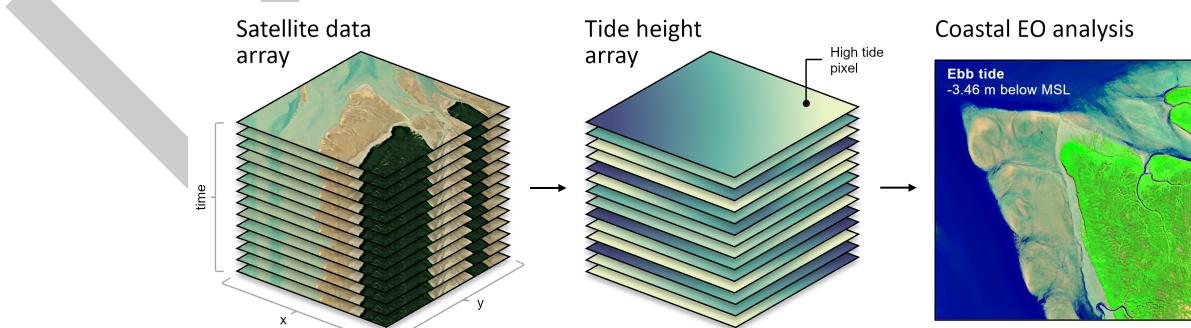
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## <sup>7</sup> Summary

<sup>8</sup> The eo-tides package provides powerful parallelized tools for integrating satellite Earth  
<sup>9</sup> observation (EO) data with ocean tide modelling. The package provides a flexible Python-  
<sup>10</sup> based toolkit for modelling and attributing tide heights to a time-series of satellite images  
<sup>11</sup> based on the spatial extent and acquisition time of each satellite observation (Figure 1).

<sup>12</sup> eo-tides leverages advanced tide modelling functionality from the pyTMD tide prediction  
<sup>13</sup> software (Sutterley et al., 2017), combining this fundamental tide modelling capability with  
<sup>14</sup> EO spatial analysis tools from odc-geo ([odc-geo contributors](#), 2024). This allows tides to  
<sup>15</sup> be modelled in parallel automatically using over 50 supported tide models, and returned in  
<sup>16</sup> standardised pandas (McKinney, 2010; [pandas development team](#), 2020) and xarray (Hoyer  
<sup>17</sup> & Joseph, 2017) data formats for further analysis.

<sup>18</sup> Tools from eo-tides are designed to be applied directly to petabytes of freely available  
<sup>19</sup> satellite data loaded from the cloud using Open Data Cube's odc-stac or datacube packages  
<sup>20</sup> (e.g. using [Digital Earth Australia](#) or [Microsoft Planetary Computer's SpatioTemporal Asset](#)  
<sup>21</sup> Catalogues). Additional functionality enables evaluating potential satellite-tide biases, and  
<sup>22</sup> validating modelled tides using external tide gauge data — both important considerations for  
<sup>23</sup> assessing the reliability and accuracy of coastal EO workflows. In combination, these open  
<sup>24</sup> source tools support the efficient, scalable and robust analysis of coastal EO data for any time  
<sup>25</sup> period or location globally.



**Figure 1:** An example of a typical eo-tides coastal EO workflow, with tide heights being modelled into every pixel in a spatio-temporal stack of satellite data (for example, from ESA's Sentinel-2 or NASA/USGS Landsat), then combined to derive insights into dynamic coastal environments.

## 26 Statement of need

27 Satellite remote sensing offers an unparalleled method to view and examine dynamic coastal  
28 environments over large temporal and spatial scales (Turner et al., 2021; Vitousek et al.,  
29 2023). However, the variable and sometimes extreme influence of ocean tides in these regions  
30 can complicate analyses, making it difficult to separate the influence of changing tides from  
31 patterns of true coastal change over time (Vos et al., 2019). This is a particularly significant  
32 challenge for continental- to global-scale coastal EO analyses, where failing to account for  
33 complex tide dynamics can lead to inaccurate or misleading insights into coastal processes  
34 observed by satellites.

35 Conversely, information about ocean tides can also provide unique environmental insights that  
36 can greatly enhance the utility of coastal EO data. Conventionally, satellite data dimensions  
37 consider the geographical “where” and the temporal “when” of data acquisition. The addition  
38 of tide height as a new analysis dimension allows data to be filtered, sorted and analysed with  
39 respect to tidal processes, delivering a powerful re-imagining of traditional multi-temporal EO  
40 data analysis (Sagar et al., 2017). For example, satellite data can be analysed to focus on  
41 specific ecologically-significant tidal stages (e.g. high, low tide, spring or neap tides) or on  
42 particular tidal processes (e.g. ebb or flow tides; Sent et al. (2025)).

43 This concept has been used to map tidally-corrected annual coastlines from Landsat satellite  
44 data at continental scale (Bishop-Taylor et al., 2021), generate maps of the extent and elevation  
45 of the intertidal zone (Bishop-Taylor et al., 2019; Murray et al., 2012; Sagar et al., 2017), and  
46 create tidally-constrained imagery composites of the coastline at low and high tide (Sagar et  
47 al., 2018). However, these approaches have been historically based on bespoke, closed-source  
48 or difficult to install tide modelling tools, limiting the reproducibility and portability of these  
49 techniques to new coastal EO applications. To support the next generation of coastal EO  
50 workflows, there is a pressing need for new open-source approaches for combining satellite data  
51 with tide modelling.

52 The `eo-tides` package aims to address these challenges by providing a set of performant  
53 open-source Python tools for attributing satellite EO data with modelled ocean tides. This  
54 functionality is provided in five main analysis modules (`utils`, `model`, `eo`, `stats`, `validation`)  
55 which are described briefly below.

## 56 Key functionality

### 57 Setting up tide models

58 The `eo_tides.utils` module simplifies the setup of global ocean tide models, addressing a  
59 common barrier in coastal EO workflows. Tools like `list_models` provide feedback on available  
60 and supported models (Figure 2), while `clip_models` can be used to improve performance by  
61 clipping large model files to smaller regions of interest, significantly reducing processing times  
62 for high-resolution models like FES2022.

63 Comprehensive documentation is available to [guide users in setting up commonly used tide](#)  
64 [models](#), including downloading, uncompressing, and organizing data files.

	Model	Expected path
✓	EOT20	tide_models/EOT20/ocean_tides
✗	FES2014	tide_models/fes2014/ocean_tide
✓	HAMTIDE11	tide_models/hamtide
✗	TPXO9.1	tide_models/TPXO9.1/DATA
...	...	...

Summary:  
Available models: 2/50

**Figure 2:** An example output from `list_tides`, providing a useful summary table which clearly identifies available and supported tide models.

## 65 Modelling tides

66 The `eo_tides.model` module is powered by advanced tide modelling functionality from the  
 67 pyTMD Python package ([Sutterley et al., 2017](#)).

68 pyTMD is an open-source tidal prediction software that aims to simplify the calculation of ocean  
 69 and earth tides. Tides are frequently decomposed into harmonic constants (or constituents)  
 70 associated with the relative positions of the sun, moon and Earth. For ocean tides, pyTMD.io  
 71 contains routines for reading major constituent values from commonly available tide models,  
 72 and interpolating those values to spatial locations. Information for each of the supported tide  
 73 models is stored within a JSON database that is supplied with pyTMD. pyTMD.astro contains  
 74 routines for computing the positions of celestial bodies for a given time. Namely for ocean  
 75 tides, pyTMD computes the longitudes of the sun (S), moon (H), lunar perigee (P), ascending  
 76 lunar node (N) and solar perigee (PP). pyTMD.arguments contains routines for combining the  
 77 astronomical coefficients with the “Doodson number” of each constituent, along with routines  
 78 for adjusting the amplitude and phase of each constituent based on their modulations over the  
 79 18.6 year nodal period. Finally, pyTMD.predict uses results from those underlying functions to  
 80 predict tidal values at a given location and time.

81 The `model_tides` function from `eo_tides.model` wraps pyTMD functionality to return tide  
 82 predictions in a standardised pandas.DataFrame format, enabling integration with satellite  
 83 EO data and parallelized processing for improved performance. Parallelisation in eo-tides  
 84 is automatically optimised based on available workers and requested tide models and tide  
 85 modelling locations. This parallelisation can significantly improve tide modelling performance,  
 86 especially for large-scale analyses run on a multi-core machine ([Table 1](#)). Additional functions  
 87 like `model_phases` classify tides or determine flow/ebb tides, critical for interpreting satellite-  
 88 observed coastal processes like changing turbidity and ocean colour ([Sent et al., 2025](#)).

**Table 1:** A [benchmark comparison](#) of tide modelling performance with parallelisation on vs. off, for a typical large-scale analysis involving a month of hourly tides modelled at 10,000 modelling locations using three tide models (FES2022, TPXO10, GOT5.6).

Cores	Parallelisation	No parallelisation	Speedup
8	2min 46s ± 663 ms	9min 28s ± 536 ms	3.4x
32	55.9 s ± 560 ms	9min 24s ± 749 ms	10.1x

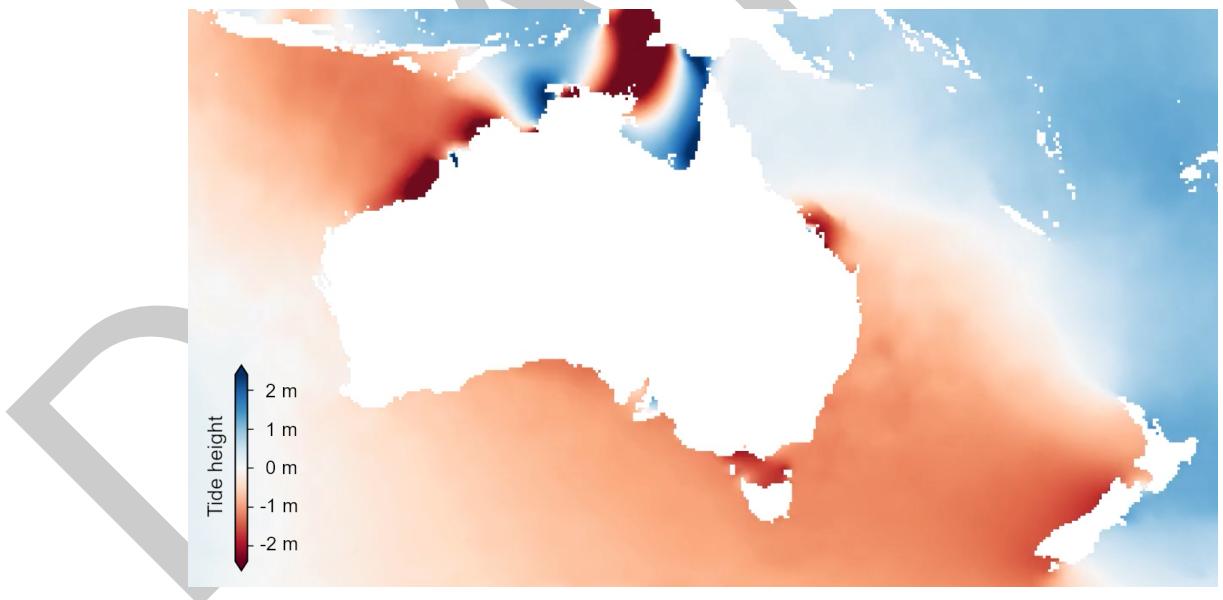
### <sup>89</sup> Combining tides with satellite data

<sup>90</sup> The `eo_tides.eo` module integrates modelled tides with xarray-format satellite data. For  
<sup>91</sup> tide attribution, eo-tides offers two approaches that differ in complexity and performance:  
<sup>92</sup> `tag_tides` assigns a single tide height per timestep for small-scale studies, while `pixel_tides`  
<sup>93</sup> models tides spatially and temporally for larger-scale analyses, producing a unique tide height  
<sup>94</sup> for each pixel in a dataset {tab:tide\_stats}.

<sup>95</sup> These functions can be applied to free and open satellite data for any coastal or ocean location  
<sup>96</sup> on the planet, for example using data loaded from the cloud using the [Open Data Cube](#) and  
<sup>97</sup> SpatioTemporal Asset Catalogue ([STAC contributors, 2024](#)).

**Table 2:** Comparison of the `tag_tides` and `pixel_tides` functions.

<code>tag_tides</code>	<code>pixel_tides</code>
<ul style="list-style-type: none"> <li>- Assigns a single tide height to each timestep/satellite image</li> <li>- Ideal for local or site-scale analysis</li> <li>- Fast, low memory use</li> <li>- Single tide height per image can produce artefacts in complex tidal regions</li> </ul>	<ul style="list-style-type: none"> <li>- Assigns a tide height to every individual pixel through time to capture spatial tide dynamics</li> <li>- Ideal for regional to global-scale coastal product generation</li> <li>- Slower, higher memory use</li> <li>- Produce spatially seamless results across large extents by applying analyses at the pixel level</li> </ul>

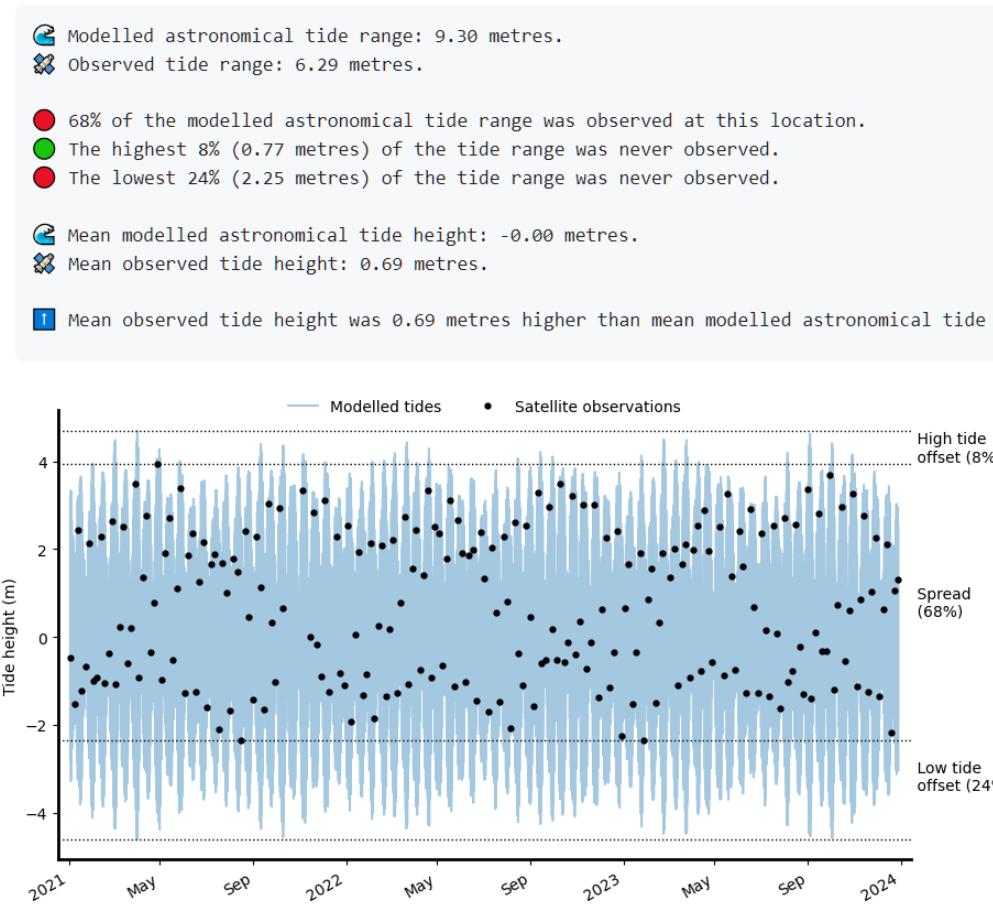


**Figure 3:** An example tide height output produced by the `pixel_tides` function, showing spatial variability in tides across Australasia for a single timestep.

### <sup>98</sup> Calculating tide statistics and satellite biases

<sup>99</sup> The `eo_tides.stats` module identifies biases caused by complex tide aliasing interactions  
<sup>100</sup> interactions between tidal dynamics and satellite observations. These interactions can prevent  
<sup>101</sup> satellites from observing the entire tide cycle ([Elefeld et al., 2014](#); [Sent et al., 2025](#)), and  
<sup>102</sup> cause coastal EO studies to produce biased or misleading results ([Bishop-Taylor et al., 2019](#)).  
<sup>103</sup> The module produces a range of useful statistics that summarise how well a satellite time series  
<sup>104</sup> captures real-world tidal conditions, include spread (coverage of tide range) and high/low-tide

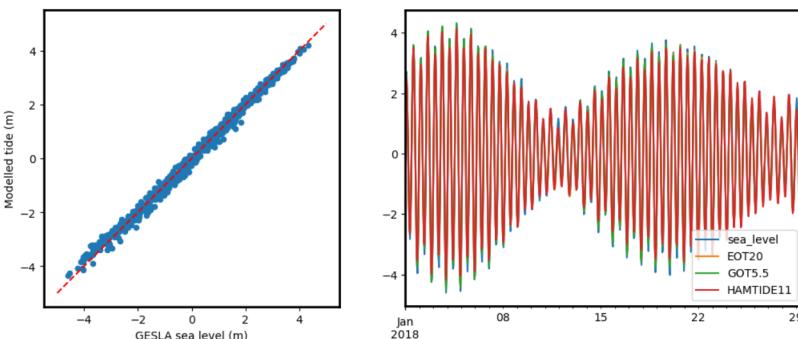
105 offsets (missed tidal extremes). Automated reports and plots provide insights further insights  
 106 into potential biases affecting the analysis.



**Figure 4:** An example of tidally-biased satellite coverage, where the sensor only observes ~68% of the modelled astronomical tide range and never observes the lowest 24% of tides. Satellite bias plots show satellite observed tides as black dots, overlaid over the full range of modelled tides (blue lines).

### 107 **Validating modelled tides**

108 The `eo_tides.validation` module validates modelled tide heights using high-quality sea-level  
 109 measurements from the GESLA Global Extreme Sea Level Analysis (Haigh et al., 2023) archive,  
 110 providing error metrics like RMSE and MAE (Figure 5). It enables comparison of multiple tide  
 111 models against observed data, allowing users to choose optimal tide models for their specific  
 112 study area or application (Figure 5).



**Figure 5:** An example comparison of modelled tides from multiple global ocean tide models (EOT20, GOT5.5, HAMTIDE11) against observed sea level data from the Broome 62650 GESLA tide gauge, Western Australia.

## 113 Research projects

114 Early versions of eo-tides functions have been used for continental-scale intertidal zone  
 115 elevation and exposure mapping ([Bishop-Taylor et al., 2024](#)), multi-decadal shoreline mapping  
 116 across Australia ([Bishop-Taylor et al., 2021](#)) and [Africa](#), and to support tide correction for  
 117 satellite-derived shorelines as part of the CoastSeg Python package ([Fitzpatrick et al., 2024](#)).

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 122 edits. This paper is published with the permission of the Chief Executive Officer, Geoscience  
 123 Australia. Copyright Geoscience Australia (2025).

## 124 References

- 125 Bishop-Taylor, R., Nanson, R., Sagar, S., & Lymburner, L. (2021). Mapping Australia's  
 126 Dynamic Coastline at Mean Sea Level using Three Decades of Landsat Imagery. *Remote  
 127 Sensing of Environment*, 267, 112734. <https://doi.org/10.1016/j.rse.2021.112734>
- 128 Bishop-Taylor, R., Phillips, C., Newey, V., & Sagar, S. (2024). *Digital Earth Australia Intertidal*.  
 129 Commonwealth of Australia (Geoscience Australia). <https://doi.org/10.26186/149403>
- 130 Bishop-Taylor, R., Sagar, S., Lymburner, L., & Beaman, R. J. (2019). Between the tides:  
 131 Modelling the elevation of australia's exposed intertidal zone at continental scale. *Estuarine,  
 132 Coastal and Shelf Science*, 223, 115–128. <https://doi.org/10.1016/j.ecss.2019.03.006>
- 133 Eleveld, M. A., Van der Wal, D., & Van Kessel, T. (2014). Estuarine suspended par-  
 134 ticular matter concentrations from sun-synchronous satellite remote sensing: Tidal  
 135 and meteorological effects and biases. *Remote Sensing of Environment*, 143, 204–215.  
 136 <https://doi.org/10.1016/j.rse.2013.12.019>
- 137 Fitzpatrick, S., Buscombe, D., Warrick, J. A., Lundine, M. A., & Vos, K. (2024). CoastSeg: An  
 138 accessible and extendable hub for satellite-derived-shoreline (SDS) detection and mapping.  
 139 *Journal of Open Source Software*, 9(99), 6683. <https://doi.org/10.21105/joss.06683>
- 140 Haigh, I. D., Marcos, M., Talke, S. A., Woodworth, P. L., Hunter, J. R., Hague, B. S.,  
 141 Arns, A., Bradshaw, E., & Thompson, P. (2023). GESLA version 3: A major update to

- 142 the global higher-frequency sea-level dataset. *Geoscience Data Journal*, 10(3), 293–314.  
143 <https://doi.org/10.1002/gdj3.174>
- 144 Hoyer, S., & Joseph, H. (2017). xarray: N-d labeled arrays and datasets in python. *Journal of*  
145 *Open Research Software*, 5(1). <https://doi.org/10.5334/jors.148>
- 146 Krause, C., Dunn, B., Bishop-Taylor, R., Adams, C., Burton, C., Alger, M., Chua, S., Phillips, C.,  
147 Newey, V., Kouzoubov, K., Leith, A., Ayers, D., & Hicks, A. (2021). *Digital Earth Australia*  
148 *notebooks and tools repository*. <https://github.com/GeoscienceAustralia/dea-notebooks/>;  
149 Commonwealth of Australia (Geoscience Australia). <https://doi.org/10.26186/145234>
- 150 McKinney, Wes. (2010). Data Structures for Statistical Computing in Python. In Stéfan van  
151 der Walt & Jarrod Millman (Eds.), *Proceedings of the 9th Python in Science Conference*  
152 (pp. 56–61). <https://doi.org/10.25080/Majora-92bf1922-00a>
- 153 Murray, N. J., Phinn, S. R., Clemens, R. S., Roelfsema, C. M., & Fuller, R. A. (2012).  
154 Continental scale mapping of tidal flats across east asia using the landsat archive. *Remote*  
155 *Sensing*, 4(11), 3417–3426. <https://doi.org/10.3390/rs4113417>
- 156 odc-geo contributors. (2024). Opendatacube/odc-geo. In *Github repository*. GitHub.  
157 <https://github.com/opendatacube/odc-geo>
- 158 pandas development team. (2020). *Pandas-dev/pandas: pandas* (latest). Zenodo. <https://doi.org/10.5281/zenodo.3509134>
- 160 Sagar, S., Phillips, C., Bala, B., Roberts, D., Lymburner, L., & Beaman, R. J. (2018).  
161 Generating continental scale pixel-based surface reflectance composites in coastal regions  
162 with the use of a multi-resolution tidal model. *Remote Sensing*, 10(3), 480. <https://doi.org/10.3390/rs10030480>
- 164 Sagar, S., Roberts, D., Bala, B., & Lymburner, L. (2017). Extracting the intertidal extent and  
165 topography of the australian coastline from a 28 year time series of landsat observations.  
166 *Remote Sensing of Environment*, 195, 153–169. <https://doi.org/10.1016/j.rse.2017.04.009>
- 167 Sent, G., Antunes, C., Spyракος, E., Jackson, T., Atwood, E. C., & Brito, A. C. (2025). What  
168 time is the tide? The importance of tides for ocean colour applications to estuaries. *Remote*  
169 *Sensing Applications: Society and Environment*, 37, 101425. <https://doi.org/10.2139/ssrn.4858713>
- 171 STAC contributors. (2024). *SpatioTemporal Asset Catalog (STAC) specification*. <https://stacspec.org>
- 173 Sutterley, T. C., Alley, K., Brunt, K., Howard, S., Padman, L., & Siegried, M. (2017). *pyTMD:*  
174 *Python-based tidal prediction software*. Zenodo. <https://doi.org/10.5281/zenodo.5555395>
- 175 Turner, I. L., Harley, M. D., Almar, R., & Bergsma, E. W. J. (2021). Satellite optical imagery  
176 in Coastal Engineering. *Coastal Engineering*, 167, 103919. <https://doi.org/10.1016/j.coastaleng.2021.103919>
- 178 Vitousek, S., Buscombe, D., Vos, K., Barnard, P. L., Ritchie, A. C., & Warrick, J. A. (2023).  
179 The future of coastal monitoring through satellite remote sensing. *Cambridge Prisms:*  
180 *Coastal Futures*, 1, e10. <https://doi.org/10.1017/cft.2022.4>
- 181 Vos, K., Splinter, K. D., Harley, M. D., Simmons, J. A., & Turner, I. L. (2019). CoastSat: A  
182 Google Earth Engine-enabled Python toolkit to extract shorelines from publicly available  
183 satellite imagery. *Environmental Modelling & Software*, 122, 104528. <https://doi.org/10.1016/j.envsoft.2019.104528>