

¹ eo-tides: Tide modelling tools for large-scale satellite Earth observation analysis

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DOI: [10.xxxxxx/draft](https://doi.org/10.xxxxxx/draft)

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Submitted: 01 January 1970

Published: unpublished

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eo-tides tools can be applied to petabytes of freely available satellite data loaded from the cloud using Open Data Cube (ODC)’s odc-stac or datacube packages (e.g. using [Digital Earth Australia](#) or [Microsoft Planetary Computer’s STAC SpatioTemporal Asset Catalogues](#)). Additional functionality allows users to assess potential satellite-tide biases and validate modelled tides with external tide gauge data — critical considerations for ensuring the reliability and accuracy of coastal EO workflows. These open-source tools support the efficient, scalable and robust analysis of coastal EO data for any time period or location globally.

Summary

The eo-tides package provides powerful parallelised tools for integrating satellite Earth observation (EO) data with ocean tide modelling. The package provides a flexible Python-based toolkit for attributing modelled tide heights to a time-series of satellite images based on the spatial extent and acquisition time of each satellite observation (Figure 1).

eo-tides leverages advanced tide modelling functionality from the pyTMD tide prediction software (Sutterley et al., 2017), combining this capability with EO spatial analysis tools from odc-geo (odc-geo contributors, 2024). This allows tides to be modelled in parallel using over 50 supported tide models, and returned in standardised pandas (McKinney, 2010; pandas development team, 2020) and xarray (Hoyer & Joseph, 2017) data formats for EO analysis.

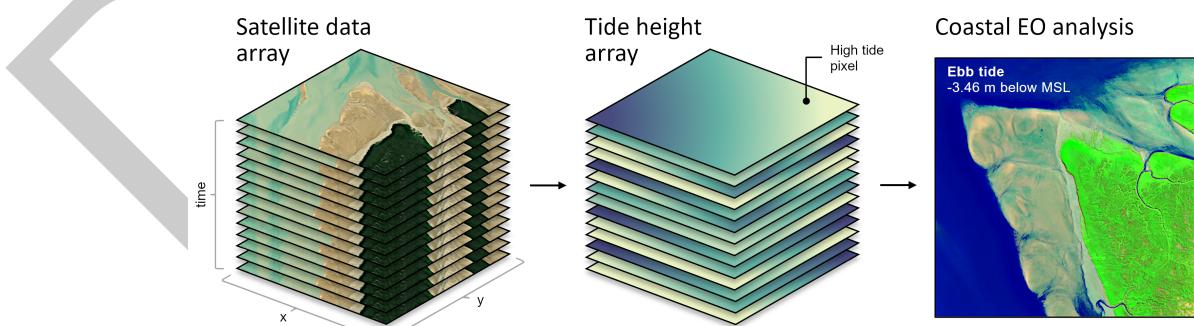


Figure 1: A typical eo-tides coastal EO workflow, with tide heights modelled into every pixel in a spatio-temporal stack of satellite data (for example, from Sentinel-2 or Landsat), then combined to derive insights into dynamic coastal environments.

24 Statement of need

25 Satellite remote sensing offers an unparalleled resource for examining dynamic coastal environments through time or across large regions (Turner et al., 2021; Vitousek et al., 2023).
 26 However, the highly variable influence of ocean tides can complicate analyses, making it difficult
 27 to separate the influence of changing tides from patterns of true coastal change (Vos et al.,
 28 2019). This is a particularly challenging for large-scale coastal EO analyses, where failing to
 29 account for tide dynamics can lead to inaccurate or misleading insights into satellite-observed
 30 coastal processes.

32 Conversely, information about ocean tides can provide unique environmental insights that can
 33 significantly enhance the value of EO data. Traditionally, satellite data dimensions include
 34 the geographic “where” and temporal “when” of acquisition. Introducing tide height as an
 35 additional analysis dimension allows data to be filtered, sorted, and analysed based on tidal
 36 dynamics, offering a transformative re-imagining of traditional multi-temporal EO analysis
 37 (Sagar et al., 2017). For instance, satellite data can be analysed to focus on ecologically
 38 significant tidal stages (e.g., high tide, low tide, spring or neap tides) or specific tidal processes
 39 (e.g., ebb or flow tides; Sent et al. (2025)).

40 This concept has been used to map coastal change at continental-scale (Bishop-Taylor et al.,
 41 2021), map intertidal zone extent and elevation (Bishop-Taylor et al., 2019; Murray et al.,
 42 2012; Sagar et al., 2017), and creating tidally-constrained coastal image composites (Sagar
 43 et al., 2018). However, these methods have traditionally relied on bespoke, closed-source, or
 44 difficult-to-install tide modelling tools, limiting their reproducibility and portability. To support
 45 the next generation of coastal EO workflows, there is a pressing need for efficient open-source
 46 tools for combining satellite data with tide modelling. eo-tides addresses this need through
 47 functionality offered in five main analysis modules (utils, model, eo, stats, validation).

48 Features

49 Setting up tide models

50 The `eo_tides.utils` module simplifies the setup of ocean tide models, addressing a common
 51 barrier to coastal EO workflows. Tools like `list_models` provide feedback on available and
 52 supported models (Figure 2), while `clip_models` can significantly improve performance by
 53 clipping large high-resolution model files (e.g. FES2022) to smaller study area extents.

| | Model | Expected path |
|-----|-----------|--------------------------------|
| ✓ | EOT20 | tide_models/EOT20/ocean_tides |
| ✗ | FES2014 | tide_models/fes2014/ocean_tide |
| ✓ | HAMTIDE11 | tide_models/hamtide |
| ... | ... | ... |

Summary:
 Available models: 2/50

Figure 2: An `list_tides` output providing a useful summary of available and supported tide models.

54 Modelling tides

55 The `eo_tides.model` module is powered by tide modelling functionality from the pyTMD Python
 56 package (Sutterley et al., 2017). pyTMD is an open-source tidal prediction software that
 57 simplifies the calculation of ocean and earth tides. Tides are frequently decomposed into

58 harmonic constants (or constituents) associated with the relative positions of the sun, moon
 59 and Earth. `pyTMD.io` contains routines for reading and spatially interpolating major constituent
 60 values from commonly available ocean tide models.

61 The `model_tides` function from `eo_tides.model` wraps `pyTMD` functionality to return tide
 62 predictions in a standardised `pandas.DataFrame` format, enabling integration with EO data
 63 and parallelisation for improved performance ([Table 1](#)). The `model_phases` function can
 64 additionally classify tides into high/low/flow/ebb phases, critical for correctly interpreting
 65 satellite-observed coastal processes like turbidity ([Sent et al., 2025](#)).

Table 1: A [benchmark comparison](#) of tide modelling parallelisation, for a typical large-scale analysis involving a month of hourly tides modelled at 10,000 points using three 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 |

66 Combining tides with satellite data

67 The `eo_tides.eo` module integrates modelled tides with xarray-format satellite data ([Hoyer &](#)
 68 [Joseph, 2017](#)). The `tag_tides` and `pixel_tides` functions ([Table 2](#), [Figure 3](#)) can be applied
 69 to attribute tides to satellite data for any coastal location on the planet, for example using
 70 open data loaded from the cloud using [ODC](#) and [STAC](#) ([STAC contributors, 2024](#)).

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

| tag_tides | pixel_tides |
|--|--|
| <ul style="list-style-type: none"> - Assigns a single tide height to each satellite image time-step - Single tide height per image can produce artefacts and discontinuities - Fast, low memory use - Ideal for local, site-scale analysis | <ul style="list-style-type: none"> - Assigns a tide height to every individual pixel through time - Produce spatially seamless results across large regions - Slower, higher memory use - Ideal for large-scale analysis |

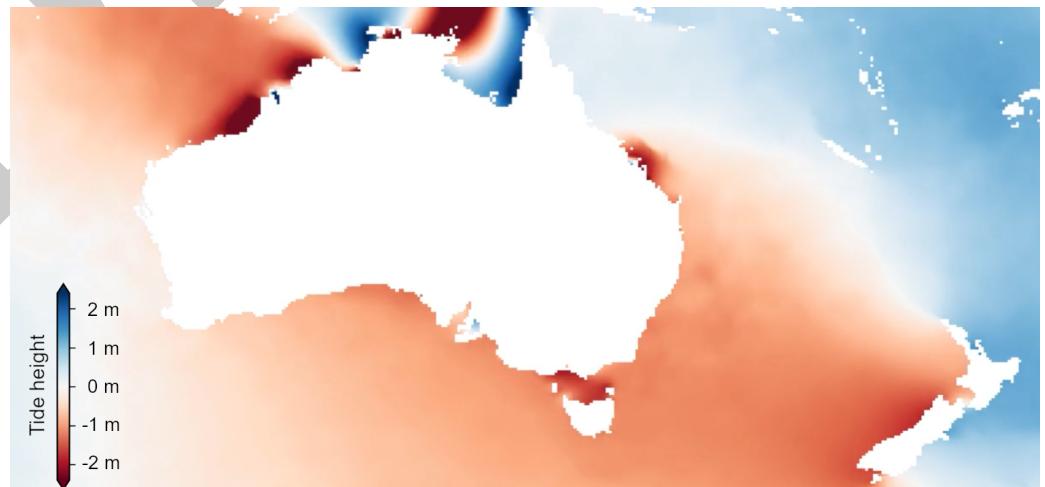
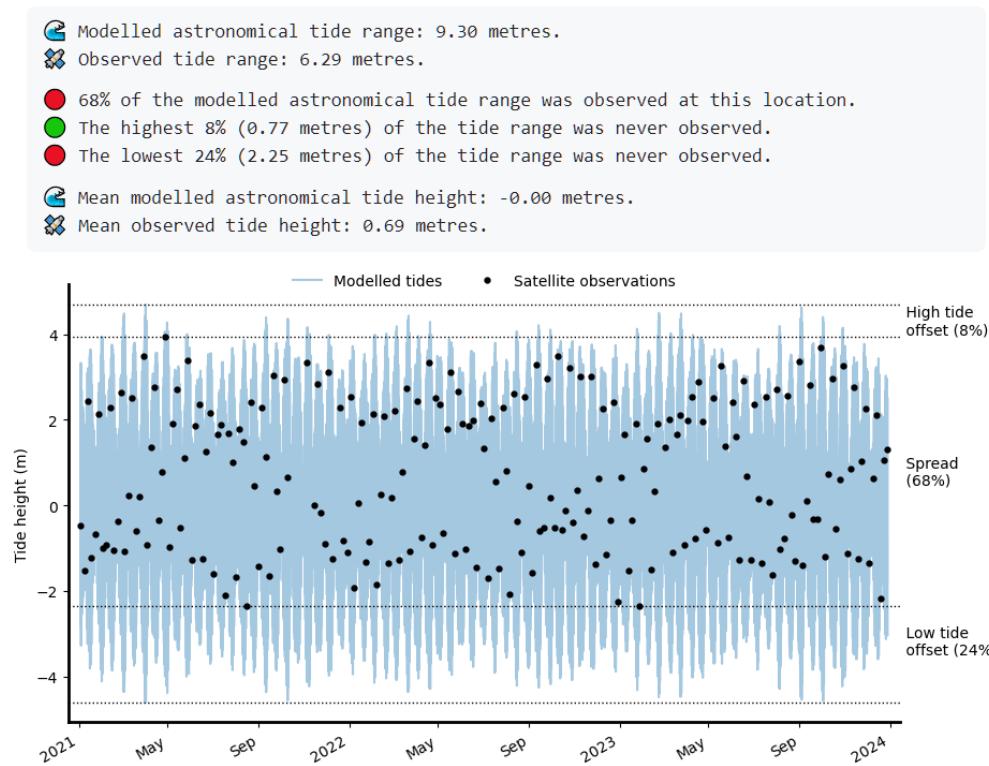


Figure 3: An example spatial tide height output produced by the `pixel_tides` function.

71 Calculating tide statistics and satellite biases

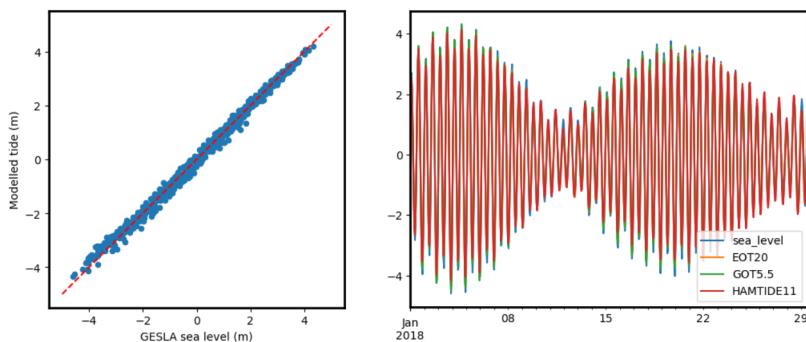
72 The `eo_tides.stats` module identifies biases caused by complex tide aliasing interactions that
 73 can prevent satellites from observing the entire tide cycle (Bishop-Taylor et al., 2019; Eleveld
 74 et al., 2014; Sent et al., 2025). The `tide_stats` and `pixel_stats` functions produce useful
 75 statistics that summarise how well satellite data captures real-world tides (Figure 4).



76 **Figure 4:** An example of tidally-biased satellite coverage, where only ~68% of the astronomical tide
 77 range is observed.

76 Validating modelled tides

77 The `eo_tides.validation` module validates modelled tides against observed sea-level measurements,
 78 assisting users to evaluate and select optimal models for their application (Figure 5).



79 **Figure 5:** A comparison of multiple tide models (EOT20, GOT5.5, HAMTIDE11) against observed sea
 80 level data from the Broome 62650 GESLA tide gauge (Haigh et al., 2023).

79 Research projects

80 Early versions of eo-tides functions have been used for continental-scale intertidal mapping
81 ([Bishop-Taylor et al., 2024](#)), multi-decadal shoreline mapping across Australia ([Bishop-Taylor](#)
82 [et al., 2021](#)) and [Africa](#), and for correcting satellite-derived shoreline in the CoastSeg Python
83 package ([Fitzpatrick et al., 2024](#)).

84 Acknowledgements

85 Functions from eo-tides were originally developed in the Digital Earth Australia Notebooks
86 repository ([Krause et al., 2021](#)). This paper is published with the permission of the Chief
87 Executive Officer, Geoscience Australia.

88 References

- 89 Bishop-Taylor, R., Nanson, R., Sagar, S., & Lymburner, L. (2021). Mapping Australia's
90 Dynamic Coastline at Mean Sea Level using Three Decades of Landsat Imagery. *Remote
91 Sensing of Environment*, 267, 112734. <https://doi.org/10.1016/j.rse.2021.112734>
- 92 Bishop-Taylor, R., Phillips, C., Newey, V., & Sagar, S. (2024). *Digital Earth Australia Intertidal*.
93 Commonwealth of Australia (Geoscience Australia). <https://doi.org/10.26186/149403>
- 94 Bishop-Taylor, R., Sagar, S., Lymburner, L., & Beaman, R. J. (2019). Between the tides:
95 Modelling the elevation of australia's exposed intertidal zone at continental scale. *Estuarine,
96 Coastal and Shelf Science*, 223, 115–128. <https://doi.org/10.1016/j.ecss.2019.03.006>
- 97 Eleveld, M. A., Van der Wal, D., & Van Kessel, T. (2014). Estuarine suspended par-
98 ticular matter concentrations from sun-synchronous satellite remote sensing: Tidal
99 and meteorological effects and biases. *Remote Sensing of Environment*, 143, 204–215.
100 <https://doi.org/10.1016/j.rse.2013.12.019>
- 101 Fitzpatrick, S., Buscombe, D., Warrick, J. A., Lundine, M. A., & Vos, K. (2024). CoastSeg: An
102 accessible and extendable hub for satellite-derived-shoreline (SDS) detection and mapping.
103 *Journal of Open Source Software*, 9(99), 6683. <https://doi.org/10.21105/joss.06683>
- 104 Haigh, I. D., Marcos, M., Talke, S. A., Woodworth, P. L., Hunter, J. R., Hague, B. S.,
105 Arns, A., Bradshaw, E., & Thompson, P. (2023). GESLA version 3: A major update to
106 the global higher-frequency sea-level dataset. *Geoscience Data Journal*, 10(3), 293–314.
107 <https://doi.org/10.1002/gdj3.174>
- 108 Hoyer, S., & Joseph, H. (2017). xarray: N-d labeled arrays and datasets in python. *Journal of
109 Open Research Software*, 5(1). <https://doi.org/10.5334/jors.148>
- 110 Krause, C., Dunn, B., Bishop-Taylor, R., Adams, C., Burton, C., Alger, M., Chua, S., Phillips, C.,
111 Newey, V., Kouzoubov, K., Leith, A., Ayers, D., & Hicks, A. (2021). *Digital Earth Australia
112 notebooks and tools repository*. <https://github.com/GeoscienceAustralia/dea-notebooks/>;
113 Commonwealth of Australia (Geoscience Australia). <https://doi.org/10.26186/145234>
- 114 McKinney, Wes. (2010). Data Structures for Statistical Computing in Python. In Stéfan van
115 der Walt & Jarrod Millman (Eds.), *Proceedings of the 9th Python in Science Conference*
116 (pp. 56–61). <https://doi.org/10.25080/Majora-92bf1922-00a>
- 117 Murray, N. J., Phinn, S. R., Clemens, R. S., Roelfsema, C. M., & Fuller, R. A. (2012).
118 Continental scale mapping of tidal flats across east asia using the landsat archive. *Remote
119 Sensing*, 4(11), 3417–3426. <https://doi.org/10.3390/rs4113417>
- 120 odc-geo contributors. (2024). Opendatacube/odc-geo. In *Github repository*. GitHub.
121 <https://github.com/opendatacube/odc-geo>

- 122 pandas development team. (2020). *Pandas-dev/pandas: pandas* (latest). Zenodo. <https://doi.org/10.5281/zenodo.3509134>
- 123
124 Sagar, S., Phillips, C., Bala, B., Roberts, D., Lymburner, L., & Beaman, R. J. (2018).
125 Generating continental scale pixel-based surface reflectance composites in coastal regions
126 with the use of a multi-resolution tidal model. *Remote Sensing*, 10(3), 480. <https://doi.org/10.3390/rs10030480>
- 127
128 Sagar, S., Roberts, D., Bala, B., & Lymburner, L. (2017). Extracting the intertidal extent and
129 topography of the australian coastline from a 28 year time series of landsat observations.
130 *Remote Sensing of Environment*, 195, 153–169. <https://doi.org/10.1016/j.rse.2017.04.009>
- 131 Sent, G., Antunes, C., Spyракος, E., Jackson, T., Atwood, E. C., & Brito, A. C. (2025). What
132 time is the tide? The importance of tides for ocean colour applications to estuaries. *Remote
133 Sensing Applications: Society and Environment*, 37, 101425. <https://doi.org/10.2139/ssrn.4858713>
- 134
135 STAC contributors. (2024). *SpatioTemporal Asset Catalog (STAC) specification*. <https://stacspec.org>
- 136
137 Sutterley, T. C., Alley, K., Brunt, K., Howard, S., Padman, L., & Siegried, M. (2017). *pyTMD:
138 Python-based tidal prediction software*. Zenodo. <https://doi.org/10.5281/zenodo.5555395>
- 139 Turner, I. L., Harley, M. D., Almar, R., & Bergsma, E. W. J. (2021). Satellite optical imagery
140 in Coastal Engineering. *Coastal Engineering*, 167, 103919. <https://doi.org/10.1016/j.coastaleng.2021.103919>
- 141
142 Vitousek, S., Buscombe, D., Vos, K., Barnard, P. L., Ritchie, A. C., & Warrick, J. A. (2023).
143 The future of coastal monitoring through satellite remote sensing. *Cambridge Prisms:
144 Coastal Futures*, 1, e10. <https://doi.org/10.1017/cft.2022.4>
- 145 Vos, K., Splinter, K. D., Harley, M. D., Simmons, J. A., & Turner, I. L. (2019). CoastSat: A
146 Google Earth Engine-enabled Python toolkit to extract shorelines from publicly available
147 satellite imagery. *Environmental Modelling & Software*, 122, 104528. <https://doi.org/10.1016/j.envsoft.2019.104528>
- 148