

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

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Summary

The eo-tides package provides powerful parallelized tools for integrating satellite Earth observation (EO) data with ocean tide modelling. The package provides a flexible Python-based toolkit for modelling and attributing 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 fundamental tide modelling capability with EO spatial analysis tools from odc-geo ([odc-geo contributors, 2024](#)). This allows tides to be modelled in parallel automatically 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 further analysis.

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

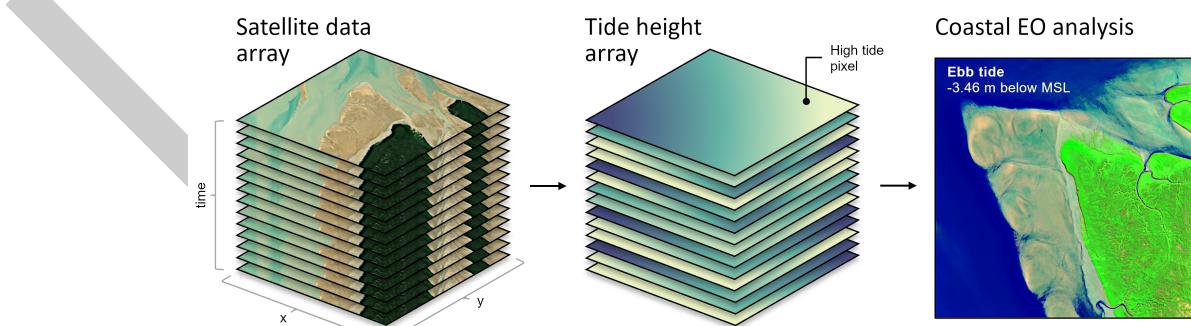


Figure 1: A typical eo-tides coastal EO workflow, with tide heights modelled into every pixel in a spatio-temporal stack of satellite data (for example, from ESA's Sentinel-2 or NASA/USGS Landsat), then combined to derive insights into dynamic coastal environments.

²⁶ Statement of need

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

³⁴ Conversely, information about ocean tides can also provide unique environmental insights that
³⁵ can greatly enhance the utility of coastal EO data. Conventionally, satellite data dimensions
³⁶ consider the geographical “where” and the temporal “when” of data acquisition. The addition
³⁷ of tide height as a new analysis dimension allows data to be filtered, sorted and analysed with
³⁸ respect to tidal processes, delivering a powerful re-imagining of traditional multi-temporal EO
³⁹ data analysis ([Sagar et al., 2017](#)). For example, satellite data can be analysed to focus on
⁴⁰ specific ecologically-significant tidal stages (e.g. high, low tide, spring or neap tides) or on
⁴¹ particular tidal processes (e.g. ebb or flow tides; [Sent et al. \(2025\)](#)).

⁴² This concept has been used to map tidally-corrected annual coastlines from Landsat satellite
⁴³ data at continental scale ([Bishop-Taylor et al., 2021](#)), generate maps of the extent and elevation
⁴⁴ of the intertidal zone ([Bishop-Taylor et al., 2019](#); [Murray et al., 2012](#); [Sagar et al., 2017](#)), and
⁴⁵ create tidally-constrained imagery composites of the coastline ([Sagar et al., 2018](#)). However,
⁴⁶ these approaches have been historically based on bespoke, closed-source or difficult to install
⁴⁷ tide modelling tools, limiting the reproducibility and portability of these techniques to new
⁴⁸ coastal EO applications. To support the next generation of coastal EO workflows, there is
⁴⁹ a pressing need for new open-source tools for combining satellite data with tide modelling.
⁵⁰ `eo-tides` aims to address these challenges through functionality provided in five main analysis
⁵¹ modules (`utils`, `model`, `eo`, `stats`, `validation`) which are described briefly below.

⁵² Features

⁵³ Setting up tide models

⁵⁴ The `eo_tides.utils` module simplifies the setup of ocean tide models, addressing a common
⁵⁵ barrier to coastal EO workflows. Tools like `list_models` provide feedback on available and
⁵⁶ supported models ([Figure 2](#)), while `clip_models` can improve performance by clipping large
⁵⁷ model files to smaller regions, significantly reducing processing times for high-resolution models
⁵⁸ like FES2022. Comprehensive documentation is available to [assist setting up commonly used](#)
⁵⁹ [tide models](#), including downloading, uncompressing, and organizing model files.

|  | 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 example output from `list_tides`, providing a useful summary table which clearly identifies available and supported tide models.

60 Modelling tides

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

63 pyTMD is an open-source tidal prediction software that aims to simplify the calculation of ocean
 64 and earth tides. Tides are frequently decomposed into harmonic constants (or constituents)
 65 associated with the relative positions of the sun, moon and Earth. `pyTMD.io` contains routines for
 66 reading major constituent values from commonly available ocean tide models, and interpolating
 67 those values spatially. `pyTMD.astro` contains routines for computing the positions of celestial
 68 bodies for a given time. For ocean tides, `pyTMD` computes the longitudes of the sun (S), moon
 69 (H), lunar perigee (P), ascending lunar node (N) and solar perigee (PP). `pyTMD.arguments`
 70 combines astronomical coefficients with the “Doodson number” of each constituent, and
 71 adjusts the amplitude and phase of each constituent based on their modulations over the 18.6
 72 year nodal period. Finally, `pyTMD.predict` uses results from those underlying functions to
 73 predict tidal values at a given location and time.

74 The `model_tides` function from `eo_tides.model` wraps `pyTMD` functionality to return tide
 75 predictions in a standardised `pandas.DataFrame` format, enabling integration with satellite
 76 EO data and parallelized processing for improved performance. Parallelisation in `eo-tides`
 77 is automatically optimised based on available workers and requested tide models and tide
 78 modelling locations. This parallelisation can significantly improve tide modelling performance,
 79 especially for large-scale analyses run on a multi-core machine ([Table 1](#)). Additional functions
 80 like `model_phases` classify high, low or flow/ebb tides, critical for interpreting satellite-observed
 81 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 |

82 Combining tides with satellite data

83 The `eo_tides.eo` module integrates modelled tides with xarray-format satellite data. For
 84 tide attribution, `eo-tides` offers two approaches that differ in complexity and performance:
 85 `tag_tides` assigns a single tide height per timestep for small-scale studies, while `pixel_tides`
 86 models tides spatially and temporally for larger-scale analyses, producing a unique tide height
 87 for each pixel in a dataset ([Table 2](#)). These functions can be applied to free and open satellite
 88 data for any coastal or ocean location on the planet, for example using data loaded from the
 89 cloud using the [Open Data Cube](#) and SpatioTemporal Asset Catalogue ([STAC contributors](#),
 90 [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"> - Assigns a single tide height to each satellite image timestep - Ideal for local or site-scale analysis - Fast, low memory use | <ul style="list-style-type: none"> - Assigns a tide height to every individual pixel through time to capture spatial tide dynamics - Ideal for regional to global-scale coastal product generation - Slower, higher memory use |

| tag_tides | pixel_tides |
|--|---|
| - Single tide height per image can produce tidal artefacts and discontinuities | - Produce spatially seamless results across large extents |

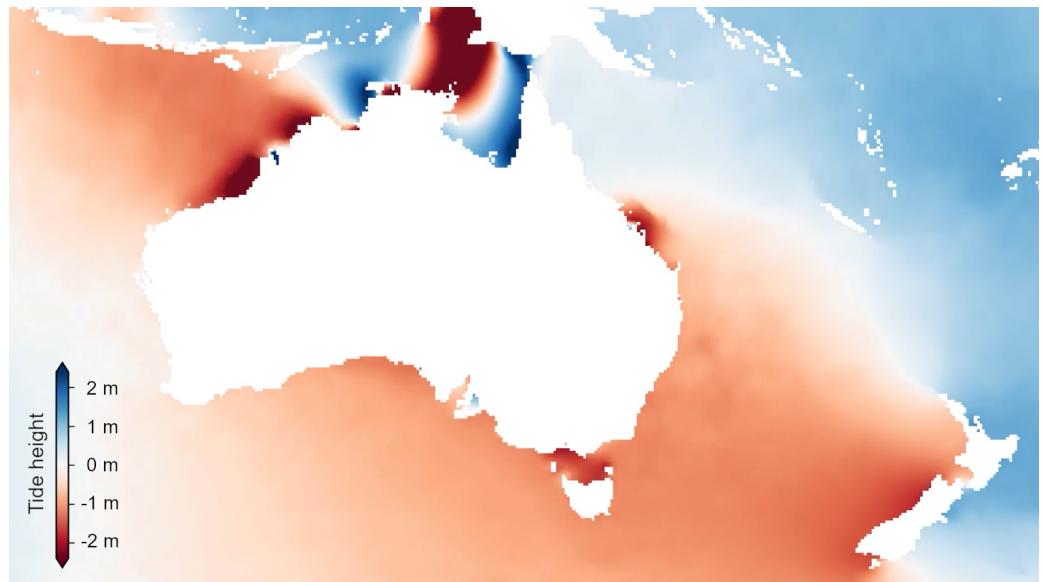


Figure 3: An example tide height output produced by the `pixel_tides` function, showing spatial variability in tides across Australasia for a single timestep.

91 **Calculating tide statistics and satellite biases**

92 The `eo_tides.stats` module identifies biases caused by complex tide aliasing interactions
 93 interactions between tidal dynamics and satellite observations. These interactions can prevent
 94 satellites from observing the entire tide cycle (Eleveld et al., 2014; Sent et al., 2025), and
 95 cause coastal EO studies to produce biased or misleading results (Bishop-Taylor et al., 2019).
 96 The module produces a range of useful statistics that summarise how well a satellite time series
 97 captures real-world tidal conditions, include spread (coverage of tide range) and high/low-tide
 98 offsets (missed tidal extremes). Automated reports and plots provide insights further insights
 99 into potential biases affecting the analysis.

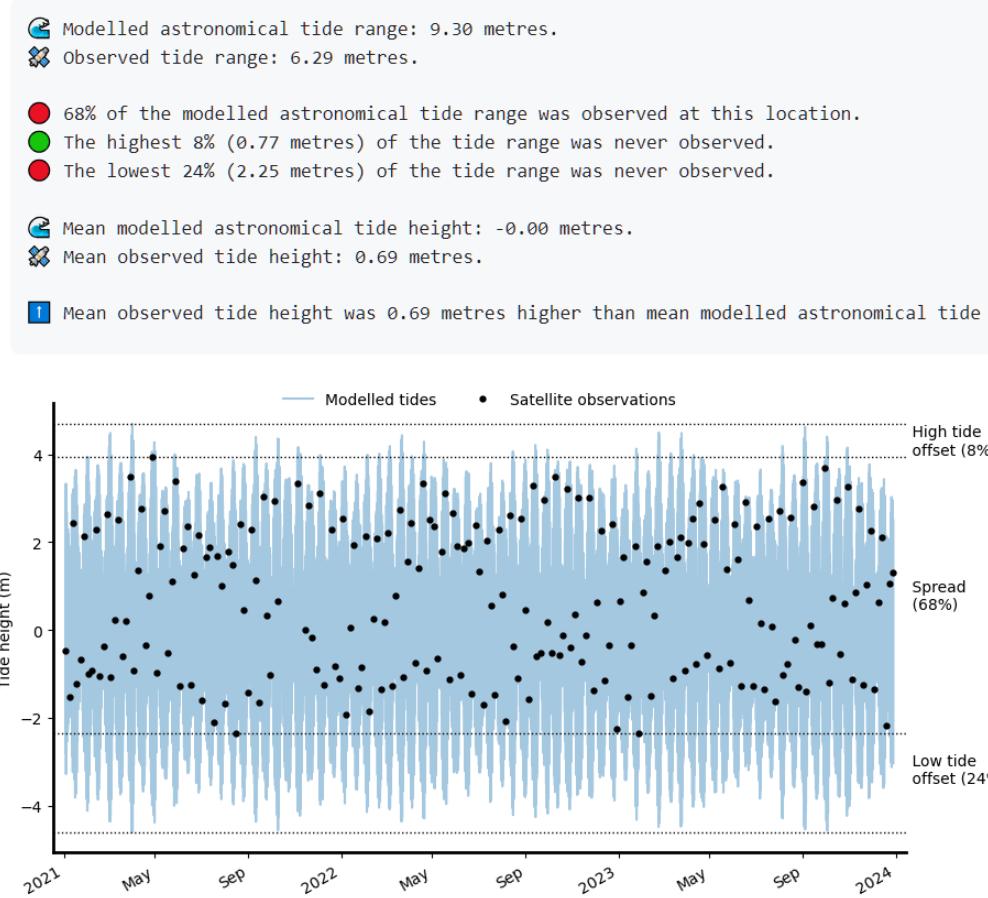


Figure 4: An example of tidally-biased satellite coverage, where the sensor only observes ~68% of the modelled astronomical tide range and never observes the lowest 24% of tides.

Validating modelled tides

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

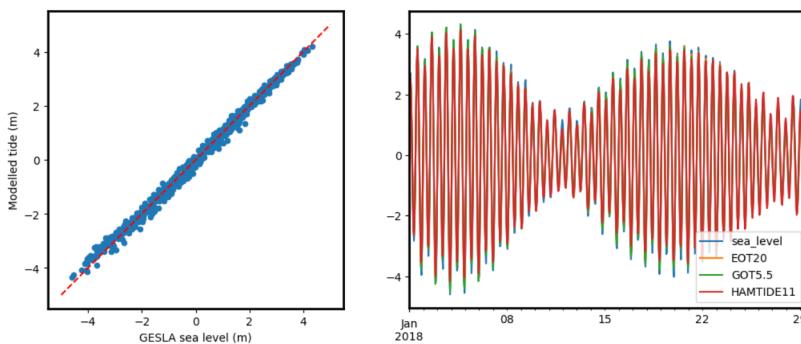


Figure 5: An example comparison of modelled tides from multiple global ocean tide models (EOT20, GOT5.5, HAMTIDE11) against observed sea level data from the Broome 62650 GESLA tide gauge.

¹⁰⁶ Research projects

¹⁰⁷ Early versions of eo-tides functions have been used for continental-scale intertidal zone
¹⁰⁸ mapping (Bishop-Taylor et al., 2024), multi-decadal shoreline mapping across Australia (Bishop-
¹⁰⁹ Taylor et al., 2021) and Africa, and to support tide correction for satellite-derived shorelines as
¹¹⁰ part of the CoastSeg Python package (Fitzpatrick et al., 2024).

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¹¹⁵ published with the permission of the Chief Executive Officer, Geoscience Australia. Copyright
¹¹⁶ Geoscience Australia (2025).

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