

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.

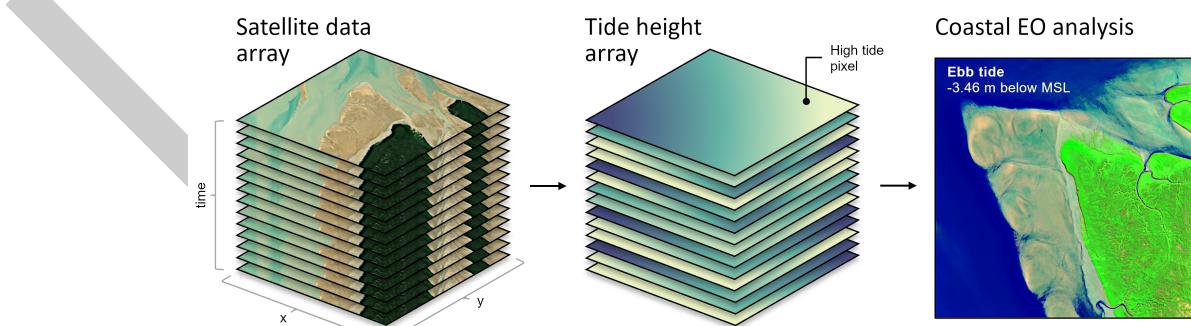


Figure 1: A typical eo-tides coastal EO workflow, with tide heights modelled into every pixel in a spatio-temporal stack of satellite data (for example, from ESA's Sentinel-2 or NASA/USGS Landsat), then combined to derive insights into dynamic coastal environments.

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 a
⁴⁹ pressing need for new open-source tools for combining satellite data with tide modelling.

⁵⁰ `eo-tides` aims to address these challenges by providing a set of performant open-source Python
⁵¹ tools for attributing satellite EO data with modelled ocean tides. This functionality is provided
⁵² in five main analysis modules (`utils`, `model`, `eo`, `stats`, `validation`) described briefly below.

⁵³ Features

⁵⁴ Setting up tide models

⁵⁵ The `eo_tides.utils` module simplifies the setup of ocean tide models, addressing a common
⁵⁶ barrier to coastal EO workflows. Tools like `list_models` provide feedback on available and
⁵⁷ supported models ([Figure 2](#)), while `clip_models` can improve performance by clipping large
⁵⁸ model files to smaller regions, significantly reducing processing times for high-resolution models
⁵⁹ like FES2022. Comprehensive documentation is available to [assist setting up commonly used](#)
⁶⁰ [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.

61 Modelling tides

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

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

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

84 Combining tides with satellite data

85 The `eo_tides.eo` module integrates modelled tides with xarray-format satellite data. For
 86 tide attribution, eo-tides offers two approaches that differ in complexity and performance:
 87 `tag_tides` assigns a single tide height per timestep for small-scale studies, while `pixel_tides`

⁸⁸ models tides spatially and temporally for larger-scale analyses, producing a unique tide height
⁸⁹ for each pixel in a dataset ([Table 2](#)).

⁹⁰ These functions can be applied to free and open satellite data for any coastal or ocean location
⁹¹ on the planet, for example using data loaded from the cloud using the [Open Data Cube](#) and
⁹² 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"> - Assigns a single tide height to each timestep/satellite image - Ideal for local or site-scale analysis - Fast, low memory use - Single tide height per image can produce artefacts in complex tidal regions 	<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 - Produce spatially seamless results across large extents by applying analyses at the pixel level

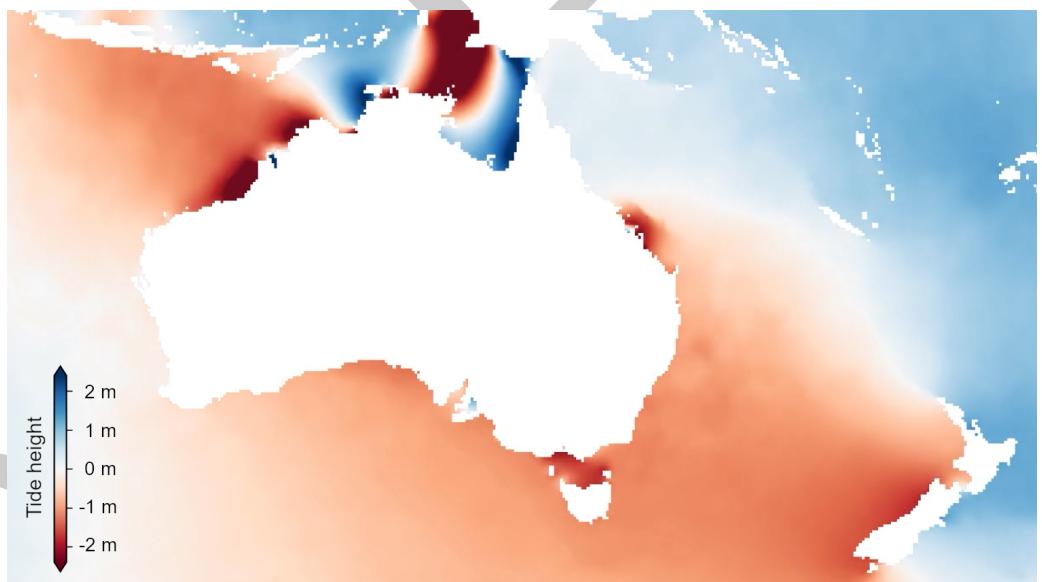


Figure 3: An example tide height output produced by the `pixel_tides` function, showing spatial variability in tides across Australasia for a single timestep.

⁹³ Calculating tide statistics and satellite biases

⁹⁴ The `eo_tides.stats` module identifies biases caused by complex tide aliasing interactions
⁹⁵ interactions between tidal dynamics and satellite observations. These interactions can prevent
⁹⁶ satellites from observing the entire tide cycle ([Eleveld et al., 2014; Sent et al., 2025](#)), and
⁹⁷ cause coastal EO studies to produce biased or misleading results ([Bishop-Taylor et al., 2019](#)).
⁹⁸ The module produces a range of useful statistics that summarise how well a satellite time series
⁹⁹ captures real-world tidal conditions, include spread (coverage of tide range) and high/low-tide
¹⁰⁰ offsets (missed tidal extremes). Automated reports and plots provide insights further insights
¹⁰¹ into potential biases affecting the analysis.

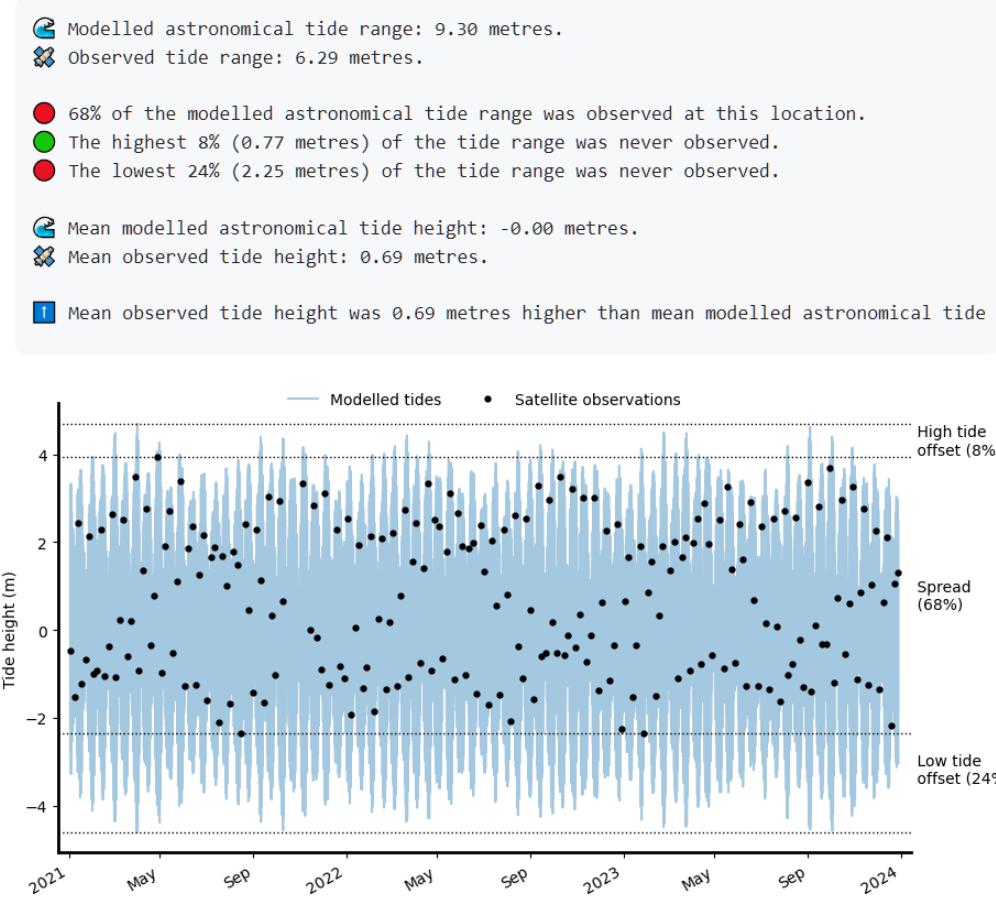


Figure 4: An example of tidally-biased satellite coverage, where the sensor only observes ~68% of the modelled astronomical tide range and never observes the lowest 24% of tides. Satellite bias plots show satellite observed tides as black dots, overlaid over the full range of modelled tides (blue lines).

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Validating modelled tides

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

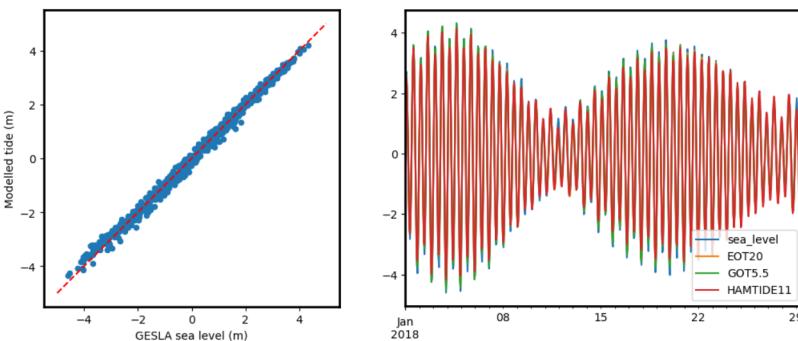


Figure 5: An example comparison of modelled tides from multiple global ocean tide models (EOT20, GOT5.5, HAMTIDE11) against observed sea level data from the Broome 62650 GESLA tide gauge, Western Australia.

108 Research projects

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

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

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