

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

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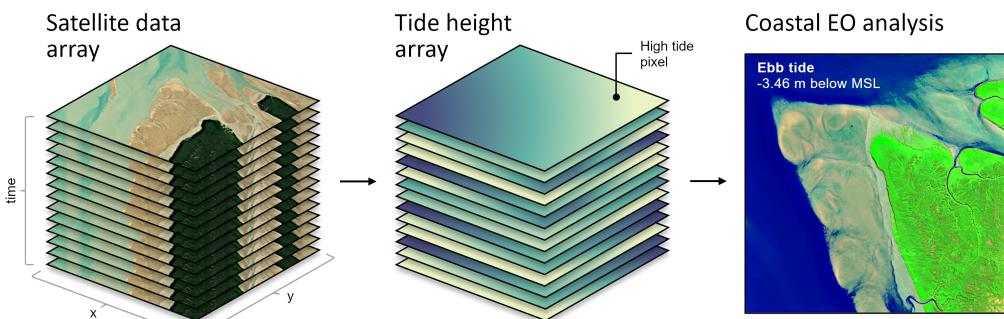
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## Summary

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 API that facilitates the modelling and attribution of 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 development team, 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 Catalogue](#)). 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:** 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.

## 27 Statement of need

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

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

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

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

## 57 Setting up tide models

58 A key barrier to utilising tide modelling in EO workflows is the complexity and difficulty of  
59 initially setting up global ocean tide models for analysis. To address this, the `eo_tides.utils`  
60 module contains useful tools for preparing tide model data files for use in `eo-tides`. This  
61 includes the `list_models` function that provides visual feedback on the tide models a user has  
62 available in their system, while highlighting the naming conventions and directory structures  
63 required by the underlying pyTMD tide prediction software (Figure 2).

64 Running tide modelling using the default tide modelling data provided by external providers can  
65 be slow due to the large size of these files — especially for recent high-resolution models like  
66 FES2022 (Carrere et al., 2022). To improve tide modelling performance, it can be extremely  
67 useful to clip tide model files to a smaller region of interest (e.g. the extent of a country  
68 or coastal region). The `clip_models` function can be used to automatically clip all suitable  
69 NetCDF-format model data files to a user-supplied bounding box, potentially improving tide  
70 modelling performance by over an order of magnitude.

71 These tools are accompanied by comprehensive documentation explaining how to set up several  
72 of the most commonly used global ocean tide models, including details on how to download or  
73 request access to model files, and how to uncompress and arrange the data on disk.

	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.

## 74 Modelling tides

75 The `eo_tides.model` module builds upon advanced tide modelling capability provided by  
 76 the pyTMD tide prediction software ([Sutterley et al., 2017](#)). pyTMD is an open-source tidal  
 77 prediction software that aims to simplify the calculation of ocean and earth tides. Tides are  
 78 frequently decomposed into harmonic constants (or constituents) associated with the relative  
 79 positions of the sun, moon and Earth. For ocean tides, pyTMD.io contains routines for reading  
 80 major constituent values from commonly available tide models, and interpolating those values  
 81 to spatial locations. Information for each of the supported tide models is stored within a  
 82 JSON database that is supplied with pyTMD. pyTMD.astro contains routines for computing the  
 83 positions of celestial bodies for a given time. Namely for ocean tides, pyTMD computes the  
 84 longitudes of the sun (S), moon (H), lunar perigree (P), ascending lunar node (N) and solar  
 85 perigree (PP). pyTMD.arguments contains routines for combining the astronomical coefficients  
 86 with the “Doodson number” of each constituent, along with routines for adjusting the amplitude  
 87 and phase of each constituent based on their modulations over the 18.6 year nodal period.  
 88 Finally, `pyTMD.predict` uses results from those underlying functions to predict tidal values at  
 89 a given location and time.

90 To support integration with satellite EO data, the `model_tides` function from `eo_tides.model`  
 91 wraps pyTMD functionality to return predicted tides in a standardised `pandas.DataFrame` format  
 92 containing information about the tide model, location and time period of each modelled tide.  
 93 This allows large analyses to be broken into smaller discrete chunks that can be processed in  
 94 parallel before being combined as a final step. Parallelisation in `eo-tides` is automatically  
 95 optimised based on the number of available workers and the number of requested tide models  
 96 and tide modelling locations. This built-in parallelisation can significantly improve tide modelling  
 97 performance for analyses involving large spatial extents or multiple tide models, especially on  
 98 large multi-core machines ([Table 1](#)).

**Table 1:** An example benchmark comparison of tide modelling performance with parallelisation on vs. off. This comparison was performed across an 8-core and 32-core Linux machine, for a typical large-scale analysis involving a month of hourly tides modelled using three tide models (FES2022, TPXO10, GOT5.6) at 10,000 modelling locations.

Cores	Parallelisation	No parallelisation	Speedup
8	2min 46s ± 663 ms	9min 28s ± 536 ms	3.4x
32	54.2 s ± 276 ms	9min 24s ± 1.51 s	10.4x

99 The `model_tides` function is primarily intended to support more complex EO-related tide  
 100 modelling functionality in the downstream `eo_tides.eo` module. However it can also be  
 101 used independently of EO data, for example for any application that requires a time series  
 102 of modelled tide heights. In addition to modelling tide heights, the `model_phases` function  
 103 can also be used to calculate the phase of the tide at any location and time. This can be  
 104 used to classify tides into high and low tide observations, or determine whether the tide was  
 105 rising (i.e. flow tide) or falling (i.e. ebb tide) — information that can be critical for correctly  
 106 interpreting satellite-observed coastal processes like changing turbidity and ocean colour (Sent  
 107 et al. (2025)).

### 108 Combining tides with satellite data

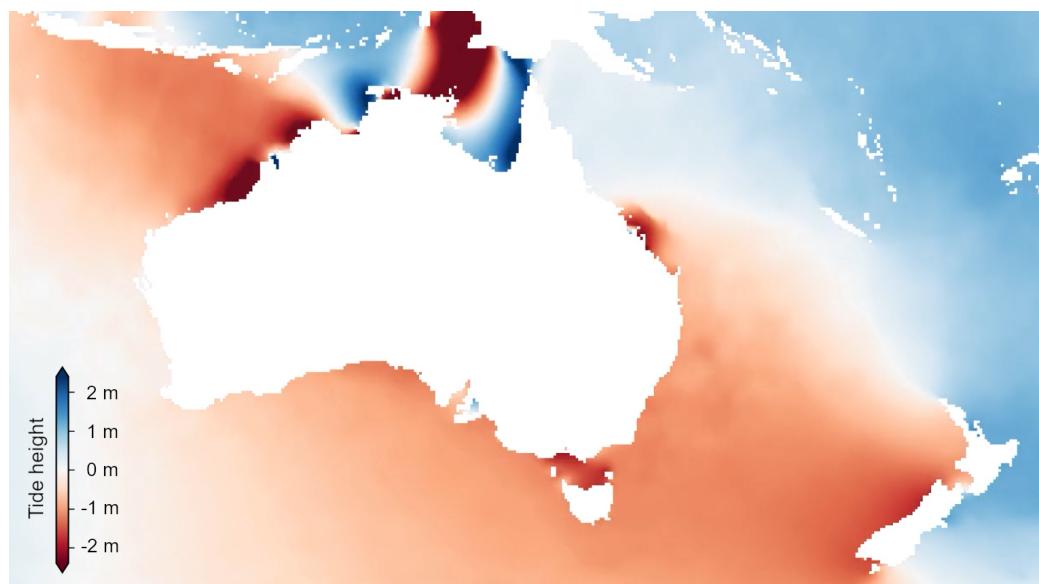
109 The `eo_tides.eo` module contains the package's core functionality, focusing on tools for  
 110 attributing satellite data with modelled tide heights. For tide attribution, eo-tides offers two  
 111 approaches that differ in complexity and performance: `tag_tides` and `pixel_tides` (Table 2).

112 The `tag_tides` function provides a fast and efficient method for small scale applications where  
 113 tides are unlikely to vary across a study area. This approach allocates a single tide height  
 114 to each satellite data timestep, based on the geographic-centroid of the dataset and the  
 115 acquisition time of each image. Having tide height as a variable allows the selection and  
 116 analysis of satellite data based on tides. For example, all available satellite observations for an  
 117 area of interest could be sorted by tide height, or used to extract and compare the lowest and  
 118 highest tide images in the time series.

119 Tide however typically exhibit spatial variability across the analysis extents relevant to satellite  
 120 EO, with sea levels sometimes varying by up to metres in height in regions of complex and  
 121 extreme tidal dynamics. This means that a single satellite image will often capture a range of  
 122 contrasting tide conditions, making a single modelled tide a simplification of reality. For larger  
 123 scale coastal EO analysis, the `pixel_tides` function can be used to seamlessly model tides  
 124 through both time and space, producing three-dimensional "tide height" datacube that can  
 125 be integrated with satellite data. For efficient processing, `pixel_tides` models tides into a  
 126 customisable low resolution grid surrounding each satellite image in the time series. These  
 127 modelled tides are then re-projected back into the original resolution of the input satellite  
 128 image, returning a unique tide height for every individual satellite pixel through time (Figure 3).

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

tag_tides	pixel_tides
<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.

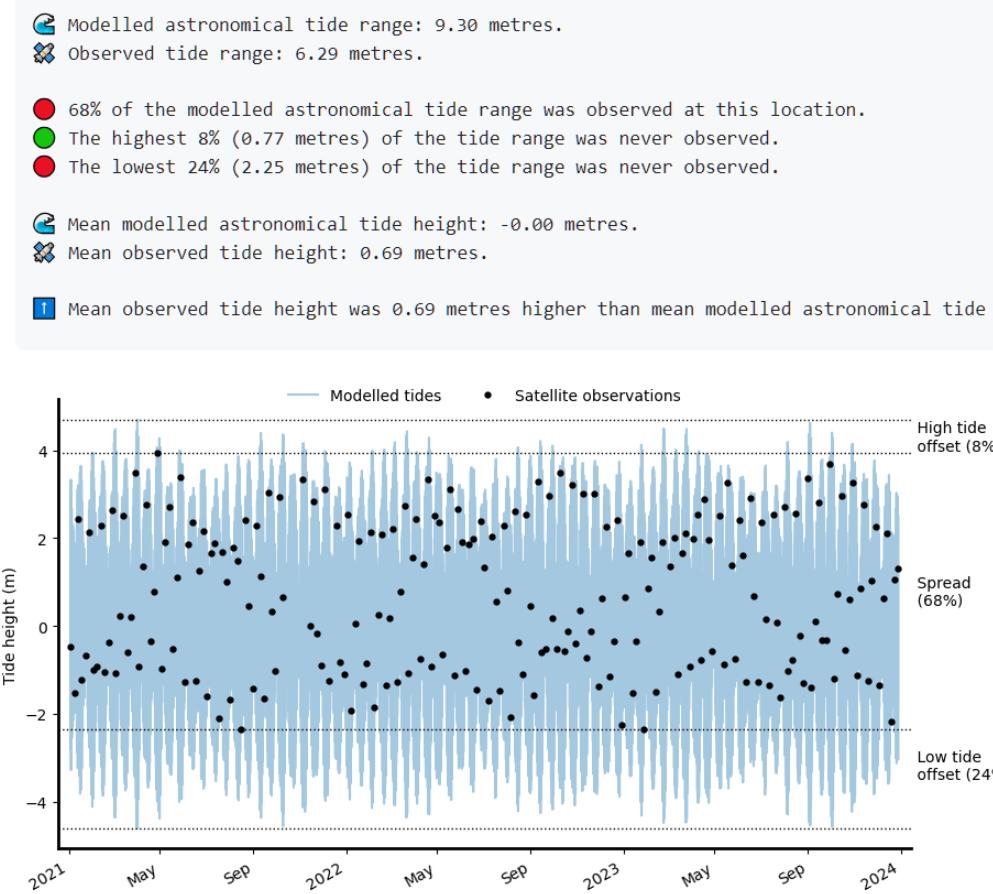
### 129     Calculating tide statistics and satellite biases

130     The `eo_tides.stats` module contains tools for calculating statistics describing local tide  
 131     dynamics, as well as biases caused by interactions between tidal processes and satellite orbits.  
 132     Complex tide aliasing interactions between temporal tide dynamics and the regular overpass  
 133     timing of sun-synchronous satellite sensors mean that satellites often do not always observe  
 134     the entire tidal cycle (Elefeldt et al., 2014). Biases in satellite coverage of the tidal cycle can  
 135     mean that tidal extremes (e.g. the lowest or highest tides at a location) or particular tidal  
 136     processes may either never be captured by satellites, or be over-represented in the satellite  
 137     record. Local tide dynamics can cause these biases to vary greatly both through time and space  
 138     (Bishop-Taylor et al., 2019), making it challenging to compare coastal processes consistently -  
 139     particularly for large-scale coastal EO analyses.

140     To ensure that coastal EO analyses are not inadvertently affected by tide biases, it is important  
 141     to understand and compare how well the tides observed by satellites match the full range of  
 142     modelled tides at a location. The `tide_stats` function compares the subset of tides observed  
 143     by satellite data against the full range of tides modelled at a regular interval through time  
 144     across the entire time period covered by the satellite dataset. This comparison is used to  
 145     calculate several useful statistics that summarise how well a satellite time series captures the  
 146     full range of real-world tidal conditions (Bishop-Taylor et al., 2019). These statistics include:

- 147         1. Spread: The proportion of the modelled astronomical tidal range that was observed by  
 148             satellites. A high value indicates good coverage of the tide range.
- 149         2. High-tide offset: The proportion of the highest tides never observed by satellites, relative  
 150             to the modelled astronomical tidal range. A high value indicates that the satellite data  
 151             never captures the highest tides.
- 152         3. Low-tide offset: The proportion of the lowest tides never observed by satellites, relative  
 153             to the modelled astronomical tidal range. A high value indicates that the satellite data  
 154             never captures the lowest tides.

155     A satellite tide bias investigation for a coastal area of interest will return an automated report  
 156     and plot (Figure 4), adding insightful tide-based context to a coastal EO analysis:



**Figure 4:** In this example satellite time series, the data captured a biased proportion of the tide range: only observing ~68% of the modelled astronomical tide range, and never observing the lowest 24% of tides. The plot visually demonstrates the relationships between satellite observed tide heights (black dots) and modelled astronomical tide height (blue lines) at this location.

### 157      Validating modelled tide heights

158      The `eo_tides.validation` module contains tools for validating modelled tides against observed  
 159      sea level data. The tide models supported by `eo-tides` can vary significantly in accuracy  
 160      across the world's coastlines. Evaluating the accuracy of modelled tides is critical for ensuring  
 161      that resulting marine or coastal EO analyses are reliable and useful.

162      Validation functionality in `eo-tides` provides a convenient tool for loading high-quality sea-level  
 163      measurements from the GESLA Global Extreme Sea Level Analysis (Haigh et al., 2023) archive  
 164      – a global dataset of almost 90,713 years of sea level data from 5,119 records across the world.  
 165      The `load_gauge_gesla` function allows GESLA data to be loaded for the same location and  
 166      time period as a satellite time series. Differences between modelled and observed tide heights  
 167      can then be quantified through the calculation of accuracy statistics that include the Root  
 168      Mean Square Error (RMSE), Mean Absolute Error (MAE), R-squared and bias ([Figure 5](#)).

169      Furthermore, different ocean tide models perform differently in different coastal locations.  
 170      `eo-tides` allows multiple tide models to be compared against GESLA data simultaneously  
 171      ([Figure 5](#)), empowering users to make informed decisions and choose the optimal tide models  
 172      for their specific location or application.



**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.

## 173 Research projects

174 Early versions of functions provided in `eo-tides` has been used for continental-scale modelling  
 175 of the elevation and exposure of Australia's intertidal zone ([Bishop-Taylor et al., 2024](#)), and to  
 176 support tide correction for satellite-derived shorelines as part of the `CoastSeg` Python package  
 177 ([Fitzpatrick et al., 2024](#)).

## 178 Acknowledgements

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 180 and Tools repository ([Krause et al., 2021](#)). The authors would like to thank all DEA Notebooks  
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