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

Robbi Bishop-Taylor [1¶], **Claire Phillips** [1], **Stephen Sagar** [1], **Vanessa Newey** [1], **and Tyler Sutterley** [2]

1 Geoscience Australia, Australia **2** University of Washington Applied Physics Laboratory, United States of America ¶ Corresponding author

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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.

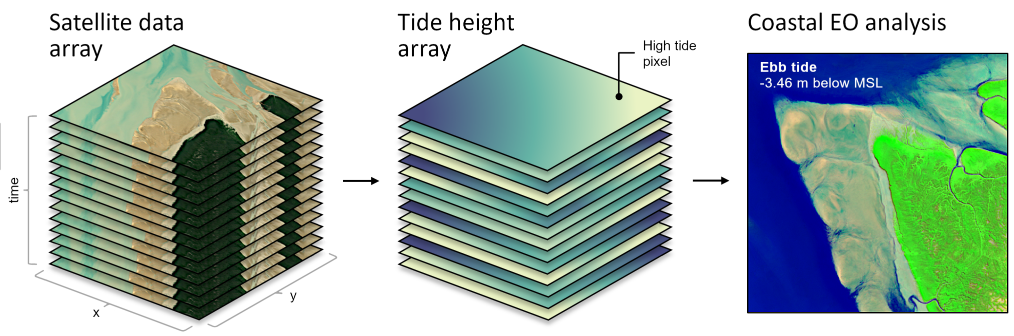

Figure 1: An example of a typical eo-tides coastal EO workflow, with tide heights being modelled into every pixel in a spatio-temporal stack of satellite data (for example, from ESA's Sentinel-2 or NASA/USGS Landsat), then combined to derive insights into dynamic coastal environments.

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Statement of need

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

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

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

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

Setting up tide models

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

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

These tools are accompanied by comprehensive documentation explaining how to set up several of the most commonly used global ocean tide models, including details on how to download or 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.

Modelling tides

The `eo_tides.model` module builds upon advanced tide modelling capability provided by the `pyTMD` tide prediction software (Sutterley et al., 2017).

[TODO Tyler: Insert brief paragraph here about the core capability of the `pyTMD` package, with general background to the science used to predict tides and the range of supported global tide models]

[TODO Robbi: Insert brief paragraph here about how `eo-tides` wraps `pyTMD` functionality to model tides in parallel and return data in pandas/xarray format required for EO analysis]

Tide modelling functionality in the `model_tides` function is primarily intended to support more complex EO-related capability in the `eo_tides.eo` module. However it can also be used independently of EO data, for example for any application that requires a time series of modelled tide heights. In addition to modelling tide heights, the `model_phases` function allows users to calculate tidal phases at any location and time. This can be used to classify tides into high and low tide observations, or determine whether the tide was rising (i.e. flow tide) or falling (i.e. ebb tide) at any point in time.

Combining tides with satellite data

The `eo_tides.eo` module contains the package's core functionality, focusing on tools for attributing satellite data with modelled tide heights. For tide attribution, `eo-tides` offers two approaches that differ in complexity and performance: `tag_tides` and `pixel_tides` (Table 1).

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

However, in reality tides vary spatially – potentially by many metres in areas of complex and extreme tidal dynamics. This means that an individual satellite image can capture a range of contrasting tide conditions. For larger scale coastal EO analysis, the `pixel_tides` function can be used to seamlessly model tides through both time and space, producing three-dimensional "tide height" datacube that can be integrated with satellite data. For efficient processing, `pixel_tides` 'models tides into a customisable low resolution grid surrounding each satellite image in the time series. These modelled tides are then re-projected back into the original resolution of the input satellite image, returning a unique tide height for every individual satellite pixel through time (Figure 3).

Table 1: Comparison of the `tag_tides` and `pixel_tides` functions.

`tag_tides`	`pixel_tides`
- 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	- 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

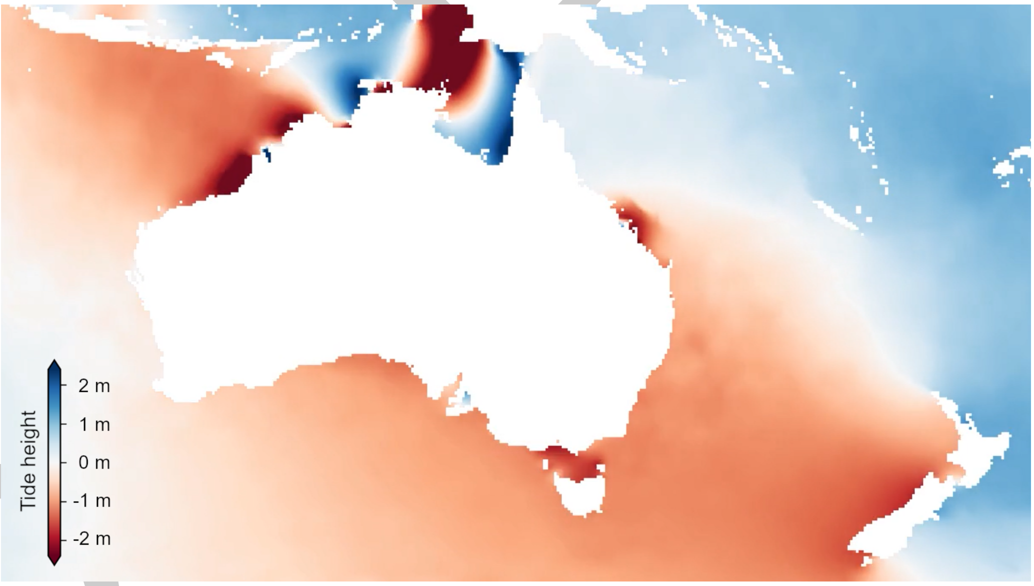

Figure 3: An example tide height output produced by the `pixel_tides` function, showing spatial variability in tides across the Australasia for a single timestep.

Calculating tide statistics and satellite biases

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

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

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

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

```
Modelled astronomical tide range: 9.30 metres.
Observed tide range: 6.29 metres.

68% of the modelled astronomical tide range was observed at this location.
The highest 8% (0.77 metres) of the tide range was never observed.
The lowest 24% (2.25 metres) of the tide range was never observed.

Mean modelled astronomical tide height: -0.00 metres.
Mean observed tide height: 0.69 metres.

Mean observed tide height was 0.69 metres higher than mean modelled astronomical tide
```

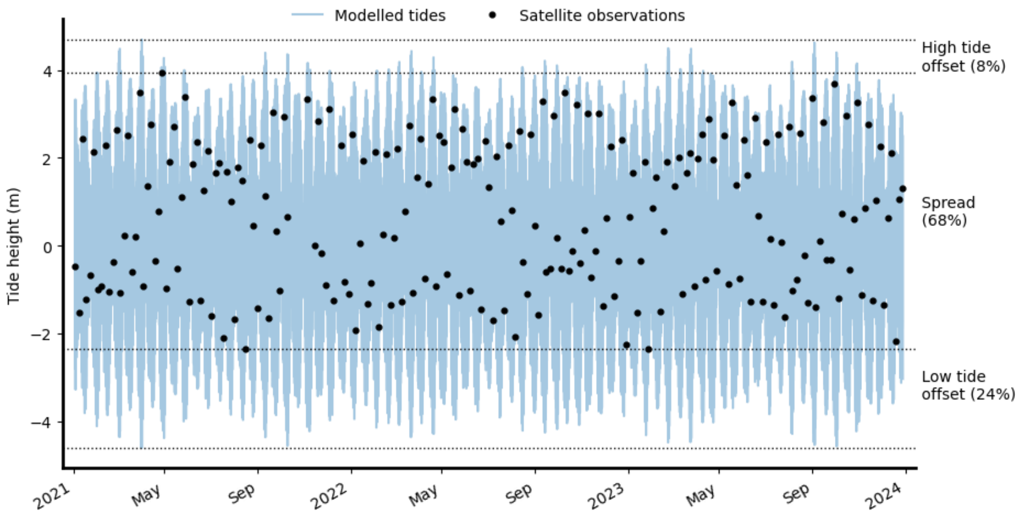

Figure 4: In this example satellite time series, the data captured a biased proportion of the tide range: only observing ~68% of the modelled astronomical tide range, and never observing the lowest 24% of tides. The plot visually demonstrates the relationships between satellite observed tide heights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

Validating modelled tide heights

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

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

Furthermore, different ocean tide models perform differently in different coastal locations. `eo-tides` allows multiple tide models to be compared against GESLA data simultaneously (Figure 5), empowering users to make informed decisions and choose the optimal tide model that best suits their specific location or application.

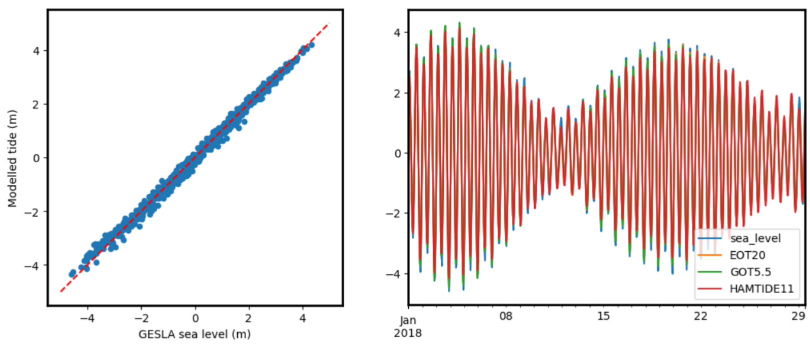

Figure 5: An example comparison of modelled tides from multiple global ocean tide models (EOT20, GOT5.5, HAMTIDE11) against observed sea level data from the Broome 62650 GESLA tide gauge, Western Australia.

Research projects

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

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