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

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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 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 the Open Data Cube (ODC)'s `odc-geo` (odc-geo contributors, 2024). This allows tides to be modelled in parallel using over 50 supported models, and returned in standardised `pandas` (McKinney, 2010; pandas development team, 2020) and `xarray` (Hoyer & Joseph, 2017) data formats for EO analysis.

`eo-tides` tools can be applied to petabytes of freely available satellite data loaded from the cloud using 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 where ocean tide model data exists.

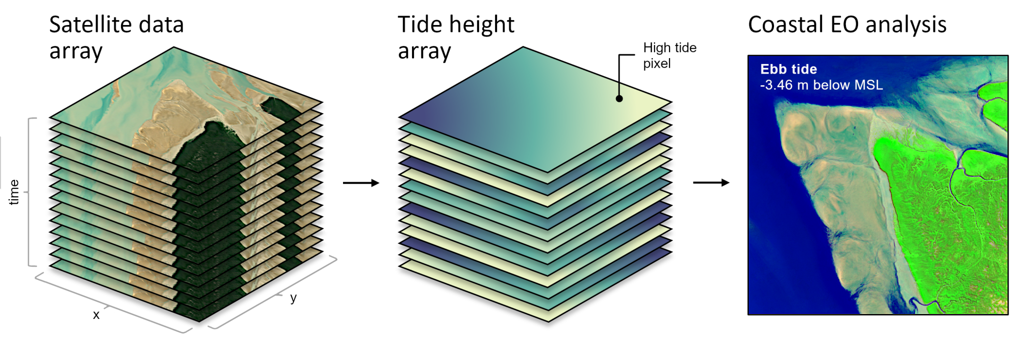

Figure 1: A typical `eo-tides` coastal EO workflow, with tide heights modelled into every pixel in a spatio-temporal stack of satellite data (e.g. Sentinel-2 or Landsat), then combined to derive insights into dynamic coastal environments.

Statement of need

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). However, the highly variable influence of ocean tides can complicate analyses, making it difficult to separate the influence of changing tides from patterns of true coastal change (Vos et al., 2023). This is a particularly challenging for large-scale coastal EO analyses, where failing to account for tide dynamics can lead to inaccurate or misleading insights into satellite-observed coastal processes.

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

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

Features

Setting up tide models

The `eo_tides.utils` module simplifies the setup of ocean tide models, addressing a common barrier to coastal EO workflows. Tools like `list_models` provide feedback on available and supported models (Figure 2), while `clip_models` can significantly improve performance by clipping large high-resolution model files (e.g. FES2022 (Carrere et al., 2022)) to smaller study area extents.

```
────────────────────────────────────────────────────────────
 🌊      | Model              | Expected path
────────────────────────────────────────────────────────────
 ✅      | EOT20              | tide_models/EOT20/ocean_tides
 ❌      | FES2022            | tide_models/fes2022b/ocean_tide
 ✅      | HAMTIDE11          | tide_models/hamtide
 ...       ...                  ...
────────────────────────────────────────────────────────────
Summary:
Available models: 2/50
```

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

Modelling tides

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

The model_tides function from eo_tides.model wraps pyTMD functionality to return tide predictions in a standardised pandas.DataFrame format, enabling integration with EO data and parallelisation for improved performance (Table 1). The model_phases function can additionally classify tides into high/low/flow/ebb phases, critical for correctly interpreting 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

Combining tides with satellite data

The eo_tides.eo module integrates modelled tides with xarray-format satellite data (Hoyer & Joseph, 2017). The tag_tides and pixel_tides functions (Table 2, Figure 3) can be applied to attribute tides to satellite data for any coastal location on the planet, for example using 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
- 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 small-scale analysis in non-complex tidal environments	- 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 and coastal product generation

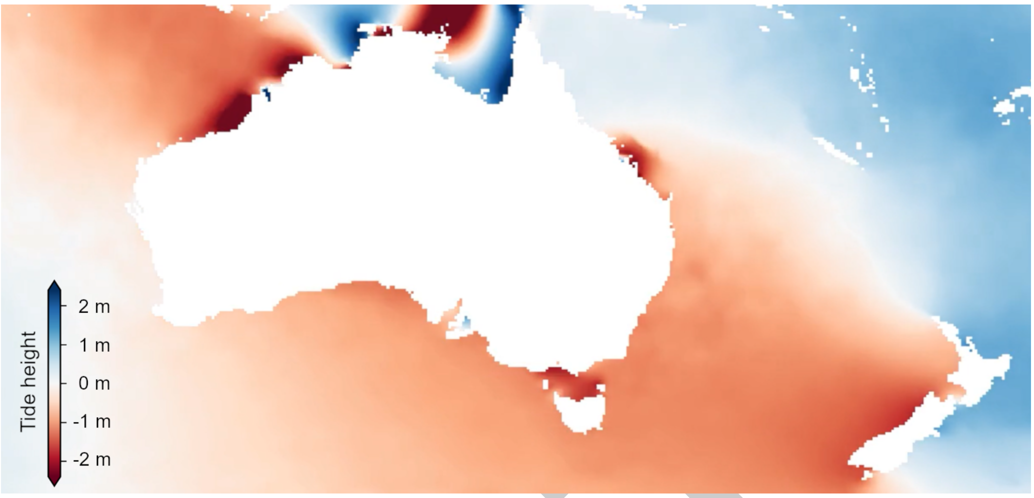

Figure 3: An example spatial tide height output produced by the `pixel_tides` function.

Calculating tide statistics and satellite biases

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

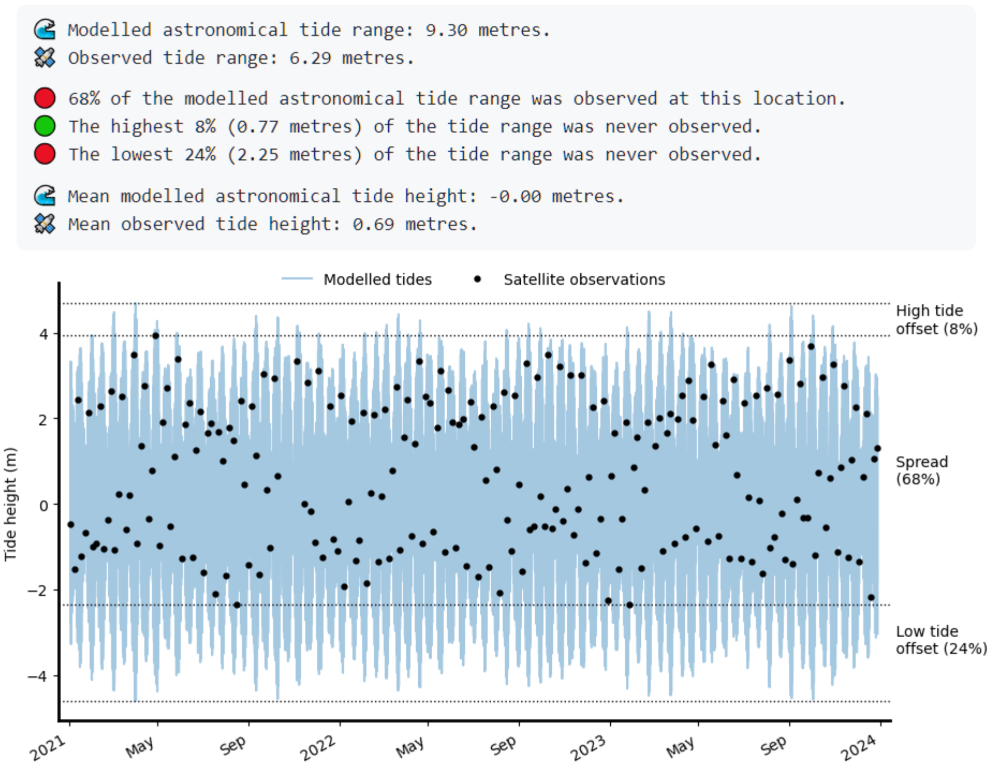

Figure 4: An example of tidally-biased satellite coverage, where only ~68% of the astronomical tide range is observed.

Validating modelled tides

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

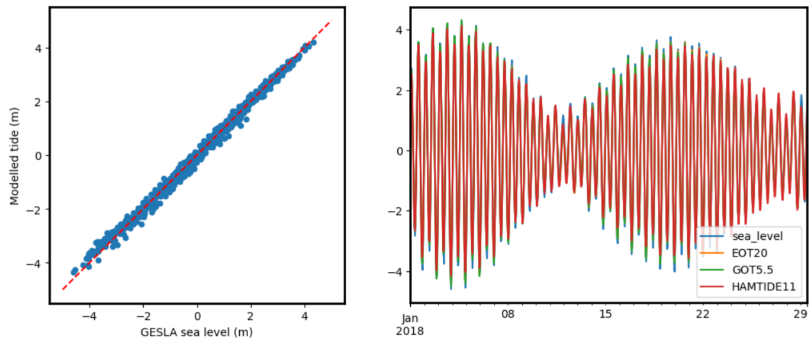

Figure 5: A comparison of multiple tide models (EOT20, GOT5.5, HAMTIDE11) against observed sea level data from the Broome 62650 GESLA tide gauge (Haigh et al., 2023).

Research projects

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

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References

Bishop-Taylor, R., Nanson, R., Sagar, S., & Lymburner, L. (2021). Mapping Australia's Dynamic Coastline at Mean Sea Level using Three Decades of Landsat Imagery. *Remote Sensing of Environment*, *267*, 112734. https://doi.org/10.1016/j.rse.2021.112734

Bishop-Taylor, R., Phillips, C., Newey, V., & Sagar, S. (2024). *Digital Earth Australia Intertidal*. Commonwealth of Australia (Geoscience Australia). https://doi.org/10.26186/149403

Bishop-Taylor, R., Sagar, S., Lymburner, L., & Beaman, R. J. (2019). Between the tides: Modelling the elevation of australia's exposed intertidal zone at continental scale. *Estuarine, Coastal and Shelf Science*, *223*, 115–128. https://doi.org/10.1016/j.ecss.2019.03.006

Carrere, L., Lyard, F., Cancet, M., Allain, D., Dabat, M.-L., Fouchet, E., Sahuc, E., Faugere, Y., Dibarboure, G., & Picot, N. (2022). A new barotropic tide model for global ocean: FES2022. *2022 Ocean Surface Topography Science Team Meeting*, 43. https://doi.org/10.24400/527896/a03-2022.3287

Eleveld, M. A., Van der Wal, D., & Van Kessel, T. (2014). Estuarine suspended particulate matter concentrations from sun-synchronous satellite remote sensing: Tidal and meteorological effects and biases. *Remote Sensing of Environment*, *143*, 204–215. https://doi.org/10.1016/j.rse.2013.12.019

Fitton, J. M., Rennie, A. F., Hansom, J. D., & Muir, F. M. E. (2021). Remotely sensed mapping of the intertidal zone: A Sentinel-2 and Google Earth Engine methodology. *Remote Sensing Applications: Society and Environment*, *22*(100499), 1–12. https://doi.org/10.1016/j.rsase.2021.100499

Fitzpatrick, S., Buscombe, D., Warrick, J. A., Lundine, M. A., & Vos, K. (2024). CoastSeg: An accessible and extendable hub for satellite-derived-shoreline (SDS) detection and mapping. *Journal of Open Source Software*, *9*(99), 6683. https://doi.org/10.21105/joss.06683

Haigh, I. D., Marcos, M., Talke, S. A., Woodworth, P. L., Hunter, J. R., Hague, B. S., Arns, A., Bradshaw, E., & Thompson, P. (2023). GESLA version 3: A major update to the global higher-frequency sea-level dataset. *Geoscience Data Journal*, *10*(3), 293–314. https://doi.org/10.1002/gdj3.174

Hoyer, S., & Joseph, H. (2017). xarray: N-d labeled arrays and datasets in python. *Journal of Open Research Software*, *5*(1). https://doi.org/10.5334/jors.148

Krause, C., Dunn, B., Bishop-Taylor, R., Adams, C., Burton, C., Alger, M., Chua, S., Phillips, C., Newey, V., Kouzoubov, K., Leith, A., Ayers, D., & Hicks, A. (2021). *Digital Earth Australia notebooks and tools repository*. https://github.com/GeoscienceAustralia/dea-notebooks/; Commonwealth of Australia (Geoscience Australia). https://doi.org/10.26186/145234

McKinney, Wes. (2010). Data Structures for Statistical Computing in Python. In Stéfan van der Walt & Jarrod Millman (Eds.), *Proceedings of the 9th Python in Science Conference* (pp. 56–61). https://doi.org/10.25080/Majora-92bf1922-00a

Murray, N. J., Phinn, S. R., Clemens, R. S., Roelfsema, C. M., & Fuller, R. A. (2012). Continental scale mapping of tidal flats across east asia using the landsat archive. *Remote Sensing*, *4*(11), 3417–3426. https://doi.org/10.3390/rs4113417

odc-geo contributors. (2024). Opendatacube/odc-geo. In *GitHub repository*. GitHub. https://github.com/opendatacube/odc-geo

pandas development team. (2020). *Pandas-dev/pandas: pandas* (latest). Zenodo. https://doi.org/10.5281/zenodo.3509134

Sagar, S., Phillips, C., Bala, B., Roberts, D., Lymburner, L., & Beaman, R. J. (2018). Generating continental scale pixel-based surface reflectance composites in coastal regions with the use of a multi-resolution tidal model. *Remote Sensing*, *10(3)*, 480. https://doi.org/10.3390/rs10030480

Sagar, S., Roberts, D., Bala, B., & Lymburner, L. (2017). Extracting the intertidal extent and topography of the australian coastline from a 28 year time series of landsat observations. *Remote Sensing of Environment*, *195*, 153–169. https://doi.org/10.1016/j.rse.2017.04.009

Sent, G., Antunes, C., Spyrakos, E., Jackson, T., Atwood, E. C., & Brito, A. C. (2025). What time is the tide? The importance of tides for ocean colour applications to estuaries. *Remote Sensing Applications: Society and Environment*, *37*, 101425. https://doi.org/10.2139/ssrn.4858713

STAC contributors. (2024). *SpatioTemporal Asset Catalog (STAC) specification*. https://stacspec.org

Sutterley, T. C., Alley, K., Brunt, K., Howard, S., Padman, L., & Siegried, M. (2017). *pyTMD: Python-based tidal prediction software*. Zenodo. https://doi.org/10.5281/zenodo.5555395

Turner, I. L., Harley, M. D., Almar, R., & Bergsma, E. W. J. (2021). Satellite optical imagery in Coastal Engineering. *Coastal Engineering*, *167*, 103919. https://doi.org/10.1016/j.coastaleng.2021.103919

Vitousek, S., Buscombe, D., Vos, K., Barnard, P. L., Ritchie, A. C., & Warrick, J. A. (2023). The future of coastal monitoring through satellite remote sensing. *Cambridge Prisms:*

Coastal Futures, 1, e10. https://doi.org/10.1017/cft.2022.4

Vos, K., Splinter, K. D., Palomar-Vázquez, J. E., Almonacid-Caballer, J., Cabezas-Rabadán, C., Kras, E. C., Luijendijk, A. P., Calkoen, F., Almeida, L. P., Pais, D., Klein, A. H. F., Mao, Y., Harris, D., Castelle, B., Buscombe, D., & Vitousek, S. (2023). Benchmarking satellite-derived shoreline mapping algorithms. *Communications Earth & Environment*, *4*(345). https://doi.org/https://doi.org/10.1038/s43247-023-01001-2