

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

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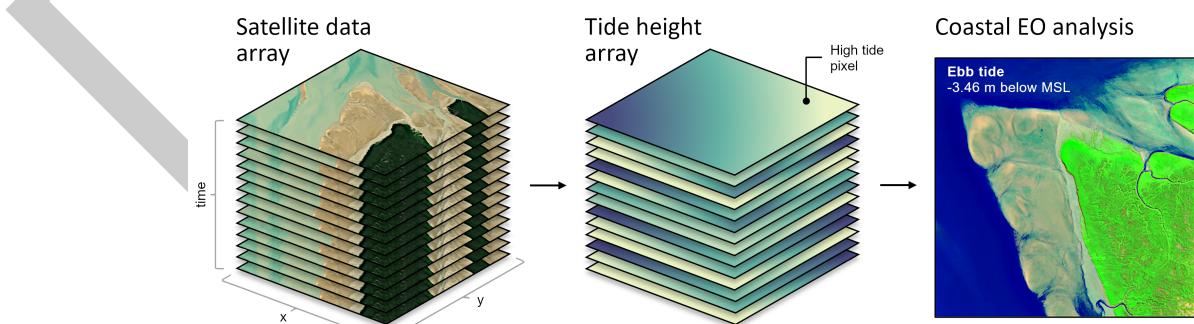
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## Summary

The eo-tides package provides powerful 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.

## <sup>26</sup> Statement of need

<sup>27</sup> 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).  
<sup>28</sup> However, the highly variable influence of ocean tides can complicate analyses, making it difficult  
<sup>29</sup> to separate the influence of changing tides from patterns of true coastal change (Vos et al.,  
<sup>30</sup> 2023). This is a particularly challenging for large-scale coastal EO analyses, where failing to  
<sup>31</sup> account for tide dynamics can lead to inaccurate or misleading insights into satellite-observed  
<sup>32</sup> coastal processes.

<sup>33</sup> Conversely, information about ocean tides can provide unique environmental insights that can  
<sup>34</sup> significantly enhance the value of EO data. Traditionally, satellite data dimensions include  
<sup>35</sup> the geographic “where” and temporal “when” of acquisition. Introducing tide height as an  
<sup>36</sup> additional analysis dimension allows data to be filtered, sorted, and analysed based on tidal  
<sup>37</sup> dynamics, offering a transformative re-imagining of traditional multi-temporal EO analysis  
<sup>38</sup> (Sagar et al., 2017). For instance, satellite data can be analysed to focus on ecologically  
<sup>39</sup> significant tidal stages (e.g., high tide, low tide, spring or neap tides) or specific tidal processes  
<sup>40</sup> (e.g., ebb or flow tides) (Sent et al., 2025).

<sup>41</sup> This concept has been used to map coastal change at continental-scale (Bishop-Taylor et  
<sup>42</sup> al., 2021), map intertidal zone extent and elevation (Bishop-Taylor et al., 2019; Fitton et  
<sup>43</sup> al., 2021; Murray et al., 2012; Sagar et al., 2017), and creating tidally-constrained coastal  
<sup>44</sup> image composites (Sagar et al., 2018). However, these methods have traditionally relied on  
<sup>45</sup> bespoke, closed-source, or difficult-to-install tide modelling tools, limiting their reproducibility  
<sup>46</sup> and portability. To support the next generation of coastal EO workflows, there is a pressing  
<sup>47</sup> need for efficient open-source tools for combining satellite data with tide modelling. eo-tides  
<sup>48</sup> addresses this need through functionality offered in five main analysis modules (utils, model,  
<sup>49</sup> eo, stats, validation).

## <sup>51</sup> Features

### <sup>52</sup> Setting up tide models

<sup>53</sup> The `eo_tides.utils` module simplifies the setup of ocean tide models, addressing a common  
<sup>54</sup> barrier to coastal EO workflows. Tools like `list_models` provide feedback on available and  
<sup>55</sup> supported models (Figure 2), while `clip_models` can significantly improve performance by  
<sup>56</sup> clipping large high-resolution model files (e.g. FES2022 (Carrere et al., 2022)) to smaller study  
<sup>57</sup> 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.

## 58    Modelling tides

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

62    The `model_tides` function from `eo_tides.model` wraps pyTMD functionality to return tide  
 63    predictions in a standardised `pandas.DataFrame` format, enabling integration with EO data  
 64    and parallelisation for improved performance (Table 1). The `model_phases` function can  
 65    additionally classify tides into high/low/flow/ebb phases, critical for correctly interpreting  
 66    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).

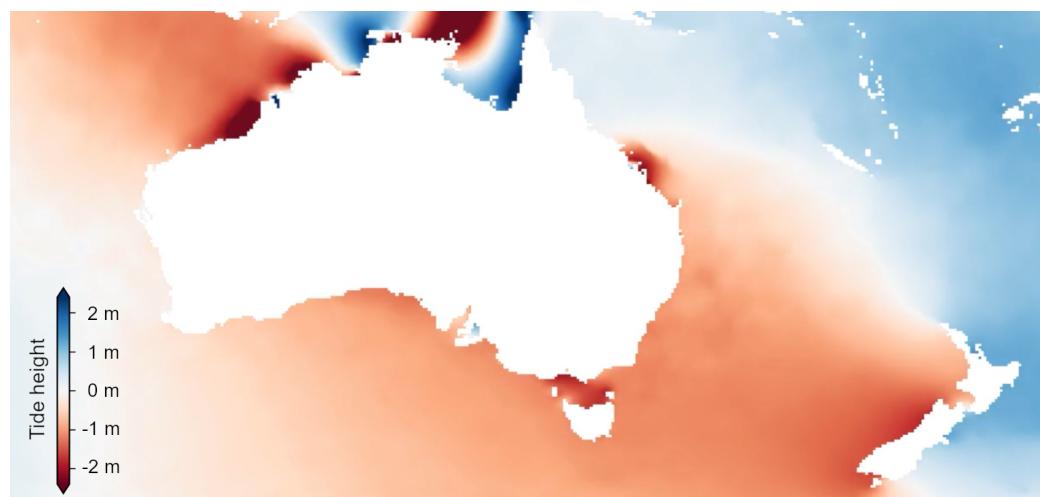
Cores	Parallelisation	No parallelisation	Speedup
8	2min 46s ± 663 ms	9min 28s ± 536 ms	3.4x
32	55.9 s ± 560 ms	9min 24s ± 749 ms	10.1x

## 67    Combining tides with satellite data

68    The `eo_tides.eo` module integrates modelled tides with xarray-format satellite data (Hoyer &  
 69    Joseph, 2017). The `tag_tides` and `pixel_tides` functions (Table 2, Figure 3) can be applied  
 70    to attribute tides to satellite data for any coastal location on the planet, for example using  
 71    open data loaded from the cloud using ODC and STAC (STAC contributors, 2024).

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

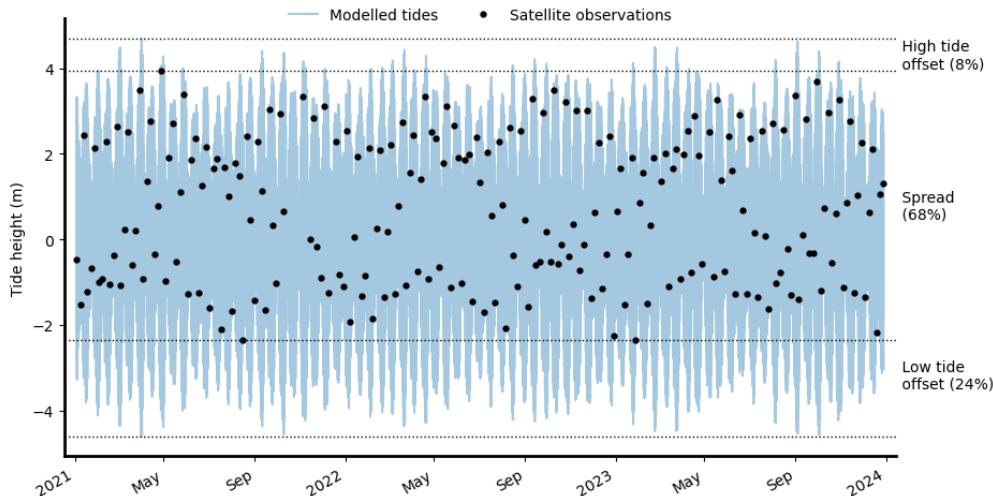
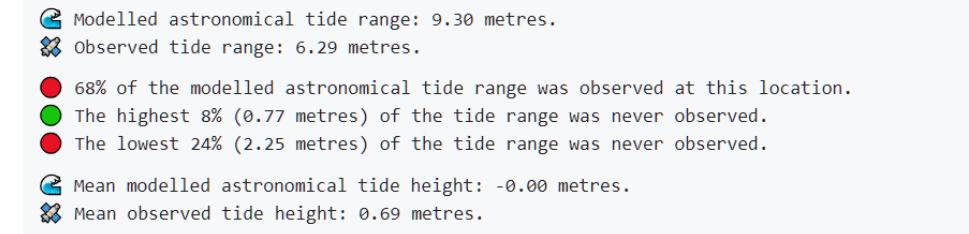
tag_tides	pixel_tides
<ul style="list-style-type: none"> <li>- Assigns a single tide height to each satellite image time-step</li> <li>- Single tide height per image can produce artefacts and discontinuities</li> <li>- Fast, low memory use</li> <li>- Ideal for small-scale analysis in non-complex tidal environments</li> </ul>	<ul style="list-style-type: none"> <li>- Assigns a tide height to every individual pixel through time</li> <li>- Produce spatially seamless results across large regions</li> <li>- Slower, higher memory use</li> <li>- Ideal for large-scale analysis and coastal product generation</li> </ul>



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

## 72 Calculating tide statistics and satellite biases

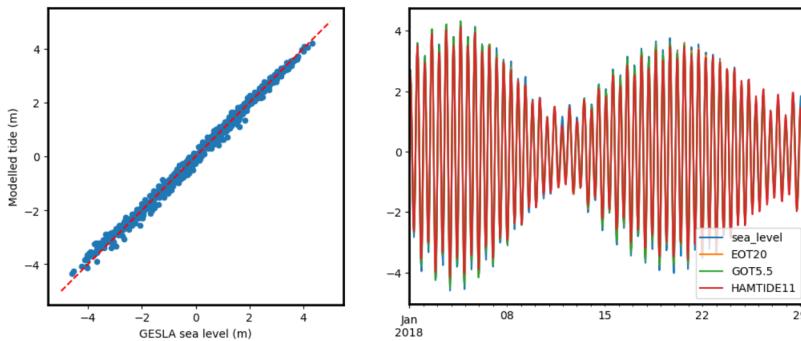
73 The `eo_tides.stats` module identifies biases caused by complex tide aliasing interactions that  
 74 can prevent satellites from observing the entire tide cycle (Bishop-Taylor et al., 2019; Elefeldt  
 75 et al., 2014; Sent et al., 2025). The `tide_stats` and `pixel_stats` functions produce useful  
 76 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.

## 77    Validating modelled tides

78    The `eo_tides.validation` module validates modelled tides against observed sea-level measure-  
 79    ments, 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).

## 80    Research projects

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

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86    Functions from eo-tides were originally developed in the Digital Earth Australia Notebooks  
 87    repository (Krause et al., 2021). This paper is published with the permission of the Chief  
 88    Executive Officer, Geoscience Australia.

## 89    References

- 90    Bishop-Taylor, R., Nanson, R., Sagar, S., & Lymburner, L. (2021). Mapping Australia's  
 91    Dynamic Coastline at Mean Sea Level using Three Decades of Landsat Imagery. *Remote  
 92    Sensing of Environment*, 267, 112734. <https://doi.org/10.1016/j.rse.2021.112734>
- 93    Bishop-Taylor, R., Phillips, C., Newey, V., & Sagar, S. (2024). *Digital Earth Australia Intertidal*.  
 94    Commonwealth of Australia (Geoscience Australia). <https://doi.org/10.26186/149403>
- 95    Bishop-Taylor, R., Sagar, S., Lymburner, L., & Beaman, R. J. (2019). Between the tides:  
 96    Modelling the elevation of australia's exposed intertidal zone at continental scale. *Estuarine,  
 97    Coastal and Shelf Science*, 223, 115–128. <https://doi.org/10.1016/j.ecss.2019.03.006>
- 98    Carrere, L., Lyard, F., Cancet, M., Allain, D., Dabat, M.-L., Fouchet, E., Sahuc, E., Faugere,  
 99    Y., Dibarboire, G., & Picot, N. (2022). A new barotropic tide model for global ocean:  
 100    FES2022. *2022 Ocean Surface Topography Science Team Meeting*, 43. <https://doi.org/10.24400/527896/a03-2022.3287>
- 102    Eleveld, M. A., Van der Wal, D., & Van Kessel, T. (2014). Estuarine suspended par-  
 103    ticulate matter concentrations from sun-synchronous satellite remote sensing: Tidal  
 104    and meteorological effects and biases. *Remote Sensing of Environment*, 143, 204–215.  
 105    <https://doi.org/10.1016/j.rse.2013.12.019>

- 106 Fitton, J. M., Rennie, A. F., Hansom, J. D., & Muir, F. M. E. (2021). Remotely sensed  
107 mapping of the intertidal zone: A Sentinel-2 and Google Earth Engine methodology. *Remote*  
108 *Sensing Applications: Society and Environment*, 22(100499), 1–12. <https://doi.org/10.1016/j.rsase.2021.100499>
- 110 Fitzpatrick, S., Buscombe, D., Warrick, J. A., Lundine, M. A., & Vos, K. (2024). CoastSeg: An  
111 accessible and extendable hub for satellite-derived-shoreline (SDS) detection and mapping.  
112 *Journal of Open Source Software*, 9(99), 6683. <https://doi.org/10.21105/joss.06683>
- 113 Haigh, I. D., Marcos, M., Talke, S. A., Woodworth, P. L., Hunter, J. R., Hague, B. S.,  
114 Arns, A., Bradshaw, E., & Thompson, P. (2023). GESLA version 3: A major update to  
115 the global higher-frequency sea-level dataset. *Geoscience Data Journal*, 10(3), 293–314.  
116 <https://doi.org/10.1002/gdj3.174>
- 117 Hoyer, S., & Joseph, H. (2017). xarray: N-d labeled arrays and datasets in python. *Journal of*  
118 *Open Research Software*, 5(1). <https://doi.org/10.5334/jors.148>
- 119 Krause, C., Dunn, B., Bishop-Taylor, R., Adams, C., Burton, C., Alger, M., Chua, S., Phillips, C.,  
120 Newey, V., Kouzoubov, K., Leith, A., Ayers, D., & Hicks, A. (2021). *Digital Earth Australia*  
121 *notebooks and tools repository*. <https://github.com/GeoscienceAustralia/dea-notebooks/>;  
122 Commonwealth of Australia (Geoscience Australia). <https://doi.org/10.26186/145234>
- 123 McKinney, Wes. (2010). Data Structures for Statistical Computing in Python. In Stéfan van  
124 der Walt & Jarrod Millman (Eds.), *Proceedings of the 9th Python in Science Conference*  
125 (pp. 56–61). <https://doi.org/10.25080/Majora-92bf1922-00a>
- 126 Murray, N. J., Phinn, S. R., Clemens, R. S., Roelfsema, C. M., & Fuller, R. A. (2012).  
127 Continental scale mapping of tidal flats across east asia using the landsat archive. *Remote*  
128 *Sensing*, 4(11), 3417–3426. <https://doi.org/10.3390/rs4113417>
- 129 odc-geo contributors. (2024). Opendatacube/odc-geo. In *GitHub repository*. GitHub.  
130 <https://github.com/opendatacube/odc-geo>
- 131 pandas development team. (2020). *Pandas-dev/pandas: pandas* (latest). Zenodo. <https://doi.org/10.5281/zenodo.3509134>
- 133 Sagar, S., Phillips, C., Bala, B., Roberts, D., Lymburner, L., & Beaman, R. J. (2018).  
134 Generating continental scale pixel-based surface reflectance composites in coastal regions  
135 with the use of a multi-resolution tidal model. *Remote Sensing*, 10(3), 480. <https://doi.org/10.3390/rs10030480>
- 137 Sagar, S., Roberts, D., Bala, B., & Lymburner, L. (2017). Extracting the intertidal extent and  
138 topography of the australian coastline from a 28 year time series of landsat observations.  
139 *Remote Sensing of Environment*, 195, 153–169. <https://doi.org/10.1016/j.rse.2017.04.009>
- 140 Sent, G., Antunes, C., Spyракος, E., Jackson, T., Atwood, E. C., & Brito, A. C. (2025). What  
141 time is the tide? The importance of tides for ocean colour applications to estuaries. *Remote*  
142 *Sensing Applications: Society and Environment*, 37, 101425. <https://doi.org/10.2139/ssrn.4858713>
- 144 STAC contributors. (2024). *SpatioTemporal Asset Catalog (STAC) specification*. <https://stacspec.org>
- 146 Sutterley, T. C., Alley, K., Brunt, K., Howard, S., Padman, L., & Siegried, M. (2017). *pyTMD:*  
147 *Python-based tidal prediction software*. Zenodo. <https://doi.org/10.5281/zenodo.5555395>
- 148 Turner, I. L., Harley, M. D., Almar, R., & Bergsma, E. W. J. (2021). Satellite optical imagery  
149 in Coastal Engineering. *Coastal Engineering*, 167, 103919. <https://doi.org/10.1016/j.coastaleng.2021.103919>
- 151 Vitousek, S., Buscombe, D., Vos, K., Barnard, P. L., Ritchie, A. C., & Warrick, J. A. (2023).  
152 The future of coastal monitoring through satellite remote sensing. *Cambridge Prisms*:

153        *Coastal Futures*, 1, e10. <https://doi.org/10.1017/cft.2022.4>

154        Vos, K., Splinter, K. D., Palomar-Vázquez, J. E., Almonacid-Caballer, J., Cabezas-Rabadán,  
155        C., Kras, E. C., Luijendijk, A. P., Calkoen, F., Almeida, L. P., Pais, D., Klein, A. H. F.,  
156        Mao, Y., Harris, D., Castelle, B., Buscombe, D., & Vitousek, S. (2023). Benchmarking  
157        satellite-derived shoreline mapping algorithms. *Communications Earth & Environment*,  
158        4(345). <https://doi.org/10.1038/s43247-023-01001-2>

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