Realization of Chart Datum and Its Connection to the Mainland Height System

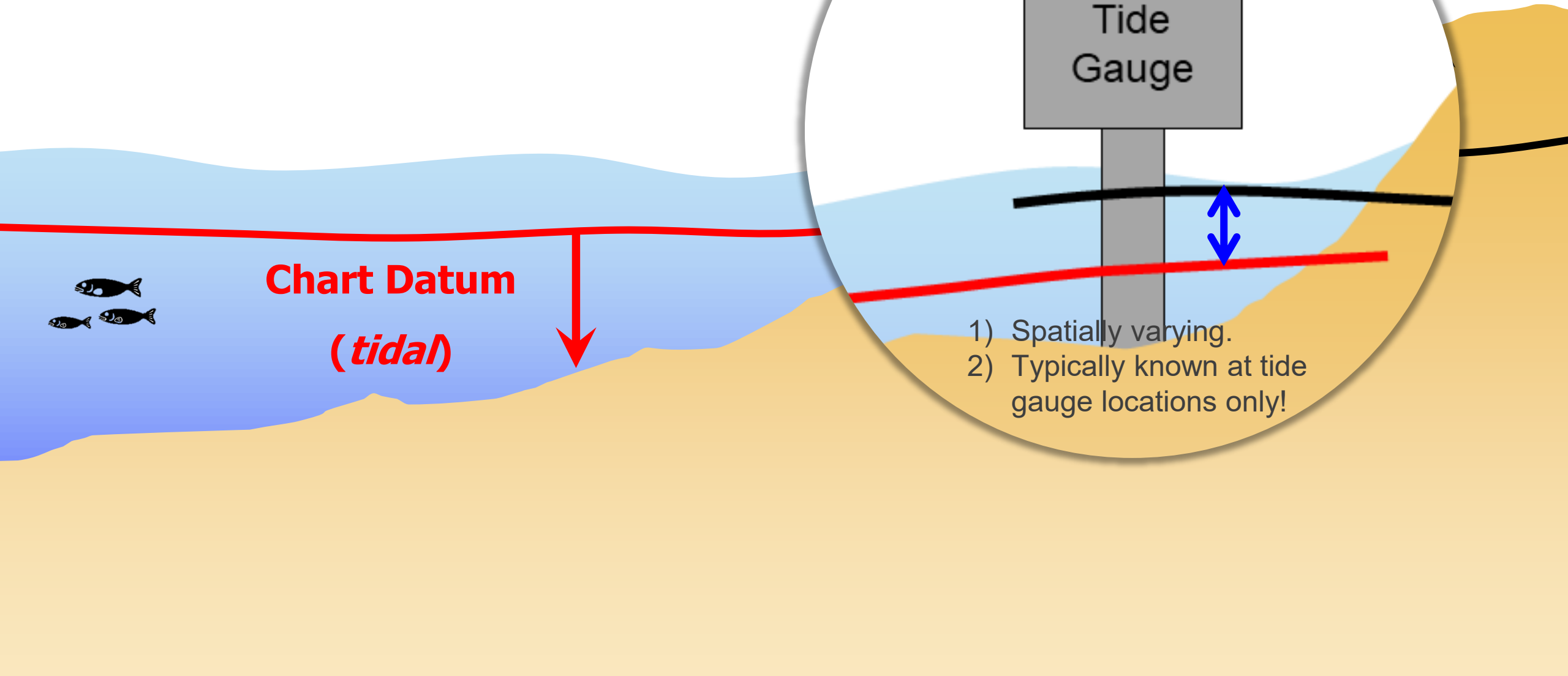
Cornelis Slobbe

TU Delft


This is an interdisciplinary exercise and not just about linking reference surfaces...
...It's about bringing together different professional worlds / disciplines, each holding a part of the solution!

Content

The Need for a CD Model...



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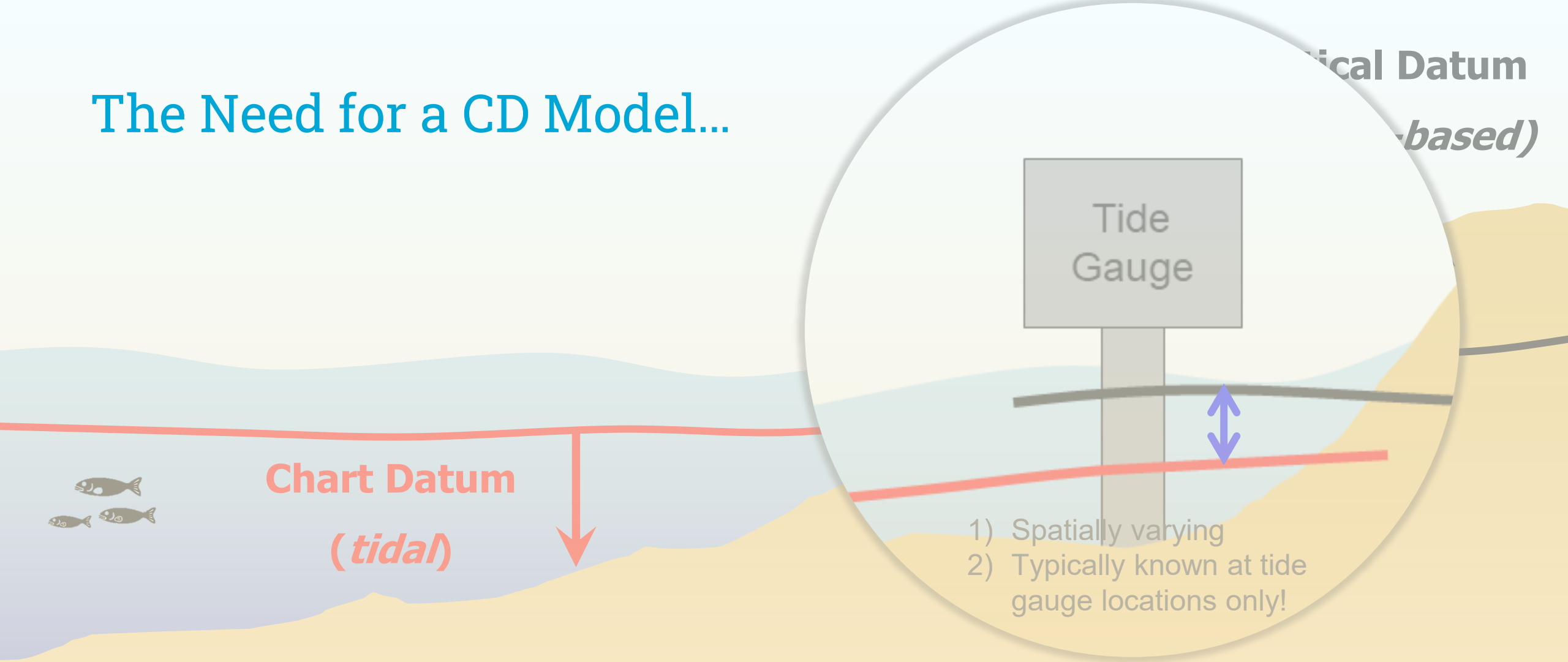
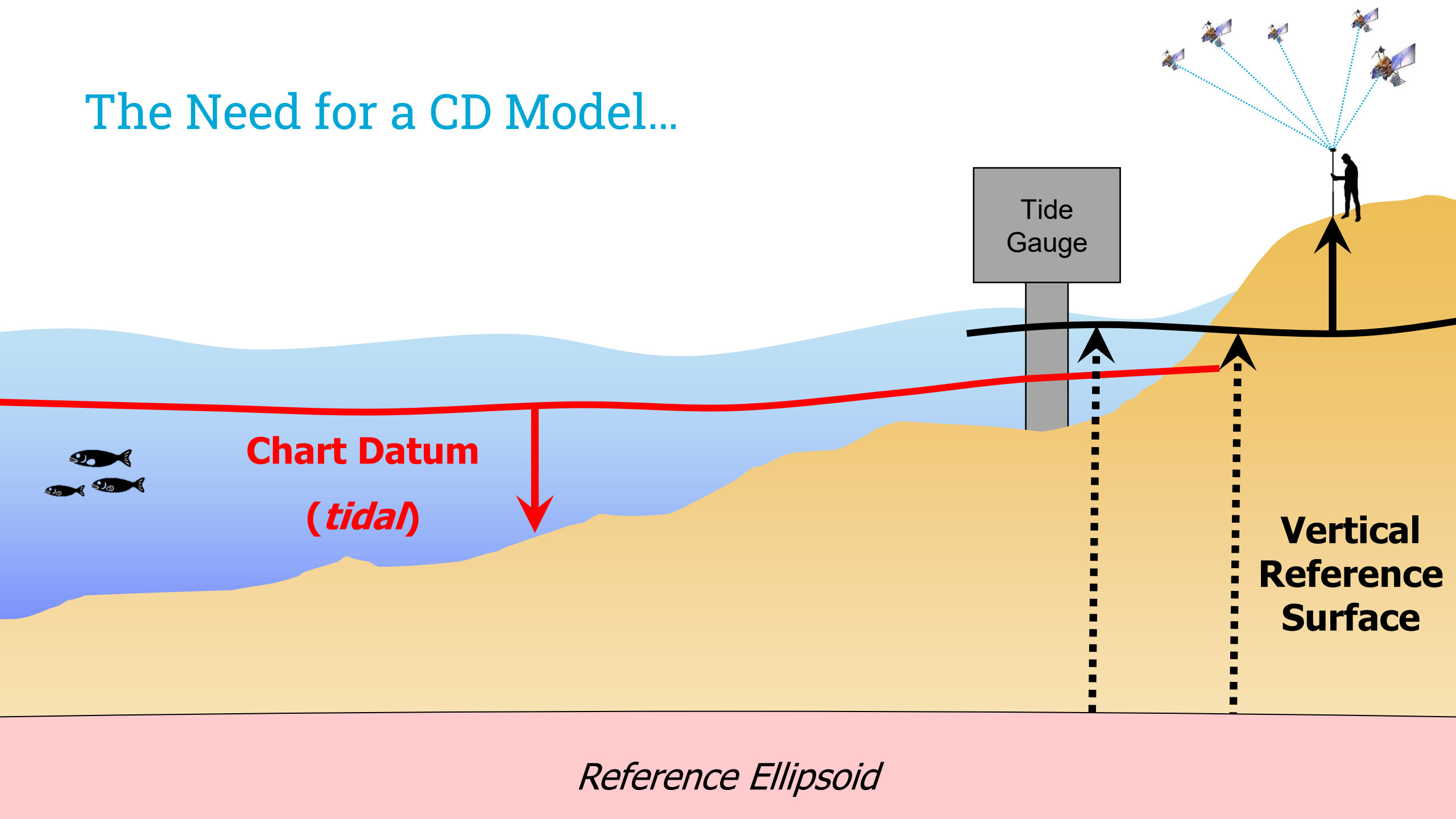


To enable the integration of land and sea datasets, both reference surfaces need to be described in 3D space.

The Need for a CD Model...



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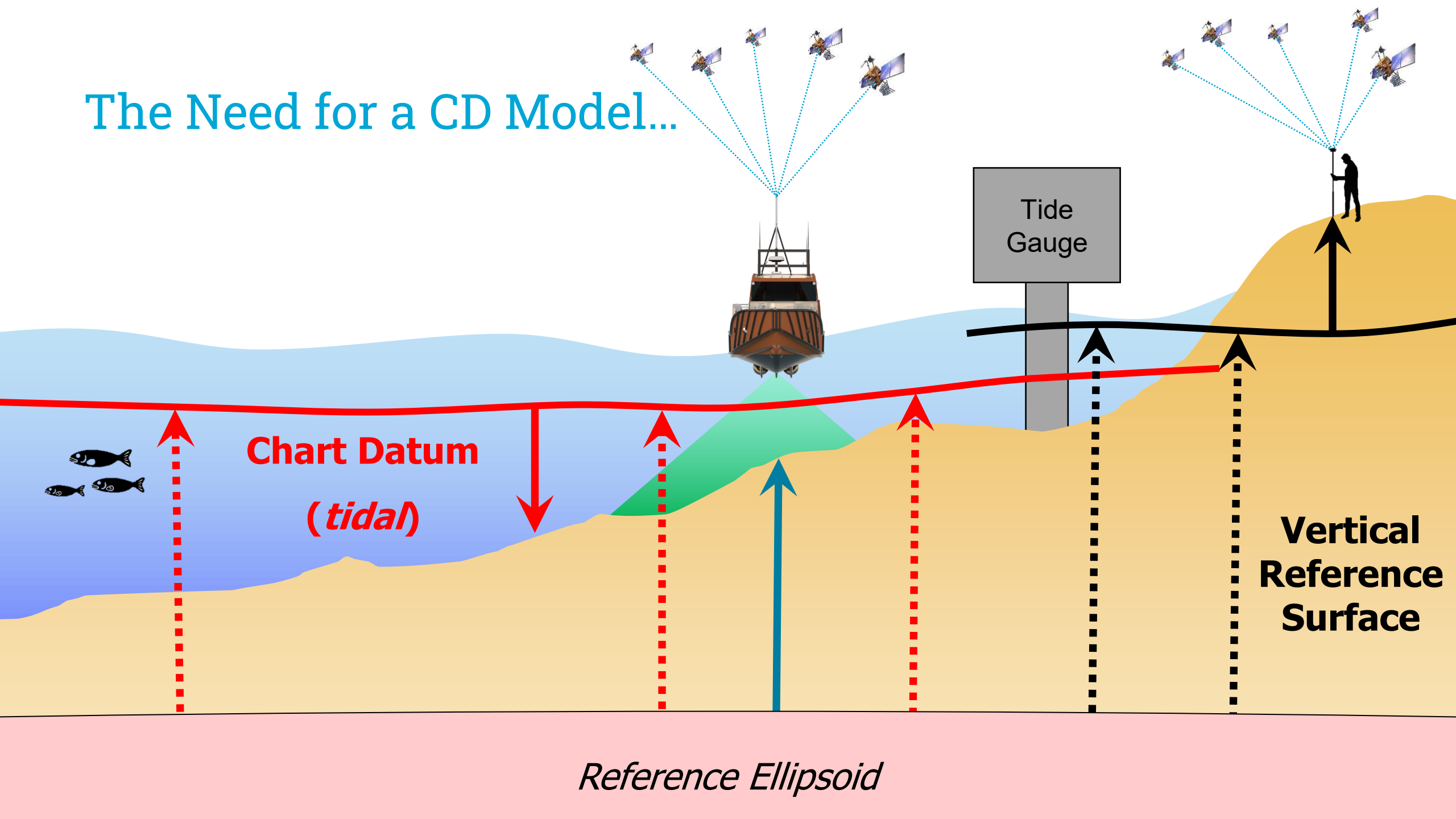

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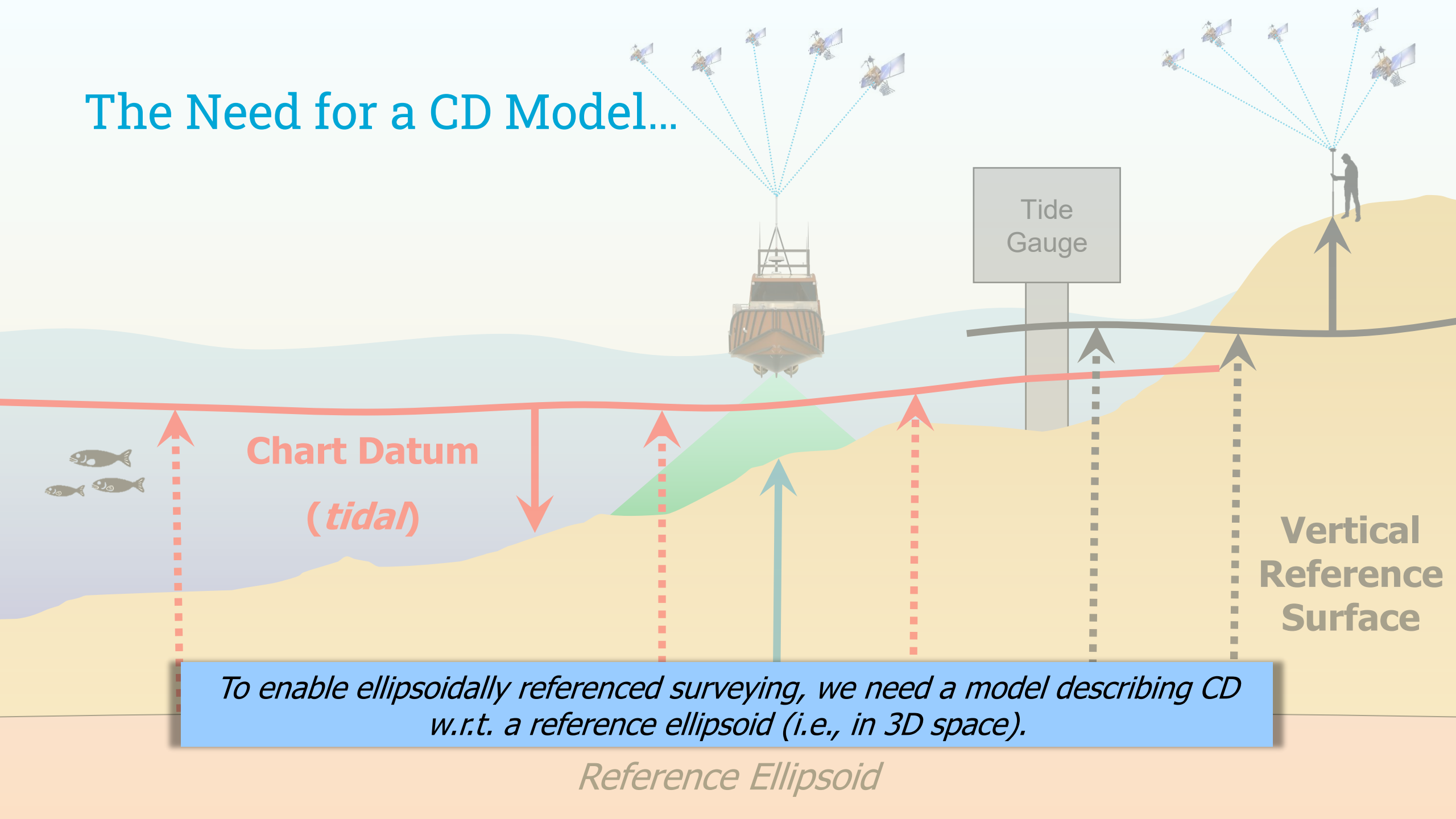


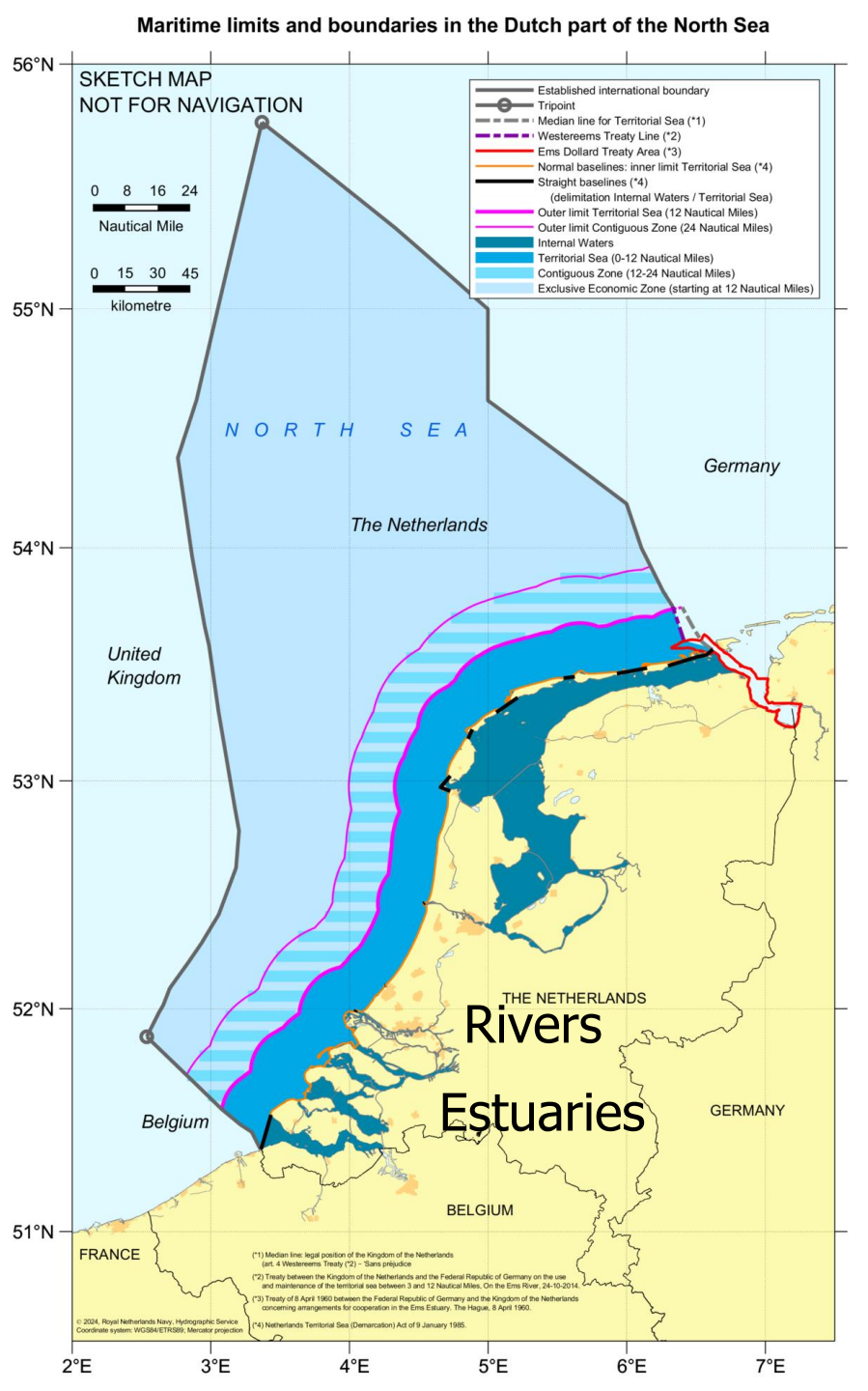
To enable ellipsoidally referenced surveying, we need a model describing CD w.r.t. a reference ellipsoid (i.e., in 3D space).

The CD Model Needs to Cover…

Exclusive Economic Zone

Coastal Waters

Inland Seas



The Question…

How to obtain ellipsoidal heights of Chart Datum?

I will not focus on rivers…

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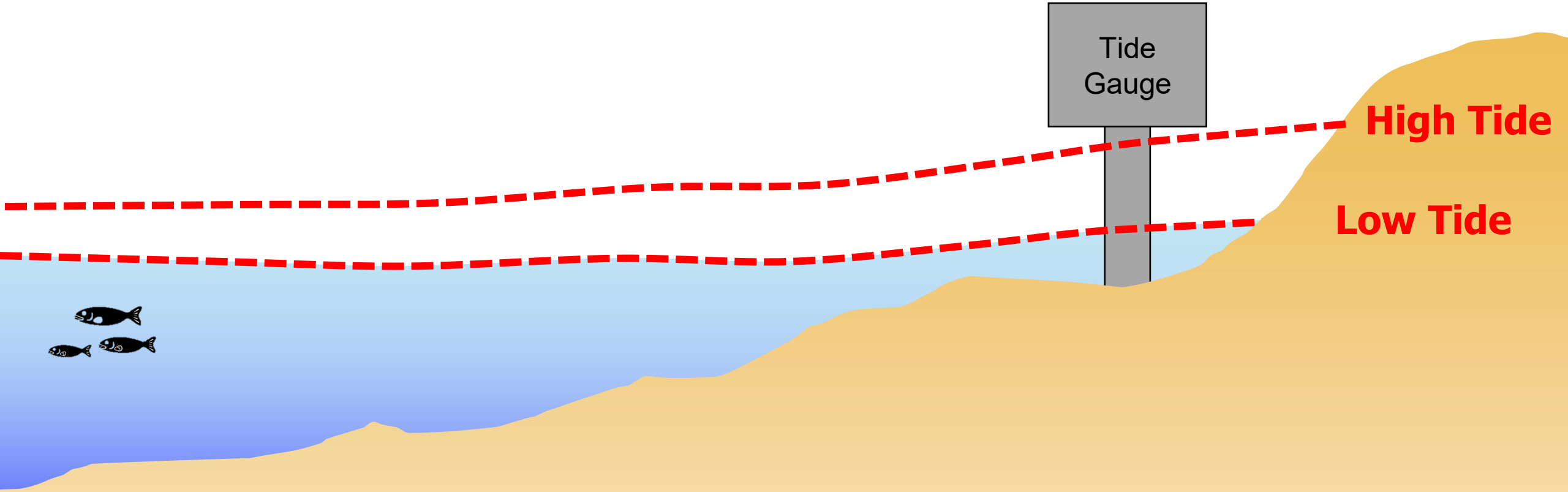
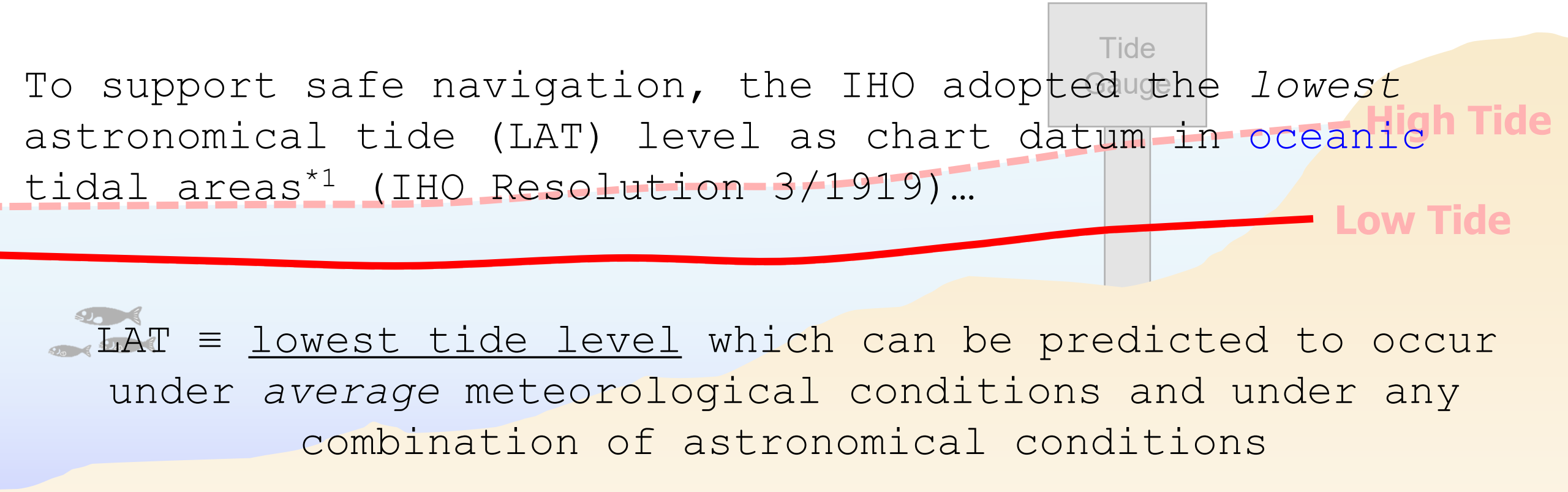
Tidal Datums



A tidal datum is a standard elevation defined by a certain phase of the tide (NOAA, 2025).

Chart Datum

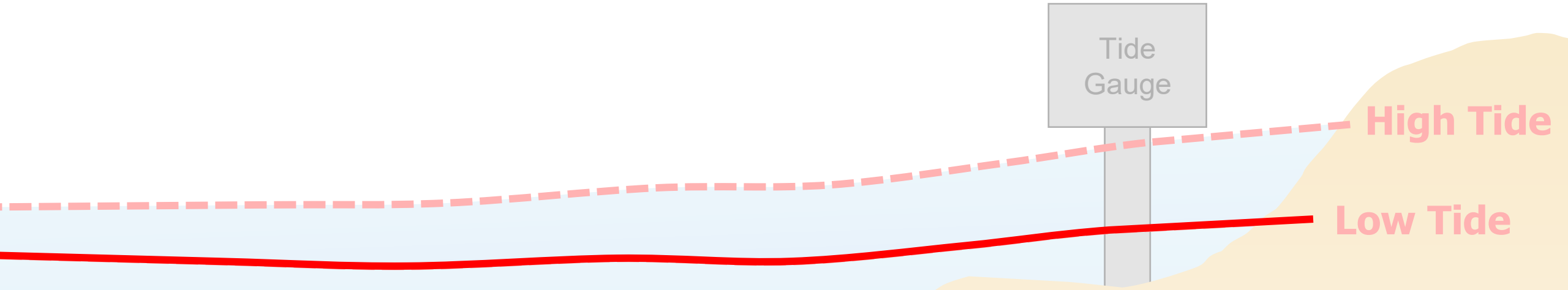
To support safe navigation, the IHO adopted the *lowest* astronomical tide (LAT) level as chart datum in oceanic tidal areas[*1] (IHO Resolution 3/1919)…



LAT ≡ <u>lowest tide level</u> which can be predicted to occur under *average* meteorological conditions and under any combination of astronomical conditions

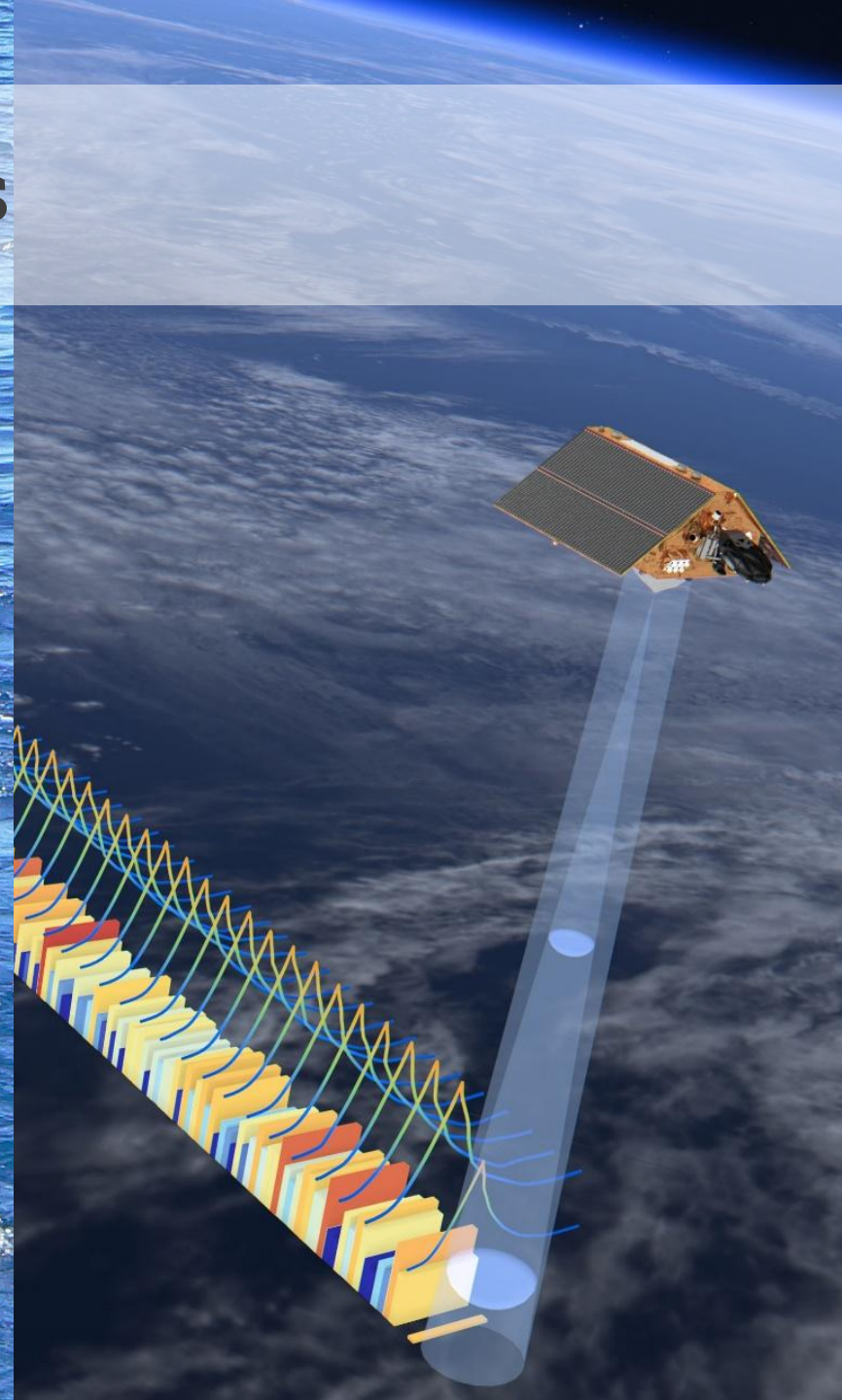
[*1] not in mixed/inland/non-tidal waters

IHO's Recommendation…



"It is recommended that LAT and HAT be calculated either over a minimum period of 19 years using harmonic constants derived from a minimum of one year's observations or by other proven methods known to give reliable results. Tide levels should, if possible, reflect the estimated uncertainty values obtained during the determination of these levels."

Needed: Observed Water Level Records



Needed: Observed Water Level Records

Temporal Resolution:	**High (5–10 minutes)**	**Low (~10 days)**
Spatial Coverage:	**Poor (mostly coastal areas)**	**Good (global coverage, except near poles & in coastal waters)**
Data Availability:	**Often restricted; not always publicly available**	**Freely and publicly available (since 1992)**
Continuity & Homogeneity of Records:	**Often discontinuous and inhomogeneous over long periods**	**Continuous and homogeneous long-term record (since 1992)**
Reference Frame:	**May use local datum; not necessarily referenced to ellipsoid**	**Referenced to ellipsoid**
Impact of Vertical Land Motion:	**Affected (unless corrected using GNSS)**	**Not affected**

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Impa

Tide gauges offer high temporal resolution and 'coverage' in coastal regions, while satellite radar altimetry provides broad spatial coverage over open oceans.

→ Both are essential!

The 'Ocean Tide Model-Derived' CD Model

- **Strategy:** Combine CD estimates from altimeter-derived tidal atlases (i.e., empirical ocean tide models) & mean sea surface (MSS) models with estimates derived from tide gauge records.
- **Available models**: DTU23 Global Ocean Tide model (DTU Space), EOT20 (DGFI-TUM), GOT5.6 (Goddard Space Flight Center).
- **Key differences** between models:
  - Estimation procedure *(e.g., response method vs. harmonic analysis).*
  - Data used *(e.g., missions, time span, data above 66° latitude).*
  - Spatial resolution *(1/8° – 1/16°).*
  - The constituents being estimated / inferred.
  - Treatment of self-attraction and loading *(in EOT/GOT, loading tides are separated from ocean tides).*

→ No single model performs best in all regions!

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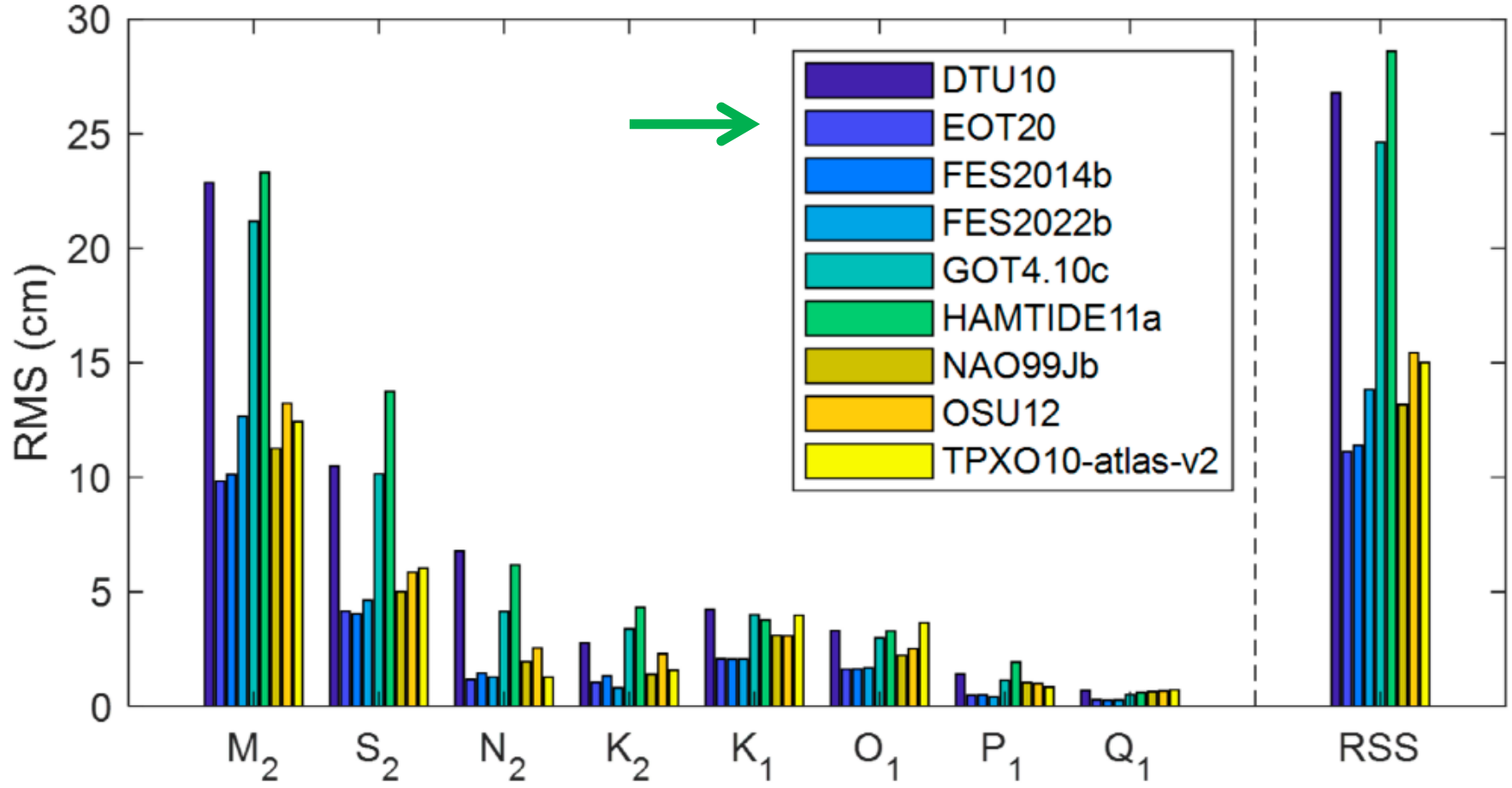
If we want to rely on observations only...

Alternative: Use Assimilative Ocean Tide Model

- Assimilative Ocean Tide Models combine numerical modeling with data assimilation.
- **Available models**: FES2022b (CNES), TPXO10 (OSU).
- **Key differences** compared to empirical ocean tide models:
  - Tide gauge-derived tides already incorporated *(FES: limited to a set of 295 tide gauges).*
  - Provided at higher spatial resolution *(1/30° degrees).*
  - More tidal constituents included *(34 for FES2022b; not all improved by data assimilation).*

→ The accuracy is not necessarily better!

Validation in the Eastern China Marginal Seas



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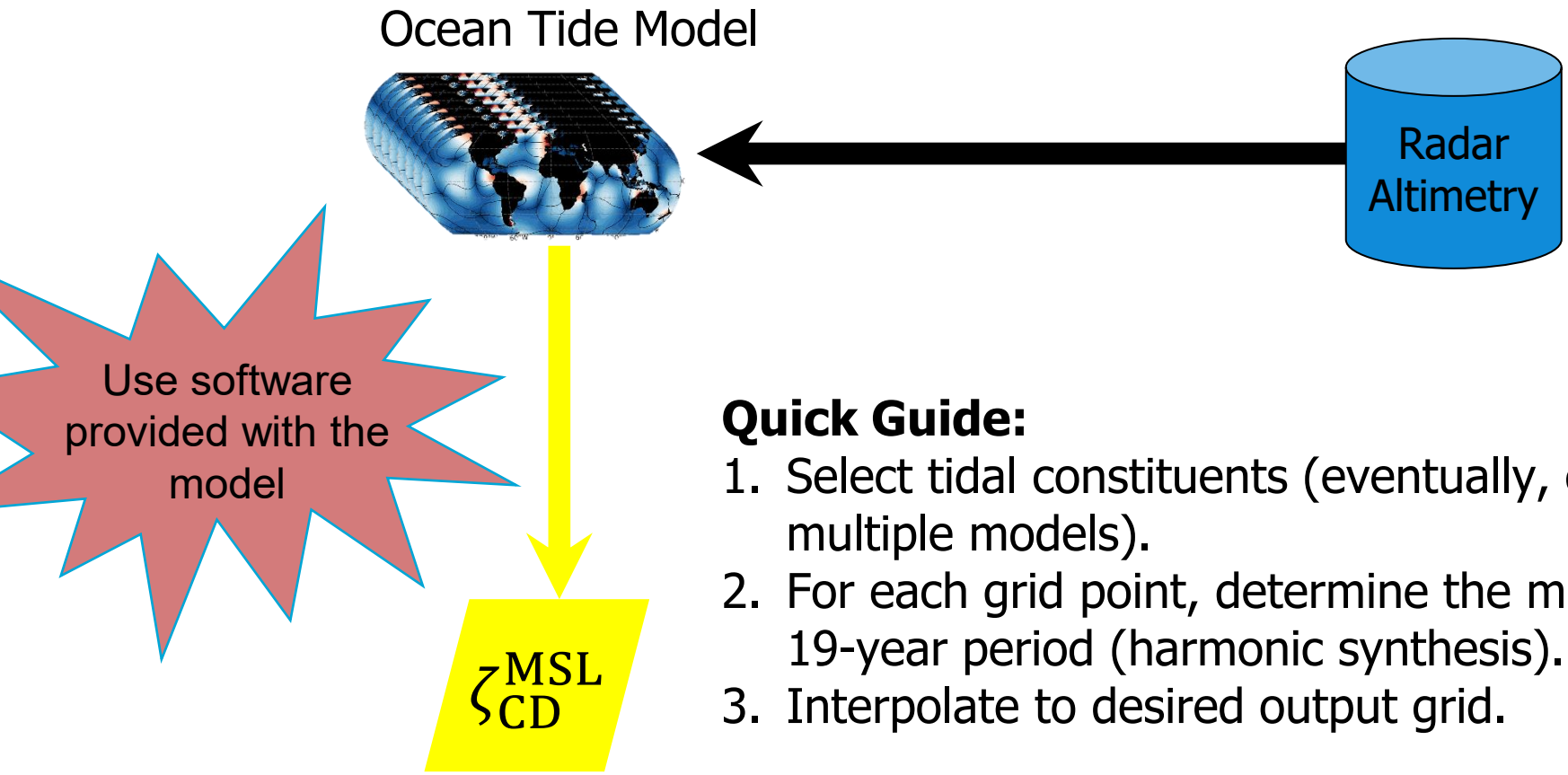
Wang, J., & He, X. (2025). Accuracy Assessment of Ocean Tide Models in the Eastern China Marginal Seas Using Tide Gauge and GPS Data. Journal of Marine Science and Engineering, 13(3), 395. https://doi.org/10.3390/jmse13030395

The 'Ocean Tide Model-Derived' CD Model

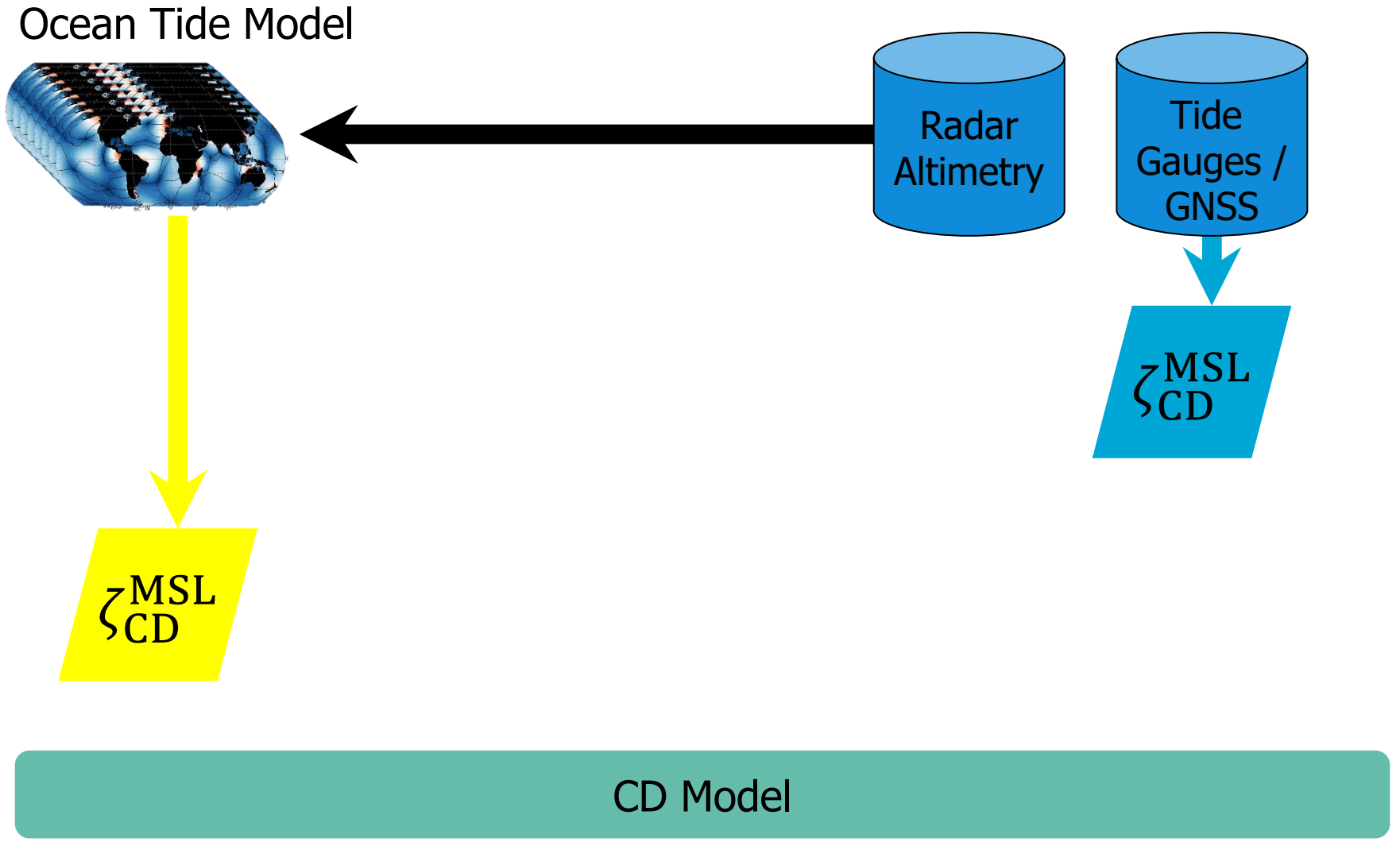


Quick Guide:

1. Select tidal constituents (eventually, combine constituents from multiple models).
2. For each grid point, determine the minimum tidal water level over a 19-year period (harmonic synthesis).
3. Interpolate to desired output grid.

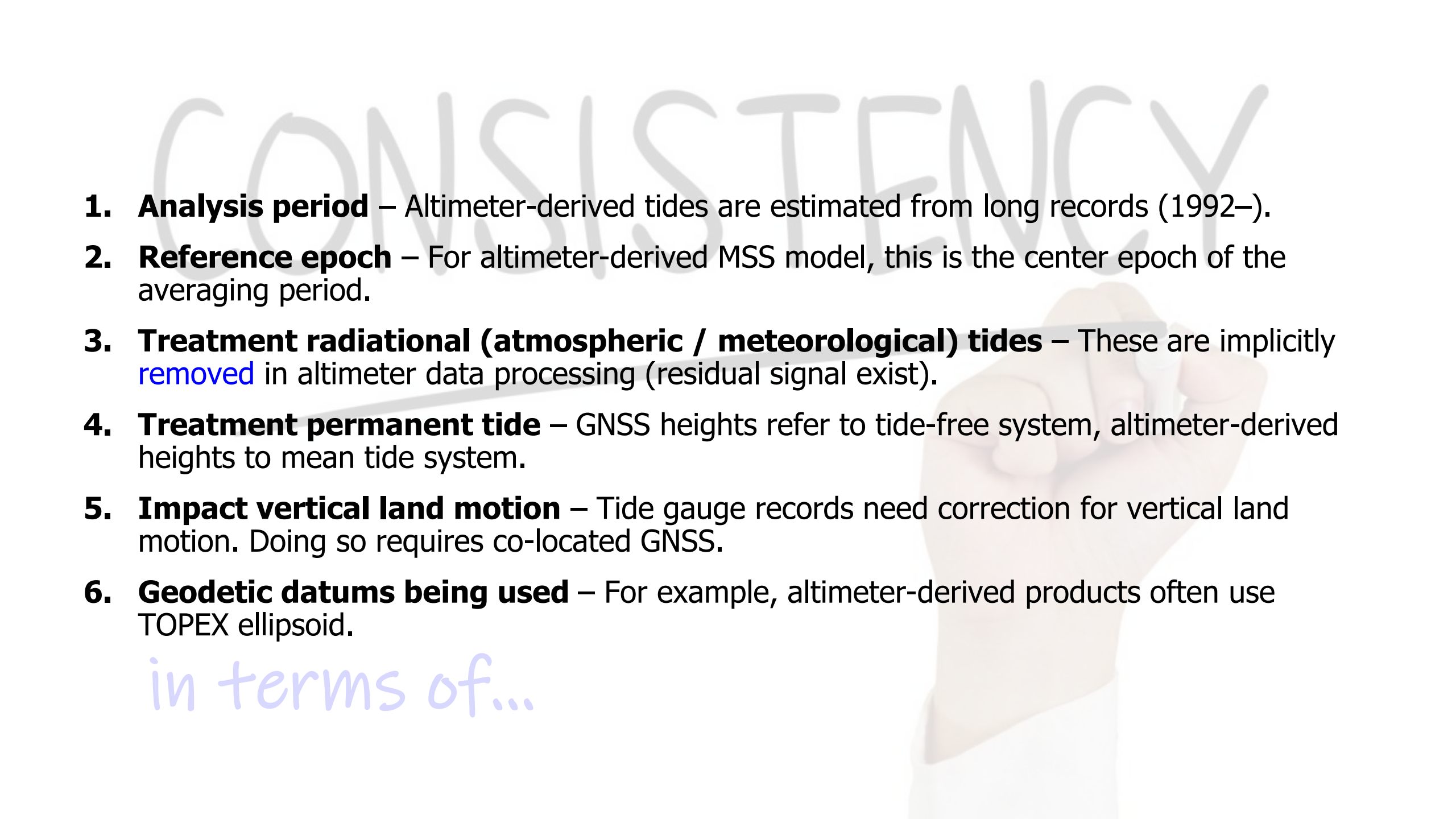
CD Model

The ‘Ocean Tide Model-Derived’ CD Model



CONSISTENCY

in terms of...



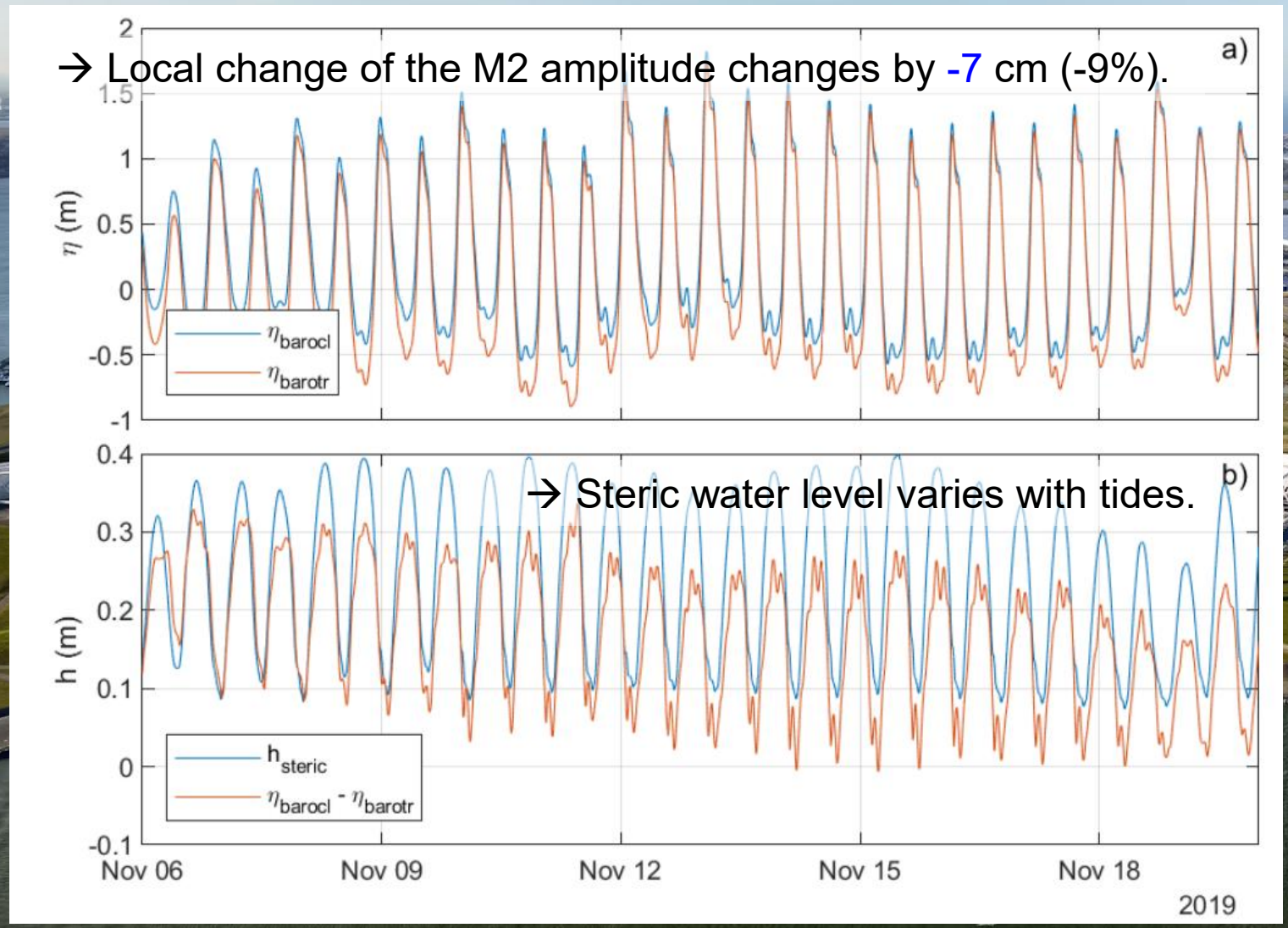
1. **Analysis period** – Altimeter-derived tides are estimated from long records (1992–).
2. **Reference epoch** – For altimeter-derived MSS model, this is the center epoch of the averaging period.
3. **Treatment radiational (atmospheric / meteorological) tides** – These are implicitly removed in altimeter data processing (residual signal exist).
4. **Treatment permanent tide** – GNSS heights refer to tide-free system, altimeter-derived heights to mean tide system.
5. **Impact vertical land motion** – Tide gauge records need correction for vertical land motion. Doing so requires co-located GNSS.
6. **Geodetic datums being used** – For example, altimeter-derived products often use TOPEX ellipsoid.

in terms of...

On the Use of Tide Gauges in River Mouths…

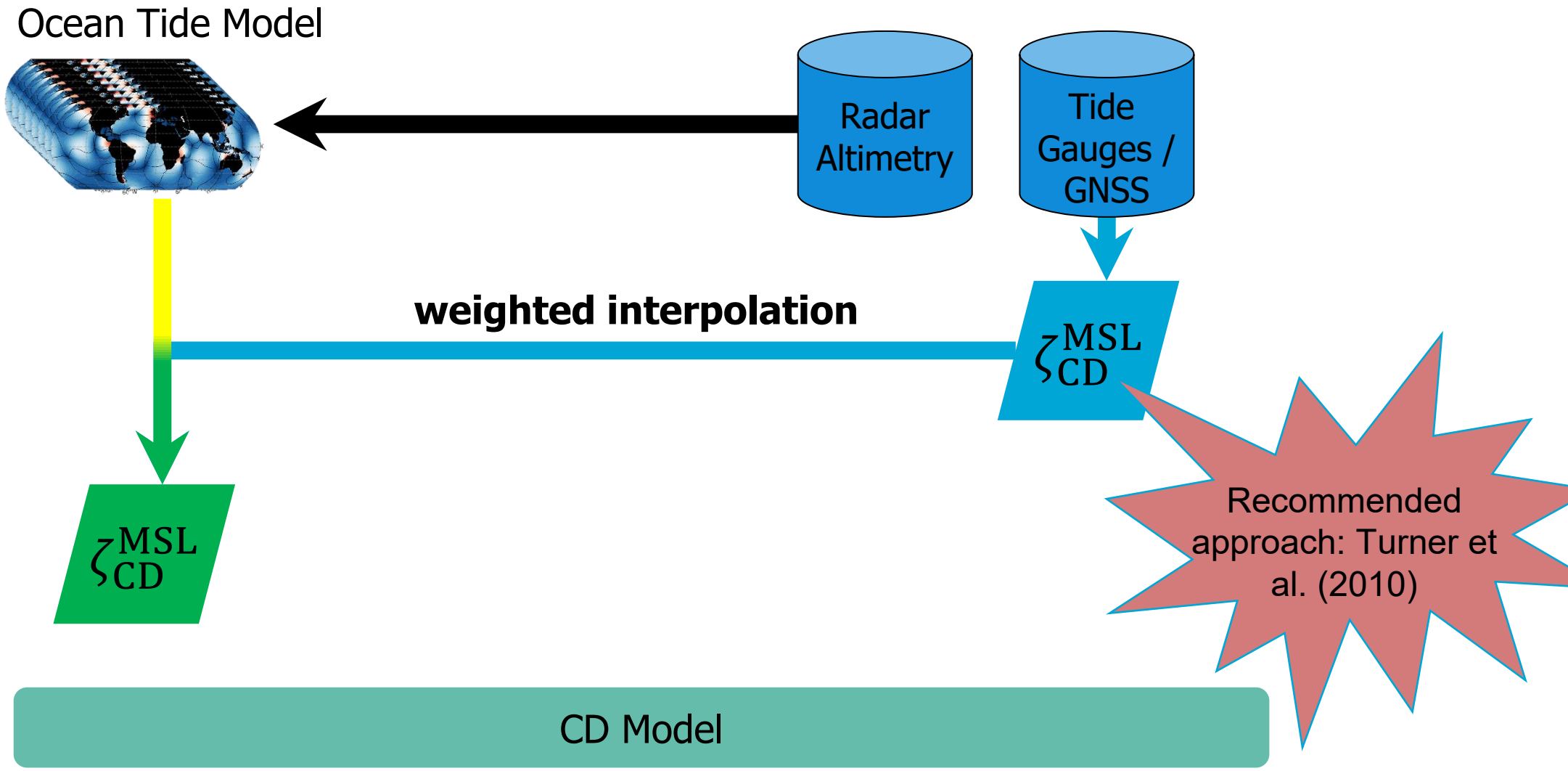
L.M. Keyzer (2025). The Rhine River plume - Unravelling its dynamics and sea-level contributions. PhD thesis TU Delft. https://doi.org/10.4233/uuid:a27be347-b9e4-45f7-885f-31b8ec466f78

On the Use of Tide Gauges in River Mouths…

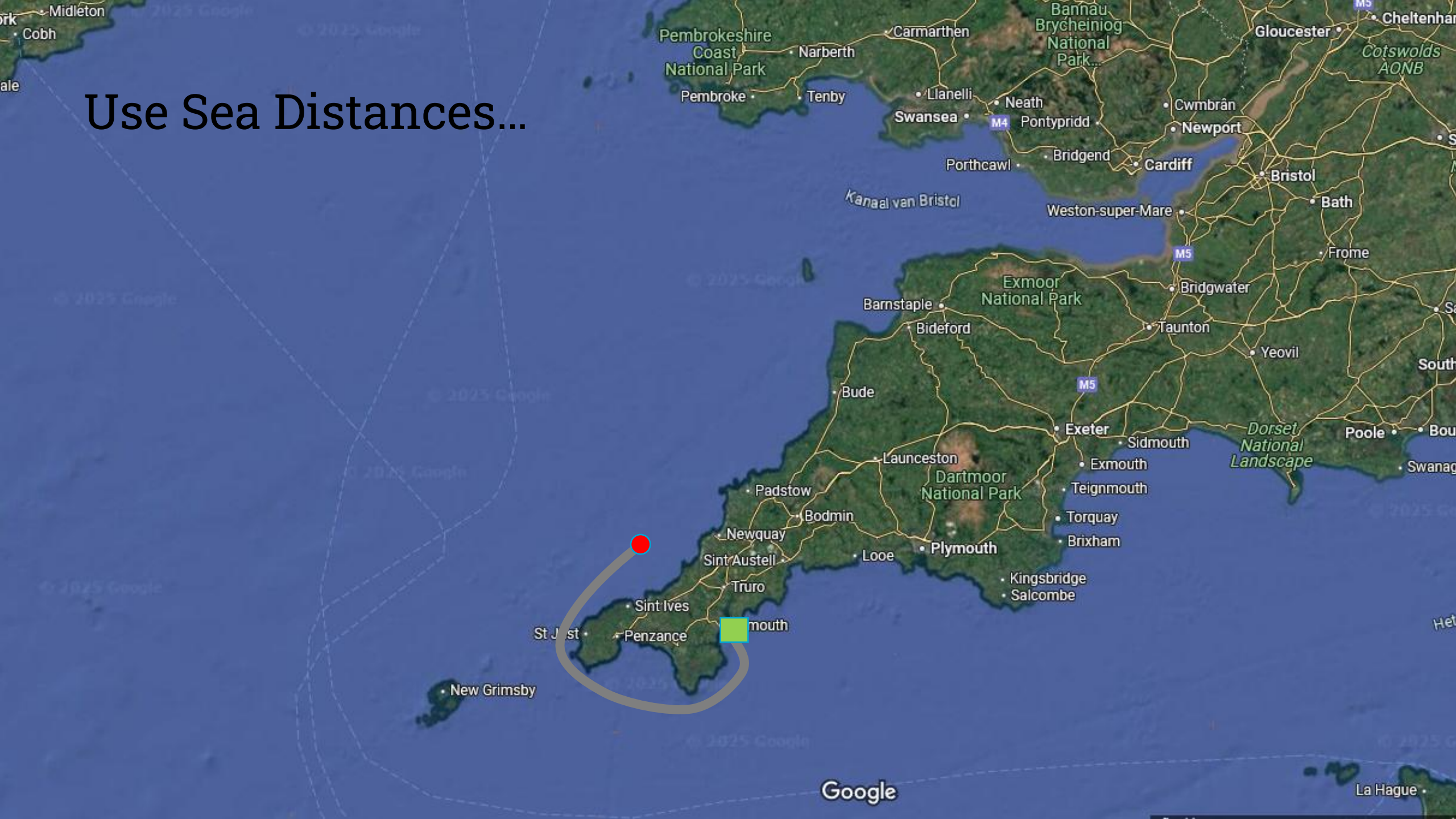


Turner et al. 2010: Interpolation of Tidal Levels in the Coastal Zone for the Creation of a Hydrographic Datum. J. Atmos. Oceanic Technol., 27, 605–613, https://doi.org/10.1175/2009JTECHO645.1.

The 'Ocean Tide Model-Derived' CD Model



Use Sea Distances...



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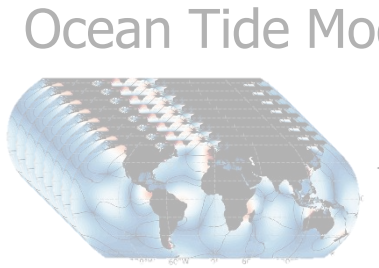

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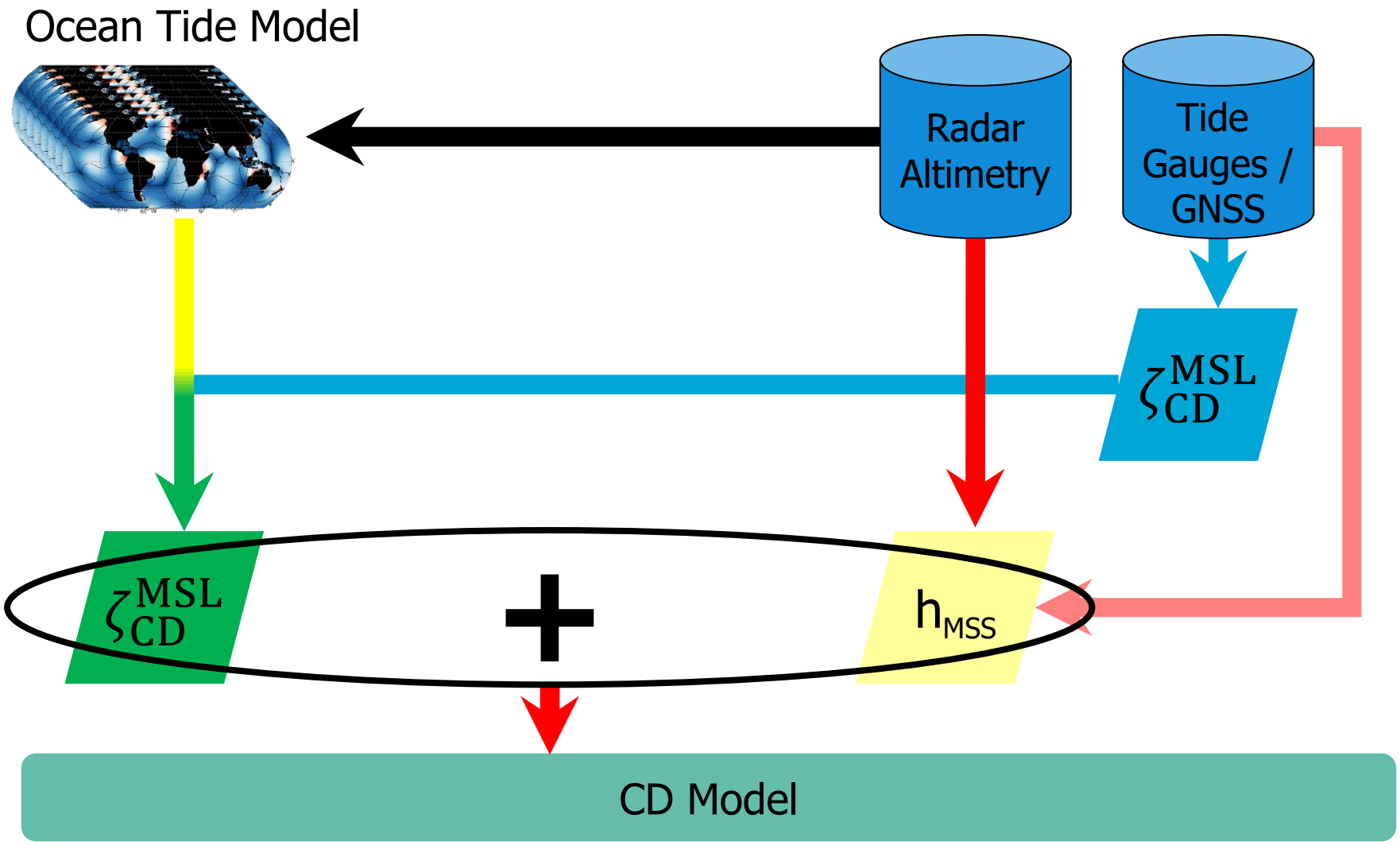
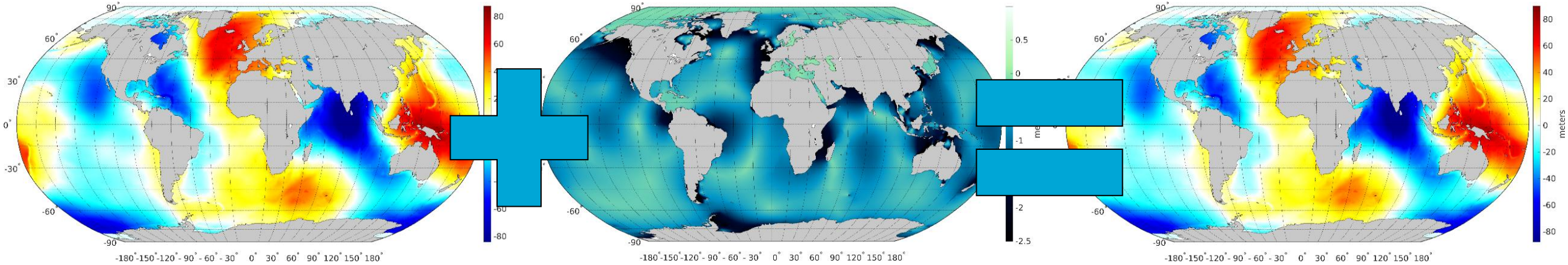


The ‘Ocean Tide Model-Derived’ CD Model

Global MSS model (time-averaged DAC restored) (h_{MSS})

LAT w.r.t. MSL

Ellipsoidal heights of LAT (h_{LAT})



→ Some LAT models are publicly available (e.g., DTU/CNES).

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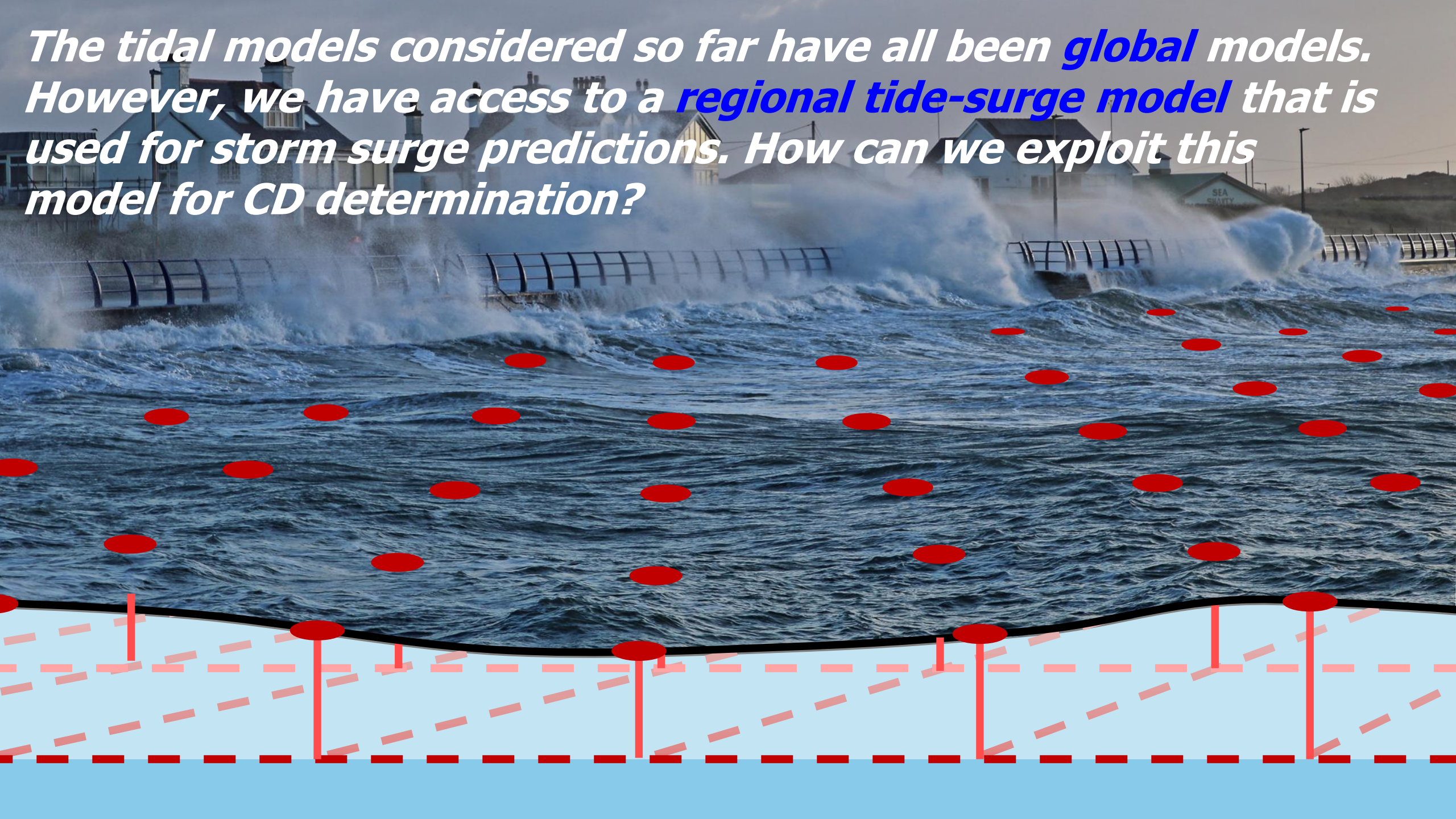
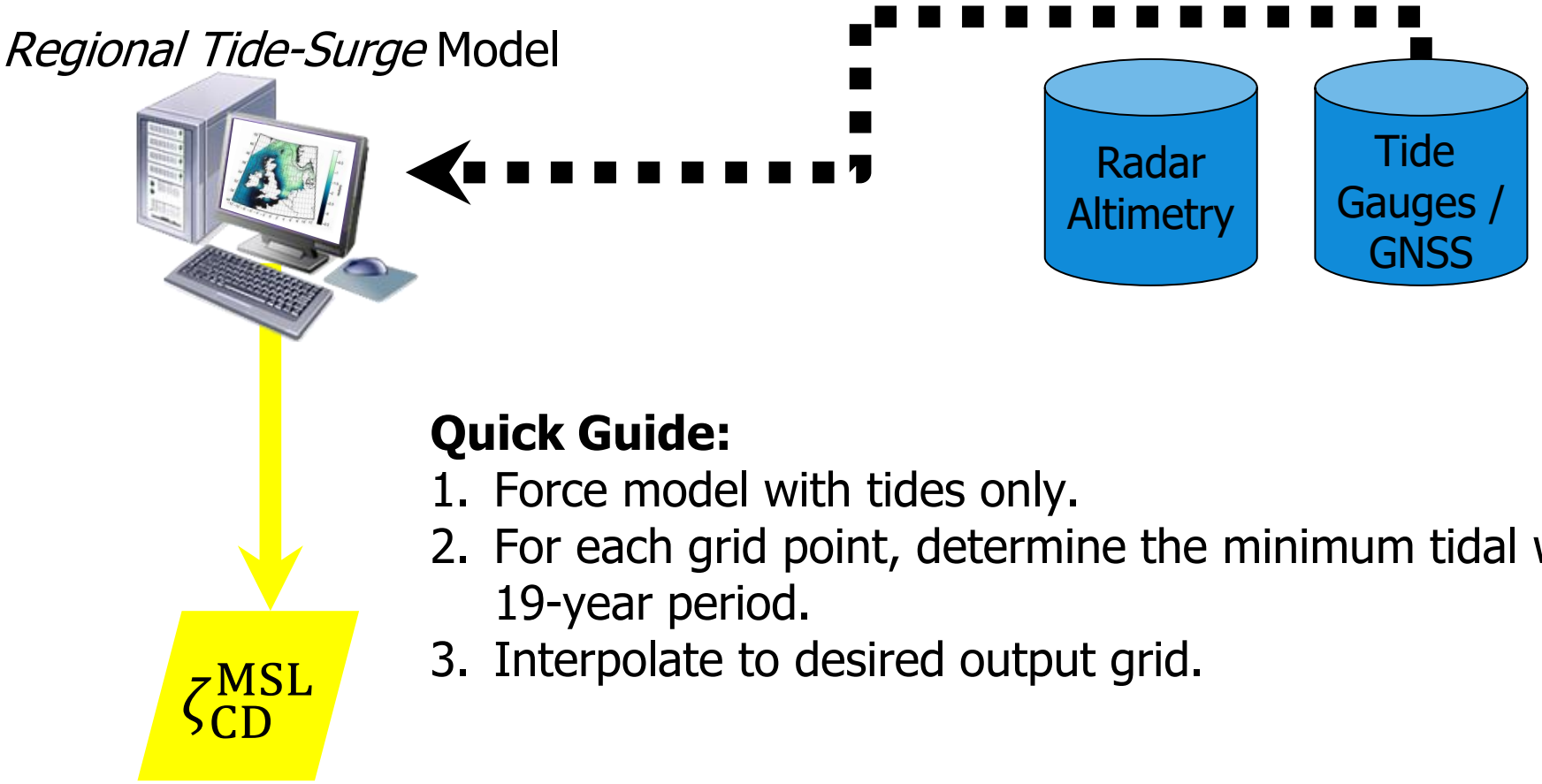
The tidal models considered so far have all been global models. However, we have access to a regional tide-surge model that is used for storm surge predictions. How can we exploit this model for CD determination?



The ‘Regional Tide Model-Derived’ CD Model

- **Strategy:** Combine CD estimates from model-derived tidal water levels with estimates derived from tide gauges.
- Approach adopted in, e.g., the UK VORF project (Empirical Ocean Tide model was used 30 km from the coast).
- Regional models typically calibrated by tide gauge data.

The ‘Regional Tide Model-Derived’ CD Model

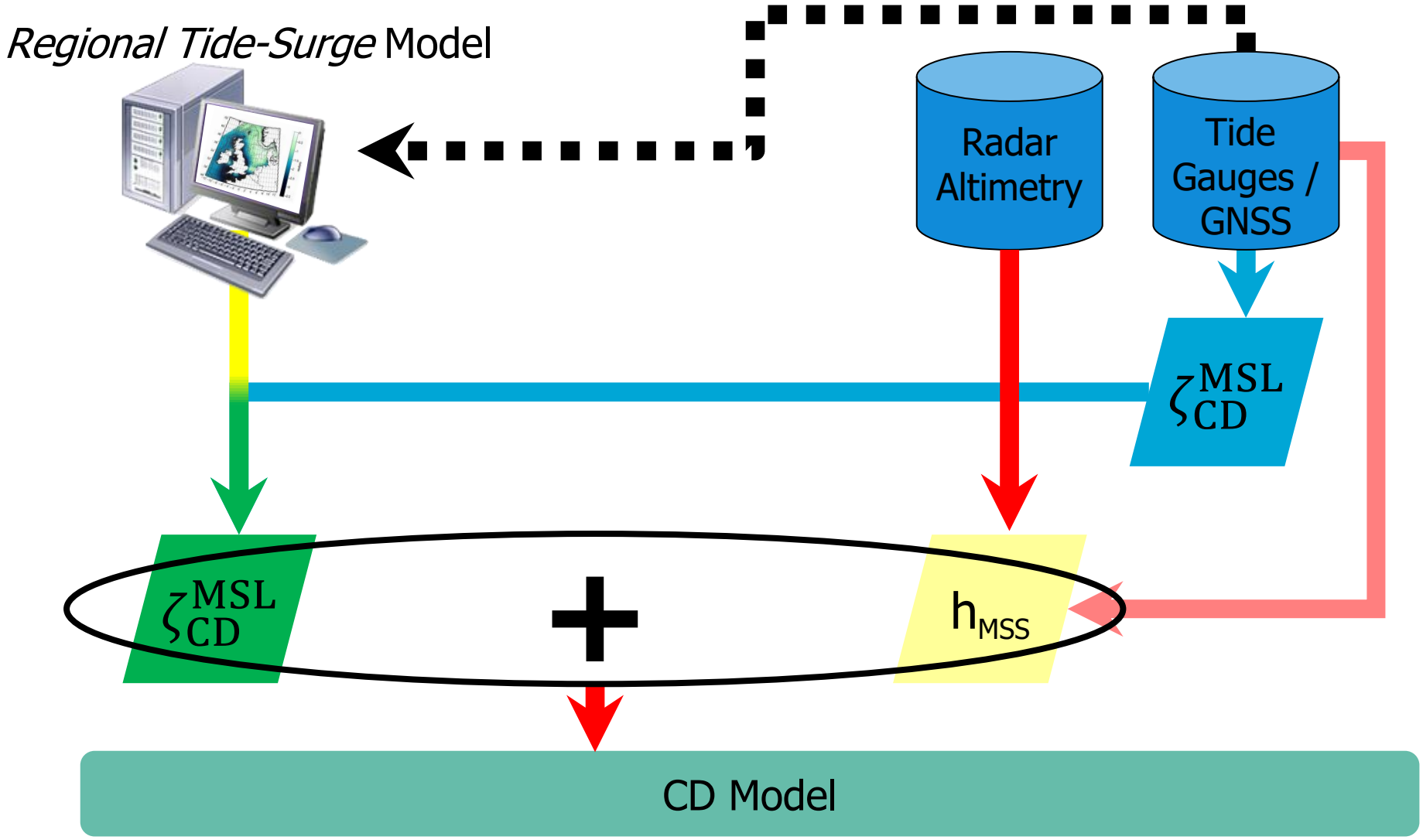


Quick Guide:

1. Force model with tides only.
2. For each grid point, determine the minimum tidal water level over a 19-year period.
3. Interpolate to desired output grid.

CD Model

The 'Regional Tide Model-Derived' CD Model

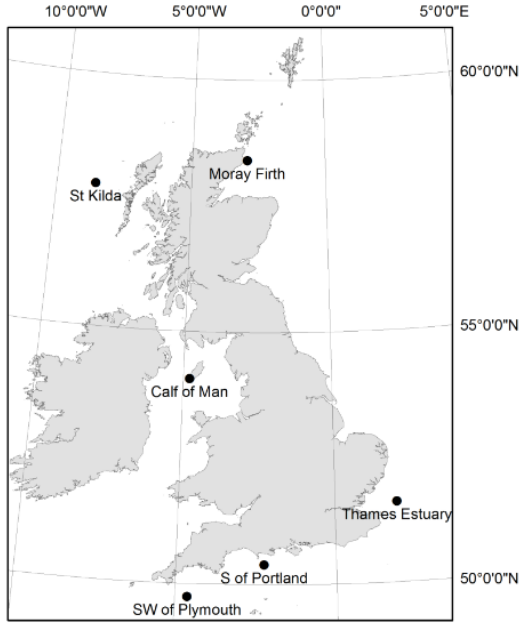


Accuracy???

- A non-trivial issue due to lack of independent estimates…
- Iliffe et al. (2013): "*It is shown that across the vast majority of the domain of applicability the VORF surfaces meet their target accuracies of 0.10 m inshore and 0.15 m offshore (both 1s values) and the formal uncertainties are a fair reflection of the errors actually encountered.*"

UCL

Accuracy testing



Point	Difference between observed value and VORF. (m)	Formal VORF uncertainty value. (m)	Distance offshore, measured to nearest land. (km)
Calf of Man	0.11	0.12	0.25
South West of Plymouth	0.11	0.12	45
South of Portland	0.69	0.18	20
Thames Estuary	0.23	0.14	45
Moray Firth	0.37	0.12	8
St Kilda	- 0.16	0.06	0 (or 65 km from Outer Hebrides)

This is the main independent check that was carried out with newly commissioned data – lots of internal checks, partial checks, etc.

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Iliffe et al. (2013). Accuracy of vertical datum surfaces in coastal and offshore zones. Survey Review, 45(331), 254–262. https://doi.org/10.1179/1752270613Y.0000000040

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- Turner et al. (2010):

TABLE 1. Comparison with 392 ATT onshore gauges. A positive mean indicates that the wide-area model has greater range in LAT than the tide gauge data.

Wide-area model	Mean (m)	σ (m)
NISE10	−0.169	0.449
CSR4.0	−0.444	1.054
FES2004	−0.618	1.161
GOT00.2	−0.259	0.998
TPXO 7.0	0.013	0.749

TABLE 2. Comparison with 187 offshore gauges. A positive mean indicates that the wide-area model has a greater range in LAT than the tide gauge data.

Wide-area model	Mean (m)	σ (m)
NISE10	−0.102	0.358
CSR4.0	0.064	0.279
FES2004	−0.036	0.267
GOT00.2	0.102	0.301
TPXO 7.0	0.104	0.310

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Turner et al. 2010: Interpolation of Tidal Levels in the Coastal Zone for the Creation of a Hydrographic Datum. J. Atmos. Oceanic Technol., 27, 605–613, https://doi.org/10.1175/2009JTECHO645.1.

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Accuracy VORF model is largely driven by tide gauge estimates…!

Today's models are indeed better, but…

…positive mean indicates that the wide-area model has a greater range in LAT than the tide gauge data.

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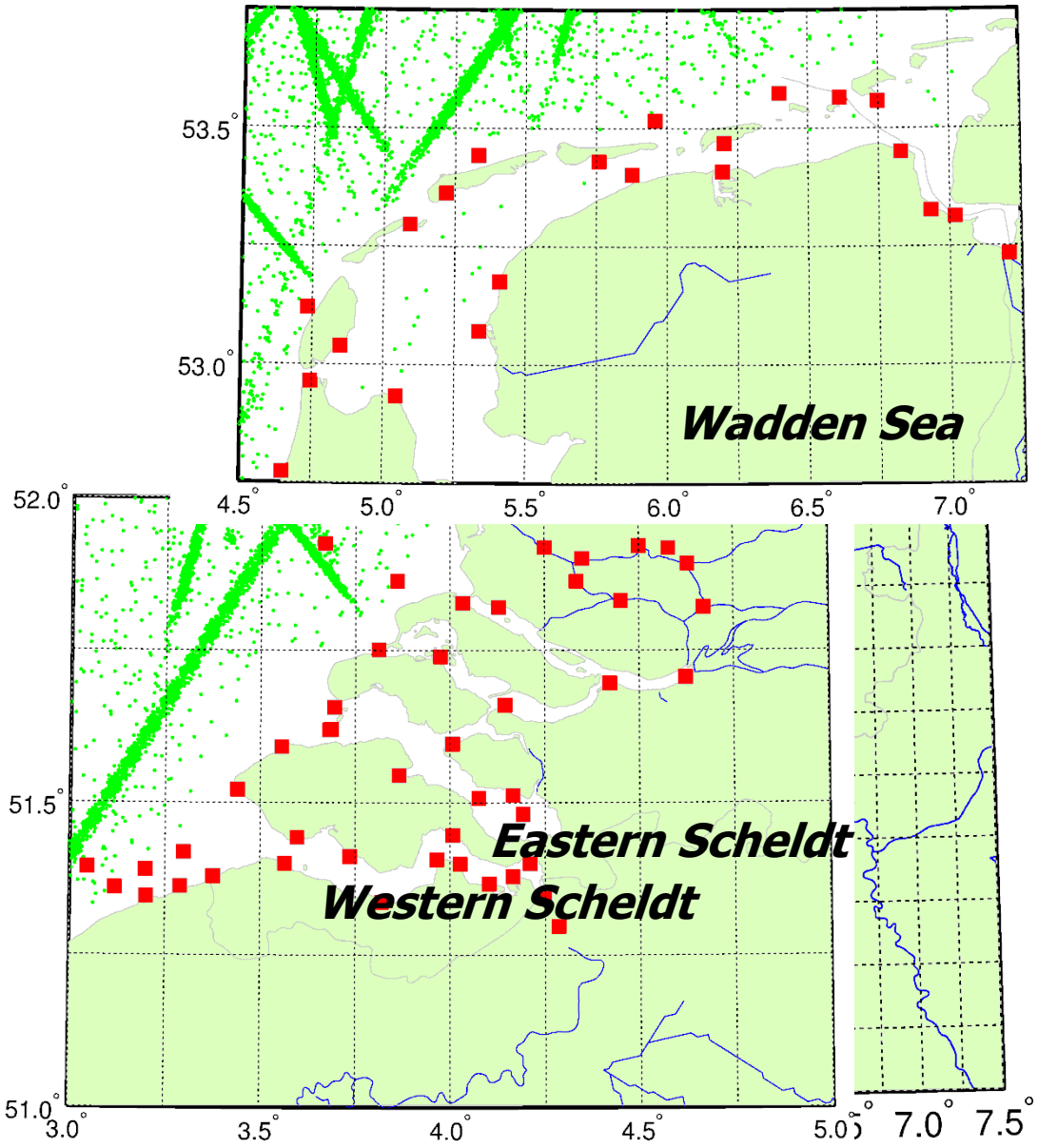
Conceptual Problems

- No reliable radar altimeter data in coastal waters + lack of tide gauges equipped with GNSS (3!) → accuracy MSS model?



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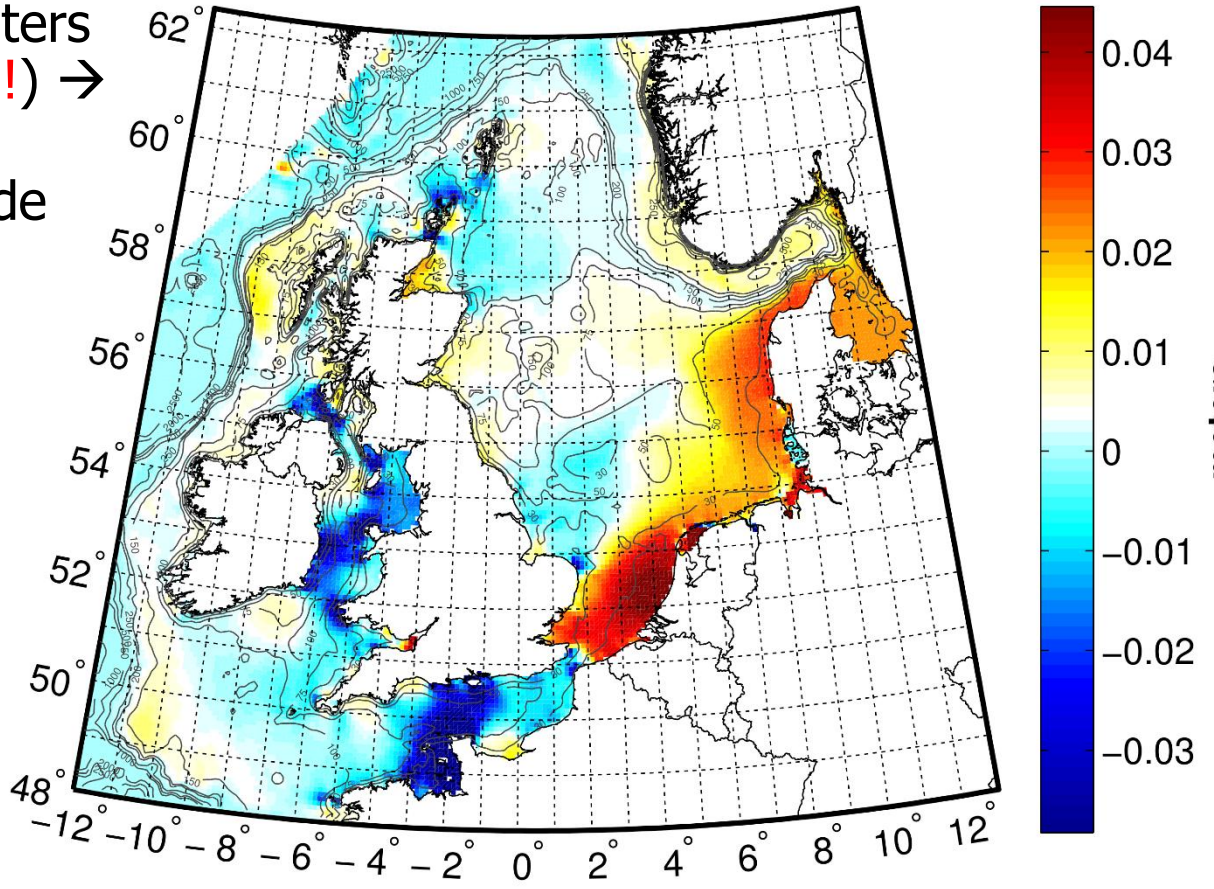
Conceptual Problems

- No reliable radar altimeter data in coastal waters + lack of tide gauges equipped with GNSS (3!) → accuracy MSS model?
- MSL not the reference surface of an ocean tide model.
  - Tides contribute to MSL.
- Tide-surge interaction ignored.
- What is the MSL?
  - Thompson, JGI 63 (1980): 57-73: annual amplitudes ~ 7 cm.



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Slobbe, D. C., Verlaan, M., Klees, R., & Gerritsen, H. (2013a). Obtaining instantaneous water levels relative to a geoid with a 2D storm surge model. Cont. Shelf Res., 52, 172-189.

Dutch Approach to Realize h_{CD} and h_{QG}

Hydro. model

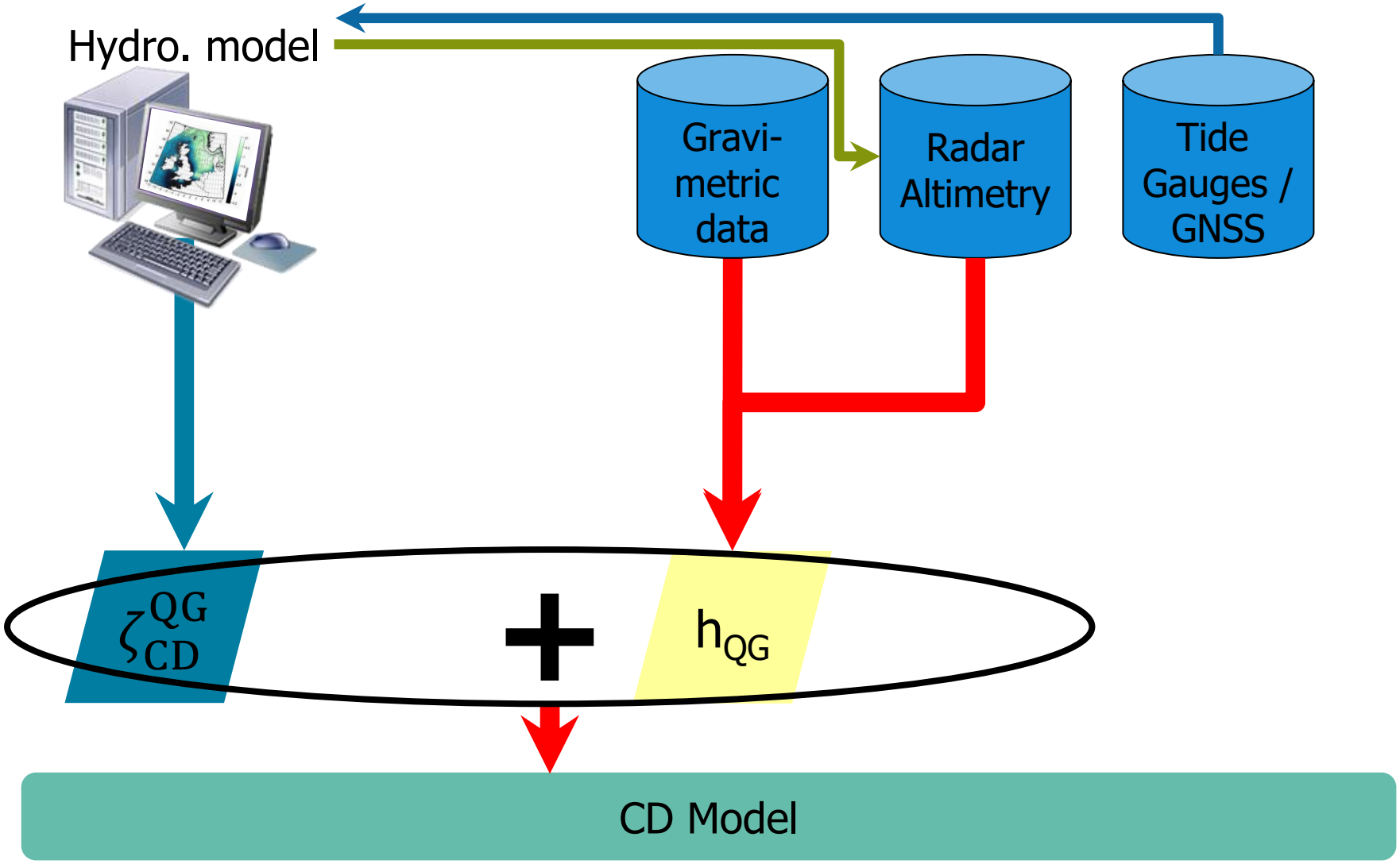
ζ_{CD}^{QG}

Quick Guide:

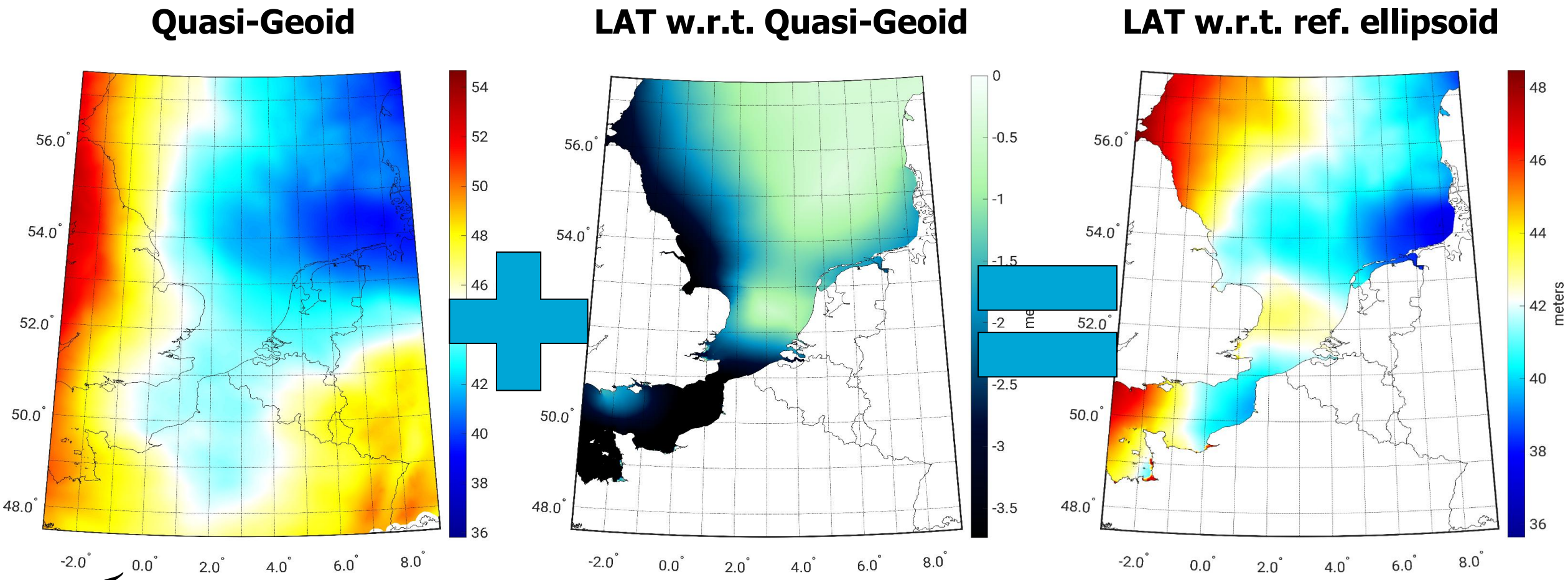
1. Force model with tides + average meteo.
2. Reference model to equipotential surface adopted as ref. (Slobbe et al., 2013a).
3. For each grid point, determine the minimum tidal water level over a 19-year period.
4. Interpolate to desired output grid.

CD Model

Dutch Approach to Realize h_{CD} and h_{QG}



NLLAT2018



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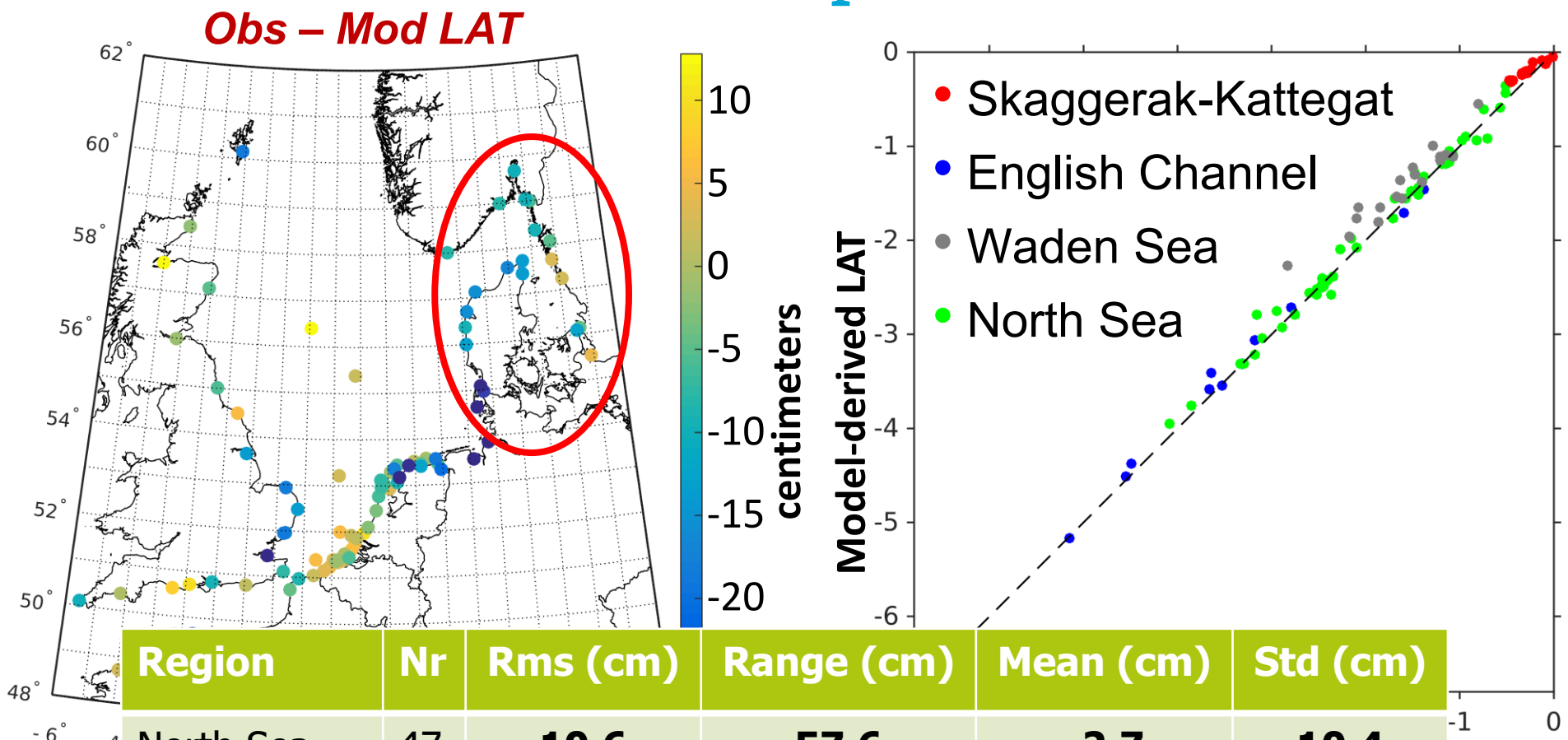
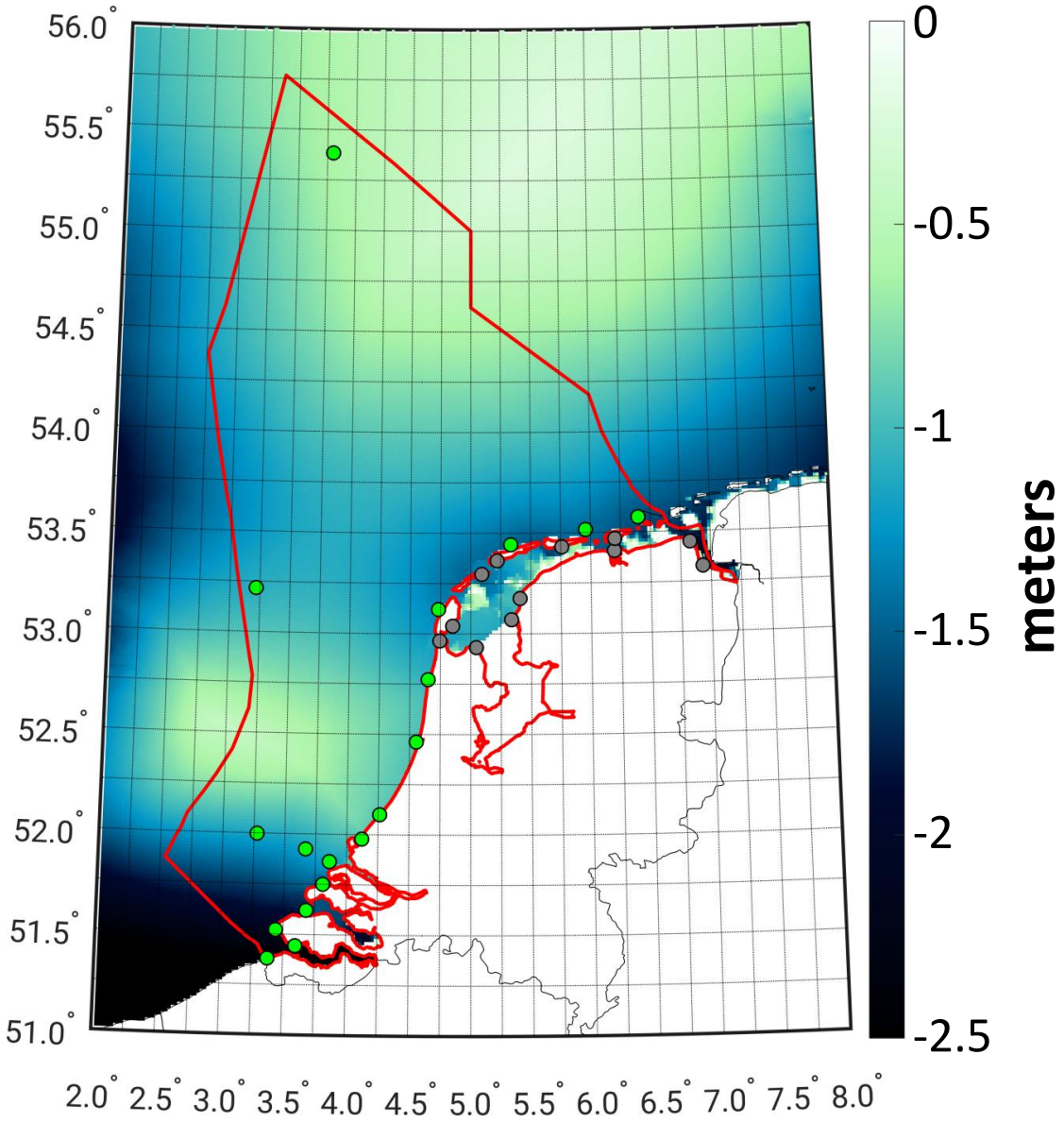
Slobbe et al. (2017). A Kalman Filter Approach to Realize the Lowest Astronomical Tide Surface. Marine Geodesy, 41(1), 44–67. https://doi.org/10.1080/01490419.2017.1391900.

LAT w.r.t. Quasi-Geoid – Comparison



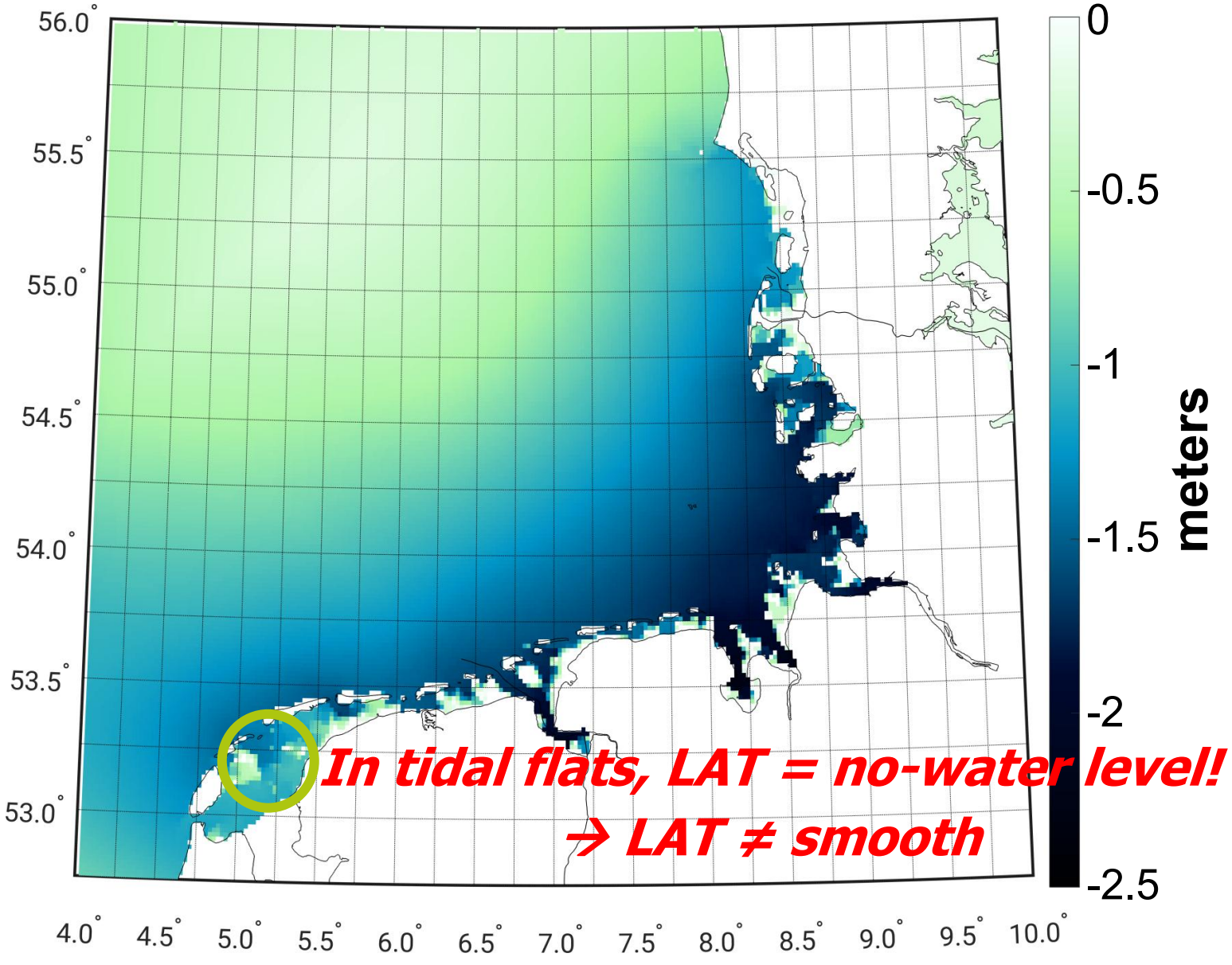
Region	Nr	Rms (cm)	Range (cm)	Mean (cm)	Std (cm)
North Sea	47	**10.6**	**57.6**	**-2.7**	**10.4**
Wadden Sea	18	**24.0**	**59.5**	**-18.7**	**15.4**
All	92	**14.9**	**77.6**	**-7.2**	**13.1**

LAT w.r.t. Quasi-Geoid –Dutch waters

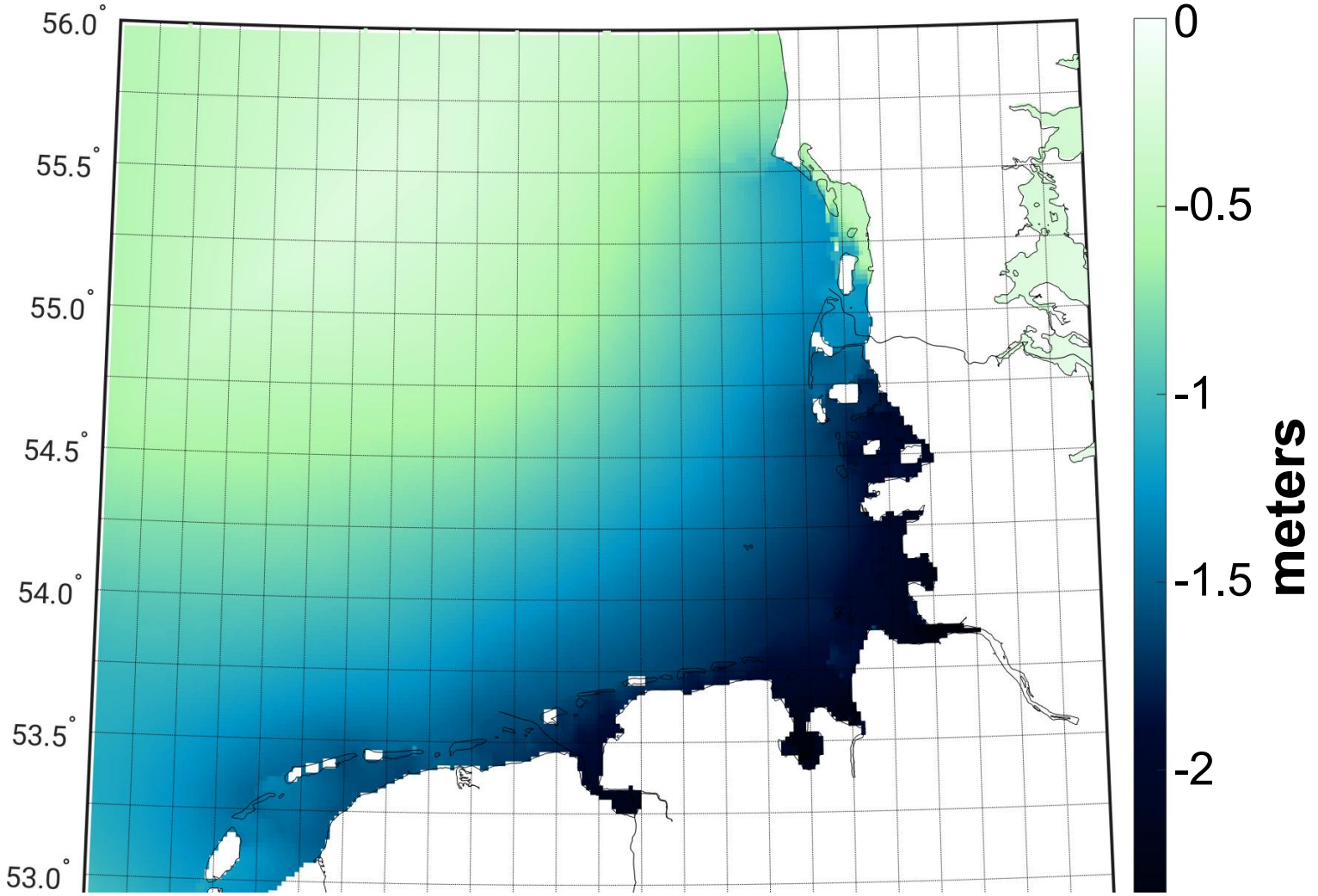


Region	Nr	rms (cm)
North Sea	19	**6.6**
Wadden Sea	12	**14.8**
All	31	**10.5**

LAT in the Wadden Sea?

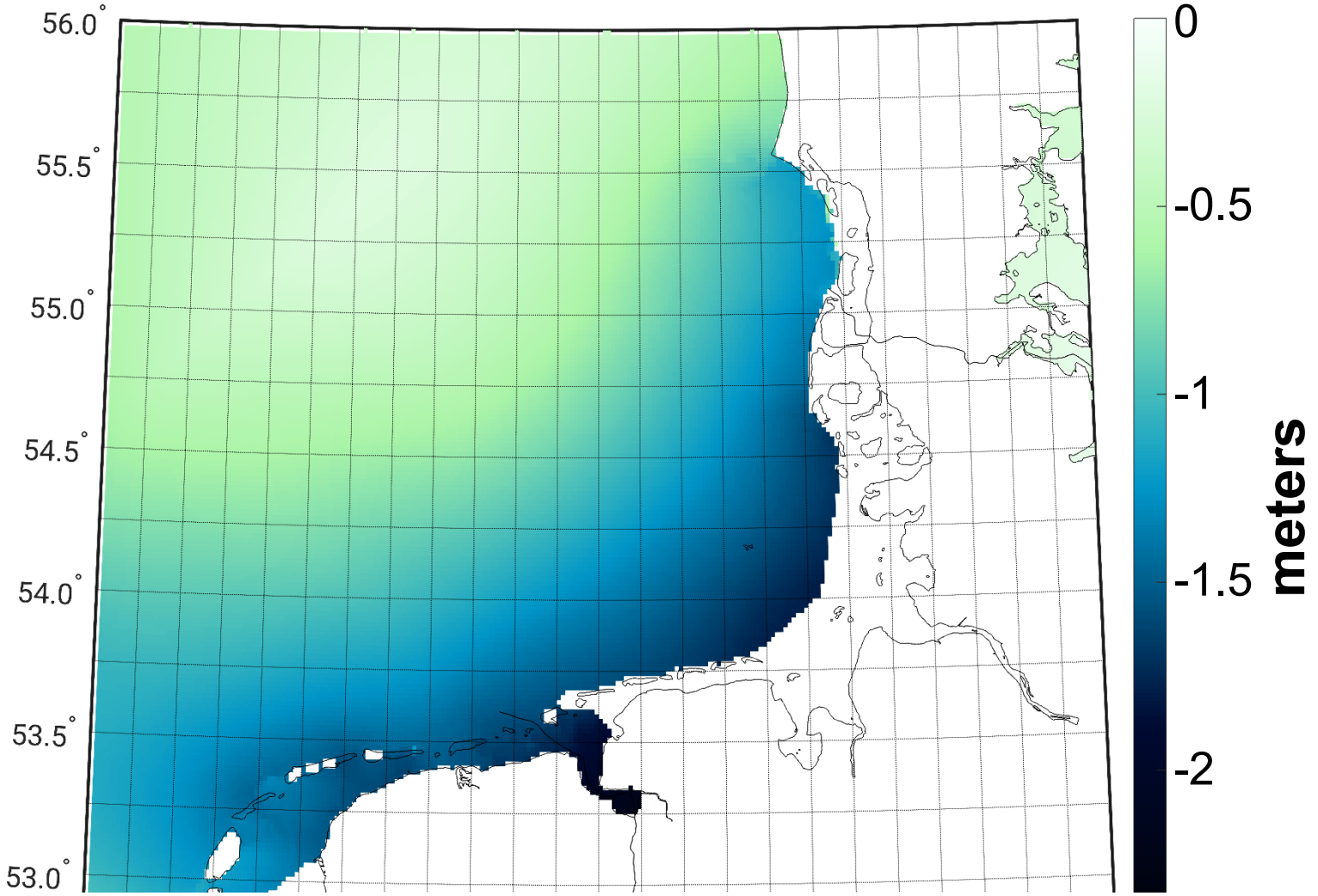


In the Wadden Sea LAT → Pseudo LAT



To obtain pseudo-LAT, we added 2 m of water to open boundary conditions & assimilated tidal water levels.

In the Wadden Sea LAT → Pseudo LAT



NOT valid outside Dutch waters!!!

A Fair Question…

Why you didn't use altimeter-derived tides?

→ Partly we did, constituents used to generate tidal water levels at open sea boundaries (in deep water) obtained from global barotropic tide model…

The Accuracy of Altimeter-Derived Tides…

"For the combined eight major tidal constituents, the root sum of squares is 0.89, 5.1, and 6.5 cm for pelagic, shelf, and coastal conditions, respectively." (Stammer et al., 2014)

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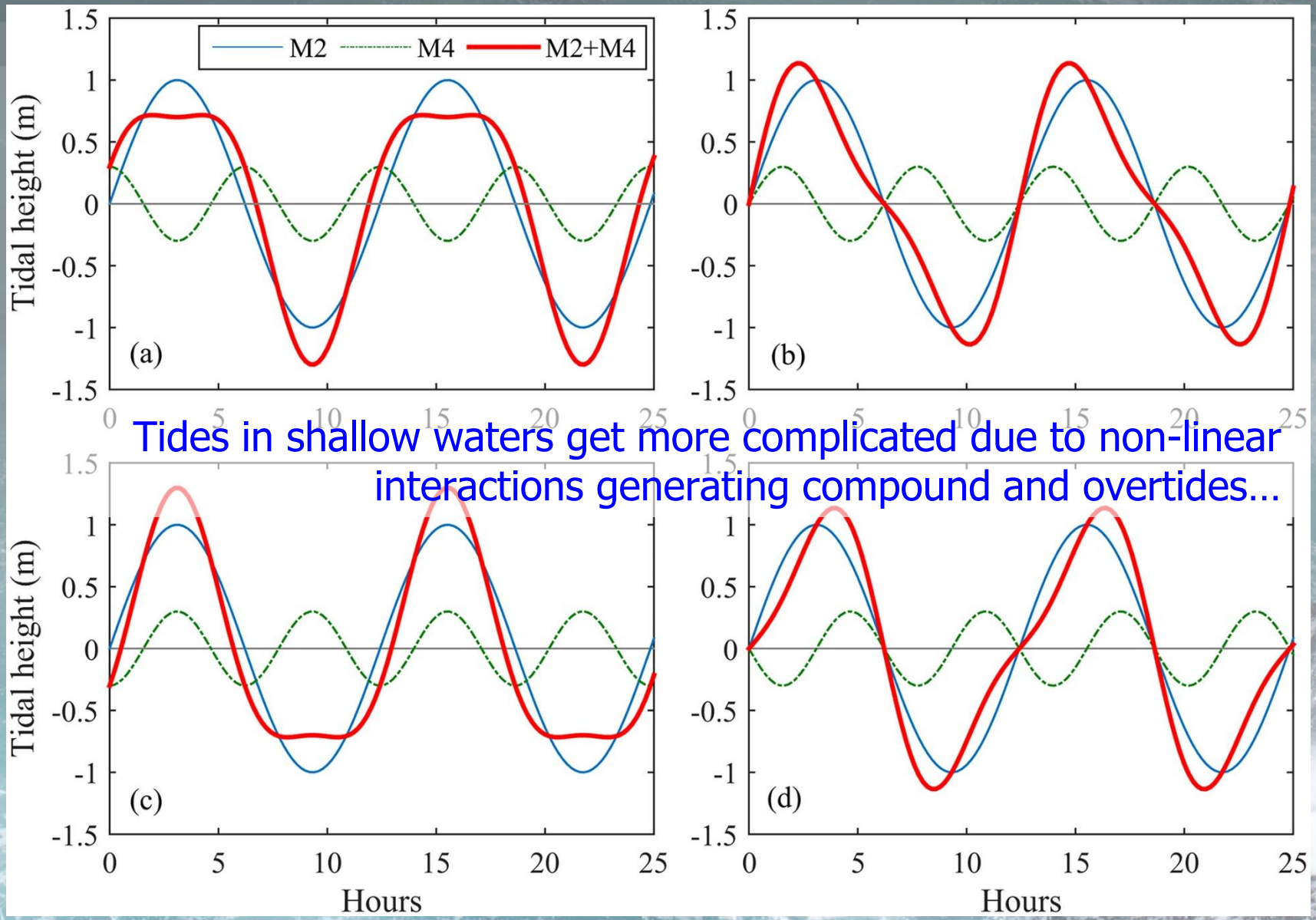
Stammer, D., et al. (2014), Accuracy assessment of global barotropic ocean tide models, Rev. Geophys., 52, 243–282, doi:10.1002/2014RG000450.

The Accuracy of Altimeter-derived tides…

Table 4
RSS (cm) across eight constituents (M2, S2, N2, O1, K1, K2, P1, and Q1) of three different statistical measures summarising the phasor residuals between model predictions and the observed values at 137 TG and BPR considered to be independent (not assimilated by the global tide models). It is displayed overall, as well as split into various zones defined by ocean depth. Bold indicates the best performance.

	FES2014b	EOT20	DTU16	TPXO9
	RMS			
Coastline	**24.46**	25.50	33.22	42.37
Coastal	8.70	8.69	8.98	**8.61**
Shelf	**4.62**	4.70	4.68	4.89
Ocean	3.21	3.38	3.57	**3.16**
Overall	**16.47**	17.07	21.66	27.09
	MAR			
Coastline	12.28	14.65	15.95	15.31
Coastal	4.77	4.77	5.02	5.33
Shelf	2.62	2.96	**2.48**	2.86
Ocean	3.16	3.22	3.34	**3.01**
Overall	5.61	5.56	**5.35**	5.89
	Voronoi-weighted RMS ($\times 10^{-2}$)			
Coastline	**9.74**	10.09	12.92	11.39
Coastal	**6.52**	6.67	6.69	6.73
Shelf	**7.02**	7.17	7.13	7.40
Ocean	5.12	5.39	5.69	**5.03**
Overall	**7.93**	8.17	9.60	8.84

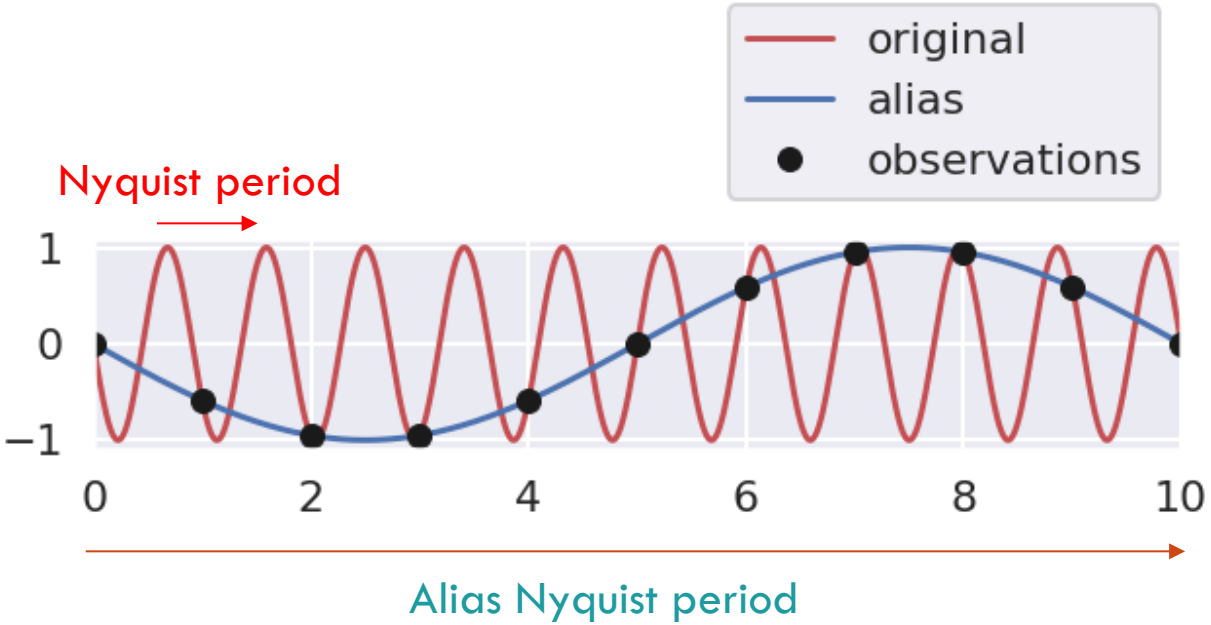
Gregg, D. E., Penna, N. T., Jones, C., & Maqueda, M. A. M. (2024). Accuracy assessment of recent global ocean tide models in coastal waters of the European North West Shelf. Ocean Modelling, 192, 102448.

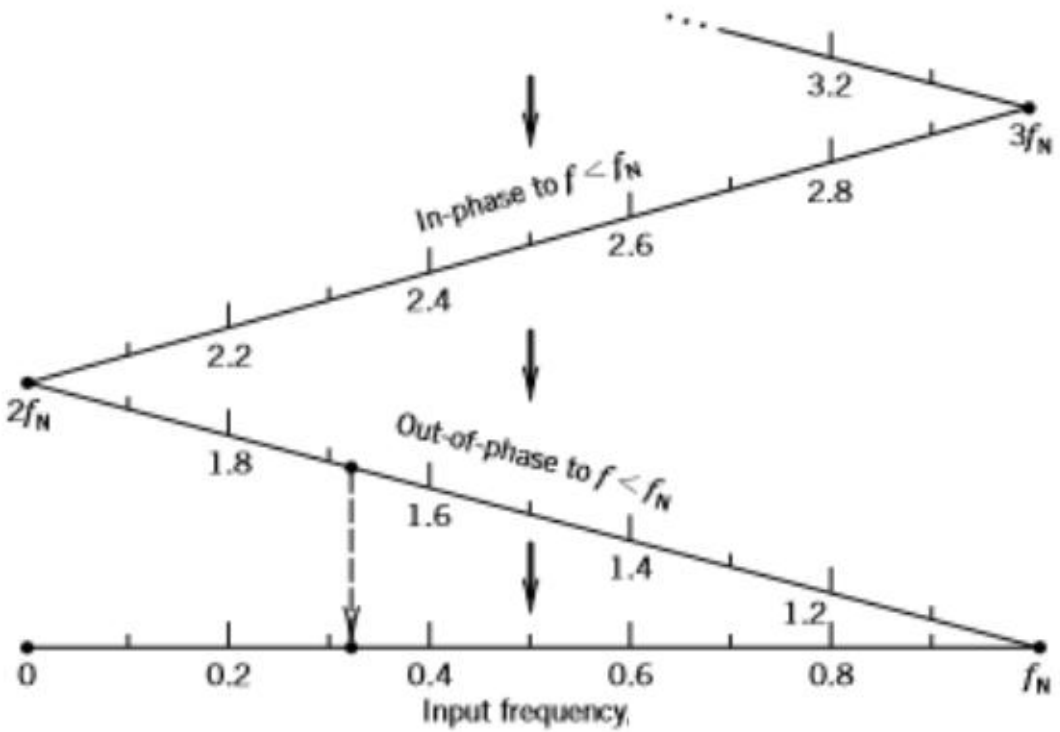


Tides in shallow waters get more complicated due to non-linear interactions generating compound and overtides…

Guo, L., Wang, Z. B., Townend, I., & He, Q. (2019). Quantification of tidal asymmetry and its nonstationary variations. *Journal of Geophysical Research: Oceans*, 124, 773–787. https://doi.org/10.1029/2018JC014372

Limitations due to poor altimeter sampling…





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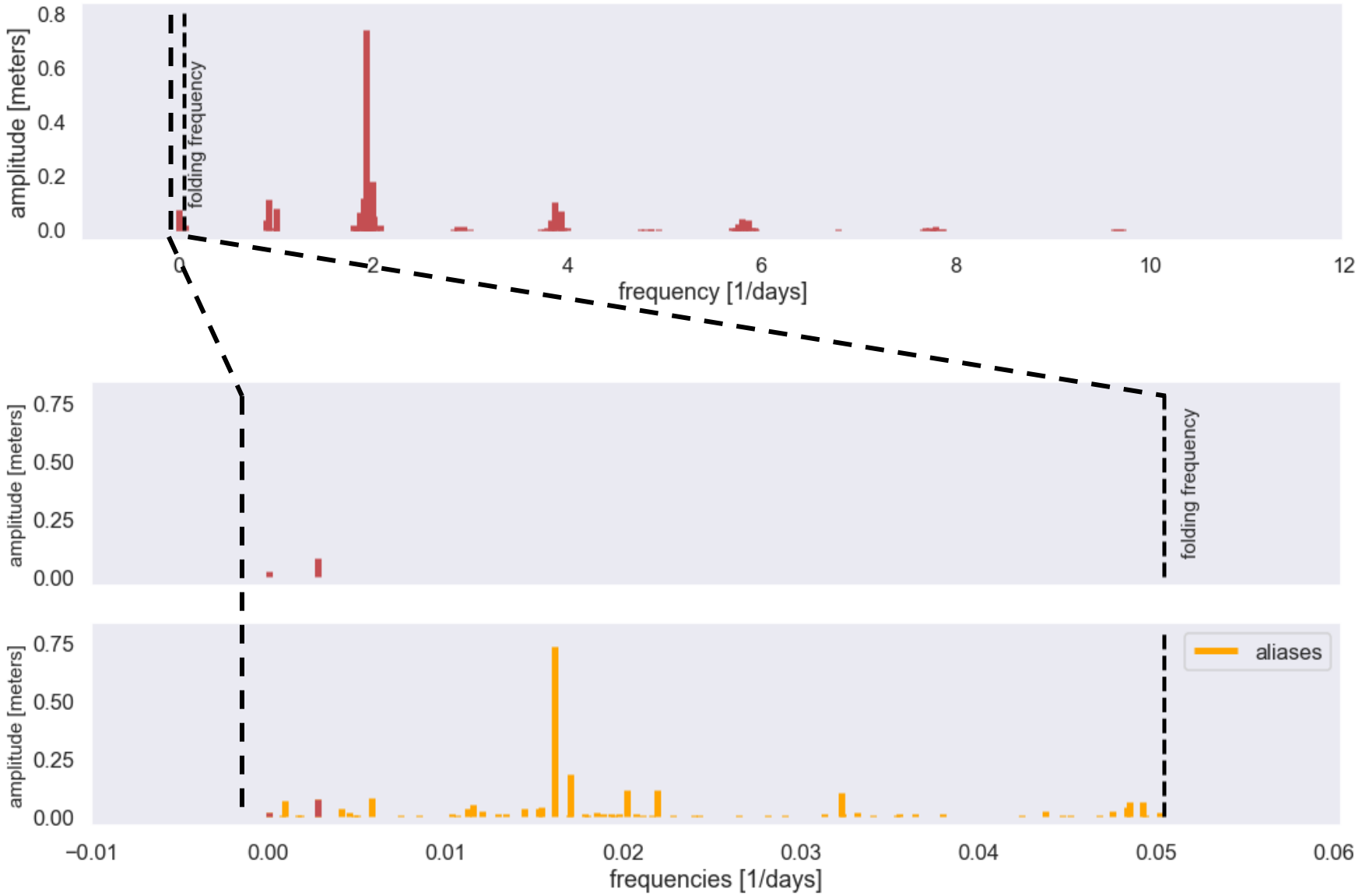
Example: Offshore Tide Gauge – North Sea

All of the frequencies right of the Nyquist (folding) frequency get folded into a new perceived frequency in between it and zero

before folding…

… and after folding



Example: Offshore Tide Gauge – North Sea

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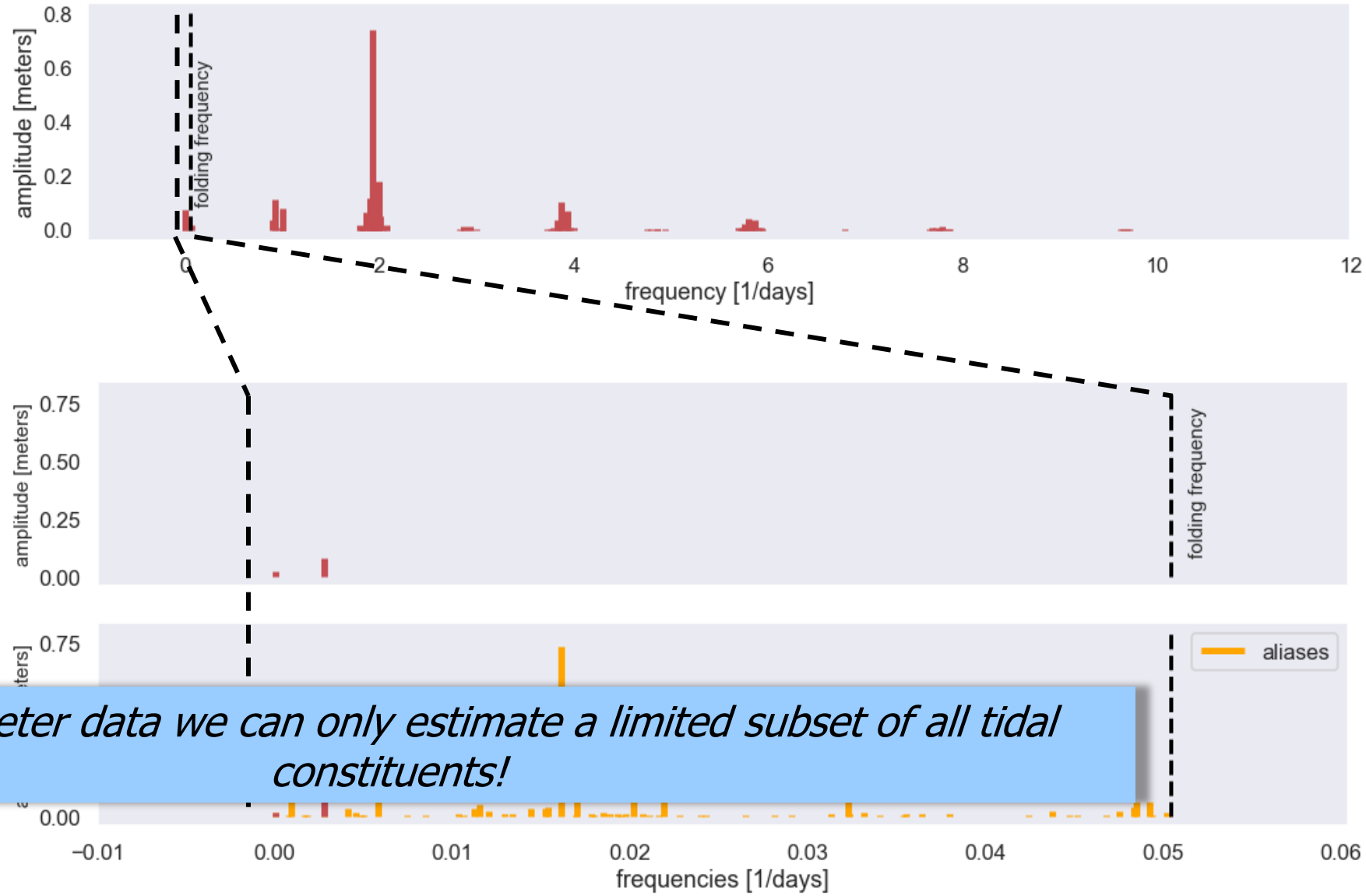

Based on altimeter data we can only estimate a limited subset of all tidal constituents!

Tide-Surge Interactions Ignored…

Nonlinear tide-surge interactions alter the phase of tidal signals while the tides themselves modulate non-tidal signals. They are reported in numerous locations globally…

Total water level ≠ Tides + Surge + …

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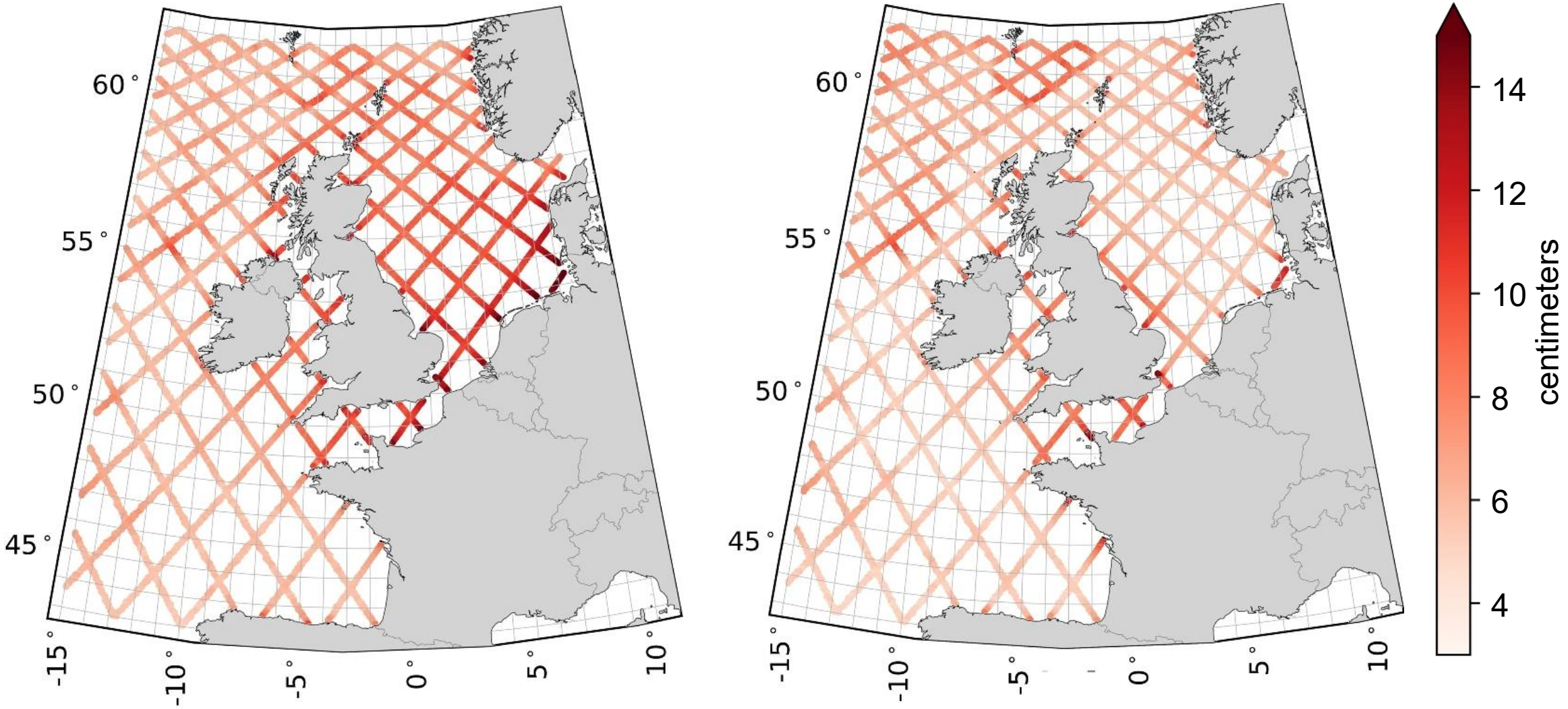
Guarneri, H., Verlaan, M., Slobbe, D.C. *et al.* Estimating tidal constituents in shallow waters from satellite altimetry using a 2D hydrodynamic model with nonlinear tide-surge interactions. *Ocean Dynamics* **75**, 24 (2025). https://doi.org/10.1007/s10236-025-01667-6

SD residual water level time series obtained by applying:

FES2022b tide + DAC surge corrections (excl. nonlinear tide-surge interactions)

DCSM-derived tide-surge corrections (incl. nonlinear tide-surge interactions)

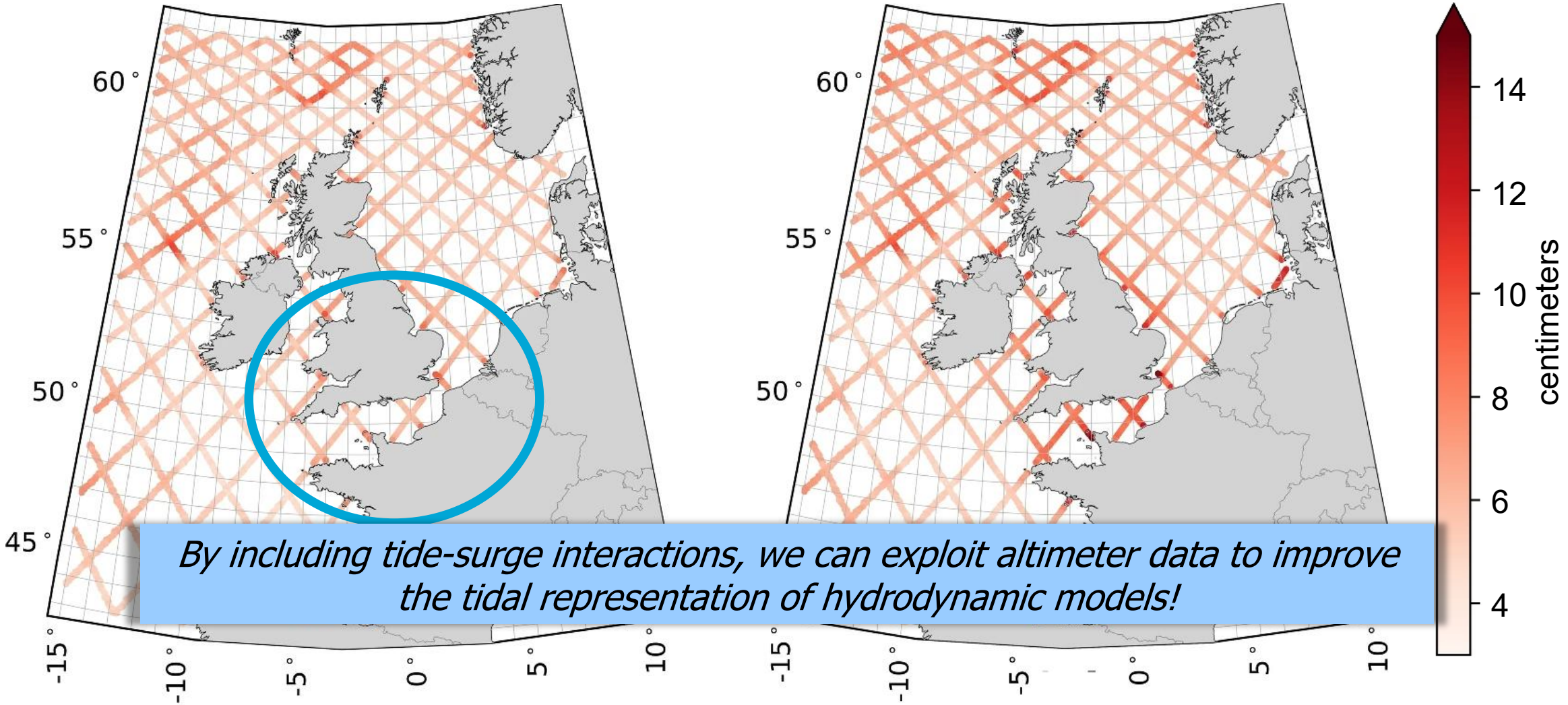


Guarneri, H., Verlaan, M., Slobbe, D.C. *et al.* Estimating tidal constituents in shallow waters from satellite altimetry using a 2D hydrodynamic model with nonlinear tide-surge interactions. *Ocean Dynamics* **75**, 24 (2025). https://doi.org/10.1007/s10236-025-01667-6

Key to Improve Tidal Representation in Hydr. Models!

DCSM-derived tide-surge corrections
+ residual tide correction

DCSM-derived tide-surge corrections
(including nonlinear tide-surge interactions)

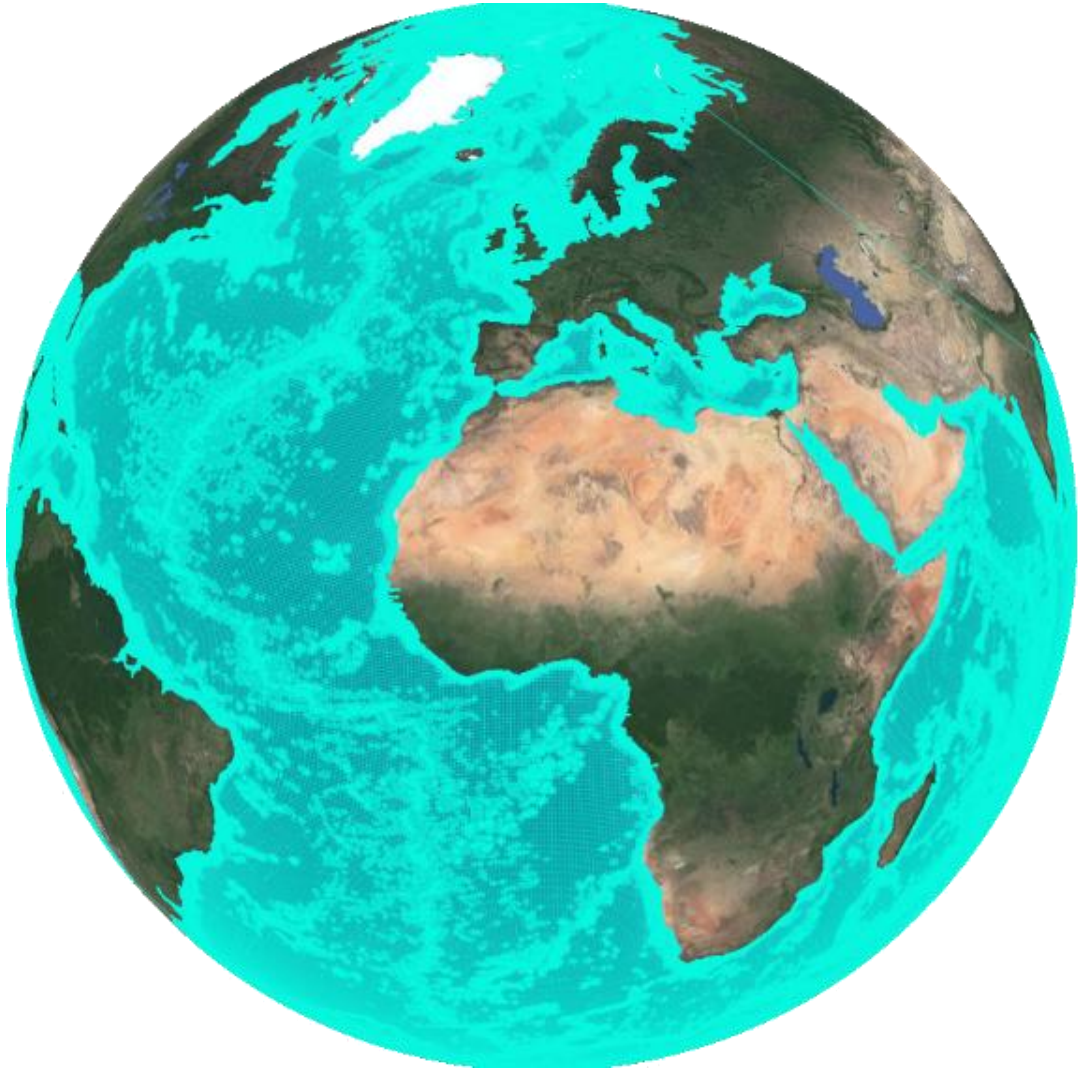


By including tide-surge interactions, we can exploit altimeter data to improve the tidal representation of hydrodynamic models!

If our HydroLev Research Proposal Will be Granted...

We Will…

- Apply the approach by Guarneri et al. (2025) to compute an altimeter-derived along-track tidal product for the global oceans < 66° latitude.
- Use the product to calibrate the Global Tide and Surge Model.
- Compute a global CD model from water level time series obtained with the recalibrated GTSM Model assimilated with tide gauge water levels and a MSS model.



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The Recommended Approach…?

- Begin with a simple approach.
- Be pragmatic.
- The main challenge lies in maintaining consistency among chart datum values derived from different sources.
- Rather than reinventing the wheel, align with established methodologies.
- If you like to discuss, feel free to contact me (D.C.Slobbe@tudelft.nl)

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Thank you!