

Modern Satellite Altimetry for Quantifying sea level rise

NKG Summer School, Tartu, Estonia, Aug 2025

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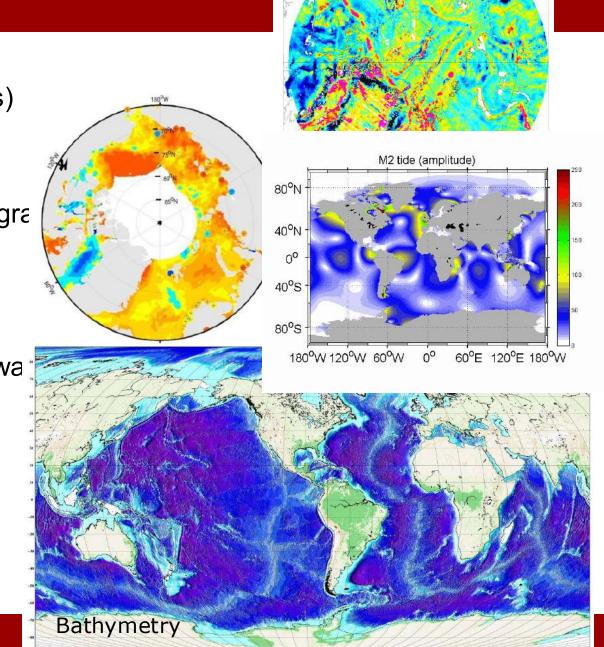
Professor, Head of hydrosphere section, DTU Space

Who am I.

Gravity

- DTU Space
- Geodesy and Earth Observation division (>60 persons)

- Author of DTU highr-es reference surfaces (bath,mss,gra
- Author of DTU tide models
- Mission scientist/advisor for ESA + NASA
- Sea level change + projection, Arctic sea level+Freshwa
- Mesoscale/sub mesoscale oceanography,
- AI/ML for oceanography + marine geodesy
- Flooding/inundation/storm-surge/marine safety
- Satellite altimetry for high-res marine biology.



Outline

- Sea level rise
- Our observing system Satellite altimetry
- Basic Principles.
- Pulse limited radar and its footprint
- Waveforms and retracking
- Accuracy or our observing system
- Sea level change/accelerattion from satellite
- Validating sea level changes (bathtub model)
- SWOT (Surface water and ocean topography mission)

First amazing results from 5 of my students.

Sea-Level rise is a societal threat (long-term)





Low-lying coastal zone is home to 680 million people

For every cm of sea level rise 3 million extra people at flooding risk + retreat of 20.000 km2 land globally

IPCC predictions for 2100 show 0.43 - 0.84 meter increase of sea level

With sea level rise extremes also increases in



magnitude and frequency



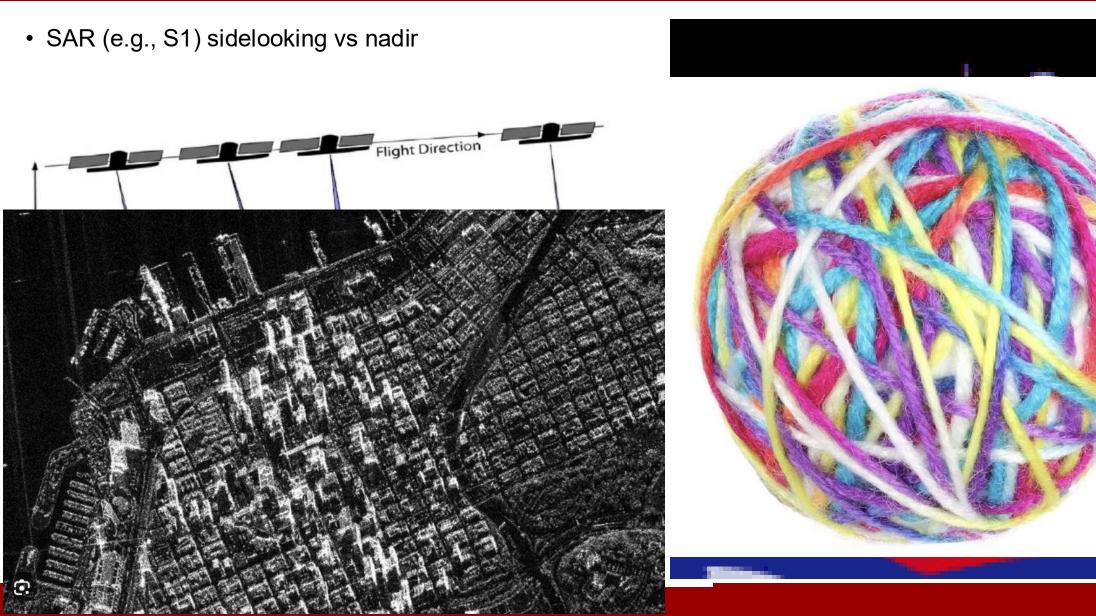
With higher sea level.....
The return period for a 100-year event will reduce significantly

The thread from water becomes more frequent and the extremes larger.

Look at the use of geodetic data for the various components of water/level and its change into the future.

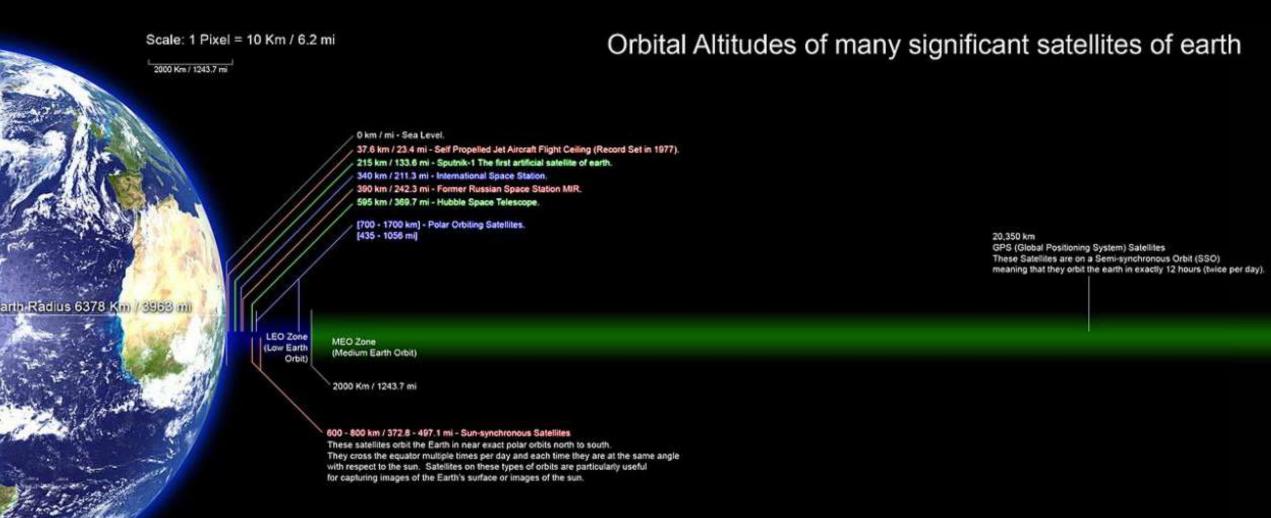
Fundamental geodetic System to: Monitor and map the shape of the Earth (surface and geoid/gravity)

How can it work from space. SAR/Optical vs Satellite Altimetry

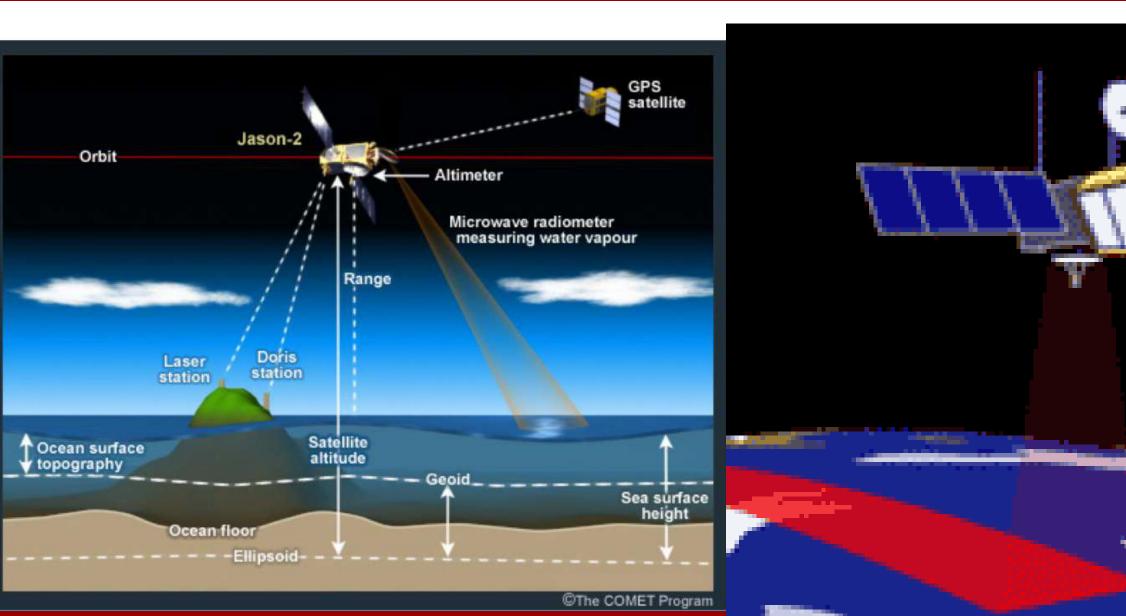




Our observing system is in LEO (Low Earth Orbit) in order to map the Earth in detail.



Components in satellite altimetry system

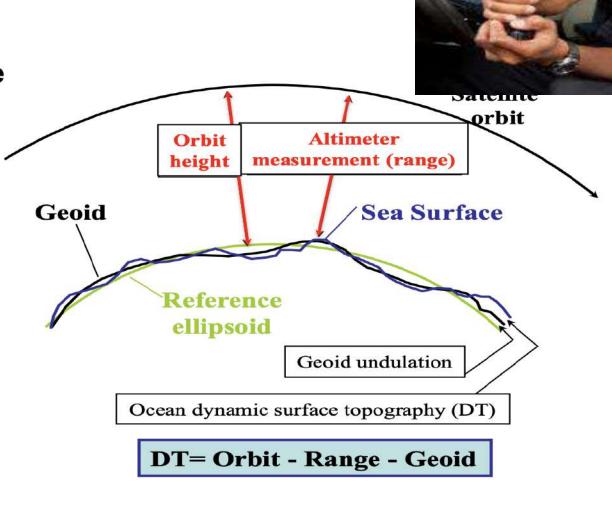


Basic Principle & the importance of geometry

 The altimeter is a radar at vertical incidence

 The signal returning to the satellite is from quasispecular reflection

- Measure distance between satellite and sea (range)
- Determine position of satellite (precise orbit)
- Hence determine height of sea surface
- Oceanographers require height relative to geoid

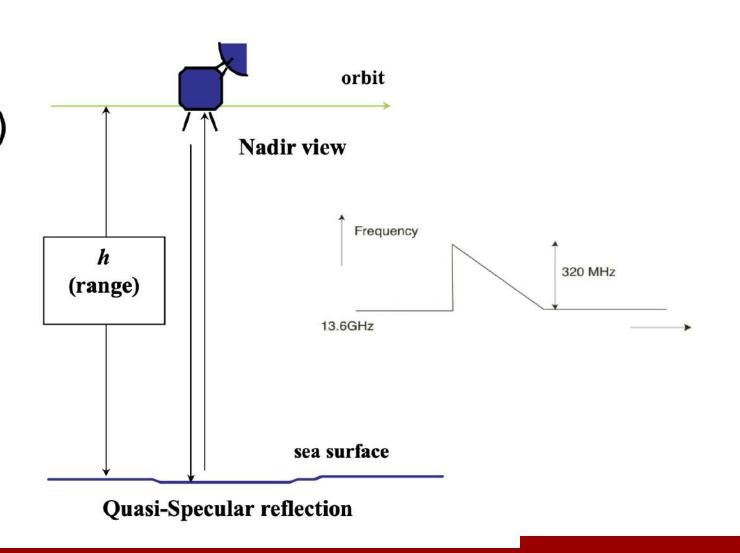


For convenience you can also use height relative to Mean Sea surface

Principle and limitation

- Measure travel time, 2T, from emit to return
- $h = (T \times c) (c \approx 3x10^8 \text{ m/s})$
- Resolution to ~1cm would need a pulse of 3x10⁻¹⁰s (0.3 nanoseconds)

 0.3ns... That would be a pulse bandwidth of >3 GHz... Impossible!



How does it work, Pulse limited Radar.

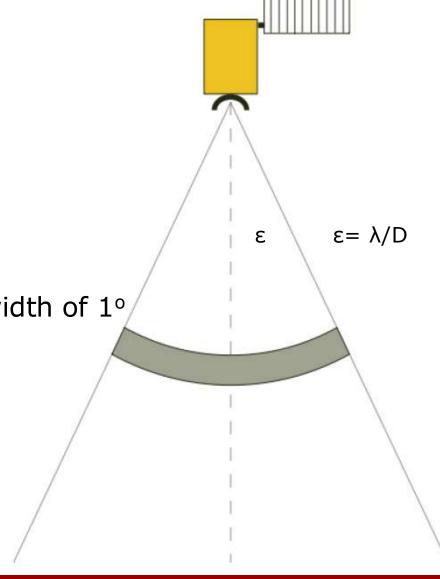
 In a pulse-limited altimeter the shape of the return is dictated by the length (width) of the pulse

A typical Antenna has a beam width of 1°

So it will illuminate a disk of

14 km in diameter if satellite

flies at 800 km altitude....



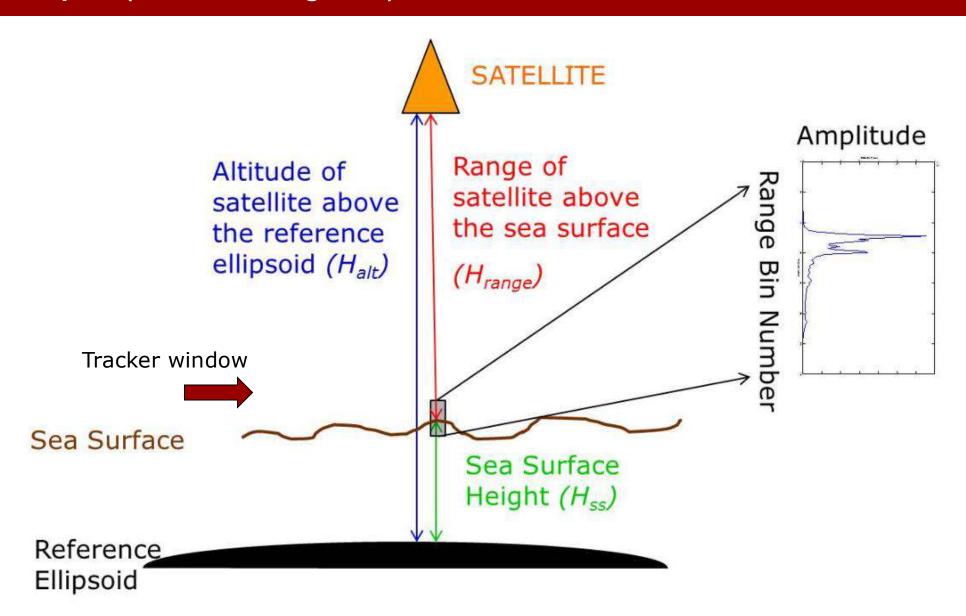
Tracker sets the "window"

where the power is sampled (128 or more "gates")

Window is open for 0.1 ms.

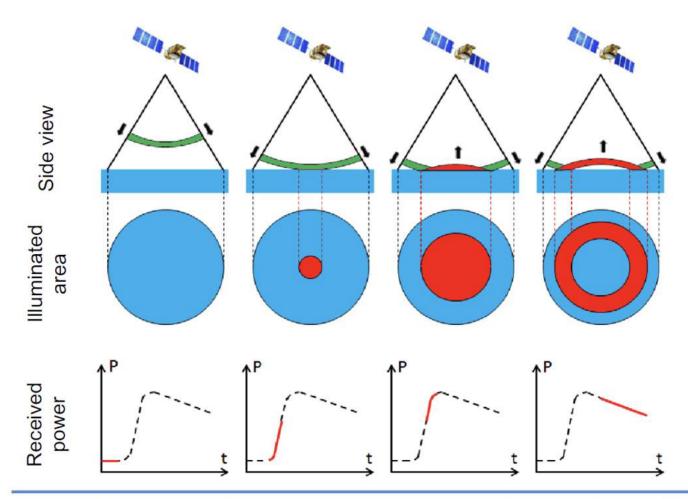
Samples POWER in >128 bins

Bins are 3 ns wide

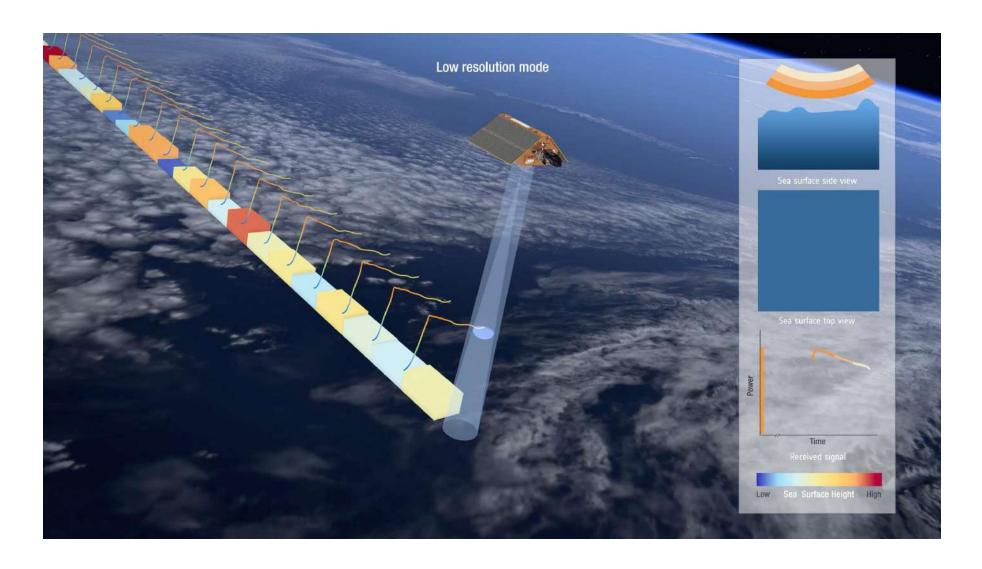


Shell of energy from the satellite

We transmit a thin 46 cm shell of Radar energy out and look at the power returned Ideal waveform



How does it work

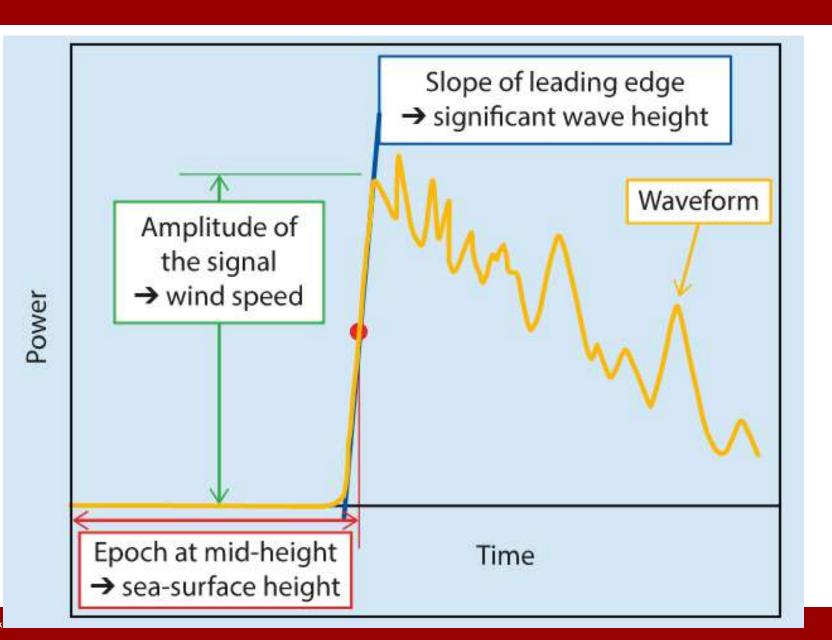


What does the waveform tell's us

Register when 50% power (relative to max) is returned.

This gives us time to range To sea surface

Multiplying with c gives
Us the range to sea surface.



Efficient size of footprint

 H_s (m) **ERS-2/1, ENVISAT Effective footprint (km)** (800 km altitude) Ground track Resolution along track to 500 meters.

TOPEX, Jason-1/2 Effective footprint (km) (1335 km altitude)



Conventional Altimetry 16 km of diameter

Unfocused SAR

~300 m in along-track direction (450 m with Hamming window) 16 km in across-track direction

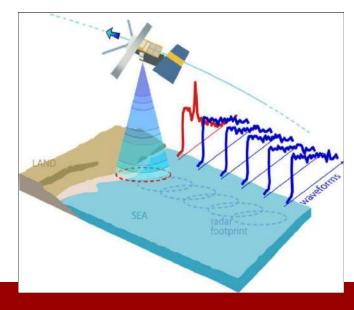
FF-SAR

~50 cm in along-track direction 16 km in across-track direction

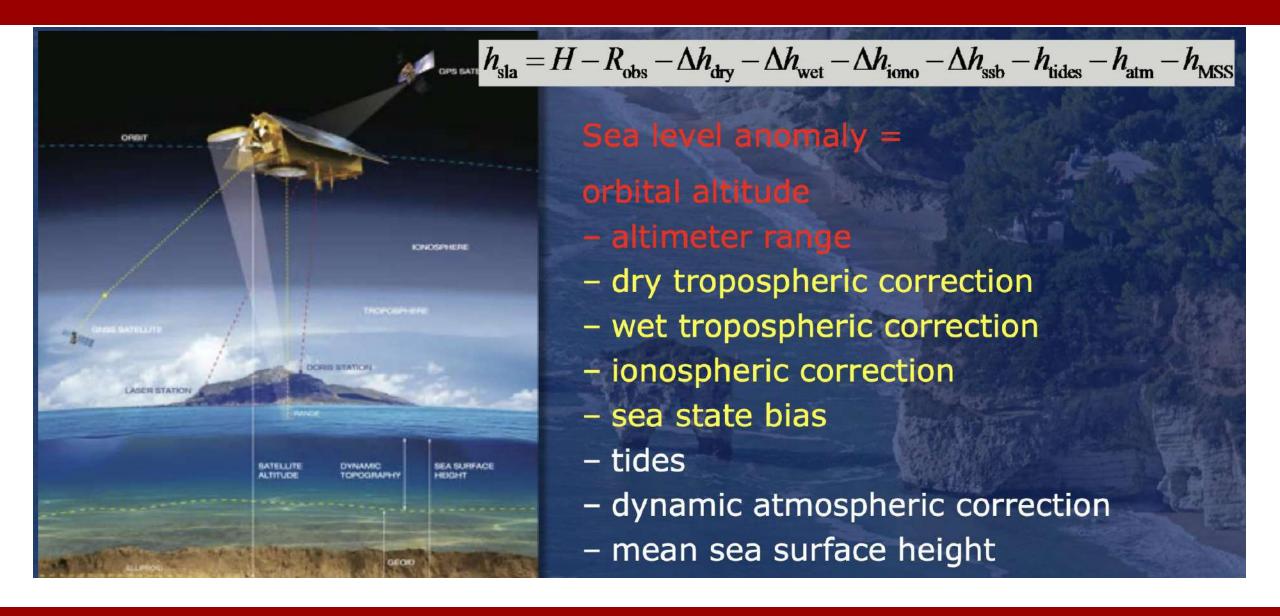
Very good for averaging out waves



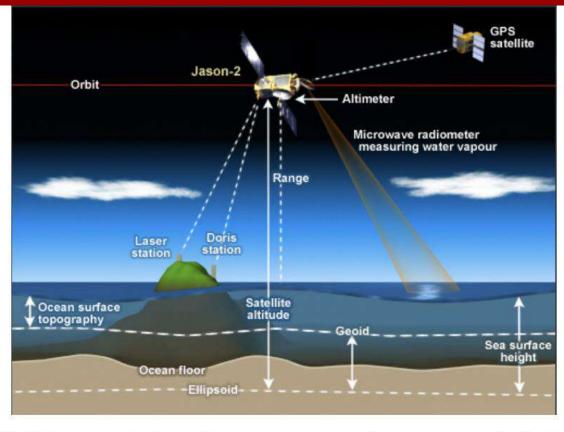
Not very good at coast



Making it accurate: Range corrections.



Accuracy and range precision



In principle RANGE precision is accurate to around 1 cm.

Orbit is precise to around 1 cm (using GPS etc).

Range correction precise to 1 cm.

So system determines SSH to a precision of 2 cm

Error propagations gives: $H_{error.} = sqrt(1+1+1) = 1.75$ cm

Creating a "geodetic" long-time timeseries - Reference missions



Reference missions

- TOPEX/Jason missions are the "reference" series for sea level climate studies.
- Error budget and instrument stability of measurements suitable for sea level change monitoring.
- Uninterrupted series of missions in same orbit for 25 years.

Tandem missions

Successful "tandem" overlaps of 6 months with successor mission ~ 1 minute behind to build a unprecedented climate data record from satellites.

Tandem flight ensures quality



30+ years – Jason + Sentinel 6 sequence

TOPEX/JASON/Sentinel-6 occupy the "optimal" OCEAN sampling pattern and repeat cycle of 9.9156 days (best for tidal separation).

Sentinel-6 is the first reference mission to use SAR........ So mission employs BOTH CONVENTIONAL LRM AND SAR For continuity.

Orbit is extremely stable and not susceptible to magnetic storms.

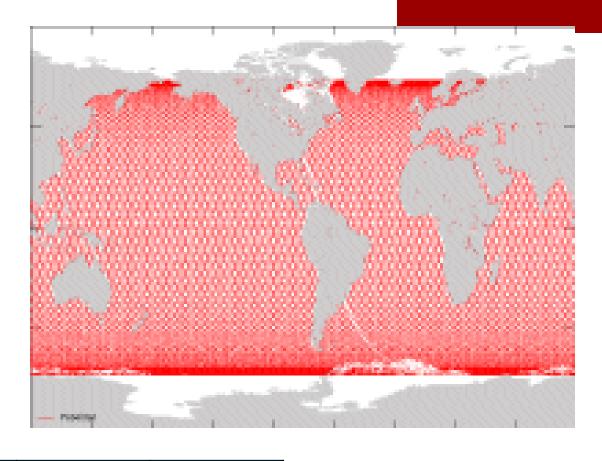
Low Inclination of 66° is VITAL to ORBIT DETERMINATION (1 cm).

Average all observations to one point globally for each 10 days Gives GLOMAL MEAN SEA LEVEL (GMSL)



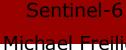




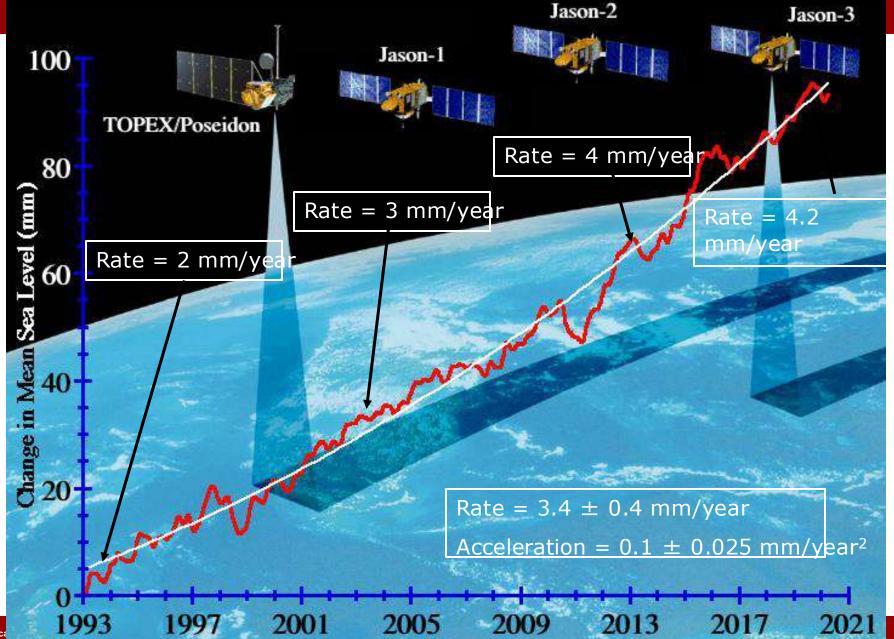


	Altitude	Inclination	Period	Repeat Cycle	Ground-track deviation	Tracj Distabce
Sentinel 3	814.5 km	98.65 deg	100.99 min	27 days	+- 1 km	70 km
Sentinel 6	1335 km	66.14 deg	103 min	9.915629 days	+/- 0.4 km	314 km

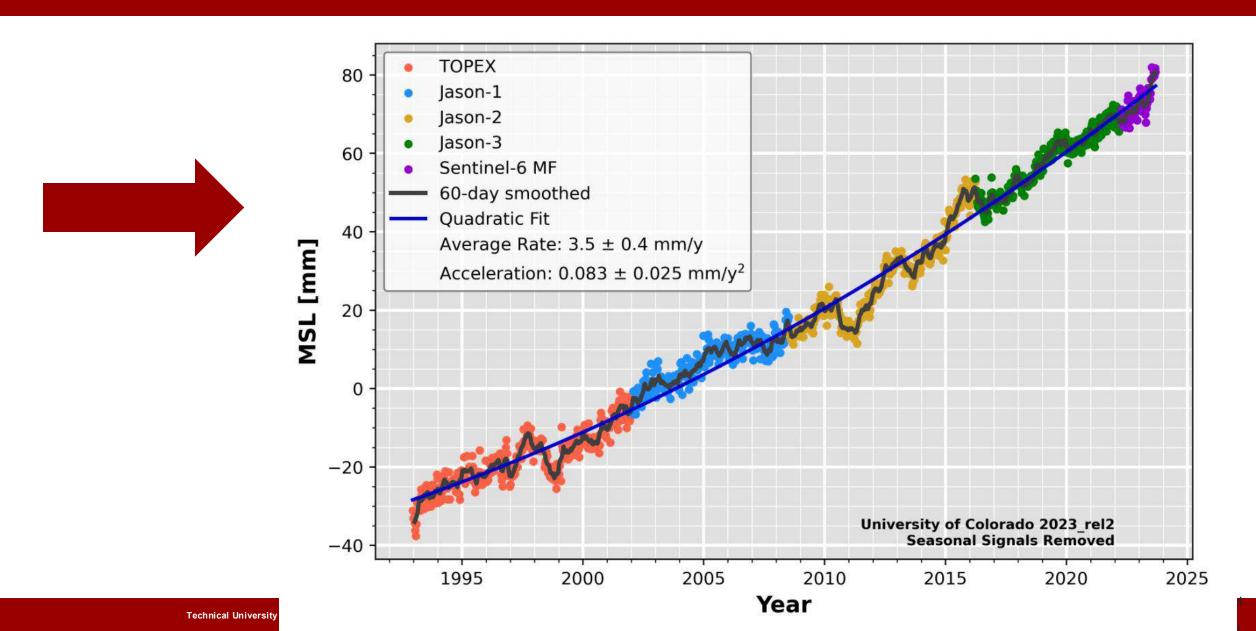
Sea level rise and/or acceleration







Updated until today with Sentinel-6



→ SEA LEVEL



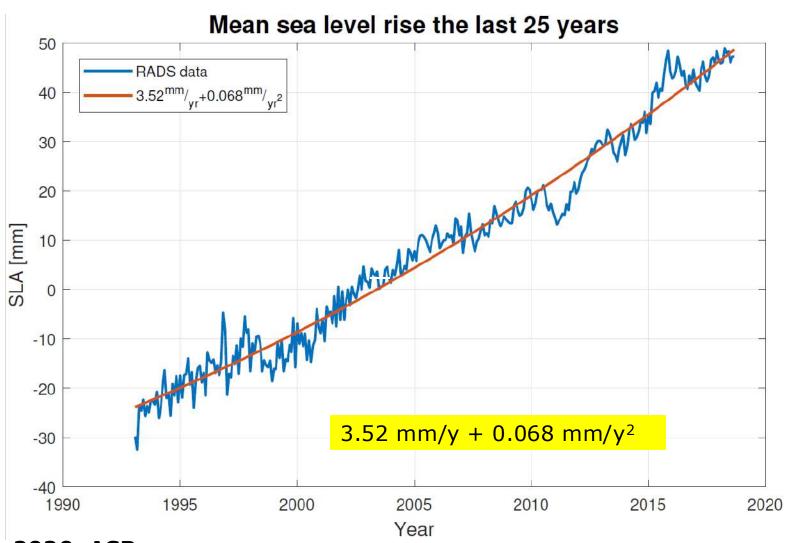
HOW DO WE MEASURE IT?

Since the early 1990s, satellite altimeters have revolutionised our understanding of sea-level rise





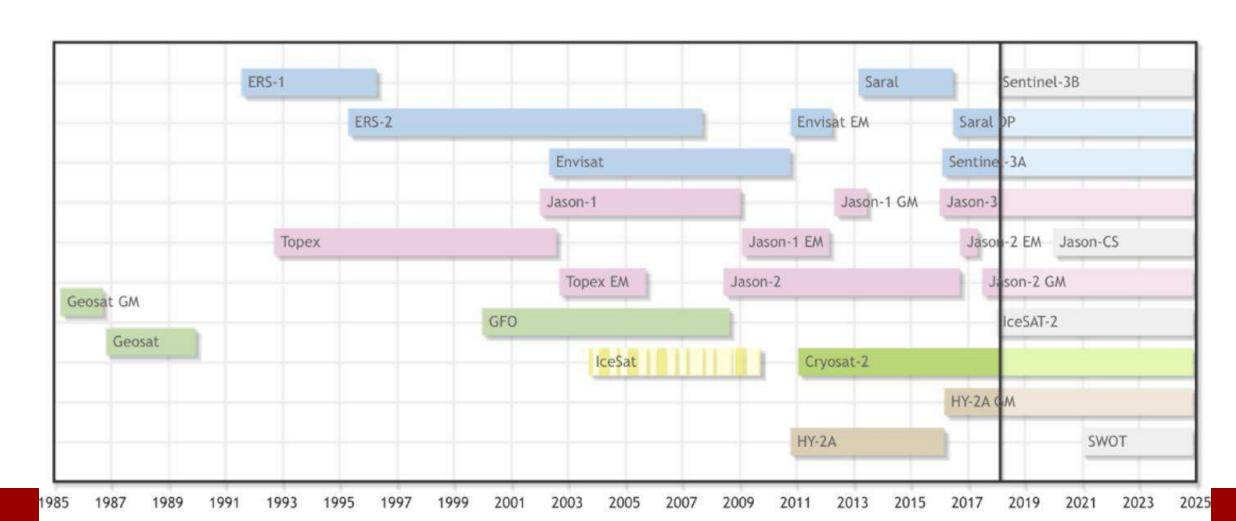
DTU 2020 sea level acceleration estimates used European satellite (ERS1+ 2, Envisat+Cryosat)



Weng and Andersen, 2020, ASR.

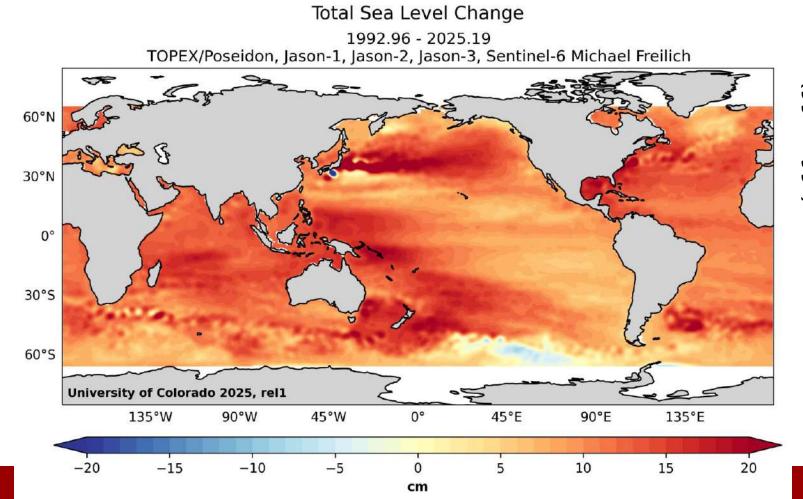
Future: Continuation and independent validation is fundamental

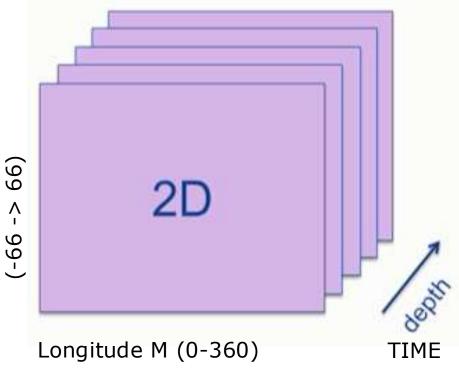
S6B (2025) and S6C (2030)???????? will be launched to ensure continuity. The S6NG is planned launch in 2035 is FUNDAMENTAL TO CLIMATE CHANGE MONITORING



Spatial sea level rise

- Use data from every 10 days
- You average all observations in say 5 degrees bin Globally.
- Must account for spherical Earth.



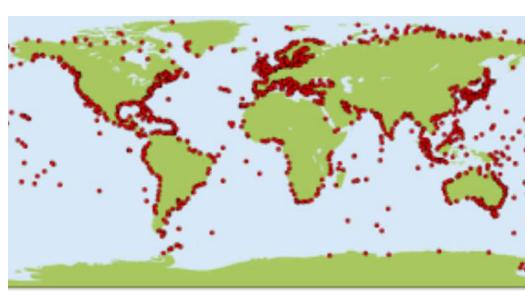


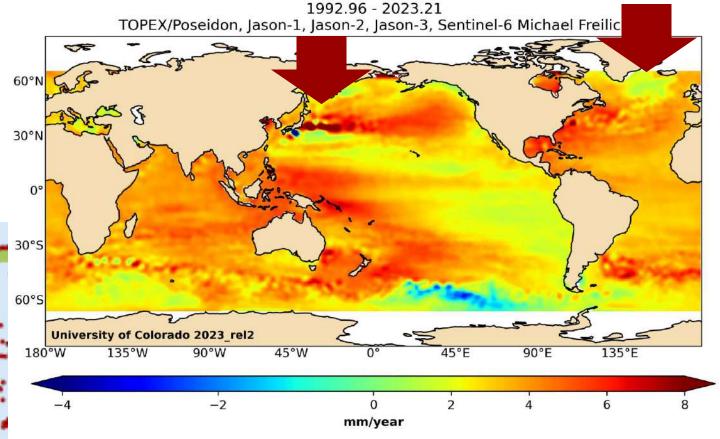
Understanding sea level rise – importance of satellites.

Satellite reveals SPATIAL PATTERN of Sea level rise........

Sea Level Trends

This is not revealed by Tide gauges.







Confirming sea level changes: Sea level budget closure

Altimetry (various satellites 1993-now)

Sea surface height: absolute sea level (ASL) w.r.t. a geocentric reference.

GRACE (2002-2017) and GRACE-FollowOn (2018-now)

Gravemetri: observes mass changes on the earth (both land and ocean), which alters the geoid.

T/S profilers (since 1950's, ARGO 2001-now)

In-situ temperature and salinity measurements can be converted to changes in density changes, called steric sea level.

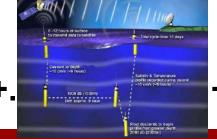


Altimetry (absolute SL) = GRACE (mass)





+ T/S profile/ARGO (steric)



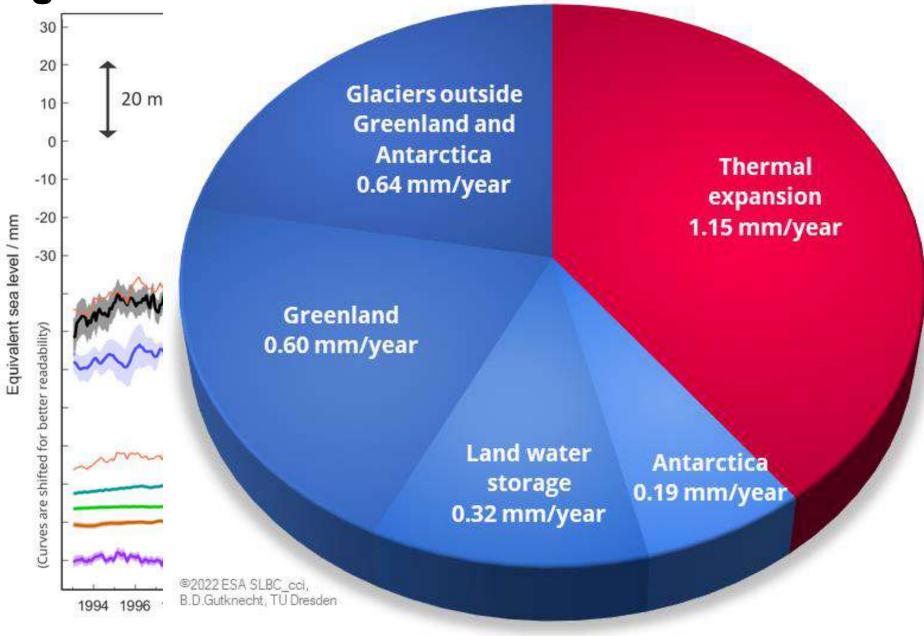
+ TWS+VLM +





Sea level budget clos

Contributions to sea-level rise 1993-2016



Horwart, Andersen & others, 2022

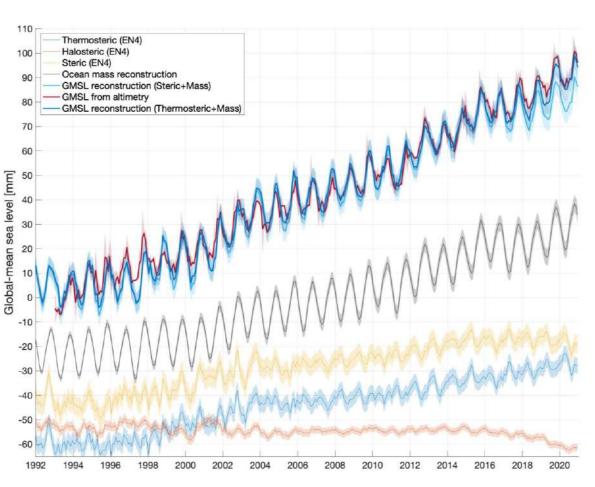
Updted by Ludwigsen et al. 2022

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Sea level-closure during 2016-2021





Altimetry GMSL
Reconstructed GMSL (thermosteric + mass)
Reconstructed GMSL (steric + mass)

Altimetry: Jason-2 -> Jason-3

mass reconstruction (land and ice)

GRACE: GRACE -> GFO

Steric sea level

Thermosteric sea level

Halosteric sea level

Argo

ARGO (conductivity)?
Something different?
..... TWS, Permafrost etc)

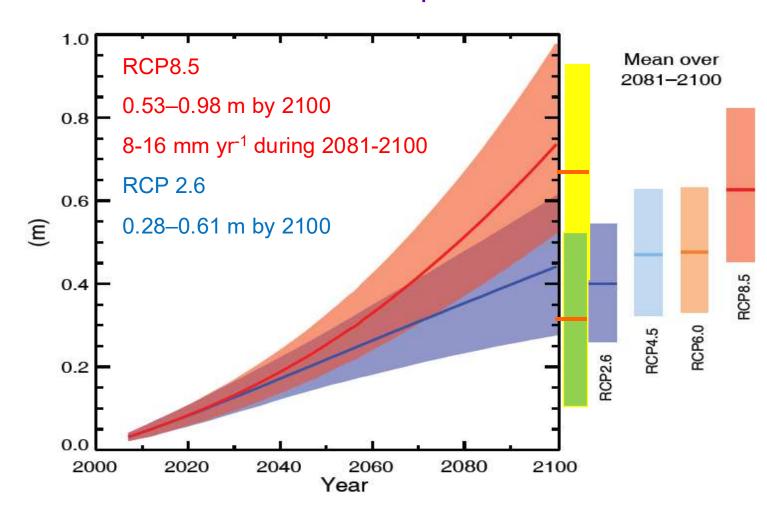
Importance of stability of reference and observing systems over decades



Future GMSL rise – importance of SL acceleration

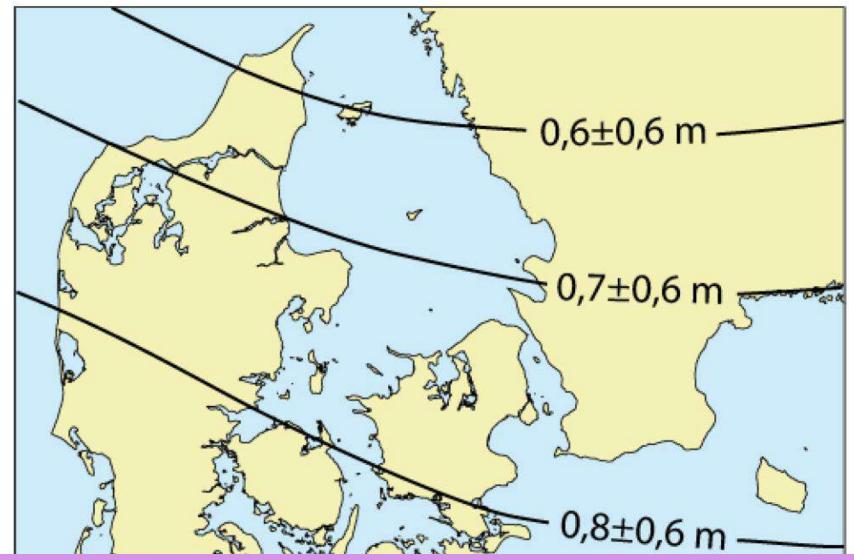
Projections of 21st-century GMSLR under Different RCPs from the IPCC 5th Assessment Report

- RCP4.5 and RCP8.5 scenario correspond to a likely global mean temperature increase of 2.0–3.6C and 3.2–5.4C in 2081–2100 above the 1850–1900 levels [Intergovermental Panel on Climate Change, 2013],
- RCP4.5 may be viewed as a moderateemission-mitigation-policy scenario, and RCP8.5 as a high-end, business-as-usual scenario.
- HERE WE EXTRAPOLATE
- ALTIMETRIC DERIVED GMSL





Sea level rise around Denmark in year 2100



We must improve the accuracy of projections.

Effective future "threat" is the combination of sea level rise and increased storm(surges).

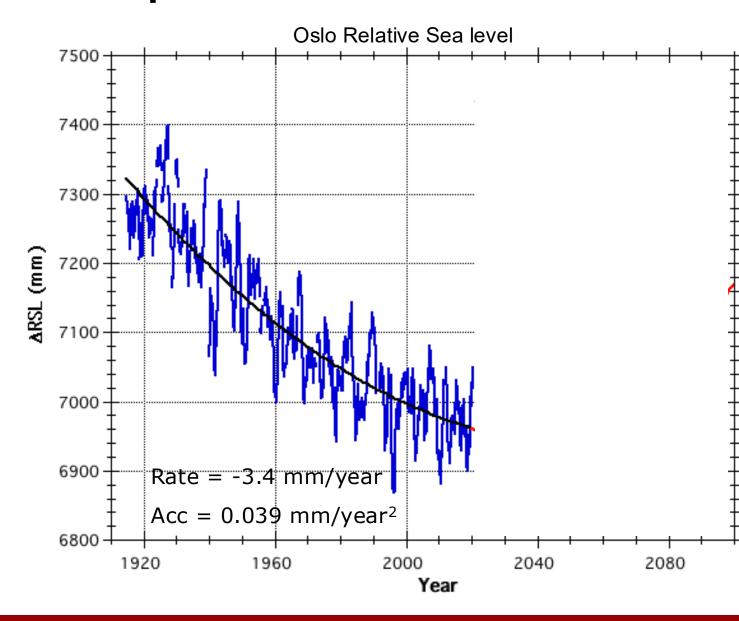
Geus, DMI (2016)



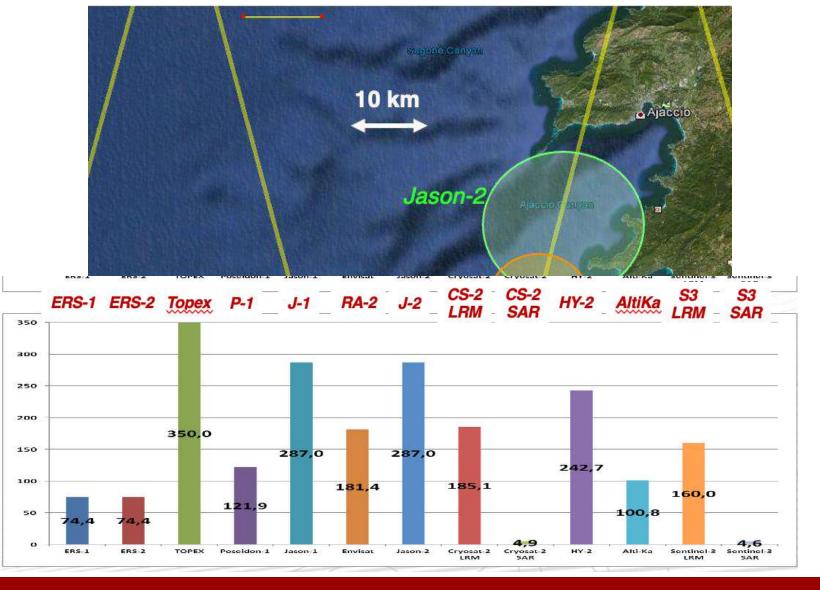
Sea Level acceleration – extrapolated for Scandinavia

Local projection onto 2150



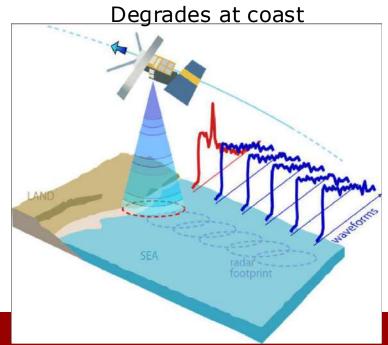


Coastal problem with conventional nadir altimetry



Very good for averaging out waves





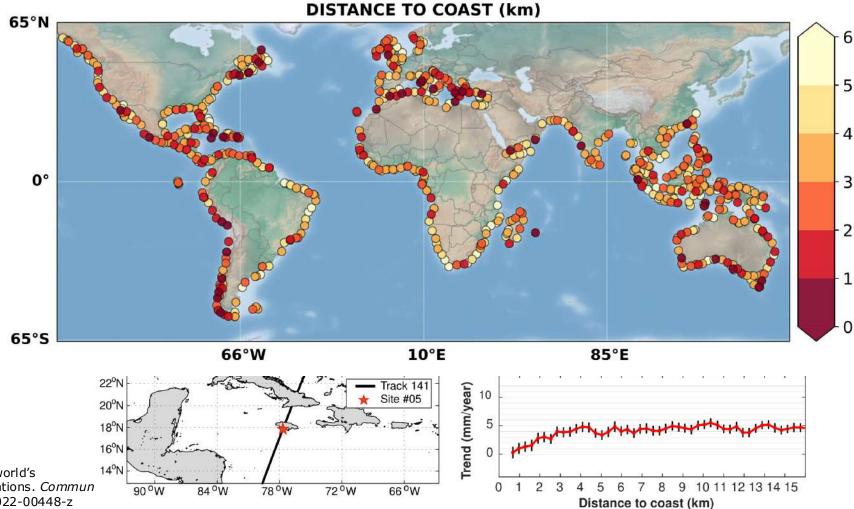
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In > 80% of "Virtual stations" SL change at coast is very close to SL change 20-50km from coast.

- Virtual station is altimetric
- Point closes to the coast
- VERY GOOD FOR BALTIC
- SEA LEVEL RESEARCH
- AND COMPARISON WITH TIDE GAUGES:





Cazenave, A., Gouzenes, Y., Birol, F. et al. Sea level along the world's coastlines can be measured by a network of virtual altimetry stations. Commun Earth Environ $\bf 3$, 117 (2022). https://doi.org/10.1038/s43247-022-00448-z

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Take-home messages.

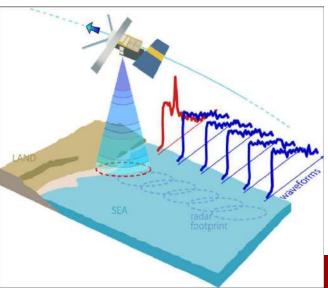
We are in "an era" of GMSL change We are maybe in "an era" of GMSL acceleration



SATELLITE ALTIMETRY has documented GLOBAL GMSL record with unprecedented accuracy (0.3 mm/year) for more than 30 years.

However, satellite altimetry is less accurate close to the coast where millions live, and we need that.

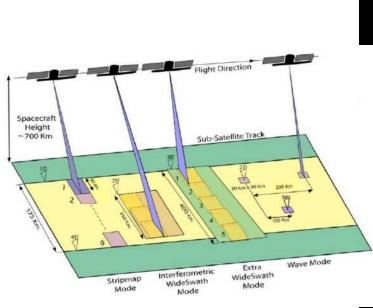
WHAT DO WE DO

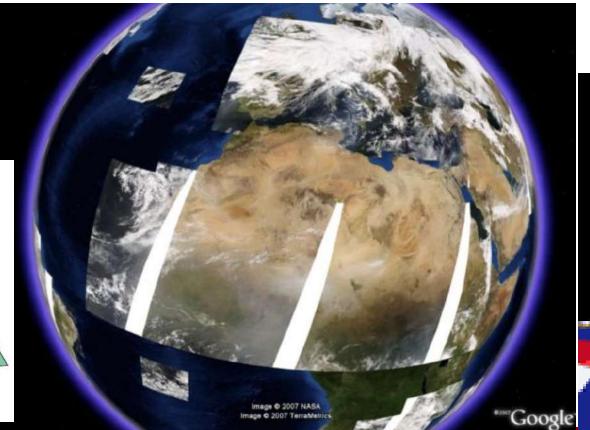


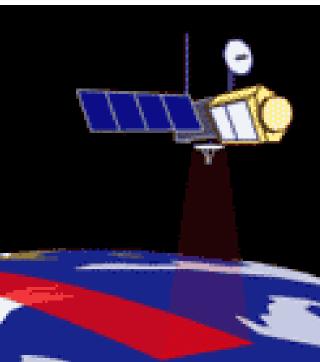
AHEAD

We start over merging SAR and Satellite Altimetry This would give interferometric or imaging altimetry

SAR + Optical (relative accuracy)









SWOT 2023 surface water and ocean topography Interferometric or imaging altimeter using near-nadir SAR.

3rd generation Imaging altimeter.

WATER DEM Every 21 day.

SWOT can
Not deliver
NEAR REAL
TIME DATA YET.

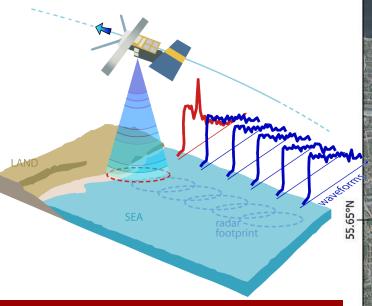




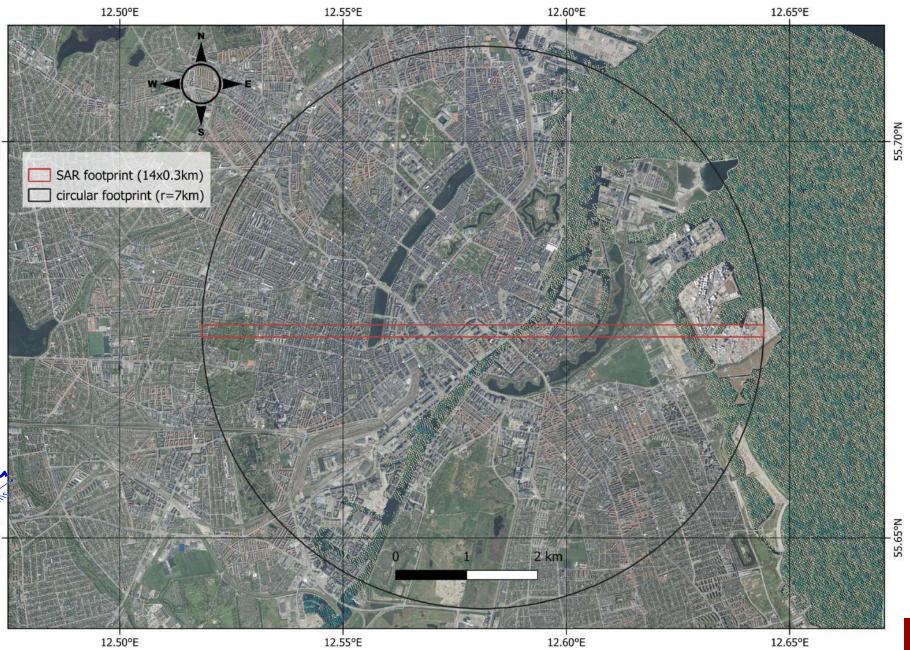
Importance of SWOT

NO DEGRADATION
AT COAST
Unless you average
The SWOT data....

Andersen, Dibarboure, 2025



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Storm surges with SWOT – Not really.

However, SWOT measured high water in Øresund on 7th

DENMARK

SWEDEN

Copenhagen

October 2023

SWOT results by my clever students







North Sea

Bjarke.

Bjarke. Rasmus. Simon



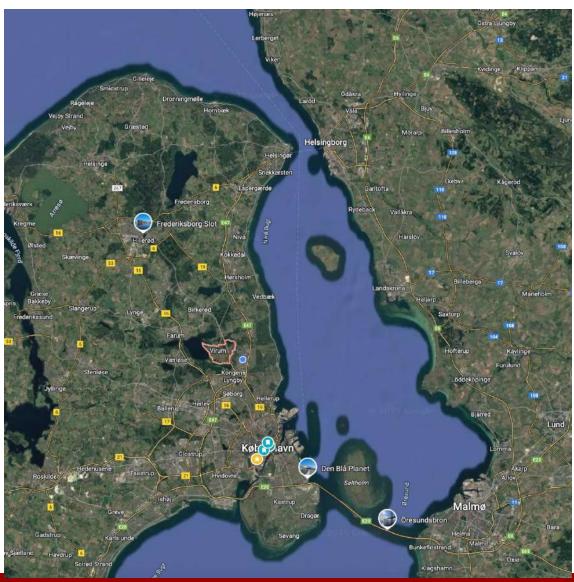


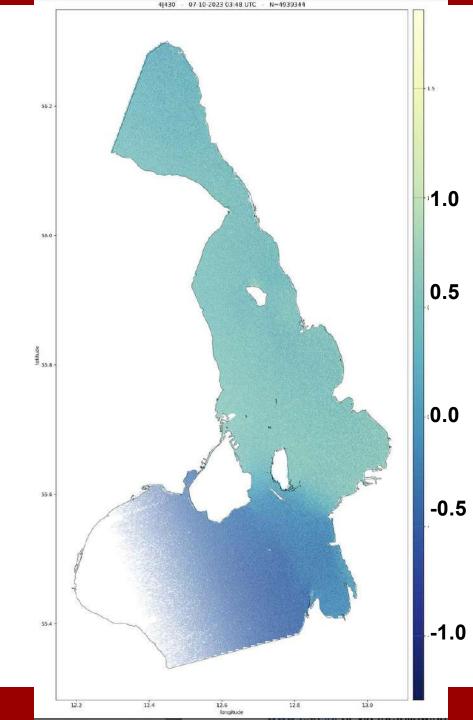
Work by Simon Kohn @ DTU



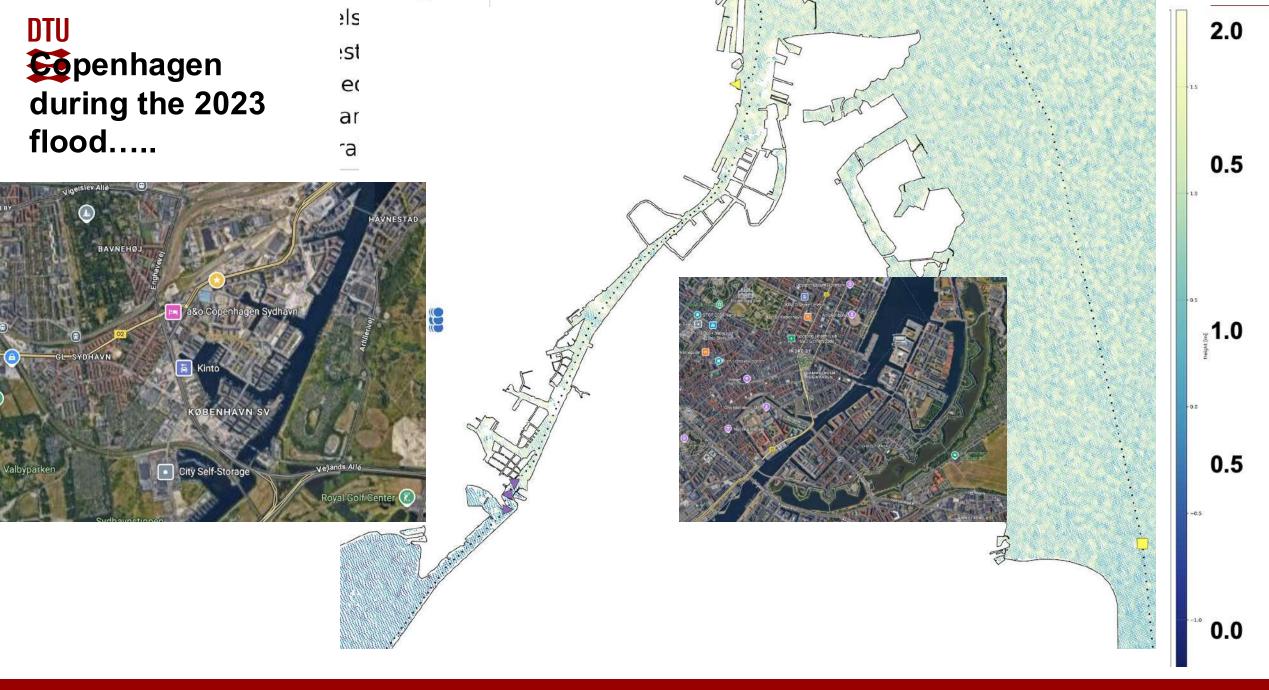


SWOT observed a small Storm Surge

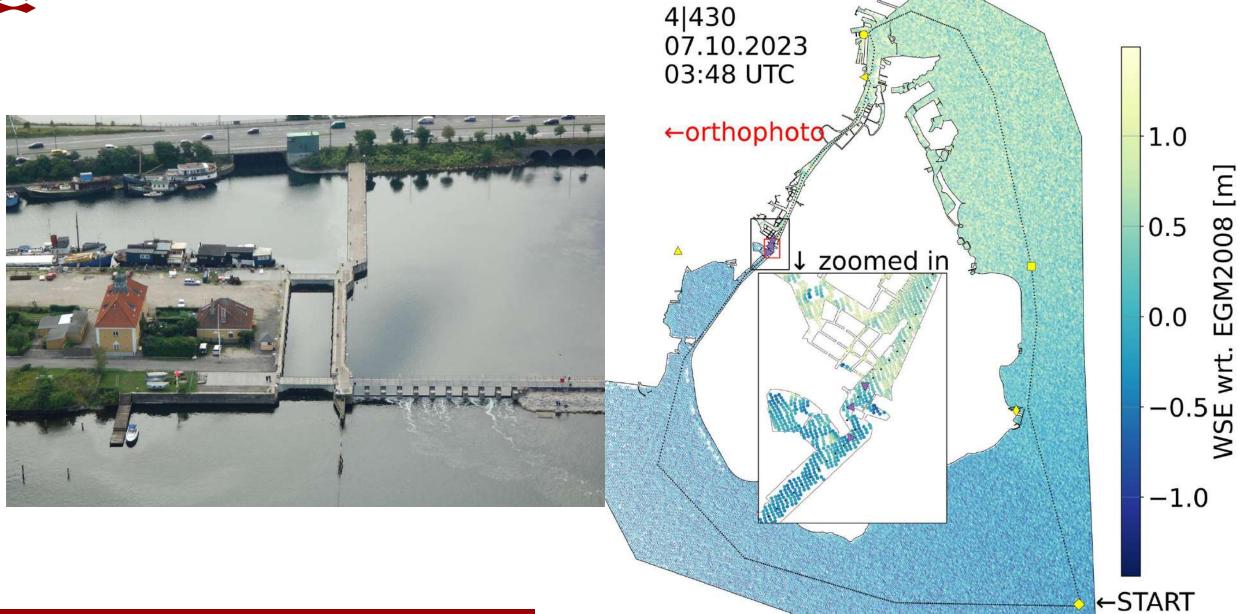




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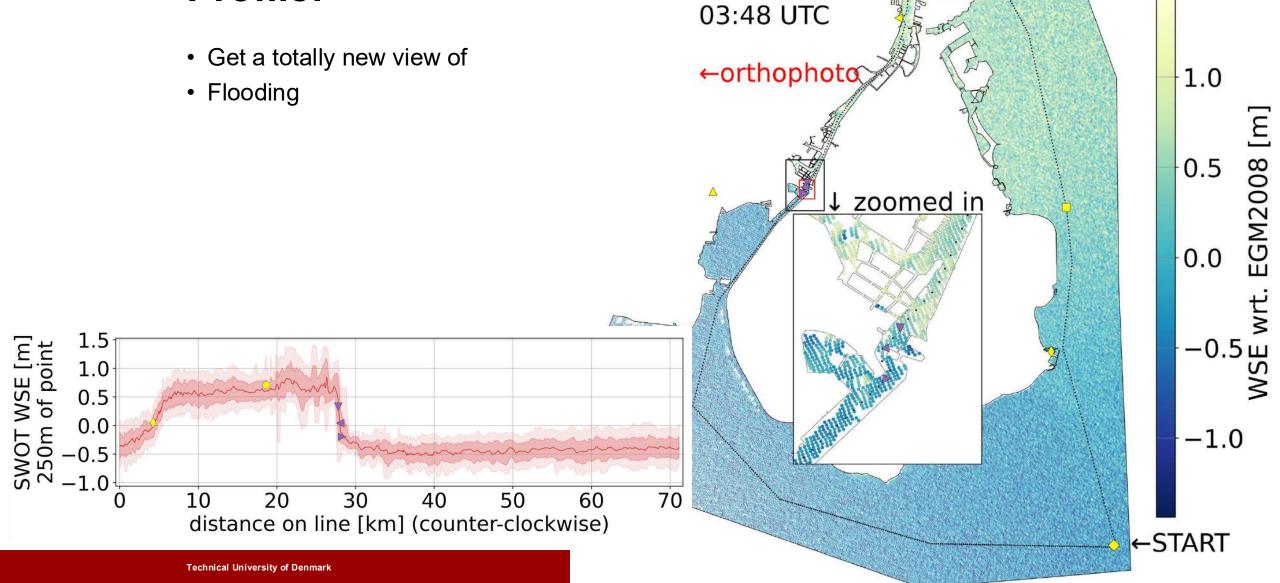








Profile.



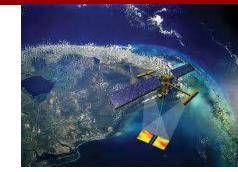
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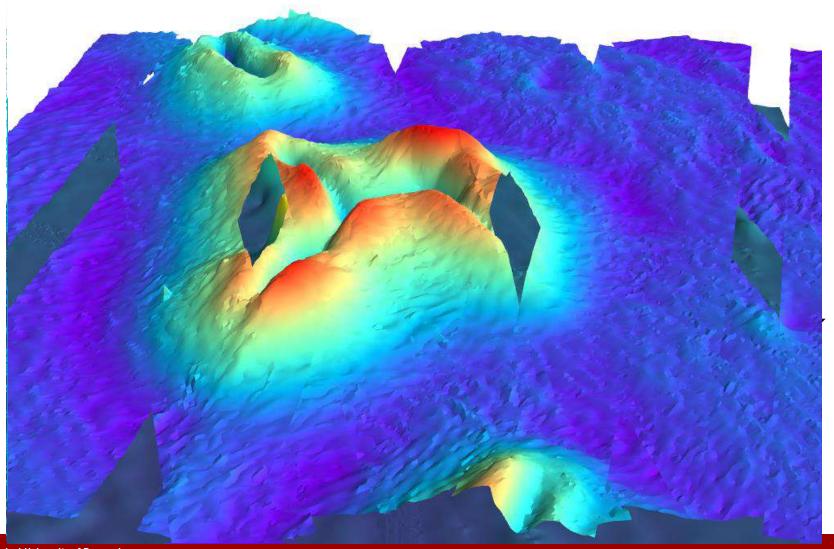
07.10.2023

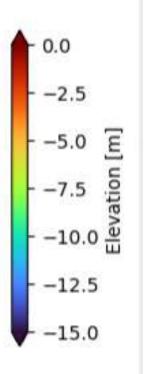




SWOT for geodesy (gravity and Mean Sea Surface)

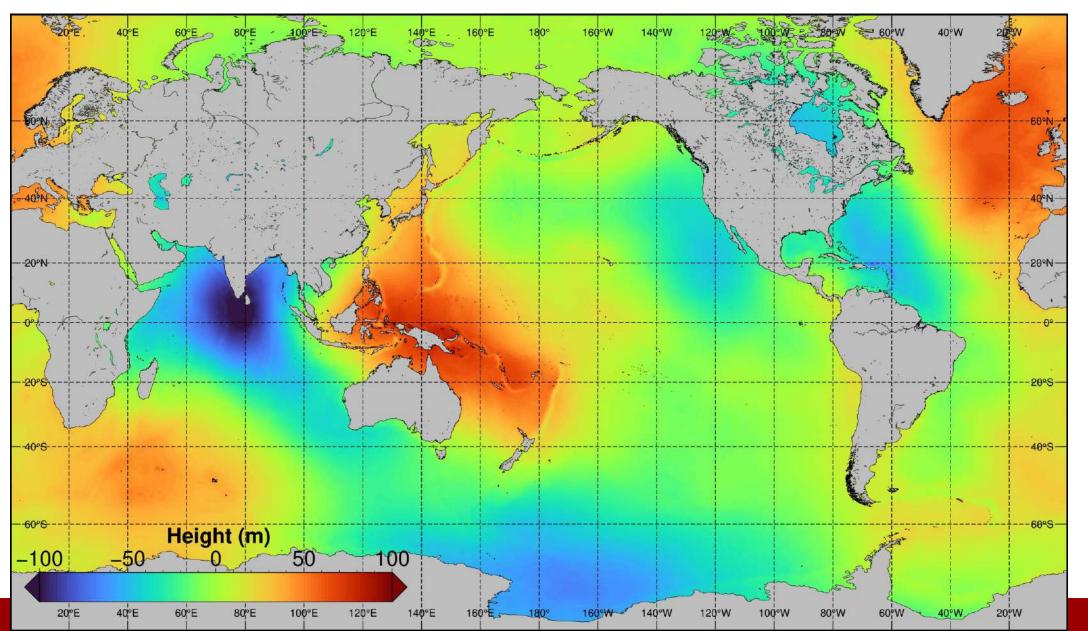


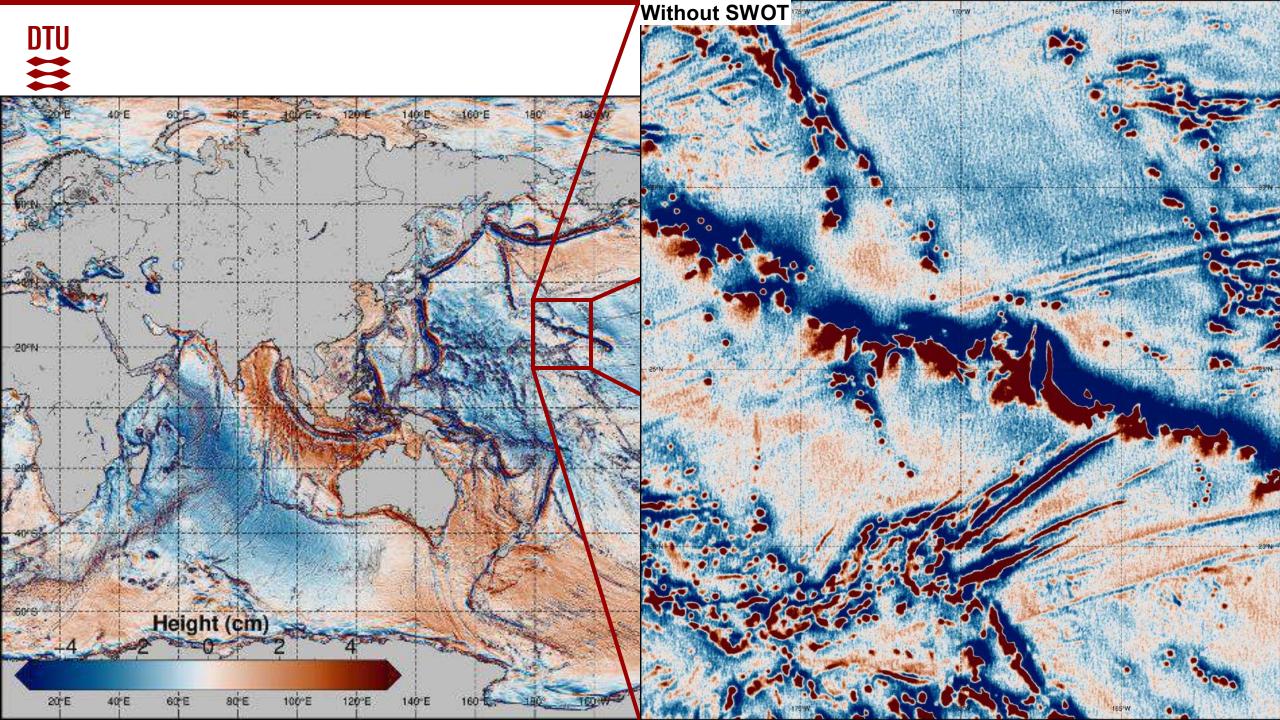


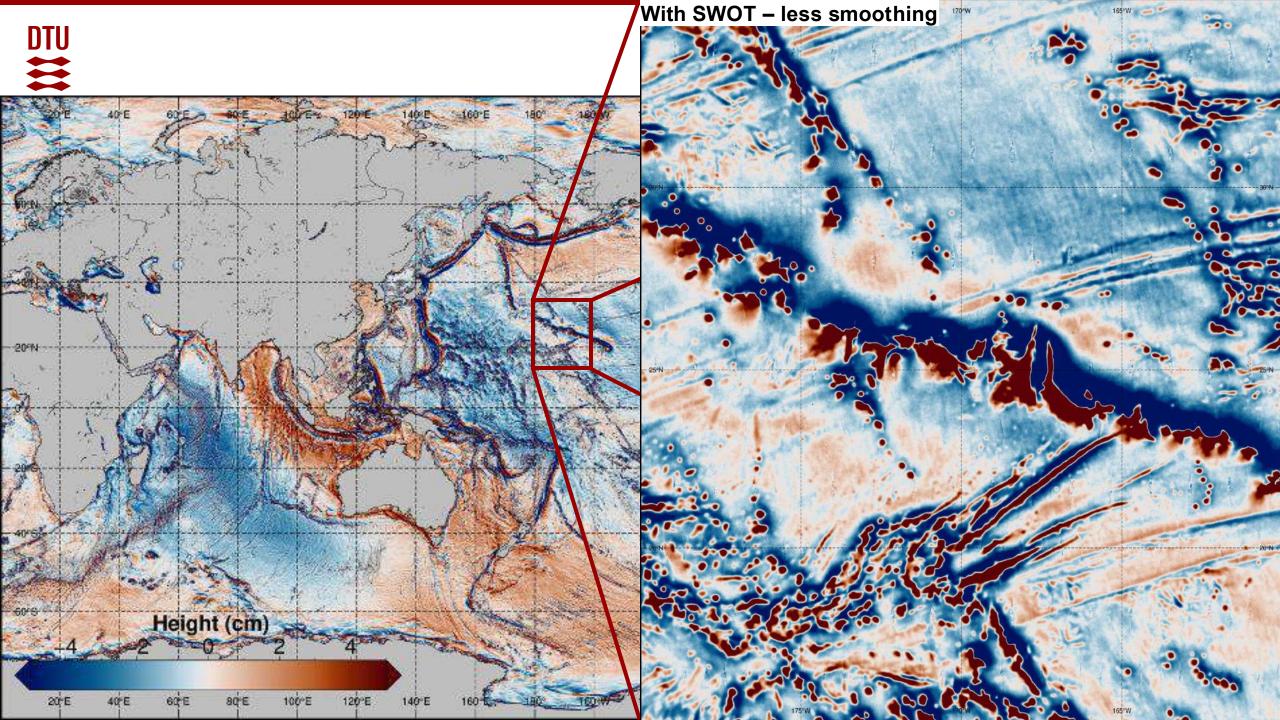




DTU25 Mean Sea Surface (under review ESSD, June, 2025) – download data.dtu.dk



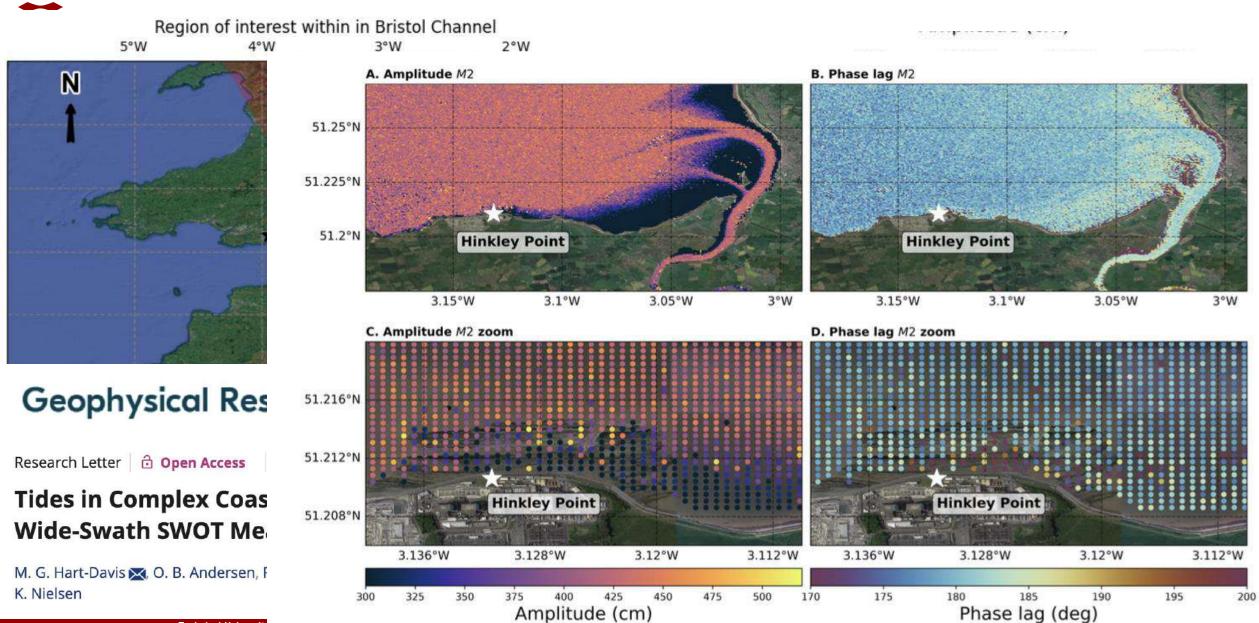






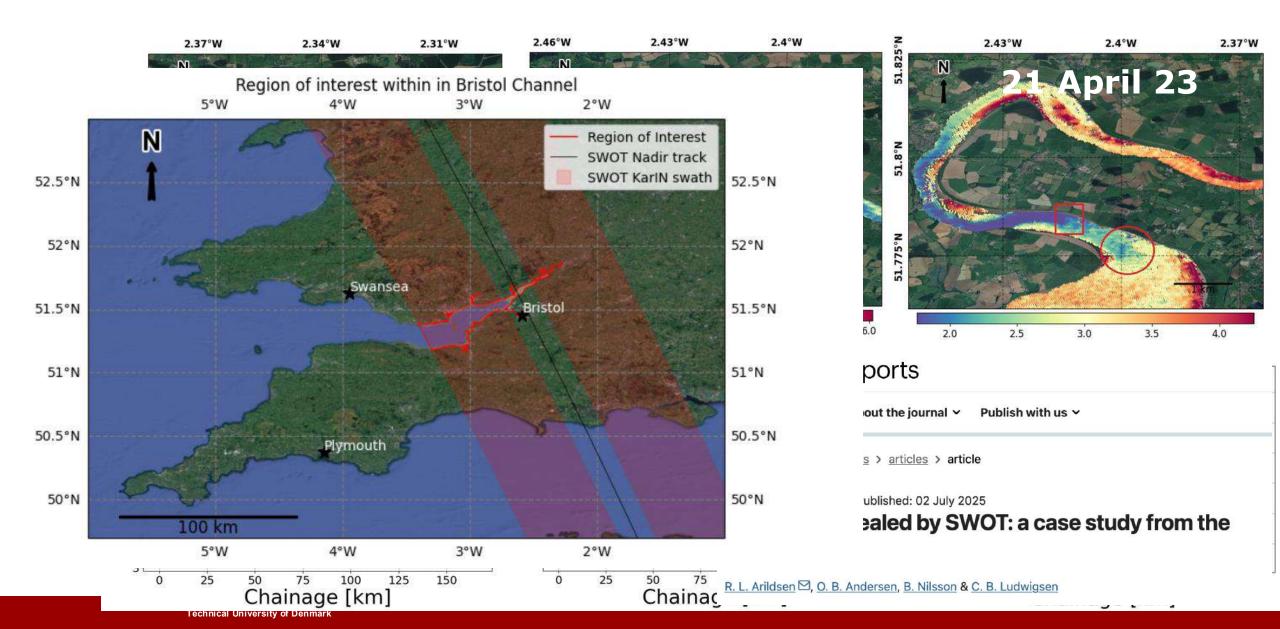
Coastal tides from SWOT

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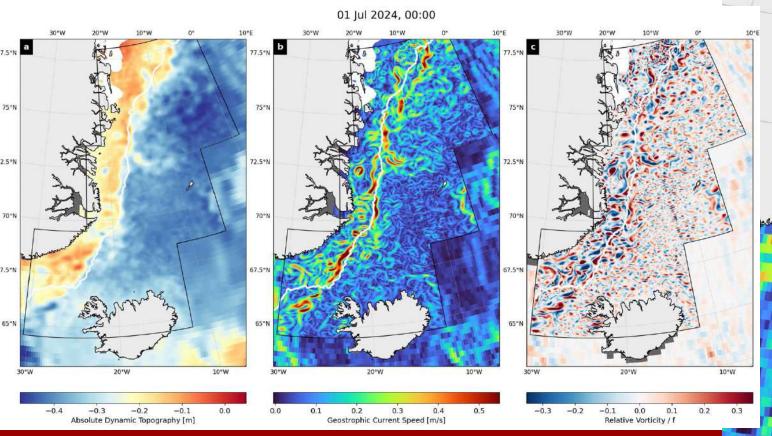
SWOT and Tidal Bores (R. Arildsen)

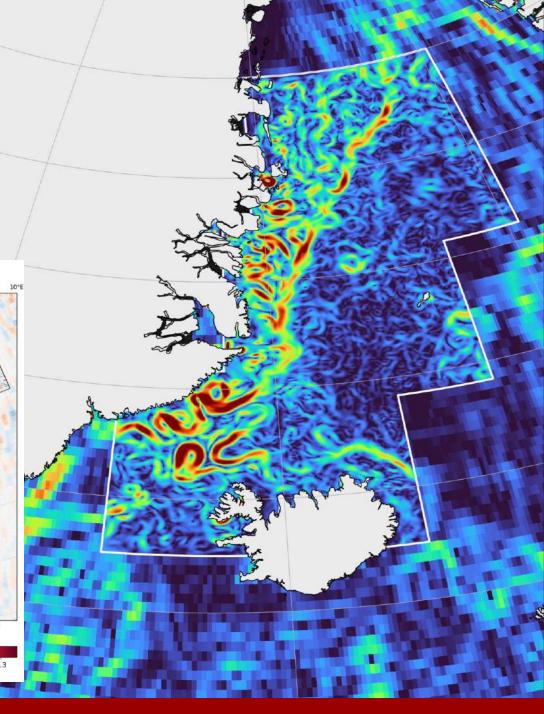


Sub mesoscale ocean currents ArcFresh and Fresh4Bio

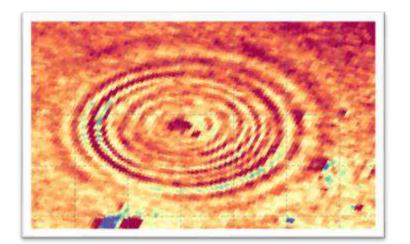
Quasi-geostrophic ocean model for East Greenland at 250 m resolution With 3 hour timestepping, Assimilating SWOT.

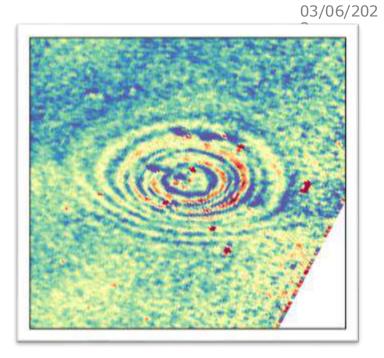
Work by Sara N. Jensen (GRL, Submitted)



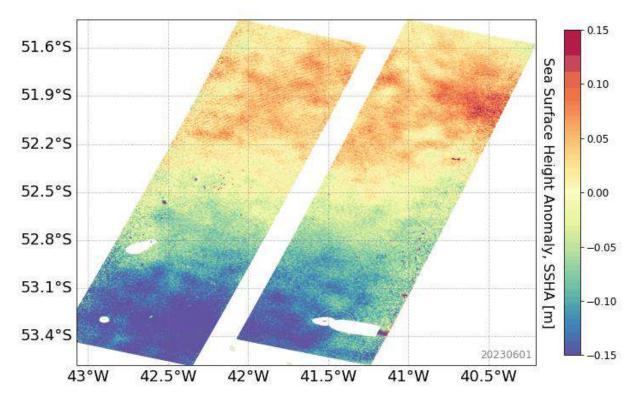








Iceberg tracking using SWOT 1-day and induced mini-tsunamis (capsizing)



55

Work by Constance Hjort GRL, Submitted

 Date
 Technical University of Denmark

 Bachelor presentation



Further take-home messages.

We are in "an era" of GMSL change
We are even in "an era" of GMSL acceleration

GMSL will manifest differently from place to place due to conditions. We are pretty fortunate in Scandinavia

SATELLITE ALTIMETRY has documented the GLOBAL GMSL record with unprecedented accuracy (0.3 mm/year) for more than 30 years.

SWOT will help us understand sea level variations at the coast for inundation/flooding and sub-mesoscale fine-scale ocean variations globally

We still need longer time series from SWOT for GMSL studies





Summary:

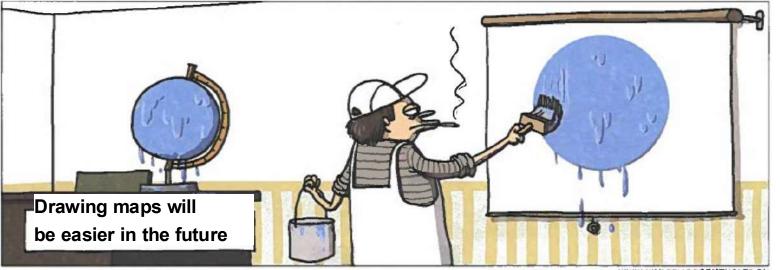
We are in an era of climate change.

Satellite data are fundamentally important for monitoring and Understanding climate change.

Geodesy is a vital part of the global observing system.



O3 JANUAR 2012



NOTE:

