Ocean Surface Currents in the northern Nordic Seas from a combination of multi-mission satellite altimetry and numerical modeling

Felix L. Müller[1], Denise Dettmering[1], Claudia Wekerle[2], Christian Schwatke[1], Marcello Passaro[1], Wolfgang Bosch[1], and Florian Seitz[1]

[1] Deutsches Geodätisches Forschungsinstitut, Technische Universität München (DGFI-TUM)
[2] Alfred-Wegener-Institut Helmholtz-Zentrum für Polar- und Meeresforschung

EGU General Assembly 2020
Virtual Presentation, 03.05.2020

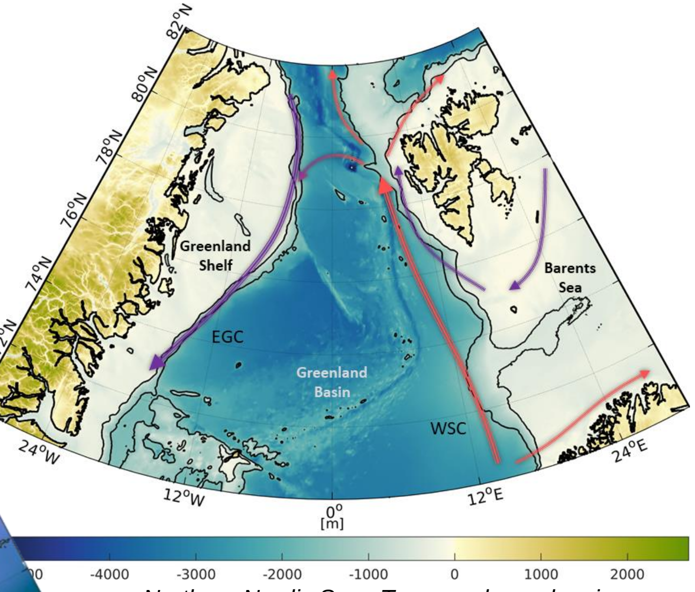
Motivation

The current status:

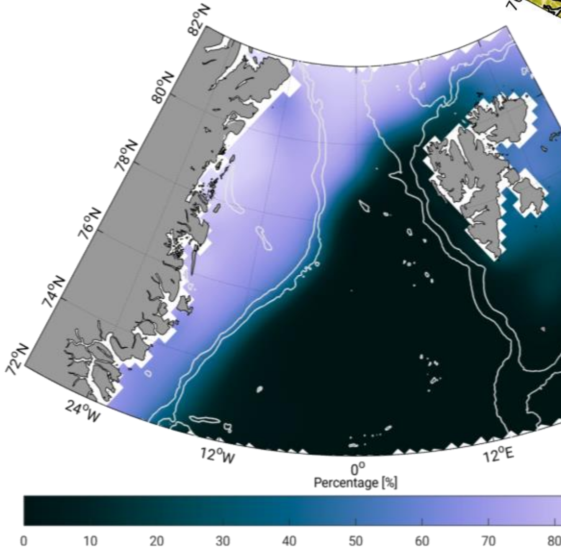
- Temporal variable Dynamic Ocean Topography (DOT) enables detection of surface current variabilities
- Altimetry derived polar DOT is affected by irregular sampling and data gaps (along-track data, sea-ice)
- Models can give spatio-temporal consistent DOT information, but are limited by mathematical assumptions and restrictions

The idea:

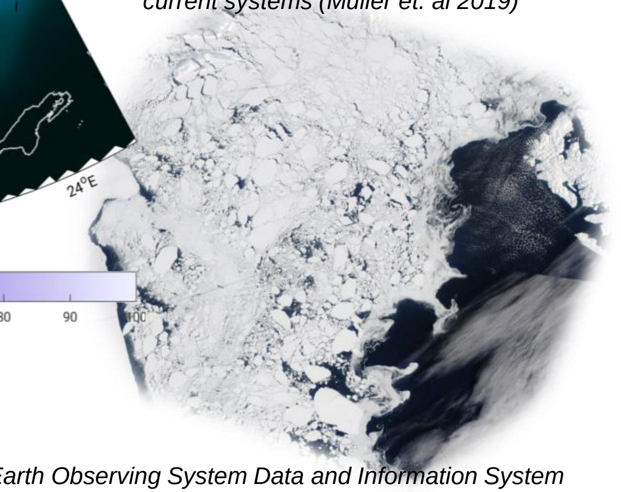
- Exploitation of possible synergy effects of both datasets
  - ➢ Altimetry Sea Surface Observations
  - ➢ Ocean Model Simulation
- Generation of an innovative homogenous, temporal-variable DOT in polar regions (i.e. combination), with the possibility to derive geostrophic surface currents – Model should support observational data.
- Requires: 1. Comparison of datasets and 2. Combination of datasets from observational point of view - **No data assimilation**



Northern Nordic Seas Topography and major current systems (Müller et. al 2019)

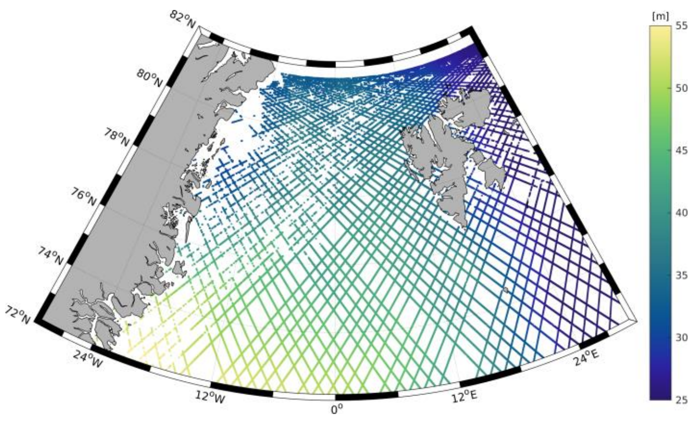


NSIDC: monthly sea-ice concentration within 2003-2009 (Müller et. al 2019)

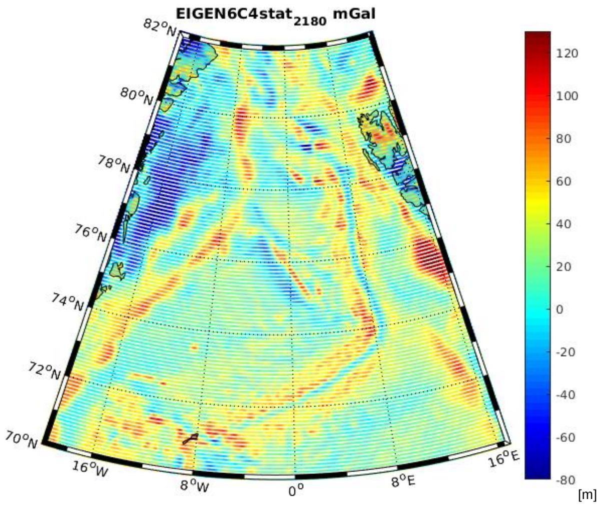


© Earth Observing System Data and Information System (EOSDIS), National Aeronautics and Space Administration (NASA)

Short excursion: Sea Surface Heights (SSH), Geoid and DOT

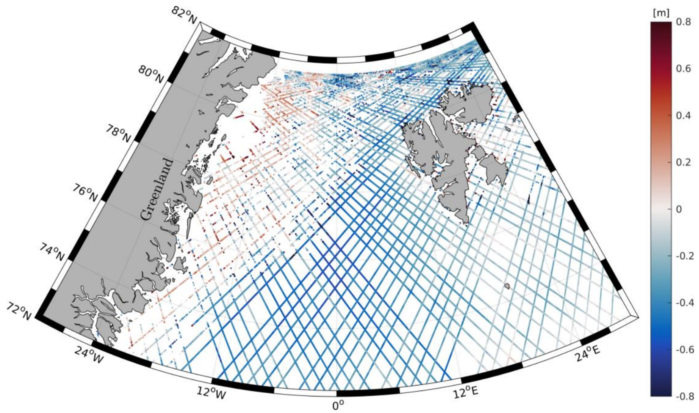


-



E.g. EIGEN-6C4 (Förste et al. 2014)

=



- **Sea surface heights** (Reference: Ellipsoid)
- Altimetry provides distance between satellite COM and sea surface (retracked altimetry range)
- SSH = satellite orbit height - (range + corrections)

- **Geoid**
- Equipotential earth surface
- Shape of the earth just considering gravity changes and Earth rotation
- Approximates the mean sea level
- Examples: EIGEN-6C4 (GFZ) or OGMOC (IAPG)

- **DOT**
- Sea surface affected by hydrodynamic processes and gravity variations (Reference: Geoid)
- Used to compute geostrophic currents

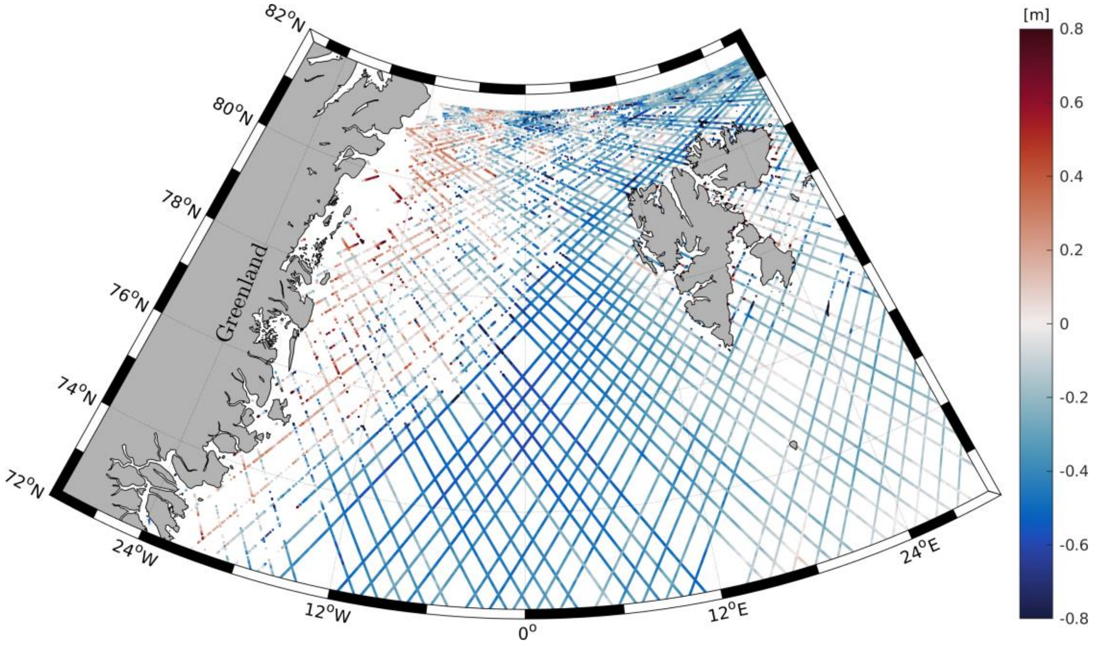
Observational DOT: Altimetry (ESA: ERS-2, Envisat)

- ➢ High-frequency altimetry data (20 Hz)
- Consistent estimated SSHs
  - Retracker, ALES+ (Passaro et al., 2018)
  - No offset between sea-ice and ocean areas

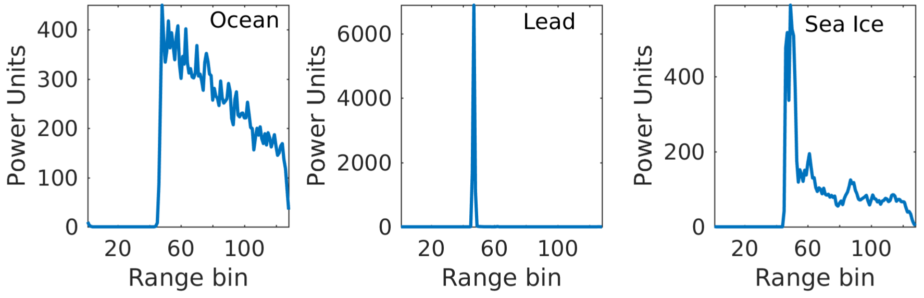
- Elimination of sea-ice contaminated radar echoes
  - Unsupervised classification (no training data)
  - Assignment of sea-ice and open water radar echoes (Müller et al., 2017)

- Transformation to DOT heights by subtracting high resolved geoid (OGMOC, Gruber & Willberg, 2019) → 2190 degrees

- Spatial filtering of profiled data with ~9km moving average filter



Example: Along-track DOT heights



Example: Envisat Waveforms

Modelled DOT: FESOM (eddy resolving configuration)

- ➢ Finite Element Sea-Ice Ocean Model (FESOM)
- Irregular, unstructured (<1km sp. resolution) mesh with local refinements

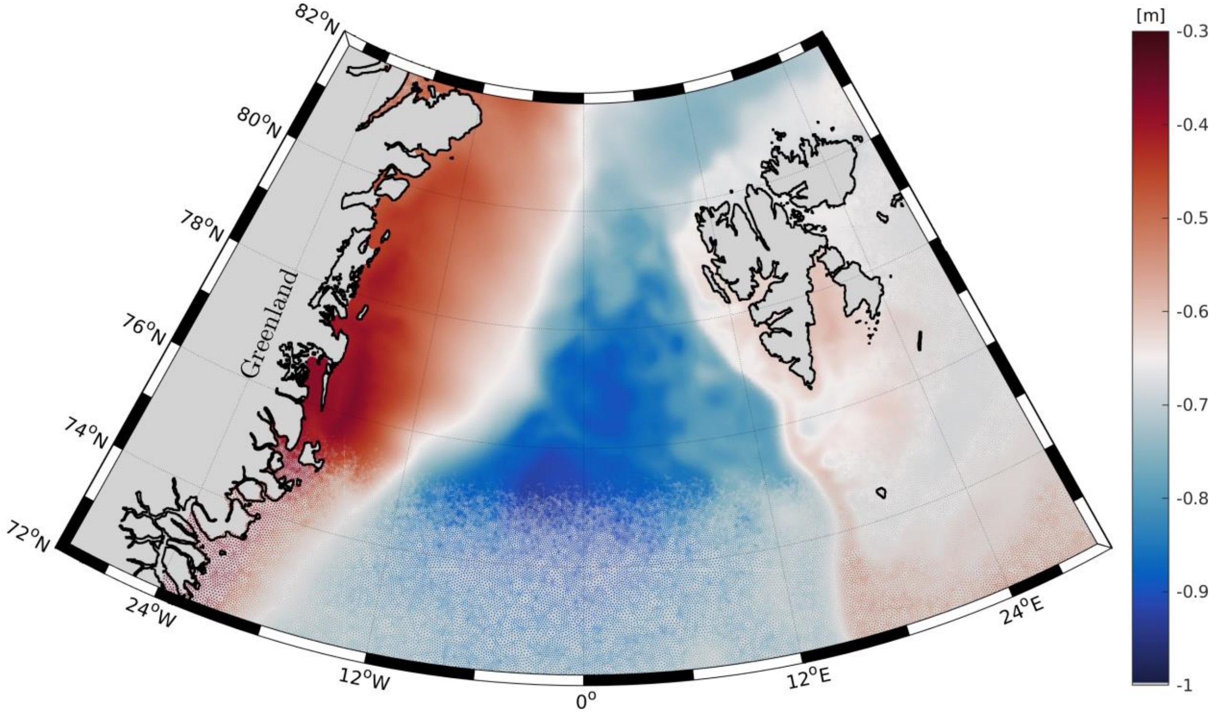
- Daily differential water heights w.r.t bathymetry
- Covers years 2002 – 2009

- Water heights are comparable to DOT heights

- Includes sea-ice component considering major sea-ice drift patterns

- Conserves for volume not for mass

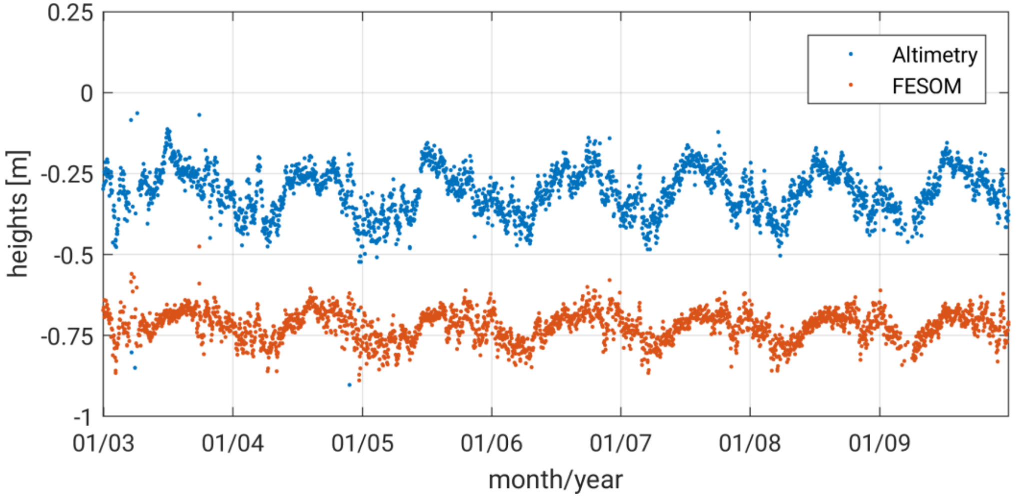
- Does <u>not</u> include: barometric effects and ocean tide signal



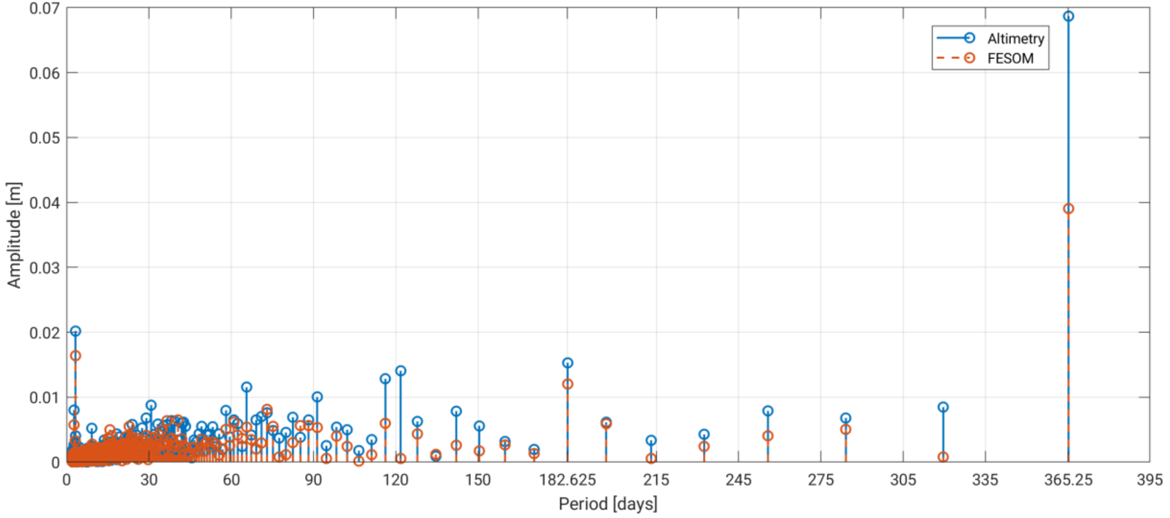
Example: FESOM Differential Water heights

Temporal Comparison – Frequency analysis

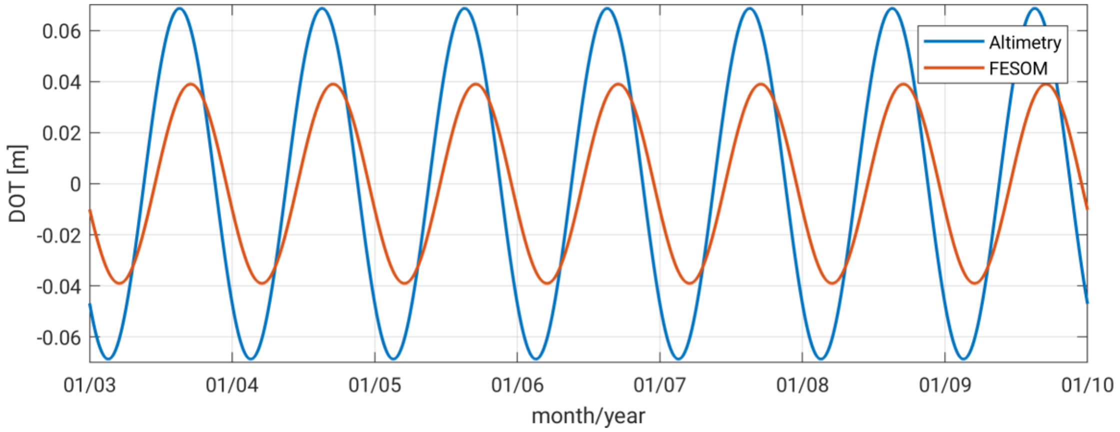
Time Series Daily means (Müller et. al 2019)



Frequency Analysis (Müller et. al al 2019)



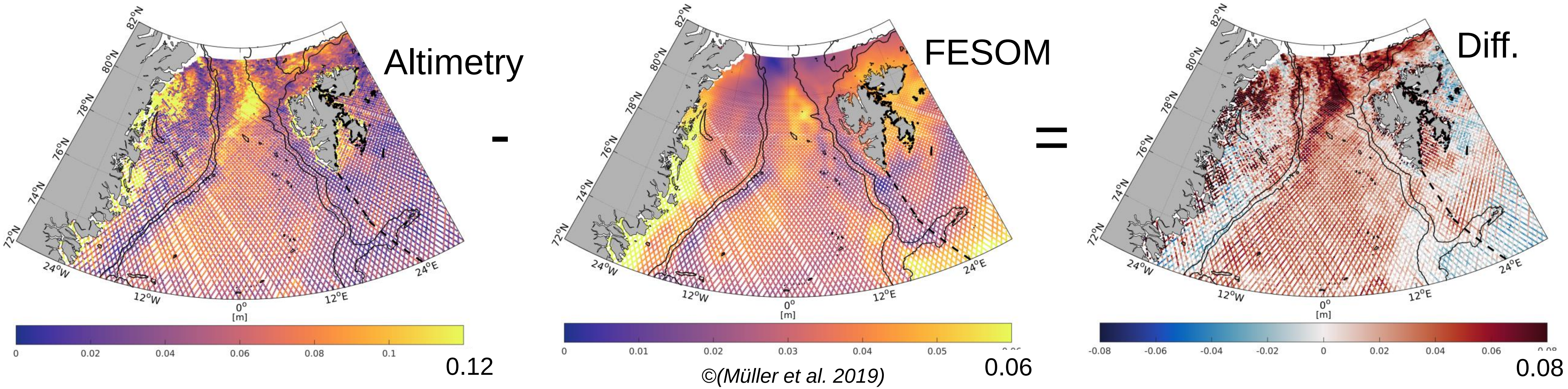
Annual signal



Annual signal (Müller et. al al 2019)

- Interpolation of FESOM water heights to altimetry ground track locations (nearest-neighbor)
- Daily means of available observations and interp. model data
- Harmonic freq. analysis of both datasets (2003 – 2009)
- ➢ Annual period dominates in both datasets (365.25 days)
- ➢ Amplitude: ~7cm (Altimetry) vs. ~4cm (FESOM)
- ➢ Minor subordinated periods
- ➢ Phase shift: ~ 30 days

Spatial Comparison - Annual Signal



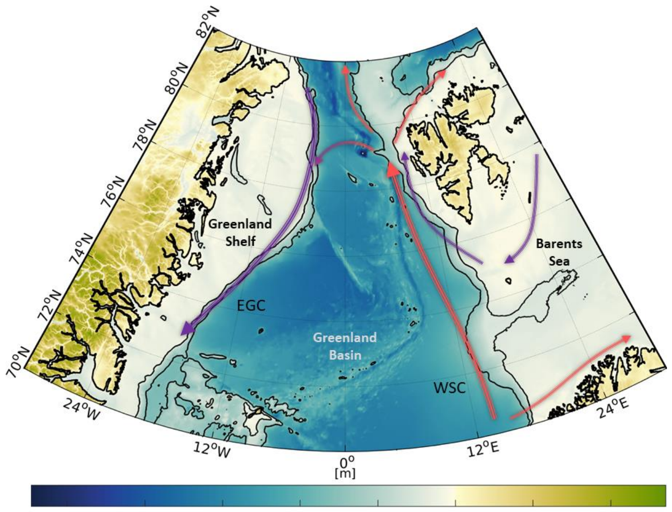
©(Müller et al. 2019)

- Comparison of altimetry DOT and FESOM water heights, based on nominal ground track
- Data is equally ordered in bins (7.5km)
- Significant differences in sea-ice regions and at the coast
- Altimetry DOT shows higher seasonal variability and stronger magnitude
- Phase differences in central Greenland Sea

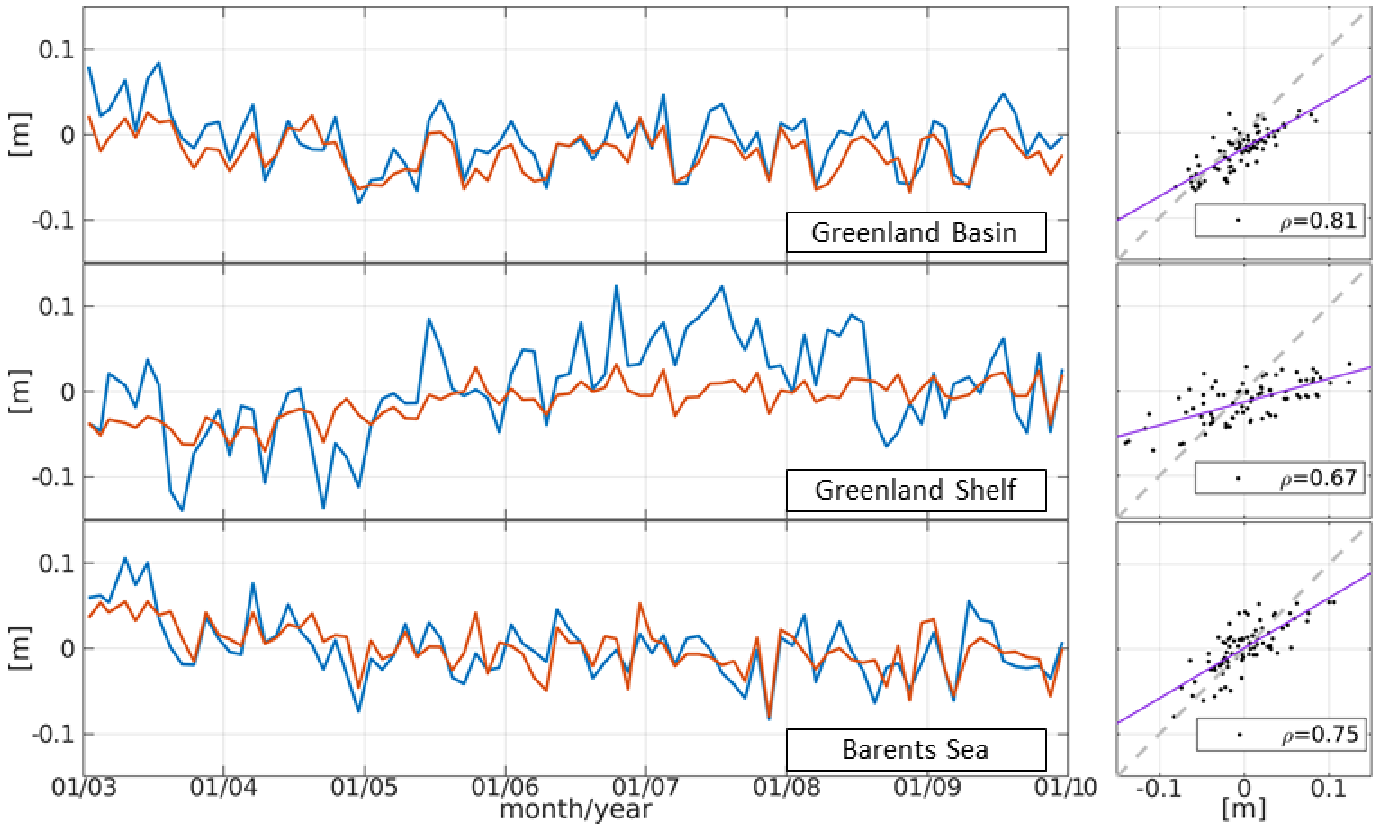
Region	**Amplitude [cm]**	**Day of maximum**
Greenland Basin	**6.3 (Altimetry)** **3.0 (FESOM)**	**233 (Aug)** **267 (Sept)**
Greenland Shelf	**5.7** **3.8**	**315 (Nov)** **312 (Nov)**
Barents Sea	**4.0** **3.8**	**284 (Oct)** **304 (Oct)**

Differential analysis: Temporal evolution

- Reduction of both datasets by constant offsets and annual oscillation
- High correlation in all sub-areas indicate good agreement
- No systematic effects in Greenland Basin and Barents Sea
- Observed trend in Greenland Shelf not significant

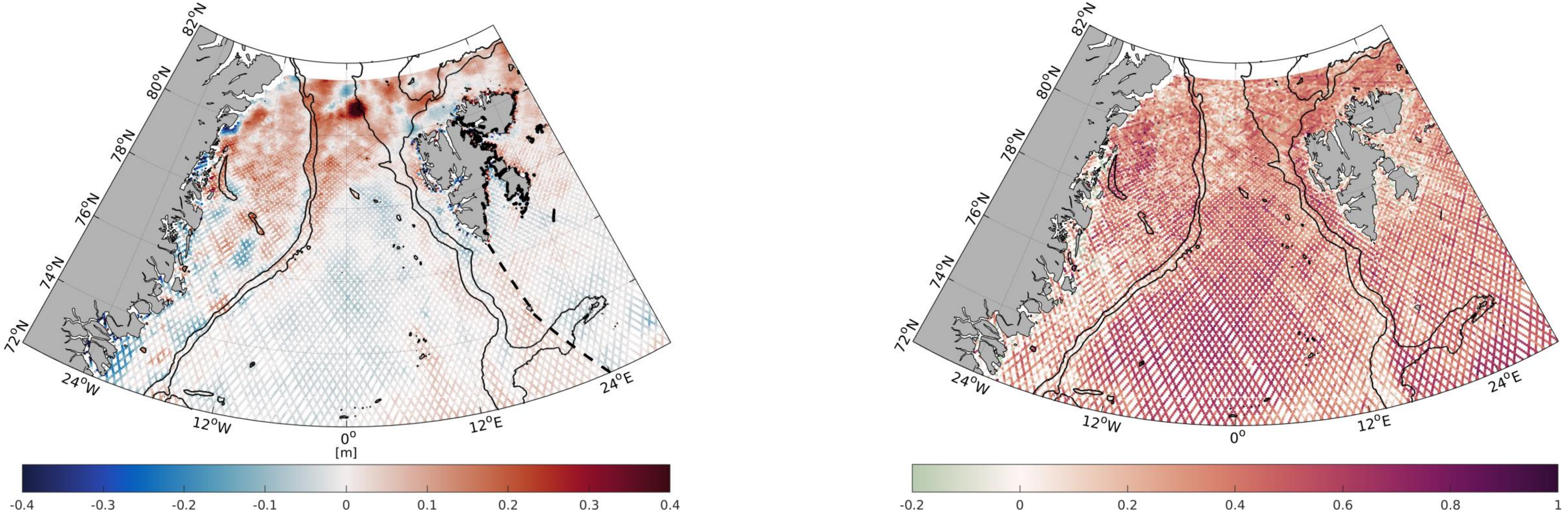


©(Müller et al. 2019)



© (Müller et al. 2019)

Differential analysis: Spatial patterns



Mean Differences 2003-2009

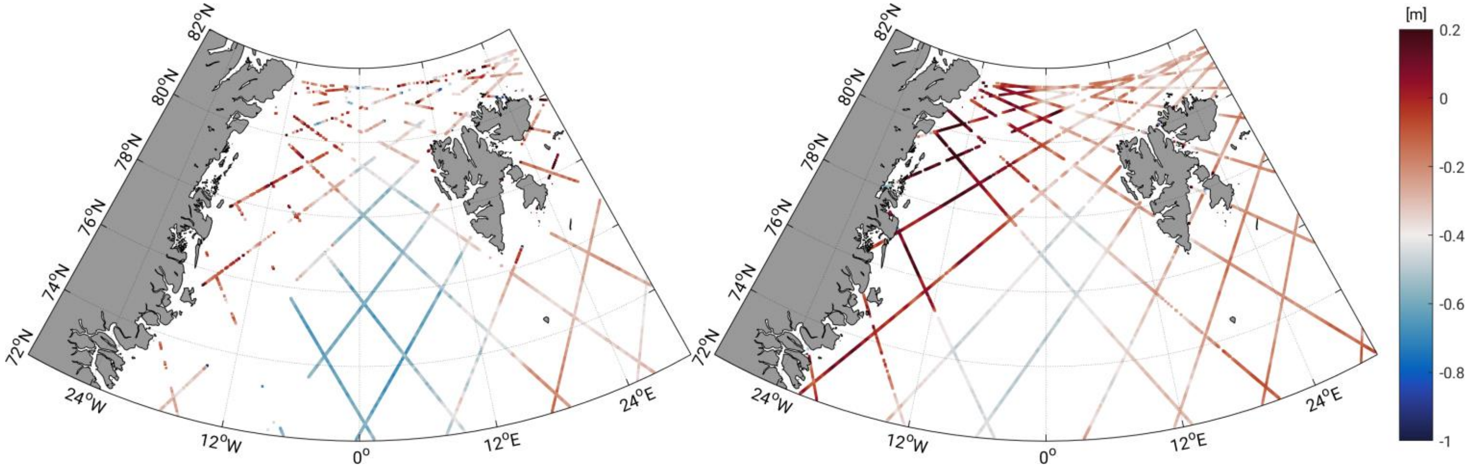
© (Müller et al. 2019)

Correlation 2003-2009

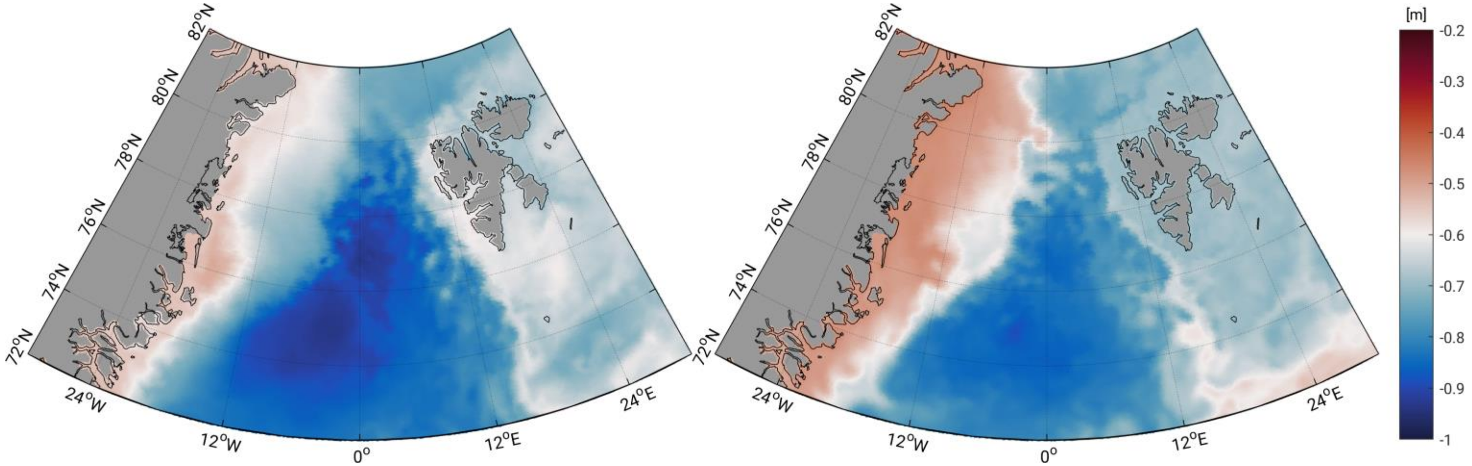
- Small differences in Greenland Basin
- Strong differences in Fram Strait (>40cm), due to geoid uncertainties
- Mostly positive correlation in study area (>0.5, 21%)
- Lower correlations in current areas

Combination of multi-mission altimetry with ocean modeling

- Combination of ~20 years multi-mission altimetry (Envisat, ERS-2) with simulated DOT heights
- Projection of along-track DOT heights to the modeled DOT heights keeping altimetry height reference
- The temporal variability is given by altimetry, whereas the spatial signal is provided by the model
- Application of Principal Component Analysis
- Enables the generation of a 20 years covering DOT and geostrophic circulation dataset (model mesh)



3-days altimetry (top) and daily FESOM (bottom) DOT in March 2004 (left) and July 2006 (right) © (Müller et al. 2019)



Short excursion: Principal Component Analysis (PCA)

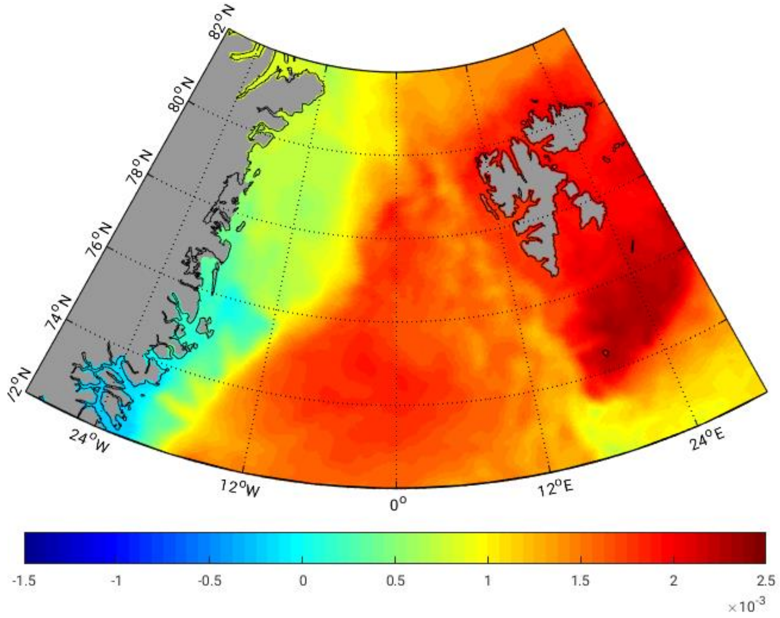
- Other name: Empirical Orthogonal Function Analysis
    - Empirical Orthogonal Functions (EOF) are part of PCA

Why and what is for?

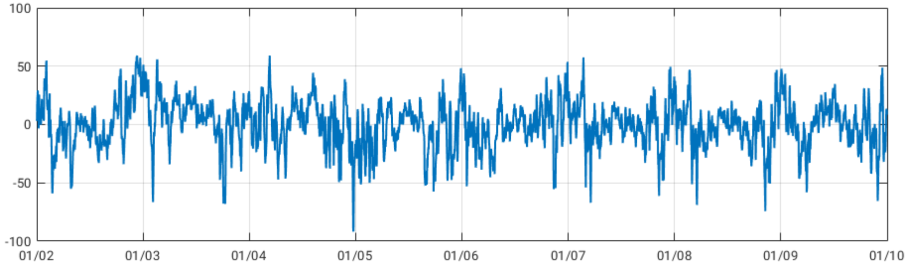
- **PCA identifies spatial structures (eigenvectors, EOF) and the temporal evolution (principal components, pc) of a multi-variate dataset (FESOM meshes, sea level grids etc.)**
- Application: Extraction of dominant ocean phenomena (e.g. El Niño)

What is a Mode?

- **A single eigenvector (EOF) multiplied with the associated pc**
- The first mode explains the most dominant part of a signal
- Modes are sorted in a decreasing order (significant contribution to the signal variance)
- Summation of i-Modes enables the reconstruction of the total signal or w.r.t. a specific degree of approximation → **PCS**



Example: FESOM EOF1 (48%)



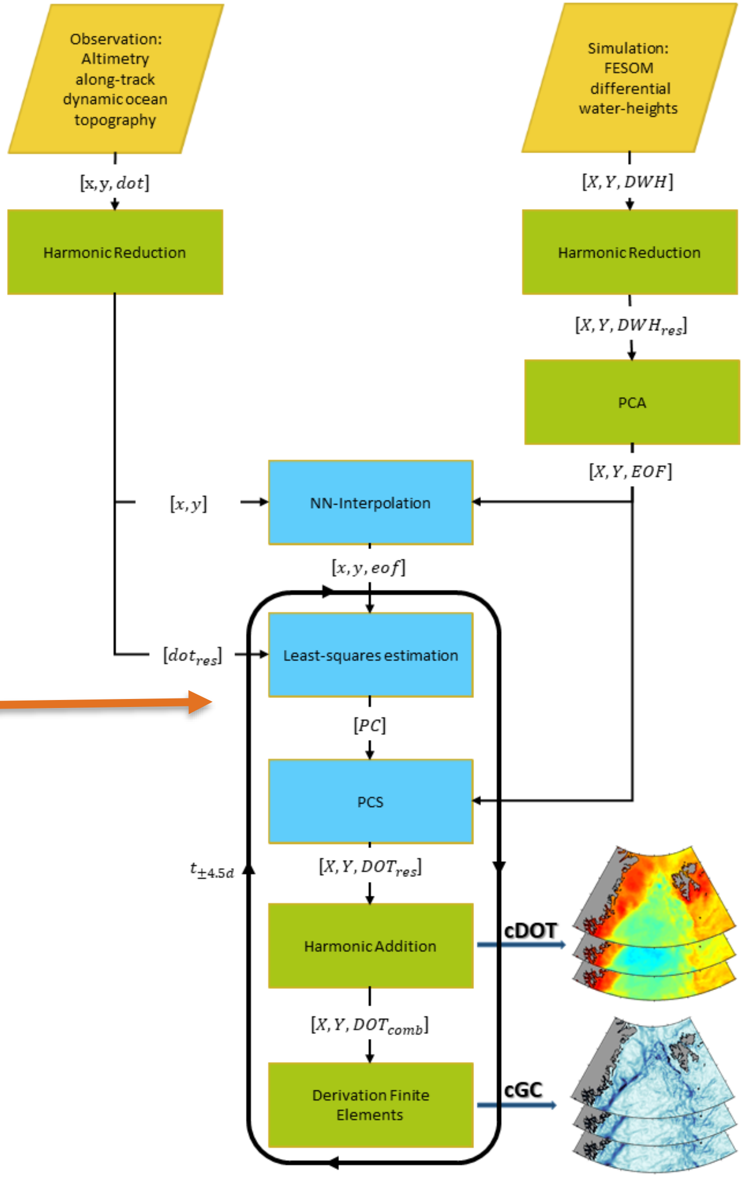
Example: FESOM pc1 (48%)

Combination – Processing Steps

- Combination of by constant offset and annual signal reduced observational and modeled datasets
- Process based on Principal Component analysis (PCA)
    - Dominant spatial patterns are provided by FESOM
    - DOT temporal variability is given by Altimetry
    - Estimation of combined principal components by least-squares solution:

$$dot_{res}(x,y,t) = \sum_{i=1}^{n} pc_{comb_i}(t) * eof_i(x,y)$$

- Reconstruction DOT by applying Principal Component Synthesis (PCS) based on estimated combined principal components, FESOM EOF and re-adding offset + annual signal → **cDOT**
- Deriving combined geostrophic currents by derivation of cDOT meshes → **cGC**

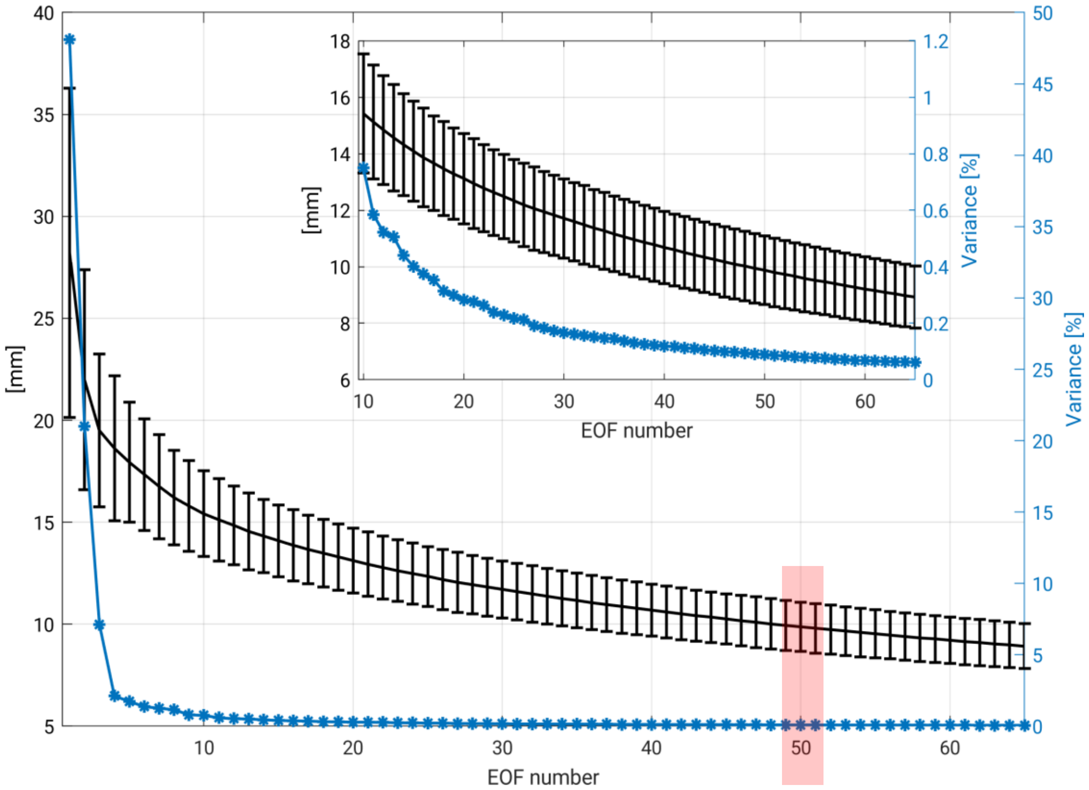


Yellow: Input, Green: auxiliary steps, Blue: Combination Steps (Müller et al. 2019)

How many Modes do we need for combination?

- Experiment: Reconstruction of the input signal
- Root Mean Square Error of original minus reconstructed signal

$$\mathrm{RMSE} = \sqrt{\overline{\left(\mathrm{FESOM_{orig}} - \mathrm{FESOM_{rec}}\right)^2}}$$

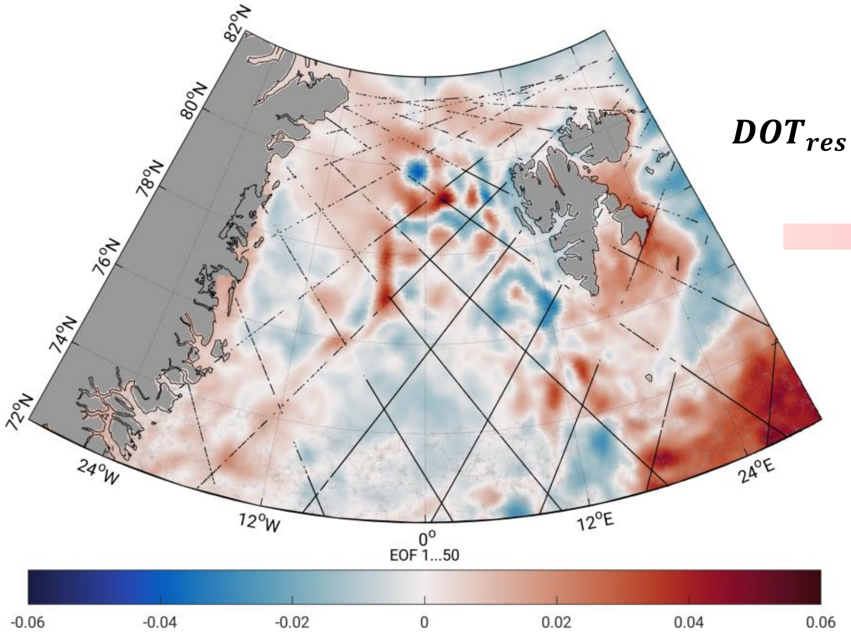


Contribution of one eigenvalue to the total variance (%)

© *(Müller et al. 2019)*

- Using 50 Modes → Mean Error <1cm (94% of total signal)

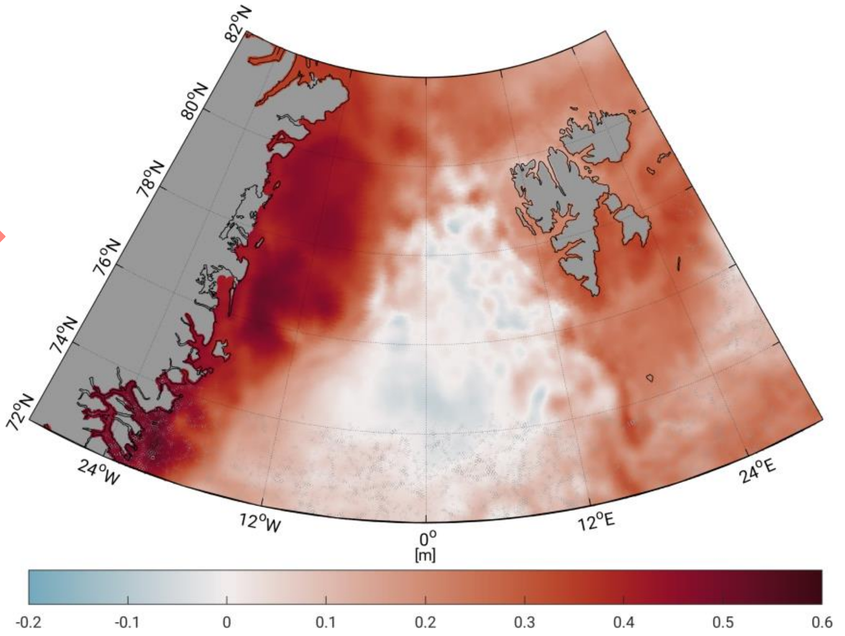
Combination of estimated pc with FESOM EOF



FESOM $\sum_{1}^{50} EOF$ and altimetry ground track pattern (3-days are shown) in 2003-01-12

$$\boldsymbol{DOT_{res}(x,y,t)} = \sum_{\boldsymbol{i=1\dots50}} \boldsymbol{pc_{comb_i}(t)} * \boldsymbol{EOF_i(x,y)}$$

- FESOM EOF
- Spatial resolution of FESOM

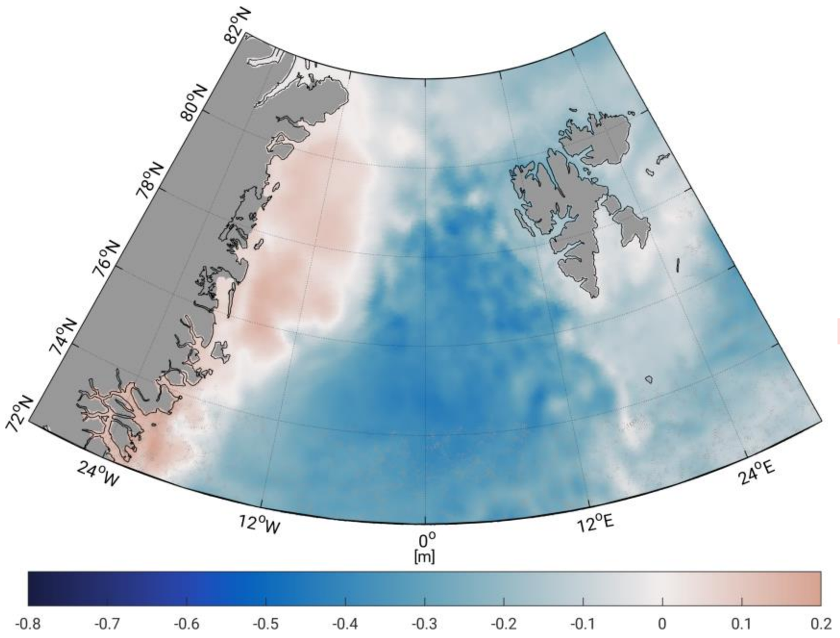


Residual DOT heights 2003-01-12

- ➢ Estimation of 50 combined principal components $pc_{1\dots50}$ based on 50 eof and 9-day altimetry residual DOT along-track heights

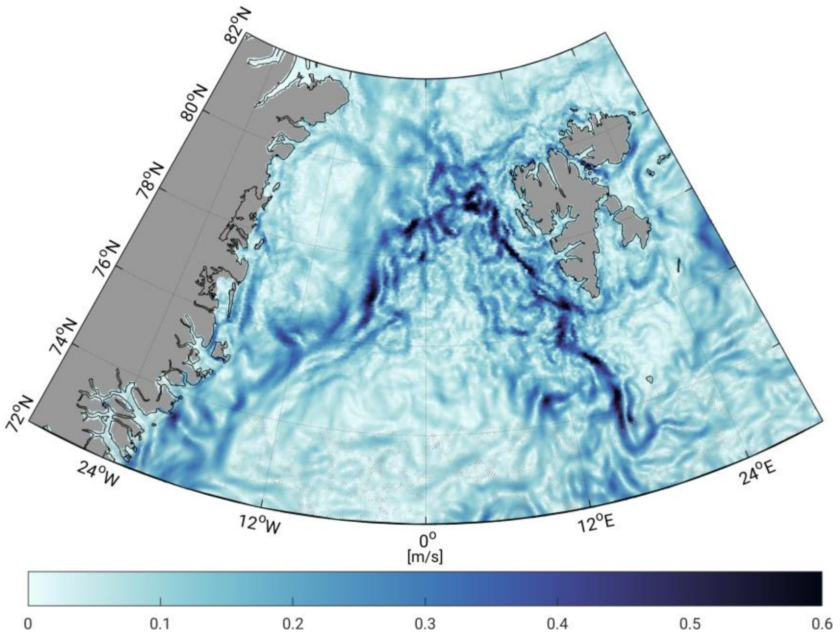
- ➢ Residual DOT heights show spatial resolution of model → no data gaps
- ➢ Time stamp $t_j \pm t_{4.5d}$
- ➢ Next step: Re-addition of annual signal and constant offset

Combined DOT and Geostrophic Currents



Combined DOT 2003-01-12

Adding:
- Coriolis force
- Gravity force
- Horizontal pressure gradient



Combined absolute geostrophic velocity 2003-01-12

- Combined DOT with altimetry height reference and altimetry-derived annual oscillation
  - Spatial resolution: up to <1km
  - Temporal resolution: daily

$$u = -\frac{g}{f} * \frac{\partial DOT}{\partial y}$$

$$v = \frac{g}{f} * \frac{\partial DOT}{\partial x}$$

- Derivation of DOT to compute geostrophic components u (zonal) and v (meridional) via Finite-Element-Method
- Computation of flow direction, abs. velocitiy and eddy-kinetic-energy

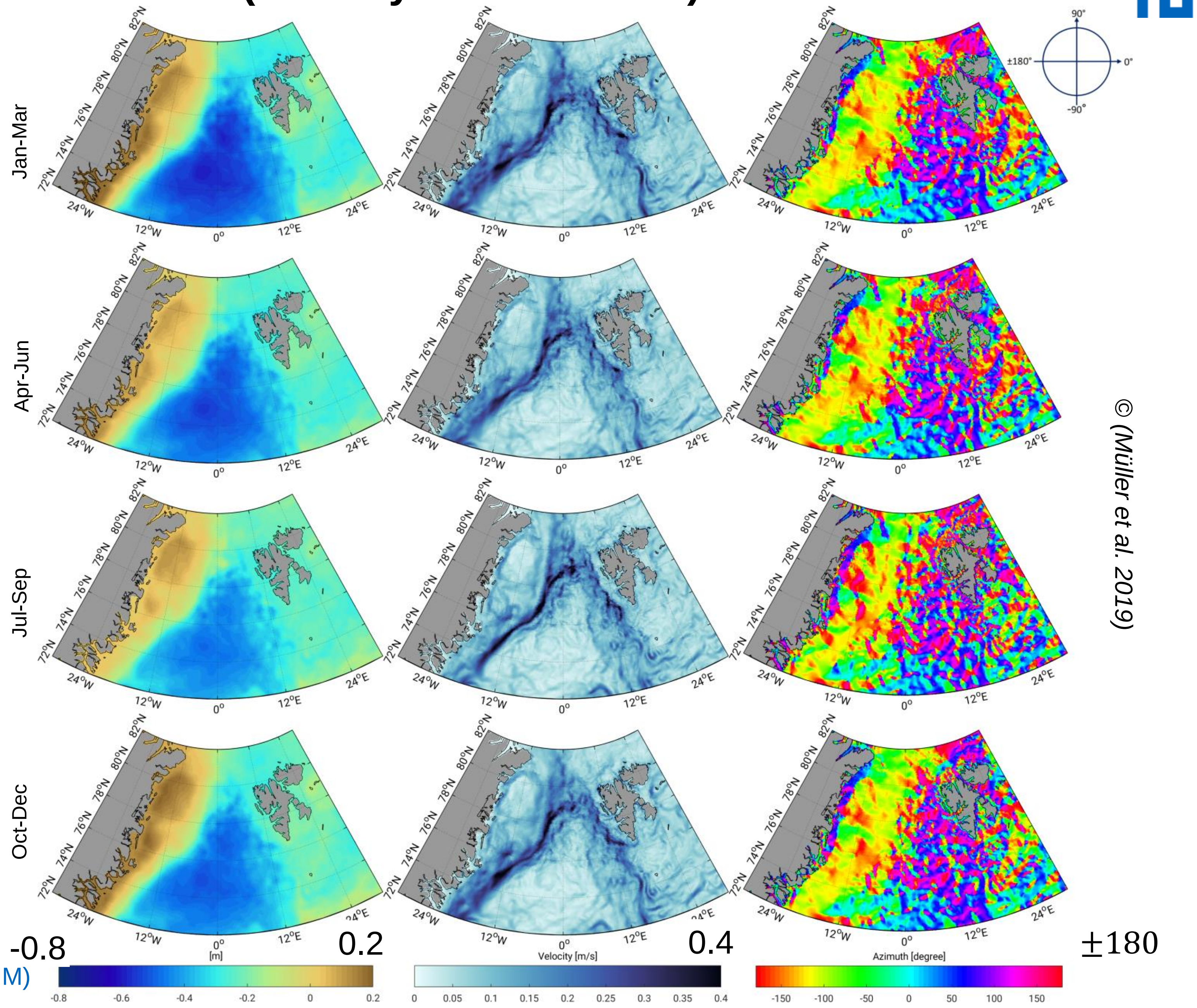
Combined DOT and Geostrophic Currents (Velocity and Direction) 1995 - 2012

- Plot shows combination products (From left to right: DOT heights, abs. geostrophic surface velocity and direction)

- Major current systems (West-Spitsbergen and East-Greenland Current) and East-Greenland Coastal Current are visible

- Seasonal variations are observable
    - Velocity maximum in Winter months
    - Anti-Phase of DOT heights in Greenland Shelf vs. Greenland Deep-Basin

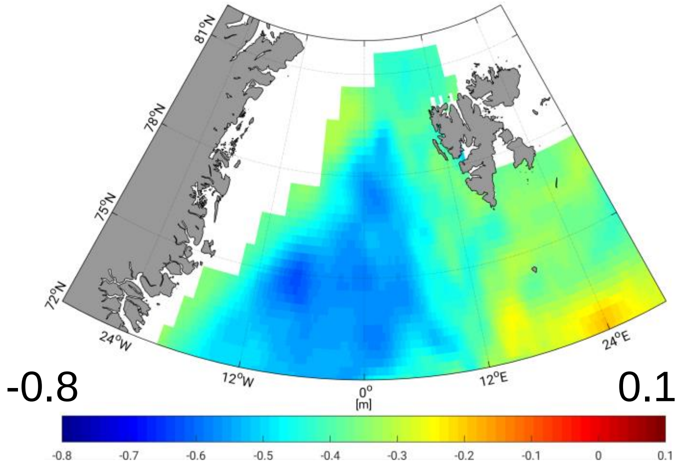
- Data freely available on PANGAEA: https://doi.pangaea.de/10.1594/PANGAEA.900691



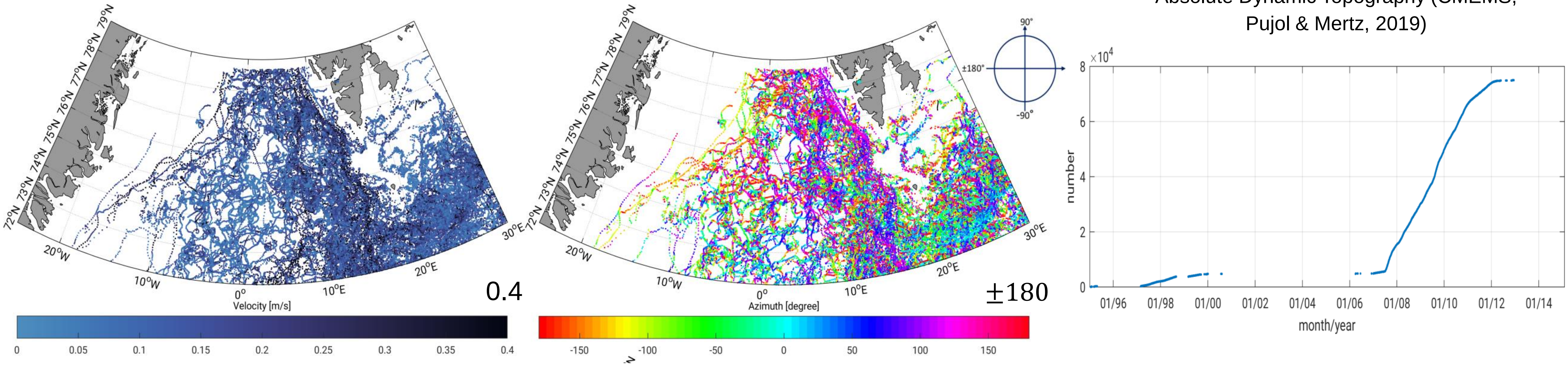
© (Müller et al. 2019)

Validation of combination products

- Point-wise and bin-wise comparison with to geostrophic surface velocities reduced surface drifter observations (Drifter Dataset: CMEMS, Rio and Etienne (2018))
- Requires: A-geostrophic velocity fields (i.e. Stokes Drift, Ekman-Drift, local wind slippage)
- Reduced availability of in-situ data – no velocity data in sea-ice regions (no validation possibilities for East-Greenland Current, East-Greenland Coastal Current)
- Comparison with altimetry only derived geostrophic velocity fields for Absolute Dynamic Topography grids (ADT, provided by CMEMS)



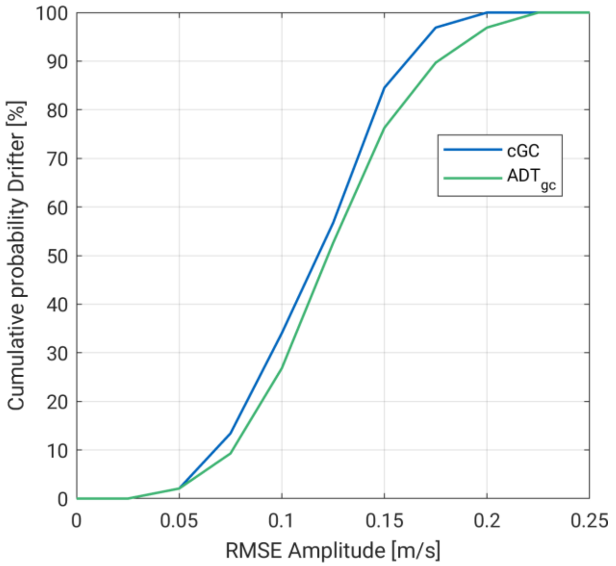
Absolute Dynamic Topography (CMEMS, Pujol & Mertz, 2019)



Comparison with to geostrophic velocities reduced Surface Drifter Measurements (from left: abs. velocity, direction, cumulative number of available drifter observations (Müller et al. 2019)

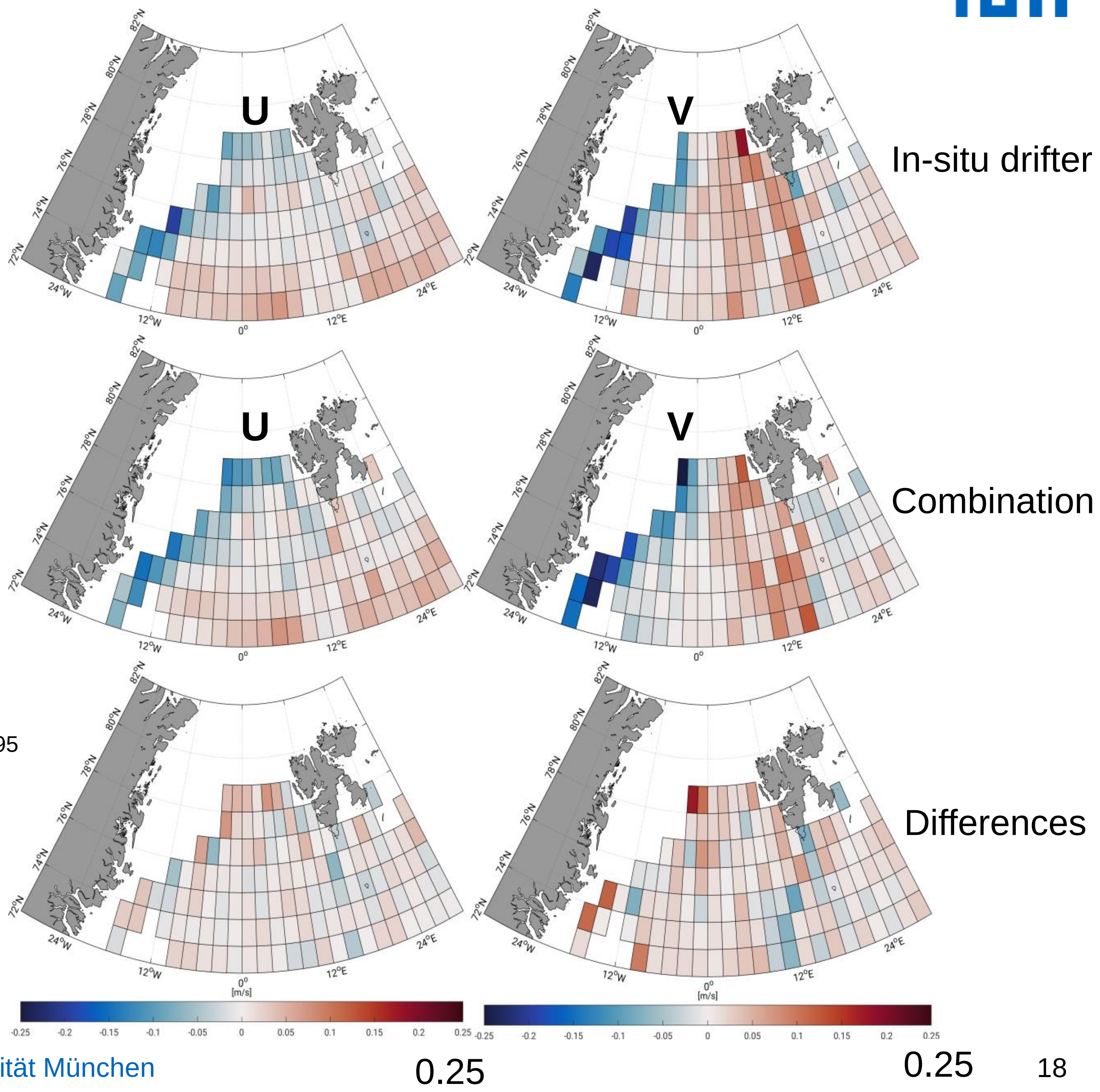
Validation of combination products

- Bin-wise comparison shows small differences in the investigation area
- Differences agree well with spatial patterns of the velocity components
- Drifter and the cGC describe same amplitude and flow direction in most of the bins
- Meridional component shows bigger differences than the zonal component.
- The combination shows smaller RMSE residuals.
    - 35% of the combined residuals are smaller than 0:1 m/s vs. 27% of altimetry only geostrophic abs.velocity



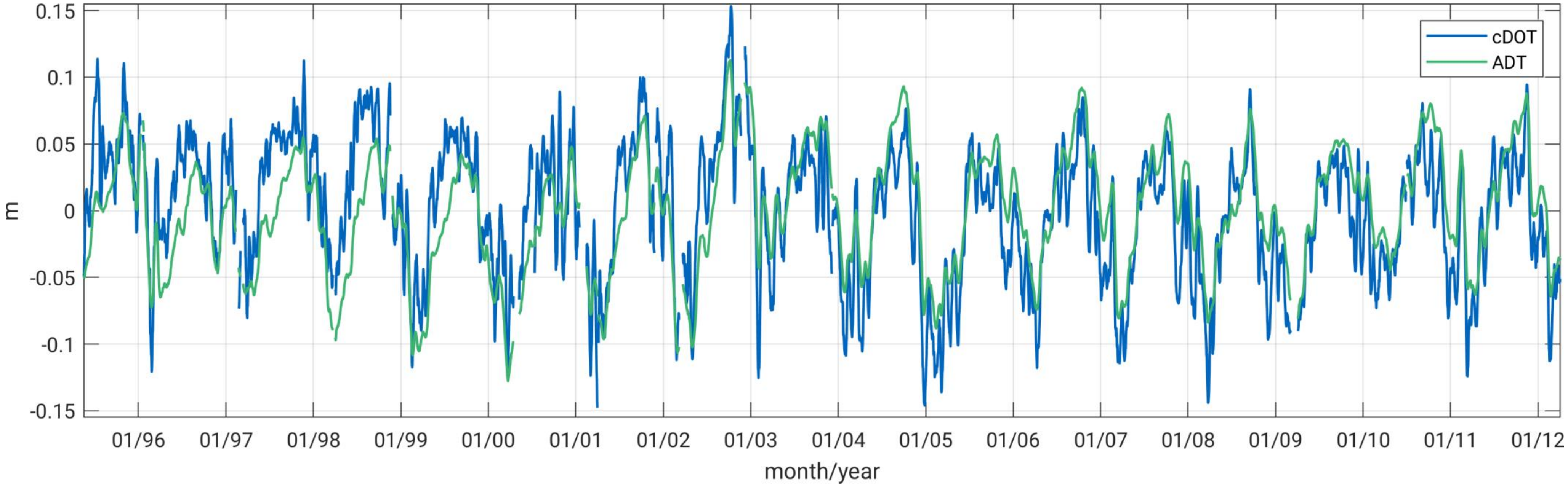
←RMSE of geostrophic absolute velocity between drifter observations and to the trajectories interpolated combined and ADT datasets from 1995 to 2012. (*Müller et al. 2019)*

→ Temporal averaged geostrophic u and v components of drifter observations, combined dataset and differences respectively, binned in 2°x1°(lon,lat) boxes (1995-2012). See Müller et al. 2019



Validation of combination products

- Comparison of mean reduced time series of ADT and Combination in the northern Nordic Seas
- Both signals display high-frequent patterns
- Comparison with ADT time series shows the same seasonal signal, but higher variabilities in combined DOT
- Positive correlation between both signals >80%



Mean-reduced time series of daily and spatial averaged altimetry-only ADT grids and to the ADT grid nodes interpolated combined DOT (cDOT) limited to ice-free regions in the northern Nordis seas (Müller et al. 2019)

Literature – Further Information – Check the links

The work has been published in Copernicus journals, *The Cryosphere* and *Earth System Science Data*

1. Comparison of datasets:

Müller F. L., Wekerle C., Dettmering D., Passaro M., Bosch W., Seitz F.: **Dynamic ocean topography of the northern Nordic seas: a comparison between satellite altimetry and ocean modeling**. The Cryosphere, 13, 611–626, 10.5194/tc-13-611-2019, 2019 *(Open Access)*

2. Combination of datasets:

Müller F. L., Dettmering D., Wekerle C., Schwatke C., Passaro M., Bosch W., Seitz F.: **Geostrophic currents in the northern Nordic Seas from a combination of multi-mission satellite altimetry and ocean modeling**. Earth System Science Data, 11(4), 1765-1781, 10.5194/essd-11-1765-2019, 2019 *(Open Access)*

3. PANGAEA link datasets:

Müller F. L., Dettmering D., Wekerle C., Schwatke C., Bosch W., Seitz F.: **Geostrophic Currents in the northern Nordic Seas - A Combined Dataset of Multi-Mission Satellite Altimetry and Ocean Modeling (data)**. Deutsches Geodätisches Forschungsinstitut, München , 10.1594/PANGAEA.900691, 2019 *(Open Access)*

Summary - Conclusions

Comparison: DOT from altimetry vs. simulated differential water heights of FESOM

- Both datasets show good agreement in dominating oscillation periods
- A combination of both quantities is useful because of a general good agreement and to benefit from both datasets enabling the computation of a homogeneous DOT and geostrophic ocean surface circulation.

Combination: high-frequent along-track altimetry observation and ocean model output

- Development of an innovative dataset based on a combination of height observations from satellite altimetry with spatial information provided by an ocean model (FESOM)
- Comprehensive variability analyses of geostrophic surface currents not only in open ocean regions, but also in the sea-ice area is possible

Further References:

FESOM Model:

- *Wang, Q., Danilov, S., Sidorenko, D., Timmermann, R., Wekerle, C., Wang, X., Jung, T., and Schröter, J.*: **The Finite Element Sea Ice-Ocean Model (FESOM) v.1.4: formulation of an ocean general circulation model**, Geosci. Model Dev., 7, 663–693, https://doi.org/10.5194/gmd-7-663-2014 , 2014.
- *Wekerle, C., Wang, Q., von Appen, W.-J., Danilov, S., Schourup-Kristensen, V., and Jung, T.:* **Eddy-Resolving Simulation of the Atlantic Water Circulation in the Fram Strait With Focus on the Seasonal Cycle**, J. Geophys. Res. Oceans, https://doi.org/10.1002/2017JC012974 ,25 2017.

Comparison dataset:

- *Rio, M.-H. and Etienne, H.:* **Copernicus in situ TAC, Global ocean delayed mode currents from drifting buoys**, Product User Manual - PUM, Report (technical document (specification, manual)), https://doi.org/10.13155/41257 , CMEMS Product ID:*INSIT U_GLO_UV _REP _OBSERV AT IONS*_013_044, 2018
- *Pujol, M. I. and Mertz, F.:* **PRODUCT USER MANUAL For Sea Level SLA products, GLOBAL OCEAN GRIDDED L4 SEA SURFACE HEIGHTS AND DERIVED VARIABLES REPROCESSED (1993-ONGOING), 1.0,** http://resources.marine.copernicus.35eu/?option=com_csw&view=details&product_id=SEALEVEL_GLO_PHY_L4_REP_OBSERVATIONS_008_047 , CMEMS Product ID:*SEALEV EL_GLO_P HY _L4_REP_OBSERV AT IONS*_008_047, 2019

Altimetry dataset:

- Envisat (SGDR) and ERS-2 (REAPER-SGDR) altimetry data access is available from ESA (Envisat, https://doi.org/10.5270/EN1-85m0a7b , ESA (2018); ERS-2, https://earth.esa.int/web/guest/-/radar-altimeter-reaper-sensor-geophysical-data-record-sgdr , Brockley et al. (2017)).

Further References:

Förste C., Bruinsma S.L., Abrikosov O., Lemoine J.-M., Marty J. C., Flechtner F. , Balmino F., Barthelmes F., and Biancale R. **Eigen-6c4 the latest combined global gravity field model including goce data up to degree and order 2190 of gfz Potsdam and grgs toulouse**. GFZ Data Services, 2014

Gruber T. and Willberg M. **Signal and error assessment of GOCE-based high resolution gravity field models**. *Journal of Geodetic Science*, 9(1):71 86, January 2019. doi:10.1515/jogs-2019-0008. URL https://doi.org/10.1515/jogs-2019-0008

Müller, F. L., Dettmering, D., Bosch, W., and Seitz, F.: **Monitoring the Arctic Seas: How Satellite Altimetry Can Be Used to Detect Open Water in Sea-Ice Regions**, Remote Sensing, 9, https://doi.org/10.3390/rs9060551 , 2017.