25 years of Sea Level Records from the Arctic Ocean using Radar Altimetry

Contribution to the ESA SL_CCI initiative

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TUM

Introduction

Why studying Arctic SL?

- Part of ESA's SL CCI
- White spot on global sea level maps. The Arctic Ocean is a important climate indicator
- The Arctic SL challenging

Figure 1: *ESA Sea Level (SL) Climate Change Initiative (CCI)*

Scientific and technical challenging

- Regional coverage (satellites/tide gauges/argo)
- Seasonal/permanent ice cover
- Satellite instruments
- Insufficient geophysical models
- Residual orbit errors
- Retracking

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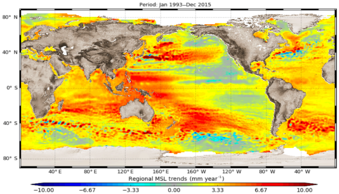

Figure 2: *SL CCI ECV v2.0 1995 - 2015*

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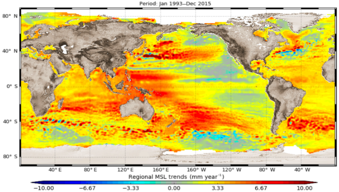

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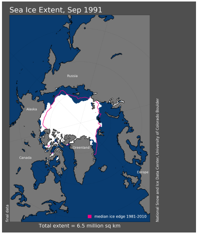

Credit: NSIDC

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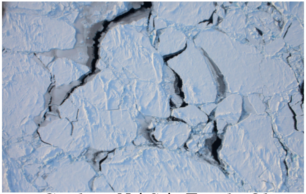

Figure 3: *Credit: NASA Earth Observatory*

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- Sea-ice affects the range corrections
- Radiometer contamination

Scientific and technical challenging

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- Sea-ice contamination
- Ocean tides and atmospheric loading most important due to the lack of leads (Ricker et al., 2016)
- Especially the tides are inaccurate in the Arctic (Cheng and Andersen, 2011; Stammer et al., 2014)

Scientific and technical challenging

- Regional coverage (satellites/tide gauges/argo)
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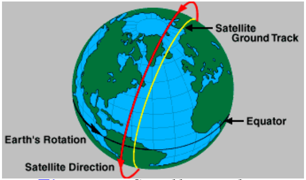

Figure 3: *Satellite orbits*

Scientific and technical challenging

- Regional coverage (satellites/tide gauges/argo)
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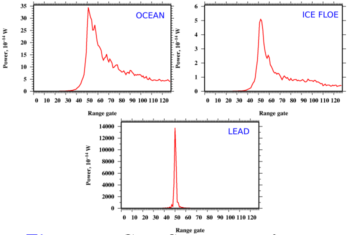

Figure 3: *CryoSat-2 waveforms*

Scientific and technical challenging

- Regional coverage (satellites/tide gauges/argo)
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Review of Arctic sea level products

Arctic Sea level products (incomplete)

- Laxon and MacAdoo (1994); Laxon et al. (2003) used SSH from ERS-1/2 making sea-ice thickness and gravity anomalies, respectively.
- Peacock and Laxon (2004) first to construct a MSS (10 year period)
- Since then several e.g. (Prandi et al., 2012) (DUACS) (1993-2009) (Cheng et al., 2015) (1993-2011), (Armitage et al., 2016) (2003-2014), (Andersen and Gaia, 2016) (1993-2015) have followed

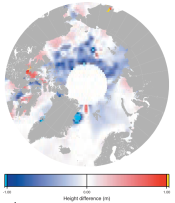

Figure 7: *(Peacock and Laxon, 2004)*

Table 1: *Trends (mm/year)*

	Period	trend (mm/year)
(Prandi et al., 2012)	(1993-2009)	3.6±1.0
(Cheng et al., 2015)	(1993-2011)	1.7 ± 1.3
(Andersen and Gaia, 2016)	(1993-2015)	2.2±1.0

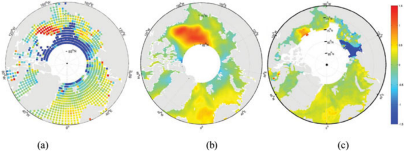

Figure 5: *(Cheng et al., 2015)*

The Arctic CCI Sea level DTU/TUM product

About

- New improved SL record
- Current version: Work in progess: Version 2.1
- Soon version 3.0 (CCI SL budget closure)

Improvements of CCI_SL DTU/TUM product

- Former (reprocessed but largely un-retracked) New (ALES+ retracked, REAPER and in house processed)
- No filtering constrains to the MSS
- Dedicated Arctic processing
- Larger amount of data, especially in the sea-ice covered regions
- Improvements of geophysical corrections

Data description

Making the 25 years SLA record based on satellite altimetry:

- ERS-1 (REAPER, (Brockley et al., 2017))
- ERS-2 (ALES+, (Passaro et al., 2018))
- Envisat (ALES+, (Passaro et al., 2018))
- CryoSat-2 (DTU inhouse LARS processing of SAR/SARIn (Stenseng and Andersen, 2011), RADS (Scharroo et al., 2013) of LRM)

Table 2: *Geophysical corrections*

Corrections	Model	Comments
Wet troposphere	Prefer using model (ECMWF)	ERS1, not possible - as far as we know?
Ocean tides, etc	FES 2014	Not defined close to the coast
Inv. baro/ Atm. corr.	Inv. baro from GDR product	Inv. baro/ atm corr?? Best for arctic?
Mean sea surface	DTU15	

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Ocean and lead discrimination

Data selecting

- Separating data into ocean/ice cover by EUMETSATs Global sea-ice Concentration Climate Data Record before 2015 (EUMETSAT, 2017) and reprocessing offline product after 2015 (EUMETSAT, 2018)
- Removing sea-ice/mixed surface measurements
- MAD outliers detected for every track

Data selecting

open ocean: Pulse peakiness and backscatter

leads: Pulse peakiness, leading edge width and stack std. (CryoSat-2)

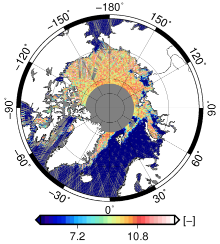

Figure 9: *Peakiness*

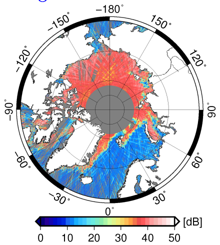

Figure 10: *Backscatter*

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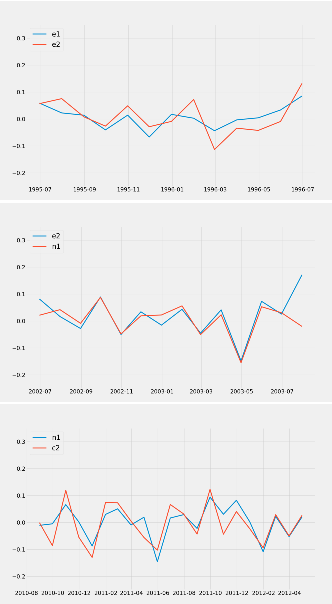
Transitions between satellites

- Possibility of large errors
- Small displacements can give large change in sea level trend estimates

Considerations:

- Data coverage
  $> 65^\circ\ N \Rightarrow$ "NO"
  T/P or Jason overlap
- Cross-overs: not possible over the sea-ice cover
- LRM/SAR/SARIn transitions
- Global comparison of overlapping time
- Start/end of satellite issues



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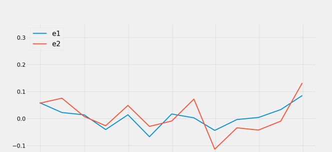

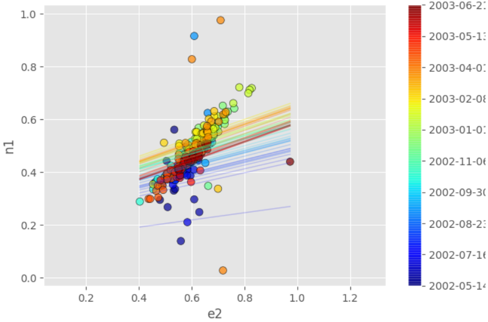

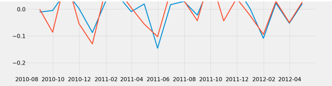

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The sea level record

Processing steps

- Inter-satellite bias determined and corrected
- Weekly data are gridded using least squares collocation with second-order Markov covariance function (Andersen, 1999)
- Grid size: 0.25° by 0.5°

Issue

- Sparse Summer data (June-Aug.)
- Prandi et al. (2012) describes: correlation between the presence of sea-ice and SLA data coverage. Using geoid data for missing data

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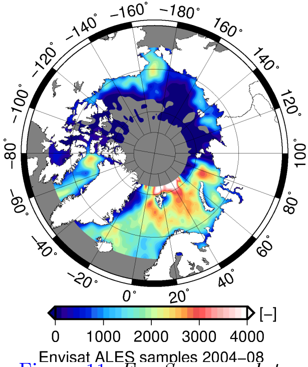
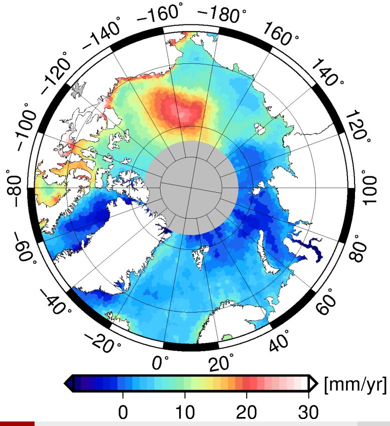


Figure 11: *Ex. Summer data*

Global trend and seasonal variability

- PRELIMINARY results
- High trend in the Beaufort Gyre and the Canadian Archipelago(!?)
- Negative trend near the Greenlandic coast (!?), Baffin Bay (!?), Kara Sea (!?) and North of Svaldbard (!?)
- Data covering: 1995-2018, weekly medians.



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27 years of sea level

- Seasonal maximum in late Autumn and minimum in late Spring
- NO GIA ajustment
- Global trend (1991-2018) 0.85±0.72 mm/yr
- Global trend (1995-2018) 1.13±0.89 mm/yr

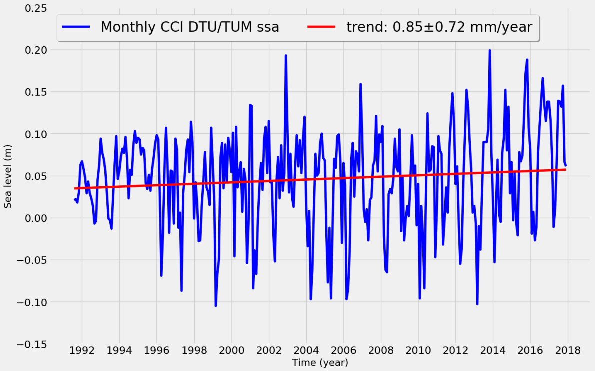

Figure 13: *Monthly SLA*

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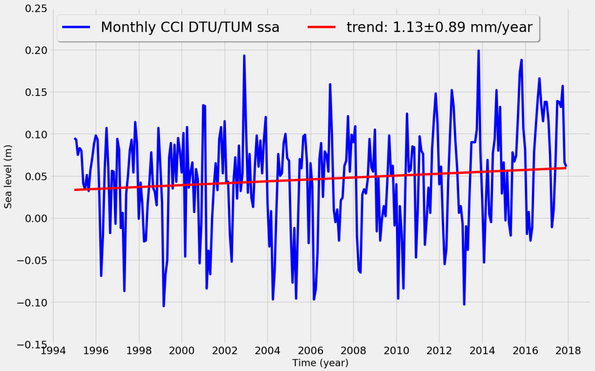

Figure 13: *Monthly SLA*

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Validating against tide gauge

- Period: 1991-2018
- Resampled to monthly median
- DTU/TUM SLA 350 km around tide gauge
- Ny-Ålesund $R = 0.51$
- Including GIA[1]: Ny-Ålesund $R = 0.77$

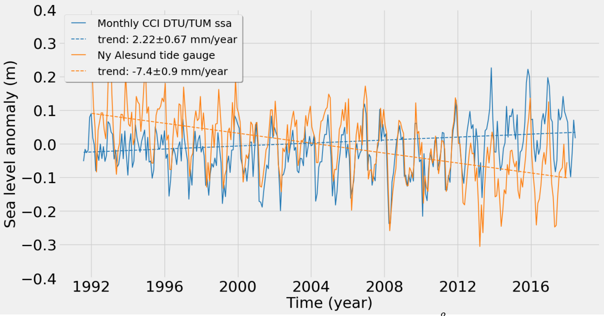

Figure 14: *Comparison against Ny-Ålesund*

[1] GPS Velocity (mm/yr): 7.98 +/- 0.49 (http://www.sonel.org)

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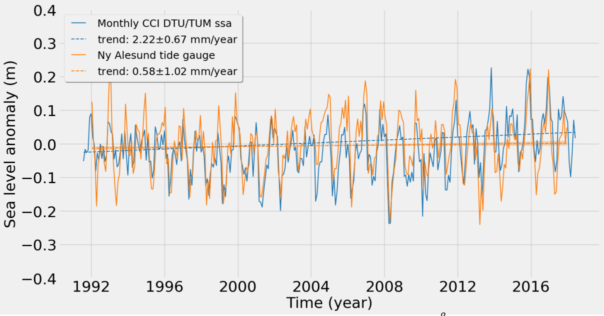

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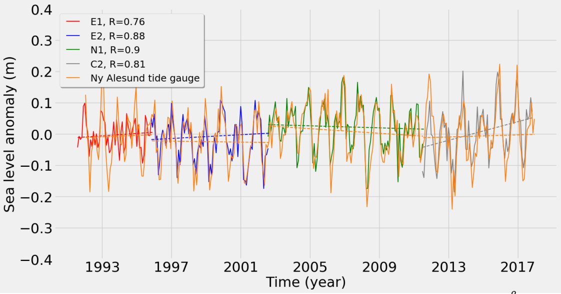

Figure 15: *Comparing individual satellites against Ny-Ålesund*

Correlation to tide gauge

Very good!

Table 3: *Trends (mm/year)*

	Ny-Ålesund	DTU/TUM
e1	2.36±13.12	3.81±3.57
e2	−0.76±3.96	3.01±3.40
n1	−3.68±3.07	−1.61±1.47
c2	1.65±5.02	12.2±5.02

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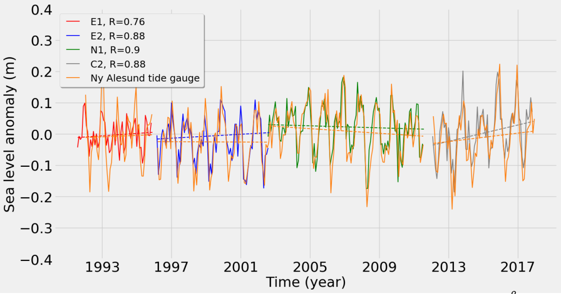
Validating against tide gauge



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e2	−0.24±4.25	3.14±3.72
n1	−1.61±1.47	−3.68±3.07
c2	13.08±2.70	6.75±5.71

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Arctic sea level budget closure

- CCI Arctic sea level budget v1 by Jan Even Ø. Nielsen, NERSC, Norway
- SSH trend for 2003-2015 is 6.2 mm/yr (v2.0) = Steric 1.6 mm/yr + mass 4.5 mm/yr

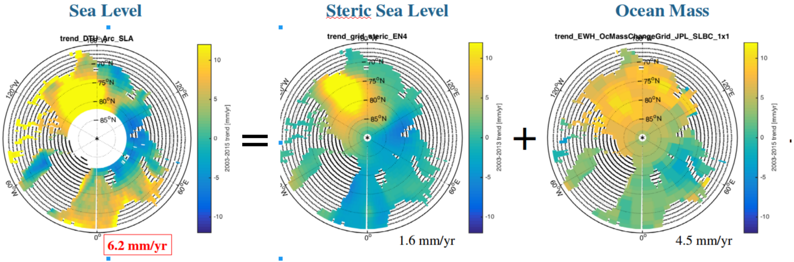

Figure 16: *CCI Arctic sea level budget closure*

Summary

- 25+ years of radar altimetry data are processed
- Leads and open ocean are found. Avoiding introducing MSS errors
- DTU/TUM SLA has a good fit to the tide gauge after GIA removal
- Issues with Summer data
- Preliminary sea level rise of 1.13 ± 0.89 mm/yr
- New version (v3.0) ready by December for ESA CCI SL Budget Closure

Future work

- Further improvement of lead/ocean discrimination (classification/machine learning, seasonal/ geographical surface discrimination parameters, ...)
- Improve/continue time series with SARAL/AltiKa and Sentinel 3a/3b data
- Apply the new MSS DTU18

Thank You for Listening!

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Classification

- Using a unsupervised clustering: Kmeans
- 12 classes and 3 parameters: (PP, LEW, Sigma0)
- Classification is run by every month
- Slightly better correlation coefficient with Ny-Ålesund tide gauge for C2

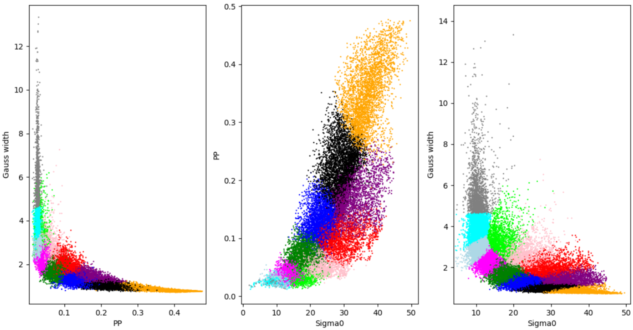

Figure 17: *Parameters plotted for all classes*

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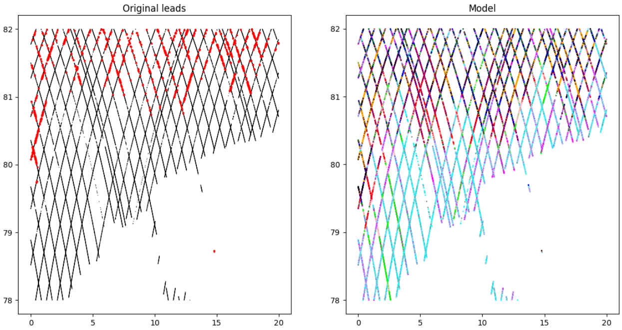

Figure 18: *Original detection versus kmeans model*