Radar Remote Sensing of the Meteo-Marine Parameters in the Baltic Sea

Rikka, S.[1], Uiboupin, R.[1], Pleskachevsky, A.[2], Alari, V.[1], Jacobsen, S.[2], Kõuts, T.[1]

[1] Tallinn University of Technology, Department of Marine Systems, Akadeemia tee 15a, 12618, Tallinn, Estonia

[2] German Aerospace Center (DLR), Remote Sensing Technology Institute, 28199, Bremen, Germany

Email: sander.rikka@ttu.ee

Motivation

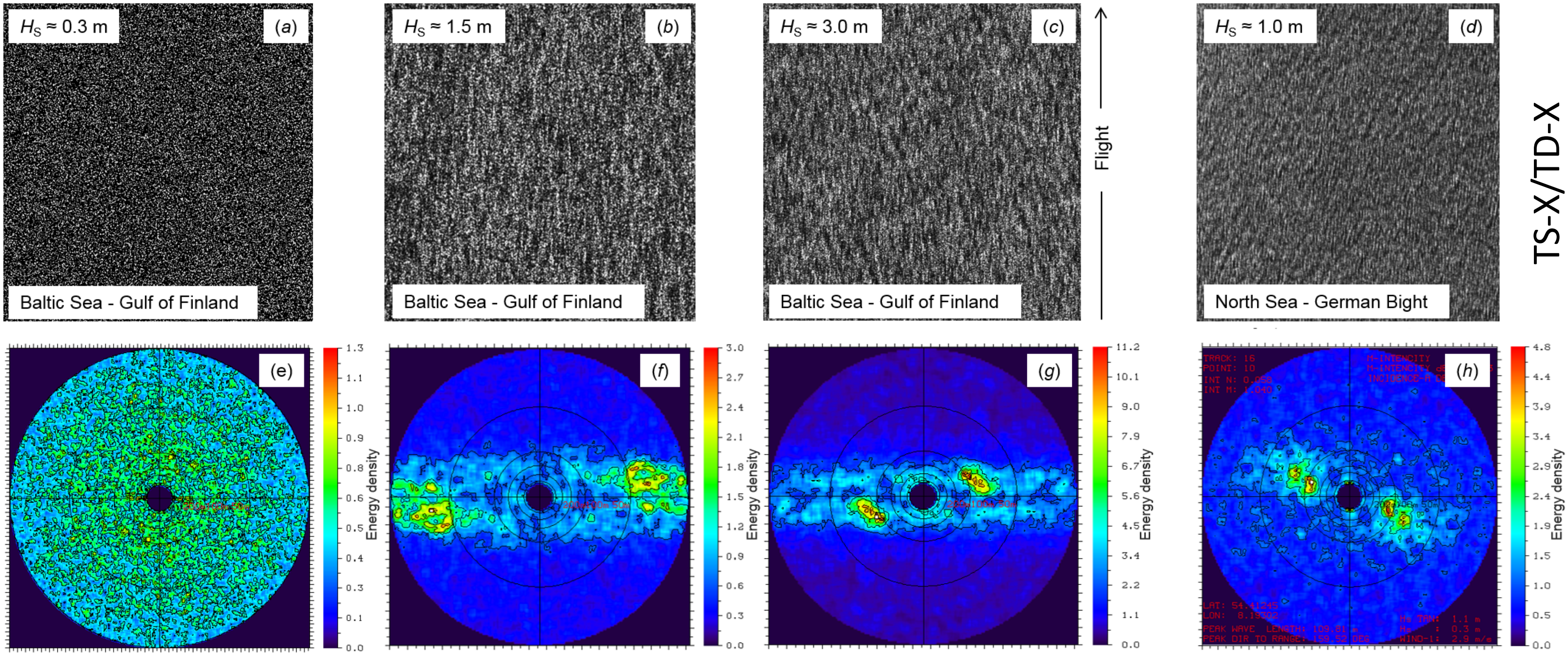
- **To develop/improve, validate and demonstrate the value of meteo-marine parameters derived from different radar data**
  - Assess current state-of-the-art methods in estimating meteo-marine parameters
    - High resolution TerraSAR-X/TanDEM-X StripMap imagery
    - Medium resolution Sentinel-1A/B IW swath imagery
    - Marine radar imagery
  - Validate wave retrieval methods in the Baltic Sea
    - XWAVE_C
      - Pleskachevsky et al. 2016, *ISPRS*, *119;* Rikka et al. 2018, *IJRS*, *39*(4)
    - CWAVE_S1-IW
      - Pleskachevsky et al. (*submitted to IJRS*); Rikka et al. 2018, *Remote Sensing, 10*(5)
    - Method for marine radar
      - Rikka et al. (*submitted to IEEE Geoscience and Remote Sensing Letters*)
  - Validate wind retrieval methods (XMOD-2 and CMOD)
      - Rikka et al. 2018, *IJRS*, *39*(4)*;* Rikka et al. 2018, *Remote Sensing*, *10*(5)
- to compare different radar (TS-X, Sentinel-1, marine radar) wave retrievals with (operational) wave model results
- to examine the added benefits of radar data to maritime situation awareness in the Baltic Sea

Meteo-marine climate in the Baltic Sea

- Complex coastline
- Thousands of islands
- Dominant wind direction
  - Sector 180° – 315° (S – NW)
  - Frequently observed slanting fetch cases, up to 50°
- Dominant wave period
  - 2 – 8 s
  - Small swell component in H_S
- Dominant wave height
  - H_S between 0–3 m
    - Up to about 10 m observed
  - Dependent of the region
  - Clear annual cycle
- Short wave „memory“
- **Hardly recognizable wave pattern on SAR imagery**
- **Noisy SAR images**

Leppäranta and Myrberg, 2009

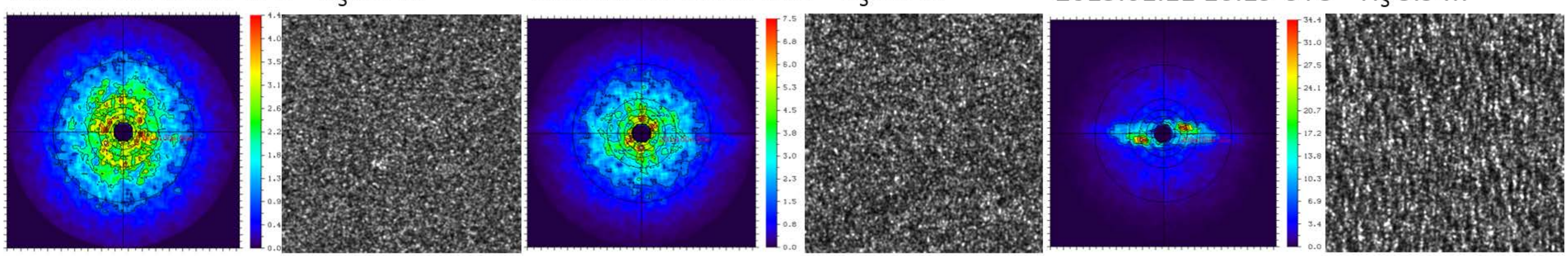
Radar imaging of sea surface: SAR



2015.07.05 04:59 UTC – H_S 0.5 m

2015.10.01 16:22 UTC – H_S 2.7 m

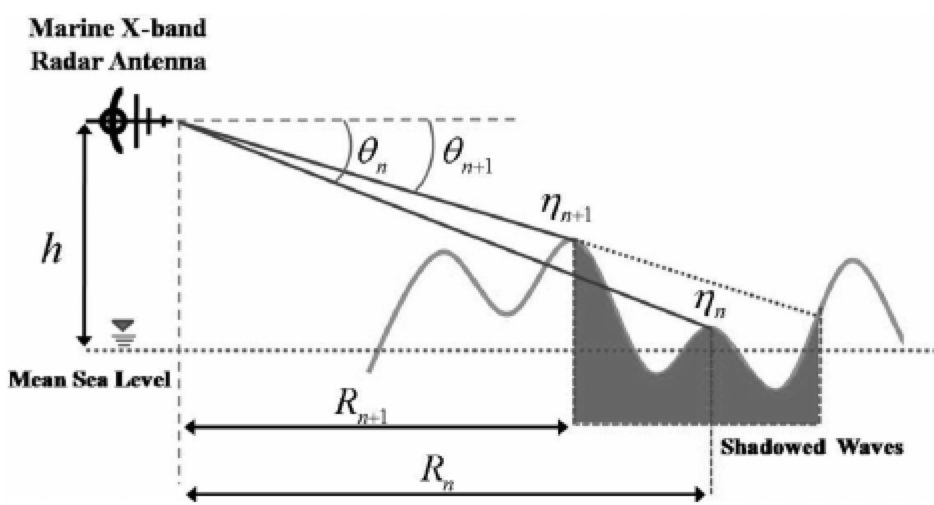
2015.01.11 16:19 UTC – H_S 3.9 m

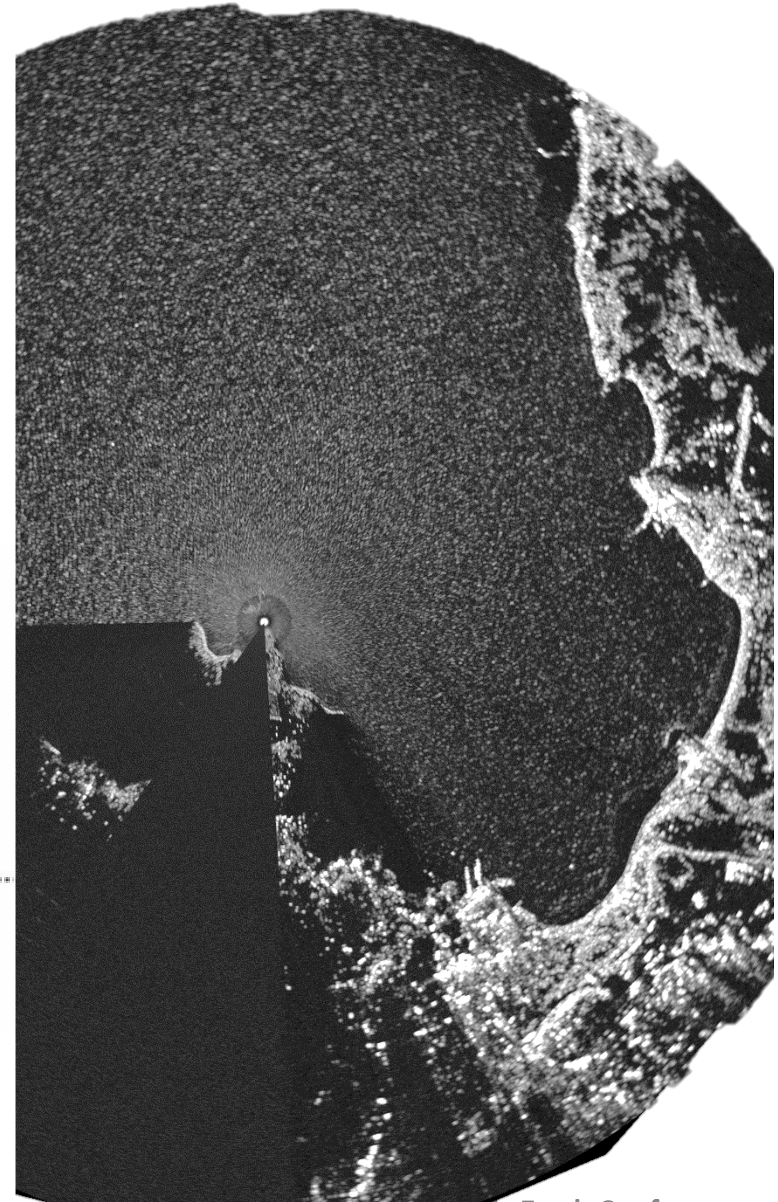


Sentinel-1A/B IW

Radar imaging of sea surface: marine radar

- Marine radar imaging introduce additional effects
  - Very high incidnce angles
  - **Shadowing**
  - Scattering from micro breakers, i.e. whitecapping





Data – *in situ* measurements, radar, wave model

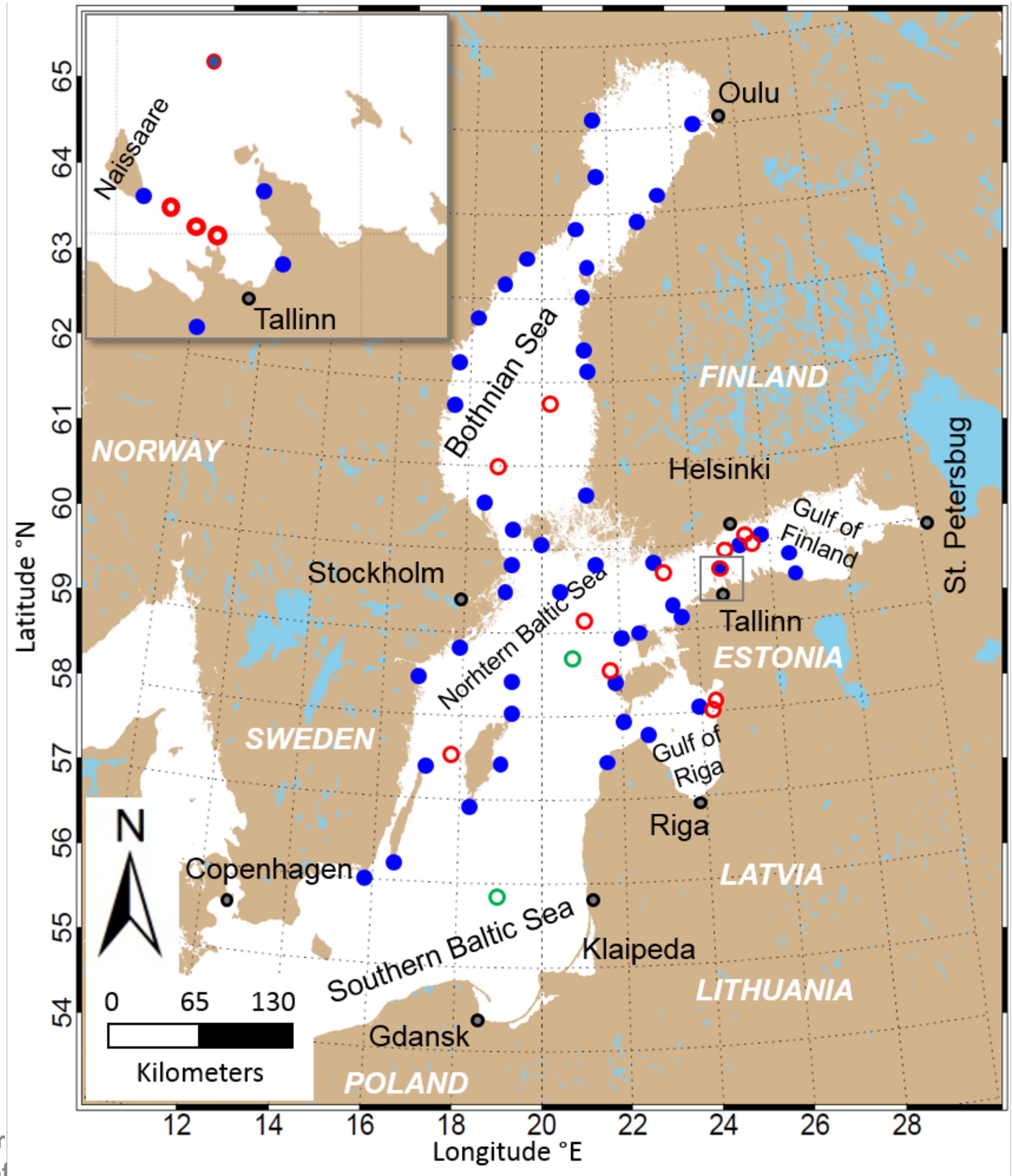
Dev. – algorithm developement; Val. – validation; Comp. – comparison with *in situ* or wave model results; Stat. – seasonal or regional statistics

Sensor	Radar wavelength	Pixel size	Temp. res.	Spatial coverage	Period	No. of images	Purpose	*In situ* collocations	Wave model collocations
TS-X TD-X	X-band 3.1 cm	3×3 m	On demand	30× up to about 250 km	2012-2017	92	Dev. Val. Comp.	117 H_S 102 U_{10} 44 L_P, γ_P	55 L_P, γ_P SWAN
Sentinel-1 IW	C-band 5.5 cm	10×10 m	1 – 2 days	250× up to about few 10^3 km	2015-2016	15	Val.	52 H_S 358 U_{10}	49314 H_S WAM
						460	Comp. Stat.	101 H_S	201 H_S
Marine radar	X-band 3.2 cm	5×5 m	1 h	About 10 km from radar tower	18.10. - 14.11.16	559	Dev.	1678 H_S	-
						Jan. & Jun. 2017	Val.	1464 H_S	-

H_S total significant wave height
U_{10} wind speed
L_P peak wave lenght
γ_P peak wave propagation direction

Department of Marine Systems
Tallinn University of Technology

Data – *in situ* measurements, radar, wave model



SAR methods: wind

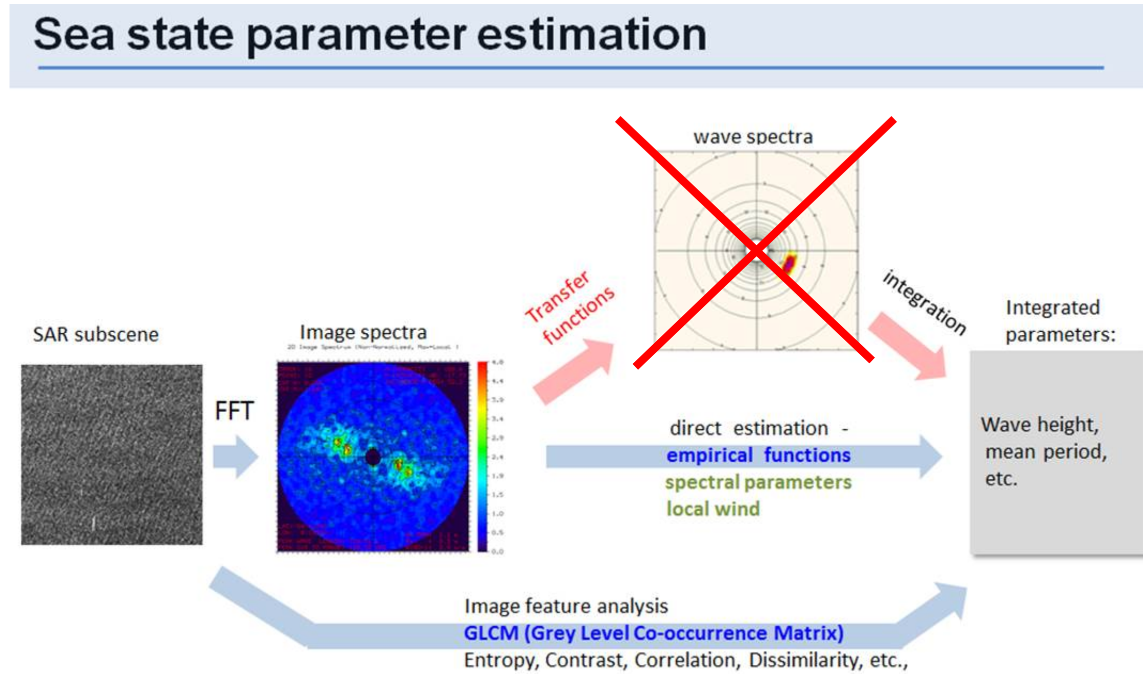
- Sea state is strongly dependent on local wind characteristics
- XMOD-2 and CMOD
- $\sigma_0(U, \theta, \phi) = B_0^p(U_{10}, \theta)(1 + B_1(U_{10}, \theta)\cos(\phi) + B_2(U_{10}, \theta)\cos(2\phi))$
    - σ_0 – Normalized Radar Cross Section (NRCS)
    - U_{10} – wind speed
    - ϕ – wind direction relative to flight direction
    - θ – local incidence angle
    - B_i - tuned function parameters for XMOD-2 and CMOD separately
  - With polarisation ratio for XMOD-2 (Li and Lehner, 2014):
    - $PR = \frac{\sigma_0^{VV}}{\sigma_0^{HH}} = X_0 EXP(X_1\theta)$, where X_0 and X_1 are tuning coefficients
- According to Monaldo et al. 2016, separate GMFs are used to receive wind speed
    - CMOD4 with Thompson, D. R., et al. (1998) PR for HH polarization and CMOD5.N for VV polarization
- Wind direction from Weather Research and Forecasting Model (WRF) is used (Skamarock et al. 2005)
- WRF wind direction are interpolated to the sea state calculation grid

Radar methods: sea state

- Calculation of NRCS from pixel's digital number
- Artefacts filtering
- Subscene normalization

$$\sigma_n(x,y) = \frac{\sigma_0(x,y) - \langle\sigma_0\rangle}{\langle\sigma_0\rangle}$$

- Fast Fourier Transform
- Empirical function without transformation into wave spectra
- Additional Grey Level Co-occurance Matrix (GLCM) image statistics
- General methods are based on validation data matchups from open source measure-ment data from all over the World



Quality Control: Buoys (location) and Wave model results (spatial distribution)

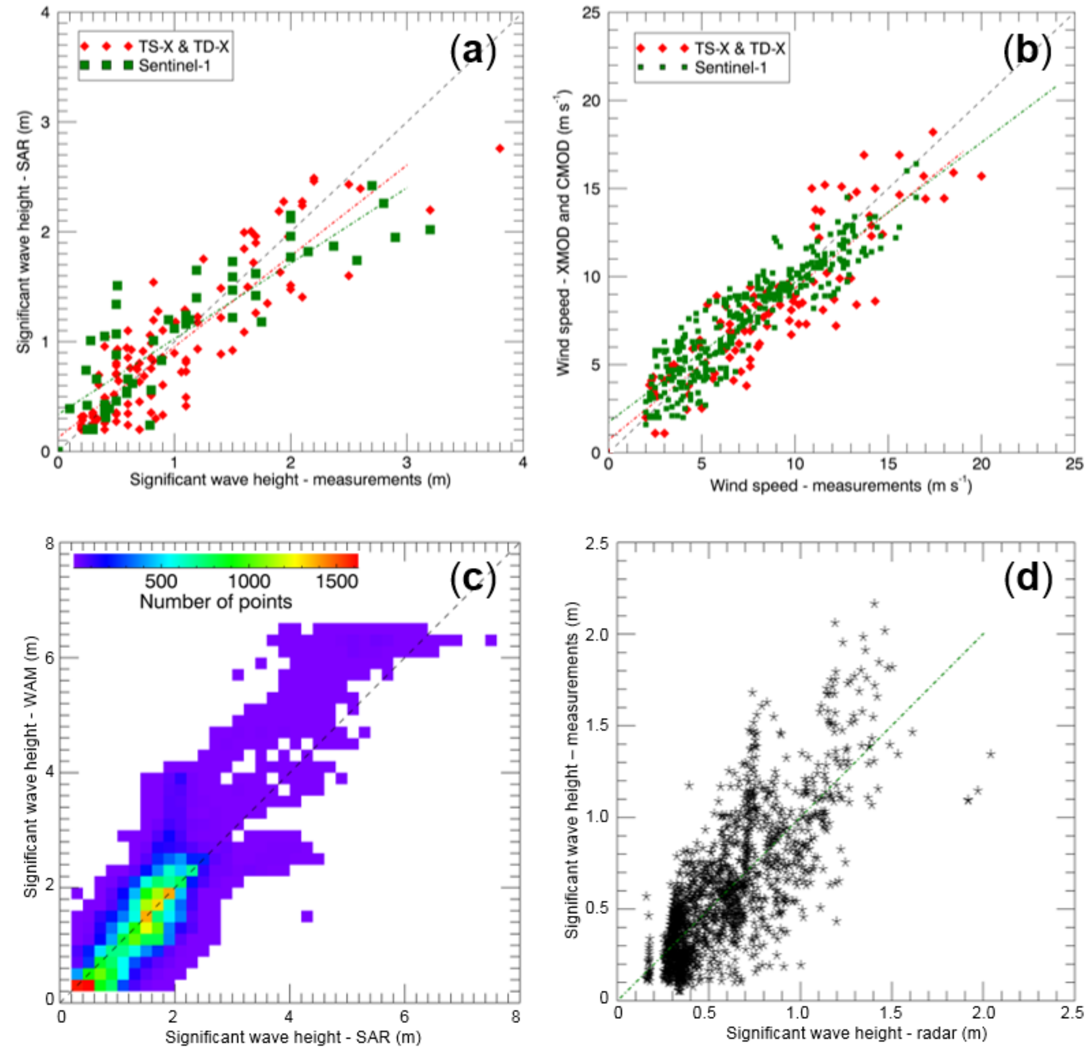
- XWAVE_C - Pleskachevsky et al. 2016, *ISPRS*, 119
- CWAVE_S1-IW - Pleskachevsky et al. (*submitted to IJRS*))

Radar methods: sea state

- Energy of image spectrum retrieved by FFT operaator
  - $E_{IS} = \int_{k_x^{min}}^{k_x^{max}} \int_{k_y^{min}}^{k_y^{max}} IS(k_x, k_y) dk_x dk_y$
    - $k = \sqrt{k_x^2 + k_y^2}$ where $k_{\max}$ and $k_{\min}$ depend on radar data used
- Significant wave height
  - $H_S = a_0 \sqrt{B_0 E_{IS} \tan(\theta)} + \sum_{i=1}^{n} a_i B_i$
    - θ is local incidence angle
    - a_i are coefficients, and B_i are functions of spectral parameters, wind and GLCM results depending on data/sensor
- Empirical algorithm for marine radar data
  - H_S estimation based on image spectra E_{IS}
  - Calculated parameters are tested against measured *in situ* values
    - Best-fit trendline technique
    - Pearson correlation coefficient
    - Minimize RMSE
  - $B_0 = f(d, \theta)$
  - $B_1 = f(d, \theta, \overline{x})$, where $\overline{x} = \sum_{i=0}^{2G-2} i \, P_{x+y}(i)$
  - $B_2 = f(d, \theta, \sigma^2)$, where $\sigma^2 = \sum_{i=0}^{G-1} \sum_{j=0}^{G-1} (i - \mu)^2 P(i, j)$
    - d distance from radar tower
    - $\overline{x}$ GLCM mean
    - σ^2 GLCM variance
    - P number of collocations in GLCM levels G

Results: validation

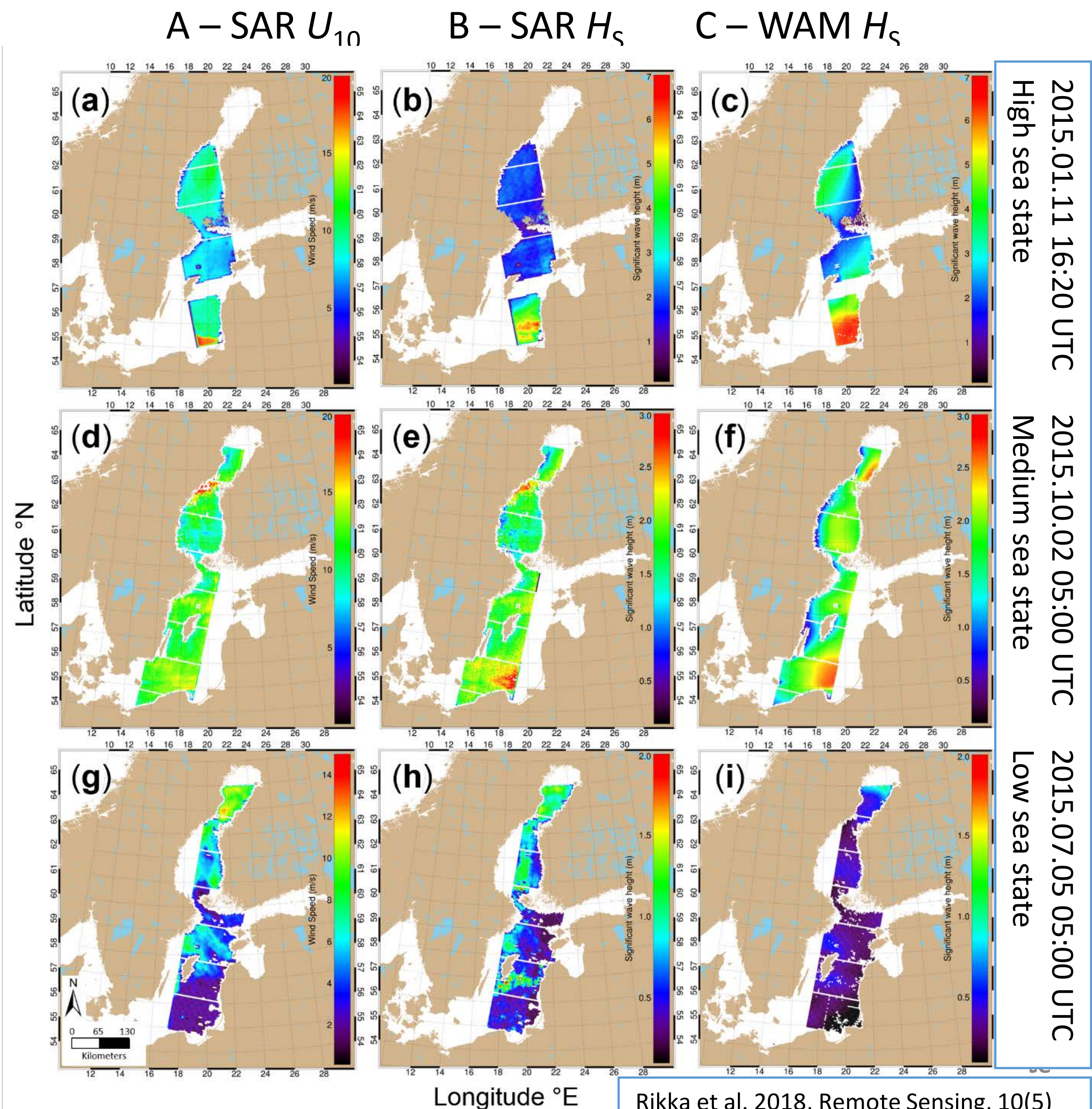
- High agreements between *in situ* wind and radar-derived wind speed, especially for Sentinel-1 results where RMSE less than 1.5 m s^{-1}
- Radar derived H_S accurate, r slightly less than 0.90, RMSE less than 0.5 m
- High agreement in range of 0 – 3 m (typical for Baltic Sea) between SAR and WAM



Collocation pair	TS-X TD-X vs. *in situ*	TS-X TD-X vs. *in situ*	Sentinel-1 vs. *in situ*	Sentinel-1 vs. *in situ*	Sentinel-1 vs. WAM	Marine radar vs. *in situ*
Parameter	H_S	U_{10}	H_S	U_{10}	H_S	H_S
r	0.88	0.90	0.88	0.91	0.86	0.78
RMSE	0.32	2.02	0.40	1.43	0.47	0.23
SI	0.33	0.24	0.37	0.19	0.33	0.41
n	117	102	52	357	49314	1678

Sentinel-1 data for regional studies

- Wave height up to 7.5 m
- General agreement in the wave height values and location of maximum
- Storm peak area smaller from SAR data
- Storm does not spread as much to the north as on WAM field
- Maximum H_S higher with SAR-derived results
- Wave field variability (STD) many times larger for SAR dataset
- Variability in wave model fields lost mostly due to wind forcing, **local fine-scale wind field variations and gusts are not included in wave model forcing**

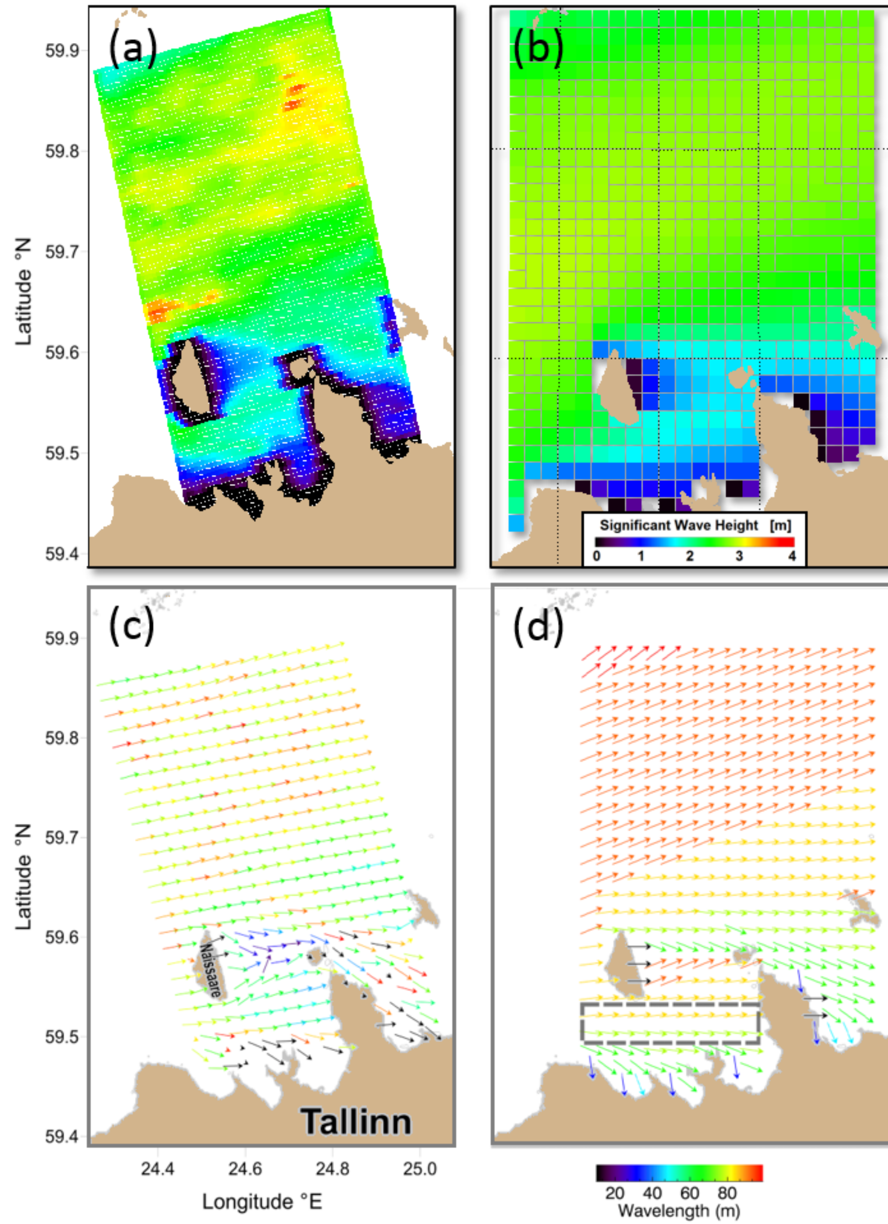


Rikka et al. 2018, Remote Sensing, 10(5)

Department of Marine Systems
Tallinn University of Technology

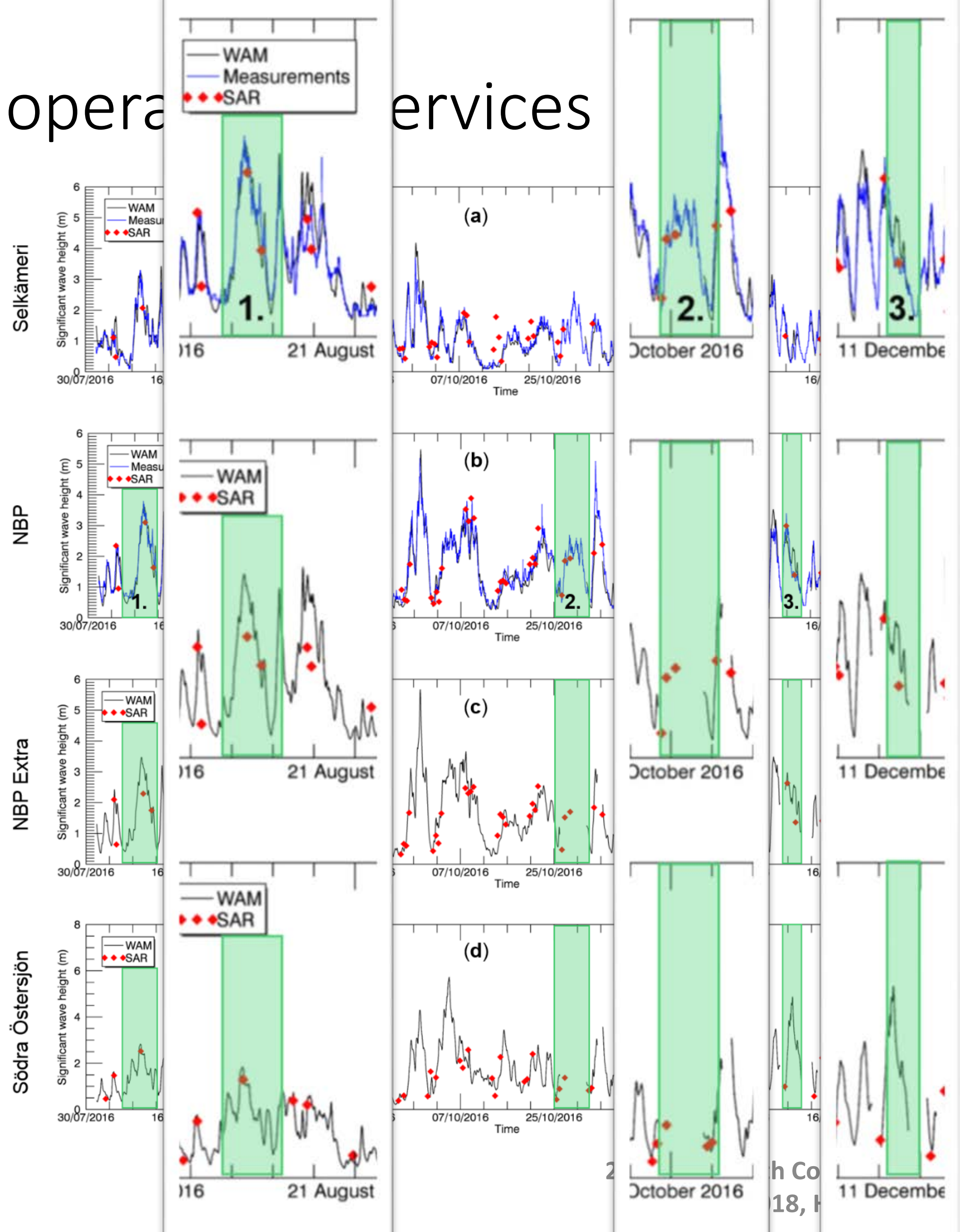
Local variability of sea state from high resolution SAR imagery

- General agreement between SWAN wave model results and SAR-derived H_S values
- Wave height, wavelenght and wave propagation direction shows more variabilty from radar-derived results



Sentinel-1 data for opera ervices

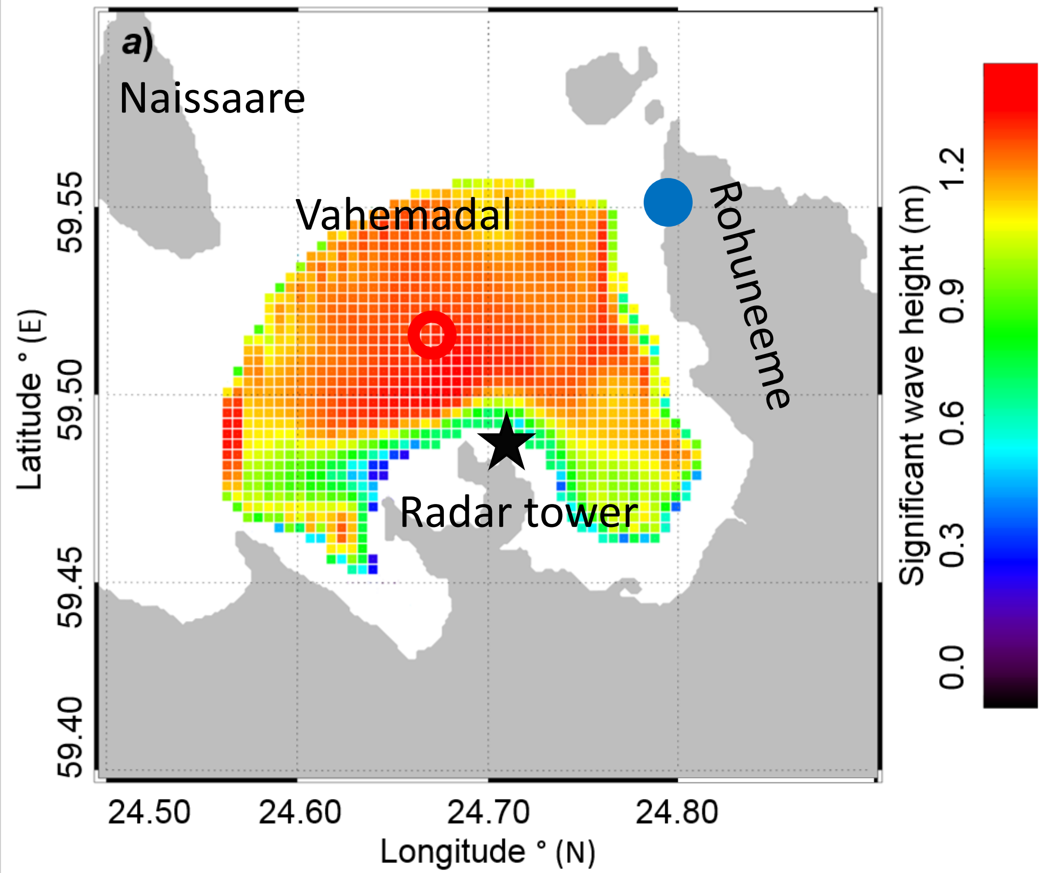
- An independent time series from 1st August 2016 until the end of 2016
- Case 1 – mismatch in wave height value on WAM
    - better detailed spatial variability
- Case 3 – similar to Case 1 but with more uniform wave field
- Case 2 – missing *in situ* or model data can be covered by SAR
    - Technical issues
    - Maintenance of measurement device
- Boos measurement station Södra Östersjön – no *in situ* data since 2011, although common high sea

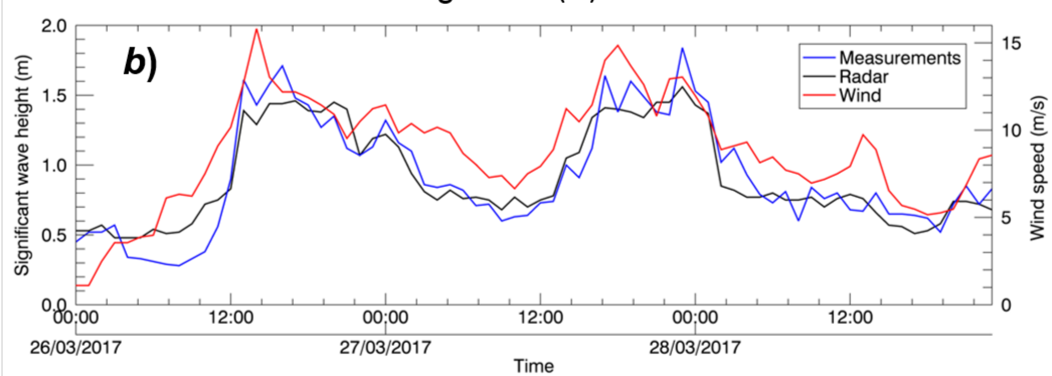


Department of Marine Systems
Tallinn University of Technology

Coastal radar data for operational service

- Average H_S field during 26.03 – 28.03.2017 for NW storm conditions
- Time series of *in situ* measurements and radar-derive H_S show good agreement during the storm
- Similar H_S field has been shown by other authors for comparable conditions
- Waves propagating into Tallinn Bay between the mainland and Naissaare
- Maximum H_S around the tip of the Paljassaare peninsula
  - Depth around 30 m

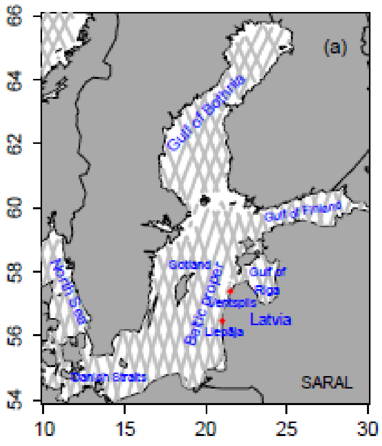


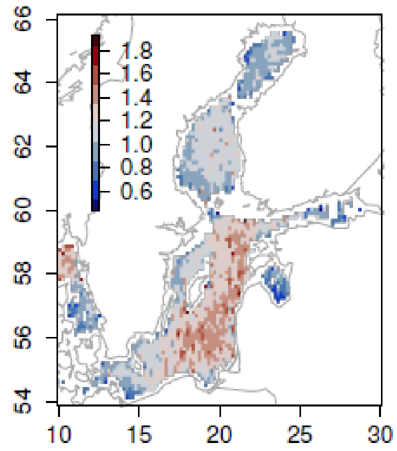


Statistical mapping of coastal wave field

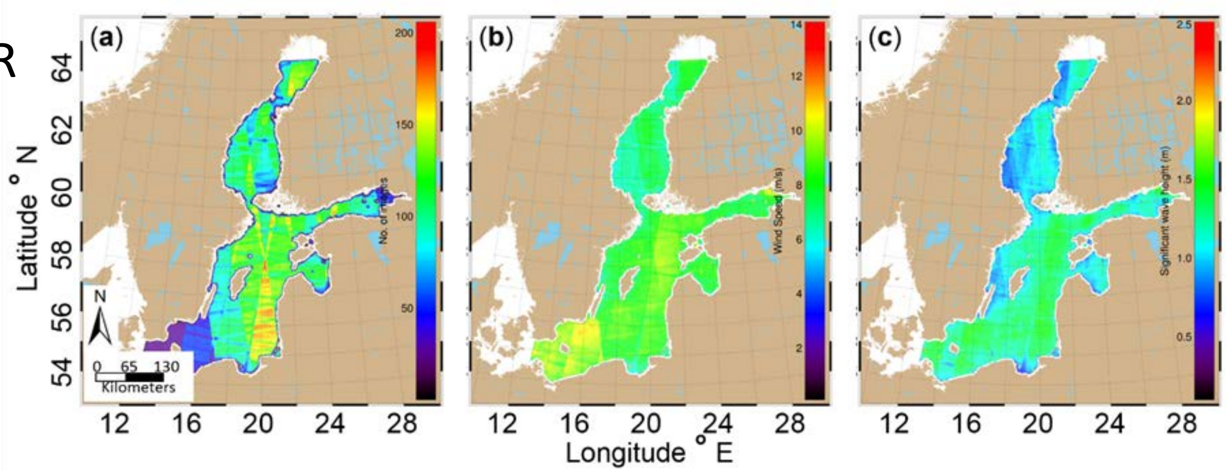
E.g. Kudryavtseva and Soomere (2017) analysed altimetry data over the Baltic Sea

- Data between 1993-2015
- Output resolution about 0.2×0.1°





No. of images | Average U_{10} | Average H_S



- Similar outcome from SAR data
- Data between 2015-2016
- Output resolution 3 nm (interpolated to 1 nm grid)

Conclusions

- Methods to estimate total significant wave heights were improved/developed and validated for the Baltic Sea wave climate conditions
  - XWAVE_C for H_S (r = 0.88, RMSE = 0.32 m)
  - CWAVE_S1-IW for H_S (r = 0.88, RMSE = 0.40 m)
  - Marine radar for H_S (r = 0.78, RMSE = 0.23 m)
  - XMOD-2 for U_{10} (r = 0.90, RMSE = 2.02 m s^{-1})
  - CMOD for U_{10} (r = 0.91, RMSE = 1.43 m s^{-1})
- The statistics show that radar-derived results are suitable for routine monitoring of meteo-marine parameters in the Baltic Sea
- SAR-derived values of geophysical parameters are spatially more variable and would provide more detailed wave field compared to wave model
- SAR-derived results could be used for wave model validation
  - Wind data from SAR could be used as wave model forcing

Conclusions

- SAR-derived wave height and wind speed results can replace measurements or wave model results in poorly sampled areas or in cases when data is missing
- SAR enables to observe coastal wave field variations in the Baltic Sea in more detail compare to other EO sensors (altimetry)
- SAR data enable to perform wave climate studies in seasonal and regional scale
- Based on Paljassaare marine radar data analysis wave height can be monitored with high accuracy in space and time
- Considering all above the radar based wind and wave data would be beneficial for maritime situation awareness applications and routine monitoring/forecasting in the Baltic Sea

Thank you for your attention!