Analysing trends and extremes of water levels in the Baltic Sea

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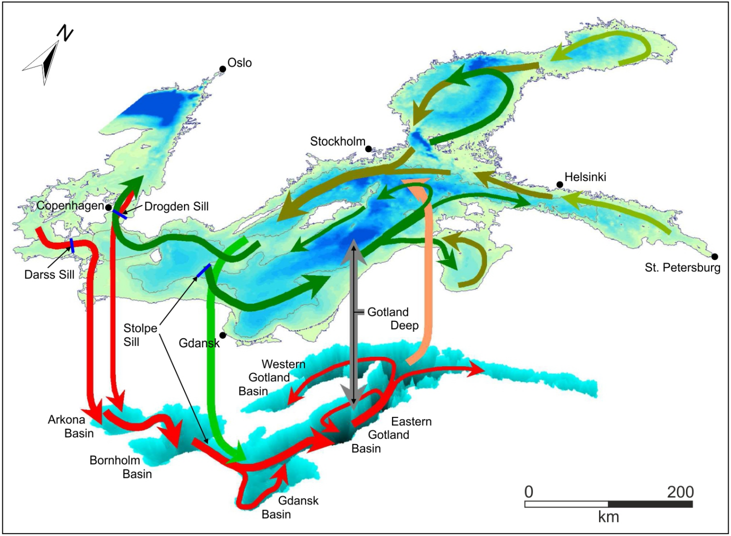
The Baltic Sea "Conveyor Belt"



Elken and Matthäus (2008)

Motivation

Storm surge on 12/13 November 1872 (3.3 m above MSL), area between Præstø and Faxe (www.wikepedia.org)

What is known

- Global mean sea level (MSL) rise: 1.8±0.3 mm/yr (*Church et al.* (2004))
- MSL-rise (*Suursaar and Sooäär* (2007); *Barbosa* (2008); *Ribeiro et al.* (2014))
  - Western Baltic Sea: 0.4±0.22 mm/yr - 1.2±0.08 mm/yr
  - Gulf of Riga: 2.3±? mm/yr
  - Stockholm: 1.55±0.07 mm/yr
- Extremes grow faster than MSL
  - Warnemünde: 1.77±0.65 mm/yr
  - Gulf of Riga: 5.7±? mm/yr
  - Tallin: 6.5±?? mm/yr

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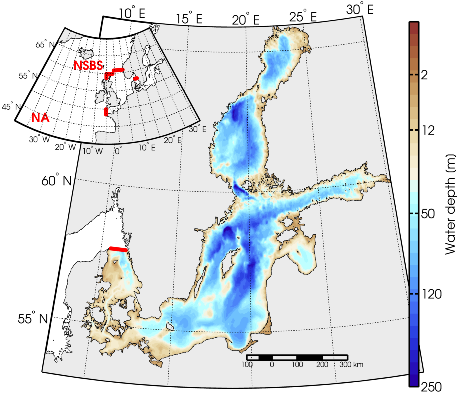
  - Warnemünde: 1.77±0.65 mm/yr
  - Gulf of Riga: 5.7±? mm/yr
  - Tallin: 6.5±?? mm/yr
- Relative vs. absolute MSL rise
- No common time period for trend analysis
- Grid resolution is a challenge (*Meier et al.* (2004); *Gräwe and Burchard* (2012))

Outline

- Motivation
- Setup
- Challenges
- 4-member ensemble (1980-2005)
- Single run (1948-2014)
- Conclusion

Model domain



Nesting

- 2D North Atlantic (4 nm)
- 3D North Sea / Baltic Sea (2 nm) (*Gräwe et al.* (2015))
- 3D Baltic Sea (1 nm)

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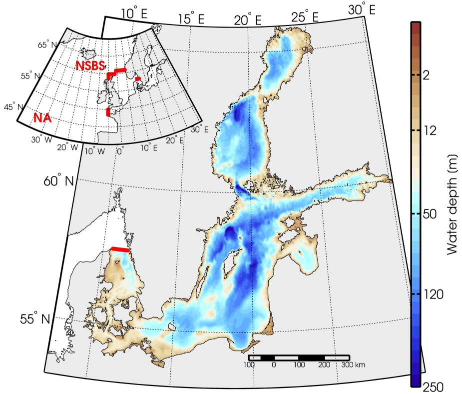

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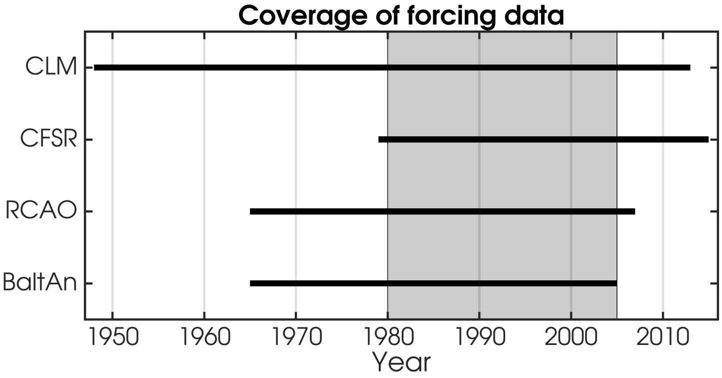
Setup

- GETM (www.getm.eu)
- 60 adaptive vertical layers
- Minimum layer thickness 30 cm
- $k - \epsilon$ closure
- Thermodynamic ice model (Winton, 2002)

Forcing



Data set	Global forcing	Coverage	Δx	Δt
CLM	ERA-40	1948-2014	19 km	hourly
CFSR	NCEP-NCAR	1979-2016	32 km	hourly
RCA	ERA-40	1961-2007	50 km	3-hourly
BaltAn	ERA-40	1965-2005	11 km	6-hourly

Analysing SSH

$$\eta = \langle \eta \rangle + \eta_{GIA} + \eta_{SLP} + \eta_{ext} + \eta_{\varrho} + \eta_{steric}$$

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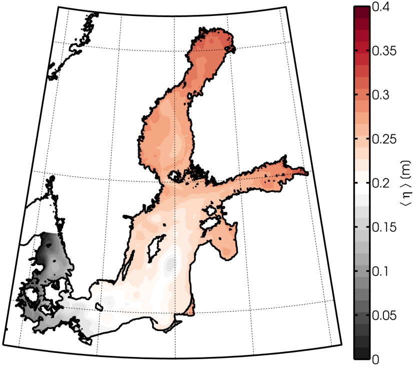

Mean sea level (MSL)
(1950-2014)

Analysing SSH

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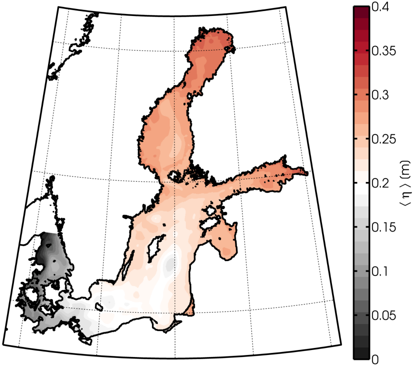
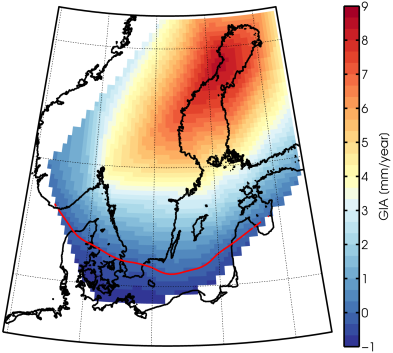
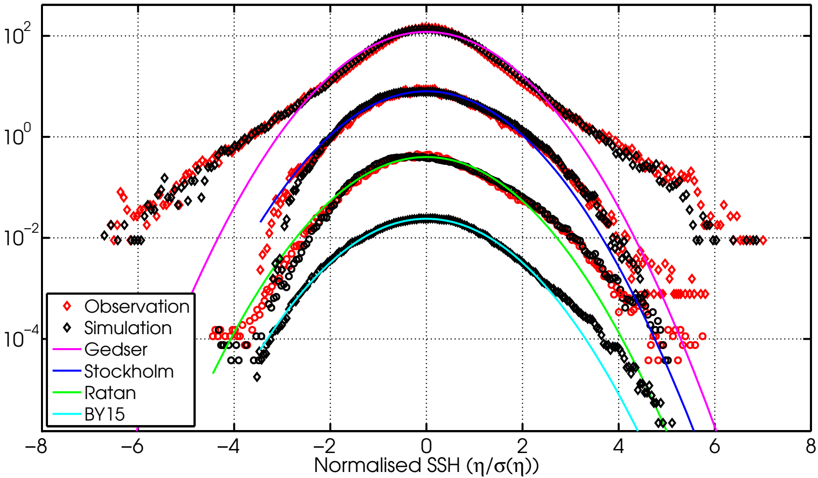


Mean sea level (MSL) (1950-2014)



Glacial isostatic adjustment (GIA) (*Ekman* (1996))

Non-Gaussianity



Pdfs of normalised (σ=1) hourly SSH at selected stations.

Trend estimates

1. Least square estimation (Robust fitting)
2. Quantile regression (*Koenker and Hallock* (2001); *Barbosa* (2008))
3. Autoregressive model fitting (*Beran* (1992); *Franzke* (2012); *Bos et al.* (2014))

$$\eta_i = \beta \cdot t_i + \varepsilon_i + \sum_{n=1}^{N} \alpha_{i-n}\eta_{i-n}$$

- account for longterm correlations
- important for estimation of uncertainty

Performance of ensemble members

	Obs	CLM	CFSR	RCA	BaltAn
Wismar	1.19	-0.07±0.08	-0.11±0.08	-0.21±0.11	-0.15±0.08
Gedser	1.00	-0.05±0.05	-0.03±0.06	-0.20±0.08	-0.10±0.05
Koserow	1.06	-0.01±0.09	-0.05±0.06	-0.20±0.11	-0.13±0.06
Stockholm	0.58	-0.01±0.05	+0.01±0.05	-0.03±0.04	+0.00±0.04
Helsinki	1.37	+0.06±0.14	+0.05±0.12	-0.19±0.13	+0.02±0.15
Kalix	1.14	-0.04±0.07	+0.02±0.08	-0.14±0.08	-0.10±0.09

Comparison of mean annual maximum SSH (m) at different stations and errors for different forcings (1980-2005)

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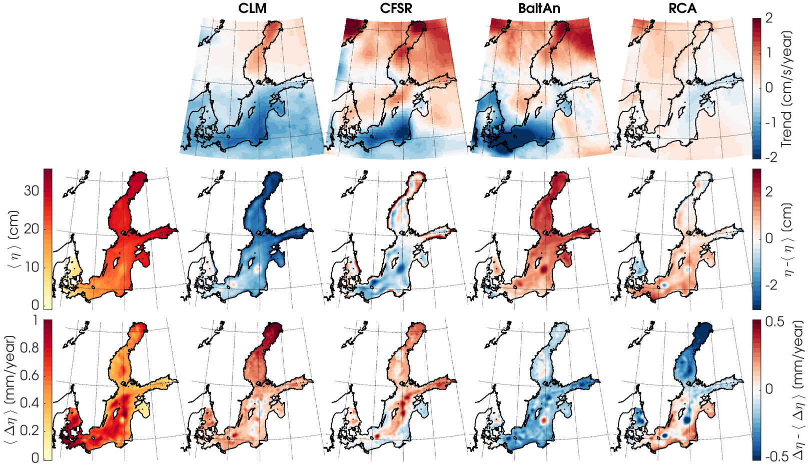
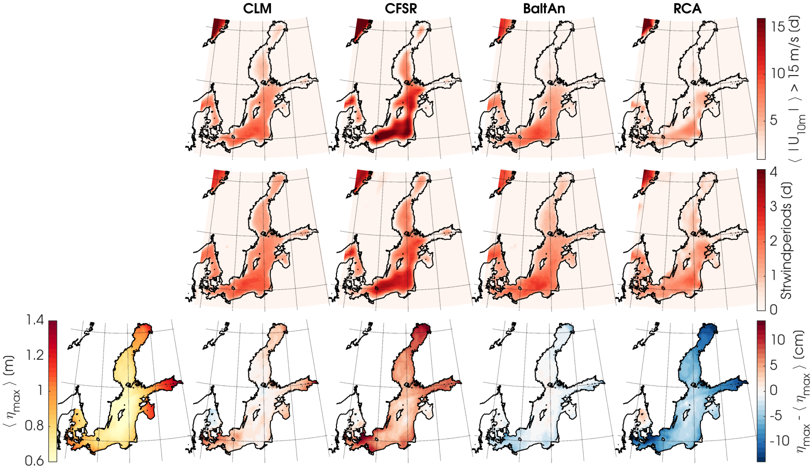
Mean trends (1980-2005)



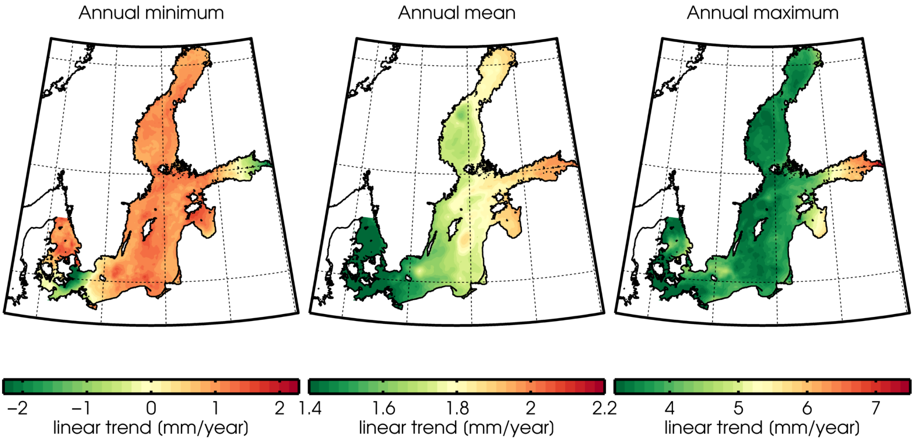
Upper panels: trends in zonal wind speed, **middle panels:** mean SSH anomaly, **lower panels:** anomaly of SSH trends

Extremes (1980-2005)



Upper panels: number of strong wind days, **middle panels:** number of consecutive strong wind days, **lower panels:** anomaly of annual maximum SSH

Long-term trends (1950-2014)



MSL trend (global 1.8±0.3 mm/yr (*Church et al.*, 2004))

- Western Baltic Sea: 1.2±0.08 mm/yr (*Barbosa*, 2008)
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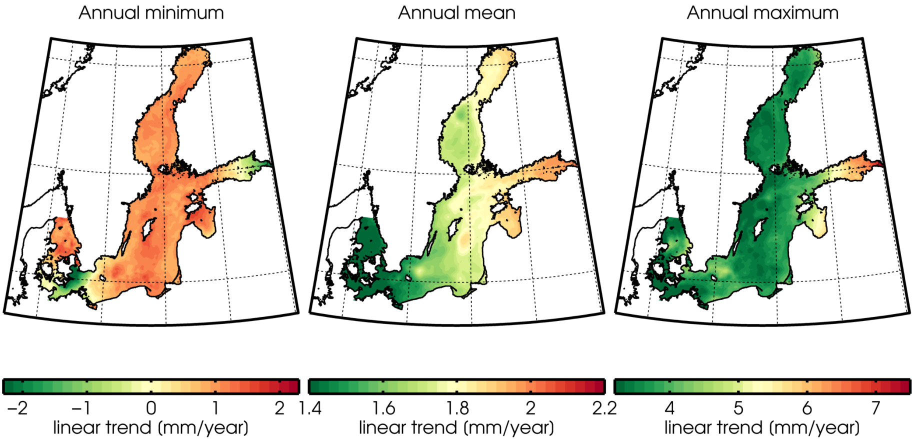


Annual maximum trend

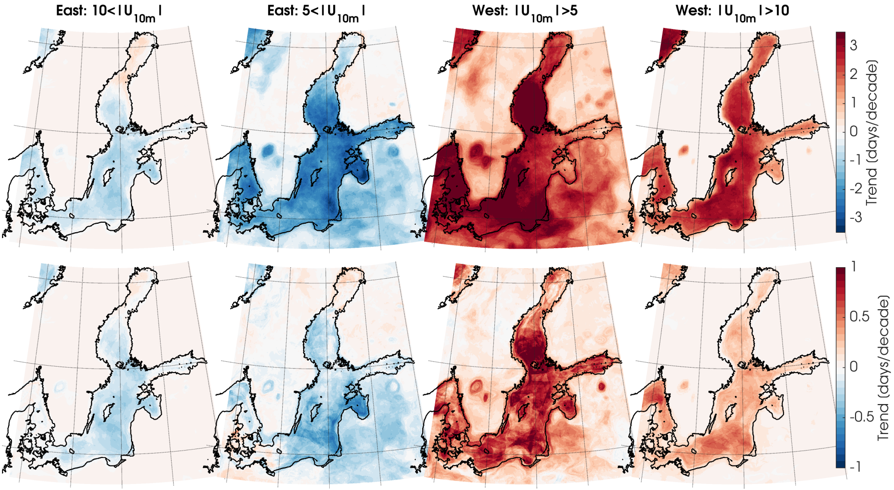
- Warnemünde: 1.77±0.65 mm/yr (*Barbosa*, 2008)
- Gulf of Riga: 5.7±? mm/yr (*Suursaar and Sooäär*, 2007)
- Tallin: 6.5±? mm/yr (*Suursaar and Sooäär*, 2007)

Trend estimates (1950-2014)

Station	linear trend (mm/yr)	95% CI level (mm/yr)
Kalix	2.54±1.35 ; 1.55±1.21	1.56
Ratan	2.00±0.58 ; 1.81±0.50	1.33
Stockholm	1.70±0.45 ; 1.79±0.35	1.08
Helsinki	1.89±0.53 ; 2.04±0.44	1.22
Kaliningrad	2.21±0.93 ; 2.38±0.81	1.28
Kungsholmsfort	1.63±0.36 ; 1.61±0.27	0.93
Gedser	1.38±0.28 ; 1.31±0.23	0.76
Wismar	1.51±0.23 ; 1.26±0.17	0.73
Aarhus	1.22±0.33 ; 1.34±0.31	0.79

- Estimation of linear trends assuming a AR(2) process. The GIA correction to absolute MSLR is already made (*Peltier* (2004)).
- 95 % CI levels are estimated based on *Schreiber and Schmitz* (1996) and *Franzke* (2013)

Driver of sea level rise (1950-2014)



Trends in **Upper panels:** wind days, **lower panels:** consecutive wind days

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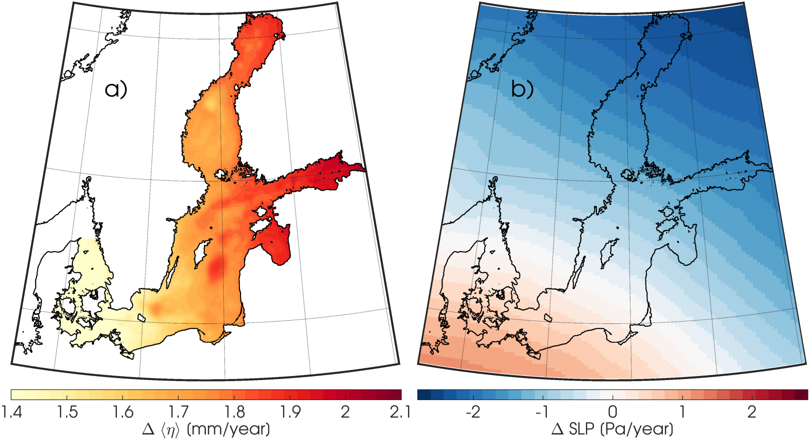
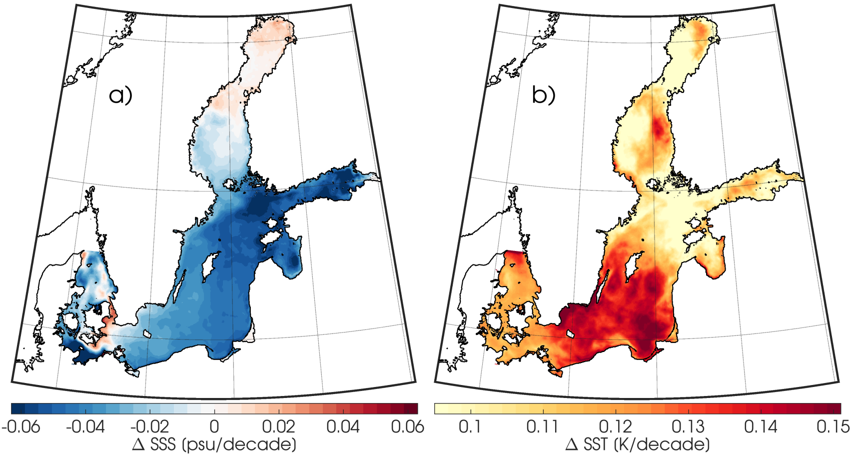


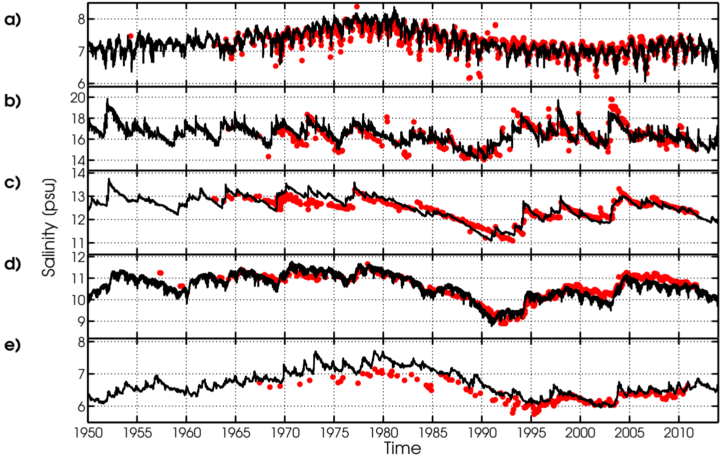
Trends in: **a)** SSH, and **b)** air pressure (inverse barometer effect (*Wunsch and Stammer* (1997))

Driver of sea level rise (1950-2014)



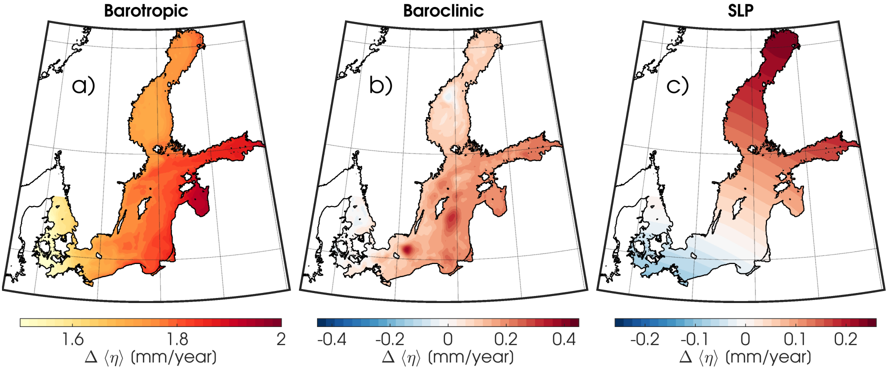
Trends in: **a)** surface salinity, and **b)** surface temperature

Salinity



a) surface salinity (central Baltic Sea BY15), **b)** bottom salinity (southern Baltic BY4), **c)** bottom salinity (central Baltic BY15), **d)** bottom salinity Landsort, **e)** bottom salinity (northern Baltic UB5S)

Driver of sea level rise (1950-2014)



Contribution to MSL rise by **a)** Wind + external, **b)** changes in T/S to MSL rise, and **c)** changes in SLP

Conclusion

- Setup for the period 1950-2014
- Mini-ensemble for the period 1980-2005
- Model derived trends agree with observations
- Extremes rise faster than MSL
- Decrease in easterly winds (duration and magnitude)
- Increase in westerly winds (duration and magnitude)
- Changes in air pressure accounts for 15% in MSL rise
- Changes in T/S accounts for 30% in MSL rise
- Changes in wind pattern might explain stagnation periods

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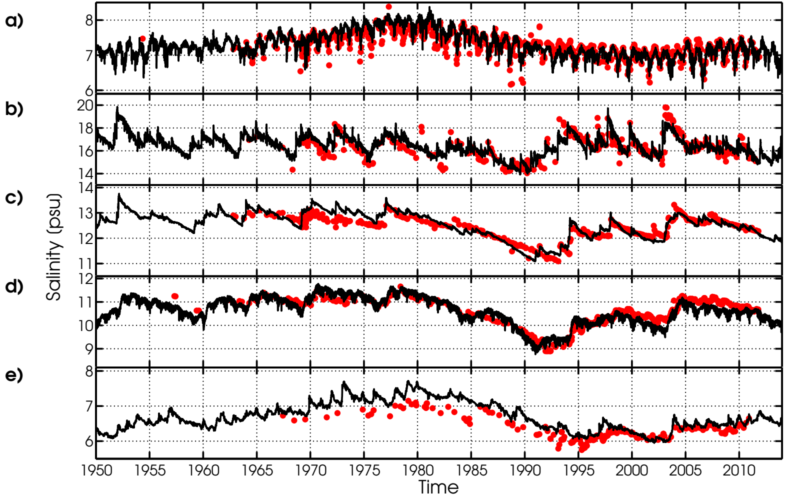
Estimation of confidence intervals (95%)

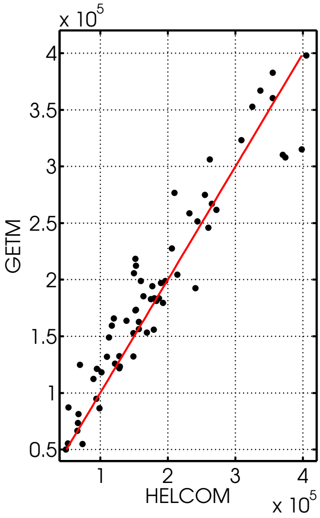
- generation of surrogate data (*Schreiber and Schmitz* (1996))
- based on 1000 realisations, estimation of 95% confidence intervals (*Franzke* (2012, 2013))

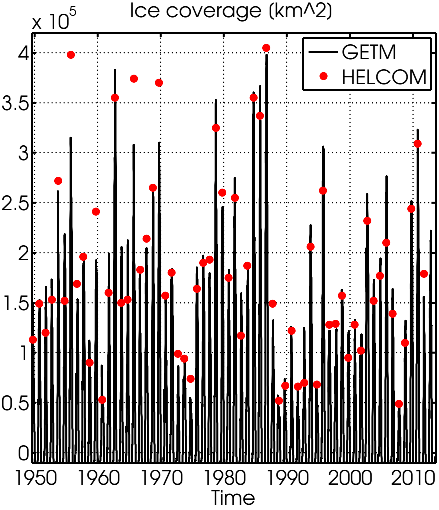
Salinity



a) surface salinity BY15, **b)** bottom salinity BY4, **c)** bottom salinity BY15, **d)** bottom salinity Landsort, **e)** bottom salinity UB5S

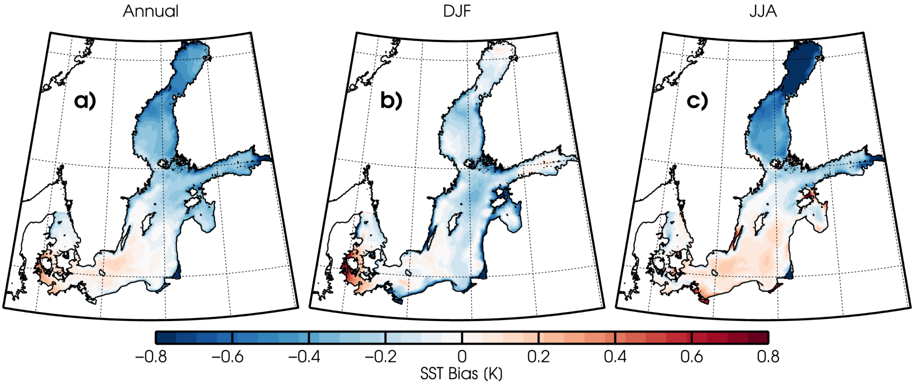
Ice coverage





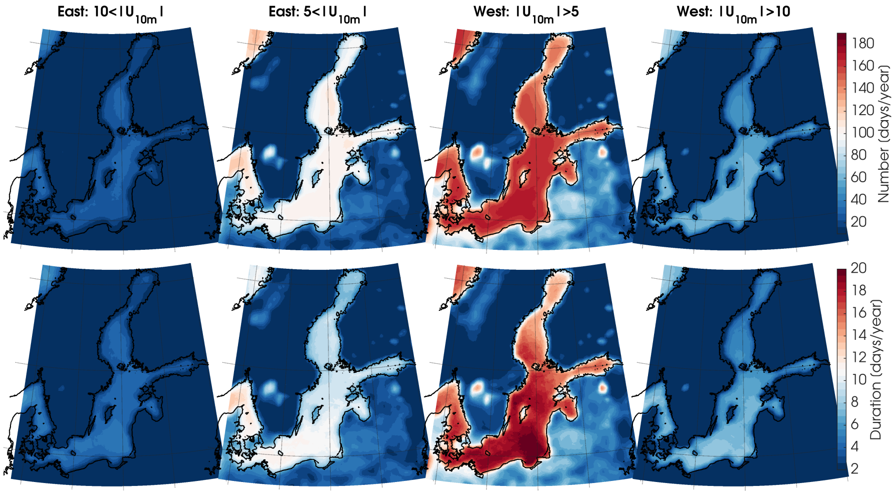
Maximum ice coverage

SST (1985-2013)



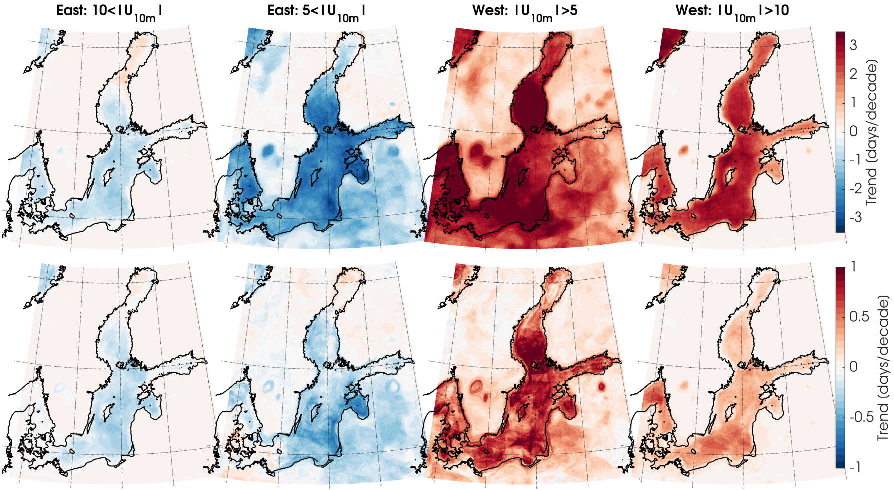
Comparisons of SST with *Reynolds et al.* (2007) OI-product

Driver of sea level rise (1950-2014)



Annual number of **Upper panels:** wind days, **lower panels:** consecutive wind days

Driver of sea level rise (1950-2014)



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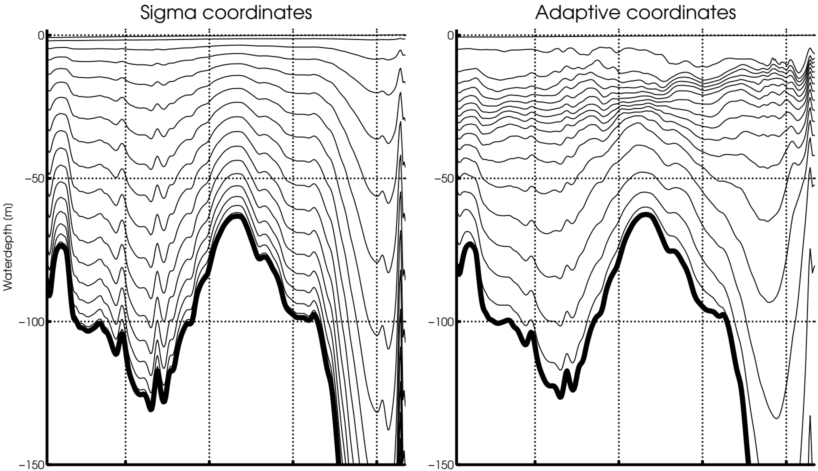

Driver of sea level rise (1950-2014)

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