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Mechanisms behind sea level variations in the North Sea

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Motivation

- Sea level rise typically is being discussed as global average, or as basin-scale variations.
- However, coastal sea level is where society is impacted by sea level rise.
- It is here where dynamics and sea level changes itself differ from basin scale dynamics due to shelf sea dynamics and additional processes kicking in.
- In addition, the observational basis is reduced in shallow seas due to additional technical challenges, e.g., for altimetry.
- An extra effort is therefore required to better understand sea level variations along coast lines and how they are being observed.
- Ultimately, we want to improve our capability to predict sea level rise and change along coastlines.

Objective

Study of the SSH variability and the underlying physical processes in the eastern shelf regions of the Northeast Atlantic, specifically the North Sea.

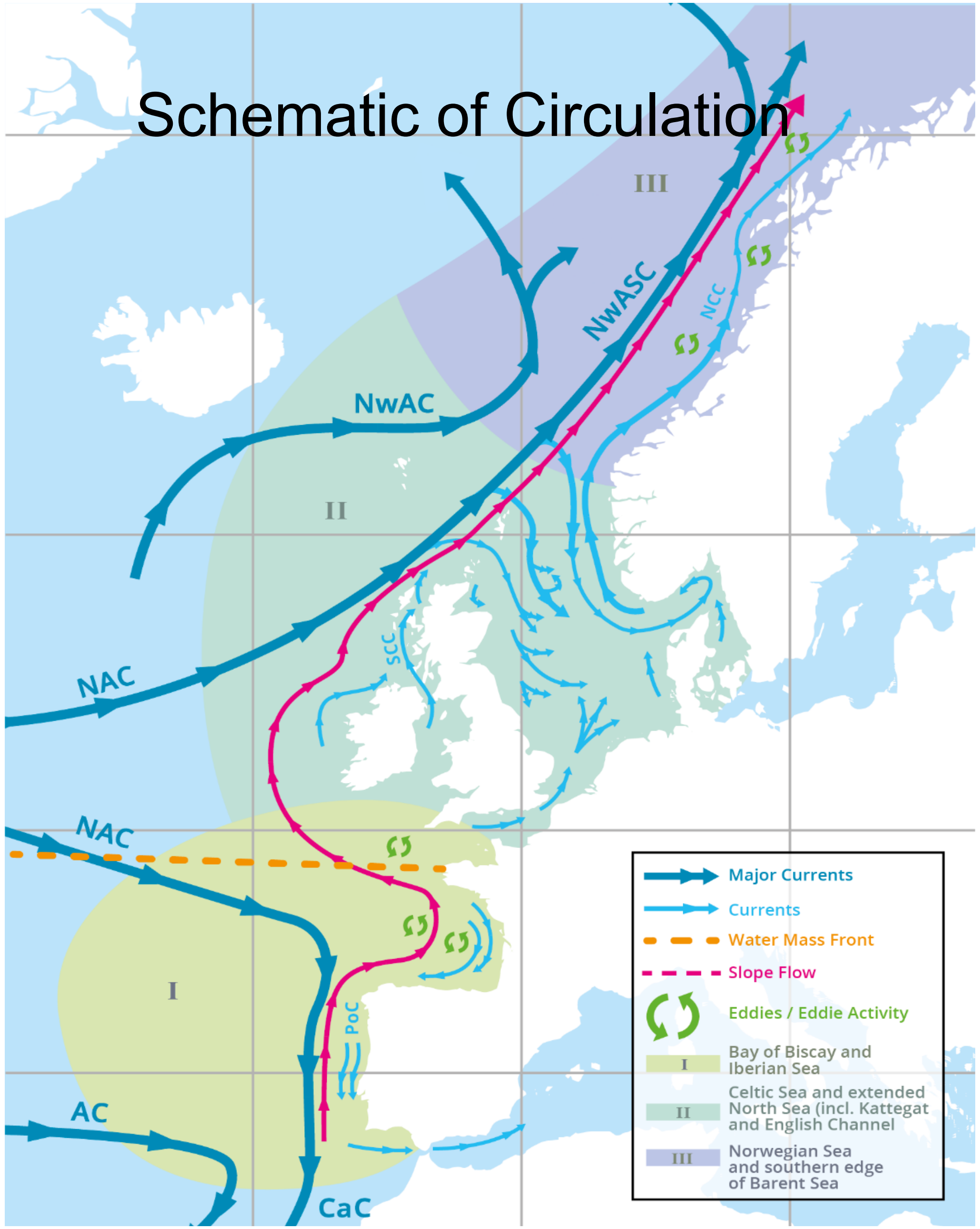
Questions investigated:

- How well does a high-resolution model represent the observed sea level variability?
- Does this differ between tide gauge observations and altimetry?
- What are the regional drivers of sea level variability and what is the frequency response of associated sea level variability around the German coast?

Numerical ocean model

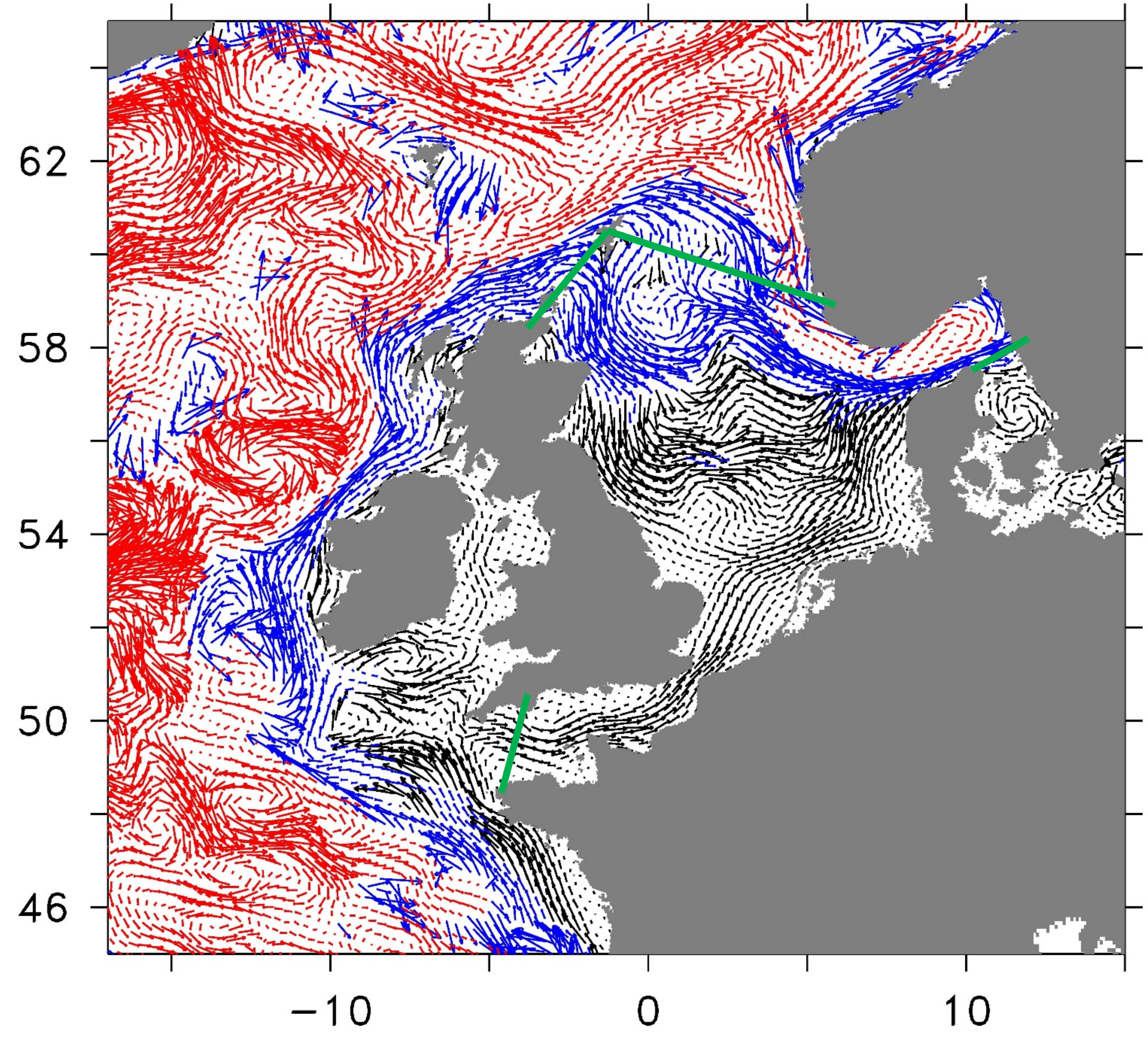
- Coupled ocean- sea ice MIT global circulation model for the Atlantic and Arctic Oceans;
- 4 km spatial resolution and daily output;
- Forced by momentum, heat and freshwater fluxes computed with the 6-hourly ECMWF ERA-Interim reanalysis and bulk formula;
- No tidal forcing included;
- Study period: 2003-2012;

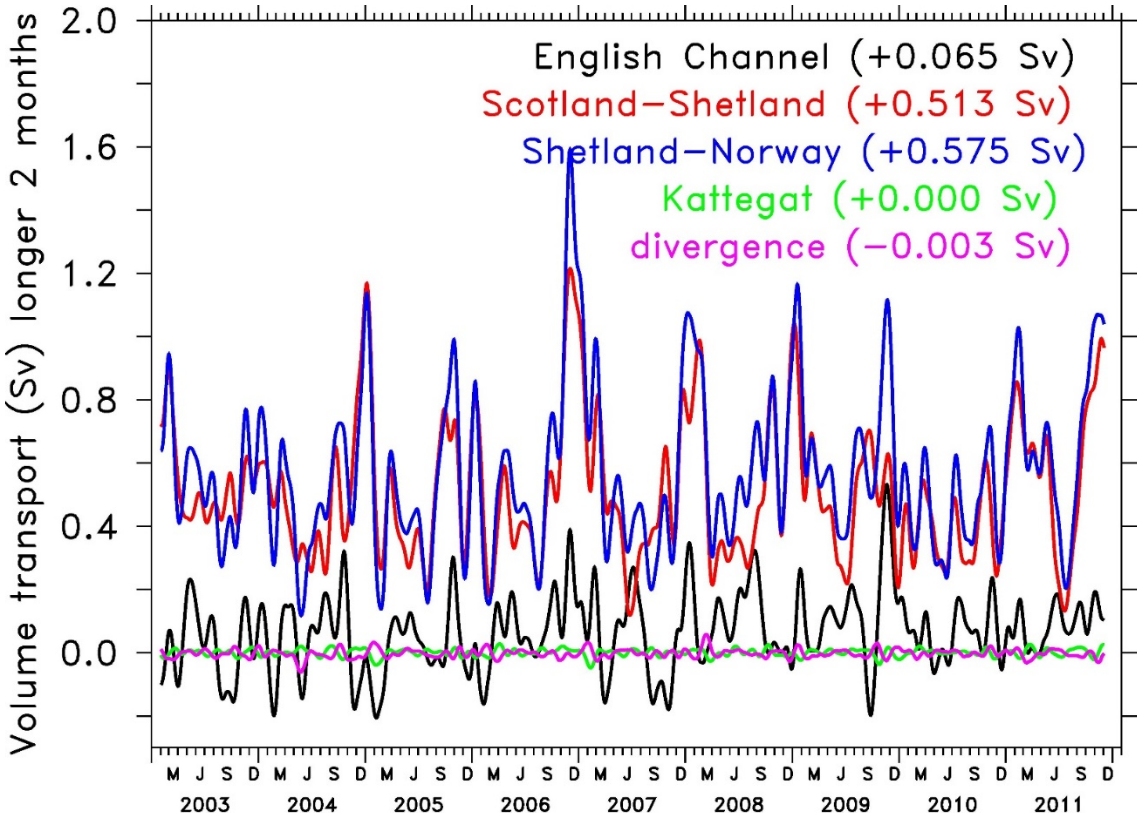
Schematic of Circulation



Study region with selected oceanographic features

Simulated averaged barotropic flow in the North Sea

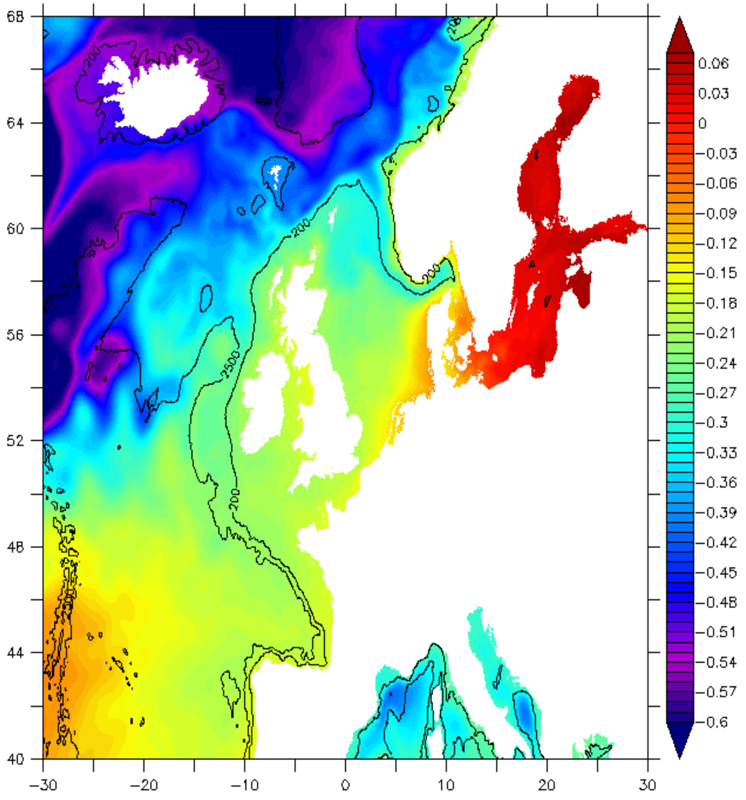




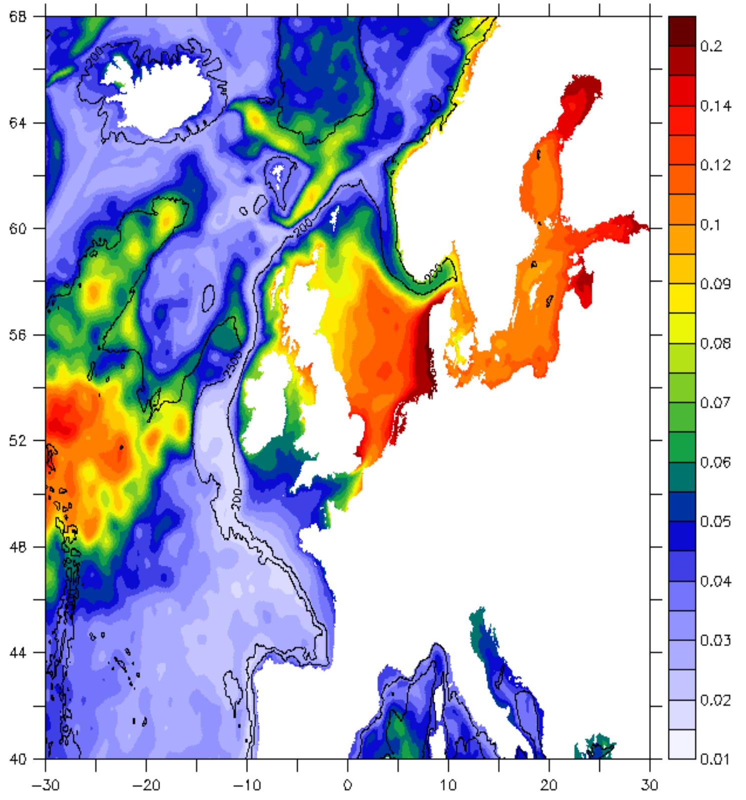
Simulated SSH: mean and variability

No tides!

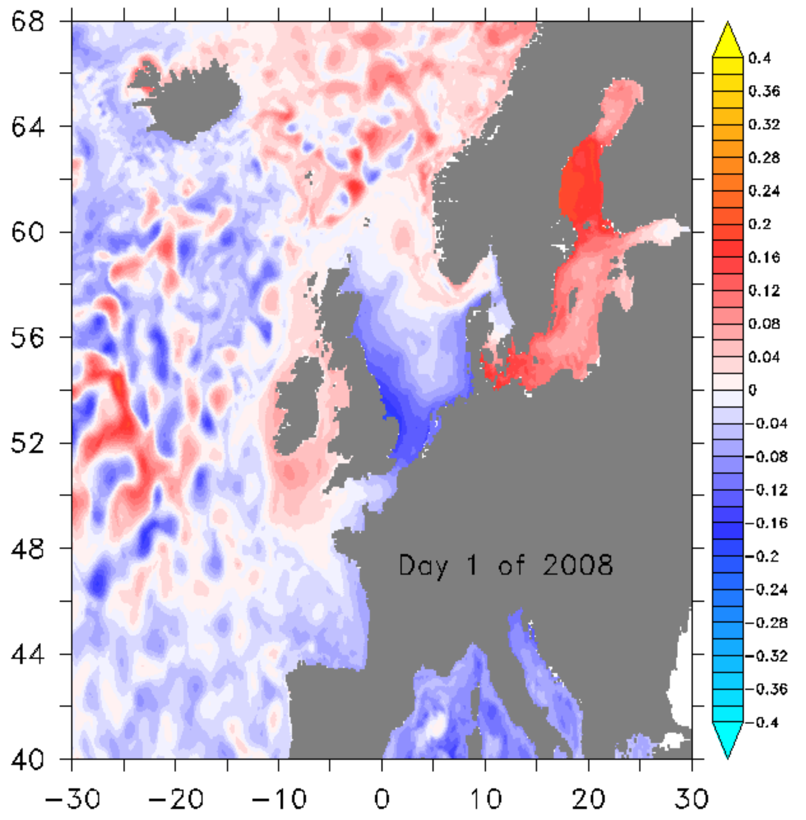
SSH mean



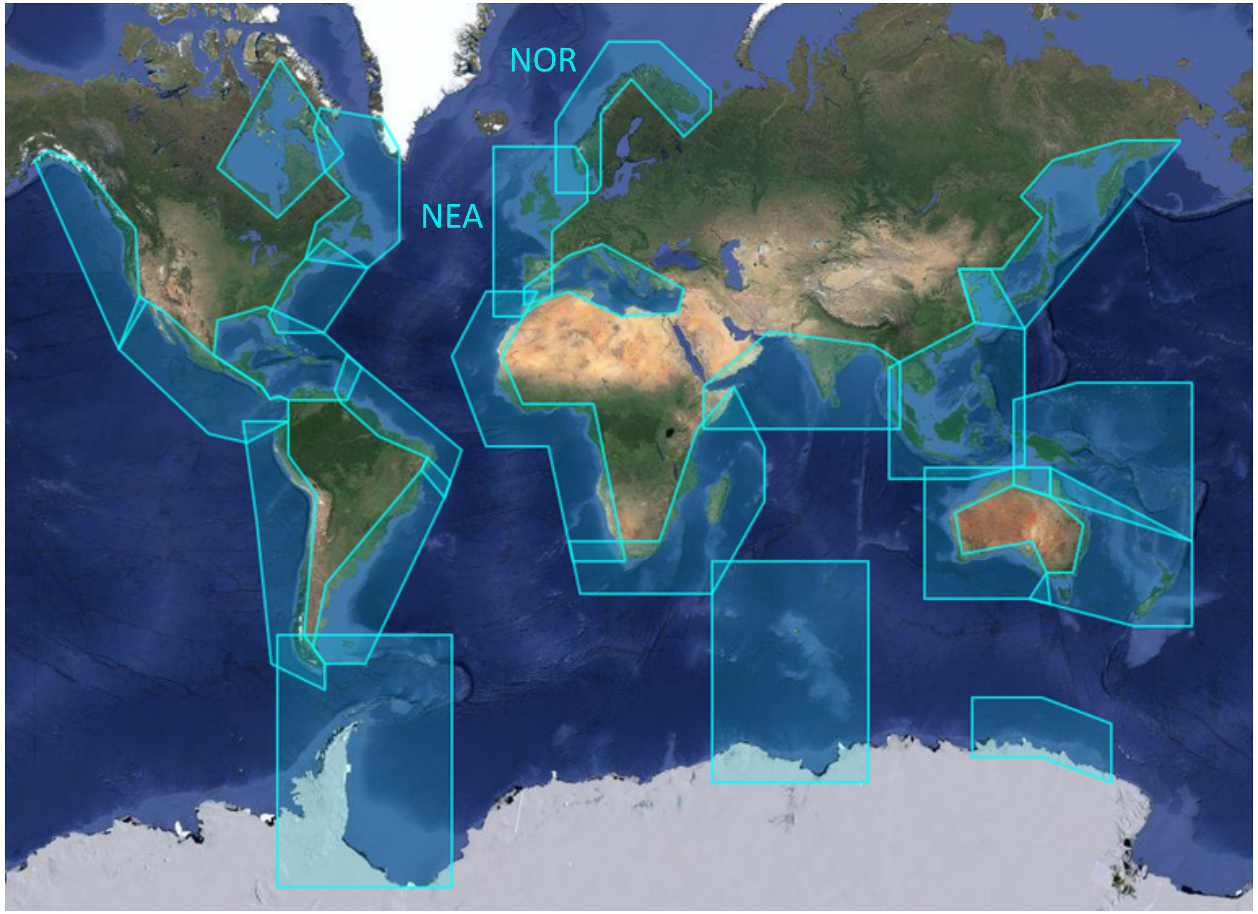
SSH standard deviation



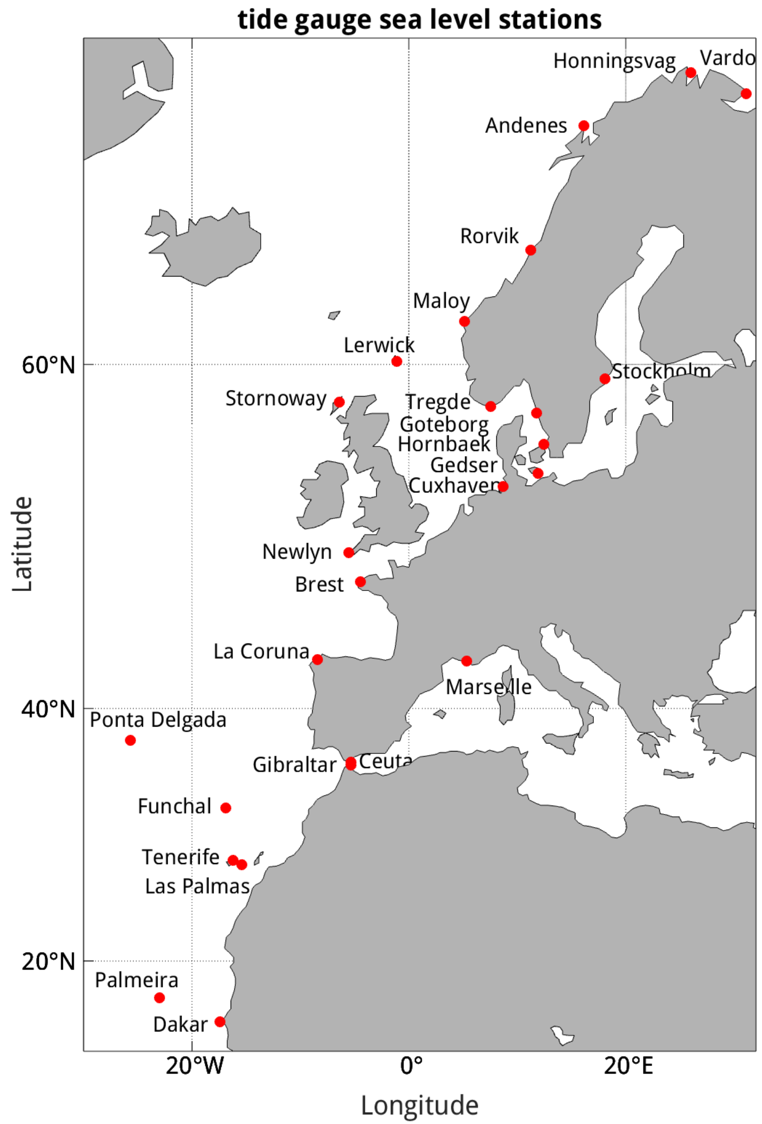
SSH daily evolution in 2008



Observations: Satellite and tide gauge data

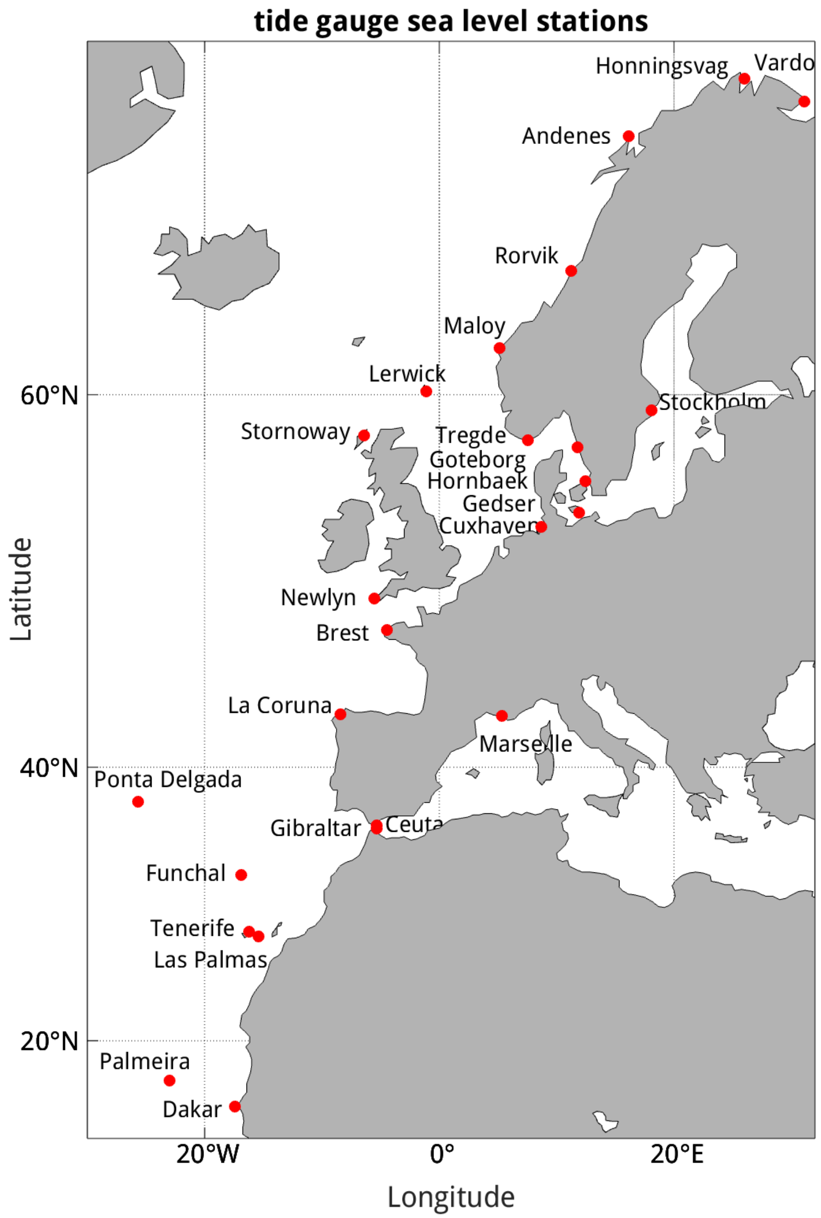


- 10-daily CTOH 1-Hz along-track sea level anomalies regional product (X-TRACK)



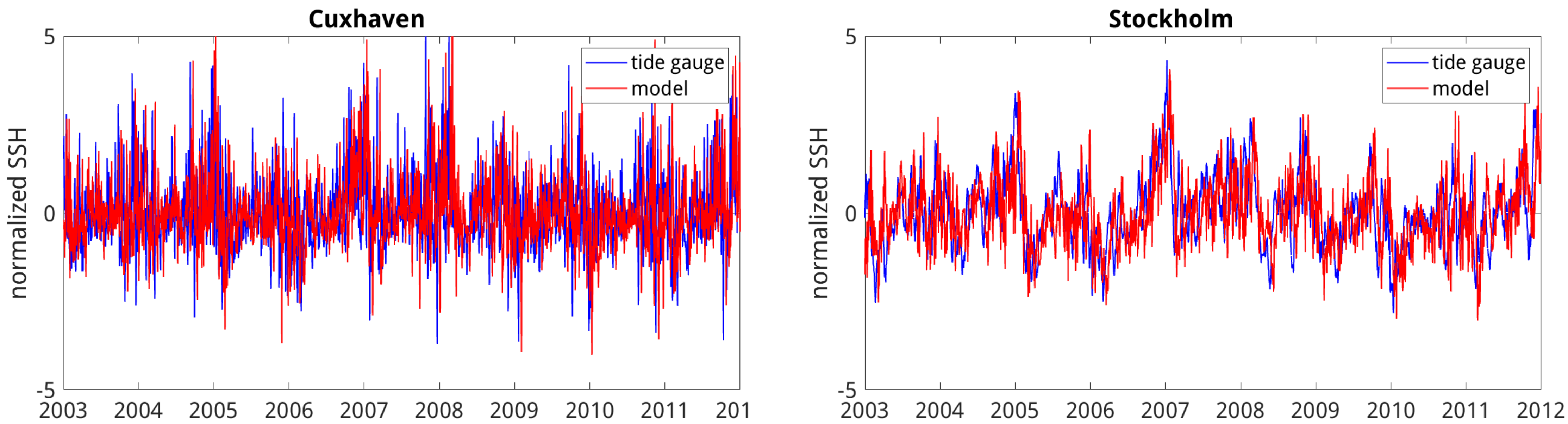
- Daily sea level anomalies (SLA) from tide gauges from the Joint Archive for Sea Level

Coherence between model and tide gauge SSH split in frequency



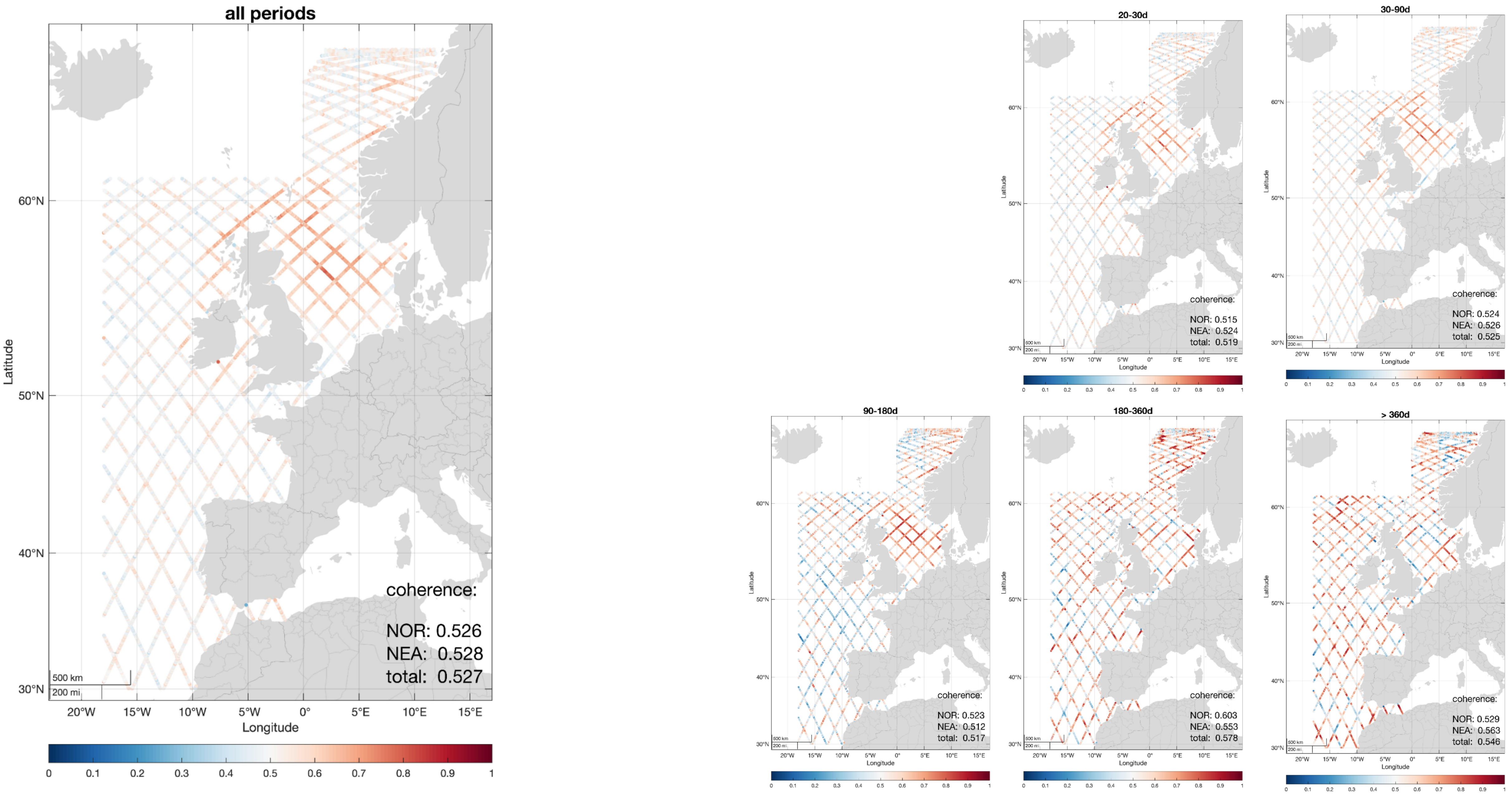
Coherence between tide gauge and model total SSH

	2d-30d	30d-90d	90d-182d	182d-574d	>574d
Vardo	0.57	0.59	0.61	0.83	0.96
Honningsvag	0.56	0.52	0.6	0.82	0.91
Andenes	0.64	0.48	0.59	0.85	0.89
Rorvik	0.68	0.54	0.7	0.87	0.83
Maloy	0.68	0.62	0.7	0.83	0.69
Tregde	0.54	0.61	0.49	0.78	0.71
Goteborgorsh.	0.63	0.8	0.84	0.92	0.95
Hornbaek	0.71	0.79	0.84	0.92	0.83
Gedser	0.83	0.78	0.47	0.78	0.9
Stockholm	0.64	0.9	0.92	0.97	0.99
Cuxhaven	0.84	0.87	0.82	0.94	0.87
Lerwick	0.52	0.46	0.5	0.56	0.2
Stornoway	0.74	0.47	0.48	0.37	0.45
Newlyn, Cornwall	0.66	0.45	0.37	0.42	0.11
Brest	0.72	0.64	0.28	0.62	0.71
La Coruna	0.63	0.64	0.41	0.6	0.72
Ponta Delgada	0.53	0.57	0.48	0.59	0.68
Gibraltar	0.47	0.51	0.61	0.33	0.69
Ceuta	0.59	0.56	0.42	0.78	0.55
Marseille	0.66	0.62	0.5	0.71	0.61
Funchal	0.5	0.54	0.68	0.78	0.52
Tenerife	0.5	0.46	0.73	0.82	0.45
Las Palmas	0.53	0.47	0.61	0.74	0.7
Palmeira	0.52	0.49	0.66	0.83	0.76
Dakar	0.52	0.43	0.46	0.31	0.14



Cuxhaven
Stockholm
tide gauge
model
normalized SSH
5
0
-5
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012

Coherence between model and altimetric SSH split in frequency



Decomposition of **total** sea surface height anomalies

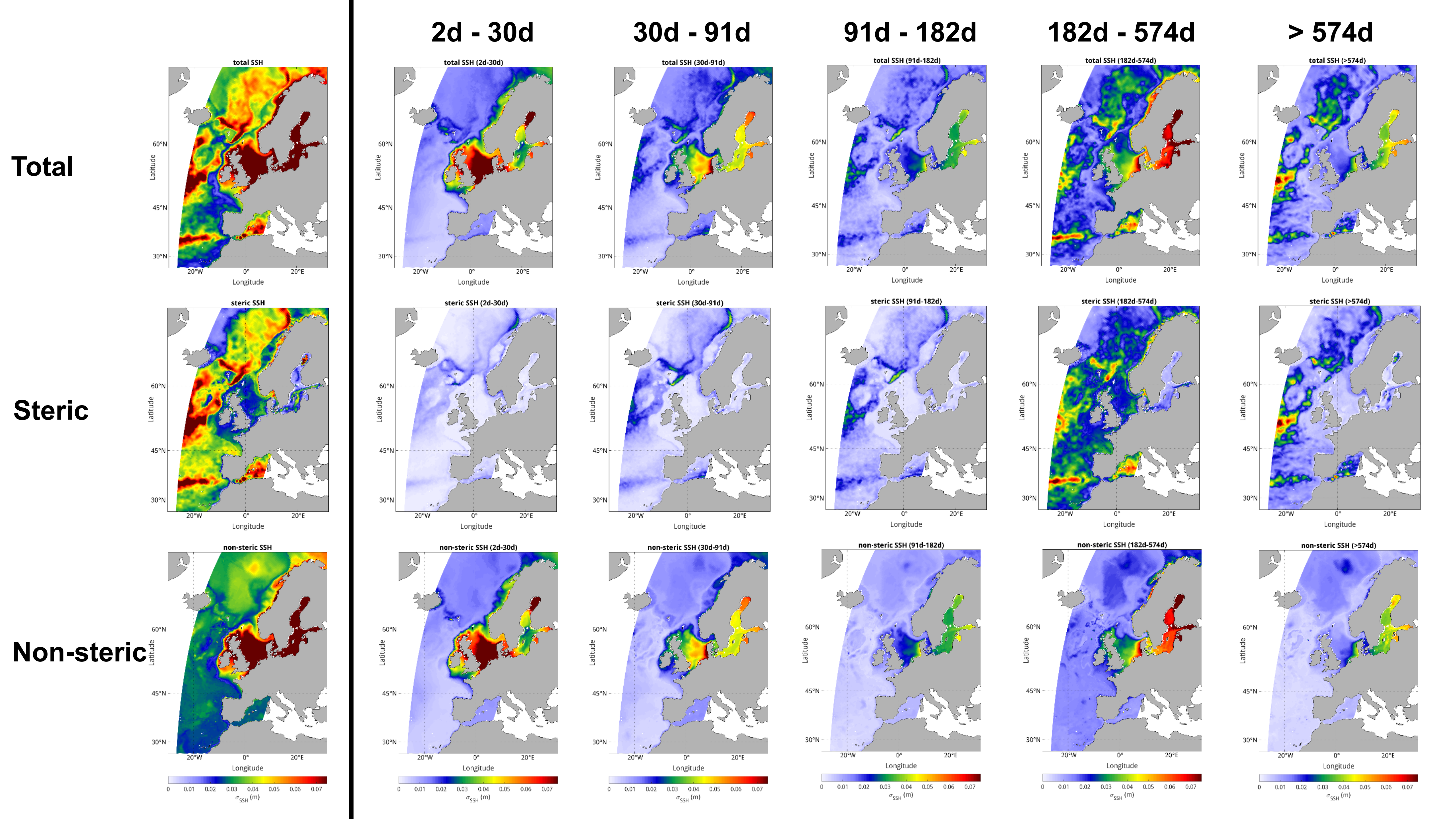
total = steric (density) + non-steric (mass)

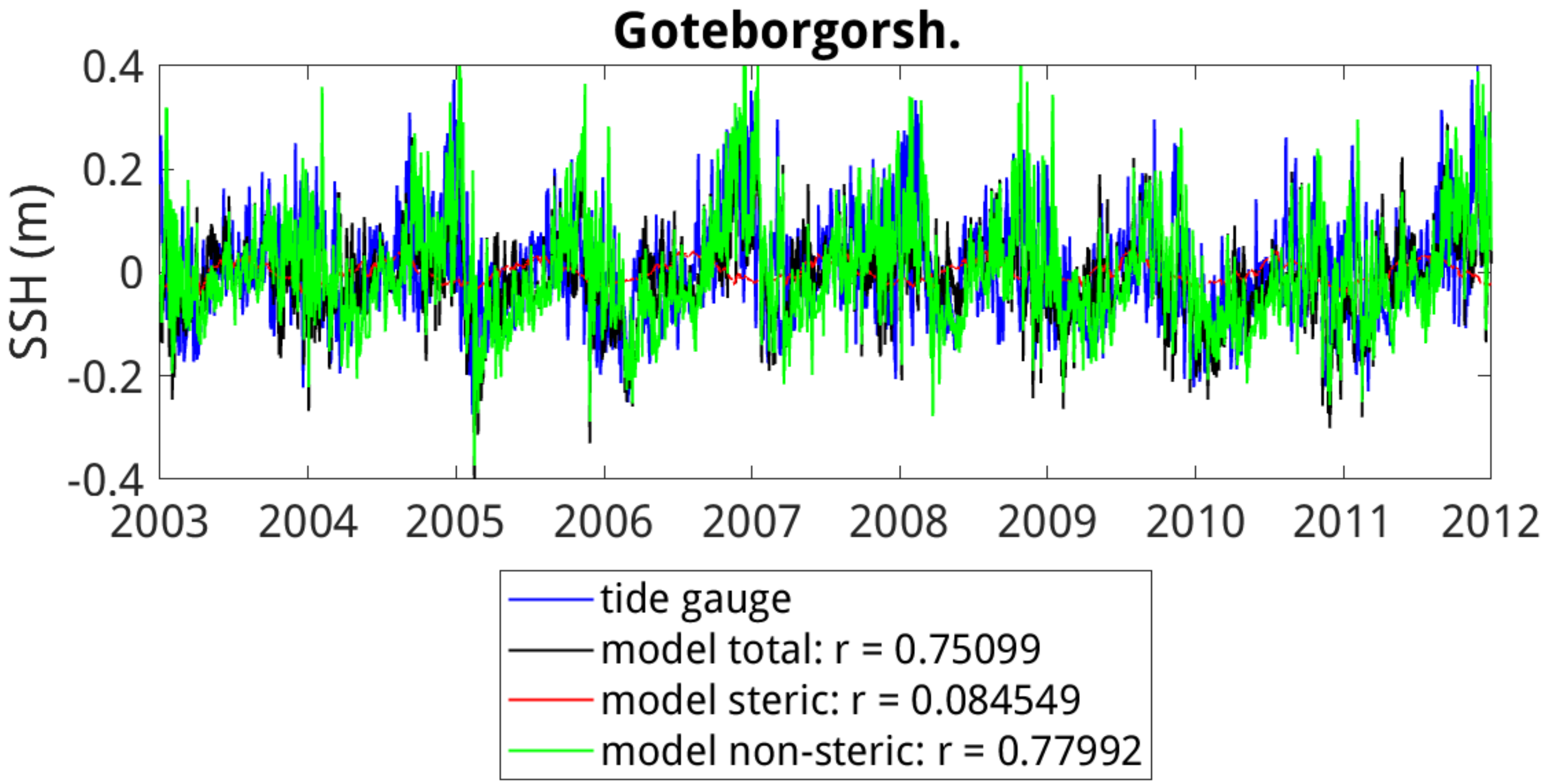
$$\eta = \eta_s + \frac{p_b}{g\rho_0}$$

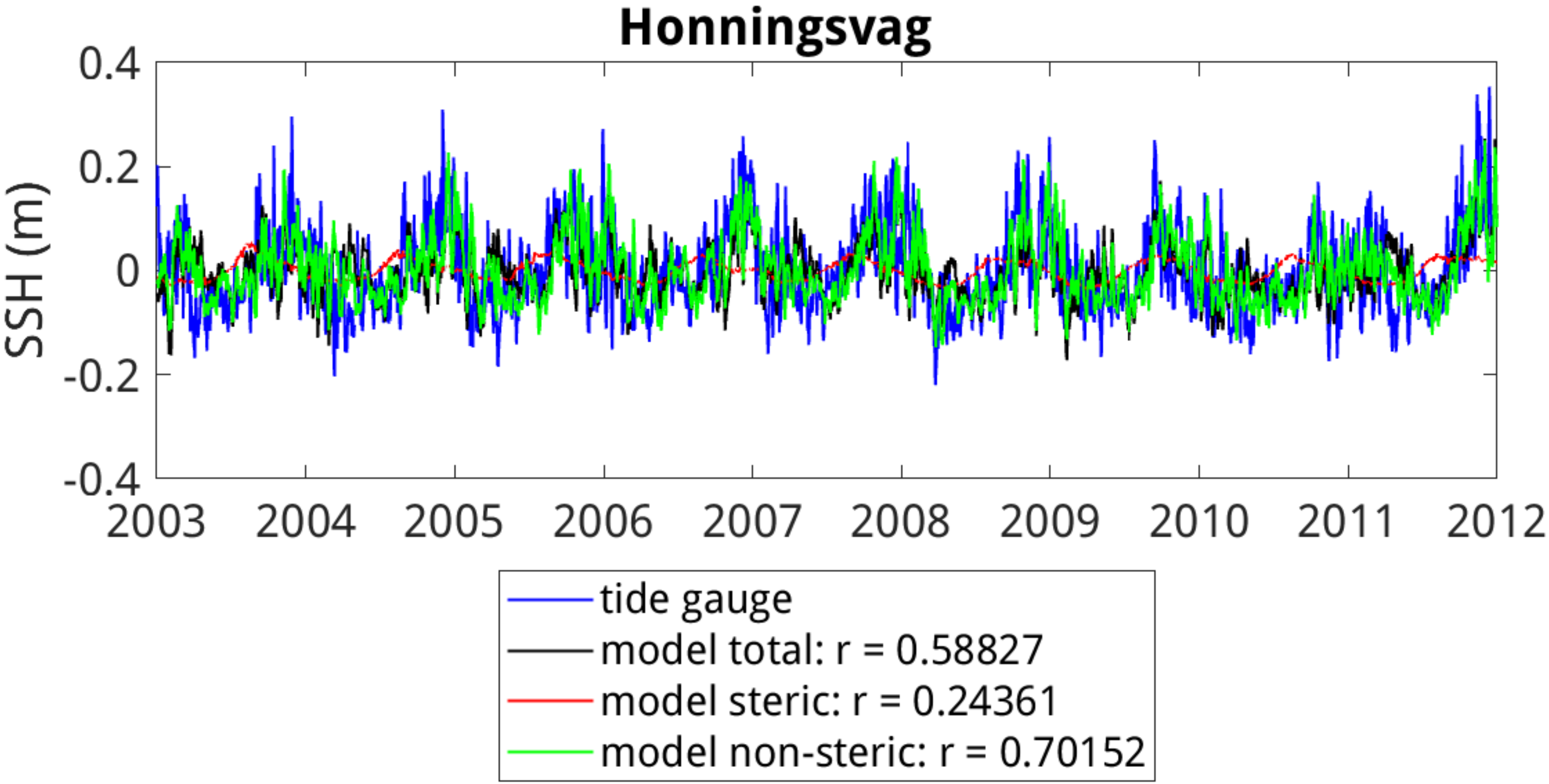
↓

steric = thermosteric (temperature) + halosteric (salinity)

$$\eta_s \simeq \eta_t + \eta_h = -\int_{-H}^{0} \frac{\rho(T,\bar{S})}{\rho_0} dz - \int_{-H}^{0} \frac{\rho(\bar{T},S)}{\rho_0} dz,$$


2d - 30d
30d - 91d
91d - 182d
182d - 574d
> 574d
Total
Steric
Non-steric
total SSH
total SSH (2d-30d)
total SSH (30d-91d)
total SSH (91d-182d)
total SSH (182d-574d)
total SSH (>574d)
steric SSH
steric SSH (2d-30d)
steric SSH (30d-91d)
steric SSH (91d-182d)
steric SSH (182d-574d)
steric SSH (>574d)
non-steric SSH
non-steric SSH (2d-30d)
non-steric SSH (30d-91d)
non-steric SSH (91d-182d)
non-steric SSH (182d-574d)
non-steric SSH (>574d)
Latitude
Longitude
60°N
45°N
30°N
20°W
0°
20°E
0 0.01 0.02 0.03 0.04 0.05 0.06 0.07
σ_{SSH} (m)


Goteborgorsh.
SSH (m)
0.4
0.2
0
-0.2
-0.4
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
tide gauge
model total: r = 0.75099
model steric: r = 0.084549
model non-steric: r = 0.77992


Honningsvag
SSH (m)
0.4
0.2
0
-0.2
-0.4
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
tide gauge
model total: r = 0.58827
model steric: r = 0.24361
model non-steric: r = 0.70152

Coherence between model and tide gauge sea level split by frequency and contribution

Coherence between tide gauge and model total SSH

	2d-30d	30d-90d	90d-182d	182d-574d	>574d
Vardo	0.57	0.59	0.61	0.83	0.96
Honningsvag	0.56	0.52	0.6	0.82	0.91
Andenes	0.64	0.48	0.59	0.85	0.89
Rorvik	0.68	0.54	0.7	0.87	0.83
Maloy	0.68	0.62	0.7	0.83	0.69
Tregde	0.54	0.61	0.49	0.78	0.71
Goteborgorsh.	0.63	0.8	0.84	0.92	0.95
Hornbaek	0.71	0.79	0.84	0.92	0.83
Gedser	0.83	0.78	0.47	0.78	0.9
Stockholm	0.64	0.9	0.92	0.97	0.99
Cuxhaven	0.84	0.87	0.82	0.94	0.87
Lerwick	0.52	0.46	0.5	0.56	0.2
Stornoway	0.74	0.47	0.48	0.37	0.45
Newlyn, Cornwall	0.66	0.45	0.37	0.42	0.11
Brest	0.72	0.64	0.28	0.62	0.71
La Coruna	0.63	0.64	0.41	0.6	0.72
Ponta Delgada	0.53	0.57	0.48	0.59	0.68
Gibraltar	0.47	0.51	0.61	0.33	0.69
Ceuta	0.59	0.56	0.42	0.78	0.55
Marseille	0.66	0.62	0.5	0.71	0.61
Funchal	0.5	0.54	0.68	0.78	0.52
Tenerife	0.5	0.46	0.73	0.82	0.45
Las Palmas	0.53	0.47	0.61	0.74	0.7
Palmeira	0.52	0.49	0.66	0.83	0.76
Dakar	0.52	0.43	0.46	0.31	0.14

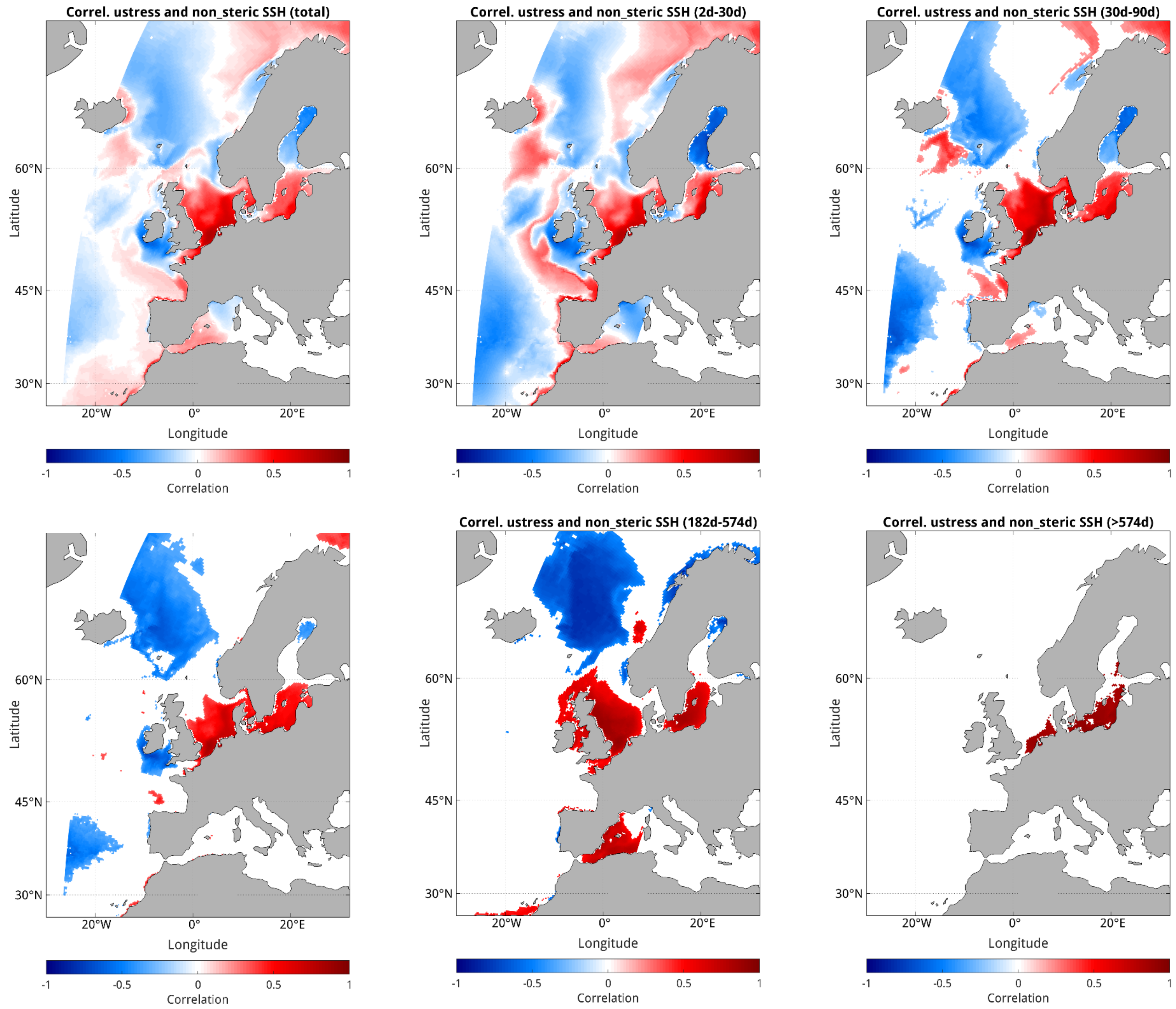
Coherence between tide gauge and model steric SSH

	2d-30d	30d-90d	90d-182d	182d-574d	>574d
Vardo	0.5	0.48	0.42	0.73	0.58
Honningsvag	0.52	0.47	0.42	0.82	0.65
Andenes	0.51	0.39	0.62	0.76	0.56
Rorvik	0.54	0.55	0.5	0.68	0.58
Maloy	0.5	0.56	0.42	0.79	0.76
Tregde	0.49	0.58	0.52	0.64	0.75
Goteborgorsh.	0.51	0.47	0.54	0.65	0.82
Hornbaek	0.51	0.6	0.71	0.66	0.73
Gedser	0.58	0.63	0.71	0.54	0.71
Stockholm	0.55	0.56	0.65	0.66	0.15
Cuxhaven	0.48	0.46	0.74	0.73	0.36
Lerwick	0.51	0.5	0.44	0.39	0.35
Stornoway	0.52	0.58	0.65	0.61	0.32
Newlyn, Cornwall	0.52	0.63	0.52	0.53	0.47
Brest	0.52	0.62	0.34	0.49	0.6
La Coruna	0.48	0.56	0.5	0.53	0.26
Ponta Delgada	0.49	0.54	0.63	0.55	0.53
Gibraltar	0.53	0.48	0.45	0.71	0.56
Ceuta	0.5	0.47	0.38	0.82	0.53
Marseille	0.55	0.46	0.54	0.51	0.2
Funchal	0.49	0.39	0.54	0.66	0.86
Tenerife	0.49	0.44	0.74	0.88	0.49
Las Palmas	0.56	0.47	0.63	0.82	0.64
Palmeira	0.55	0.6	0.62	0.85	0.91
Dakar	0.56	0.5	0.45	0.46	0.15

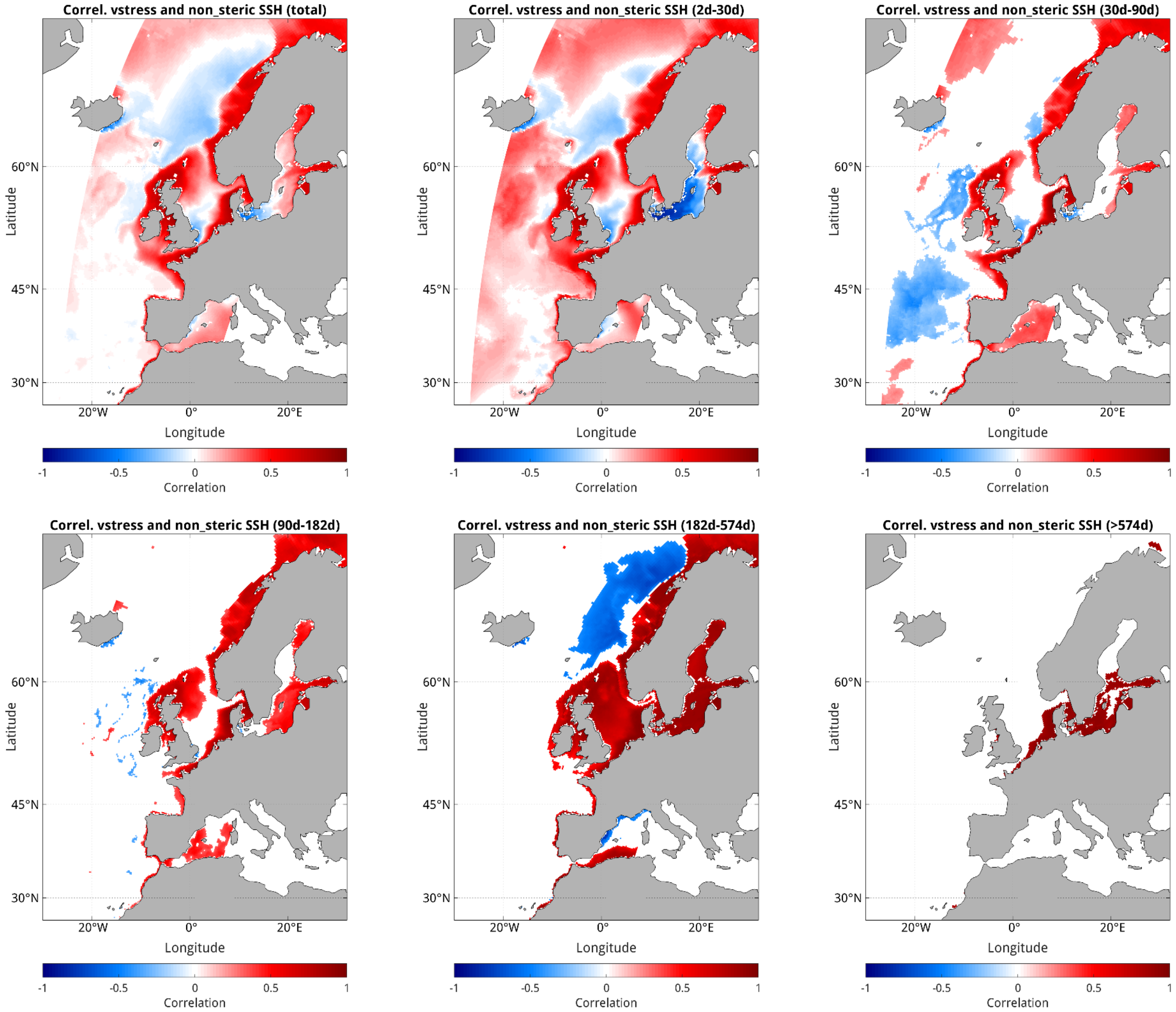
Coherence between tide gauge and model non-steric SSH

	2d-30d	30d-90d	90d-182d	182d-574d	>574d
Vardo	0.58	0.56	0.63	0.92	0.95
Honningsvag	0.56	0.5	0.65	0.89	0.96
Andenes	0.64	0.49	0.63	0.91	0.92
Rorvik	0.68	0.55	0.82	0.96	0.83
Maloy	0.68	0.62	0.78	0.94	0.77
Tregde	0.54	0.57	0.55	0.92	0.86
Goteborgorsh.	0.63	0.79	0.94	0.95	0.94
Hornbaek	0.71	0.8	0.9	0.94	0.85
Gedser	0.83	0.79	0.66	0.69	0.85
Stockholm	0.65	0.89	0.92	0.97	0.98
Cuxhaven	0.84	0.87	0.9	0.97	0.91
Lerwick	0.52	0.44	0.67	0.43	0.38
Stornoway	0.74	0.47	0.47	0.78	0.5
Newlyn, Cornwall	0.66	0.46	0.48	0.5	0.14
Brest	0.72	0.66	0.73	0.87	0.75
La Coruna	0.63	0.64	0.62	0.81	0.65
Ponta Delgada	0.53	0.59	0.44	0.76	0.61
Gibraltar	0.48	0.53	0.56	0.44	0.39
Ceuta	0.61	0.54	0.68	0.75	0.3
Marseille	0.65	0.64	0.68	0.81	0.82
Funchal	0.53	0.61	0.69	0.84	0.44
Tenerife	0.5	0.56	0.66	0.76	0.51
Las Palmas	0.53	0.58	0.52	0.84	0.25
Palmeira	0.52	0.53	0.42	0.78	0.75
Dakar	0.51	0.38	0.58	0.27	0.21

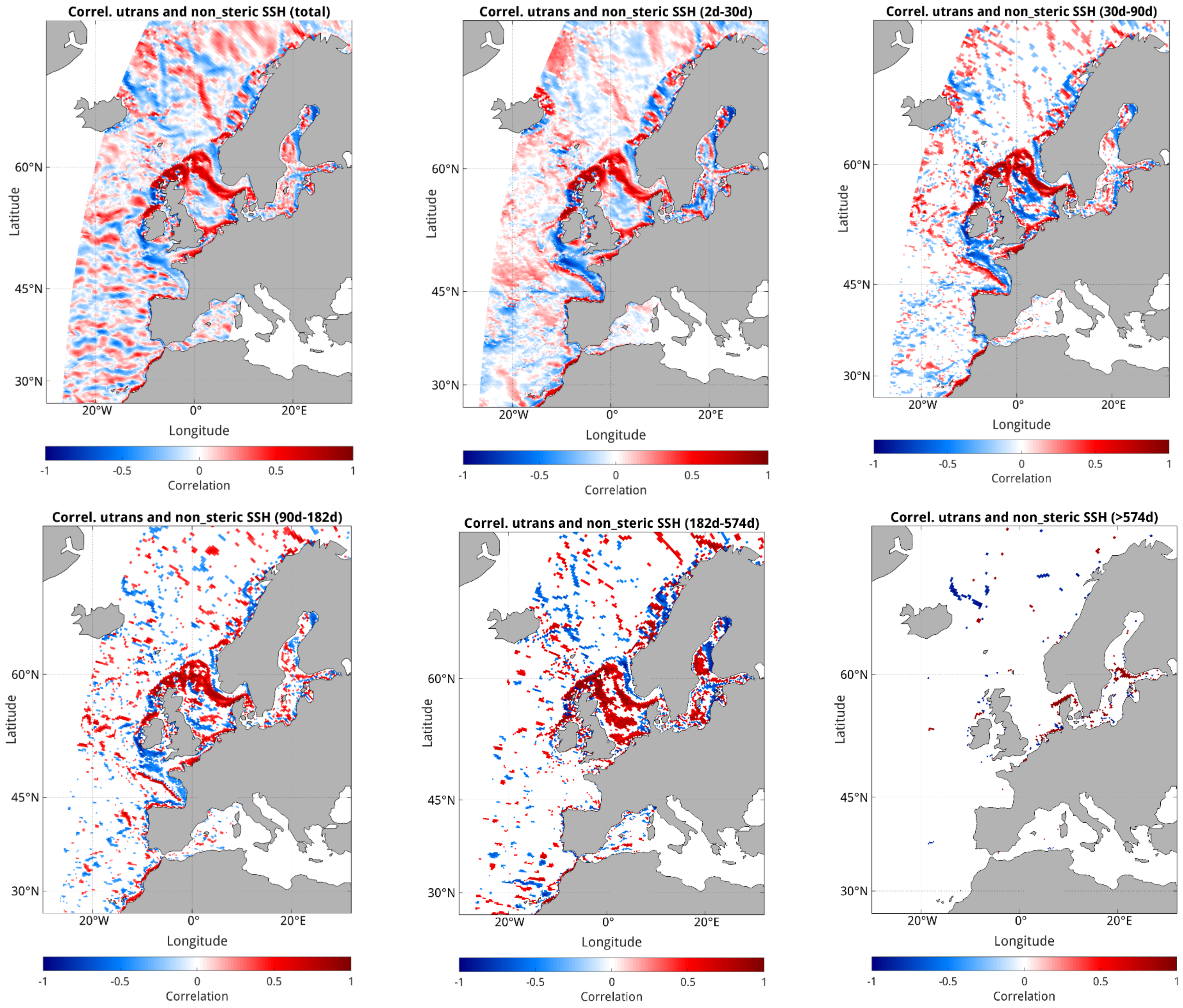
Forcing of **non-steric** SSH: zonal wind stress



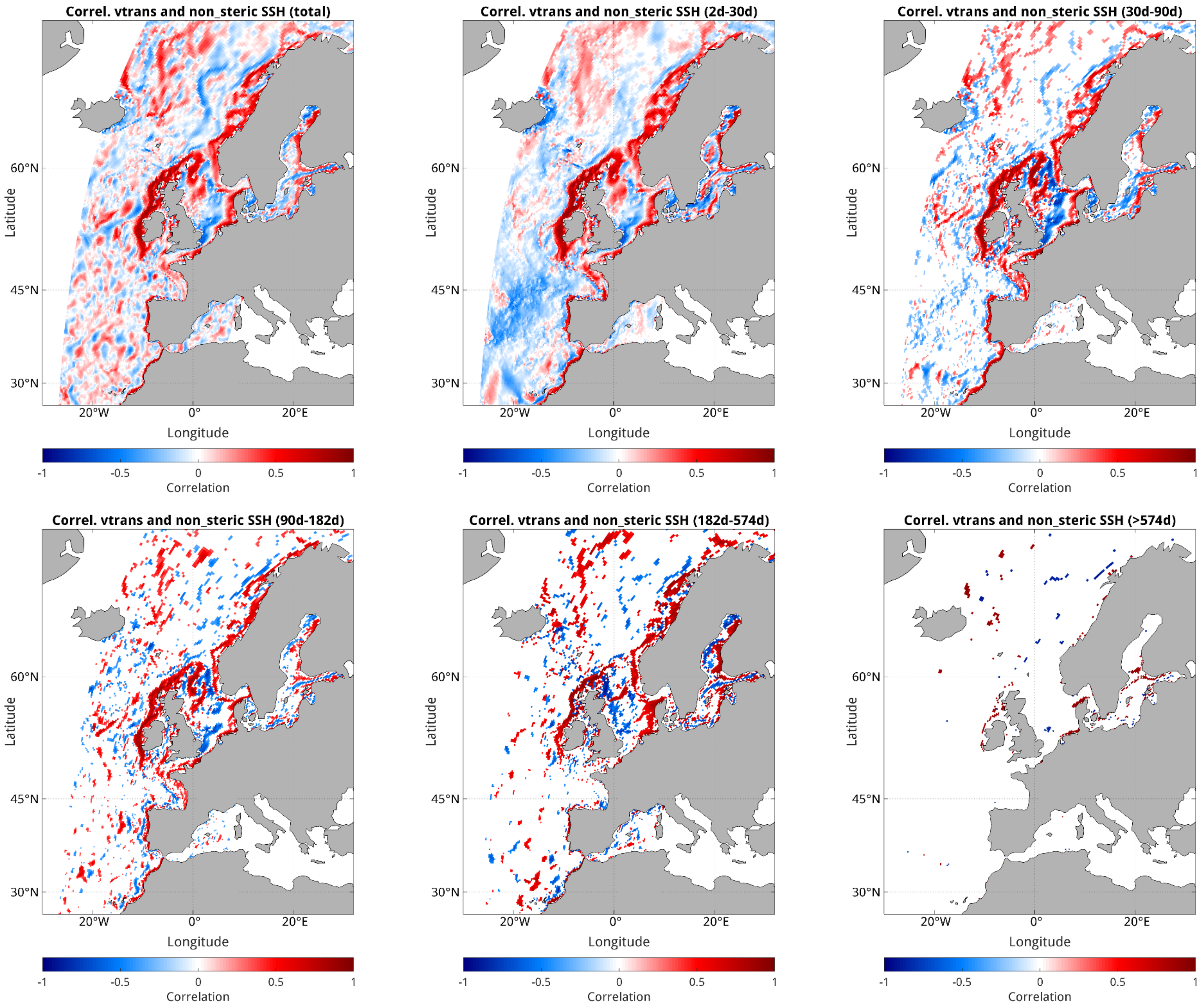
Forcing of **non-steric** SSH: meridional wind stress



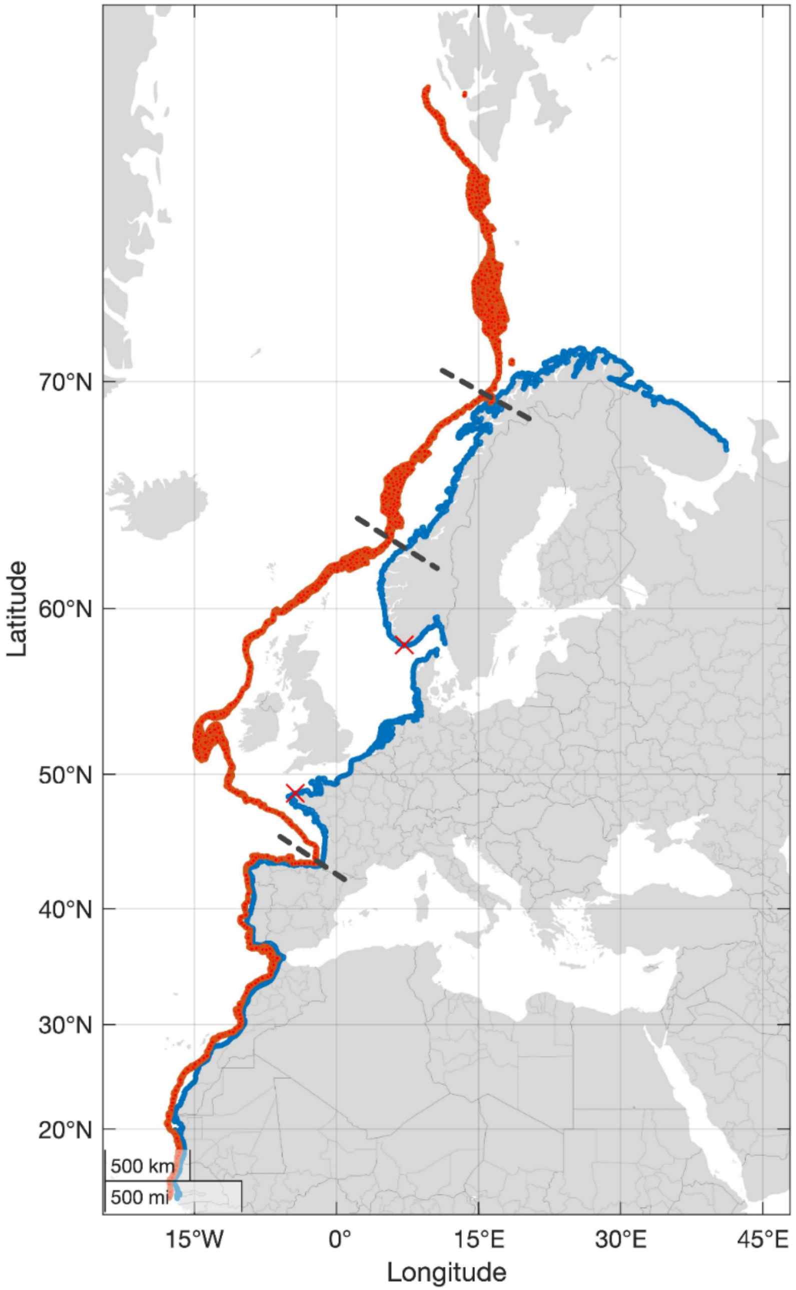
Forcing of **non-steric** SSH: depth-integrated zonal transport

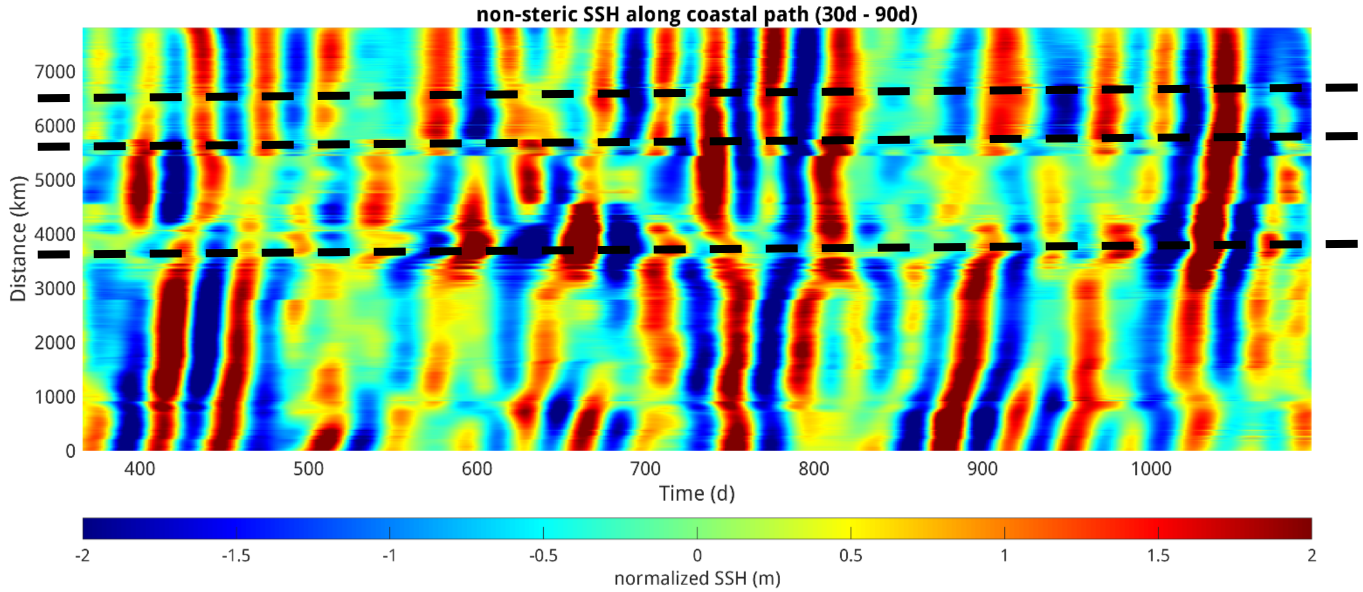


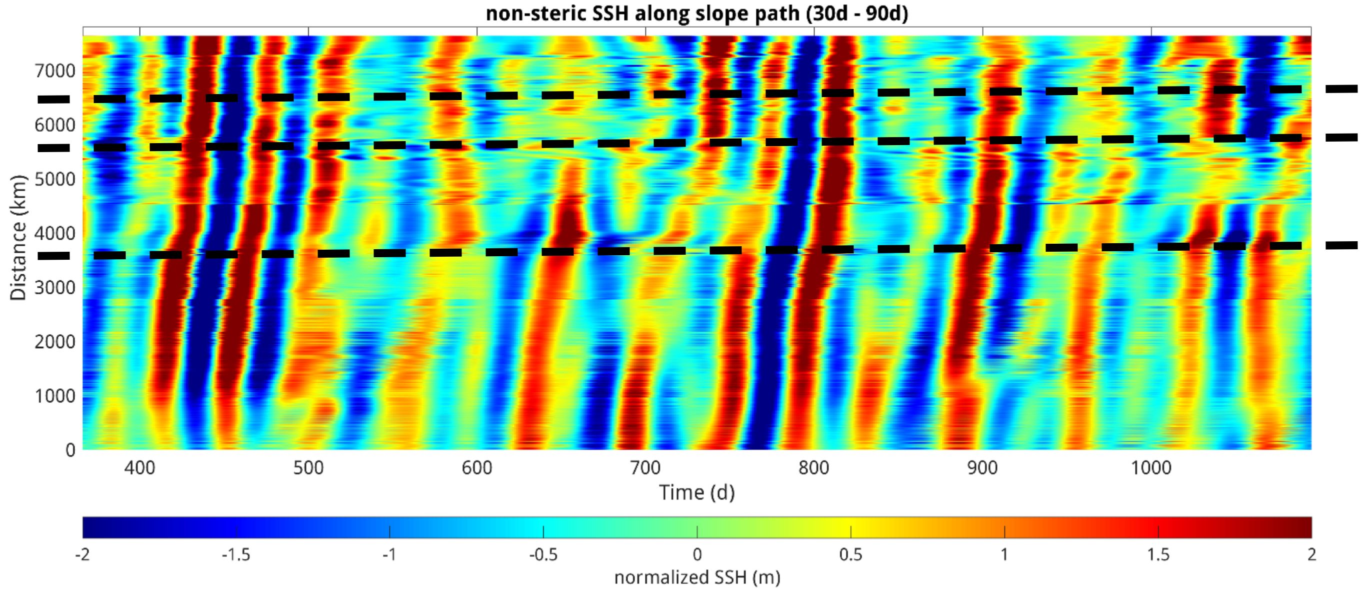
Forcing of **non-steric** SSH: depth-integrated meridional transport



Forcing of **non-steric** sea surface height variability: coastal trapped waves







Conclusions

- Overall significant coherence between model and altimeter/tide gauge observations over all periods.

  - Non-steric SSH is larger contribution in the North Sea and along Norwegian coast for all frequency bands.

  - Steric contribution to SSH is larger in southern locations (and in islands). Maybe due to weak wind/barotropic forcing?

- Zonal wind stress is the main driver at high-frequency in the North Sea and La Coruna and meridional wind stress along the whole meridional coastline (e.g. in Cuxhaven and Maloy).

- Barotropic transport is important along the west Celtic Sea slope current, along the Norwegian coast, at inflow and outflow regions of the North Sea and in La Coruna.