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Evaluation of the FjordOs-model

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1 Introduction - André/Karina

Provided is an evaluation of the FjordOs-model (*Røed et al.*, 2016). This study is a part of the FjordOs project. FjordOs is a cooperation between MET Norway, University College of Southeast Norway (HSN), The Norwegian Institute for Water Research (NIVA), The Norwegian Coastal Administration (Kystverket), Exxonmobil, Norwegian Defence Research Establishment (FFI), Vestfold, Buskerud, and Østfold county, and AGNES AB Miljøkonsulent.

The evaluation is based on existing observations in the area of interest and results from the FjordOs model (*Røed et al.*, 2016). The observations are gathered from different sources and not carried out as a part of the FjordOs project. The observations include measurements of water level, current measurements, water temperature, and CTD measurements. A short scientific cruise on board the research vessel (R/V) Trygve Braarud in September 2015 provided additional observations of hydrography and trajectories of drifters. These observations are compared with simulated results in *Hjelmervik et al.* (2016).

The aim of this study is to reveal any weaknesses of the FjordOs and clarify the extent to which the model can be trusted.

2 Area of interest - Karina

The area of interest is the Oslofjord including the Drammensfjord (Fig. 1). The Oslofjord is located in Southern Norway with the capital of Norway, Oslo, in the innermost part of the fjord.

The Oslofjord is about 100 km long. About halfway the fjord splits into two branches, the Inner Oslofjord and the Drammensfjord. The width varies from about 25 km at the entrance to about 1-2 km at Drøbak Sound in the Inner Oslofjord and 180 meters at Svelvik in the Drammensfjord.

Numerous smaller and larger islands combined with deeper and shallower basins (Fig. 1) contributes to a complex circulation pattern. In addition several river discharge fresh water into the fjord, including two of Norway's largest rivers, namely Glomma (near Fredrikstad) and Drammenselva (near Drammen).

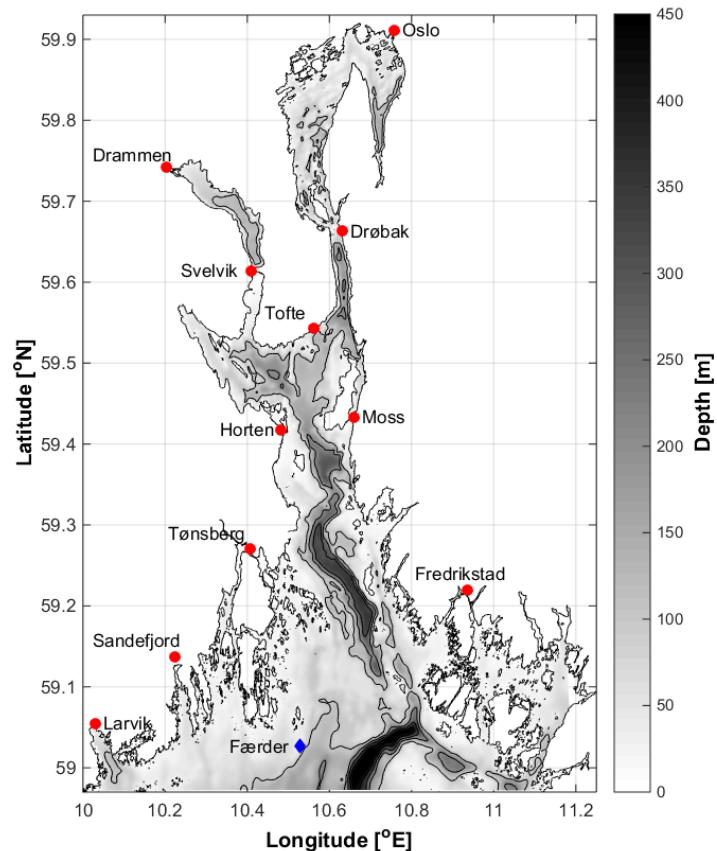


Figure 1: Area of interest.

3 Model - Karina

The FjordOs model is a curvilinear, free-surface, and terrain-following model based on the Rutgers Regional Ocean Modeling System (ROMS) (*Haidvogel et al.*, 2008; *Shchepetkin and McWilliams*, 2003, 2005, 2009) adapted to the Oslofjord (*Røed et al.*, 2016).

The model applies several external inputs, such as atmospheric input, river input, tides, and input of sea level, currents and hydrography at the model's open lateral boundaries, in addition to bathymetry (Fig. 2). Mean values of sea level, currents, and hydrography from the NorKyst800 model (*Albretsen et al.*, 2011) is applied on the open boundary towards Skagerak. The necessary atmospheric input is extracted from the AROME-MetCoOp model that runs operationally at MET Norway (*Müller et al.*, 2015). The tidal input is based on the TPXO Atlantic database (*Egbert and Erofeeva*, 2002) and modified using the measurements at Viker close to the southern boundary. The freshwater discharges from the rivers are based on the discharge data from a database constructed by use of the hydrological model HBV (*Beldring et al.*, 2003). For more details on the FjordOs model, see *Røed et al.* (2016).

The FjordOs model covers the area of interest (Fig. 1). The model period in this study is April 2014 to December 2015.

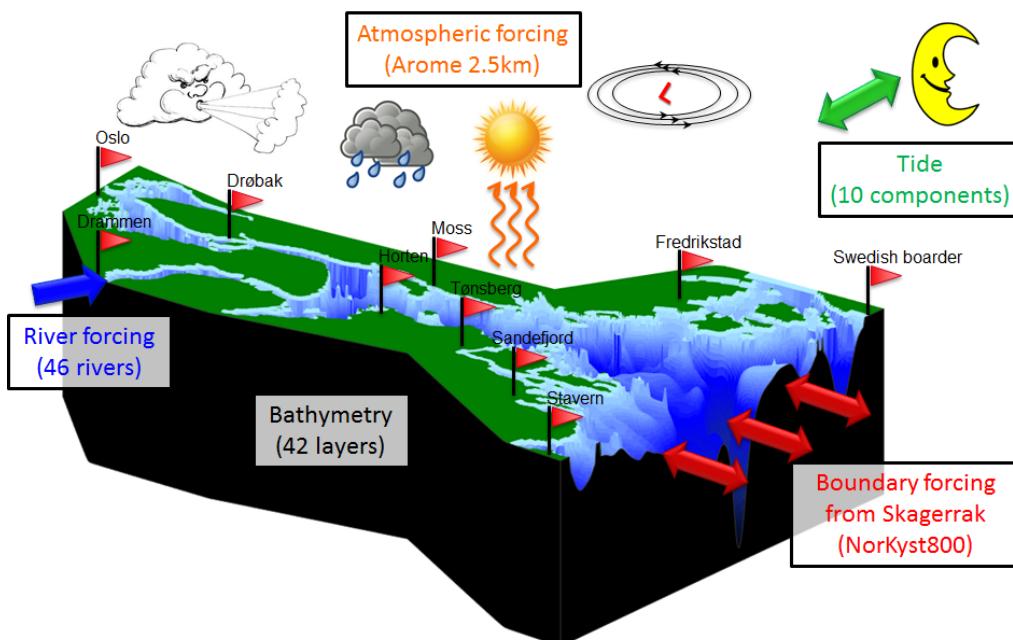


Figure 2: Illustration of external inputs to the FjordOs model.

4 Observed data

Figure 3: Area of interest. Positions for observations are marked. (Karina)

The relevant observed data in the area of interest are scattered in both time and space (Fig. 1). Observations over longer time period includes three stations measuring sea level, one bottom-mounted doppler measuring currents in two depths level, and one device measuring sea temperature. In addition more occasional observations includes CTD measurements, current measurements, ferrybox, some drifter experiments, and sea temperature at three beaches during the summer.

4.1 Water level observations - Karina

The Norwegian Mapping Authority has three permanent stations measuring sea level in the area of interest. The station at Viker is placed close to the open boundary of the model area. The station at Oscarsborg is placed in the middle of the inner Oslofjord, and the station at Oslo is placed in the innermost part of the fjord.

Water level is a result of both baroclinic and barotropic. The difference between high and low tides are ...

4.2 Observations of currents

4.2.1 Currents in two cross sections - André/Karina

Current measurements were performed by Statnett in two cross sections. To be continued

...

4.2.2 Currents at Slagentangen - Karina

Using a bottom-mounted doppler Exxonmobil has measured the currents in two depths since 1997. The device is placed 50-80 meters northwest of Turning Dolphin at the Slagen Refinery (Fig. 4).

4.3 Observations of hydrography

4.3.1 CTD measurements - André

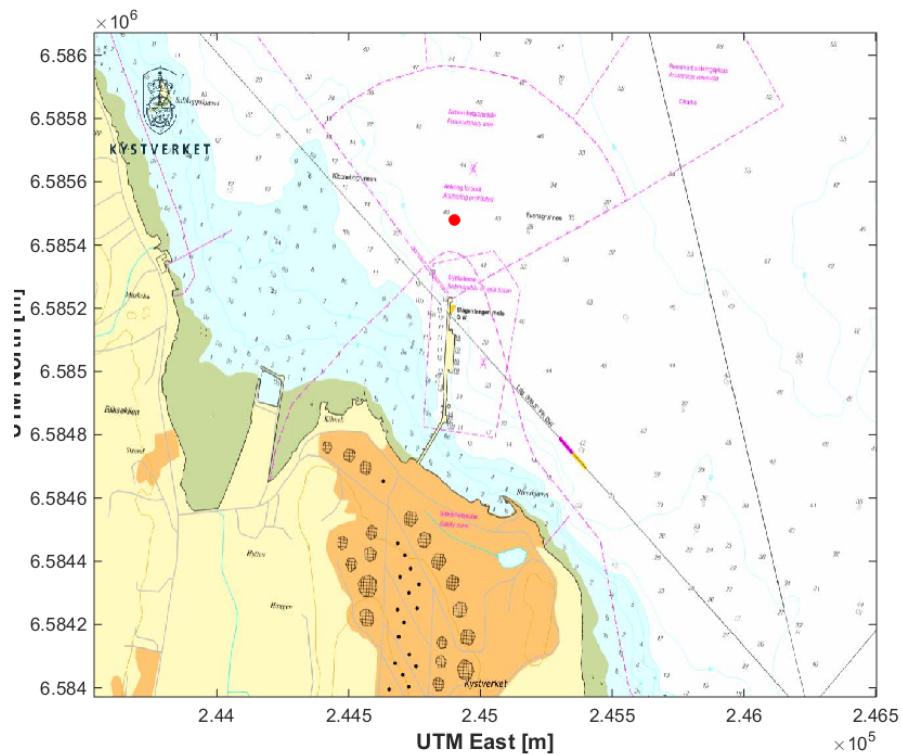


Figure 4: Map of Slagen Refinery. The red dot marks the position corresponding to the extracted simulated data. Source: the Norwegian Coastal Administration

4.3.2 Water temperature 3km south of Åsgårdstrand - Karina

Hourly temperature measurements at one meter depth for the last 10 years have been measured by Scanmar AS located south of Åsgårdstrand. The device has an accuracy of $\pm 0.15^{\circ}\text{C}$ in the range from -5 to $+30^{\circ}\text{C}$.

4.3.3 Beach temperature in the inner Oslofjord - Karina

Temperature measurements at three beaches in the inner Oslofjord (Fig. 5) are performed in a cooperation between Asker and Bærum kommune, and Finnerud Elektronikk. The digital thermometers (Maxim Integrated DS18B20) have an accuracy of $\pm 0.5^{\circ}\text{C}$ and are placed 40 cm beneath the water surface in positions where the water depths are several meters. Temperatures are measured every three hours from 09:00 to 18:00 during the summer months.

With some exceptions the mean temperature is higher at the southern beach, Sjøstrand, than at the northern beach, Storøyodden during the summer (Tab. 1). The observed

temperatures in 2014 were higher than in both 2013 and 2015. The temperature increases up to 2-3 degrees during the day and decreases during the night.

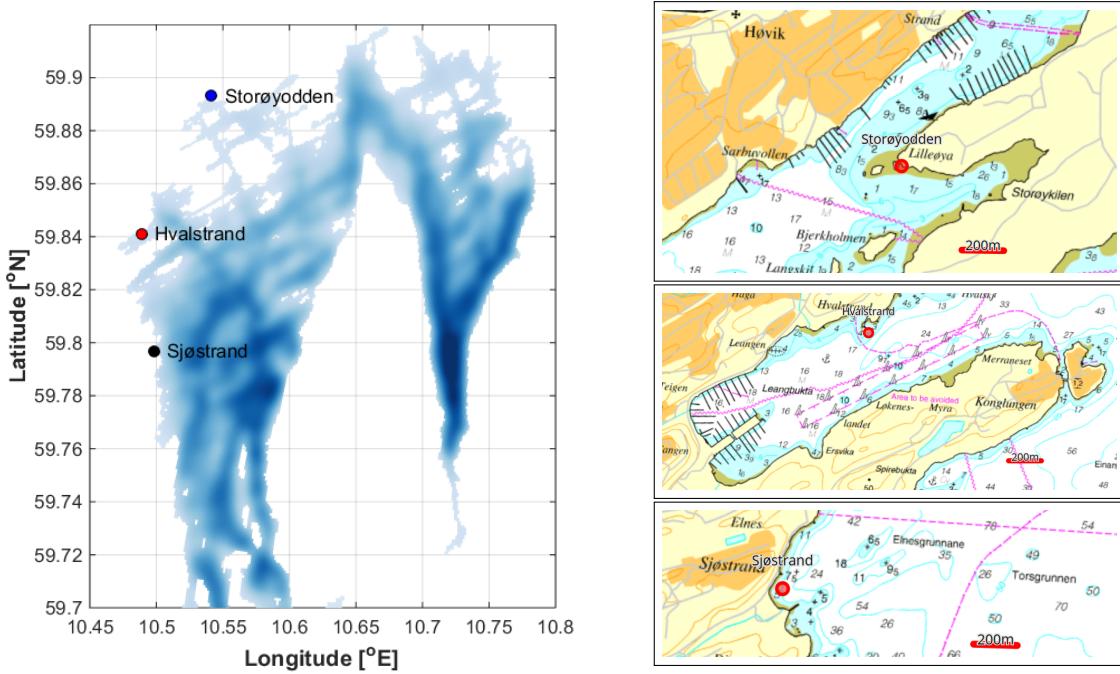


Figure 5: The position of the temperature measurements performed at three beaches in the inner Oslofjord

4.3.4 Ferrybox - André

4.4 Drifting lanes - Karina

Godafoss ...

Table 1: Mean observed temperatures at three beaches in the inner Oslofjord. Only time periods with more than 8 days of observations during the given time period are included.

Time period	Storøyodden			Hvalstrand			Sjøstrand		
	2013	2014	2015	2013	2014	2015	2013	2014	2015
16 - 31 May	13.7	-	11.6	-	-	12.2	-	-	12.8
01 - 15 Jun	15.0	19.0	13.3	15.9	19.4	13.7	-	19.9	14.6
16 - 30 Jun	16.2	17.3	17.1	16.7	17.7	17.5	-	17.9	18.0
01 - 15 Jul	17.8	17.6	18.2	18.3	18.3	19.8	19.4	19.3	-
16 - 31 Jul	20.1	22.2	18.1	19.7	-	18.9	21.2	23.9	18.4
01 - 15 Aug	19.5	21.3	18.0	19.8	21.3	-	20.6	21.7	18.8
16 - 31 Aug	18.9	19.6	19.1	18.9	19.6	19.3	19.5	19.4	19.0
01 - 15 Sep	17.9	18.3	16.1	17.7	18.6	16.5	18.1	18.9	16.2
16 - 30 Sep	-	15.9	14.1	-	16.2	14.1	15.1	16.3	13.7
01 - 15 Oct	-	-	12.0	-	-	11.9	-	-	11.5

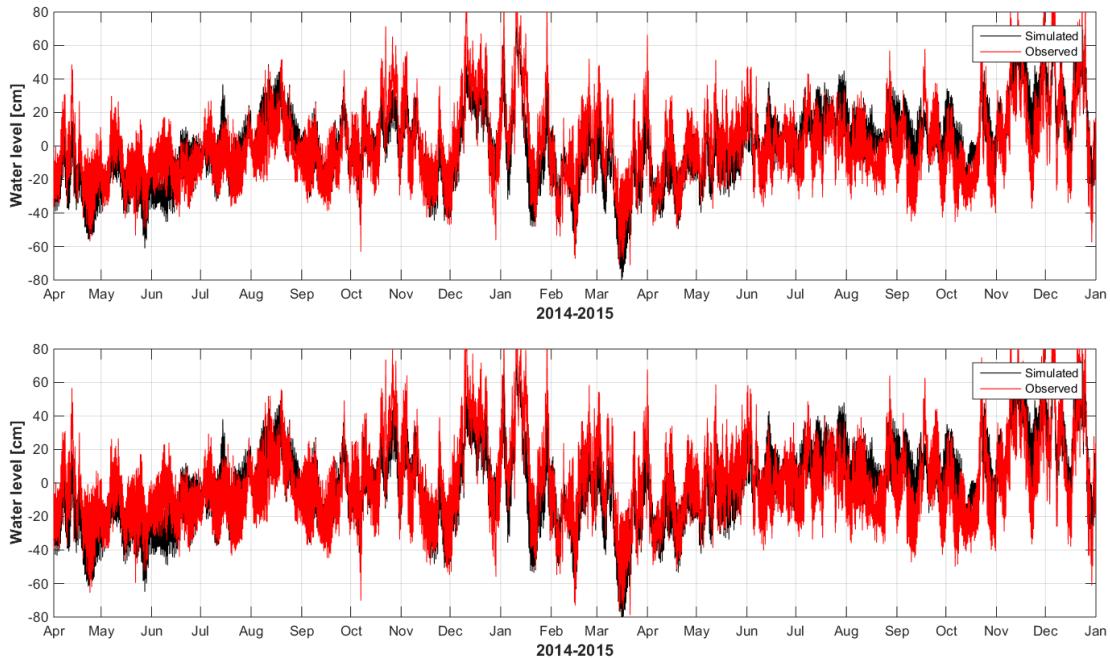


Figure 6: Observed and simulated water level for Viker (upper) and Oscarsborg (lower)

5 Evaluation

5.1 Water level and tide - Karina

Time series from the three permanent stations measuring sea level have been analysed and compared with simulated time series of waterlevel from the same period in time.

Tides are included in the model at the southern open boundary in two ways. The FjordOs model is nested into NorKyst800 through daily mean forced on the boundary. This forcing includes the tidal components with longer periods. In addition 11 components with shorter periods are introduced explicitly using their corresponding amplitudes and phases for both depth integrated currents and water level (ref. tidevannsartikkelen?). The timeseries of tides originating from explicit tidal forcing are in fairly good agreement (Fig. 7, upper, and Fig. 8,upper). The main characteristics of the remaining tidal components are present in both the observed and the simulated timeseries (Fig. 7, lower).

To be continued... Karina (Figurer og tabeller er laget og satt inn, men en del tekst mangler fortsatt)

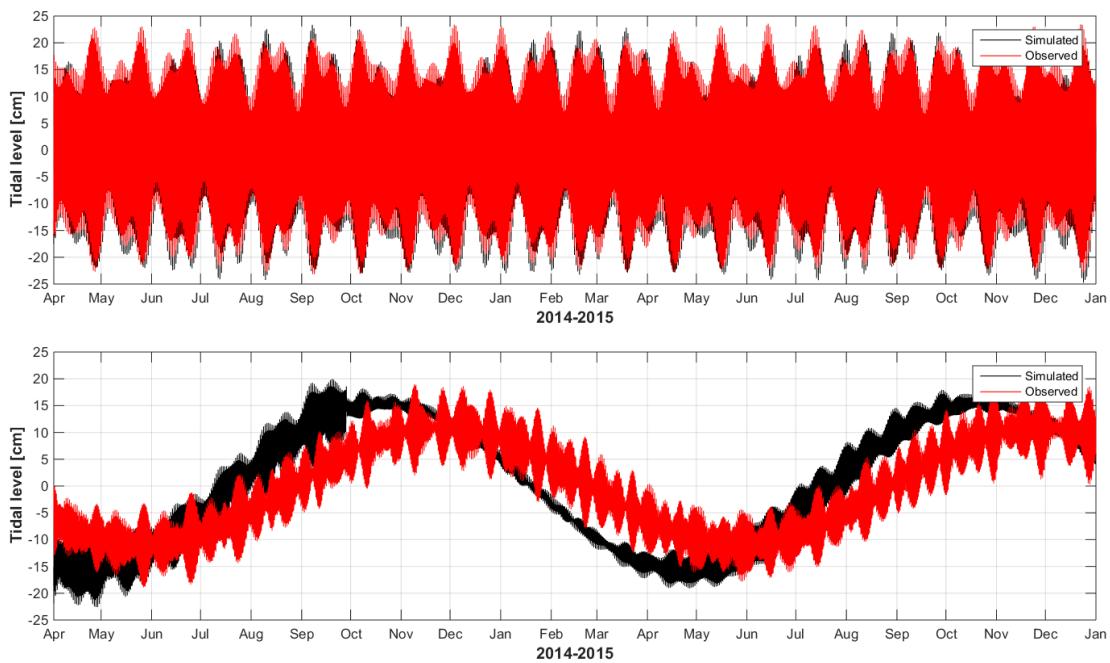


Figure 7: Timeseries at Oscarsborg of the tidal components included (upper) and not included (lower) in the explicit tidal forcing.

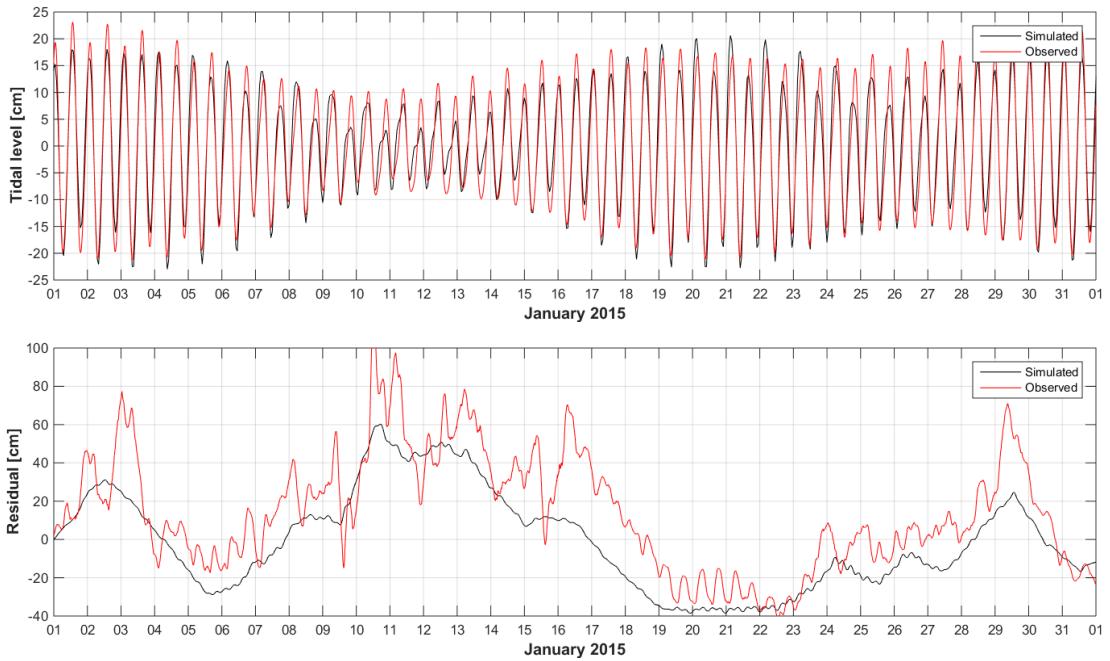


Figure 8: Timeseries of tides originating from explicit tidal forcing (upper) and the residual (lower) at Oscarsborg

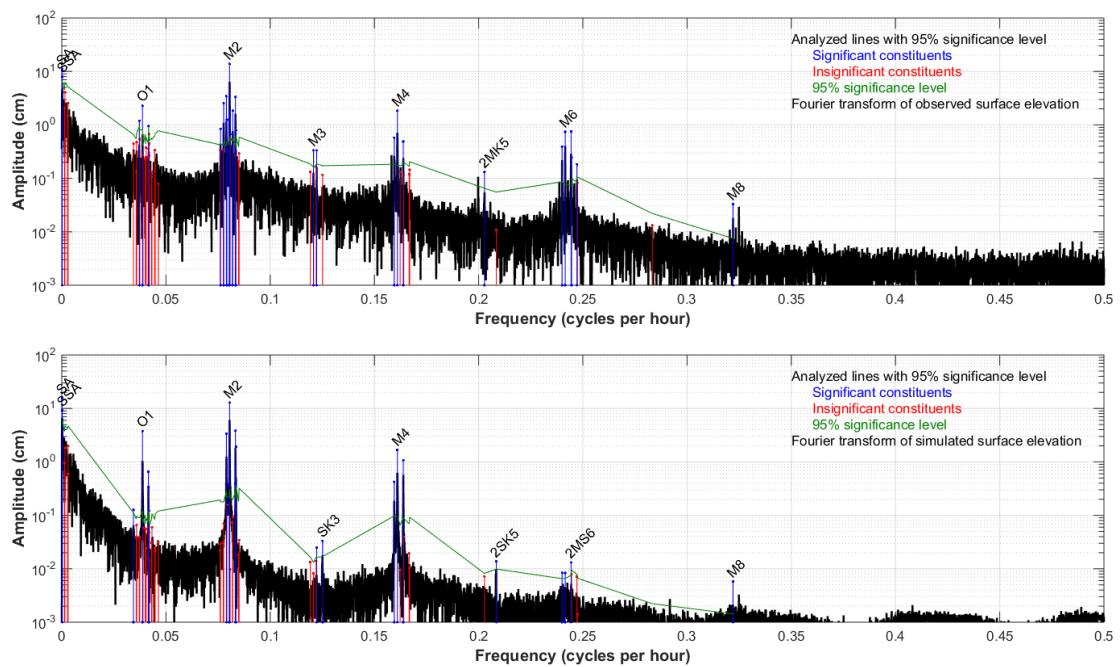


Figure 9: Frequency series of Fourier transformed observed (upper) and simulated (lower) water levels at Oscarsborg

Table 2: Simulated and observed tidal amplitude and phase for selected tidal components.

Comp.	Period [h]	sim/ obs	Viker		Oscarsborg		Oslo		Included in tidal forcing
			amp. [cm]	phase. [deg]	amp. [cm]	phase. [deg]	amp. [cm]	phase. [deg]	
SA	365 days	sim	15.5	284	15.5	286	15.2	286	no
		obs	10	319	11	322	11.3	324	
SSA	182 days	sim	8.8	198	9.2	199	9.3	200	no
		obs	7.5	188	7.9	188	8.2	190	
K2	11.9672	sim	1.6	32	1.9	35	2.1	37	yes
		obs	0.7	46	0.8	66	0.9	67	
S2	12.0000	sim	3.3	87	3.8	91	4.1	92	yes
		obs	2.9	46	3.3	65	3.5	69	
M2	12.4206	sim	11.2	127	12.9	134	13.6	135	yes
		obs	11.9	105	13.8	121	14.4	125	
N2	12.6584	sim	2.9	91	3.4	96	3.6	98	yes
		obs	3	60	3.4	76	3.6	80	
K1	23.9345	sim	0.2	194	0.1	185	0.1	165	yes
		obs	0.4	125	0.7	128	0.8	129	
P1	24.0659	sim	0.6	335	0.7	346	0.7	352	yes
		obs	0.2	123	0.4	100	0.4	95	
O1	25.8193	sim	3.5	347	3.8	348	3.8	349	yes
		obs	2.3	276	2.3	281	2.4	282	
Q1	26.8684	sim	0	177	0	188	0.1	201	no
		obs	1.1	189	1.2	197	1.3	199	
MN4	6.2692	sim	0.2	50	0.4	76	0.6	78	yes
		obs	0.4	249	0.6	289	0.7	297	
M4	6.2103	sim	0.9	37	1.7	61	2.2	65	yes
		obs	1.2	281	1.8	324	2.3	332	
MS4	6.1033	sim	0.5	123	1.1	150	1.4	154	yes
		obs	0.3	360	0.5	44	0.7	56	

5.2 Currents

5.2.1 Currents in two cross sections - André/Karina

To be continued... André?

5.2.2 Current at Slagentangen - Karina

The observed currents at Slagentangen are compared with simulated data from 1st October 2014 until 30th November 2015 at approximately the same location and depth.

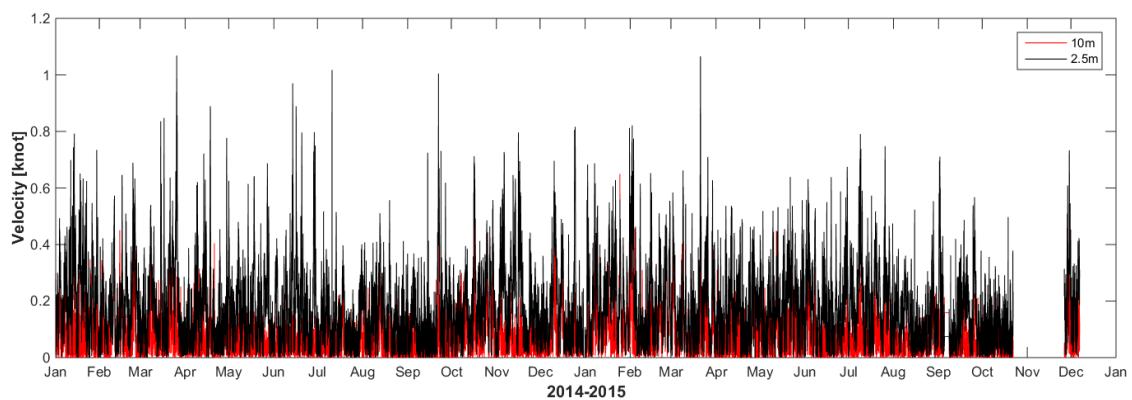


Figure 10: Timeseries of observed velocities at Slagen from 1st of January 2014 to 31st of December 2015.

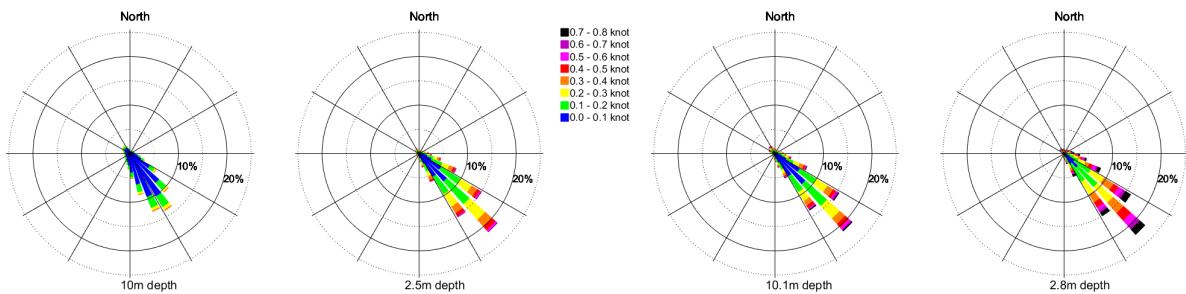


Figure 11: Current roses for observed (left) and simulated (right) velocities at two depths from 1st of October 2014 to 1st of October 2015.

Time series show that the observed velocities varies and follows no striking pattern (Fig. 10). Current roses show that the both the observed and the simulated velocities are stronger in the upper layer (Fig. 11). The simulated velocities are stronger than the observed velocities. This is in accordance with the probability density functions (Fig. 12).

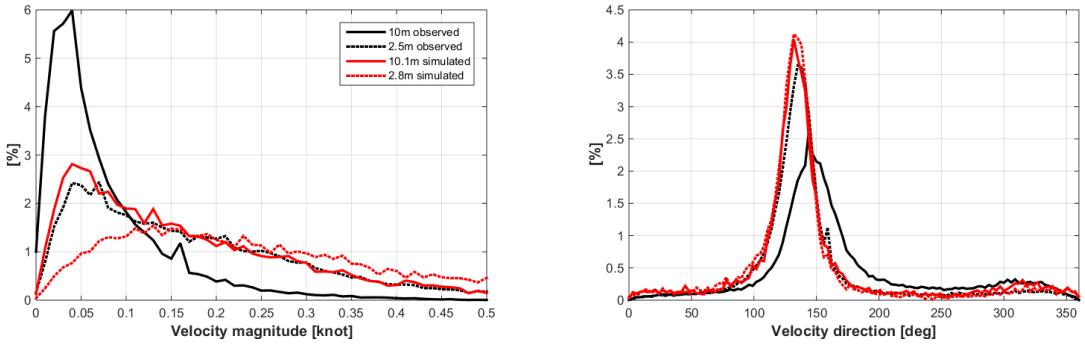


Figure 12: Probability density functions of velocities and directions at Slagen for 1st of October 2014 to 1st of October 2015. The bin width is 0.01 knots for velocity and 3 degrees for direction.

Table 3: Maximum observed velocity at Slagen.

Year	Max. velocity at 10m depth			Max. velocity at 2.5m depth		
	Date	[knots]	[deg]	Date	[knots]	[deg]
2006	21 January	0.81	139	31 October	1.10	140
2007	14 January	0.81	172	21 August	2.00	359
2008	22 March	0.70	149	19 December	1.10	160
2009	17 December	0.87	142	24 March	1.10	139
2010	09 November	0.81	138	09 November	1.05	138
2011	01 January	0.76	146	30 March	1.21	185
2012	05 December	0.75	138	29 May	1.11	140
2013	10 October	0.82	143	10 October	0.95	144
2014	18 April	0.85	147	26 March	1.07	143
2015	24 January	0.65	128	21 March	1.07	141

The maximum velocities are approximately 0.8 and 1.1 knots at 10 and 2.5 meters depth respectively (Tab. 3). During 2014 and 2015 maximum observed velocity at 2.5 meters depth was 1.07 knots in southeast direction (143°N) the 26th of March 2014. The velocity at 10 meters depth was 0.15 knot at the time of maximum velocity at 2.5 meters depth indicating that the velocities are different in the two layers.

The mean directions are to the south east. At approximately 2.5 meters depth the mean directions are 146°N and 141°N for observed and simulated directions respectively which is in fairly good agreement. At approximately 10 meters depth the observed mean direction shifts to 170°N while the simulated mean direction is 149°N . The probability

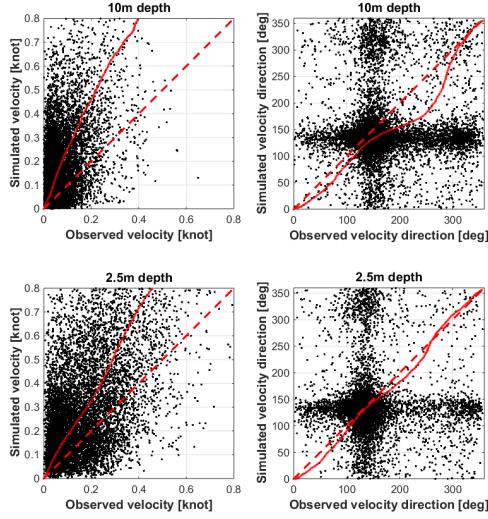


Figure 13: Combined QQ- and scatterplot of observed and simulated current at Slagen from 1st of October 2014 to 1st of October 2015.

density functions reveals that the model captures the distribution of directions in the upper layer, but does not capture the change in direction between the two depths (Fig. 12). The standard deviations at 2.5 and 10 meters are 55 and 66 degrees respectively for the observed directions, and 58 and 65 for the simulated directions.

The scatter plots reveal that the correlation in time is not satisfying (Fig. 13). The model seen to have difficulties with capturing the right phenomena influencing the currents to the right time. This is a well known problem when it comes to forecasting currents. The QQ-plots also confirms that the simulated currents are stronger than the observed currents.

5.3 Hydrography

5.3.1 CTD-measurements - André

To be continued... André

5.3.2 Water temperature 3km south of Åsgårdstrand - Karina

The temperature observations from Scanmar AS are compared with simulated data from 1st October 2014 until 30th November 2015 at the same location at 1.15 meters depth.

Timeseries show that the simulated temperatures are between 2 and 8 degrees lower than the observed temperatures [14]. The model captures the variations in temperature fairly good (Fig. 15). Notice for example the variations in January with around three days period, and the local minimum around 1st of August. (Karina: Her bør det nevnes hva som forårsaker disse variasjonene.)

The probability density functions reveals that not only are the simulated temperatures lower than the observed temperatures, but the variation is larger in the observed temperatures (Fig. 16). The mean of the observed and simulated temperatures are 10.1°C and 5.5°C respectively, while the variances are 27.2°C and 16.4°C respectively.

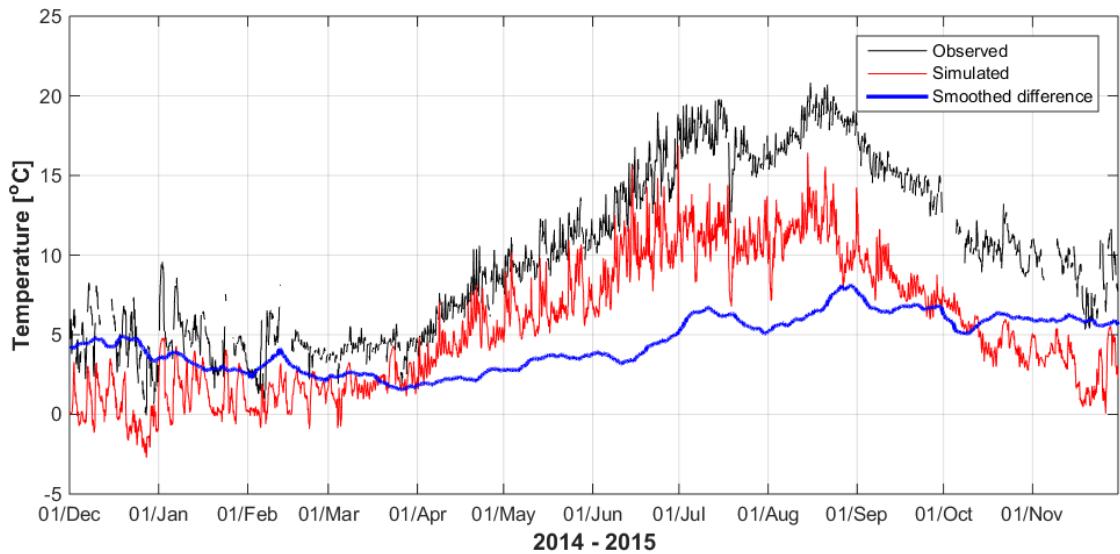


Figure 14: Timeseries of observed and simulated temperature at Åsgådstrand from 1st of December 2014 to 1st of December 2015. The difference is smoothed over 10 days.

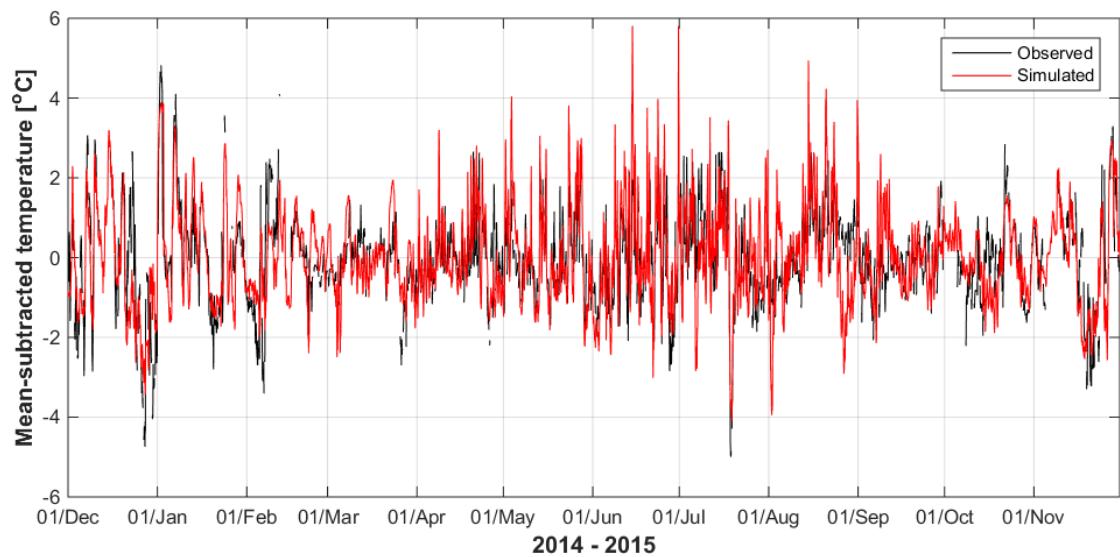


Figure 15: Mean-subtracted timeseries of observed and simulated temperature using a gliding mean of one month.

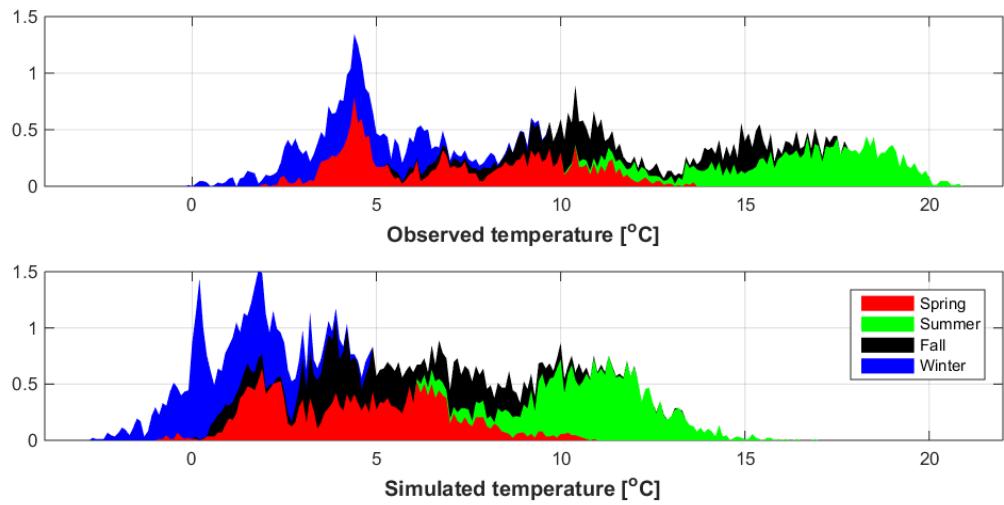


Figure 16: Probability density functions of observed and simulated temperature at Åsgådstrand from 1st of December 2014 to 1st of December 2015.

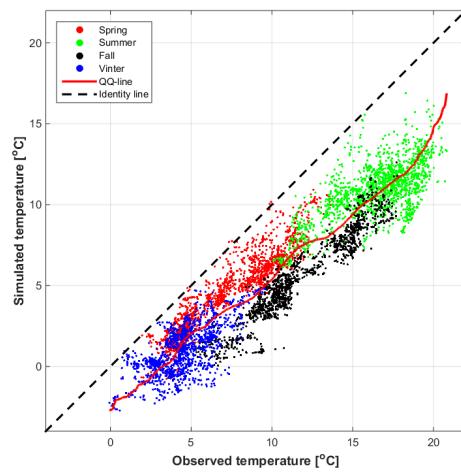


Figure 17: Combined QQ- and scatterplot of observed and simulated temperature at Åsgådstrand from 1st of December 2014 to 1st of December 2015.

5.3.3 Beach temperature in the inner Oslofjord - Karina

The observed and modelled temperature at three beaches in the inner Oslofjord are in relativ good agreement (Fig. 18 - 19). Since the temperature is observed close to the shoreline, near river outlets, and only 40 cm under the surface, the observations are heavily influenced by the weather situation and local circulation patterns. The model is not expected to capture such detailed effects. Still there are similarities between the modelled and the observed temperatures both in temperature level and in fluctuations.

During the summer 2014 the model predicts higher temperatures at Sjøstrand than was observed. The observations in Hvalstrand have some of the same trends as the modelled temperature with temperatures up to 25 degrees. The air temperatures in 2014 was higher than in 2015 and resulted in higher water temperatures, especially in shallow areas.

The temperature differences during the day are larger in the model than in the observations. Temperature is not measured during the night, but only from 09:00 to 18:00, and this might explain some of the differences in fluctuations.

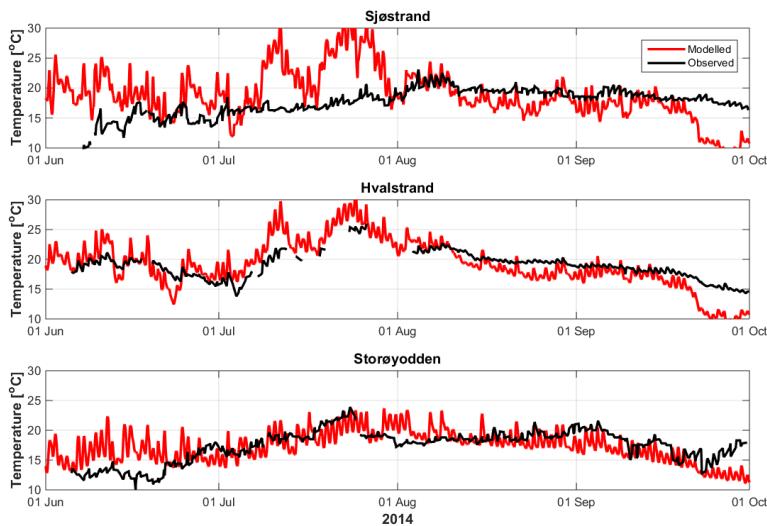


Figure 18: The observed and modelled temperature at three beaches in the inner Oslofjord during the summer 2014

5.3.4 Ferrybox - André?

To be continued... André?

5.3.5 Drifting lanes - Karina/Nils

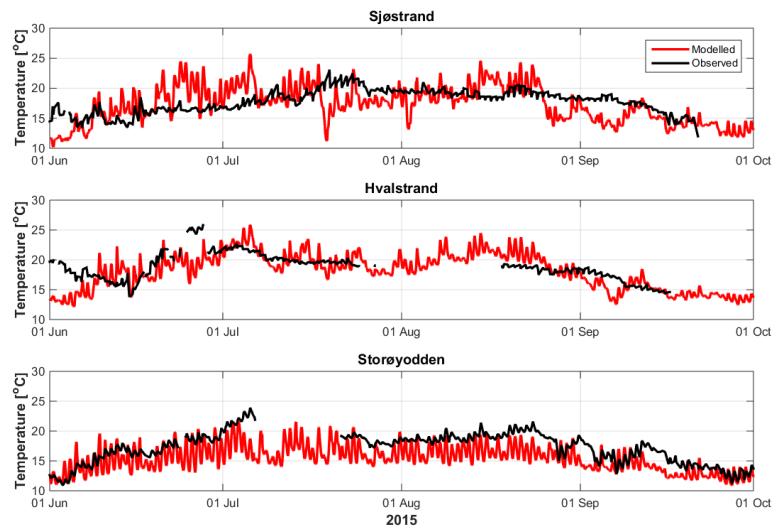


Figure 19: The observed and modelled temperature at three beaches in the inner Oslofjord during the summer 2015

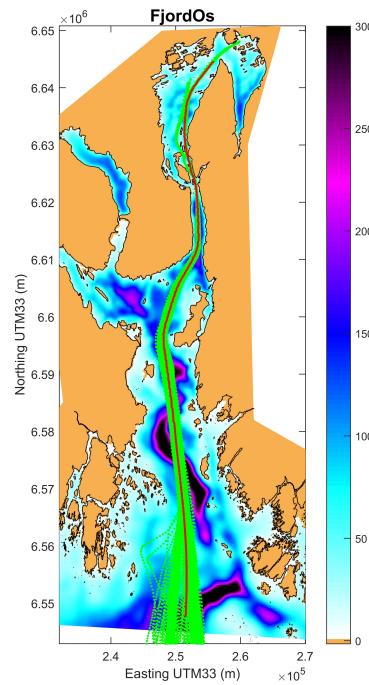


Figure 20: The track of Color Fantasy.

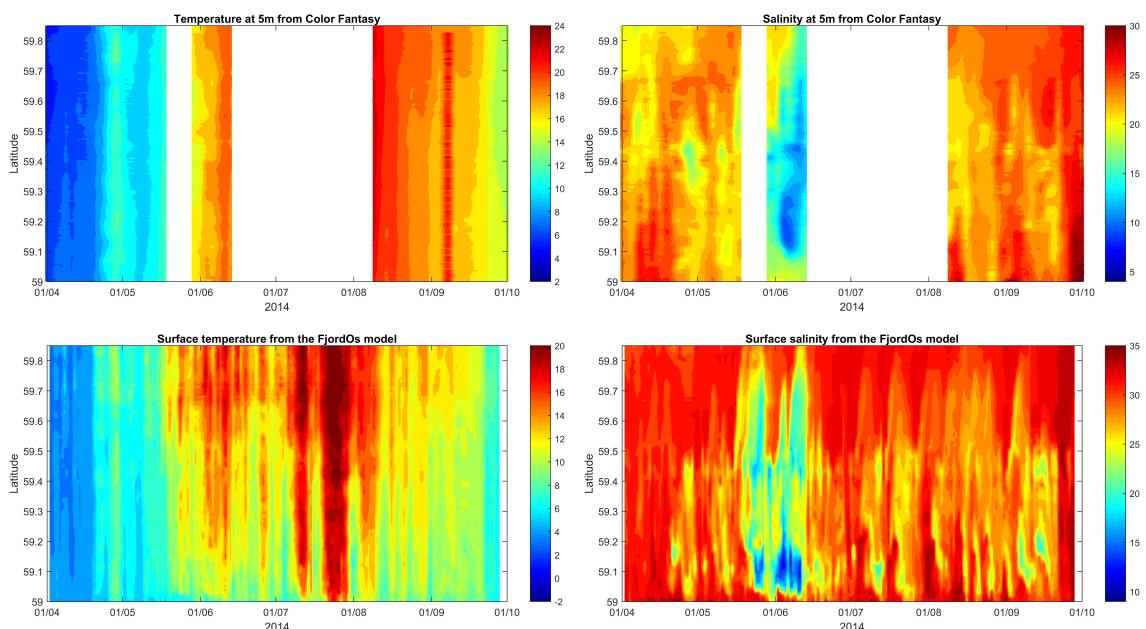


Figure 21: Simulated daily mean compared with observations from ferryboxes for temperature (left) and salinity (right).

6 Summary and final remarks

Acknowledgements

Appendix

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