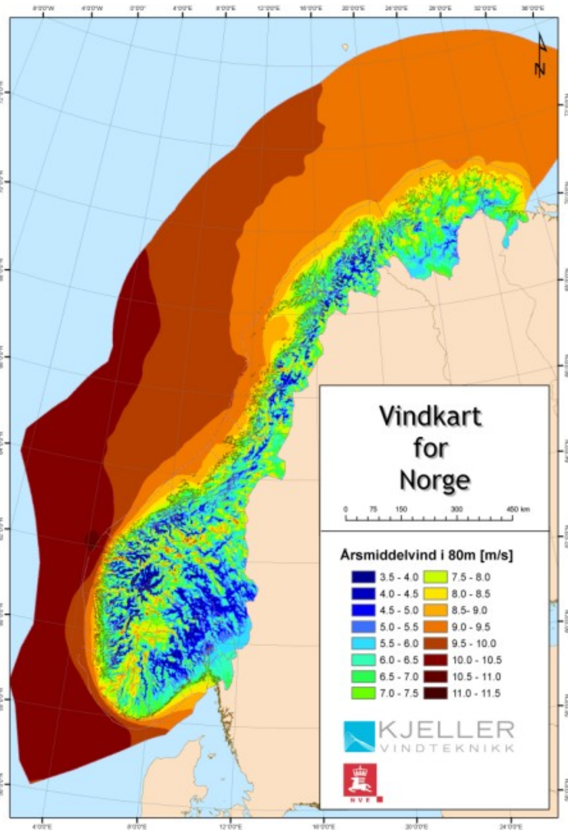
High-resolution simulations of surface wind climate, ocean currents and waves

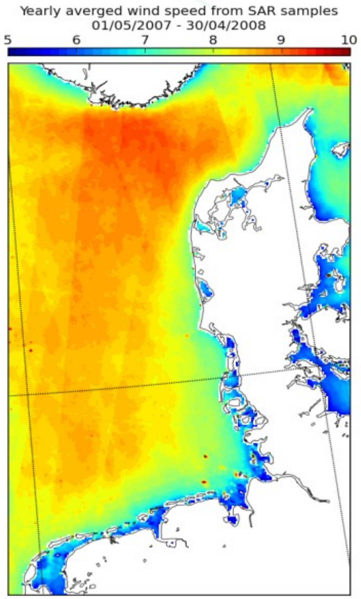
Hálfdán Ágústsson[1], Oyvind Birkjedal[1],
Jon Albrecthsen[2] og Birgitte Furevik[3]

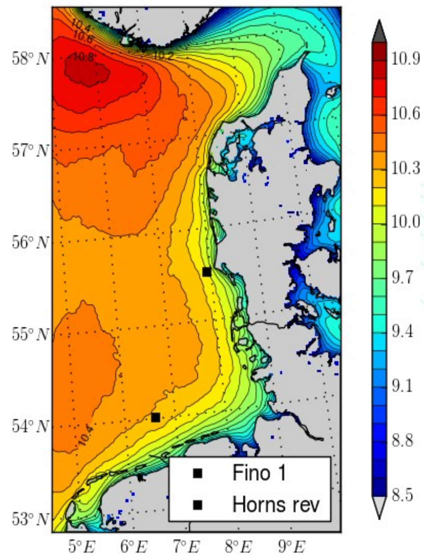
With contributions from Rolv Bredesen and Knut Harstveit

Offshore structures

- Design loads:
  - Extreme winds,
  - Waves and currents.
- Wind-energy production
  - Pre- and post-construction.
- Planning of maintenance.
- Intra-windfarm interactions.



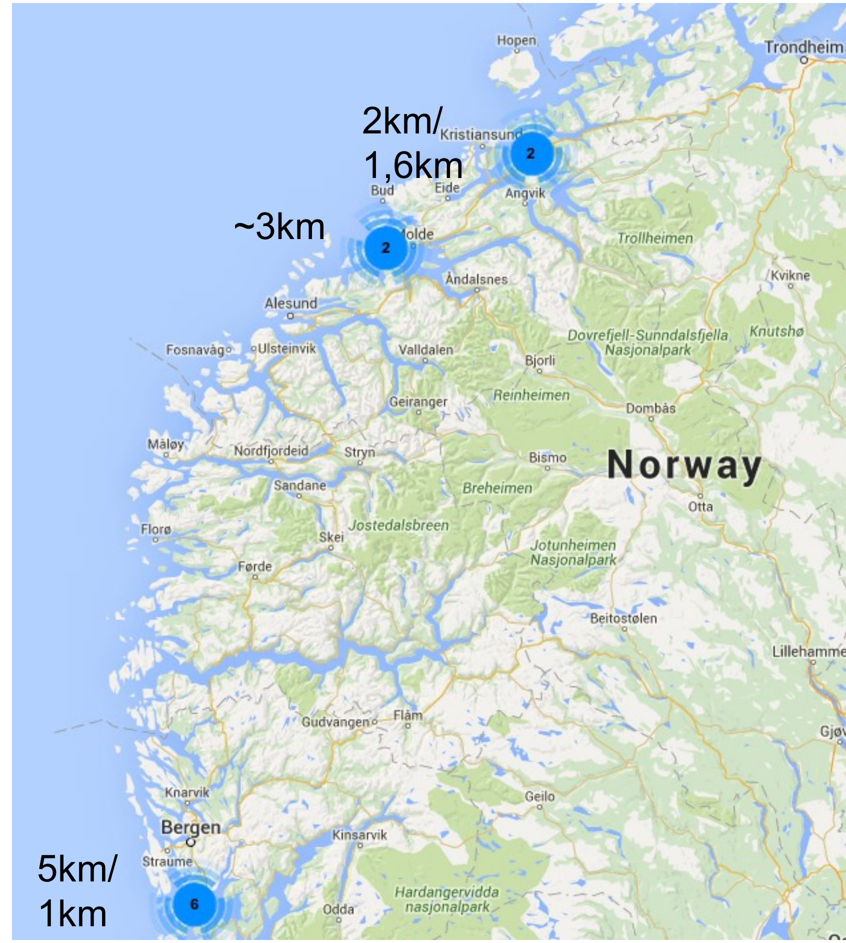


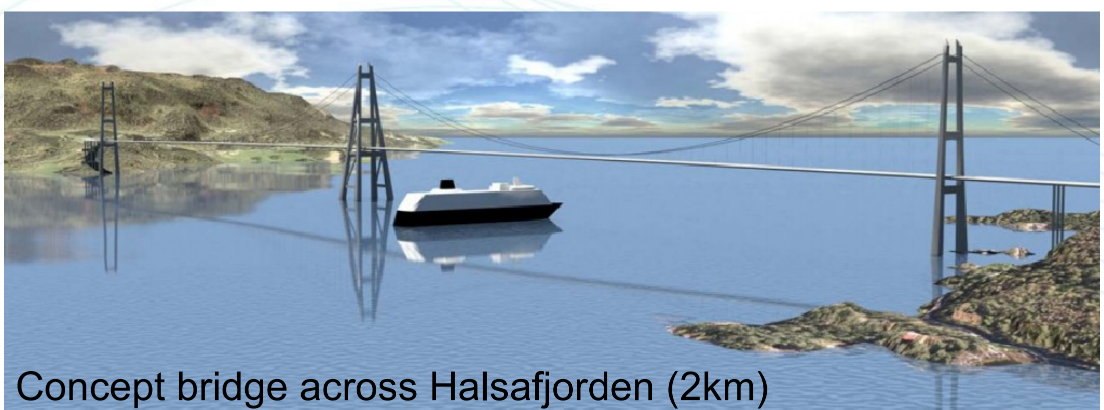


KJELLER
VINDTEKNIKK

Experience from 'extreme' bridges

- The Norwegian road authorities shall bridge the remaining ferry crossings along the E39:
  - Fjord width 2-7.5 km.
  - Fjord depth 300-1300 m.
  - High and variable wind, wave and current loads.




Concept bridge across Halsafjorden (2km)

KJELLER VINDTEKNIKK

Design loads and climatic conditions

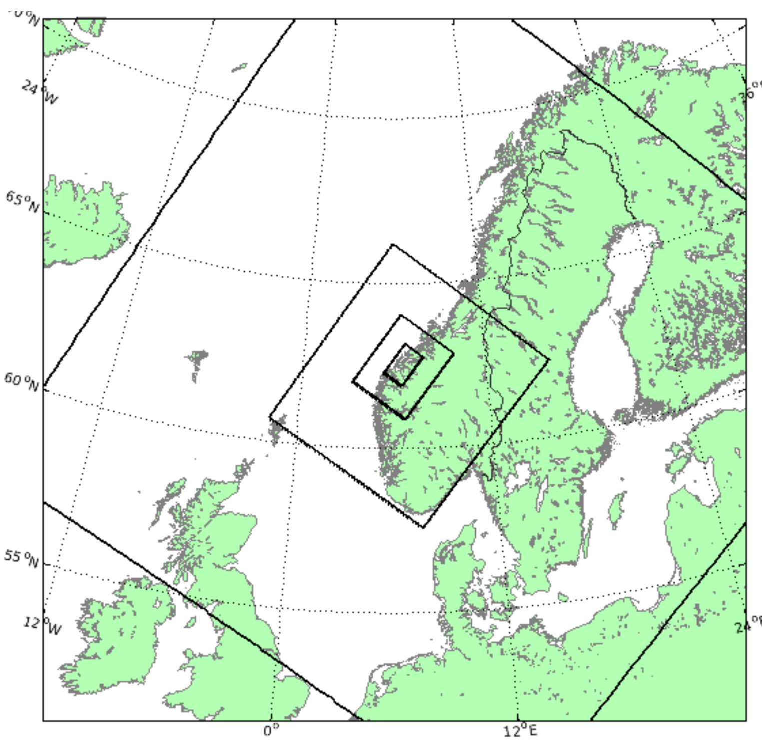
- Very high resolution (500 m) meso-scale atmospheric simulations (WRF).
  - Estimating wind climate and extreme winds.
  - Extrapolate observed winds to middle of fjord.
  - Input to high-res. wave (ROMS) and current (SWAN) models.
- Observations of wind for model verification and load estimates.

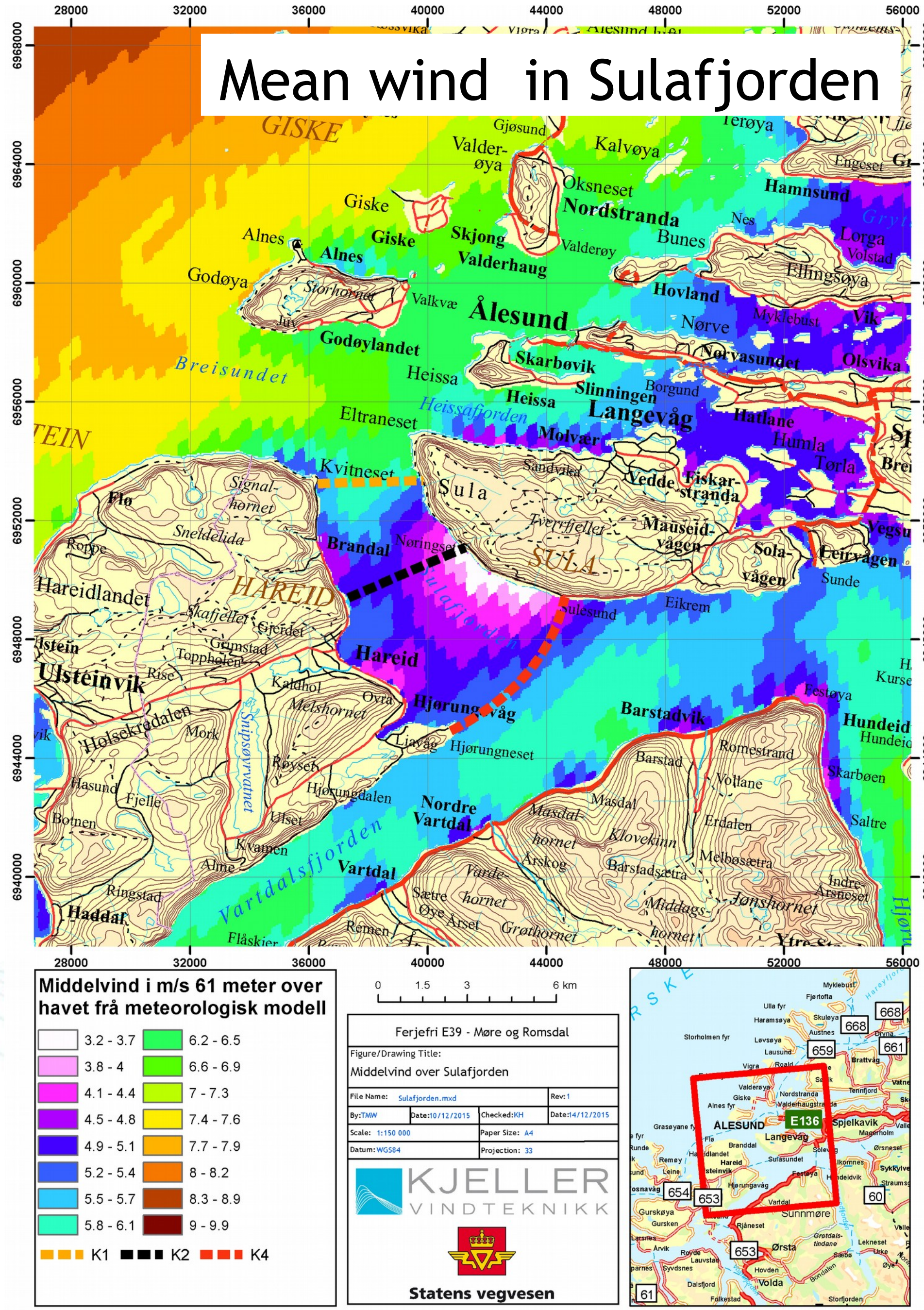

Concept bridge across Bjornafjorden (5km)

KJELLER VINDTEKNIKK

Atmospheric simulations

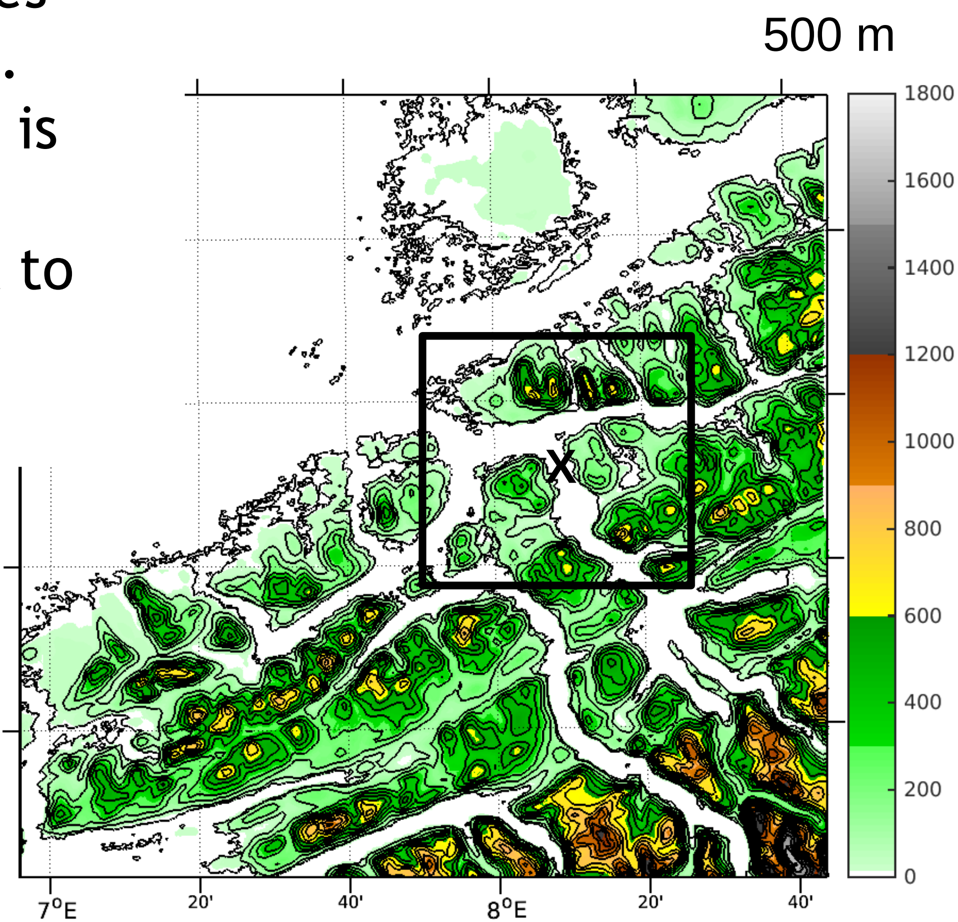
- WRF-ARW state-of-the-art numerical weather model.
- Down-scaling from global atmospheric analysis (FNL).
- ~10 years at 500 m resol.

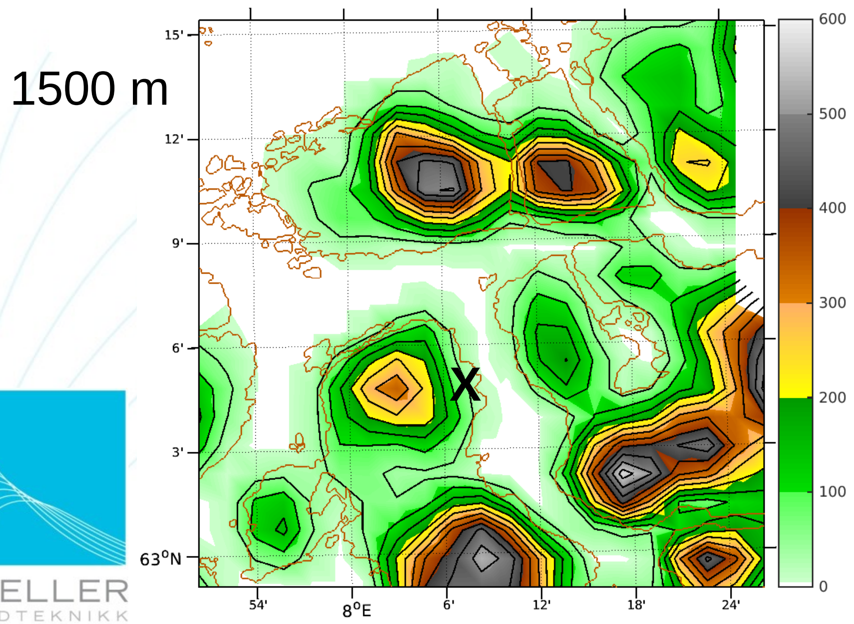




Setup of atmospheric simulations

- Model in Halsafjorden includes 177x183 grid points at 500 m.
- Complex orography but fjord is reasonably well resolved.
- Simulated data used as input to wave and current-models.

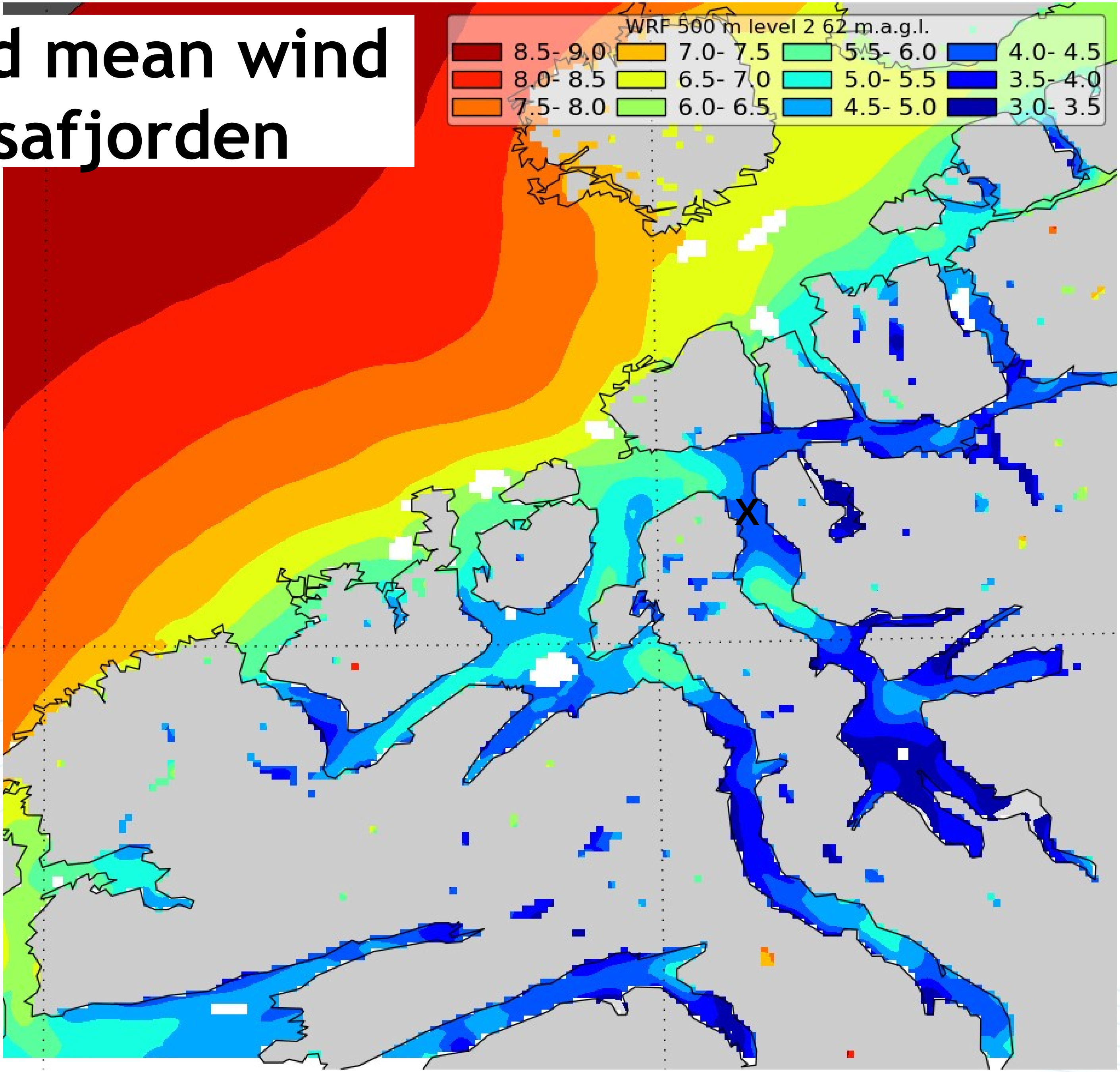




KJELLER VINDTEKNIKK

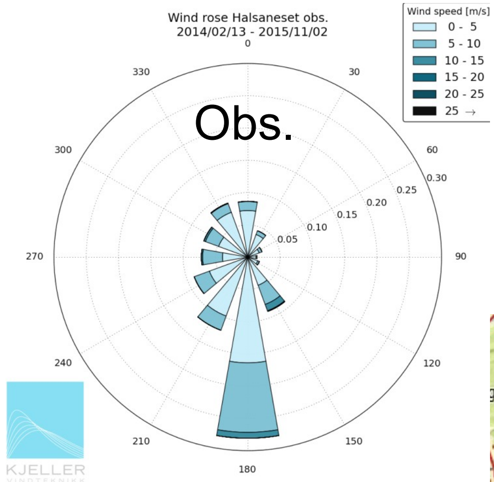
Simulated mean wind in Halsafjorden

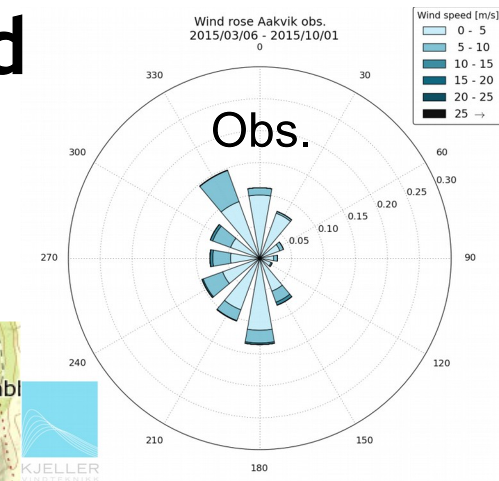
Large spatial variations which extend away from the shore

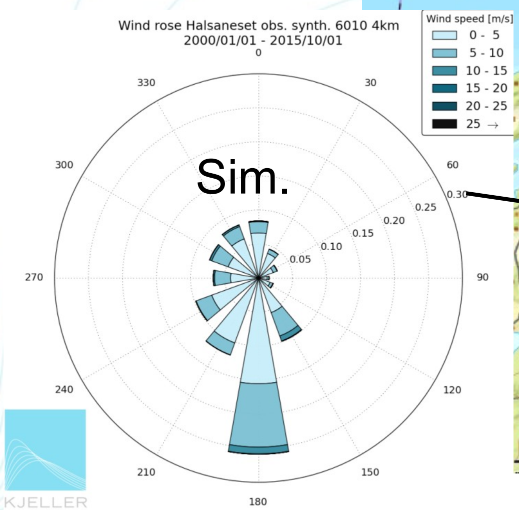


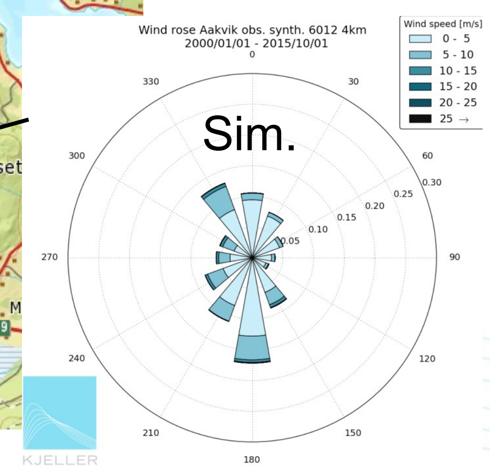
KJELLER VINDTEKNIKK

Validation of simulated flow with mast data



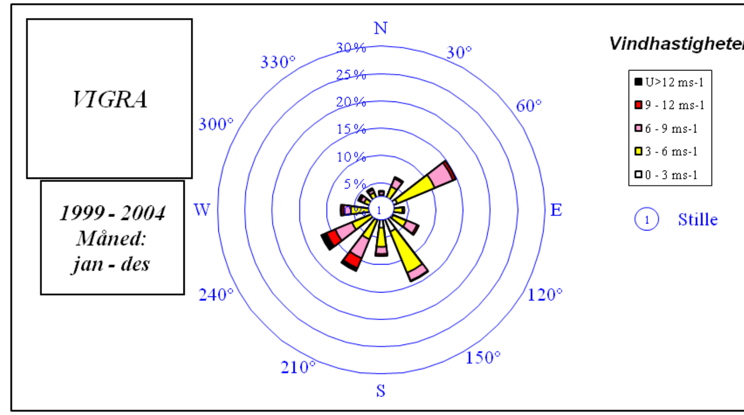


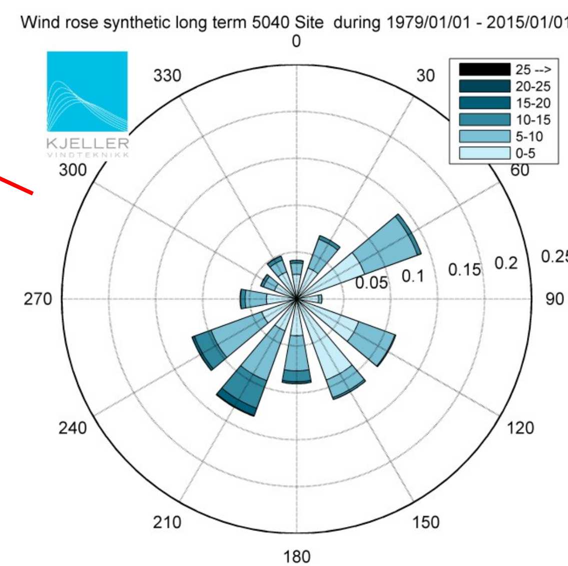




Validation of simulated flow with airport data

Observations





500 m data

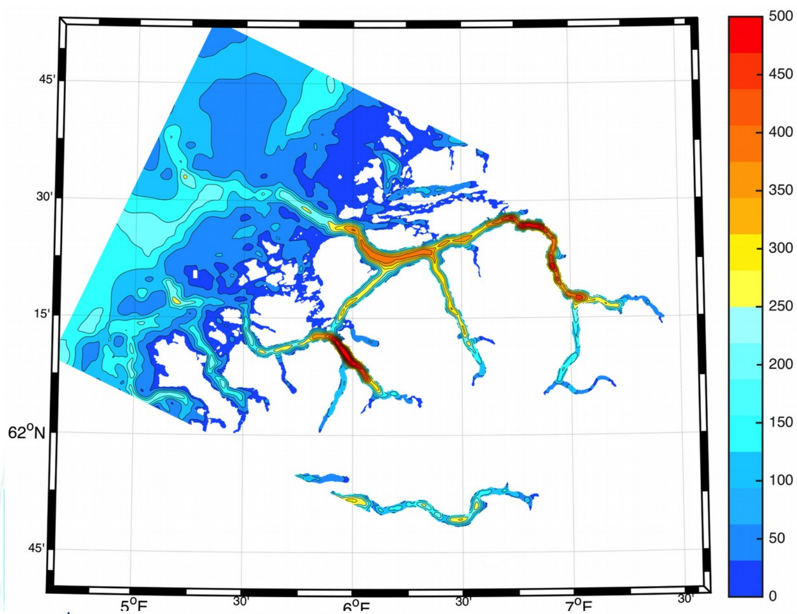
Important to long-term correct the relatively short 500 m time series!

KJELLER VINDTEKNIKK

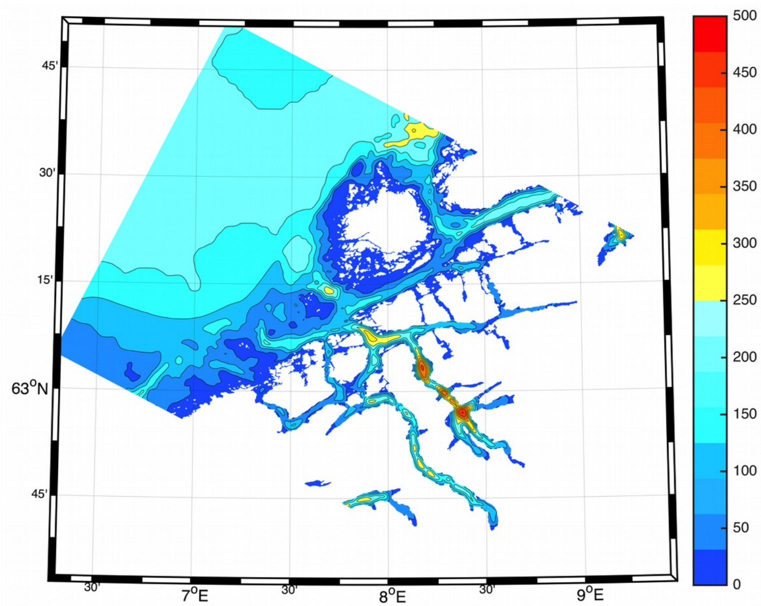
Ocean model system - currents

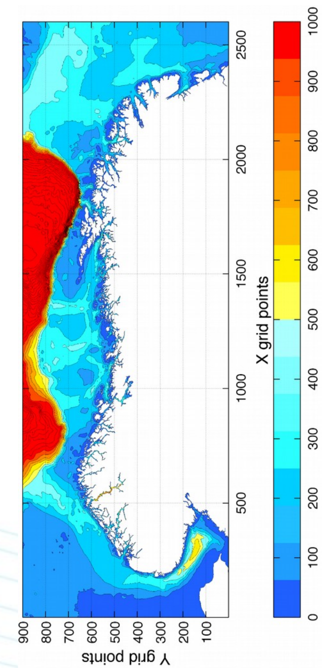
- **Tool:** ROMS (Regional Ocean Modeling System)
- **Resolution (hor.):** 800m and 160m
- **Model period:** 2005-2014 (800m) and 2013-2014 (160m)
- **Forcing:** High-res. atm. surface fields (WRF 3km/500m), 4 km ocean model at the open boundaries, tides (TPXO), river runoffs (from NVE)

160m - Sulafjorden



160m - Halsafjorden



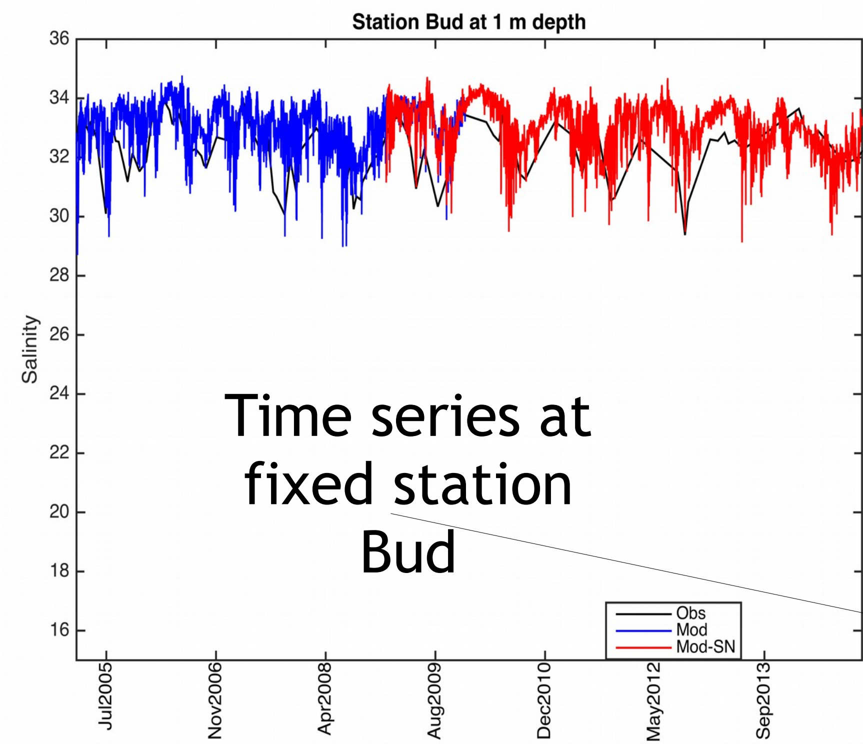


NorKyst-800m

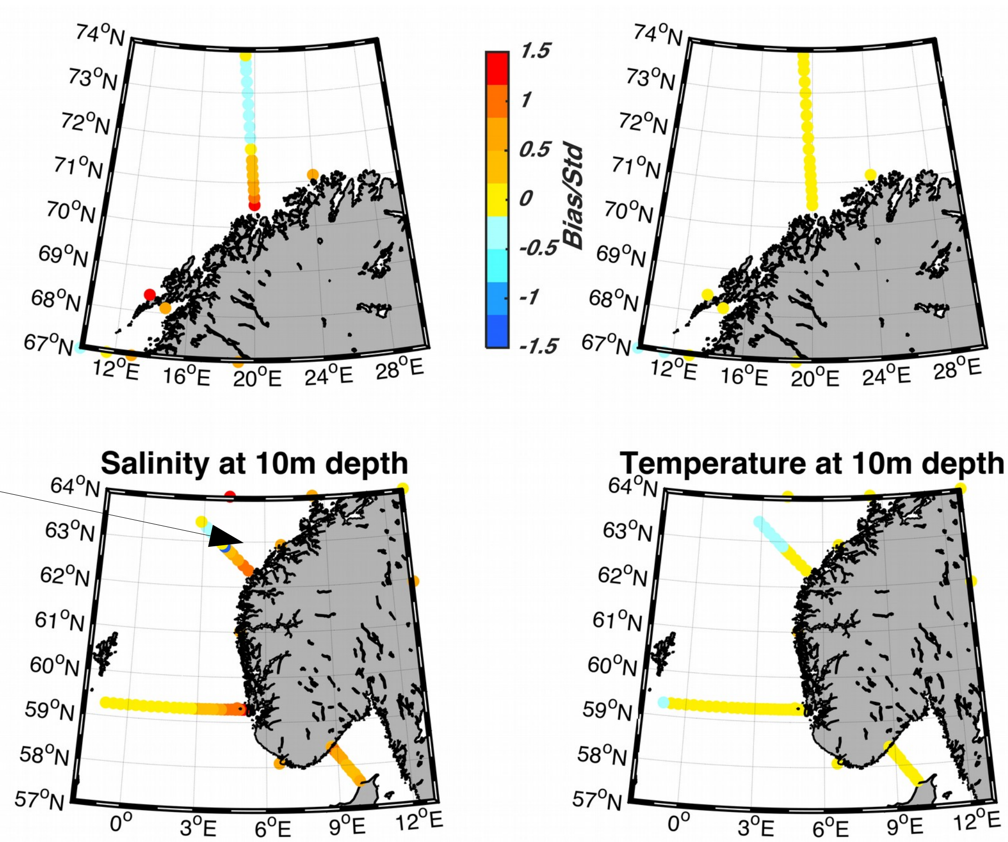
Validation of coastal model (800m)

Observed STD-profiles:

- Offshore transects (~4#/year),
- Fixed coastal stations (~20#/year).

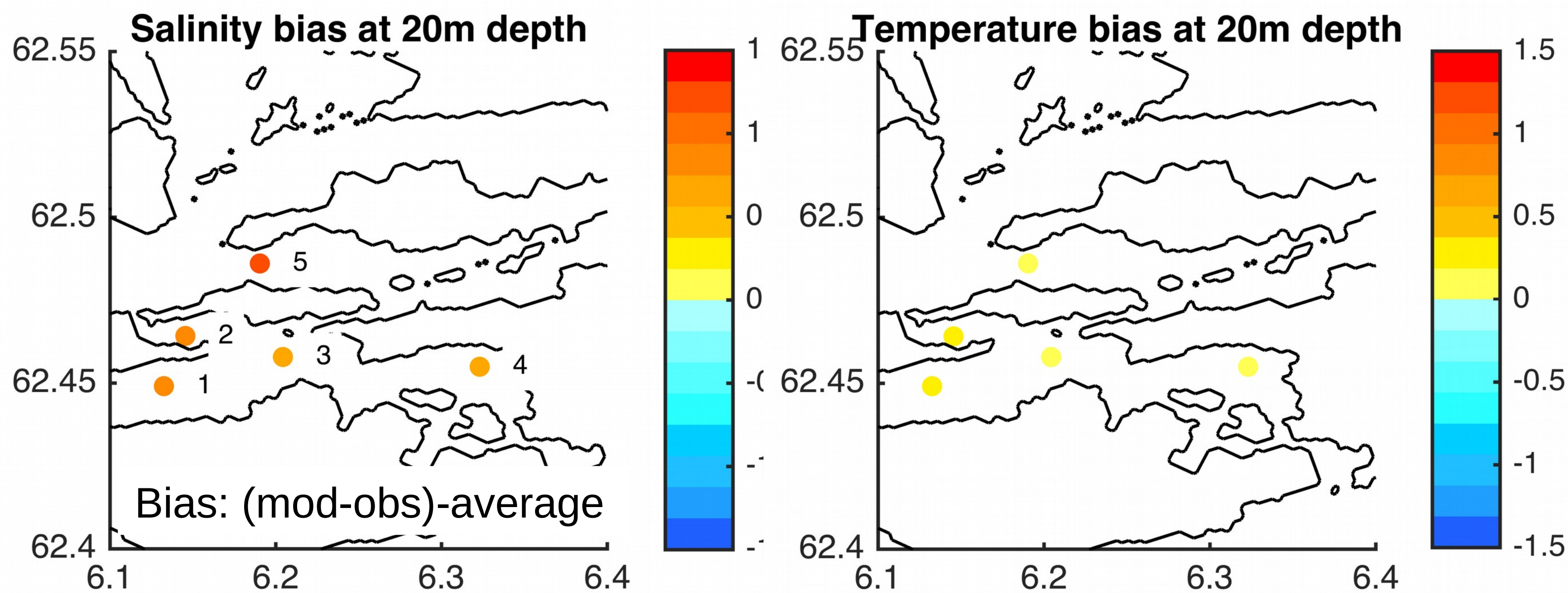


Normalized bias: (mod-obs)/std(obs)

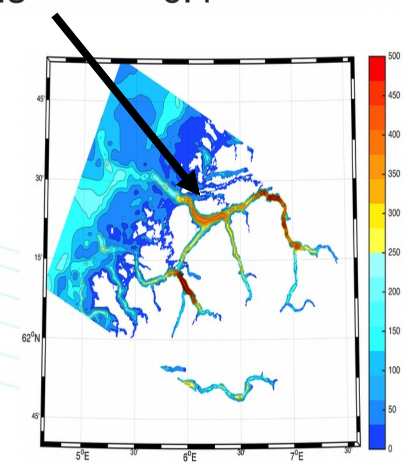


KJELLER VINDTEKNIKK

Validation of fjord model (160m)

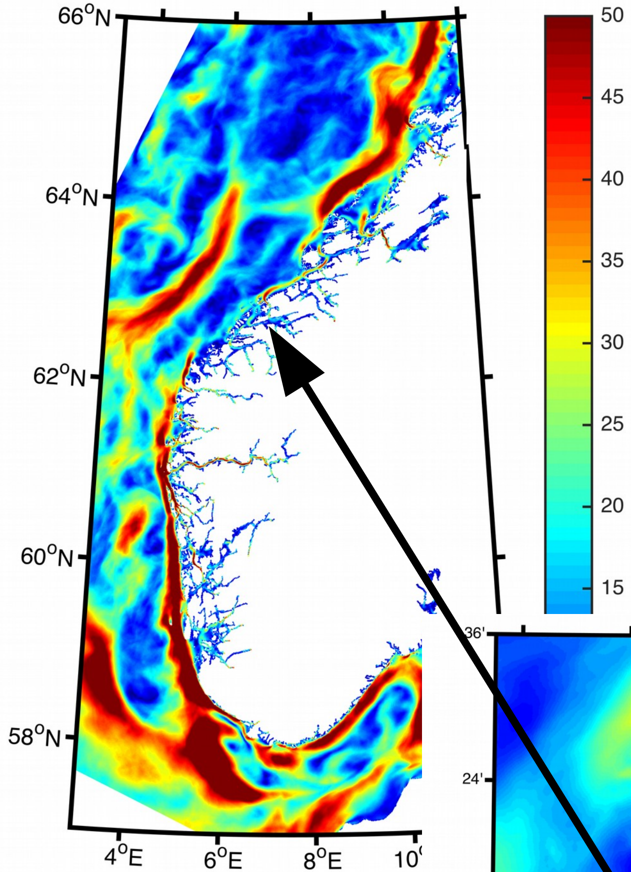


Observations: Inshore CTDs from surveys in 2012, 2013 and 2015 near Sulafjorden



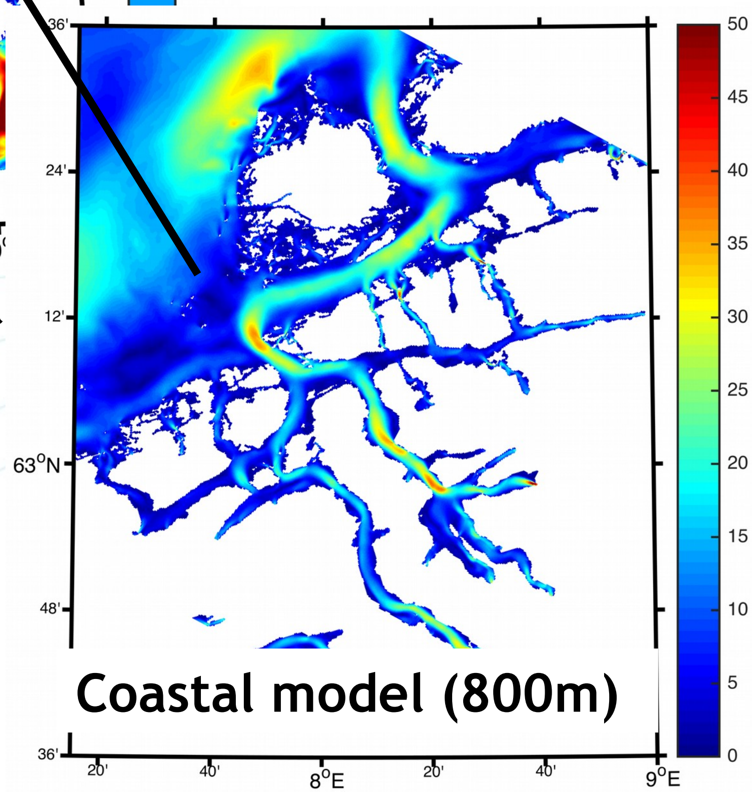
KJELLER
VINDTEKNIKK

High resolution is required

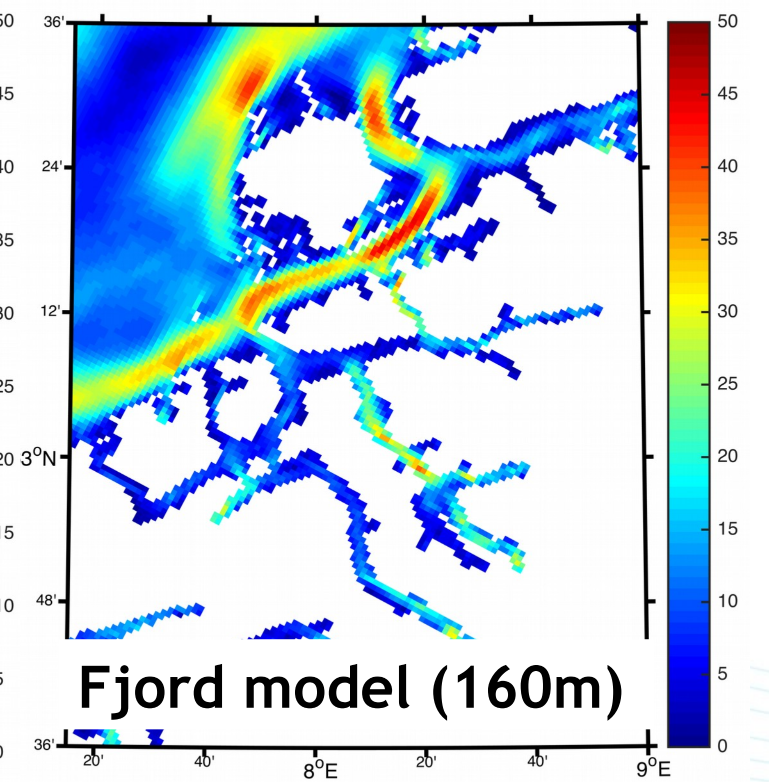


Coastal model (800m)

Average surface current (cm/s)



Coastal model (800m)



Fjord model (160m)

KJELLER
VINDTEKNIKK

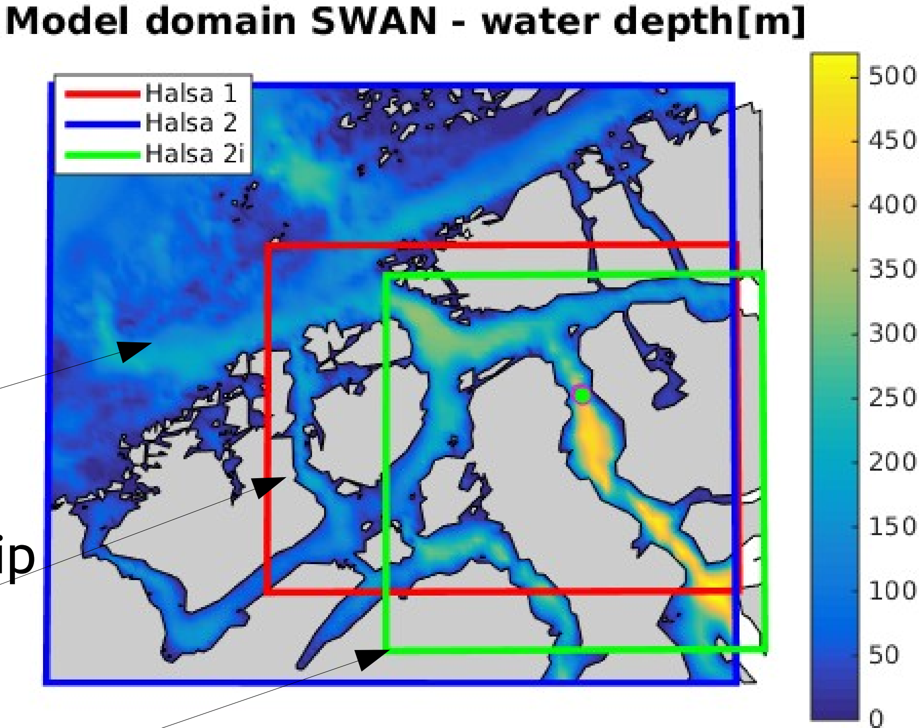
Modeling waves in Halsafjorden

- Challenges include:
  - Setup of model domains.
  - Horizontal resolution.
  - No available observations.
- Three domains tested:

  Halsa 1: Fine-scale w/Grip
  - 250 m resolution,
  - Forced by NORA10.

  Halsa 2: Coarse-scale w/Grip
  - 500 m resolution,
  - Forced by NORA10.

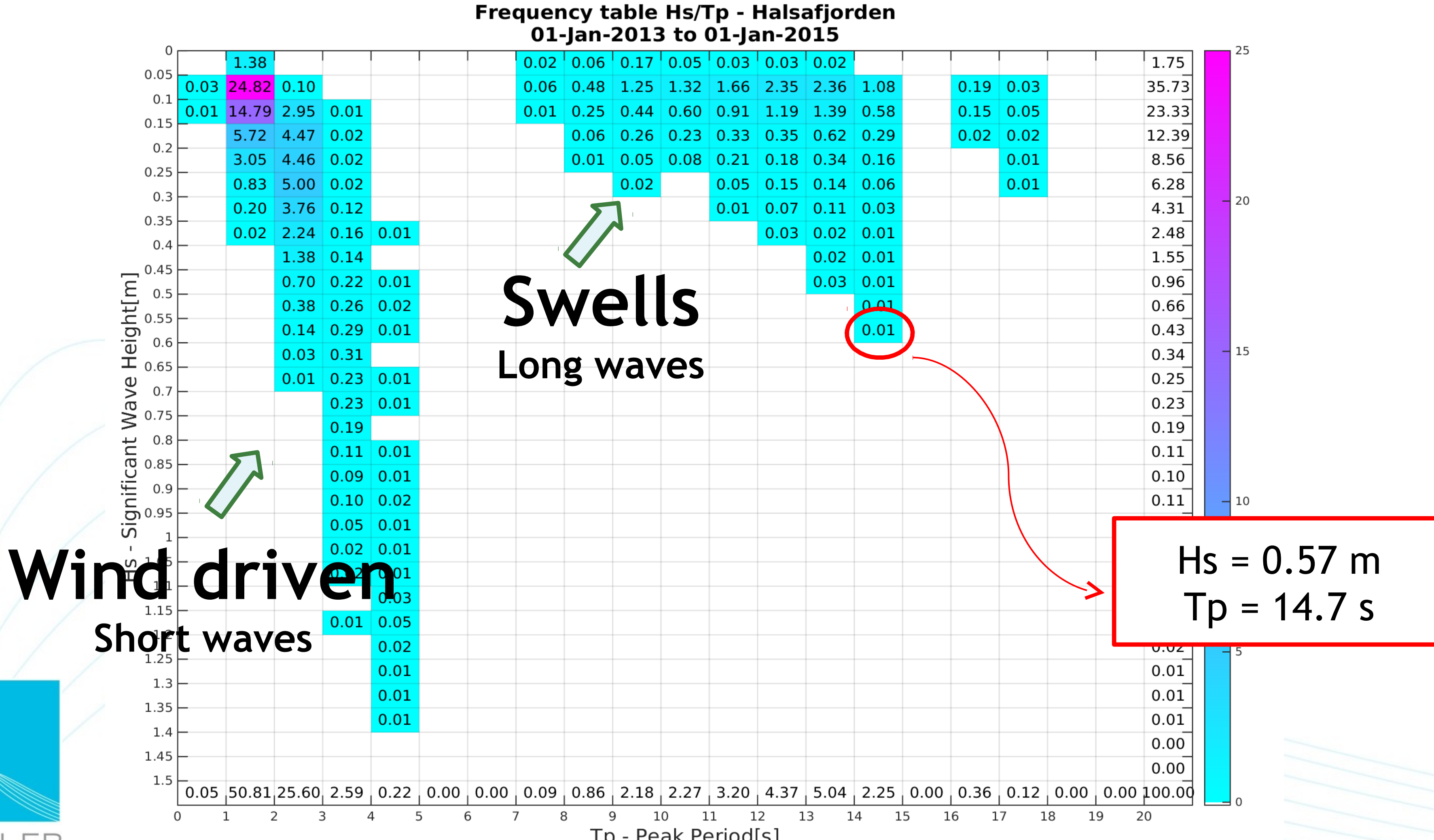
  Halsa 2i: Fine-scale:
  - 250 m resolution,
  - Forced by WRF-data.



KJELLER VINDTEKNIKK

Meteorologisk institutt

Simultanous waveheight/period in Halsafjorden (Halsa1, fine-scale, Nora10)



KJELLER VINDTEKNIKK

Simultanous waveheight/period in Halsafjorden (Halsa2, coarse-scale, Nora10)

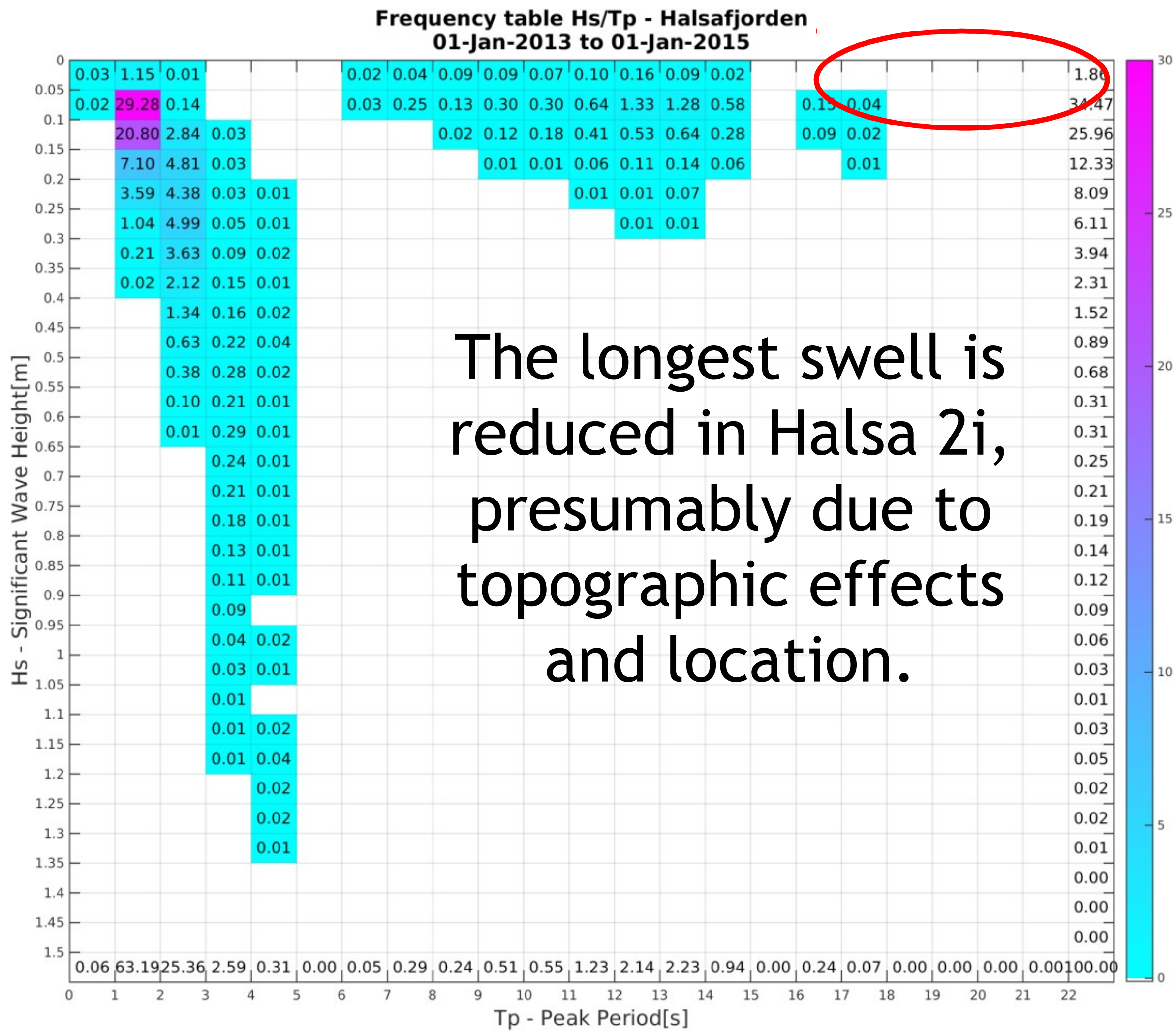
Frequency table Hs/Tp - Halsafjorden
01-Jan-2013 to 01-Jan-2015

Hs - Significant Wave Height[m] \ Tp - Peak Period[s]	0–1	1–2	2–3	3–4	4–5	5–6	6–7	7–8	8–9	9–10	10–11	11–12	12–13	13–14	14–15	15–16	16–17	17–18	18–19	19–20	Total
0–0.05	0.09	2.72						0.06	0.03	0.07	0.16	0.27	0.50	0.21	0.10		0.01	0.03		0.01	4.26
0.05–0.1	0.10	28.59	0.13					0.02	0.02	0.19	0.37	0.74	1.52	1.42	0.70		0.23	0.13			34.14
0.1–0.15		19.22	2.73	0.02						0.01	0.04	0.27	0.42	0.49	0.21		0.11	0.09			23.61
0.15–0.2		7.02	4.50									0.03	0.05	0.14	0.07			0.02			11.83
0.2–0.25		3.48	4.41	0.02									0.02	0.04	0.01			0.01			7.98
0.25–0.3		0.88	4.82	0.01																	5.71
0.3–0.35		0.18	3.67	0.08	0.01																3.94
0.35–0.4			1.97	0.18																	2.15
0.4–0.45			1.39	0.11																	1.51
0.45–0.5			0.72	0.20	0.01																0.93
0.5–0.55			0.37	0.22	0.01																0.59
0.55–0.6			0.11	0.29																	0.41
0.6–0.65			0.05	0.23																	0.28
0.65–0.7			0.01	0.23	0.01																0.24
0.7–0.75				0.20	0.01																0.21
0.75–0.8				0.18	0.01																0.19
0.8–0.85				0.15																	0.15
0.85–0.9				0.11	0.01																0.12
0.9–0.95				0.07																	0.07
0.95–1				0.02	0.01																0.03
1–1.05				0.02	0.02																0.04
1.05–1.1																					0.00
1.1–1.15				0.02	0.02																0.04
1.15–1.2					0.04																0.04
1.2–1.25					0.02																0.02
1.25–1.3					0.01																0.01
1.3–1.35																					0.00
1.35–1.4																					0.00
1.4–1.45																					0.00
1.45–1.5																					0.00
Total	0.18	62.10	24.88	2.37	0.16	0.00	0.00	0.08	0.05	0.27	0.57	1.31	2.51	2.29	1.08	0.00	0.35	0.27	0.00	0.01	98.49

Halsa 2 reduces the swell

KJELLER VINDTEKNIKK

Simultanous waveheight/period in Halsafjorden (Halsa2i, fine-scale, WRF)

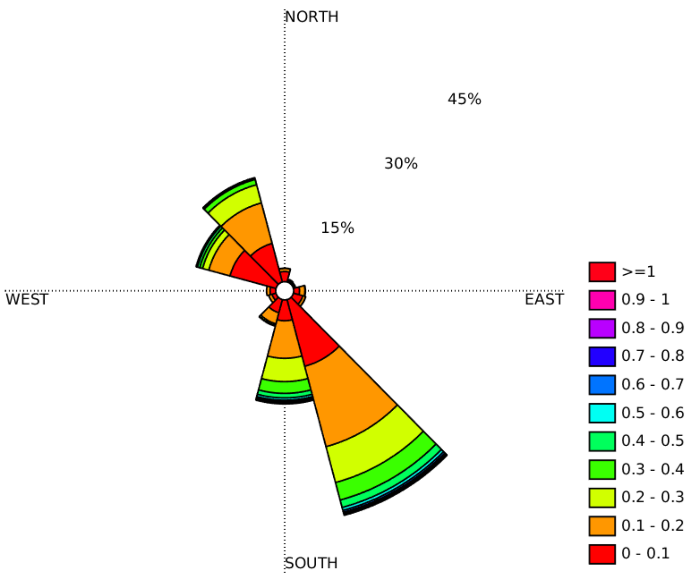


The longest swell is reduced in Halsa 2i, presumably due to topographic effects and location.

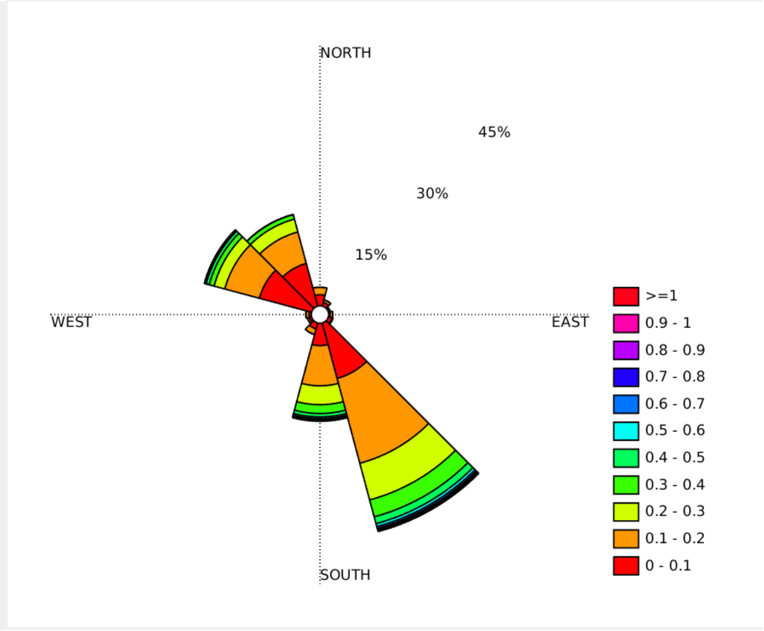
KJELLER VINDTEKNIKK

Most frequent wave direction

Halsa 1



Halsa 2i



- The most frequent wave direction is along the fjord axis.
- Results from Halsa 1 and Halsa 2 are similar.
- Observations are sorely needed!!!

KJELLER VINDTEKNIKK

What is simulated?

- Wind speed and direction at 500 m horizontal resolution and at many vertical levels.
  - Time series with 1 hour temporal resolution.
  - Wind climate and return periods of extreme winds.
- Ocean currents at 800 and 160 m resolution and at many depth levels.
  - Daily values and temporal behaviour.
- Wave height, period, direction and wave spectrum at 250 m resolution.
  - Mean values and temporal behaviour.
  - Max, mean, median, percentiles, variance, return periods, directional and frequence distribution.

- Observations are critically important to verify model results and help understand important processes.

KJELLER VINDTEKNIKK

Main conclusions and summary

- A high resolution atmospheric model coupled with wave and current-models is used to describe in detail the sea-state, wind- and wave climate.
- This study is focusing at in- and near-shore locations in complex orography.
  - ➔ High resolution is also needed off-shore to accurately capture relevant atmospheric and oceanic phenomena.
- Relevant for design and planning but also during operations.

KJELLER
VINDTEKNIKK

We present results from high-resolution simulations of mesoscale atmospheric flow, sea currents and waves which are used to study large- and small-scale features of the surface wind climate and sea state in the Sula- and Halsafjords in West-Norway.
The atmospheric simulations are performed with the state-of-the-art AR-WRF numerical weather prediction model at a resolution of 6 km for 1979-2015 and at 500 m for 2005-2014, and a temporal resolution of 1 hour. The coarse grid simulated dataset is used to long-term correct the high resolution simulated dataset so that both datasets represent the same period (1979-2015). The simulated flow from the final high-resolution dataset are compared with observations from weather stations in the region, including wind speed and direction observed at various heights in dedicated meteorological masts as well as with airport data.

The simulated atmospheric parameters, including winds, surface pressure, temperature, humidity, precipitation and radiative fluxes, are used as additional forcing for a fine scale wave model (SWAN) running at a horizontal resolution of 250 m and a the ROMS ocean current model running at a horizontal resolution of 800 and 160 m, producing hourly and daily values describing the sea state. Additional input to these models includes high resolution datasets describing the coastline and the bottom topography of the fjords.

The results of the study show that high-resolution atmospheric simulations and coupled current/wave models are a valuable tool that can be used to describe the wind and wave climate. The results are not only valid for the meteorological and ocean conditions near complex orography but they are also applicable for locations away from orography. This is in particular important in the context of reproducing and forecasting winds, waves and currents near offshore constructions such as wind turbines and platforms. Both during the building and planning period but also with regard to accessibility during the operation of the sites.

KJELLER
VINDTEKNIKK

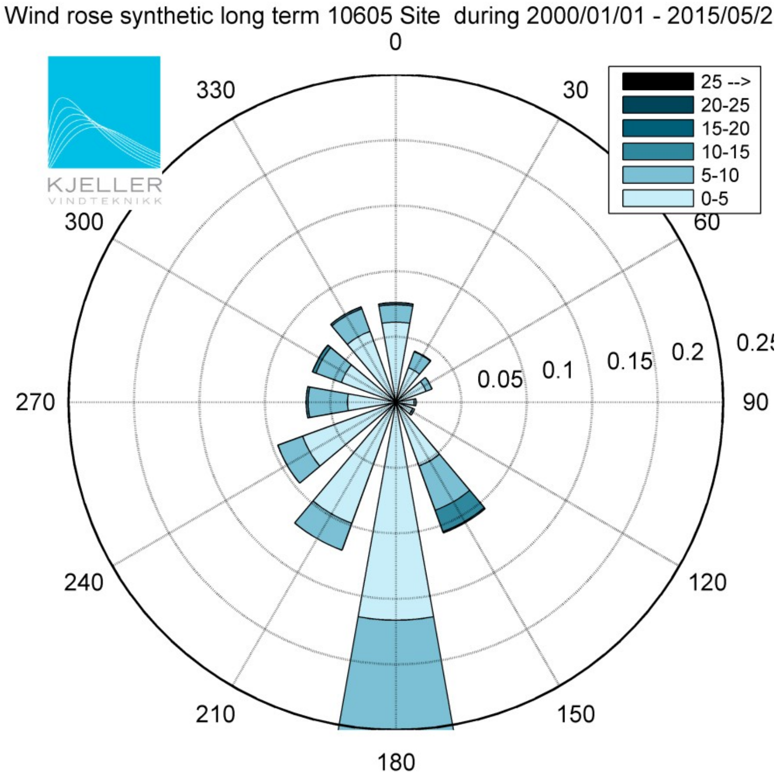
Eksempel på datauttak fra 500m modell

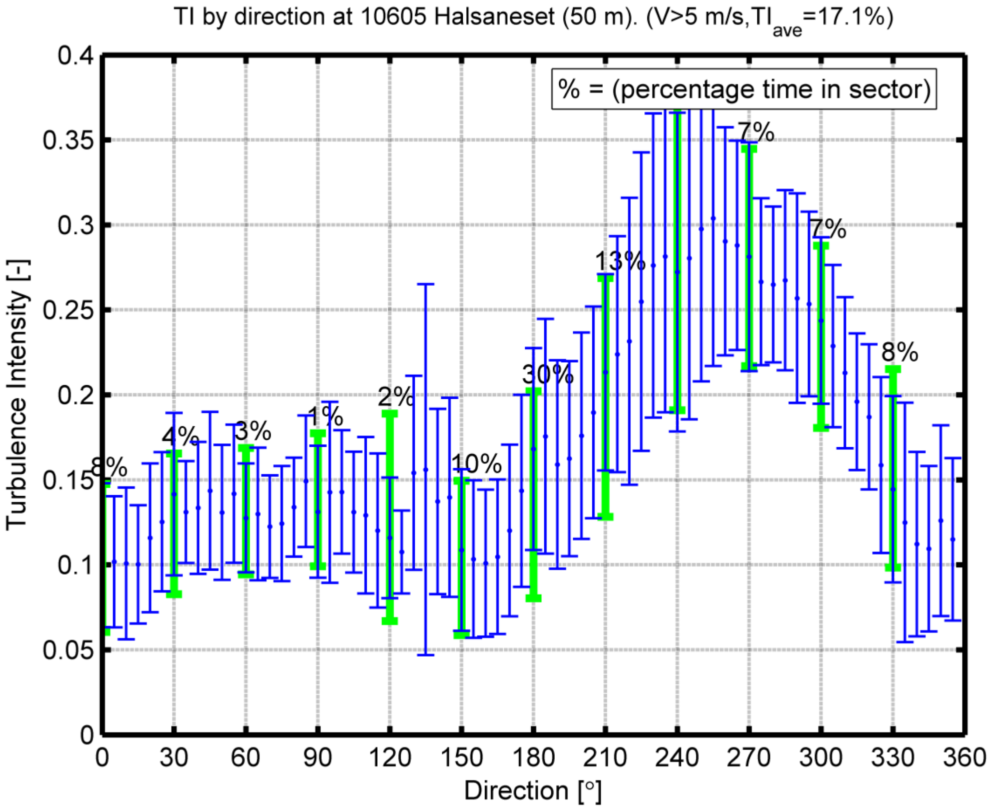
```
#SiteInformation:
Site Number          - 5050
Location             - Julsundet_W_500m_a1
Elevation            - 19.6 m
Latitude             - 62.729839
Longitude            -  6.939510
Landmask             - 0
Landuse              - 16
Distance from station - 220 m
I pos in grid        - 178
J pos in grid        - 80
Displacement height  - 0 m


#SensorDescription; COL.NO; TYPE ; OPERATOR ; UNITS ; HEIGHT ; NAME; MODEL; ANEM TYPE; DESCRIPTION
 1; DATE; VAL; yyyy-mm-dd
 2; TIME; VAL; hh-min-ss
 3;   WS; AVG;  m/s;  20.0; WRF model; WRF model; FF; Wind speed - interpolated height value
 4;   WS; AVG;  m/s;  40.0; WRF model; WRF model; FF; Wind speed - interpolated height value
 5;   WS; AVG;  m/s;  60.0; WRF model; WRF model; FF; Wind speed - interpolated height value
 6;   WS; AVG;  m/s;  80.0; WRF model; WRF model; FF; Wind speed - interpolated height value
 7;   WS; AVG;  m/s; 100.0; WRF model; WRF model; FF; Wind speed - interpolated height value
 8;   WS; AVG;  m/s; 120.0; WRF model; WRF model; FF; Wind speed - interpolated height value
 9;   WS; AVG;  m/s; 140.0; WRF model; WRF model; FF; Wind speed - interpolated height value
10;   WS; AVG;  m/s; 160.0; WRF model; WRF model; FF; Wind speed - interpolated height value
11;   WS; AVG;  m/s; 200.0; WRF model; WRF model; FF; Wind speed - interpolated height value
12;   WS; AVG;  m/s; 250.0; WRF model; WRF model; FF; Wind speed - interpolated height value
13;   WS; AVG;  m/s; 300.0; WRF model; WRF model; FF; Wind speed - interpolated height value
14;   WS; AVG;  m/s; 350.0; WRF model; WRF model; FF; Wind speed - interpolated height value
15;   WS; AVG;  m/s; 400.0; WRF model; WRF model; FF; Wind speed - interpolated height value
16;   WS; AVG;  m/s; 450.0; WRF model; WRF model; FF; Wind speed - interpolated height value
17;   WS; AVG;  m/s; 500.0; WRF model; WRF model; FF; Wind speed - interpolated height value
18;   WD; AVG;  deg;  20.0; WRF model; WRF model; DD; Wind direction - interpolated height value
19;   WD; AVG;  deg;  40.0; WRF model; WRF model; DD; Wind direction - interpolated height value
20;   WD; AVG;  deg;  60.0; WRF model; WRF model; DD; Wind direction - interpolated height value
21;   WD; AVG;  deg;  80.0; WRF model; WRF model; DD; Wind direction - interpolated height value
22;   WD; AVG;  deg; 100.0; WRF model; WRF model; DD; Wind direction - interpolated height value
23;   WD; AVG;  deg; 120.0; WRF model; WRF model; DD; Wind direction - interpolated height value
24;   WD; AVG;  deg; 140.0; WRF model; WRF model; DD; Wind direction - interpolated height value
25;   WD; AVG;  deg; 160.0; WRF model; WRF model; DD; Wind direction - interpolated height value
26;   WD; AVG;  deg; 200.0; WRF model; WRF model; DD; Wind direction - interpolated height value
27;   WD; AVG;  deg; 250.0; WRF model; WRF model; DD; Wind direction - interpolated height value
28;   WD; AVG;  deg; 300.0; WRF model; WRF model; DD; Wind direction - interpolated height value
29;   WD; AVG;  deg; 350.0; WRF model; WRF model; DD; Wind direction - interpolated height value
30;   WD; AVG;  deg; 400.0; WRF model; WRF model; DD; Wind direction - interpolated height value
31;   WD; AVG;  deg; 450.0; WRF model; WRF model; DD; Wind direction - interpolated height value
32;   WD; AVG;  deg; 500.0; WRF model; WRF model; DD; Wind direction - interpolated height value
33;   WS; AVG; ms-1;  10.0; WRF model; WRF model; FF10; WIND SPEED AT 10 M - surface level
34;   WD; AVG;  deg;  10.0; WRF model; WRF model; DD10; WIND DIRECTION AT 10 M - surface level
```

KJELLER VINDTEKNIKK

Utvalgte resultater: Halsaneset





Utvalgte resultater

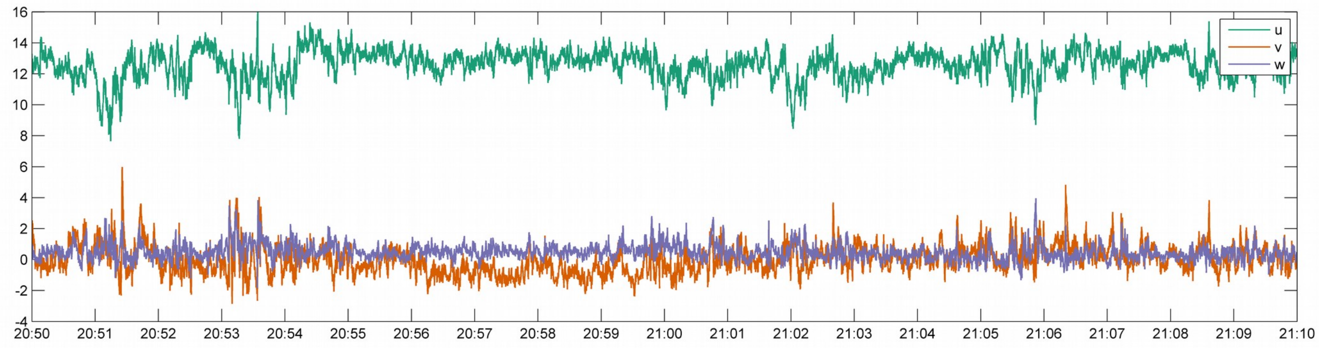
Tabell 1: Ekstremverdier med 10 min middelvind og 50 års returperiode hentet fra rapport KVT/TMW/2015/R052

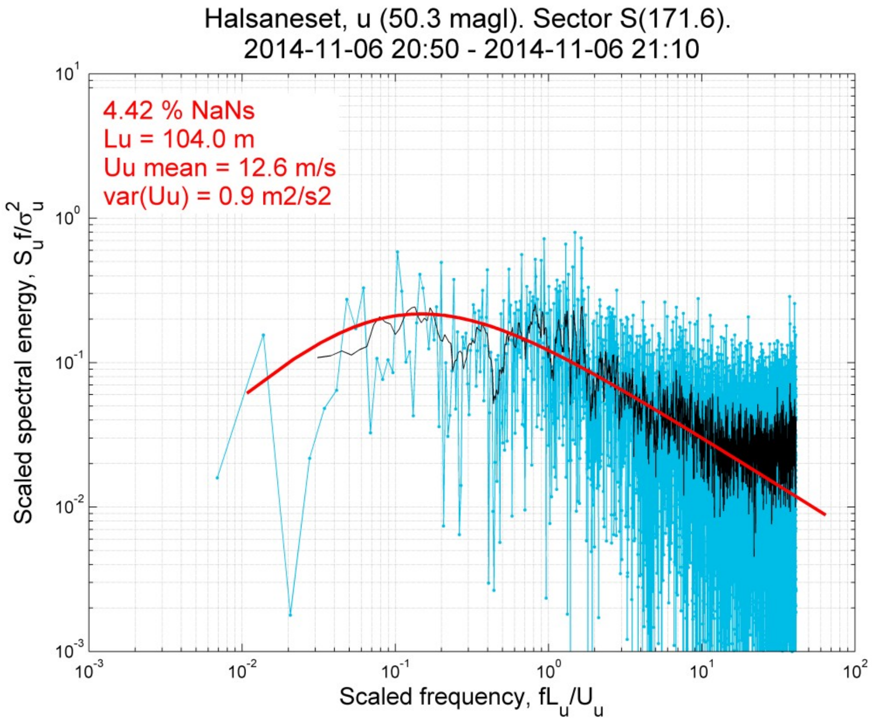
	N	NE	E	SE	S	SW	W	NW	Omni
Midsund	25.5	18.6	19.0	23.9	26.4	19.4	15.8	23.6	27.2
Julbø	26.8	17.5	18.5	21.7	27.8	25.7	26.8	25.9	29.1
Halsaneset	22.3	17.9	22.6	28.2	25.6	19.8	21.7	21.1	28.4
Åkvik	20.1	20.4	16.8	25.3	24.6	22.5	23.6	23.2	26.3

Tabell 2: Ekstremverdier med 3 sec vindkast og 50 års returperiode hentet fra rapport KVT/TMW/2015/R052 [1]

	N	NE	E	SE	S	SW	W	NW	Omni
Midsund	36.5	25.1	25.4	30.8	35.3	32.4	35.2	39.2	40.0
Julbø	34.0	24.6	25.8	31.6	36.3	40.4	40.5	32.5	42.1
Halsaneset	32.1	23.8	29.3	36.8	30.6	33.5	38.0	32.7	39.0
Åkvik	30.3	30.6	27.2	30.5	30.6	33.8	36.3	30.0	36.7

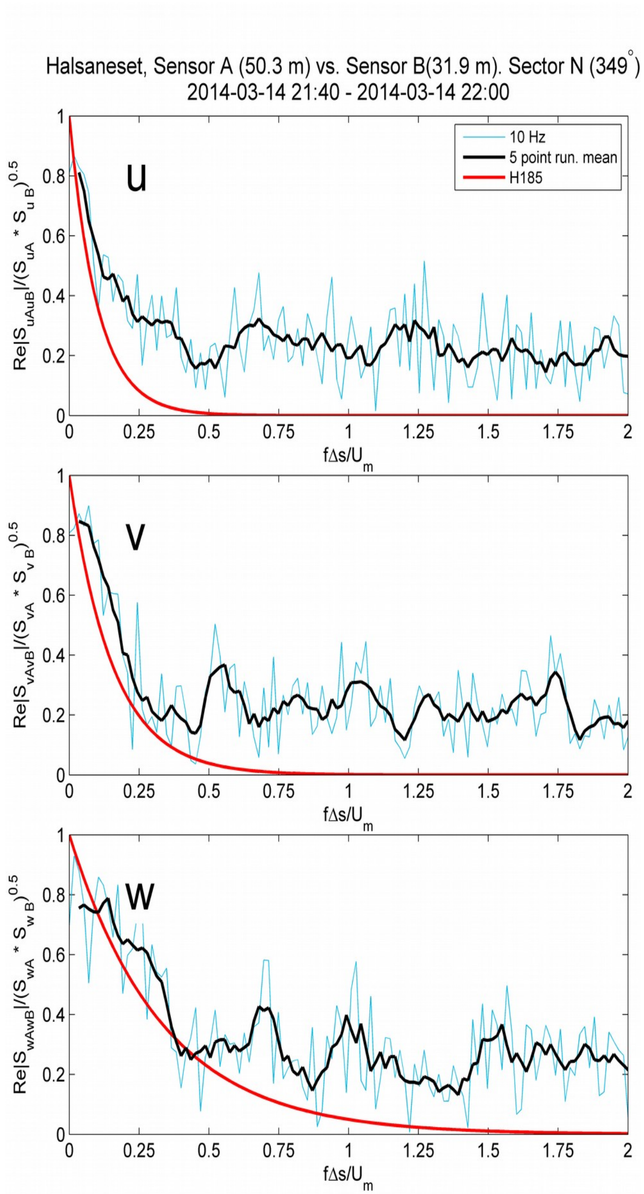
Frekvensspekter- Halsaneset (171°)





KJELLER VINDTEKNIKK

Koherens som funksjon av frekvens ved gitt vertikal separasjon



Med Um=10 m/s og Δs=50.3-31.9m=18.4 m, ser vi at fΔs/Um=0.2 svarer til 0.1 Hz (10 sek). Dvs at koherensen er sterkt til stede når tidsskala på virvlene overstiger 10 sekunder, mens den dør ut på kortere tidsskala.

Økes vindhastigheten til 20 m/s, fåes respons ned til 5 sekunder.

KJELLER VINDTEKNIKK