Ship-icing forecasting

Overview

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HERMES
KYSTVERKET NORWEGIAN COASTAL ADMINISTRATION
SINTEF
Gratanglaks
Norwegian Meteorological Institute
The Research Council of Norway

Ice accumulation on ships

Marine/sea-spray icing (saline water)
- Wave-ship interaction icing
- Wind-driven icing

Atmospheric icing (fresh water)
- Snow
- Freezing rain
- Supercooled fog

Combination of saline and fresh water icing
- Spray icing and snow is a common combination

Freezing temperature dependent on salinity:

$$T_f = -54.1126 \left(\frac{S_b}{1000 - S_b} \right), S_b \in [0, 124.7] \text{ ppt}$$

Tf = -4 deg C in the mean,
due to salt expulsion the Tf is lower than out in the sea



Photos: 10 May 2022, Ine-Therese Pedersen, Longyearbyen

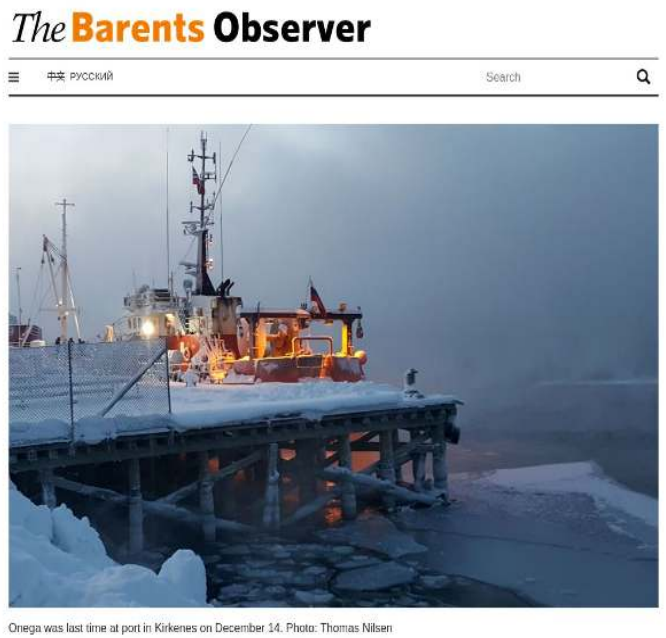
Icing may cause capsizing of small boats

14 February 1979 in Denmark
- 6 ships capsized
- 15 deceased



Kilde: http://www.tvmidtvest.dk/midt-og-vestjylland/den-hvide-dod-den-morkeste-dag-vi-nogensinde-har-haft

December 2020

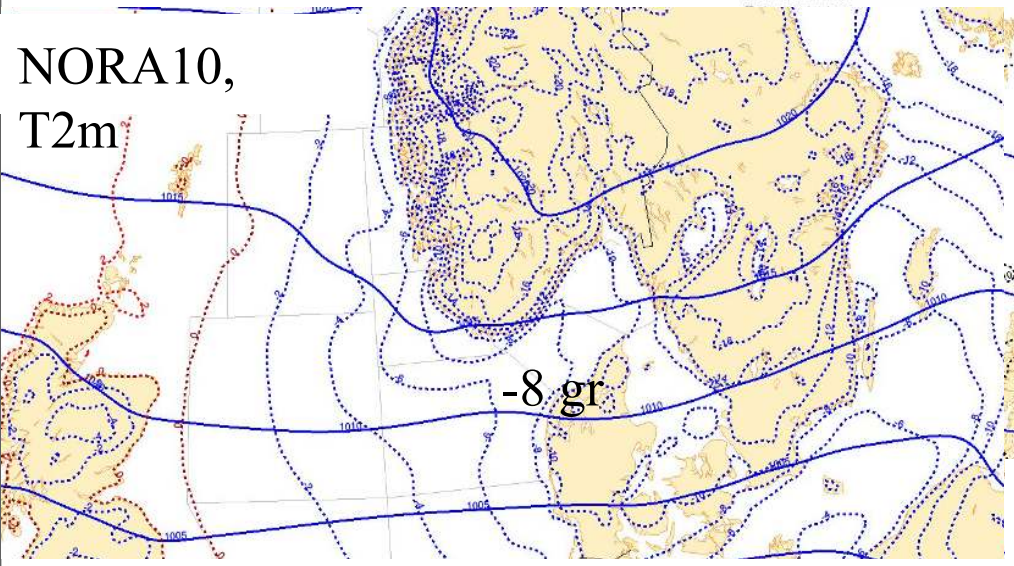


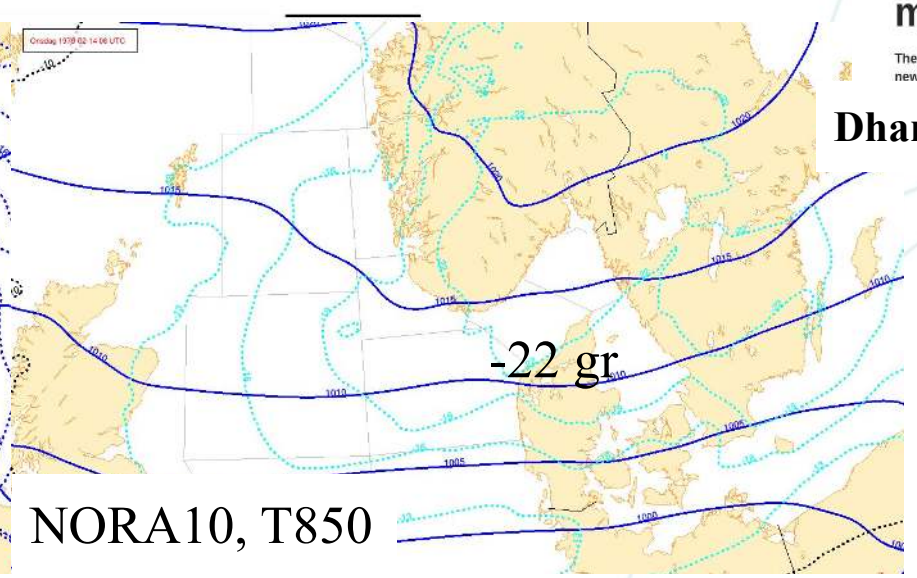
Onega was last time at port in Kirkenes on December 14. Photo: Thomas Nilsen

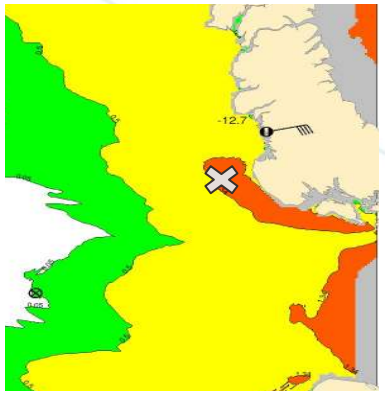
Icing believed to cause sinking of fishing boat in Barents Sea, 17 missing

The Russian fishing boat «Onega» sank near Novaya Zemlya. Two of the crew of 19 have been rescued, news agencies report citing the emergency ministry.

Dhar et al. (2022), conference paper







Safety risk, expensive

- Large ships
  - Slippery decks
  - Slippery ladders
  - Slippery handrails
  - Disabled life boats
  - Hamper radio communication
- De-icing with heat
  → energy consuming

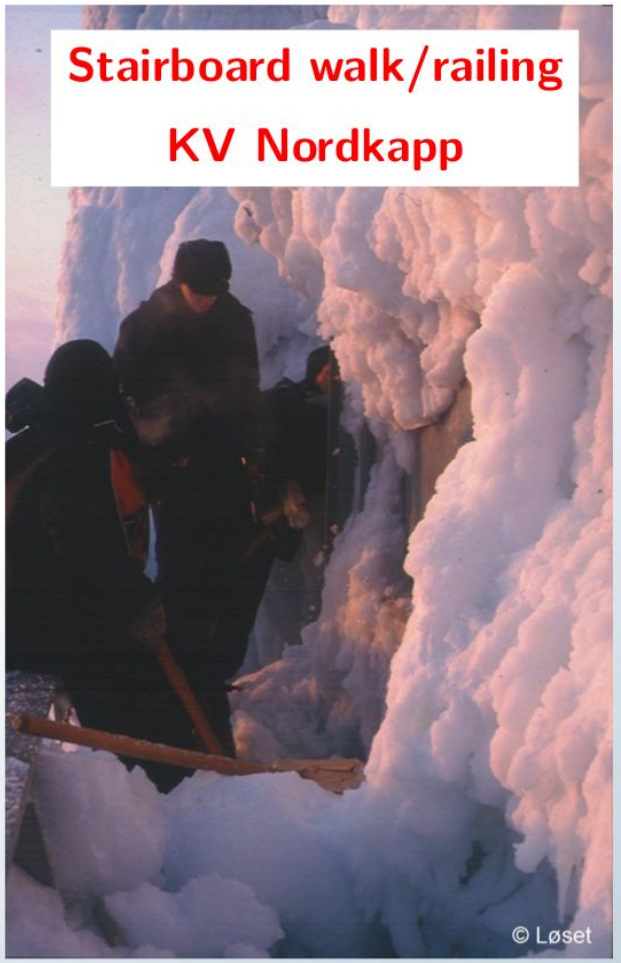


Photo: Sveinung Løset

https://www.youtube.com/watch?app=desktop&v=iQcf964yZK4



From Japan to Russia: Frozen Cars on the deck of the ship! Vladivostok.



Photo: Sveinung Løset

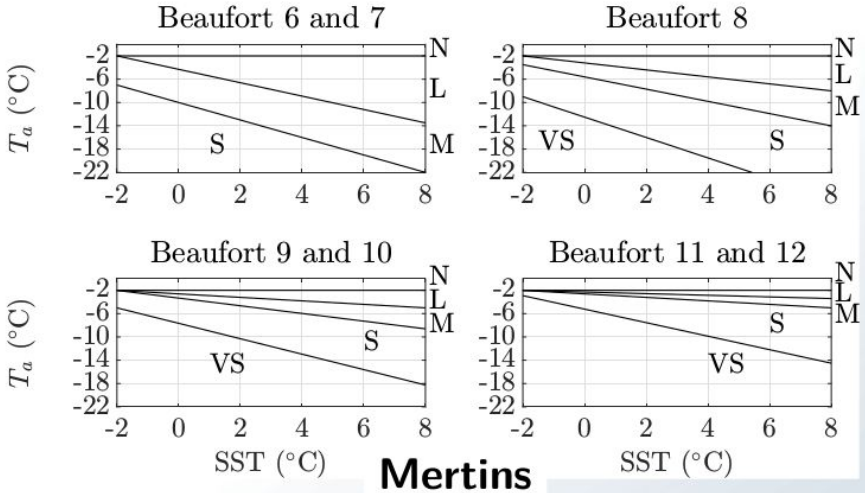
Samuelsen et al. (2015)
“Spray-icing during a most beautiful polar low”

Icing forecasts (Historically)

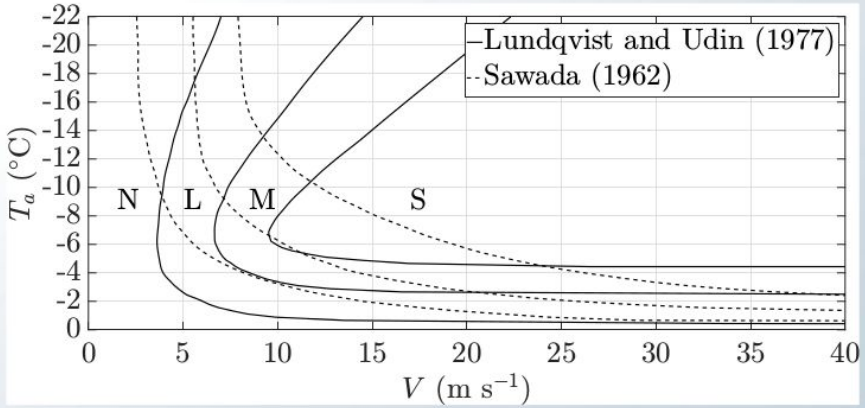
- Icing warnings
  → since 1960s/1970s
- Simple nomograms

Nomogram	Applied today in
Mertins (1968)	UK, Den., Nor.
Lundqvist and Udin (1977)	Germany, Sweden
Sawada (1962)	Japan, Canada

- Easy to apply.
  Difficult to verify.
- Little icing data + necessary atm./ocean/ship data exist



Mertins



LU, Sawada

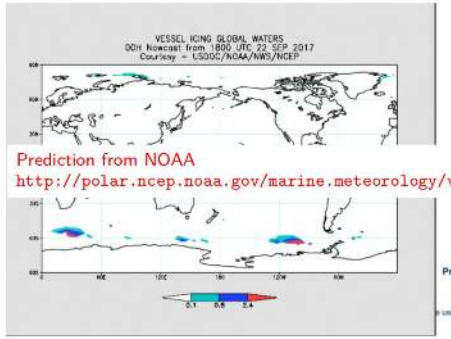
$$\mathrm{PPR} = \frac{V_a(T_f - T_a)}{1 + 0.3(T_w - T_f)}$$

Physics-based icing models

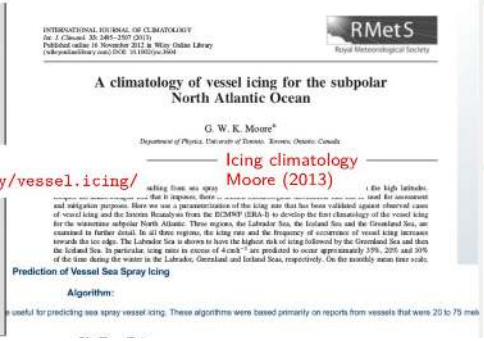
- Several wave-ship interaction icing models exist, e.g.:
  - Kachurin et al. (1974)
  - Stallabrass (1980)
  - Makkonen (1987)
  - Horjen (1990)
  - Lozowski et al. (2000)
  - Kulyakhtin (2014)
- Operational weather forecasting:

Model	Applied in
Overland (1990)	USA, Canada, Norway Sweden, Japan, Finland
Mod. Stallabrass (1980)	Canada, Norway

Overland (1990): the most applied model



Prediction from NOAA
http://polar.ncep.noaa.gov/marine.meteorology/vessel.icing/



Icing climatology
Moore (2013)

PhD thesis, Samuelsen (2017): https://hdl.handle.net/10037/11801

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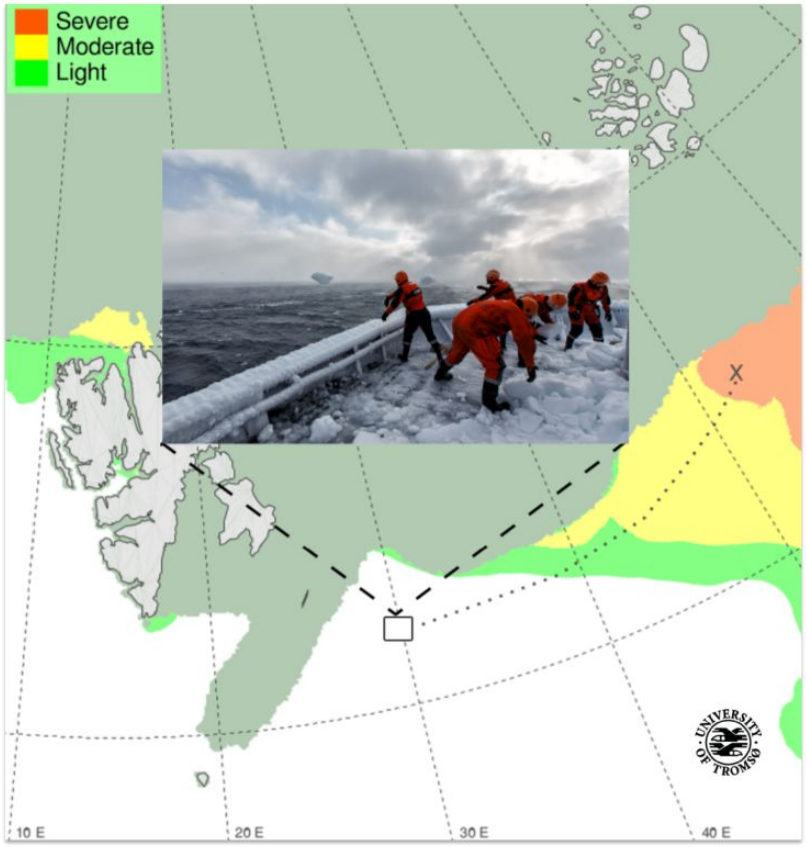
Faculty of Science and Technology
Department of Engineering and Safety IVT

Prediction of ship icing in Arctic waters

Observations and modelling for application in operational weather forecasting

—

Eirik Mikal Samuelsen
A dissertation for the degree of Philosophiae Doctor – June 2017



Main result:
Spray-icing model for ships based on heat-flux calculation and spray-flux calculation

2.3.2 Heat-flux calculation

A heat balance is calculated from the heat fluxes acting on the estimated R_w in the position at the horizontal mid-point of the almost vertical plate ($\gamma = 85\ ^\circ$). The full set of heat fluxes pr unit area acting on this plate may be written as:

$$Q_f = -Q_v - Q_k + Q_c + Q_e + Q_r + Q_d + Q_s + Q_{\text{cond}} \quad (5)$$

The fluxes on the right hand side of Eq. (5) are arranged in such a manner that they contribute to freezing if they are positive, and negative if they contribute to melting. These fluxes will then balance the heat released due to freezing (Q_f) on the left-hand side of Eq. (5). A short explanation of these fluxes is as follows:

- Q_f - Latent heat released during freezing
- Q_v - Viscous/frictional/aerodynamic heating from the air
- Q_k - Kinetic energy of spray converted to heat in the interaction process
- Q_c - Convective or sensible heat flux from the air
- Q_e - Evaporative or latent heat flux from the air
- Q_r - Heating or cooling from radiation (↓↑ LW, ↓↑ SW)
- Q_d - Heating or cooling from the spray
- Q_s - Heating or cooling from snow
- Q_{cond} - The conductive heat flux through the ice



Modelling wave-ship interaction icing

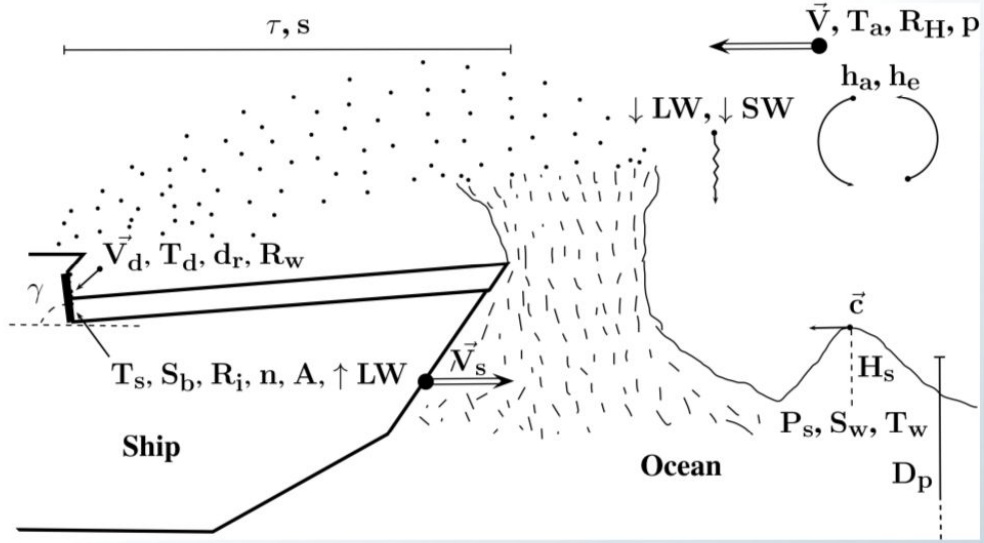
Wave-ship interaction is reckoned to be the most influential water source (Stallabrass, 1980; Zakrzewski, 1987; Lozowski et al., 2000).

Icing cause[a]

	Spray	Fog	Spray and fog	Fr. rain	Spray and fr. rain	N
Frequency	83.6%	6.5%	8.5%	0.3 %	1.1%	645

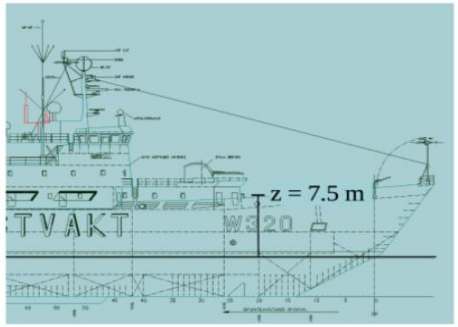
[a] Spray and snow or snow alone is not an option in the synop code

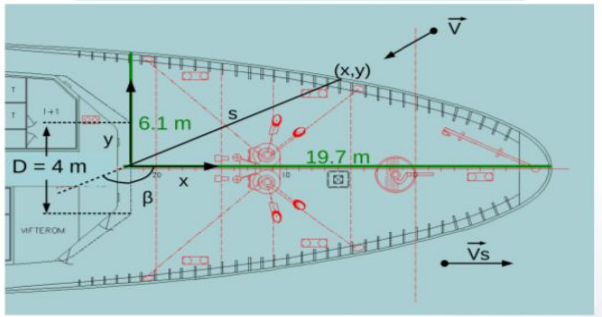
- Spray flux (R_w)
- Heat balance at a specific position of the ship ($Q_f = \sum_{i=1}^{N} Q_i$)
- Icing flux ($R_i = nR_w$)



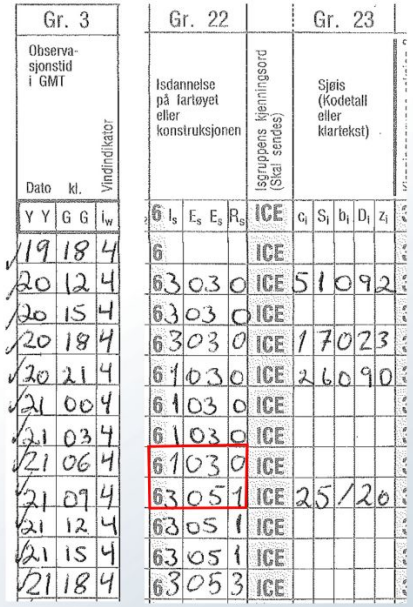
Sketch of wave-ship-interaction icing process

Using reference ship: KV Nordkapp



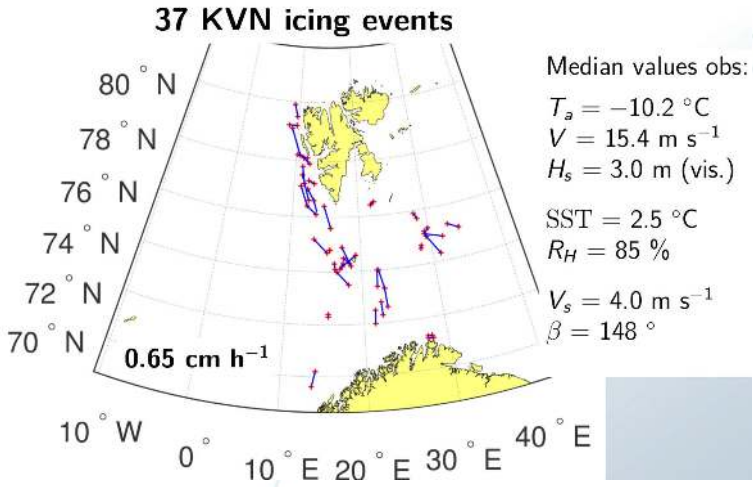


Above view/side view KV Nordkapp.



Gr. 3					Gr. 22						Gr. 23				
Observasjonstid i GMT				Vindindikator	Isdannelse på fartøyet eller konstruksjonen				Isgruppens kjenningsord (Skal sendes)		Sjøis (Kodetall eller klartekst)				
Dato		kl.													
Y Y	G G	i_w			6 I_s	E_s	E_s	R_s	ICE	c_i	S_i	b_i	D_i	z_i
19	18	4			6				ICE					
20	12	4			6	3	0	3	ICE	5	1	0	9	2
20	15	4			6	3	0	3	ICE					
20	18	4			6	3	0	3	ICE	1	7	0	2	3
20	21	4			6	1	0	3	ICE	2	6	0	9	0
21	00	4			6	1	0	3	ICE					
21	03	4			6	1	0	3	ICE					
21	06	4			6	1	0	3	ICE					
21	09	4			6	3	0	5	ICE	2	5	1	2	0
21	12	4			6	3	0	5	ICE					
21	15	4			6	3	0	5	ICE					
21	18	4			6	3	0	5	ICE					

Icing group in Ship synop code (19-21 January 1987).



Median values obs:

$T_a = -10.2$ °C
$V = 15.4$ m s^{-1}
$H_s = 3.0$ m (vis.)

SST $= 2.5$ °C
$R_H = 85$ %

$V_s = 4.0$ m s^{-1}
$\beta = 148$ °

Spray-flux calculation

Official U.S. Navy photo NH 98517 from the U.S. Navy Naval History and Heritage Command



Spray generation → complex process → many factors:

- Ship type, bow shape, movement, and velocity
- Wave characteristics (H_s, P_s, $\vec{c}$, $\vec{c_g}$)
- Variable in time. Pulsed-spray sequences → irregular.
- Empirically-derived expressions applying spray data from literature:

Important to use observed or modelled wave height from a physical model

Ri <= Rw (ice amount always less then spray amount in pure spray-icing events)

$$R_w = (\vec{V_d} \cdot \vec{n_1})\ I_{wc} N t_{dur}$$

Horjen (2013):

$$H_s = 0.752 V^{0.723} \quad \text{From North Sea}$$

$$P_s = 6.161 H_s^{0.252} \quad \text{From Tromsøflaket}$$

Borisenkov et al. (1975)

$$I_{wc} = 6.36 \times 10^{-5} H_s V_r^2 e^{(-0.55z)} \quad \text{Spray data from fishing boat}$$

Other parameters adjusted for large ship

$$\frac{d\vec{V}_d}{dt} + \frac{3}{4}\frac{C_d}{D}\frac{\rho_a}{\rho_w}|\vec{V}_{rel}|\vec{V}_{rel} - \vec{g^*} = 0, \quad \text{Traj. model for KV Nordkapp}$$

$\vec{n_1} = [\sin\gamma, 0, \cos\gamma]$ γ tilt angle of plate

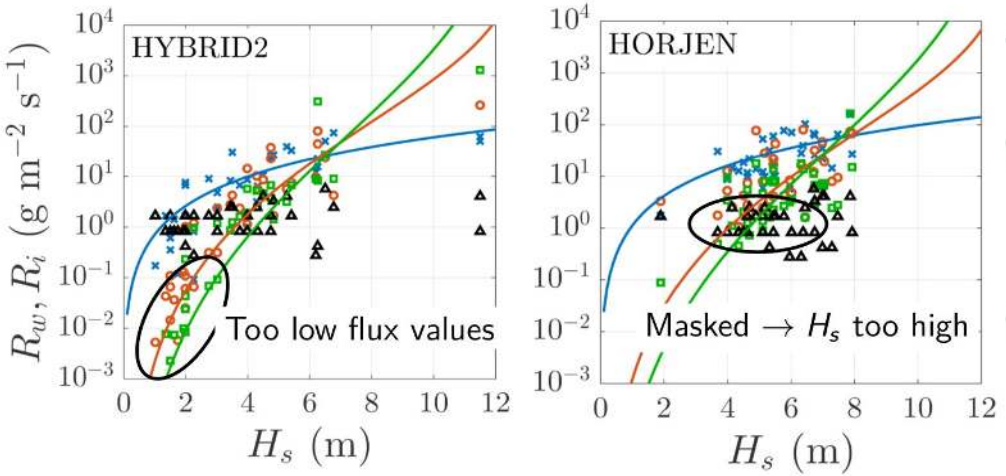
Time averaging terms!

$$N = \frac{V_r}{4\lambda}, \quad \text{Spray frequency large ship}$$

$$t_{dur} = 0.1230 + 0.7009\frac{V_r H_s}{V}, \quad \text{Expr. derived from USCGC Midgett data}$$

Spray-flux formulation vs wave height

x R_w Borisenkov, ○ R_w Horjen, □ R_w Horjen (2013), △ R_i obs



Heat balance

$$Q_f = Q_c + Q_e + Q_d + Q_r$$

Most important heat fluxes:

- $Q_f = L_{\mathrm{fs}} R_i = L_{\mathrm{fs}} \rho_i \frac{dh}{dt} = (1 - k^*) L_f \rho_i \frac{dh}{dt}$
- $Q_c = h_a (T_s - T_a)$
- $Q_e = h_a \frac{1738.6}{p} (e_s(T_s) - R_H e_s(T_a))$
- $Q_d = R_w c_w (T_s - T_{\mathrm{sp}})$
- $Q_r = \uparrow \mathrm{LW} - \downarrow \mathrm{LW} + \uparrow \mathrm{SW} - \downarrow \mathrm{SW}$
  $= \sigma (T_s + 273.15)^4 - \downarrow \mathrm{LW} - (1 - A) \downarrow \mathrm{SW}$

k*: interfacial distribution coefficient

$k^* = 0.3$ (30% spray water entrapped) (Makkonen, 2010)

$A = 0.56$ (ice albedo) (Curry and Webster, 1999)

$h_a = w_1 h_{\mathrm{ax}} + w_2 h_{\mathrm{ay}} \quad \rightarrow h_a \propto \mathrm{Re}^{0.8 \text{ to } 0.9}$ in a turb. flow (parameterization of turbulent transport)

Currently set to constant in the icing model. May easily be adjusted according to the results from the MICROSPRAY project.

Icing-rate calculation (dh/dt)

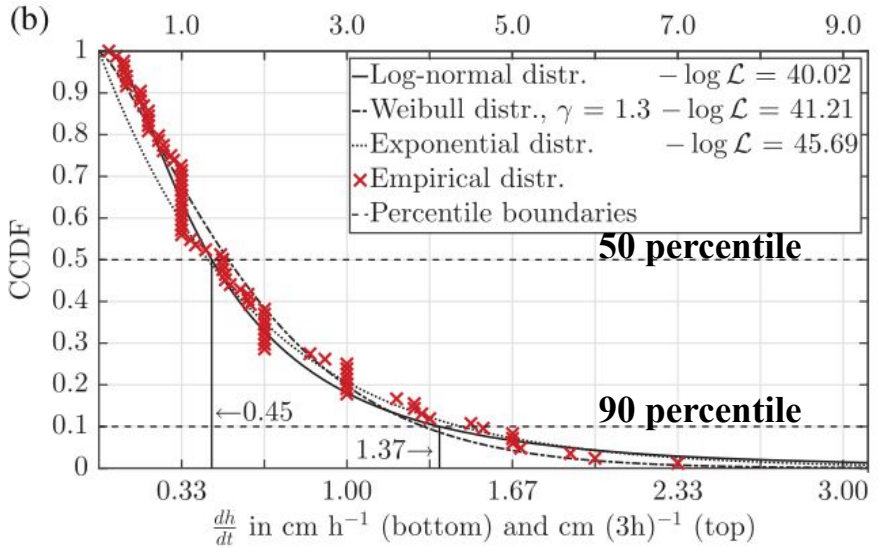
$$\frac{dh}{dt} \times 0.7 L_f \rho_i = f\left(T_a, p, R_H, T_{\mathrm{sp}}(\mathrm{SST}, T_d), \vec{V}, \vec{V}_s, \downarrow \mathrm{LW/SW}, R_w, T_s(S_b)\right)$$

$$R_w = f\left(\vec{V}, \vec{V}_s, H_s, P_s, \vec{c}(D_p, D_w, P_s), z\right)$$

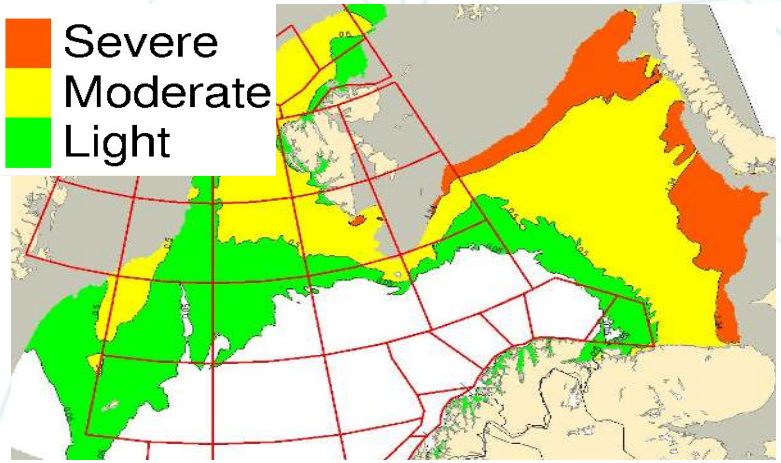
$$S_b = \frac{S_w}{1 - 0.7n}, \qquad T_s = -54.1126 \left(\frac{S_b(n)}{1000 - S_b(n)}\right)$$

- $T_{\mathrm{sp}} = \frac{T_d + \mathrm{SST}}{2}$ - separated and consolidated droplets
  - $\frac{dT_d}{dt} = \frac{6}{\rho_w c_w d_r}(Q_{\mathrm{cd}} + Q_{\mathrm{ed}})$ - separate spherical droplets (2 mm)
- Cannot freeze more water than available:
  - $R_i \leq R_w \rightarrow n = \frac{R_i}{R_w} \leq 1$
- $n = \frac{\rho_i \frac{dh}{dt}}{R_w}$ solved iteratively (steady ice growth controlled by time-averaged water amount and heat fluxes)

Icing-rate severity based on frequency



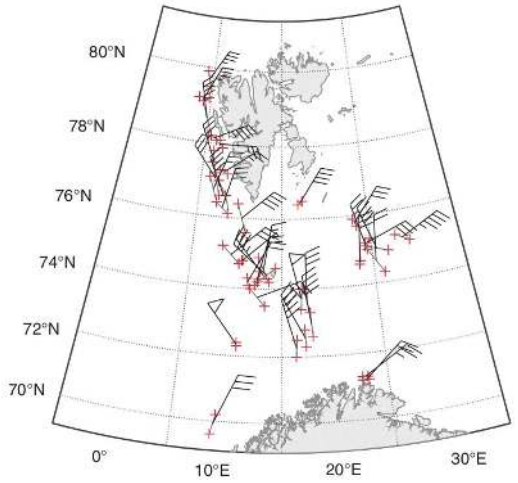
- Light: $x \leq 0.50$ cm h^{-1}
- Moderate: $0.50 < x \leq 1.34$ cm h^{-1}
- Severe: $x > 1.34$ cm h^{-1}



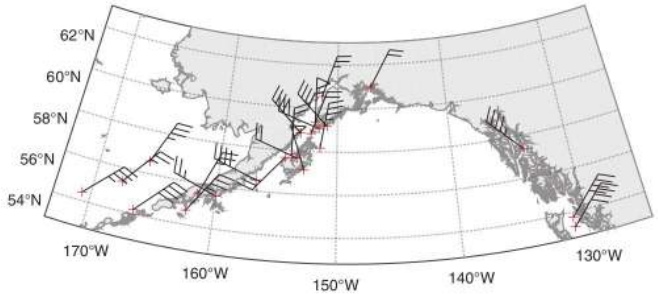
Verification in classes

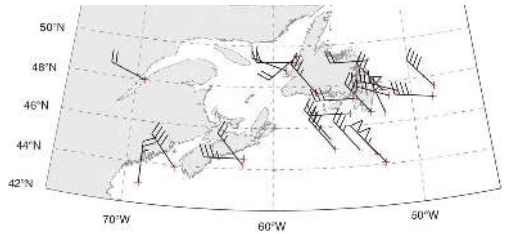
Modelname	KVN with no-icing ($N = 67$) PC	HSS	PSS	GMSS	All data ($N = 114$) PC	HSS	PSS	GMSS
New category definition								
Ref. (unif.)†	**0.34**	**0.11**	**0.13**	**0.19**	**0.32**	**0.09**	**0.09**	**0.14**
Ref. (obs.)††	0.42	0.13	0.13	0.14	0.37	0.10	0.10	0.10
Over	0.21	0.05	0.07	**0.28**	0.25	0.07	0.08	**0.22**
Over bulk 2	0.30	0.07	0.08	**0.22**	**0.42**	**0.16**	**0.15**	**0.24**
ModStall	0.19	0.05	0.06	**0.26**	0.25	**0.10**	**0.12**	**0.29**
MINCOG	**0.40**	**0.17**	**0.18**	**0.30**	**0.45**	**0.20**	**0.20**	**0.26**
Mertins	**0.34**	**0.14**	**0.16**	0.39	**0.37**	**0.18**	**0.19**	0.32
LU	0.18	0.02	0.03	**0.26**	0.21	0.03	0.03	**0.20**
Sawada	0.19	0.04	0.04	**0.28**	0.27	0.09	**0.10**	**0.24**

Coast guard data.
KV Nordkapp ship type



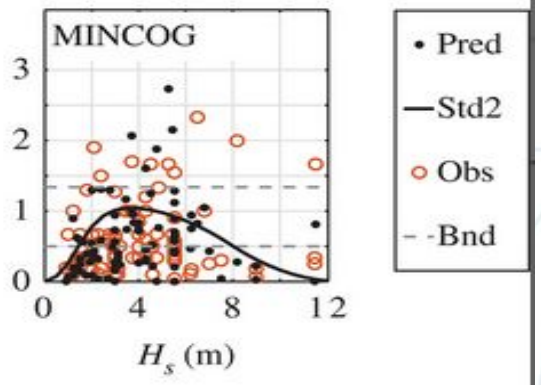
Data from Alaska and Canada (and KV Nordkapp). Differ types of ships.



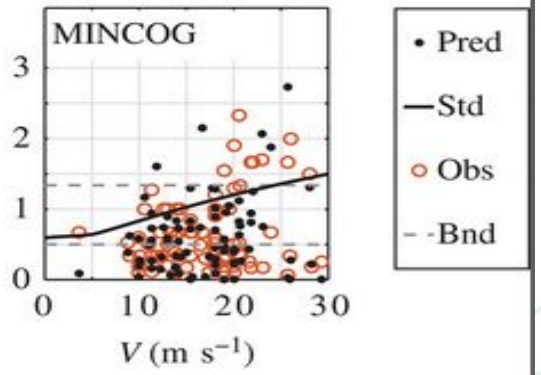


3 most important parameters:

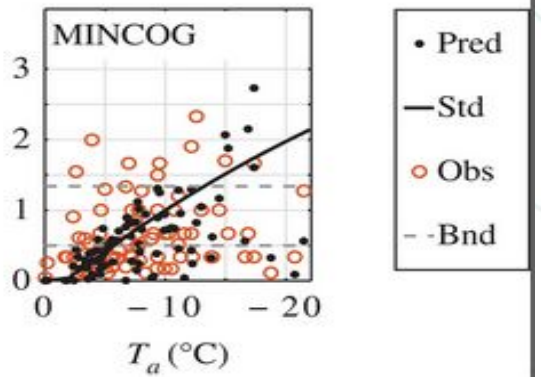
Wave height



Wind speed

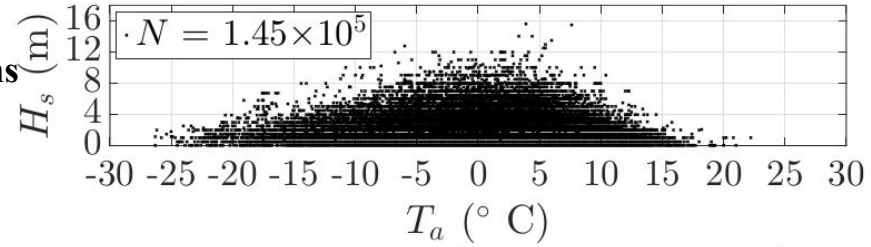


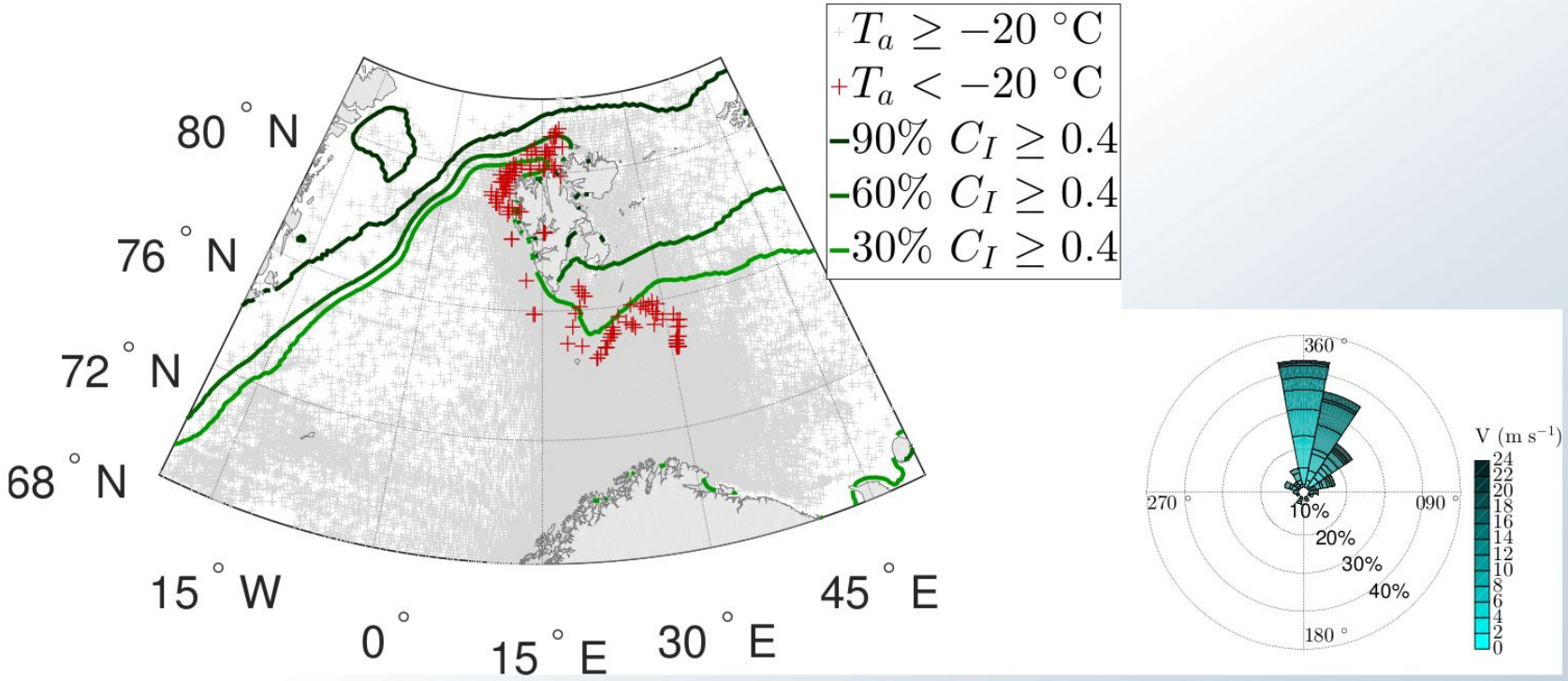
Air temperature



High H_s and low T_a rarely coexist in nature

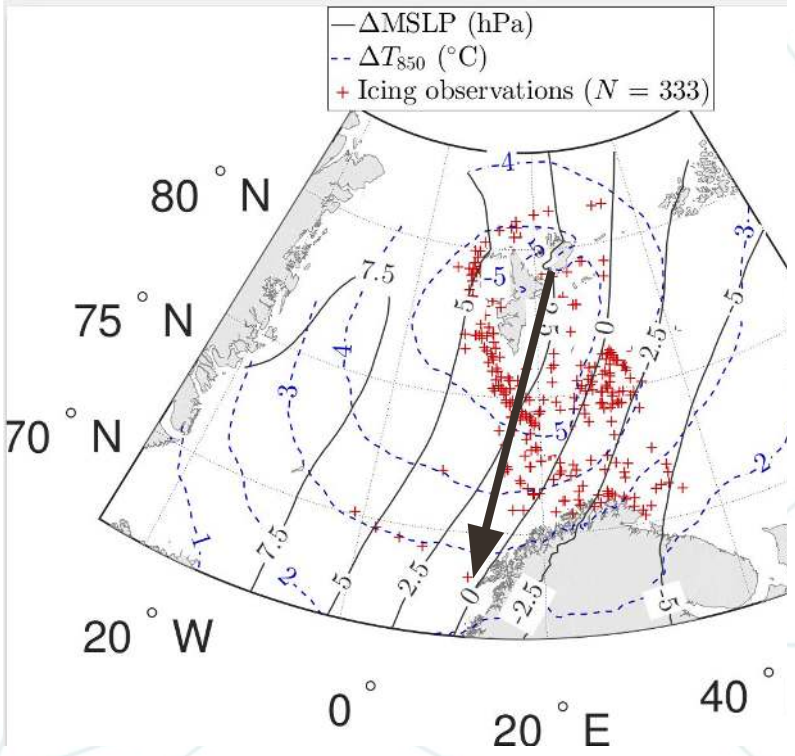
145.000 ship observations with wave heights and temperature





145,000 ship observations (1976-2007)

MSLP anomaly and T850 anomaly during icing events



Mean flow during icing events

Derivation of Overland model

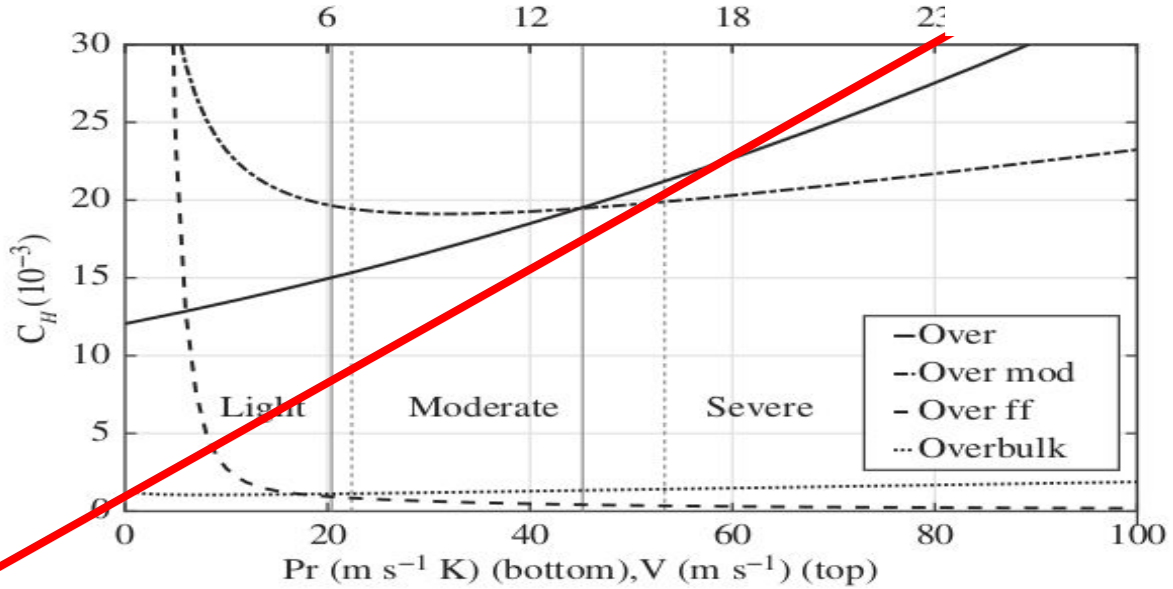
Assuming only convective heat flux, and heat flux from spray:

$$Q_f = Q_c + Q_d$$

- assuming $T_s = T_f$ (no salt expulsion during freezing) which is set const. to $-2^{\circ}\mathrm{C}$ (35 ppt)
- no cooling of spray temperature in air ($T_{\mathrm{sp}} = \mathrm{SST}$)
- heat transfer between ocean and atmosphere = heat transfer between brine water on ship and atmosphere (Bulk formula)
- fraction (n) between spray water and the water that freezes is const. $\rightarrow R_w$ indirectly dependent on the parameters determining freezing (T_a, SST, V)

Too high convective heat transfer!

Do not apply!



met/vessel/predict.html

>83.0	
Extreme	
>4.0	
>1.6	

MINCOG model in an operational system

Atmospheric variables

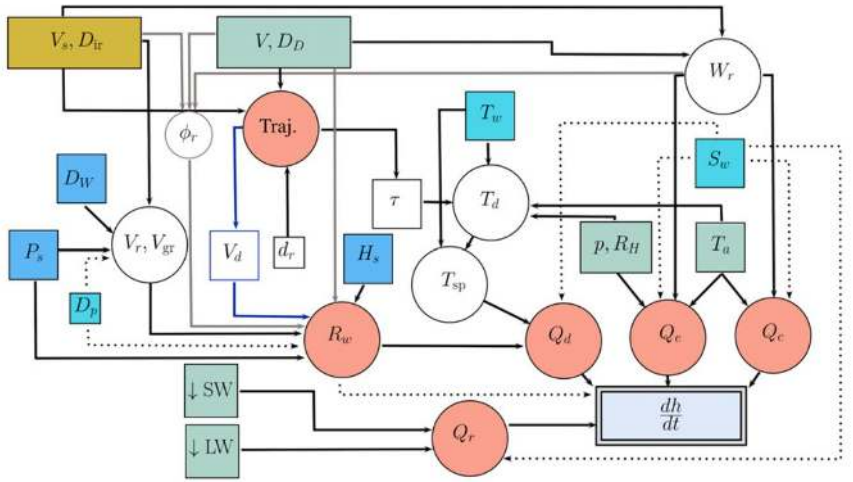
Ocean-wave variables

Ocean variables

Ship variables

Spray-flux calculation

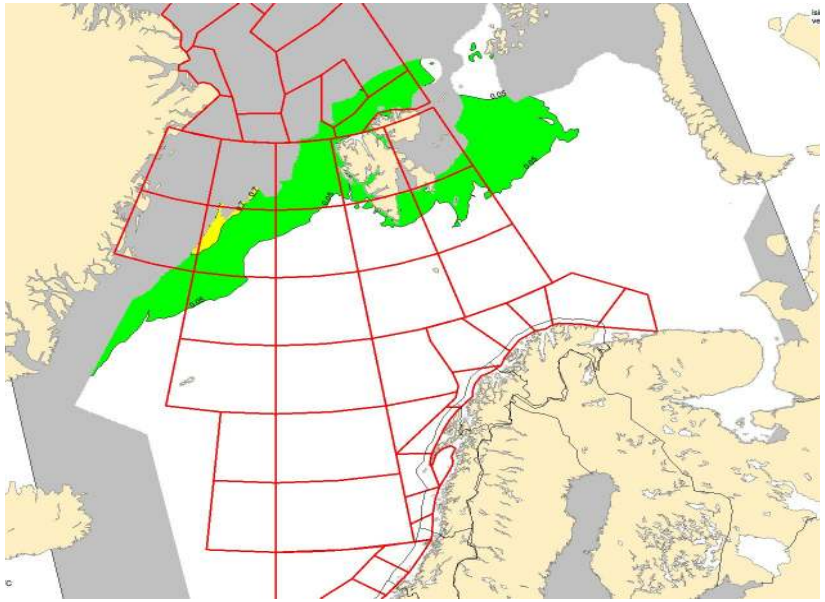
Icing-rate calculation



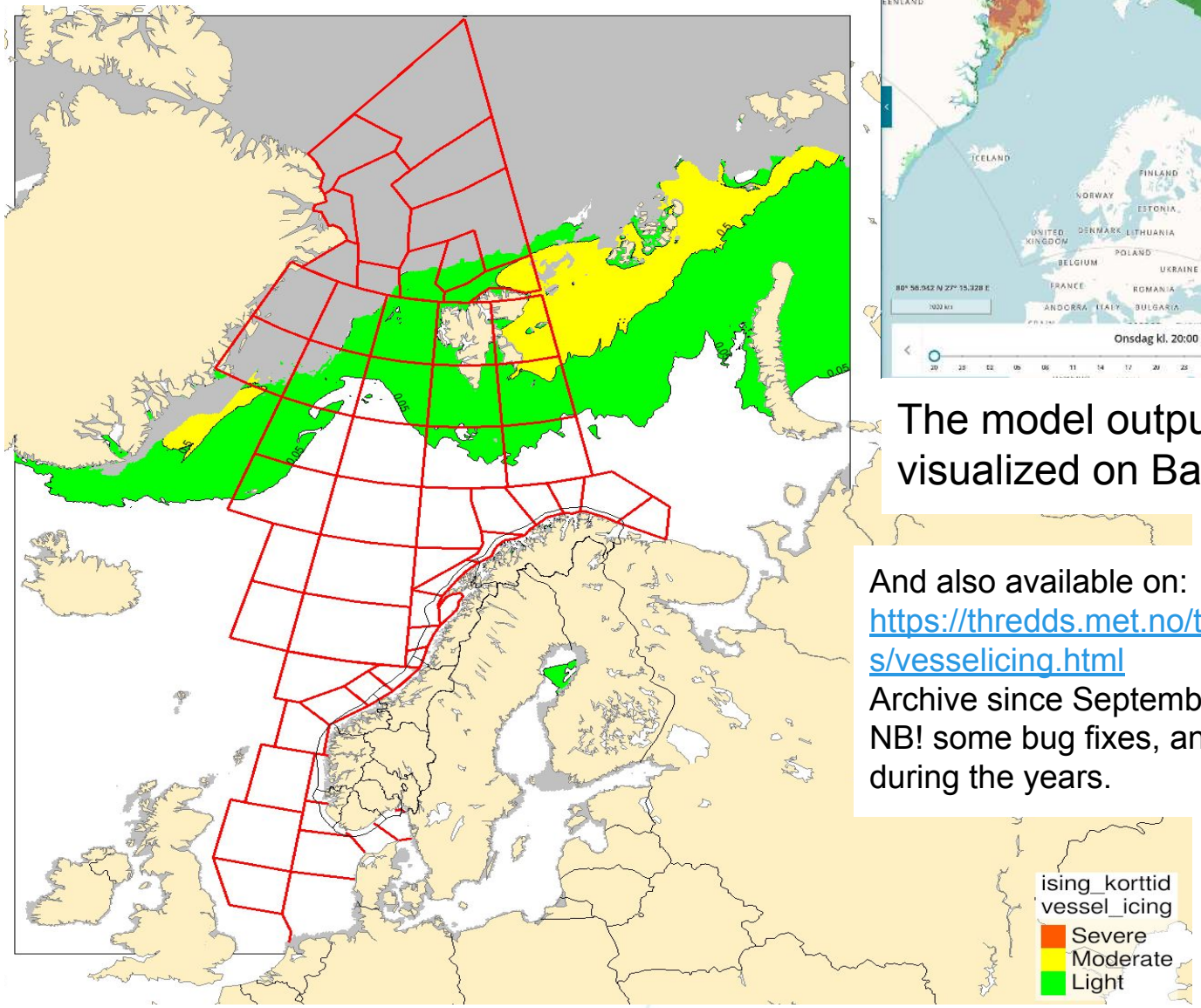
Samuelsen et al., 2017

Updated domain in October 2021

Previous domain



New domain





The model output is visualized on Barentswatch

And also available on:
https://thredds.met.no/thredds/projects/vesselicing.html
Archive since September 2019
NB! some bug fixes, and changes during the years.

Ship variables set to constant values:
vs = 5 m/s
beta = 180 degree
(but may also be calculated in a more dynamic manner)

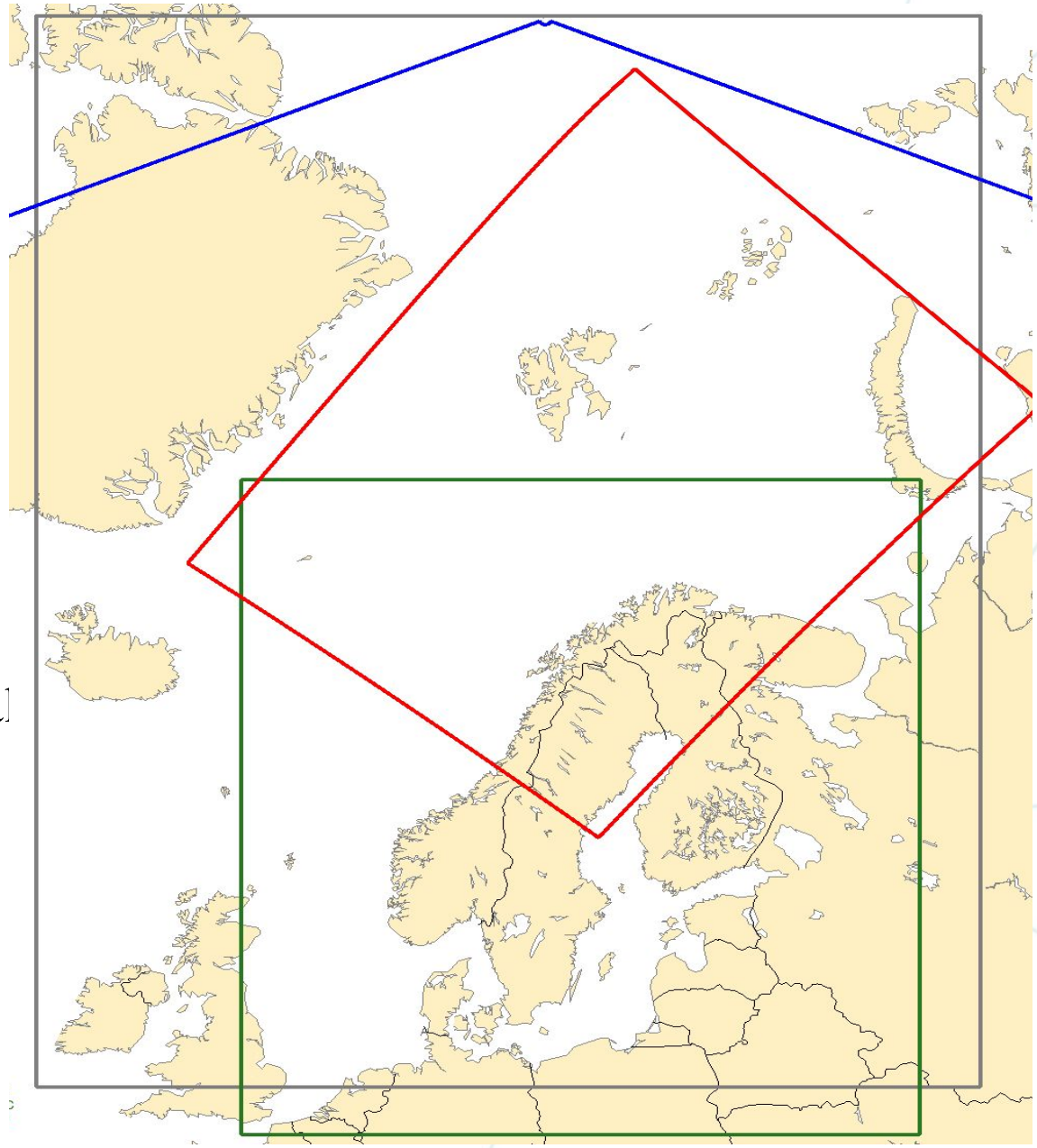
Atmospheric input

Arctic 2.5 km + MEPS 2.5 km + ECMWF
(AA first, then MEPS, finally ECMWF)

- Wind speed 10 m
- Temperature 2 m
- Relative humidity 2 m
- MSLP

Some assumptions:

- Incoming shortwave radiation (SW) = 0
- Incoming longwave radiation (LW) equal to:
- 0.7 * sigma * T^4

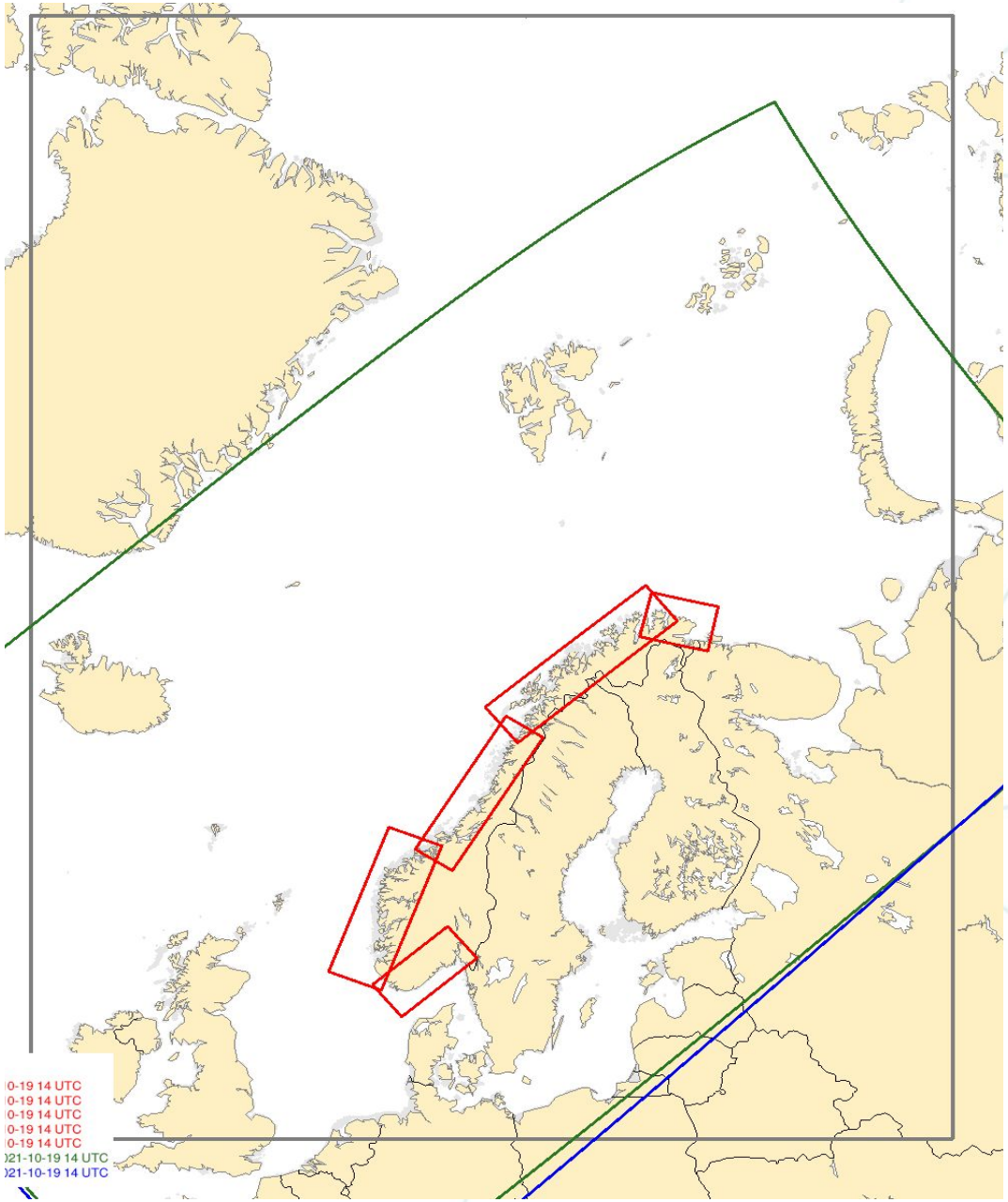


Wave models

Wam 800 m (5 models, MEPS wind) + Wam 4 km (ECMWF + MEPS wind) + Wam 3 km (ECMWF wind)

- Sig. wave height
- Mean wave period

(Ideally take the wave spectrum and the energy of the waves hitting the ship better into account)

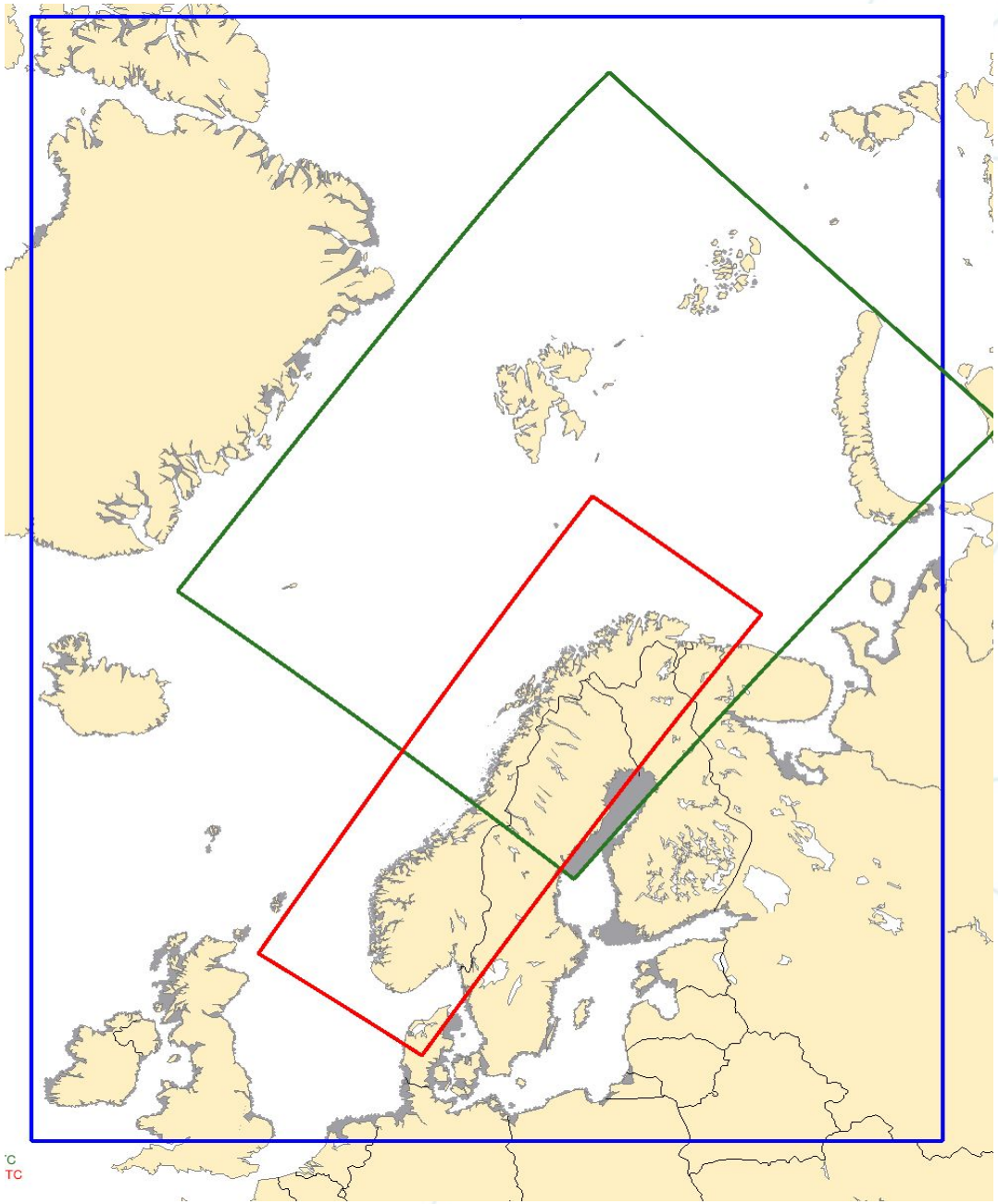


Ocean models

Norkyst 800 m + Barents 2.5 km + Topaz5

- Sea water salinity
- Sea ice (undefined with above 40 % ice-concentration, no sea ice in Norkyst 800 m)
- Depth (for wave-speed calculation)
- Sea-surface temperature (may also be extracted from Arome/IFS)

Salinity is important when there is large variation in it, e.g. in Bottenviken where there is low salinity



Icing warnings in 2021

12 warnings issued on the coast/in the fjords of mainland Norway in 2021:

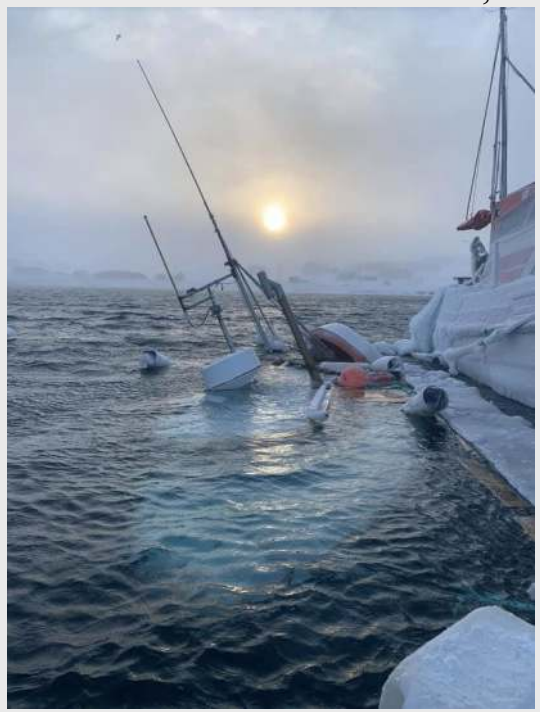
- 2 incidents of severe icing:
- Frank (21 -22 January 2021)
- Orange wind and icing warning (21-23 February 2021)

This is a high number. Most warnings are normally issued further north.

Ukenr.	Startdato	Evt. sluttdato	Tag	Farevarselområder	Farevarsel	Observasjoner?
1	07.01.2021	08.01.2021		Kyst- og fjordstrøkene i Finnmark	1	
1	08.01.2021	10.01.2021		Kyst- og fjordstrøkene i Finnmark	1	
2	11.01.2021	12.01.2021		Kyst- og fjordstrøkene i Finnmark	1	
3	20.01.2021	20.01.2021		Troms, Kyst- og fjordstrøkene i Finnmark	1	
3	21.01.2021	22.01.2021	Frank	Troms	2	2?
3	21.01.2021	22.01.2021	Frank	(Nord-)Helgeland, Salten, Ofoten, Lofoten og Vesterålen, Kyst- og fjordstrøkene i Finnmark	1	
3	23.01.2021			Ofoten, Kyst- og fjordstrøkene i Finnmark	1	
3	23.01.2021	(24.01.2021)	Senere kansellert for 24.01	Troms	1	1?
4	29.01.2021	30.01.2021		Troms, Kyst- og fjordstrøkene i Finnmark	1	
5	05.02.2021	10.02.2021		Rogaland, Agder, Telemark, Trøndelag	1	0/1?
7/8	21.02.2021	23.02.2021	Oransje farevarsel	Øst-Finnmark	2	2?
7/8	21.02.2021	23.02.2021	Oransje farevarsel	Nord-Troms og Vest-Finnmark	2	2?
8	**22.02.2021**	**23.02.2021**		Vest-Finnmark	1	2?
8	23.02.2021	23.02.2021		Øst-Finnmark	1	
10	09.03.2021	12.03.2021		Finnmark	1	1?
11	19.03.2021	19.03.2021		Øst-Finnmark	1	1?
47/48	28.11.2021	30.11.2021		Troms og Kyst og fjordstrøkene i Finnmark	1	1?
48/49	04.12.2021	08.12.2021	Først til 6/12, senere 7/12 12 UTC, senere 08/12 07 UTC	Øst-Finnmark, fra søndag 5/12 vesentlig i Varangerfjorden	1	
49	06.12.2021	08.12.2021	Fra 7/12, sør og nord splittet med ulik varighet.	Nord-Trøndelag + Helgeland, Salten, Lofoten og Ofoten	1	
49	09.12.2021	10.12.2021		Øst-Finnmark	1	
51	22.12.2021	23.12.2021	N-NW case	Nord-Troms + Kyst og fjordstrøkene i Finnmark	1	

Some of these cases

Hammerfest, Photo: iFinnmark/private





Båtsfjord/Kildinbanken, Photo: ?



Torsvåg, Photo: Audun Mathiassen



Dyrøy, Photo: Cecilie Larsen

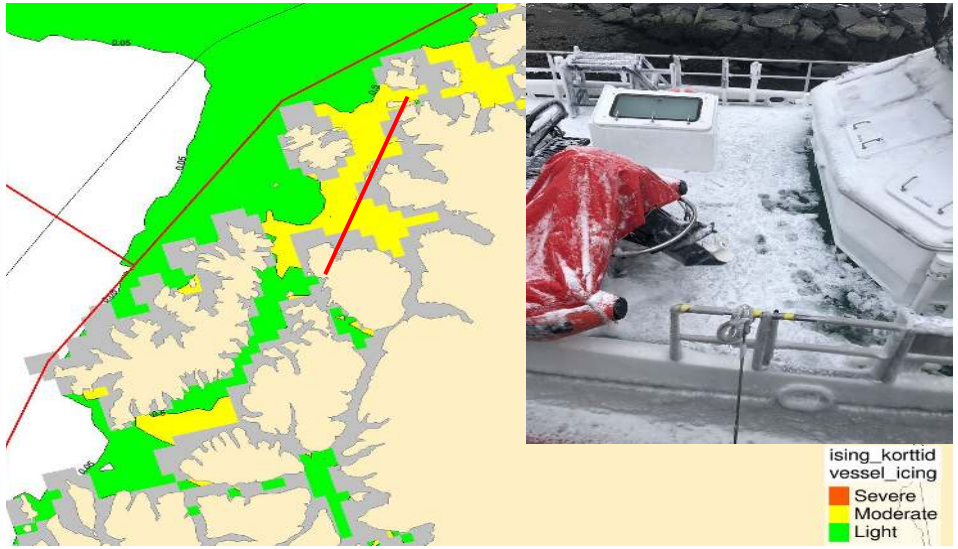


Åsgårdsstrand (Ytre Oslofjord)

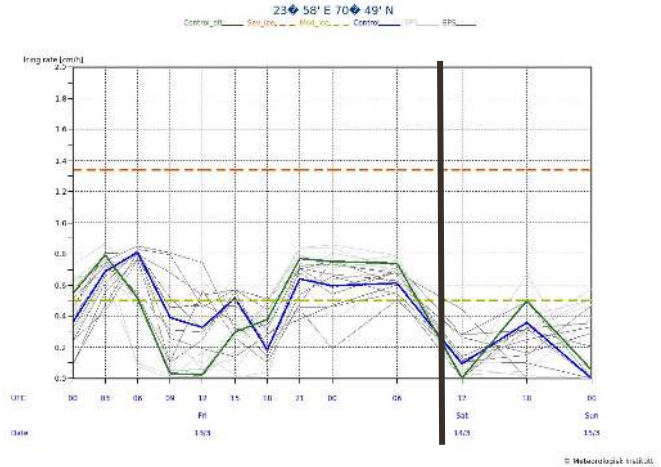


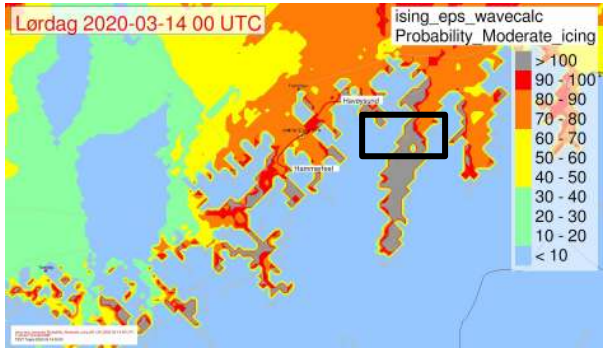
Photo: Kristian T Bollæren

Testing out different EPS methods



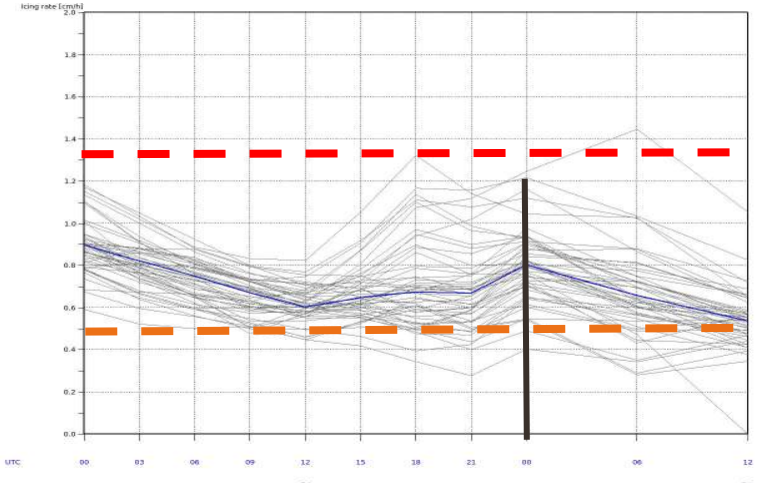
Wave height and period calculated from AAeps wind speed and constant fetch. SST from AA.
2 spray flux formulation tested. 22 members



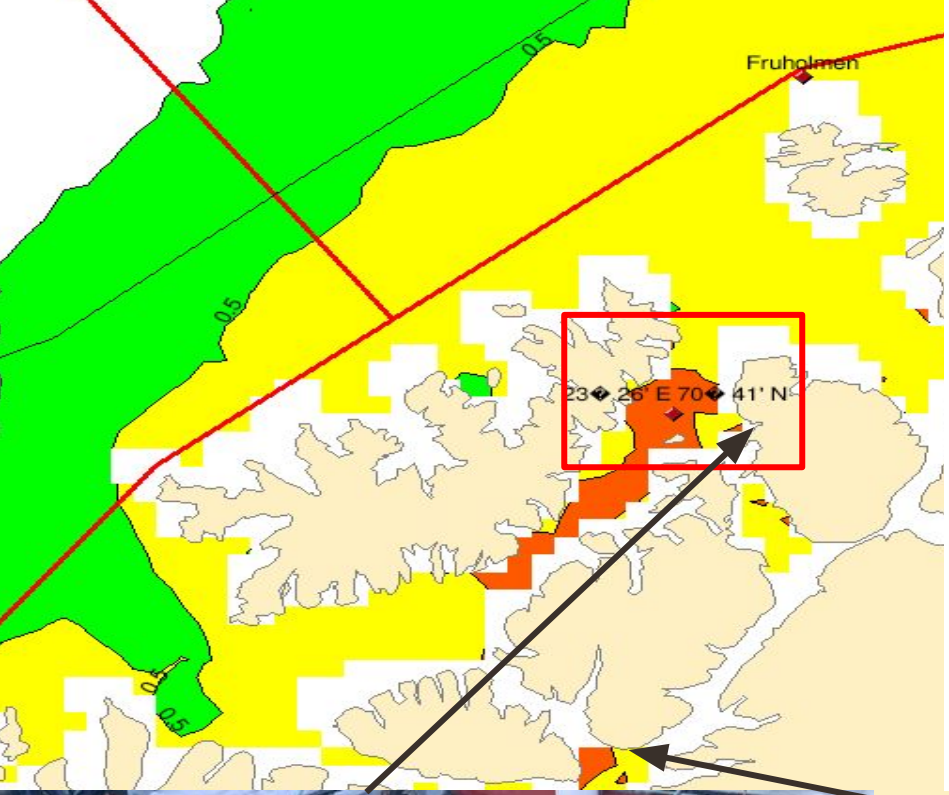


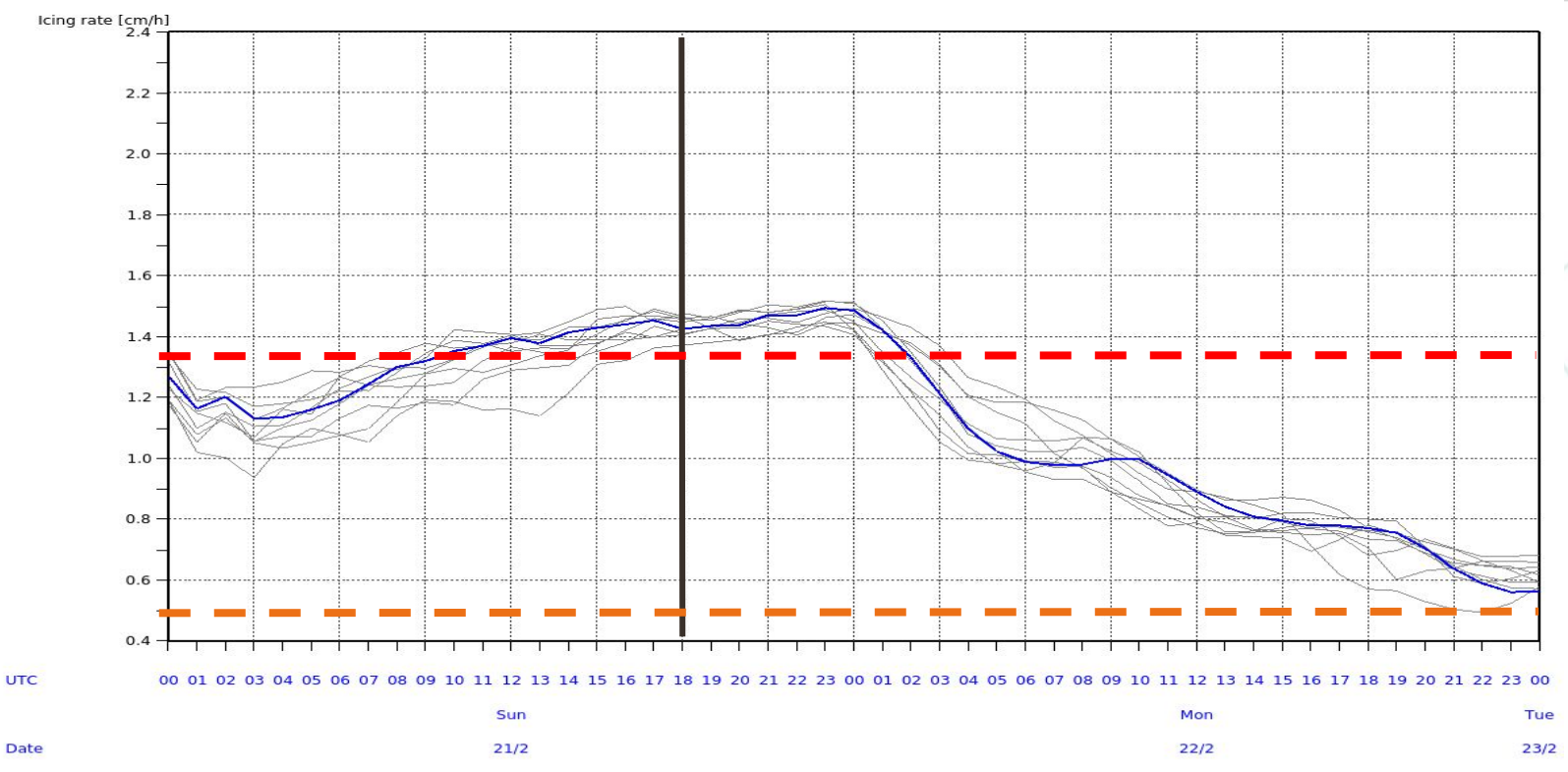
Wave height and period from wam 4km.
Standard spray flux formulation tested. 51 members

ECEPS



Probability for moderate icing
Suboptimal to calculate waves from winds with constant fetch







Hammerfest, Photo: iFinnmark/private

Hakkstabben, Photos: Merete Bergly





Icing warnings in 2022

10 warnings issued on the coast/in the fjords of mainland Norway so far in 2022:

- No incidents of severe icing issued, probably one observed.
- Orange wind warning (4 February 2022)

Rare to have icing so late in the season as 28 April 2022

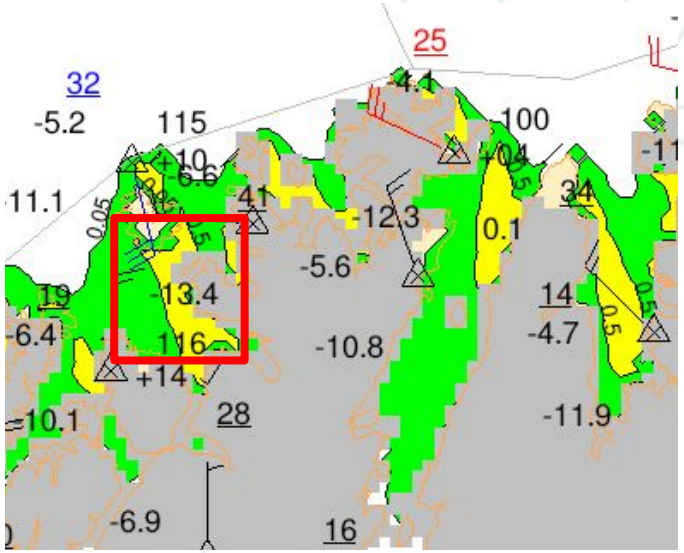
	Startdato	Evt. sluttdato	Tag	Farevarselområder	Farevarsel	Observasjoner?
1	03.01.2022	06.01.2022		Kyst- og fjordstrøkene i Finnmark	1	1?
1	07.01.2022	08.01.2022		Øst-Finnmark	1	
2	10.01.2022	12.01.2022		Øst-Finnmark	1	
3	22.01.2022	23.01.2022		Øst-Finnmark	1	
5	01.02.2022	03.02.2022		N-Trøndelag/Nordland	1	
5	03.02.2022	04.02.2022	Oransje farevarsel vindkast	Nordland	1	
5	03.02.2022	05.02.2022	Oransje farevarsel vindkast (forlenget oppdatering av varighet på isingen)	Troms	1	2?
5	04.02.2022	06.02.2022	Oppdatert 5/2 12UTC, senere 6/2 00UTC	Kyst- og fjordstrøkene i Finnmark	1	
6	13.02.2022	13.02.2022	Stor synoptisk usikkerhet gjorde at Vest-Finnmark ble glemt.	Øst-Finnmark	1	
			Bra case for EPS varsling.			
8	23.02.2022	24.02.2022		Troms + Kyst- og fjordstrøkene i Finnmark	1	
8	25.02.2022	26.02.2022	NW case	Kyst- og fjordstrøkene i Finnmark	1	
10	07.03.2022	08.03.2022		Øst-Finnmark	1	
12	25.03.2022	26.03.2022	N-NW case	Kyst- og fjordstrøkene i Finnmark	1	1
17	26.04.2022	27.04.2022	N-NW late April case. Snow and spray icing	Nord-Troms + Kyst- og fjordstrøkene i Finnmark	1	1
17	27.04.2022	28.04.2022	NW-W case, E-Finnmark	Kyst- og fjordstrøkene i Finnmark	1	



26 March 2022. Pure spray icing. Photo: Redningsselskapet



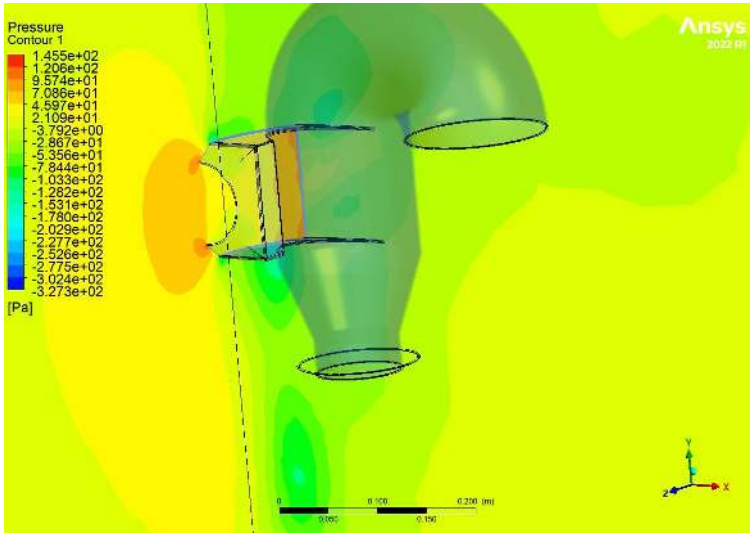
26 April 2022. Spray and snow icing. Photo: Redningsselskapet



Even without considering snow there is some moderate icing in the model

Sushmit will focus on measurements and data collection of spray (and other variables) in SPRICE





Fish farms- fixed location

Spray measurements in Gratangen



May wind-generated spray in conjunction with mountain waves be included in the model?

Wind generated spray



Downslope windstorms

Photo: Bernt Aksel Jensen, 23.08.2022



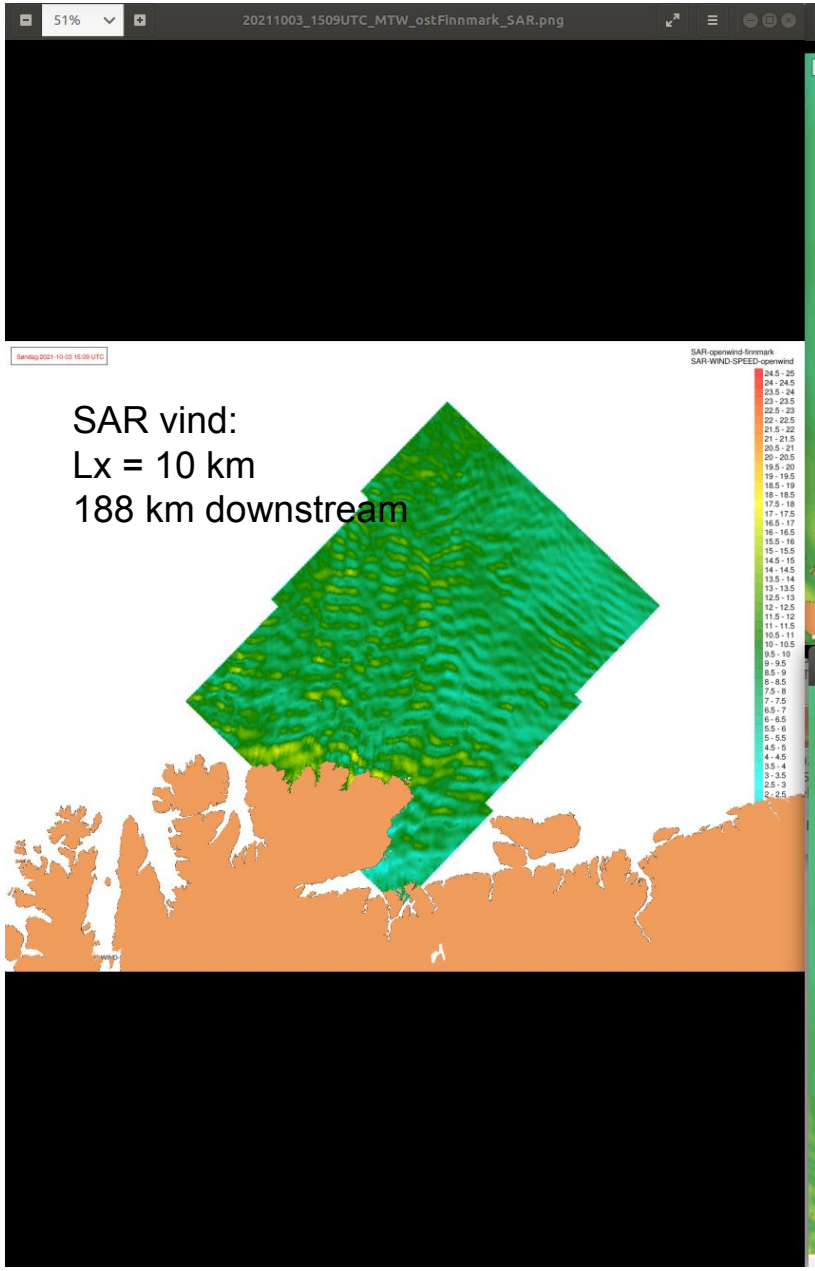
Photo: Mary-Ann Ring, 14.09.2014



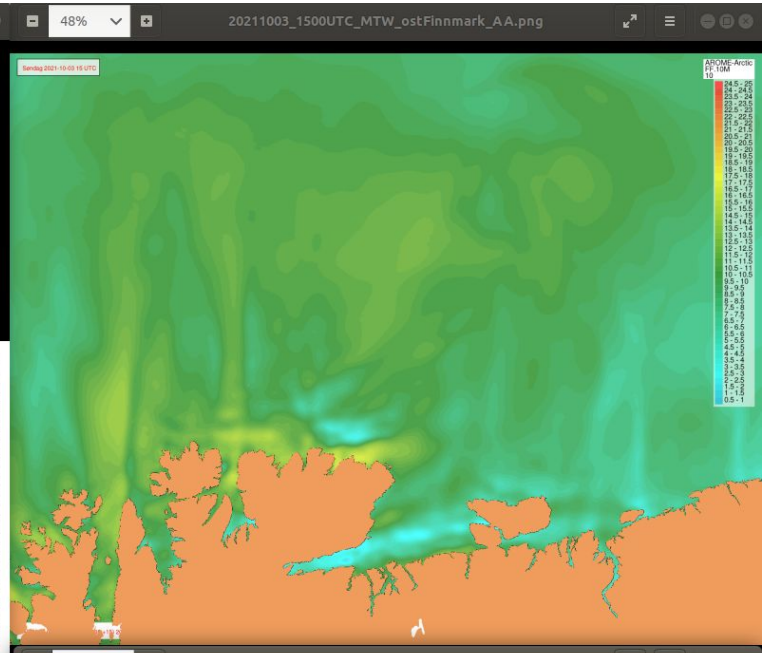
Photo: ✞ Heidi Nilima Monsen, 26.05.2018



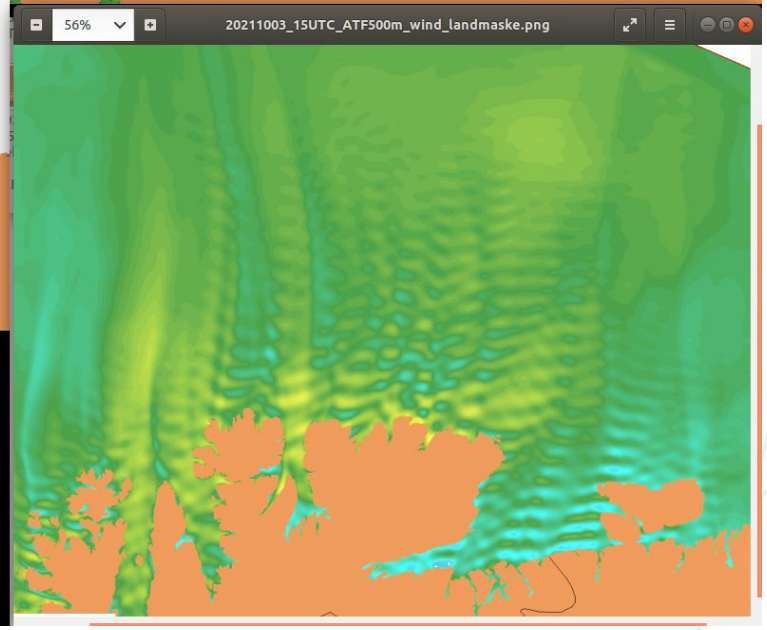
But then we probably would need a better atmospheric model



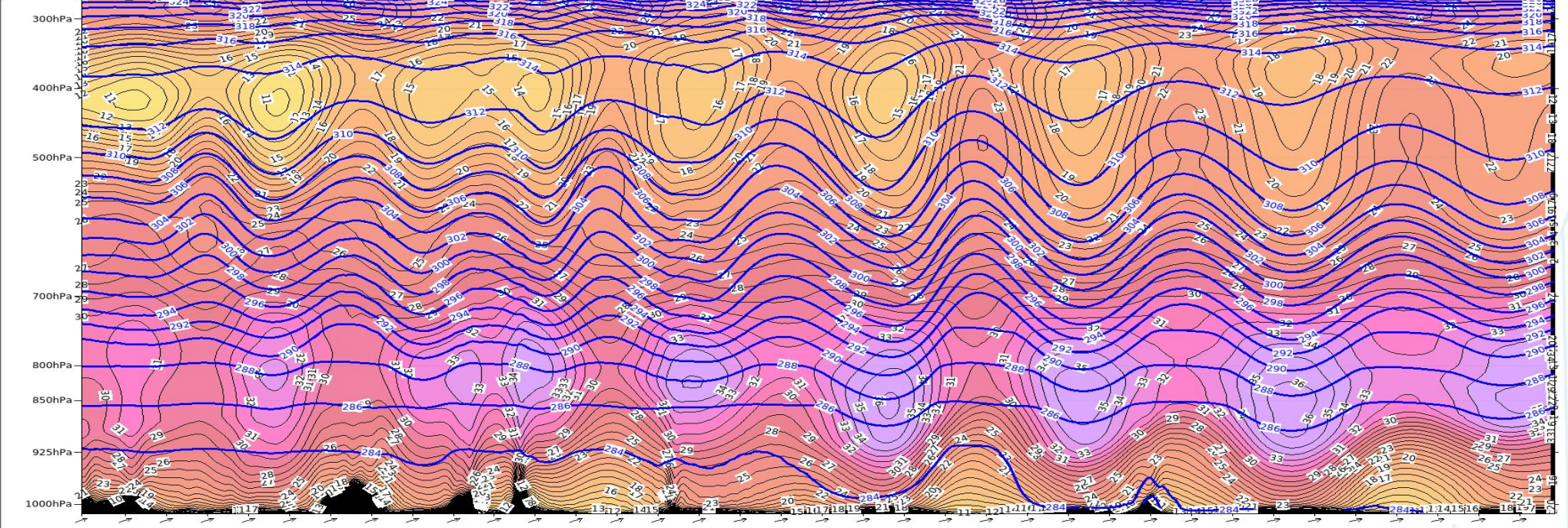
SAR vind:
Lx = 10 km
188 km downstream



Arome Arctic
dx = 2.5 km
20 km
downstream

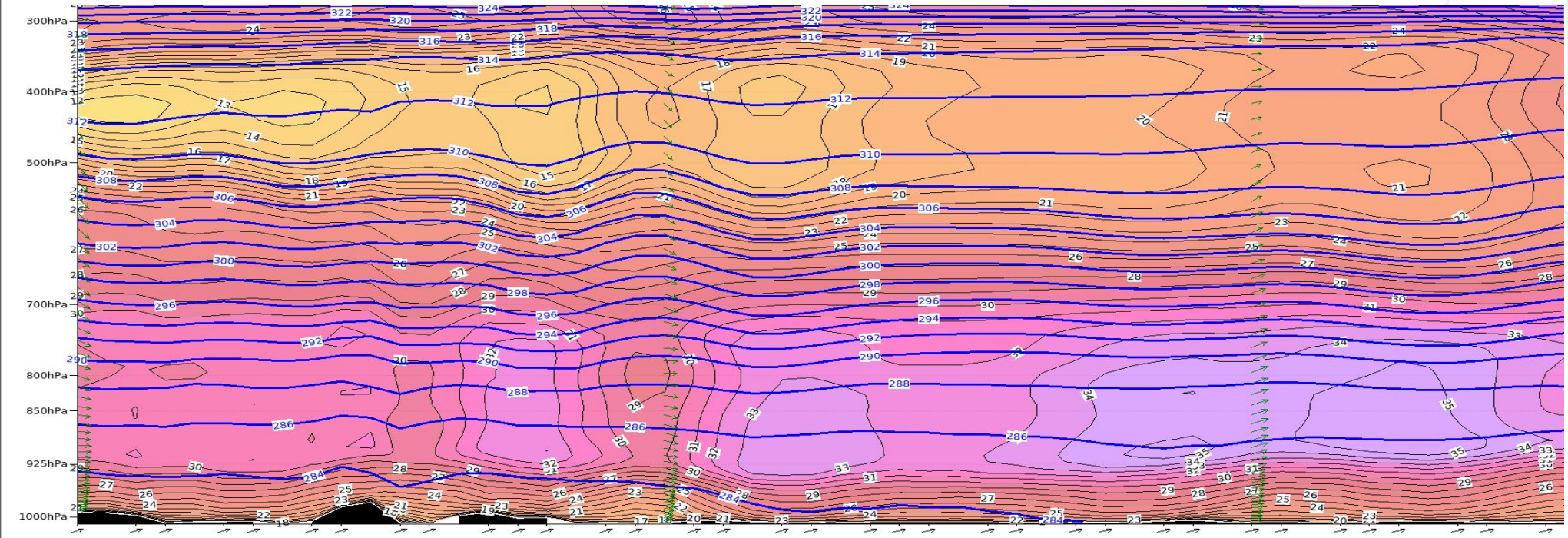


Arome 500 m
dx = 0.5 km
No DA.
150 km
downstream.



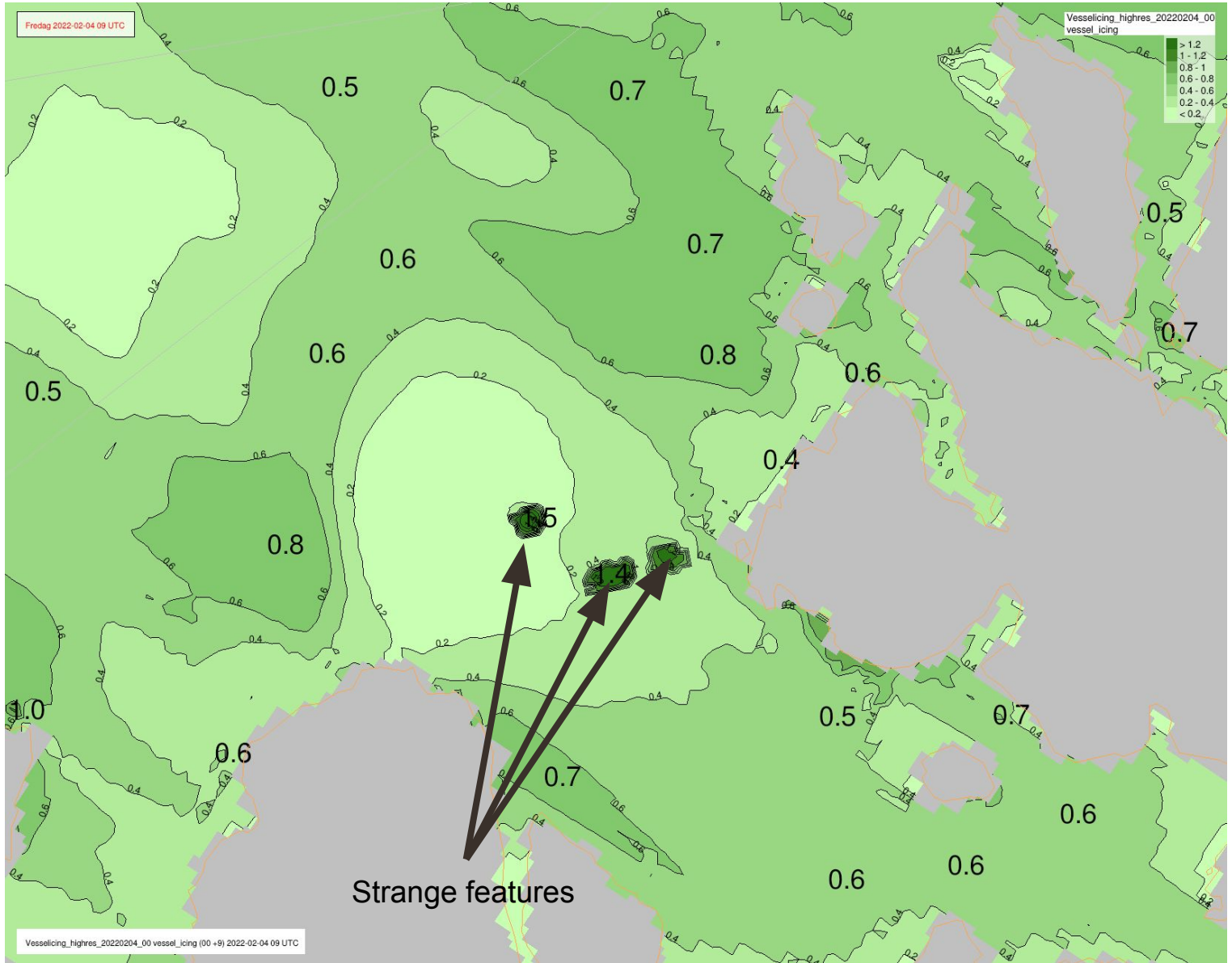
Arome dx = 300 m

- Potential temperature
- Wind speed

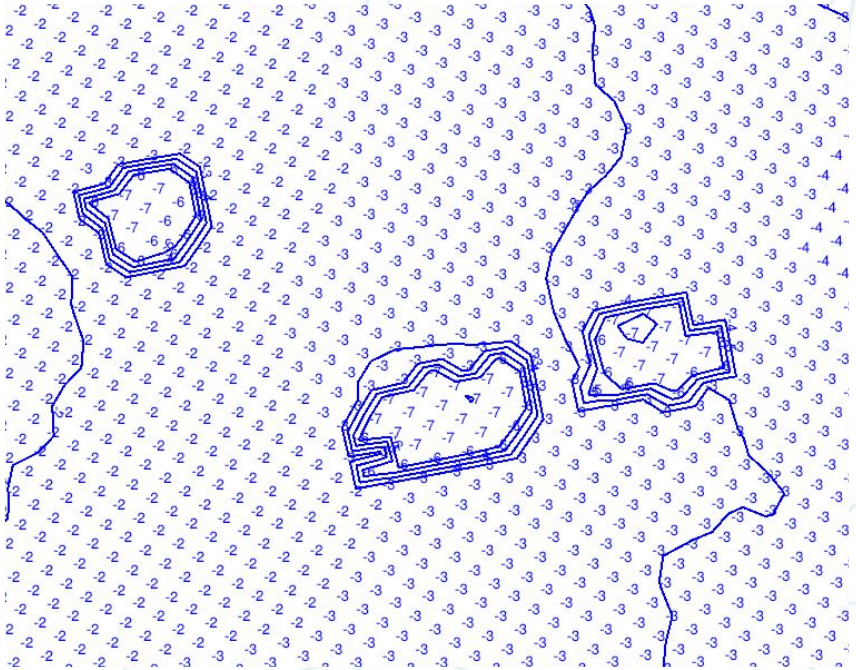


Arome dx = 2500 m
(operational model used in current icing forecasts)

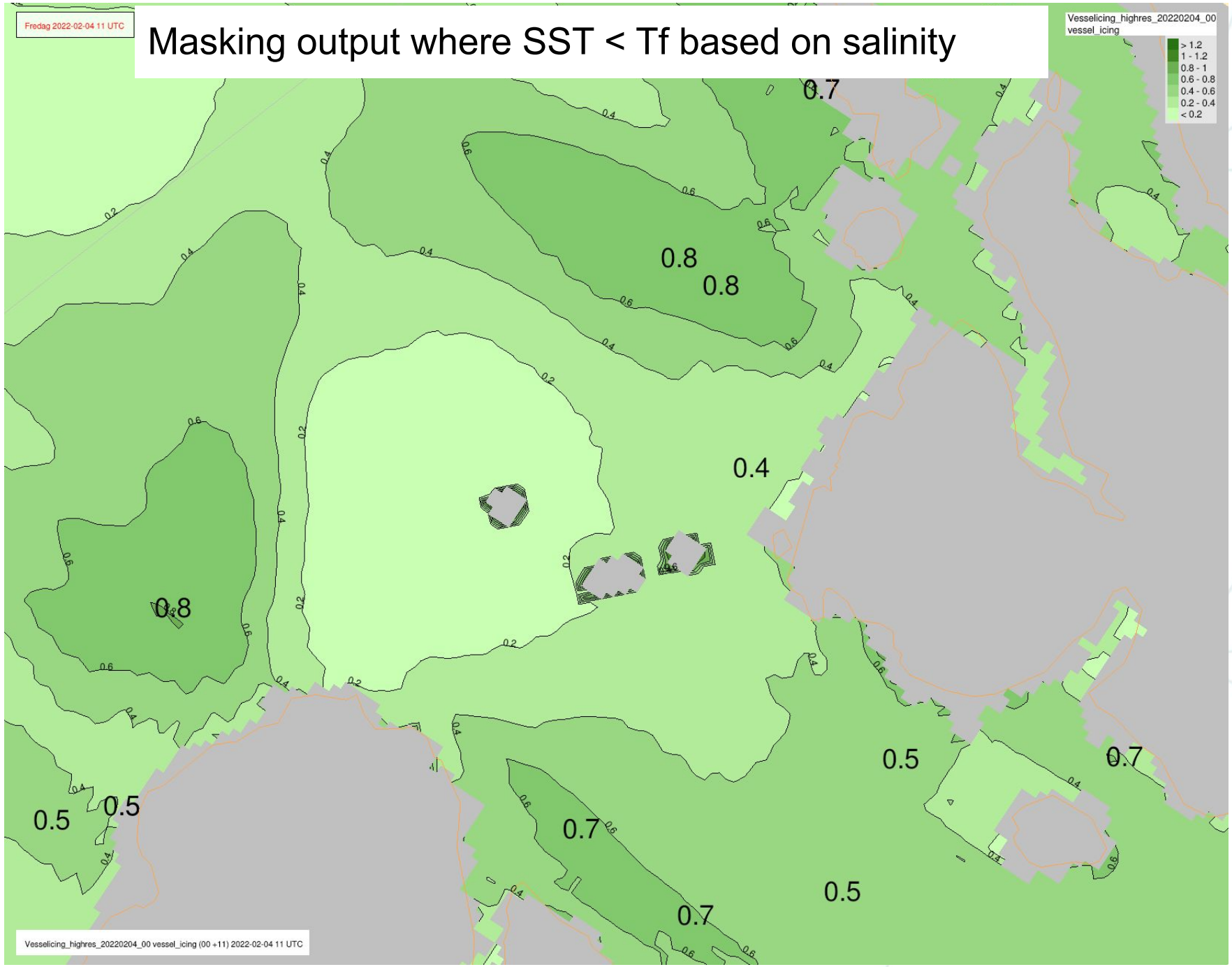
Icing rate calculated from atmospheric model with dx = 300 m



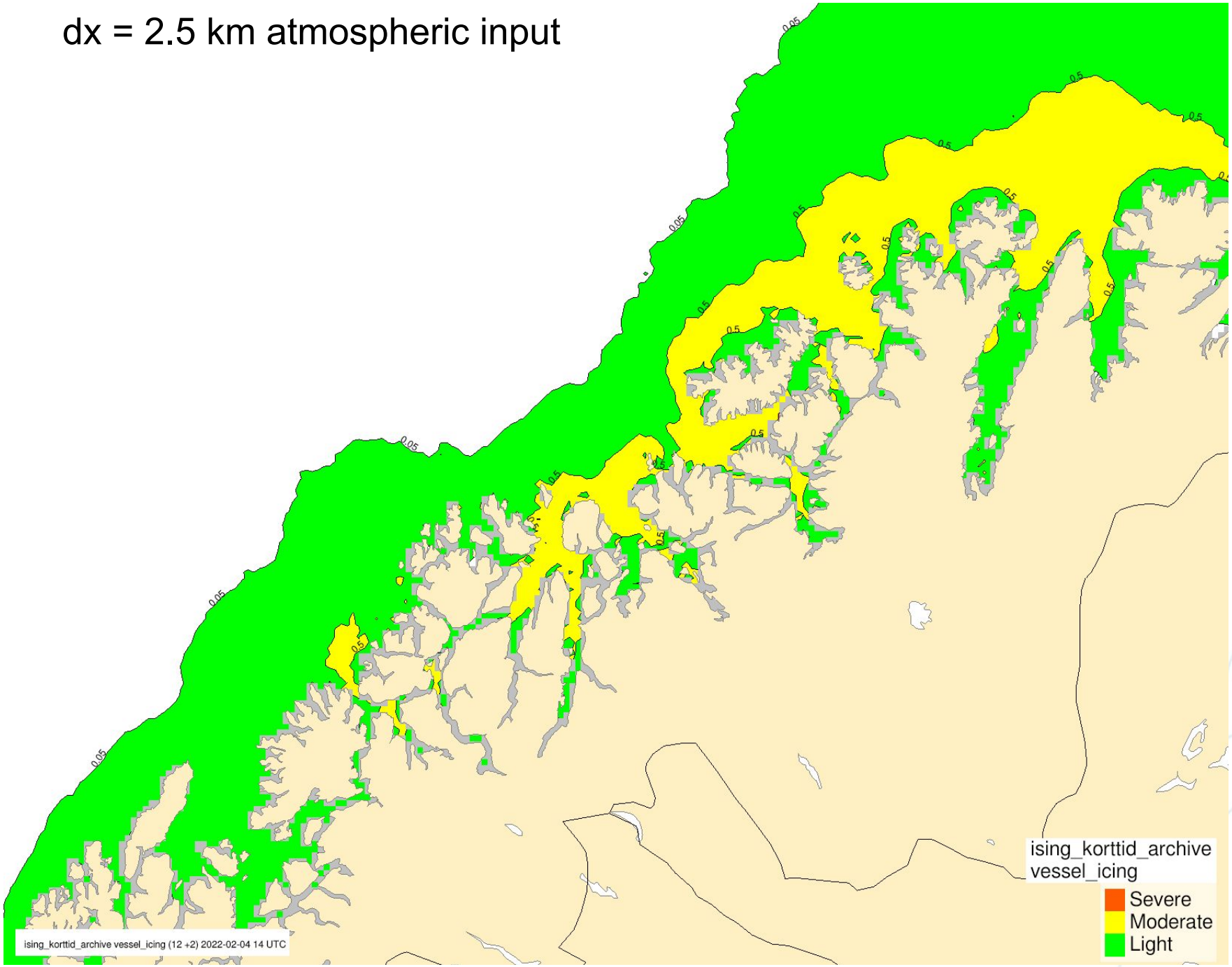
Artifical islands in the physiography making unrealistic low air and sea temperatures in the sea



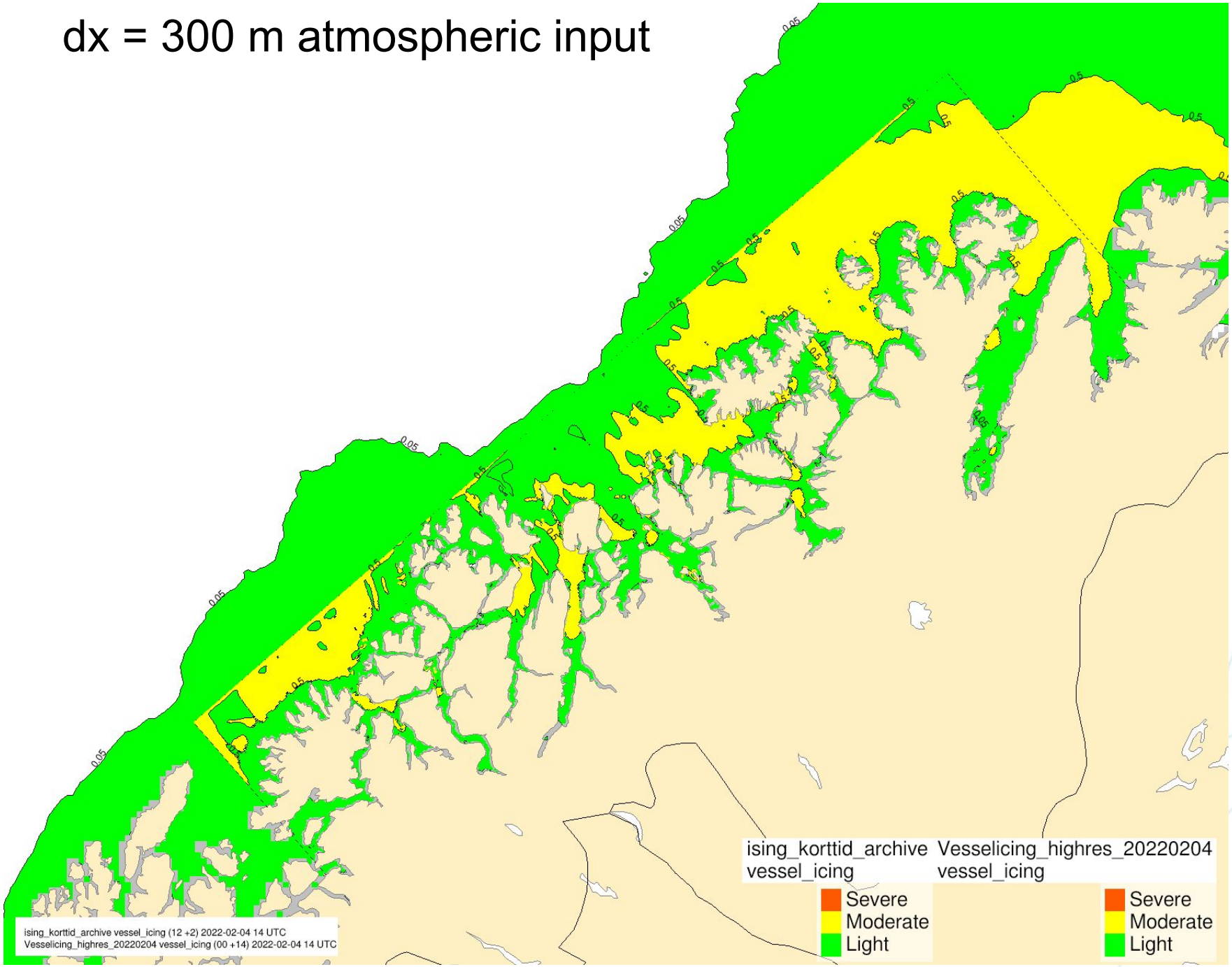
Masking output where SST < Tf based on salinity



dx = 2.5 km atmospheric input



dx = 300 m atmospheric input



- Wind driven spray is not considered
- Waves are not forced by the new model

Questions/comments?

eiriks@met.no

SPRICE web page:
https://uit.no/project/sprice