Fit(ch) for shipping

Wind farm wake effects at 10 m height

(KNMI publication by Ine Wijnant and Andrew Stepek 22-12-2023 using WINS50 data)

Special thanks to the KNMI-RDWD-innovation Wake(s)Up! team: Steven Knoop, Mariska Koning, Lukas Phaf, Maarten Plieger, Paul van Schayck, Rinus Scheele, Wietse Terpstra and Jasper Wijnands.

Content:

Abbreviations

- bft = Beaufort (unit for wind speed)
- Fitch WFP = WFP according to [Fitch, 2012]
- HARMCy43-CTL = Harmonie Cycle 43 without the Fitch WFP (CTL= control)
- HARMCy43-WFP = Harmonie Cycle 43 including the Fitch WFP
- TKE = Turbulent Kinetic Energy
- WFP = wind farm parametrization

1. Introduction

1.1 Wind turbines: energy harvesters, obstacles, momentum sinks, atmosphere mixers

- **Blockage effect**. Wind turbines are obstacles in the flow: wind slows approaching the wind farm and the air wants to move around and above the farm.
- **Wake effect**. Wind turbines cause a momentum sink and produce power and turbulent kinetic energy (TKE). The wake (figure 1) is the area behind the wind farms where there is less wind and more mixing/turbulence (which affects temperature and humidity and maybe therefore cloud).

Figure 1: example of a wake effect at Horns Rev wind farm off the Danish coast where turbines mix humid air to higher colder levels where the air condensates and forms clouds (source: Vattenfall).

1.2 Wake effects

Wake effects are very relevant for wind energy resource assessments (where the yield is determined by the wind at rotor/hub height), but also for weather forecasting[1], in particular for shipping forecasts (wind/waves at 10 m height) and low cloud/visibility forecasts for helicopter operations at sea. The study in this report focusses on the effect of wind farms on wind at 10 m height.

Wake effects are already significant and will only get bigger (increasingly larger turbines and more wind farms): the combined installed offshore wind capacity on the North Sea is expected to quadruple before 2030 (from 30 to 120GW) and possibly become 10 times as high in 2050 (300 GW)[2]. This is even more ambitious than in the hypothetical wind farm scenario for 2050 used in WINS50 – Winds of the North Sea in 2050 (190GW). Figure 2 shows an example of the wake effects at 100 m height in 2020 with (1) the wind farms in 2020 and (2) the wind farms in 2050 according to the WINS50 wind farm scenario: in the WINS50 wind farm scenario, there will not be many places on the North Sea where the wind is not affected by wind farms and it might even be 'worse'[3] in reality.

[1] KNMI - Windparken mengen zich in het weer (Dutch)
[2] Combined aim for 9 countries: Netherlands, Germany, Belgium, Denmark, France, Norway, Ireland, UK and Luxembourg: North Sea Countries Plan to Quadruple Offshore Wind Energy Capacity by 2030 (intelatus.com). Ambitions are changing all the time: https://nos.nl/collectie/13963/artikel/2500519-mogelijke-doorbraak-in-dubai-drie-keer-zoveel-duurzame-energie-in-2030.
[3] Worse between quotes because we do not want to imply that the energy transition is not necessary to stop climate change.

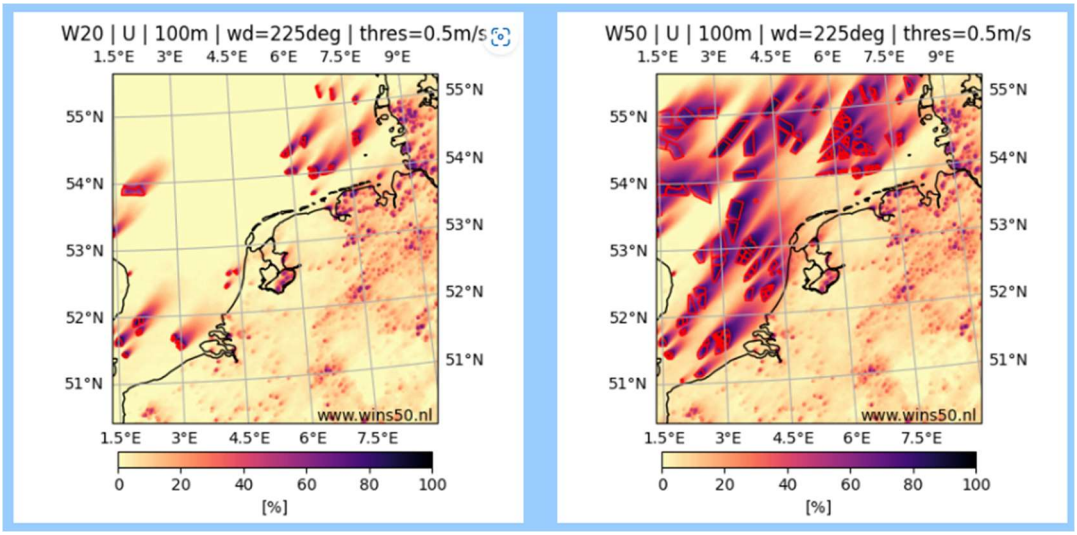


Figure 2: more than 0.5 m/s wake effect at 100 m height for southwesterly winds (2020 weather) for 2020 wind farms (left) and 2050 wind farms (right) (source: image library https://wins50.nl/)

1.3 Wind Farm Parametrisation (WFP)

Since the summer of 2022 the effect of wind farms is included in KNMI's weather model HARMONIE (HARMCy43), using the Fitch, 2012 Wind Farm Parametrisation [Fitch, 2012] (figure 3). HARMCy43-WFP is an experimental product (HARMCy40-without WFP is the official operational model). The Fitch WFP is not a postprocessing exercise: locations and turbine specifications (e.g. hub height, thrust and power curve) need to be included in the HARMONIE code before running the model. Figure 4 shows which turbines are included in HARMONIE (updates on the 1st of January every year; last update mid-2022, so the turbines present on 1-1-2022 are included).

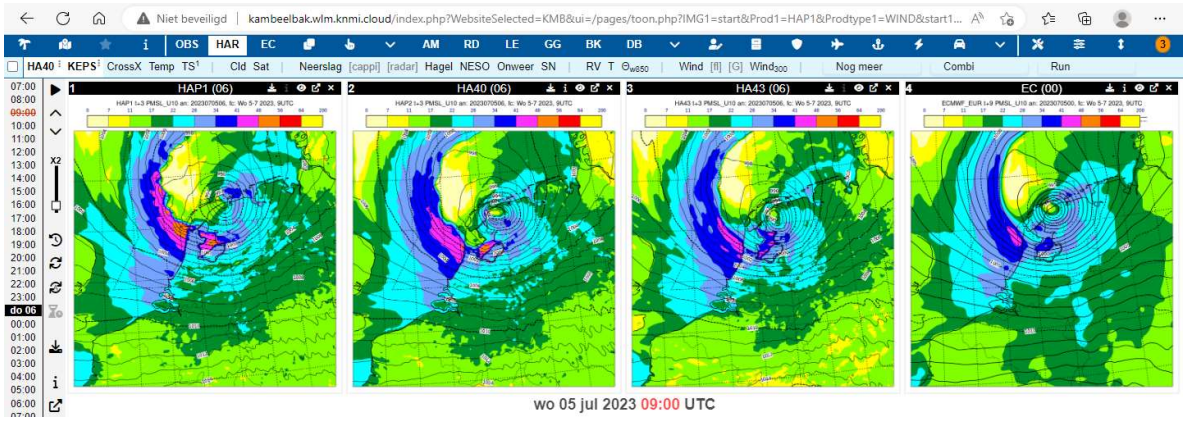


Figure 3: 'Kambeelbak' model comparison for summer storm Poly 5-7-2023 (HAP1 = very old settings HARMONIE, HA40 = HARMCY40 without WF; HA43 = HARMCY43 with WFP and EC = ECMWF-model)

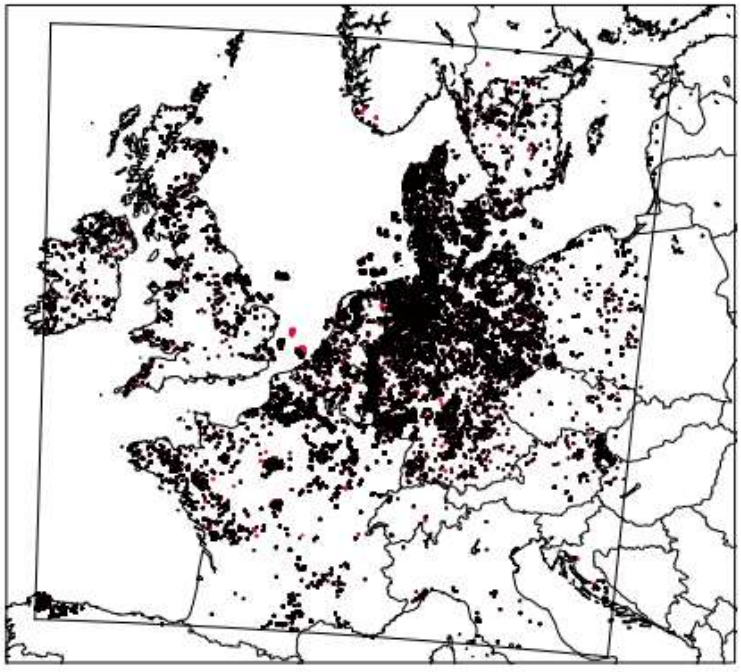


Figure 3: Onshore and offshore wind turbines included in HARMONIE since 1-1-2021 (red) and before (black) (source: https://wins50.nl/publications/ "windfarms in WINS50 climatology")

The WFP assumes ideal wind turbines (performing according to a turbine specific power curve, e.g. the one in figure 4) in an ideal wind farm (turbines always turning when winds are favorable). In reality this is not the case: turbines may be old or off due to maintenance, curtailment or bird/bat migration.

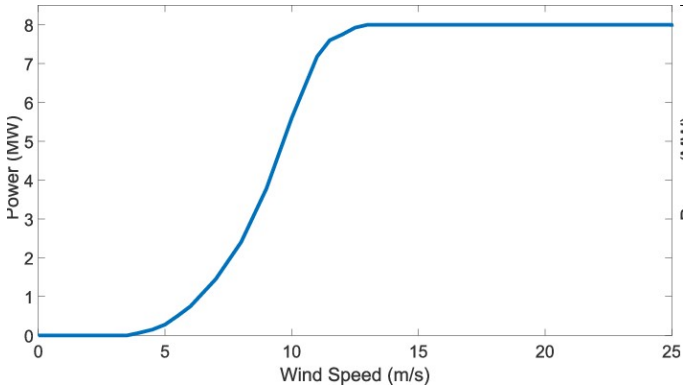


Figure 4: Power curve shows the power (yield) as a function of the wind speed at hub height. This is and example of the power curve of the Siemens Gamesa 8M which is used in Borssele I and II wind farm (rated power 8MW, cut-in wind speed 3 m/s, cut-out wind speed 25 m/s).

2. Goal

The goal of the study described in this report is twofold:

- to validate HARMCy43 with Fitch WFP (HARMCy43-WFP) at 10 m height (section 2.1)
- to assess the uncertainty in the HARMCy43-WFP wind forecast as a result of the fact that the Fitch WFP assumes ideal wind turbines in an ideal wind farm (section 2.2)

2.1 Validation of HARMCy43-WFP at 10 m height

The Fitch WFP has been extensively validated, both by KNMI as well as by other institutes [Larsen, 2021; Stratum, 2022; Dirksen, 2022; Fishereit, 2023]. Focus is however often on average wakes at hub height (decides the yield of a wind turbine). Here we are interested in max wakes at 10 m height: this gives us information on the max uncertainty of the wind forecast in the wake for shipping.

2.1.1. Validation wake strength with KNMI measurements

For this validation the results of the wake analyses by [Dirksen, 2022] are used (a) for KNMI-stations with measuring height closest to 10m (Oosterschelde/BG2 at 16.5m, Vlakte van de Raan at 16.5m, Huibertgat at 18m, IJmond at 17m and Europlatform at 29m) and (b) for stable and weakly stable stratification because we are interested in the strongest wakes. The strongest wakes occur for stable stratification [e.g. Platis, 2018 and Zoer, 2021], but also when the hub height wind speed is 12-15 m/s (and wind turbines reach their rated power). For those wind speeds, weakly stable (often referred to as 'neutral') conditions prevail due to turbulent mixing of the boundary layer caused by rough seas. Above rated wind speed, the wind turbines work less efficiently and therefore the reduction of the wind speed in the wake becomes lower relative to the undisturbed wind speed. Wakes in an unstable boundary layer will dissipate quickly.

The wind deficit in the wake can be calculated by subtracting the disturbed wind from the undisturbed wind in the wake. Instead of taking the maximum wind deficit, we compare extreme percentiles, which are more robust values:

- Modelled max wake strength: 97 percentile of the difference between the undisturbed and the disturbed WINS50-winds in the wake over 3 years (2019, 2020 and 2020).
- Observed max wake strength: 97.5 percentile[4] of the difference between the undisturbed and the disturbed measured wind in the wake calculated as explained in table 1 and blue box below.

The max value of the 97th percentile in table 1 is determined based on figures similar to the ones shown in figure 17 for the wind direction bin dependent 95th percentiles (figures with 97th percentile not shown) For every measurement location we selected the wind direction bins that contribute to the wake effect. For three of the stations this is just one wind direction bin (Oosterschelde 240-270^{o}, Vlakte van de Raan 270-300^{o} and Huibertgat 0-30°), for Europlatform two (180-210° and 210-240°) and for IJmond, with wind farms in several directions, four (240-270^{o}, 270-300^{o}, 300-330^{o} and 330-360^{o}). For Europlatform and IJmond we took the weighted average of the 97th percentile maxima where we gave more weight to the wind direction bin where the location is closer to the strongest wake effect in that wind direction bin. It would have been better to determine the max value of the 97th percentile by using a running 30 degree average of the 97th percentile (to avoid underestimation we now expect to get at the 30 degree bin edges), but that information was not available. Based on comparison between the max value of the modelled 97 percentile and the observed 97.5 percentile, we conclude that Fitch WFP underestimates strong wakes at 10 m height for weakly stable (= neutral) conditions by a factor of 1.4 ± 0.4 and for stable conditions by a factor of 1.9 ± 0.6 (table 1).

[4] Note that 97,5 percentile of CTL-WFP includes all stability classes whereas 97.5 percentile of CTL-OBS only includes weakly stable (= neutral) or stable. The wake effects for unstable conditions are less strong and are not expected to contribute significantly to the 97.5 percentile of CTL-OBS for all stability regimes.

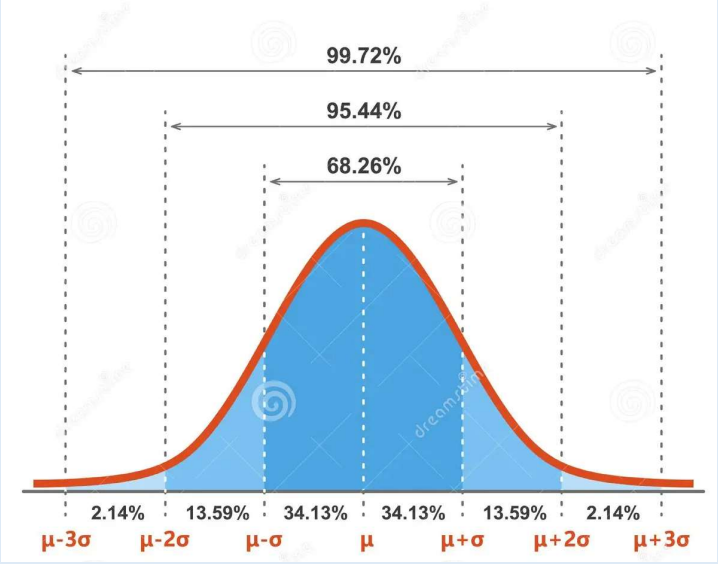
Multiply 97th percentile of CTL-WFP by 1.4 ± 0.4 to get real effect of the wake (weakly stable = neutral)

(*) CTL-OBS derived from table 6 of: Validation of wind farm parameterisation in Weather Forecast Model HARMONIE-AROME - Analysis of 2019 (2022), M Dirksen, I Wijnant, P Siebesma, P Baas, NE Theeuwes https://wins50.nl/publications/		CTL-OBS (*) [in wake]			CTL-OBS (*) [outside wake]	CTL-WFP [in wake]
Location name [distance to nearest wind farm]	Lat/Lon	Stability	Bias(CTL)in [m/s]	97.5 percentile = Bias(CTL)in + 2(RMSE-Bias(CTL)in) – Bias(CTL)out [m/s] [wind directions where location is downwind of wind farm]	Bias(CTL)out [m/s]	Maximum of the 97 percentile of 30° wide sectors at OBS distance from wind farm centre
Europlatform [80 km]	52.00/3.28	Weakly stable	0.22	2.6 [202-228°]	0.45	1.35
Huibertgat [25 km]	53.57/6.40	Weakly stable	0.26	2.0 [0-36°]	0.08	1.79
IJmond [30 km]	52.46/4.25	Weakly stable	0.99	2.2 [249-261, 300-311, 330-348°]	0.51	1.23
Oosterschelde [80 km]	51.77/3.62	Weakly stable	1.20	1.5 [243-255°]	0.96	1.40
Vlakte van de Raan [40km]	51.50/3.24	Weakly stable	1.23	2.2 [277-309°]	0.76	1.70

Multiply 97th percentile of CTL-WFP by 1.9 ± 0.6 to get real effect of the wake (stable)

(*) CTL-OBS derived from table 6 of: Validation of wind farm parameterisation in Weather Forecast Model HARMONIE-AROME - Analysis of 2019 (2022), M Dirksen, I Wijnant, P Siebesma, P Baas, NE Theeuwes https://wins50.nl/publications/		CTL-OBS (*) [in wake]			CTL-OBS (*) [outside wake]	CTL-WFP [in wake]
Location name [distance to nearest wind farm]	Lat/Lon	Stability	Bias(CTL)in [m/s]	97.5 percentile = Bias(CTL)in + 2(RMSE-Bias(CTL)in) – Bias(CTL)out [m/s] [wind directions where location is downwind of wind farm]	Bias(CTL)out [m/s]	Maximum of the 97 percentile of 30° wide sectors at OBS distance from wind farm centre
Europlatform [80 km]	52.00/3.28	Stable	-0,05	3.4 [202-228°]	-0,1	1.35
Huibertgat [25 km]	53.57/6.40	Stable	0,07	2.4 [0-36°]	-0,02	1.79
IJmond [30 km]	52.46/4.25	Stable	0,16	3.2 [249-261, 300-311, 330-348°]	0,08	1.23
Oosterschelde [80 km]	51.77/3.62	Stable	0,91	2.6 [243-255°]	0,35	1.40
Vlakte van de Raan [40km]	51.50/3.24	Stable	0,66	2.3 [277-309°]	0,41	1.70

Table 1: maximum wake strength as modelled (97 percentile) and observed (97.5 percentile). Modelled: 97 percentile of CTL-WFP where CTL = control (HARMCy43) and WFP = Wind Farm Parametrization (HARMCy43 with Fitch WFP); Observed: 97.5 percentile of CTL-OBS in wake which equals [bias(CTL)in) + 2{RMSE-Bias(CTL)in}] – Bias(CTL)out (see explanation in blue box). The top table is for weakly stable (=neutral) conditions and the bottom table for stable conditions (classification according to [Dirksen, 2022]).



For a Gaussian distribution:

Stand deviation (SD) = Root Mean Square Error (RMSE)-Bias. And 2SD = 95% spread around the bias (2.5% in each tail). So, the 97.5 percentile = Bias + 2SD = bias + 2(RMSE-bias)

Validation shows that 10m CTL winds outside of the wake are too high compared to the observations, so to get a measure of the effect of wind farms which we can compare to CTL-WFP we have to subtract bias(CTL)out. So 97.5 percentile of (CTL-OBS) = [bias(CTL)in + 2{RMSE-Bias(CTL)in}] – Bias(CTL)out where Bias (CTL)out = the bias of the CTL compared to observation outside the wake and Bias (CTL)in = the bias of the CTL compared to observation in the wake.

2.1.2. Validation with SAR measurements

For a number of selected SAR-images with clear wake effects in 2019, 2020 and 2021 wake strength, length and speed-up are compared to HARMCy43-WFP.

- **STEP1:** manually select SAR-images with wakes on southern half North Sea 2019-2021[5] suitable for validation (clear wake, no fronts, end of wake included; figure 5)
- **STEP2:** include (selected) SAR and WINS50-data in the KNMI Adaguc viewer[6]
- **STEP3:** compare wakes in SAR and WINS50 (exclude wakes where the SAR image shows that the WFP misses relevant turbines or wind farms because the WFP is only updated once a year, on the 1st of January; figure 6)

SAR uncertainty is 0.4 dB [7] which is about 10%. That is why we validate the wind speed deficit in the wake (difference wind speed inside and outside of the wake) instead of the wind speed in the wake itself: 10% of a difference between wind speeds is smaller than 10% of individual wind speeds. Also, SAR uses model wind direction, which can be wrong. That's why we only use uniform flow situations (no changes in wind direction) for validation. A possible wind direction error is then (mostly) eliminated if you consider the wind speed deficit.

[5] Using https://science.globalwindatlas.info/#/map/satwinds (description in https://orbit.dtu.dk/en/datasets/offshore-wind-fields-in-near-real-time).
[6] With the Adaguc viewer, which is publicly available, (ADAGUC Viewer (knmi.nl)) information can be combined in space and time.
[7] Personal communication with Ad Stoffelen (http://dx.doi.org/10.1109/JSTARS.2017.2681806) and conform https://doi.org/10.3390/rs11172025

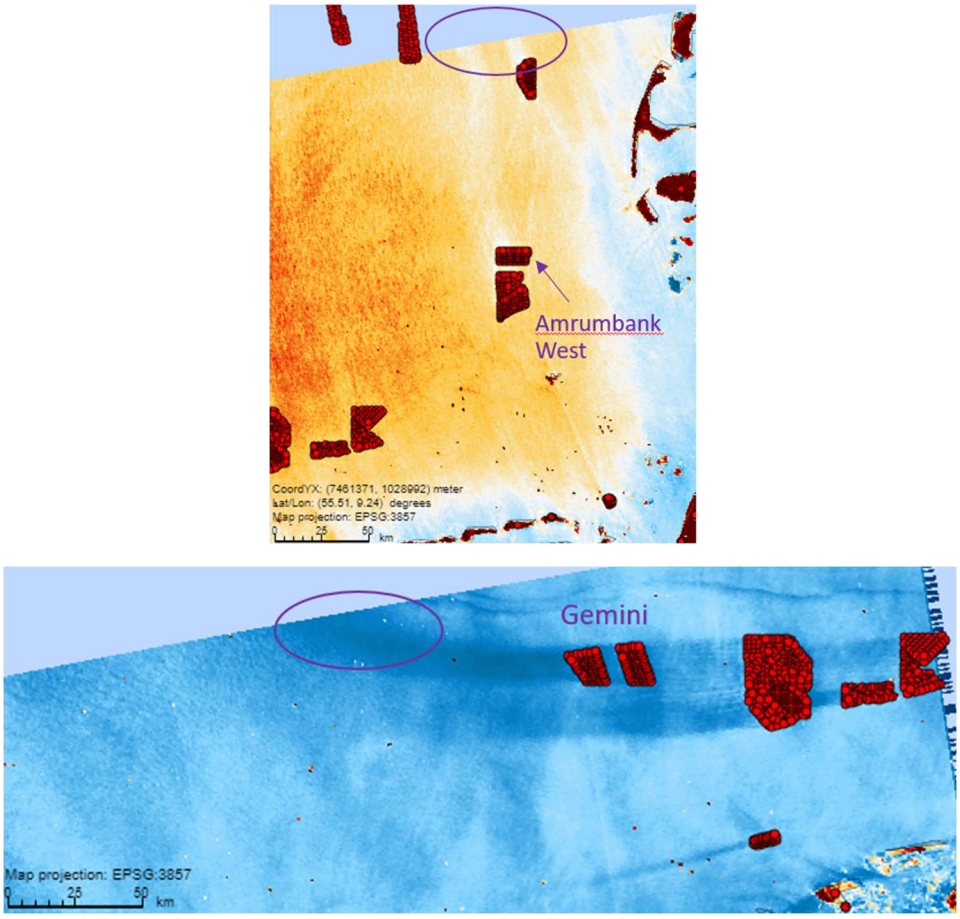


*Figure 5: two examples of wakes in SAR that are excluded because the end of the wake is (just) outside the SAR-image**: 21-12-2020** 17:17:46 UTC: wake length from Amrumbank W > 120 km (above) and **02-03-2021** 17:25:00 UTC: wake length from Gemini > 100 km (below)*

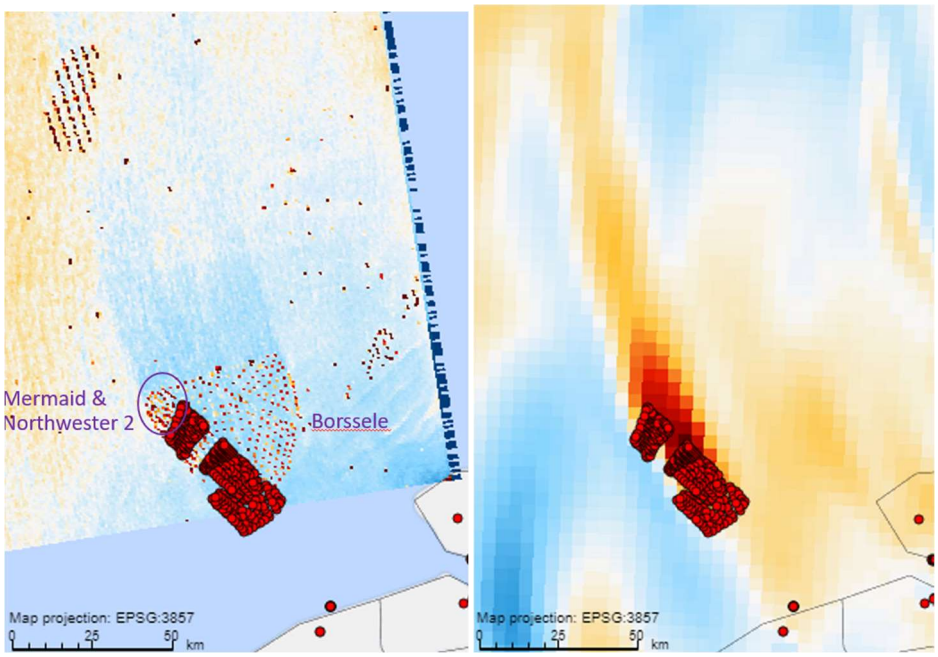


*Figure 6: example of wakes in SAR that are excluded because WFP misses relevant turbines or wind farms that are visible in SAR (Borssele, Mermaid and Southwester 2): SAR-image **19-10-2020** 17:41:16 UTC (left), wake effect Fitch WFP **19-10-2020** 17:00:00 UTC (right).*

2.1.2.1. Wake occurrence

For the assessment of wake occurrence, we used all SAR-images available in 2019, 2020 and 2021.

Wakes occur about 25% of the days in a year (figure 7). In [Djath, 2019] it is suggested that wakes occur most often in March- August (based on an analyses of the year 2017), but we cannot confirm that for 2021: (**2019):** twice as many days with wakes in March-Aug (64) than in Sept-Febr (32), (**2020):** still more wakes in March-Aug (51) than in Sept-Febr (36), but smaller difference and (**2021):** equal number of days with wakes in March-Aug (50) and Sept-Febr (50). [March-Aug 184 days and Sept-Febr 181 days, in 2020 182]

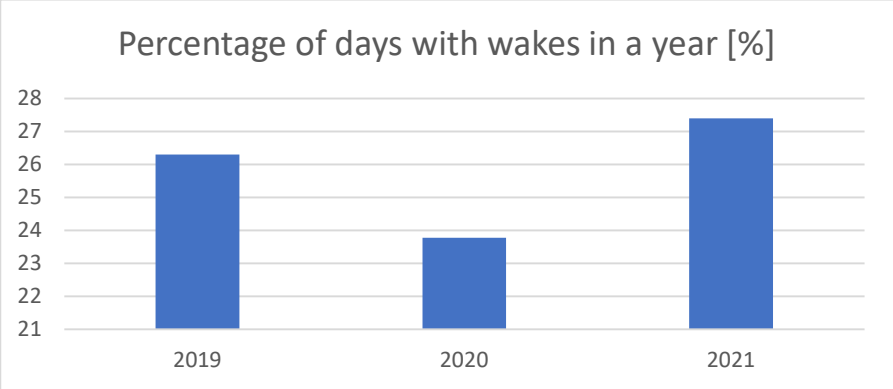
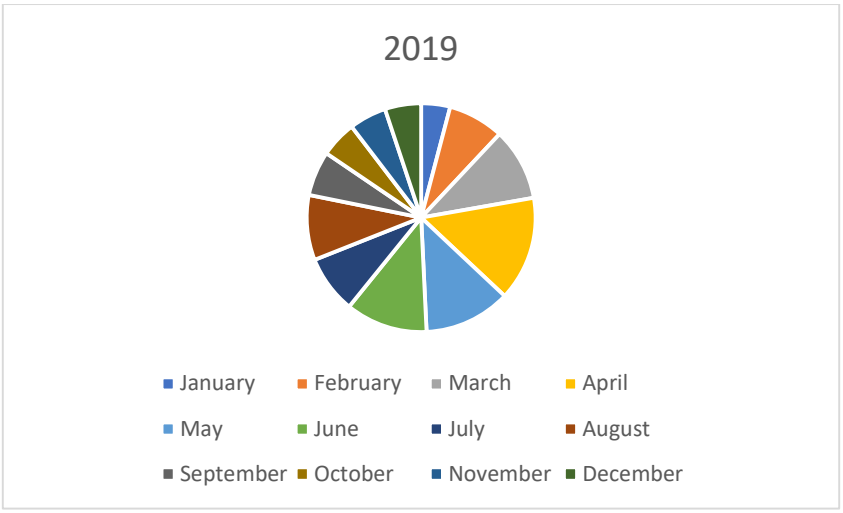
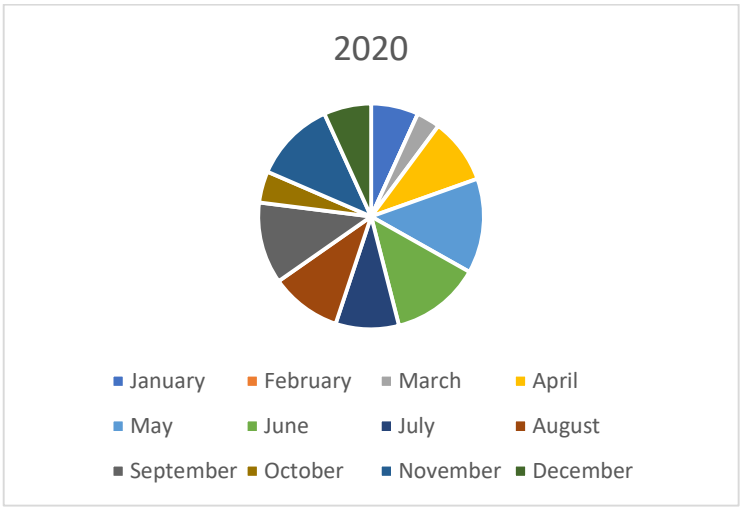


Figure 7: Number of days where SAR shows clear wakes on the southern North Sea divided by the total number of days in the year (365 in 2019/21 and 366 in 2020). This gives the percentage of days in a year with wakes if there are SAR-images for every day (the latter is not checked).

Figure 8 shows that wakes can occur in every month, up to half the days in the month (often clustered in time): for April 2019 e.g. 14 out of the 30 days, for May 2020 12 out of 31 days and for August 2021 13 out of 31 days. Figure 9 shows seasonal[8] variations in wake occurrence. Wakes occur least often in winter when the atmosphere is most likely unstable (coldest air over relatively warm sea water) or neutral (when it is windy), but based on the SAR analyses of 2019-2021 there is no clear 'favorite' season for wakes: (**2019):** wakes occur most in spring (36 out of 92 days), (**2020):** wakes occur most in summer (28 out of 92 days) and (**2021):** wakes occur most in autumn (33 out of 91 days).

[8] **Winter** = December, January, February; **Spring** = March, April, May; **Summer** = June, July, August; **Autumn** = September, October, November.





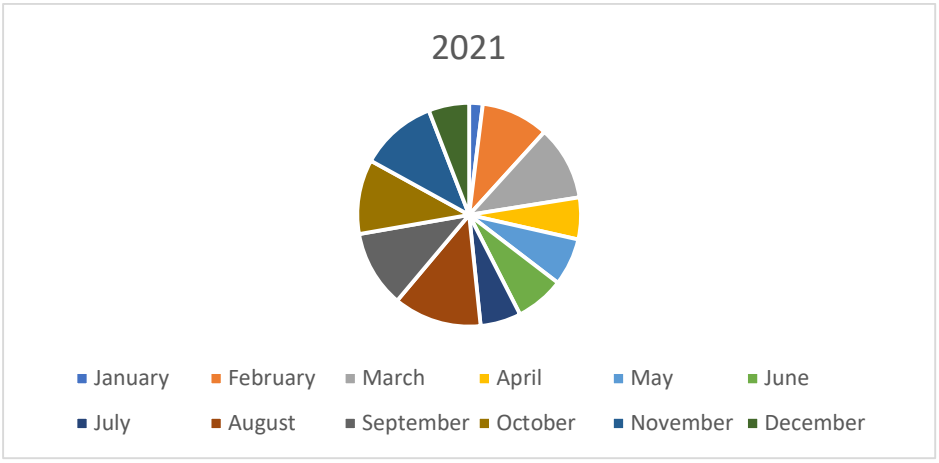


Figure 8: Number of days with wakes on the southern half of the North Sea per month based on SAR measurements in 2019, 2020 and 2021.

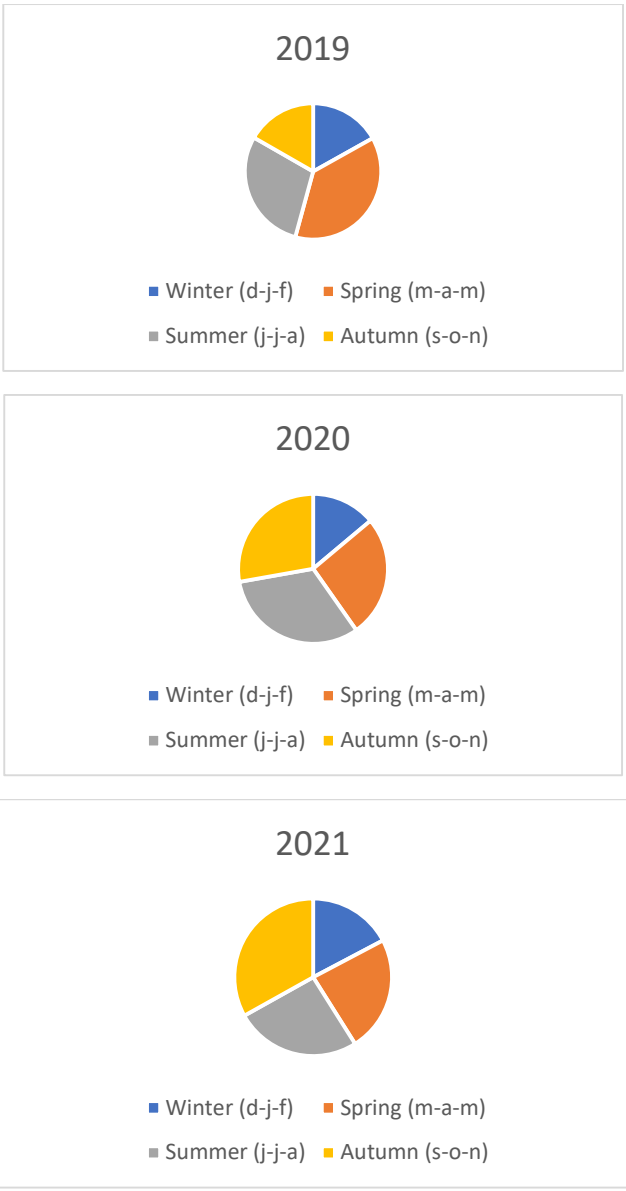


Figure 9: Number of days with wakes on the southern half of the North Sea per season based on SAR measurements in 2019, 2020 and 2021.

2.1.2.2 Max wake length

For the validation of max wake length, we used 20 of the first selected SAR-images for 2019, 2020 and 2021 (Appendix A). The max wake length [km] is defined as the distance from the edge of the wind farm (in downwind direction) to where the difference between the wind speed and the undisturbed wind speed (outside the wake) equals 1 m/s. Table 2 gives a summary of the results.

Figure 10 (left) shows the max wake length observed in SAR (x-axis) and according to Fitch WFP (y-axis): there is no significant relationship (trendline $R^2 = 0.1$) between the two. In 7 of the 20 analysed cases (which is about a third of the cases) Fitch WFP matches SAR perfectly (few points overlap in the figure). For about a third of the cases the max wake length modelled by Fitch WFP is too high and for the remaining third of the cases too low. Note that the observed wake length (SAR) can be longer than 120 km and Fitch WFP can be ±80 km wrong (worst 'mismatch' in figure 10 (left): max wake length SAR 70 km and Fitch WFP 150 km).

Max wake lenght				
Date/time	Wind Farm	SAR [km]	CTL-WFP [km]	Difference [km]
05-04-2019 17UTC	Northwind	65	65	0
05-04-2019 17UTC	Luchterduinen	40	40	0
23-06-2019 17 UTC	Gemini	70	150	-80
23-06-2019 17 UTC	Borkum Riffgrund 2 (*)	100	125	-25
22-07-2019 17 UTC	Belgian Wind Farms (*)	100	30	70
21-09-2019 17 UTC	Riffgat	20	20	0
03-03-2020 05 UTC	Belgian Wind Farms	80	10	70
16-04-2020 17 UTC	Belgian Wind Farms (*)	80	75	5
18-04-2020 17UTC	Deutsche Bucht	60	80	-20
18-04-2020 17UTC	Hohe See (*)	10	65	-55
18-04-2020 17UTC	Borkum Riffgrund 2	30	95	-65
18-04-2020 17UTC	Nordsee 1	30	30	0
02-03-2021 17 UTC	Riffgat	60	30	30
02-03-2021 17 UTC	Borkum Riffgrund 2	110	105	5
23-04-2021 17 UTC	Belgian Wind Farms	20	10	10
28-04-2021 05 UTC	Borkum Riffgrund 2	45	20	25
28-04-2021 05 UTC	Veija Mate	45	45	0
24-07-2021 17 UTC	Gemini	60	35	25
24-07-2021 17 UTC	Borkum	30	60	-30
24-07-2021 17 UTC	Borkum Riffgrund 2	30	30	0
09-08-2021 17 UTC	Borssele	30	30	0
19-9-2020 17 UTC	Belgian Wind Farms (*)	110	90	20
19-10-2021 05 UTC	Borkum/Merkur	100	80	20
21-12-2020 17 UTC	Amrumbank West	120	60	60
02-03-2021 17 UTC	Gemini	100	120	-20
19-10-2021 05 UTC	Global Tech 1	125	75	50

Table 2: SAR cases used for validation of max wake length. Purple (*) indicates that for these cases not all wind farms that are visible in SAR are in the Fitch WFP (figure 6). Because this did not affect the max wake length, these cases are still included in the validation. The 3 cases in red are cases where the wake ends just outside the SAR-image. These 3 cases are not included in the validation (figure 10 left). Including them (figure 10 right) does not have a large impact anyway.

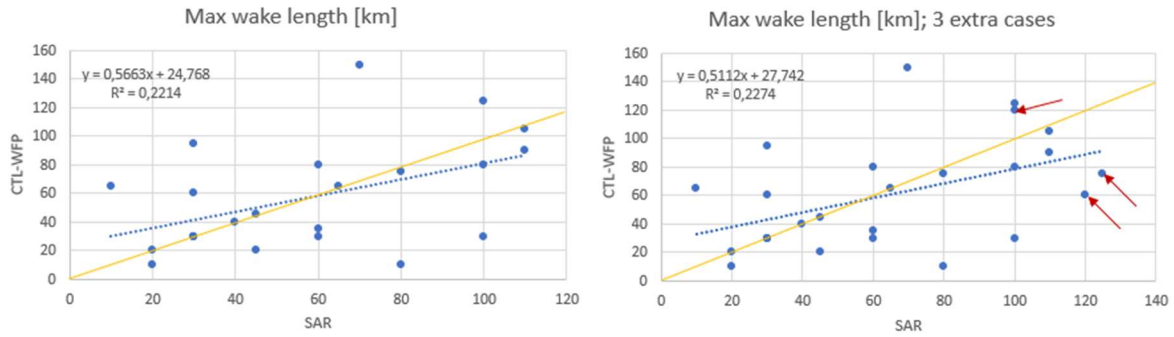


Figure 10: Max wake length [km] observed in SAR (x-axis) and according to Fitch WFP = CTL-WFP (y-axis). For validation of the max wake length we used 20 of the selected SAR cases. For 9 cases that we used for the wake strength validation (2.1.2.3), the wake length could not be determined in SAR (wake strength still > 1 m/s at edge of the SAR-image, so wake ends outside the SAR-image) or with Fitch WFP (wake in HARMCy43-WFP too weak: CTL-WFP nowhere ≥1 m/s). For points on the orange line, the wake length according to Fitch WFP matches perfectly with the wake length observed in SAR. Figure 10 (right) is the same as figure 10 (left), but with extra 3 cases with wakes ending just outside the SAR-image (makes almost no difference for the validation results).

2.1.2.3 Wake strength

For the validation of the wake strength, we used 29 of the first selected SAR-images for 2019, 2020 and 2021 (Appendix A). Table 3 gives a summary of the results.

Figure 11 shows that there is no relationship (trendline $R^2 = 0.03$) between the max wake strength in SAR and the Fitch WFP. In only 2 of the 29 analysed cases Fitch WFP matches SAR perfectly, in about half of the cases the wake strength according to Fitch WFP is too high and for the other half too low. The strongest wakes (≥ 2.5 m/s in SAR) are all underestimated by Fitch. Note that the observed wake strength (SAR) can be 4 m/s and Fitch WFP can be 2 m/s too low (worst 'mismatch' in figure 12: max wake strength SAR 3.2 m/s and Fitch WFP 1.2 m/s).

If (as suggested in section 2.1.1) we multiply the 97th percentile of the Fitch WFP wake strengths by 1.4±0.4 (for weakly stable = neutral conditions) we already get a better match with the strongest wakes observed in SAR (97.5 percentile), but multiplying by 1.9±0.6 (for stable conditions) makes it even better (figure 12).

Max wake strength				
Date/time	Wind Farm	SAR [m/s]	CTL-WFP [m/s]	Difference [m/s]
05-04-2019 17UTC	Northwind	1,9	2	-0,1
05-04-2019 17UTC	Luchterduinen	1,9	1,2	0,7
23-06-2019 17 UTC	Gemini	2,4	2,1	0,3
23-06-2019 17 UTC	Borkum Riffgrund 2 (*)	3,2	2	1,2
23-06-2019 17 UTC	Riffgat	2	0,5	1,5
22-07-2019 17 UTC	Belgian Wind Farms (*)	1,4	1,4	0
21-09-2019 17 UTC	Riffgat	2,7	1,1	1,6
03-03-2020 05 UTC	Belgian Wind Farms	2,9	1,5	1,4
16-04-2020 17 UTC	Belgian Wind Farms (*)	3,2	1,5	1,7
18-04-2020 17UTC	Deutsche Bucht	1,6	2	-0,4
18-04-2020 17UTC	Hohe See (*)	1,6	2,3	-0,7
18-04-2020 17UTC	Gemini	0,8	1,7	-0,9
18-04-2020 17UTC	Borkum Riffgrund 2	1,6	2,5	-0,9
18-04-2020 17UTC	Nordsee 1	2,6	2	0,6
19-9-2020 17 UTC	Belgian Wind Farms (*)	3,2	2,3	0,9
21-12-2020 17 UTC	Gemini	1,6	0,3	1,3
21-12-2020 17 UTC	Amrumbank West	3,2	1,2	2
02-03-2021 17 UTC	Riffgat	2,2	1	1,2
02-03-2021 17 UTC	Gemini	4	2,9	1,1
02-03-2021 17 UTC	Borkum Riffgrund 2	2,4	2,9	-0,5
23-04-2021 17 UTC	Belgian Wind Farms	1,6	1,7	-0,1
28-04-2021 05 UTC	Borkum Riffgrund 2	3,2	1,4	1,8
28-04-2021 05 UTC	Veja Mate	2,4	2	0,4
24-07-2021 17 UTC	Gemini	1,5	1	0,5
24-07-2021 17 UTC	Borkum	1,6	1,6	0
24-07-2021 17 UTC	Borkum Riffgrund 2	2,4	1,3	1,1
09-08-2021 17 UTC	Borssele	3,5	1,7	1,8
19-10-2021 05 UTC	Gemini	0,8	1,4	-0,6
19-10-2021 05 UTC	Borkum/Merkur	2,4	3,2	-0,8
19-10-2021 05 UTC	Godewind	1,1	2,2	-1,1
19-10-2021 05 UTC	BARD	1,6	2	-0,4
19-10-2021 05 UTC	Global Tech 1	2,1	2,3	-0,2

Table 3: SAR cases used for validation of max wake strength. Purple (*) indicates that for these cases not all wind farms that are visible in SAR are in the Fitch WFP (figure 6). Because this did not affect the max wake strength, these cases are still included in the validation. The 9 cases in red are cases where the wake ends outside the SAR-image. Because this does not affect the max wake strength, these cases are also included in the validation (figure 11).

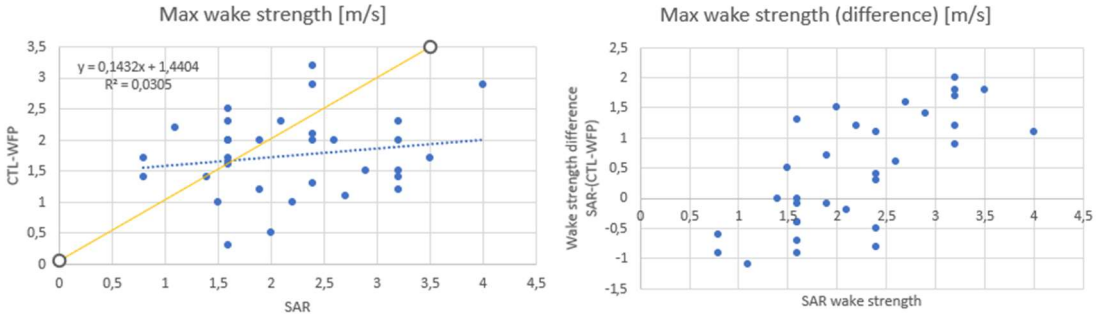


Figure 11 (left): Max wake strength [m/s] observed in SAR (x-axis) and according to Fitch WFP (y-axis). For validation of the max wake strength we used 29 of the selected SAR cases. For points on the orange line, the wake strength according to Fitch WFP matches perfectly with the wake strength observed in SAR. Figure 11 (right), based on the same data, shows the difference in wake strength between Fitch WFP and SAR on the y-axis.

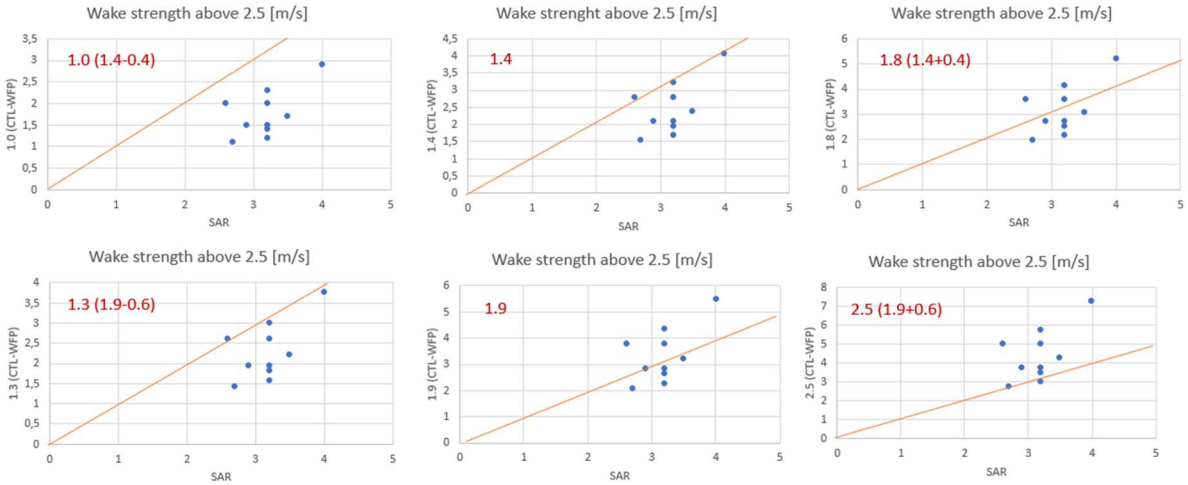


Figure 12: wake strength according to Fitch WFP multiplied by 1.4±0.4 (above) and 1.9±0.6 (below) compared to SAR cases with a wake strength of more than 2.5 m/s (from 23-6-2019, 21-9-19, 3-3-20, 16-4-2020, 18-4-20, 19-9-2020, 21-12-20, 2-3-21, 28-4-21 and 9-8-21).

2.1.2.4 Effect of atmospheric stability

Table 4 lists the 10 strongest wakes (wake strength of 2.5 m/s or more) and the 10 longest wakes (wake length of 75 km or more) observed in SAR on the southern half of the North Sea during the 3-year period of this study (2019-2021). Using the temperature from HARMCY43-CTL at levels 10 and 200m (Appendix C) and a stability assessment according to the Pasquill Class[9], we found that for none of the strongest/longest wakes the atmosphere was unstable (table 5). The same result was found by comparing the Environmental Lapse Rate (ERL) with the Dry Adiabatic Lapse Rate (DALR). So, for the strongest and longest wakes the atmosphere is either stable or neutral.

Table 5 shows that of the 10 cases with strongest wake strength (≥ 2.5 m/s), the atmosphere is not stable (but neutral)[10] for only 3 cases (3-3-20, 21-12-20 and 9-8-21). For 21-12-20 and 9-8-21 the wind speed around hub height (100m) is between 12 and 15 m/s where wind turbines reach their rated power and the wake effect is expected to be largest (section 2.1). For 3-3-2020 the atmospheric conditions might not be the most 'ideal' for strong wakes, but we are looking at a wake behind the most dense wind farm on the North Sea (Northwind 16.9 MW/km^2)[11]. And we know that the most cost-efficient wind farms in the North Sea are operating with a capacity density of about 5 MW per square kilometer [Deutsche WindGuard Gmb, 2018). Increasing the capacity increases the power production from wind but also increases the price of production due to higher wake losses.

Of the 10 cases with the longest wake length (> 75 km), the atmosphere is not stable (but neutral) for only 4 cases (3-3-20, 19-10-21 at Borkum Merkur, 21-12-20 and 19-10-21 at Global Tech1). Again these are for the most part situations either behind Northwind (3-3-20) or with rated wind speeds at hub height (19-10-21 Borkum Merkur and 21-12-20). The only exception is the case of 19-10-21 at Global Tech1: this is the longest wake that we observed in SAR (> 125 km). The stability assessment is done near wind farm Global Tech1, but this is probably not representative for the whole 125 km long wake because the sea further north is colder and the stratification most likely more stable.

Max wake strength > 2.5 m/s in SAR								
Date/time	Wind Farm	SAR [m/s]	Wind 10m (SAR)	Wind 10m (CTL)	Wind 100m (CTL)	Air temp 10m (CTL)	Air temp 100m (CTL)	Air temp 200m (CTL)
23-06-2019 17 UTC	Borkum Riffgrund 2 (*)	3,2	7,2	8,6	14,4	290,3	294,3	294,8
21-09-2019 17 UTC	Riffgat	2,7	7,5	7,5	9,2	290	290,9	290,6
03-03-2020 05 UTC	Belgian Wind Farms	2,9	8,5	9,4	10,3	279,8	278,5	277,6
16-04-2020 17 UTC	Belgian Wind Farms (*)	3,2	5,6	5,6	6,2	282,9	286,5	287,1
18-04-2020 17UTC	Nordsee 1	2,6	8	9,2	12,6	281,7	281,8	282,6
19-9-2020 17 UTC	Belgian Wind Farms (*)	3,2	8	8,8	10,4	291,6	291,4	293,2
21-12-2020 17 UTC	Amrumbank West	3,2	12	12,6	14,5	281,1	279,9	279
02-03-2021 17 UTC	Gemini	4	6,4	7,6	8,4	276,6	275,4	279,1
28-04-2021 05 UTC	Borkum Riffgrund 2	3,2	7,2	5,6	6,6	280,7	279,8	281,2
09-08-2021 17 UTC	Borssele	3,5	11,5	12	13,6	290,8	289,8	288,9
Max wake length > 75 km in SAR								
Date/time	Wind Farm	SAR [km]	Wind 10m (SAR)	Wind 10m (CTL)	Wind 100m (CTL)	Air temp 10m (CTL)	Air temp 100m (CTL)	Air temp 200m (CTL)
23-06-2019 17 UTC	Borkum Riffgrund 2 (*)	100	7,2	8,6	14,4	290,3	294,3	294,8
22-07-2019 17 UTC	Belgian Wind Farms (*)	100	6,2	6,7	10,4	292,2	292,6	293,6
03-03-2020 05 UTC	Belgian Wind Farms	80	8,5	9,4	10,3	279,8	278,5	277,6
16-04-2020 17 UTC	Belgian Wind Farms (*)	80	5,6	5,6	6,2	282,9	286,5	287,1
02-03-2021 17 UTC	Borkum Riffgrund 2	110	6,4	7,4	10	276,6	277,2	279,9
19-9-2020 17 UTC	Belgian Wind Farms (*)	110	8	8,8	10,4	291,6	291,4	293,2
19-10-2021 05 UTC	Borkum/Merkur	100	8	13,6	15,8	278,4	277,2	276,6
21-12-2020 17 UTC	Amrumbank West	120	12	12,6	14,5	281,1	279,9	279
02-03-2021 17 UTC	Gemini	100	6,4	7,6	8,4	276,6	275,4	279,1
19-10-2021 05 UTC	Global Tech 1	125	8,5	6,4	7	284,8	283,2	282,2

Table 4: wind and temperature at different heights from HARMCy43-CTL for cases with the strongest and longest wakes observed in SAR on the southern half of the North Sea in 2019-2021.

[9] https://www.ready.noaa.gov/READYpgclass.php

[10] According to the Pasquill stability class and/or based on comparison of the Environmental Lapse Rate from HARMCy43-CTL to the Saturated diabatic Lapse Rate.

[11] https://vasab.org/wp-content/uploads/2018/06/BalticLINes_CapacityDensityStudy_June2018-1.pdf

Max wake strength > 2.5 m/s in SAR					
Date/time	Wind Farm	dT/dz (°C/190m); dz = 200-10	Pasquil Class (dz = 200-10)	ELR> -1.14°C/190m (stable)	ELR< -18.62°C/190m (unstable)
23-06-2019 17 UTC	Borkum Riffgrund 2 (*)	4,5	F (moderately stable)	yes	no
21-09-2019 17 UTC	Riffgat	0,6	D (neutral)	yes	no
03-03-2020 05 UTC	Belgian Wind Farms	-2,2	D (neutral)	no	no
16-04-2020 17 UTC	Belgian Wind Farms (*)	4,2	F (moderately stable)	yes	no
18-04-2020 17UTC	Nordsee 1	0,9	D (neutral)	yes	no
19-9-2020 17 UTC	Belgian Wind Farms (*)	1,6	E (slightly stable)	yes	no
21-12-2020 17 UTC	Amrumbank West	-2,1	D (neutral)	no	no
02-03-2021 17 UTC	Gemini	2,5	E (slightly stable)	yes	no
28-04-2021 05 UTC	Borkum Riffgrund 2	0,5	D (neutral)	yes	no
09-08-2021 17 UTC	Borssele	-1,9	D (neutral)	no	no
Max wake length > 75 km in SAR					
Date/time	Wind Farm		Pasquil Class (dz = 200-10)	ELR> -1.14°C/190m (stable)	ELR< -18.62°C/190m (unstable)
23-06-2019 17 UTC	Borkum Riffgrund 2 (*)	4,5	F (moderately stable)	yes	no
22-07-2019 17 UTC	Belgian Wind Farms (*)	1,4	E (slightly stable)	yes	no
03-03-2020 05 UTC	Belgian Wind Farms	-2,2	D (neutral)	no	no
16-04-2020 17 UTC	Belgian Wind Farms (*)	4,2	F (moderately stable)	yes	no
02-03-2021 17 UTC	Borkum Riffgrund 2	3,3	F (moderately stable)	yes	no
19-9-2020 17 UTC	Belgian Wind Farms (*)	1,6	E (slightly stable)	yes	no
19-10-2021 05 UTC	Borkum/Merkur	-1,8	D (neutral)	no	no
21-12-2020 17 UTC	Amrumbank West	-2,1	D (neutral)	no	no
02-03-2021 17 UTC	Gemini	2,5	E (slighty stable)	yes	no
19-10-2021 05 UTC	Global Tech 1	-2,6	D (neutral)	no	no

Table 5: Atmospheric stability assessment for the 10 strongest and the 10 longest wakes observed in SAR on the southern half of the North Sea in 2019-2021.

Pasquill Stability Classes	delta T/delta Z [°C/100 m]
A (extremely unstable)	-1.9
B (moderately unstable)	-1.9 to -1.7
C (slightly unstable)	-1.7 to -1.5
D (neutral)	-1.5 to -0.5
E (slightly stable)	-0.5 to 1.5
F (moderately stable)	1.5 to 4.0
G (extremely stable)	>4.0

Pasquill Stability Classes	delta T/delta Z (°C/190 m)
A (extremely unstable)	-3.61
B (moderately unstable)	-3.61 to -3.23
C (slightly unstable)	-3.23 to -2.85
D (neutral)	-2.85 to 0.95
E (slightly stable)	0.95 to 2.85
F (moderately stable)	2.85 to 7.6
G (extremely stable)	>7.6

Comparing ELR to DALR and SALR

- Dry Adiabatic Lapse Rate = DAL = - 9.8°C/km (= 1.9*9.8) = - 18.62°C/190m
- Saturated Adiabatic Lapse Rate = SALR = -6°C/km (=1.9*0.6) = - 1.14°C/190m
- Absolutely unstable if ELR (Environmental Lapse Rate) < DALR
- Absolutely stable if ELR > SALR

2.1.3 High wind speed streaks at edges and between wind farms

Figure 13 shows that there is not only an area with less wind downwind from a wind farm, but there are also areas with more wind. These high wind speed streaks can either be between wind farms or at the edge of a wind farm. For the northern hemisphere they are mostly on the left hand side of the wind farm (looking down wind) because of the Coriolis force, which is conform the LES simulations in the X-wakes project (figure 14). However, we also see high wind speed streaks on the right hand side or on both sides of the wind farm in SAR (figure 13). A mesoscale model such as HARMONIE is too course to capture these high wind speed streaks, so for the analyses we only looked at SAR. Table 6 gives a summary of the results. For the SAR-images that were part of this study, we observed wind speed-ups of up to 4.8 m/s (edge wind farm) and 5.3 m/s (between wind farms). Figure 15 shows that the relationship between wind speed-up and max wake strength is not significant (trendline R^2 = 0.3), but wind streaks are generally stronger for stronger wakes. Wind speed-up and max wake length (trendline R^2 = 0.0009) do not seem to be related at all (not shown).

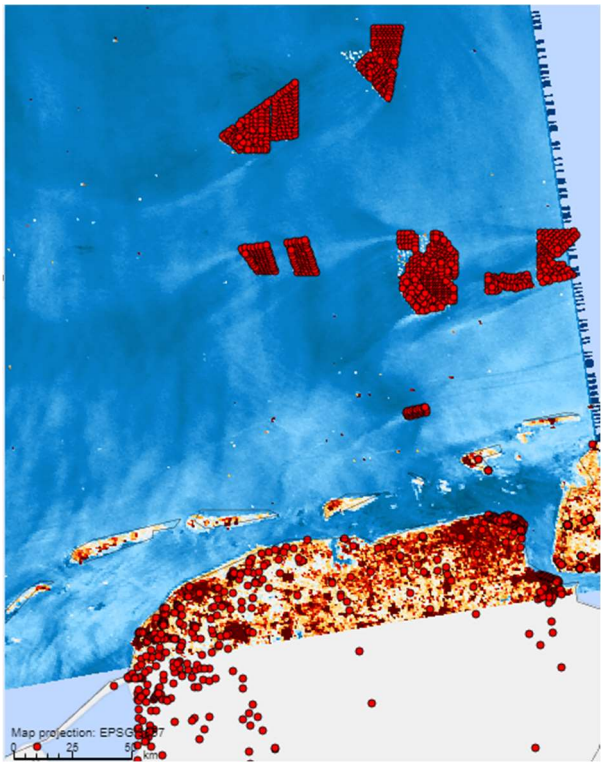


Figure 13: SAR-image 16-08-20 (17:25:52) showing high wind speed streaks downwind German offshore wind farms, some only on the left side, others on both sides of the wind farm (Gemini and cluster Trianel, Borkum I and II, Merkur, Alpha Ventus and Borkum Riffgrund I and II). Note that some turbines Borkum I and II in SAR, but not yet in Fitch WFP.

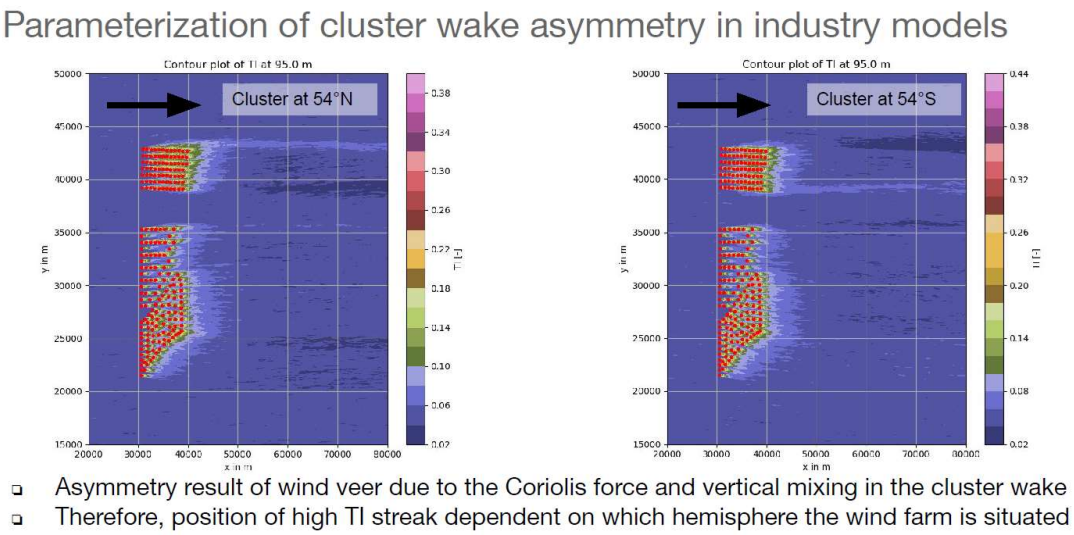


Figure 14: Asymmetry in the wake due to Coriolis force: this LES study with the PALM model confirms turbulence intensity streak to the left of the wind farm wake (downwind) on the northern hemisphere (and opposite in southern hemisphere). This will be studied further in the X-wakes follow-up project C²Wakes (source: X-wakes workshop 26-6-23: G. Centurelli from ForWind - Carl von Ossietzky university of Oldenburg: FInal_workshop_x-wakes_GS.pptx (rave-offshore.de)).

SAR max speed-up versus max wake strength				
Date/time	Wind Farm	Wake strength [m/s]	Speed-up [m/s]	
05-04-2019 17UTC	Northwind	1,9	2	left
23-06-2019 17 UTC	Gemini	2,4	2,4	right
23-06-2019 17 UTC	Riffgat	2	1,2	left
22-07-2019 17 UTC	Belgian Wind Farms (*)	1,4	3,4	left
21-09-2019 17 UTC	Riffgat	2,7	1,3	left
18-04-2020 17UTC	Hohe See (*)	1,6	1,6	left
18-04-2020 17UTC	Gemini	0,8	1,6	left
18-04-2020 17UTC	Borkum Riffgrund 2	1,6	1,6	left
18-04-2020 17UTC	Nordsee 1	2,6	2,4	left
21-12-2020 17 UTC	Gemini	1,6	2,4	both
02-03-2021 17 UTC	Borkum Riffgrund 2	2,4	1,6	left
23-04-2021 17 UTC	Belgian Wind Farms	1,6	2,6	left
28-04-2021 05 UTC	Borkum Riffgrund 2	3,2	4	left
28-04-2021 05 UTC	Veija Mate	2,4	4,8	left
24-07-2021 17 UTC	Gemini	1,5	0,5	both
24-07-2021 17 UTC	Borkum	1,6	1,5	both
09-08-2021 17 UTC	Borssele	3,5	5,3	middle
19-10-2021 05 UTC	Gemini	0,8	1,6	left
19-10-2021 05 UTC	Godewind	1,1	1,3	right
19-10-2021 05 UTC	BARD	1,6	3,6	right
19-10-2021 05 UTC	Global Tech 1	2,1	1,9	both

Table 6: 21 SAR cases used for high wind streak analyses. Purple (*) indicates that for these cases not all wind farms that are visible in SAR are in the Fitch WFP (figure 7). Because this did not affect the max wake strength or speed-up, these cases are still included in the analyses. The 7 cases in red are cases where the wake ends outside the SAR-image. Because this does not affect the max wake strength or speed-up, these cases are also included in the analyses (figure 16).

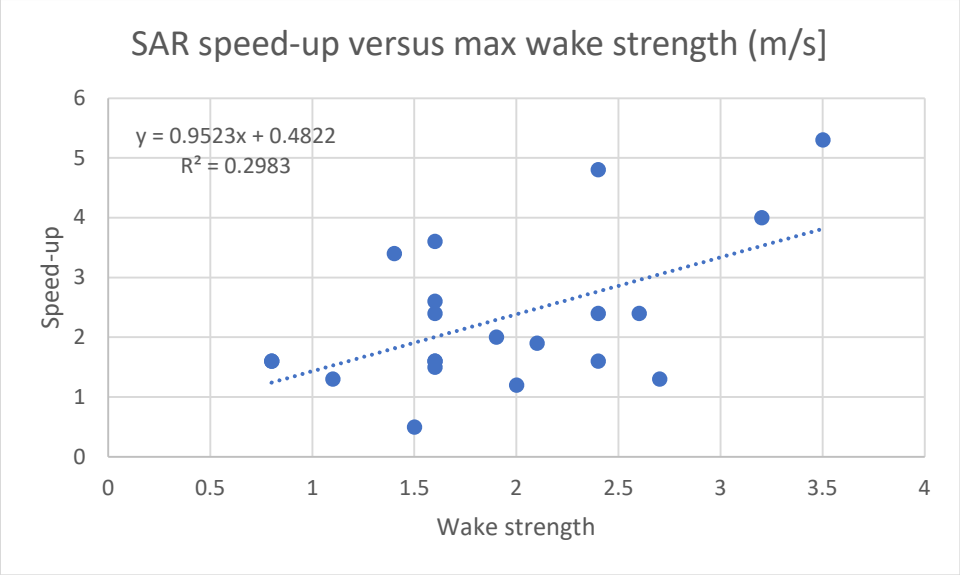


Figure 15: max wake strength (x-axis) and speed-up (y-axis) observed in SAR [both in m/s]. For this comparison 21 SAR cases with high wind streaks were used.

2.1.4 Consequences of wind farms for shipping

Ships may experience a decrease of wind speed in the wind farm wake, but also speed-up between or at the edge of wind farms. Figure 16 illustrates that the effect may be large: in this particular case ships sailing downwind of the Belgian wind farms experienced a change in wind speed of almost 5 m/s at least twice within 15 km.

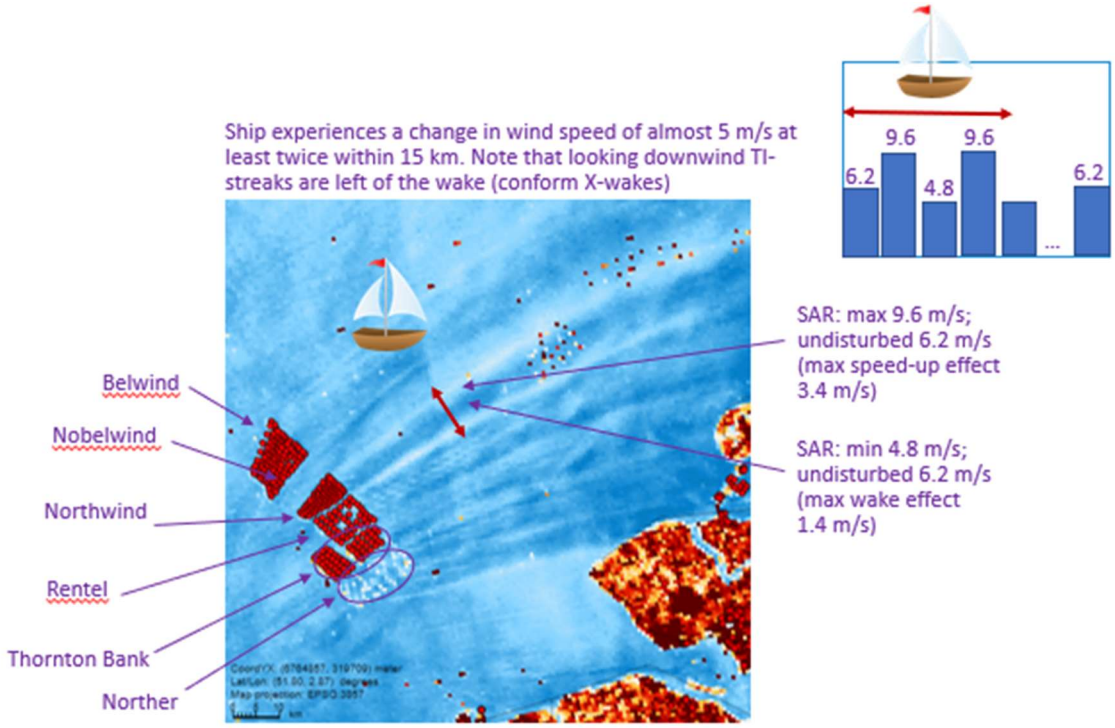


*Figure 16: SAR-image **22-7-2019** 17:33:25 UTC with clear wakes and high wind streaks between and at the edges of the Belgian wind farms (wind farm Borssele was not yet built).*

The maximum wake strength that we observed in SAR is 4 m/s and the max speed-up 5 m/s. So assuming the undisturbed wind is 6 m/s (which means that the operational HARMONIE model probably suggested a wind forecast of 4 bft), the wind in the wake can be 2 bft (6-4 = 2 m/s) and in the wind streak 6 bft (6+5 = 11 m/s). So due to the wind farm there should have been a wind warning (coastal wind warnings are issued for wind speeds of 6 bft and higher)!

So wind farms change the wind at 10m height (relevant for shipping forecasts and warnings) and in doing so, also waves. Wind and waves affect each other, but in currently used regional weather models, they are usually only one-way coupled (the atmospheric model uses a drag relation that depends on wind speed to determine the roughness length of the sea [Brink, 2013]). The non-negligible effect of wind farm wakes on wind and waves is studied [Bärfuss, 2021], Fischereit, 2021], but not yet (operationally) included and beyond the scope of this report.

2.2 Forecast uncertainty due to wind farm operation being a 'black box'

As mentioned in section 1.3, Fitch WFP assumes that all wind turbines are turning according to the power curve when winds are favorable. So there are no turbines off for reasons such as maintenance, legislation or curtailment and no turbines perform worse than the turbine specifications provided by the manufacturers. Off course this is not always the case. The Entsoe transparency platform[12] provides some near-real time open data about outage due to maintenance and bird migration, but the data is not complete and there is no information available on curtailment or the performance of the wind turbines (to our knowledge).

Basically there might be more wind downwind of the wind farm than Fitch WFP suggests because the turbines are (partly) off instead of on: the wake effect is not (fully) there whereas HARMCy43(WFP) expects it to. To represent the largest possible error HARMCy43(WFP) makes because of this, we use the max wake effect per 30° wind direction bin based on climatology from the 3 WINS50-years (figure 17). By taking the 95 percentile[13] of the difference between HARMCy43(CTL) and HARMCy43(WFP) instead of the max difference, we expect to get a more robust value for the maximum, less dependent of the sampling size which is only 3 years split into 12 wind direction bins.

The corrected wind field in the wake (more wind) is presented on Geoweb and is constructed like so:

- Take HARMCy43(WFP) wind direction per grid cell
- Look for associated correction factor (95 percentile of CTL-WFP based on 3 years of WINS50-data) in lookup file (also per grid cell) which depends on the 30° wind direction bin the grid point wind direction falls in (225° will fall in the 210-240° bin)
- Apply this correction factor to the HARMCy43(WFP) windspeed in a GeoWeb-Adaguc-Server development branch (live data stream)

[12] https://transparency.entsoe.eu/outage-domain/r2/unavailabilityOfProductionAndGenerationUnits/show?name=&defaultValue=true&viewType=TABLE&areaType=CTA&atch=false&dateTime.dateTime=15.06.2023+00:00|UTC|DAY&dateTime.endDateTime=16.06.2023+00:00|UTC|DAY&CTY|10YNL----------L|MULTI=CTY|10YNL----------L|MULTI&area.values=CTY|10YNL----------L!CTA|10YNL----------L&assetType.values=PU&assetType.values=GU&outageType.values=A54&outageType.values=A53&outageStatus.values=A05&masterDataFilterName=&masterDataFilterCode=&dv-datatable_length=10

[13] The 95 percentile looks less noisy than the 99 percentile with clearer wake edges, that's why the 95 percentile was chosen over the 99 percentile one.

Note that this correction factor is likely to change in the future: it is based on only 3 years of data (2019-2021) and the wind farms present in those years. Therefore the correction factor needs to be updated. How is still to be decided.

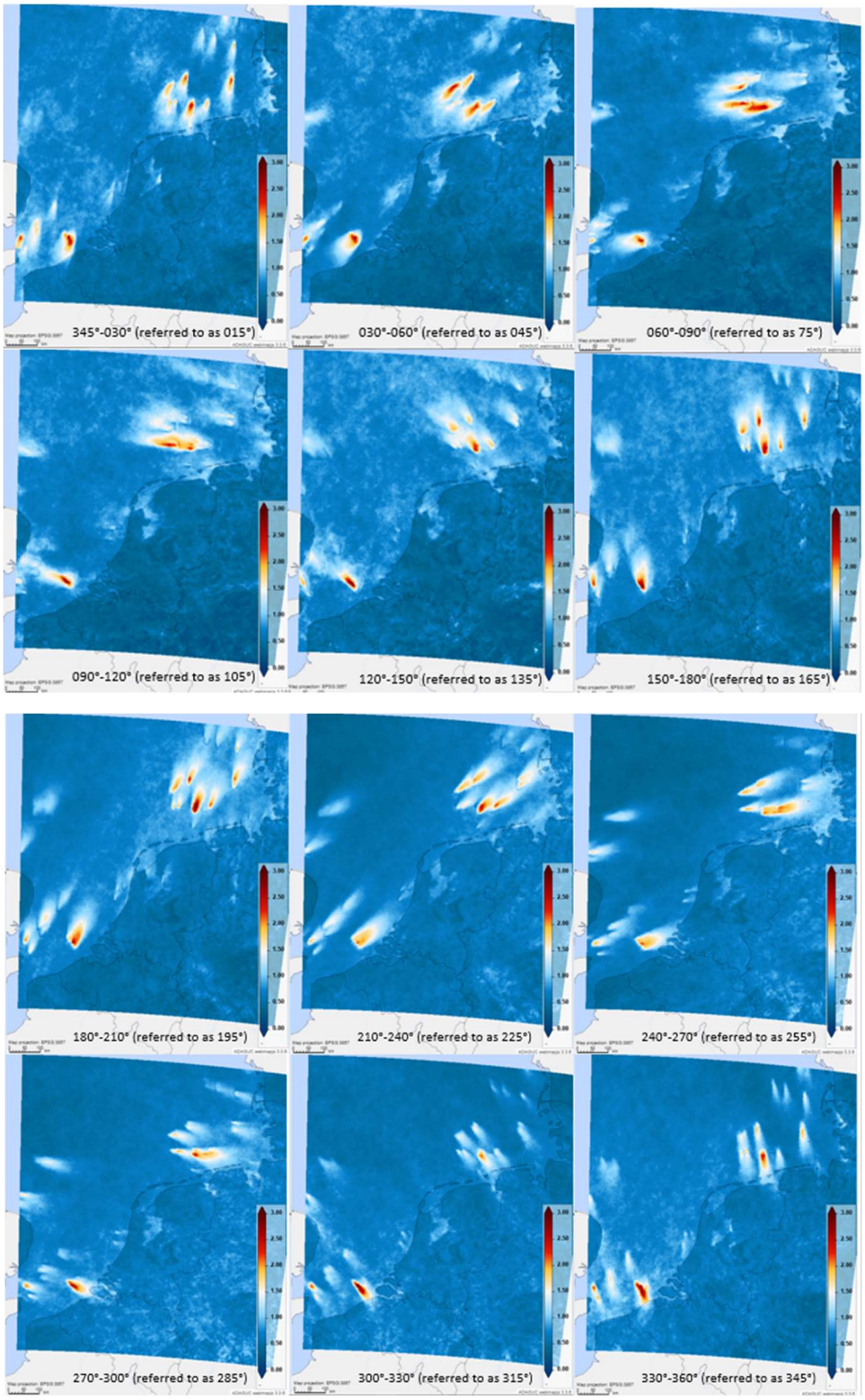


Figure 17: 95 percentile of 3 year CTL-WFP per 30° wind direction bin.

3. Conclusion

The effect of wind farms on the weather is already large and will only get larger with the expected growth of the number and size of wind farms on the North Sea in the next decennia. For the 3 year period of this analyses (2019-2021), SAR measurements (at 10m height) show that (1) wakes occur on average about 25% of the days in a year, least in winter and (2) ships may experience a wind speed decrease of up to 4 m/s in the wake downwind from a wind farm as well as a 5 m/s increase as a result of speed-up between and on the edge of wind farms. The Fitch WFP does not capture these effects at 10 m height.

As expected, wakes are strongest and longest for stable or neutral atmosphere and/or wind speeds at hub height of 12-15 m/s. Strong wakes can occur under less favorable atmospheric conditions downwind from wind farms with high capacity densities.

To conclude there are 3 main sources of uncertainty in the wind forecast behind a wind farm:

1. less wind in wake because HARMCy43(WFP) underestimates wake effect: HARMCy43(WFP) **MINUS** 0.9 x '30°-wind-direction-bin-dependent' 97 percentile of CTL-WFP
2. more wind in wake because HARMCy43(WFP) expects all wind turbines to be on while they might be all off: HARMCy43(WFP) **PLUS** '30°-wind-direction-bin-dependent' 95 percentile of CTL-WFP
3. more wind in the wake because of the speed-up effect between or at the edge of wind farms. HARMCy43(WFP) cannot capture these high wind streaks because it's grid spacing is too course. The max speed-up observed in this study 5.3 m/s.

4. Literature

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5. Appendix A: First SAR selection

We distinguished 3 subsets and make a date-selection per subset:

1. Wake length/interaction
2. Turning wakes
3. Storms

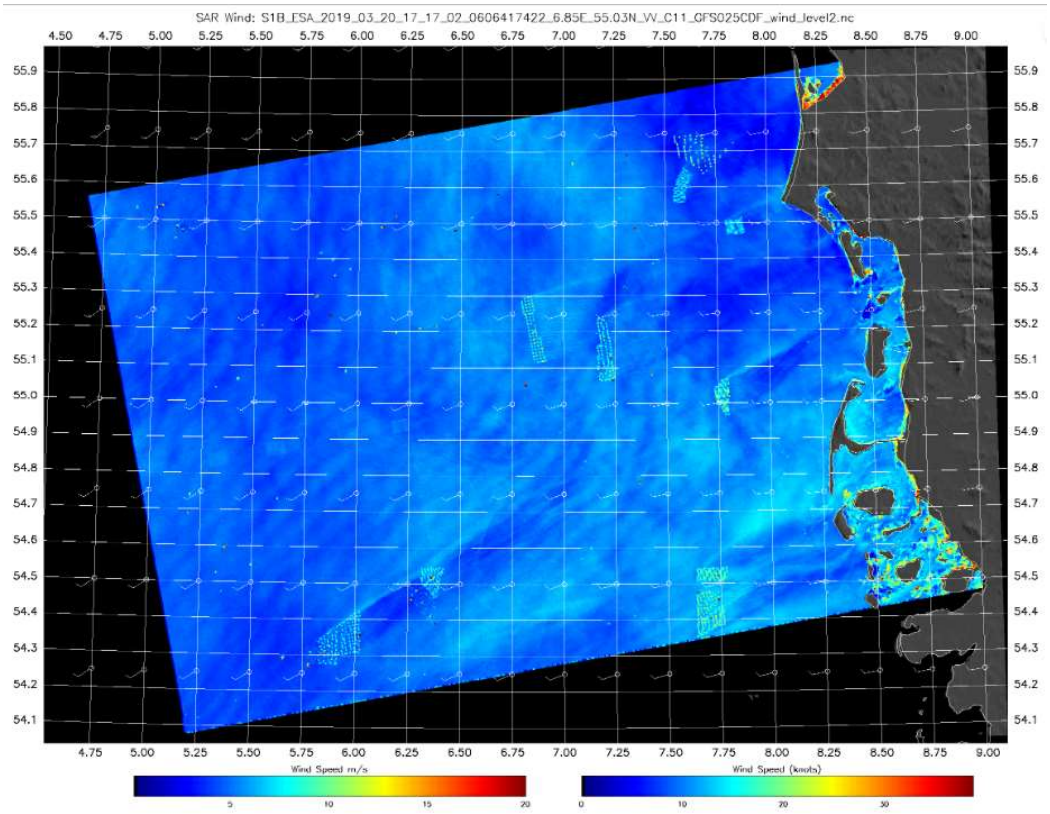
5.1. Wake length/interaction (18 cases selected)

There are quite a few suitable SAR-pictures for studying length and interaction. Suggestion to use:

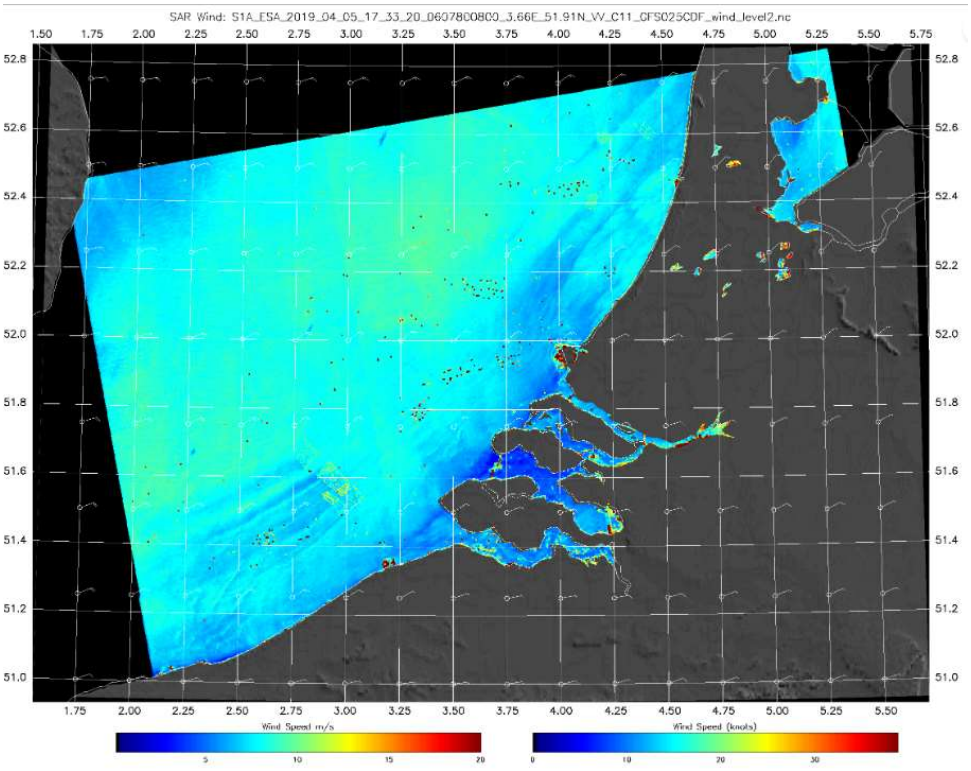
- Wakes Belgian wind farms / Borssele[14] for different wind directions (total 8):
  - SW (2): **03-03-20** (05:58:36) and **09-08-21** (17:41:45)
  - NE (4): **05-04-19** (17:33:20), **16-04-20** (17:41:33) and **19-09-20** (17:41:41) and **23-4-21** (17:41:39); this means we have 3 'comparable' spring ones with different wind farms.
  - SE (1): **19-10-20** (17:41:16)
- Wakes German Bight (total 8):
  - (6) Most relevant situations for the Netherlands where Dutch wind farms are or can be (E'ly and N'ly winds) affected: **21-09-19** (17:24:58) with strong background wind, **18-04-20** (17:25:45), **11-08-20** (17:17:45), **03-09-20** (17:25:12) with wake Gemini, 0**2-03-21** (17:25:00) and **28-4-21** (05:49:20)
  - (1) interesting short wake: **21-12-20** (17:17:46)
  - (1) Interesting long wake: **19-10-21** (05:49:53)

Red bold and underlined are selected for the case study

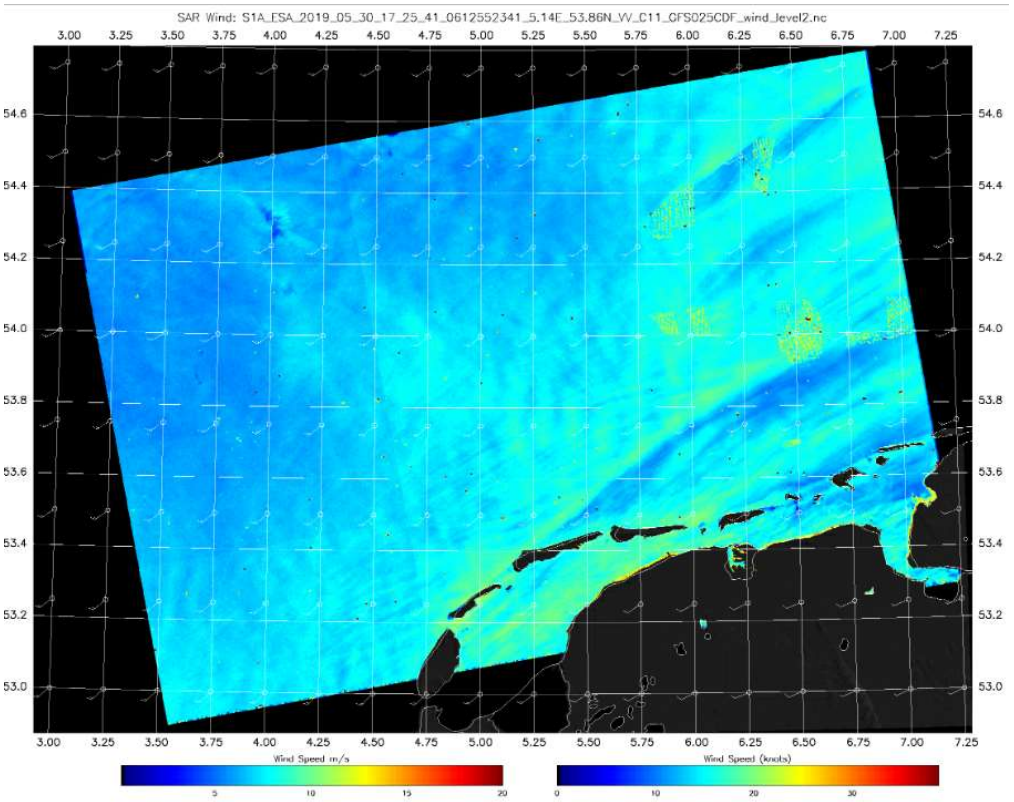
[14] **Norther**: first turbine built 4-2-19; first turbine delivers power 26-2-19; fully operational end of summer 2019; **Northwester 2**: first turbine built 18-12-19; first turbine delivers power 11/12-1-20; fully operational May 2020; **SeaMade (Seastar and Mermaid)**: first turbine built 22-6-2020; first turbine delivers power 3-7-2020; fully operational end 2020; **East Anglia One**: first turbine built 28-6-19; first turbine delivers power 13-9-19; fully operational 21-8-20; **Borssele I/II**: first turbine built April 2020; first turbine delivers power 28-4-20; fully operational 27-11-20; **Borssele III/IV**: first turbine built 28-5-20; first turbine delivers power 10-8-20; fully operational 6-1-21 (note: despite not being fully operational 1-1-21, Borssele III/IV is included in the WFP run 2021)



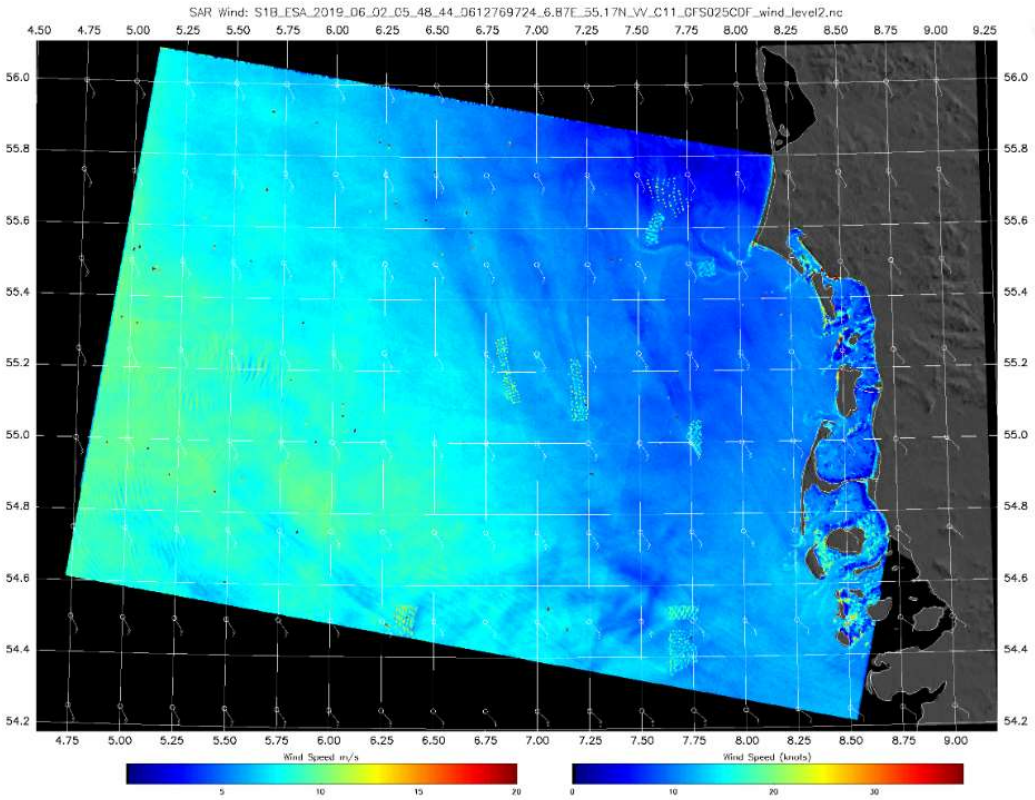
20-03-19 (17:17:02): wake length and interaction



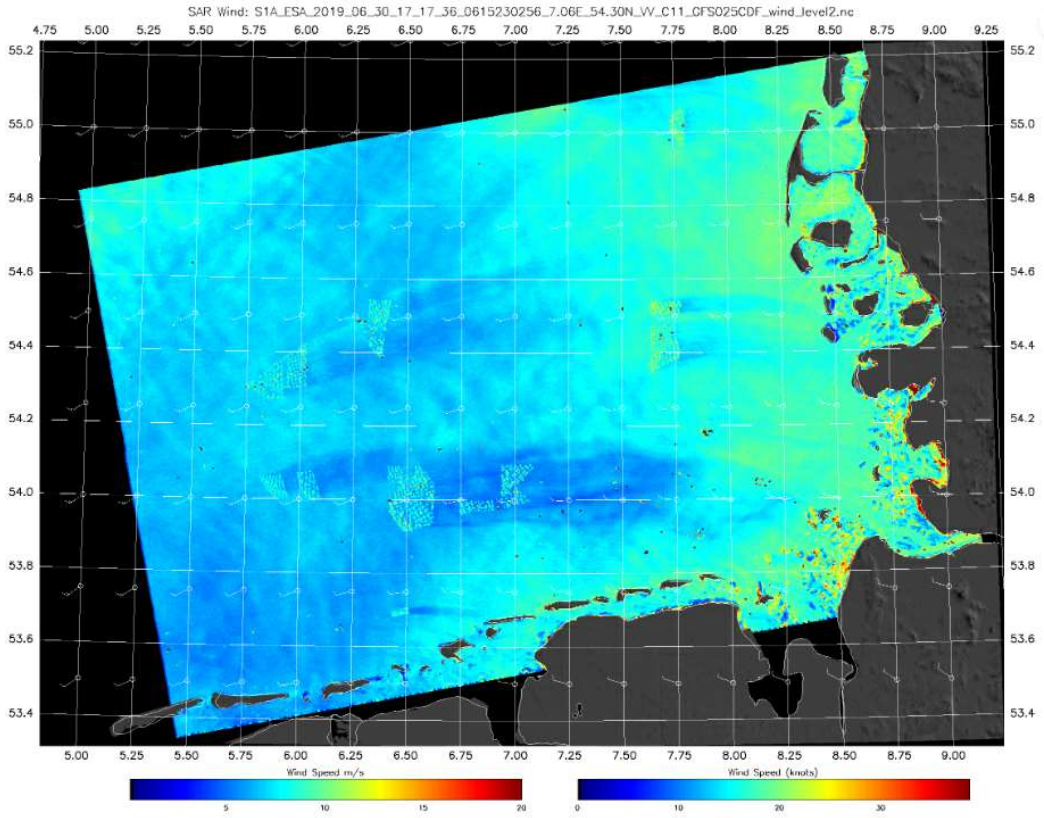
05-04-19 (17:33:20) wake length



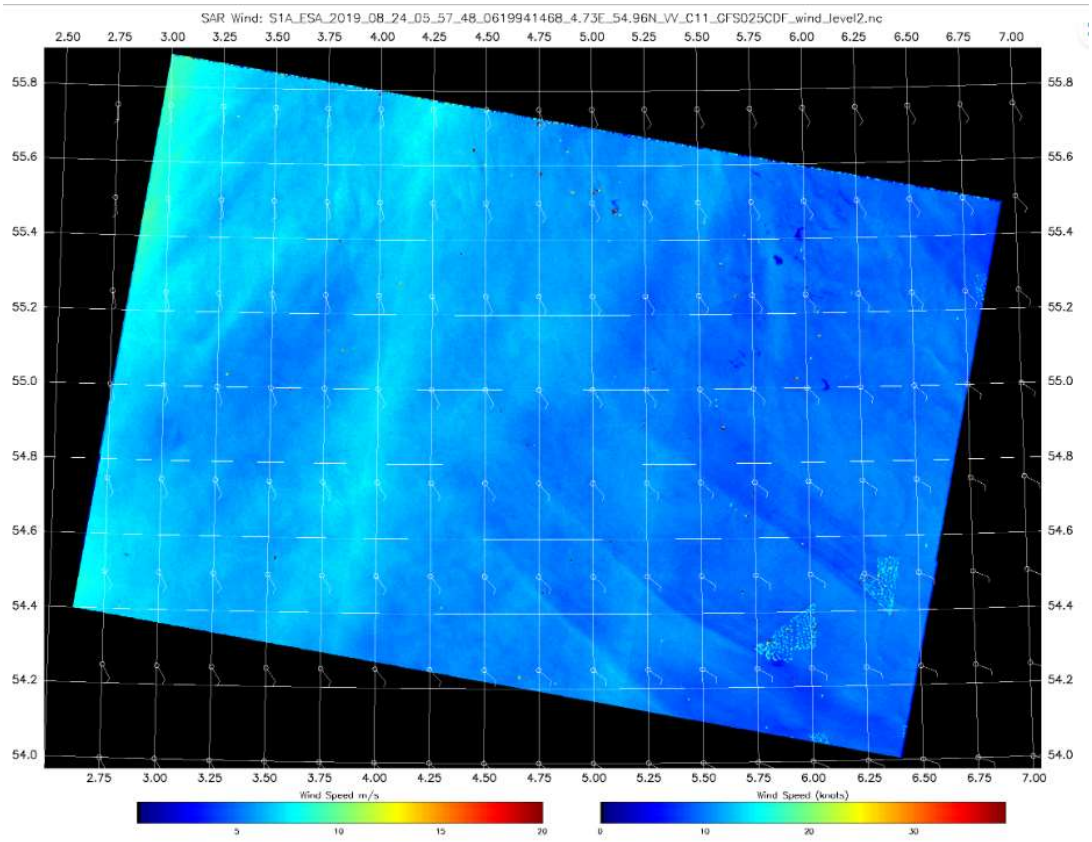
30-05-19 (17:25:41): wake length and interaction



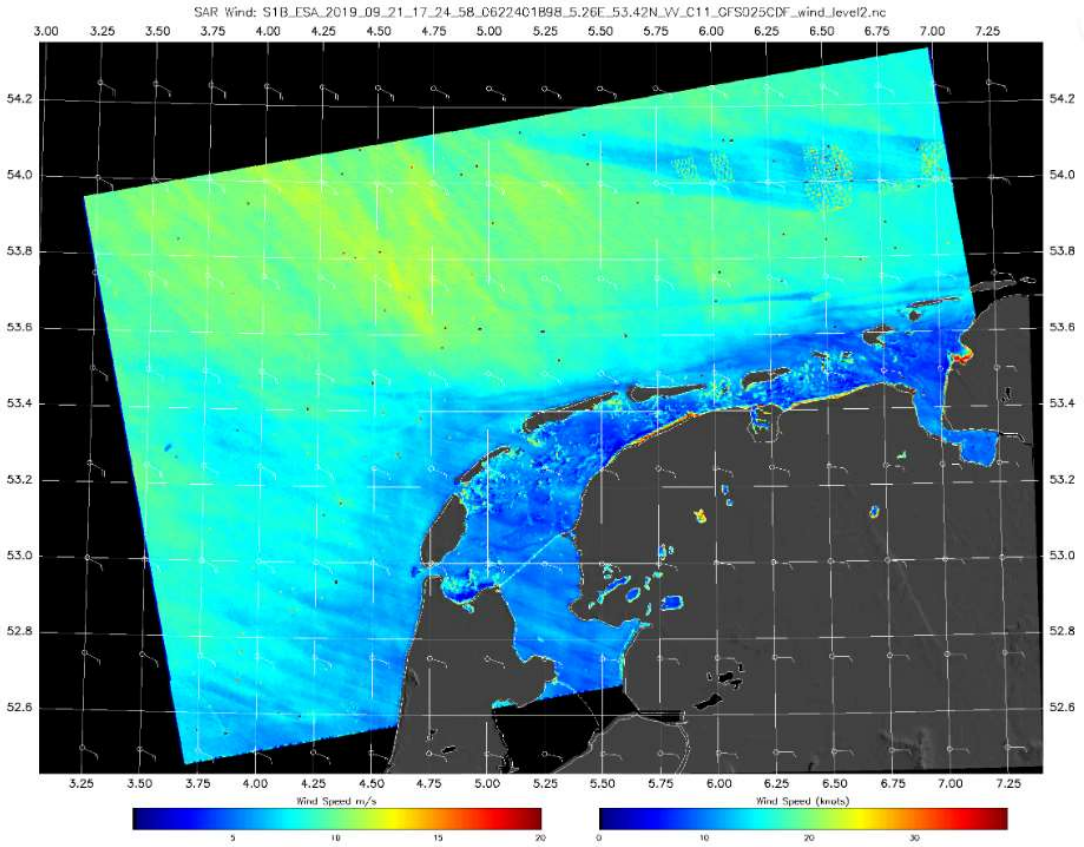
02-06-19 (05:48:44): wake length



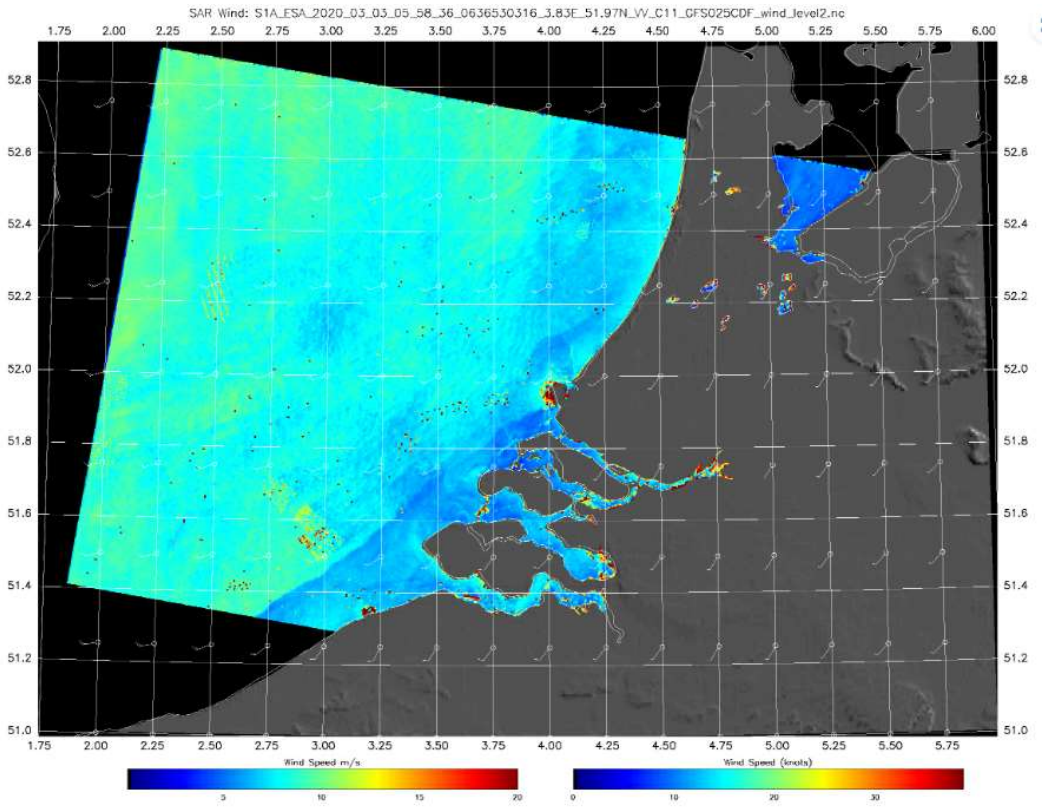
30-06-19 (17:17:36): wake length and interaction



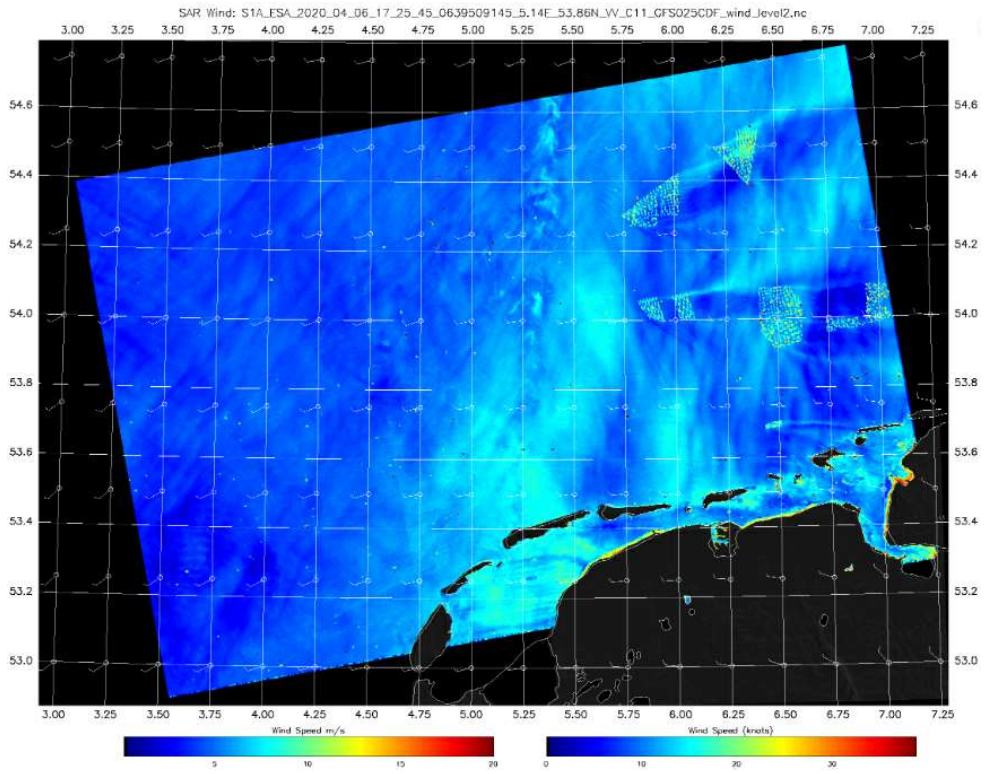
24-08-19 (05:57:48): wake length



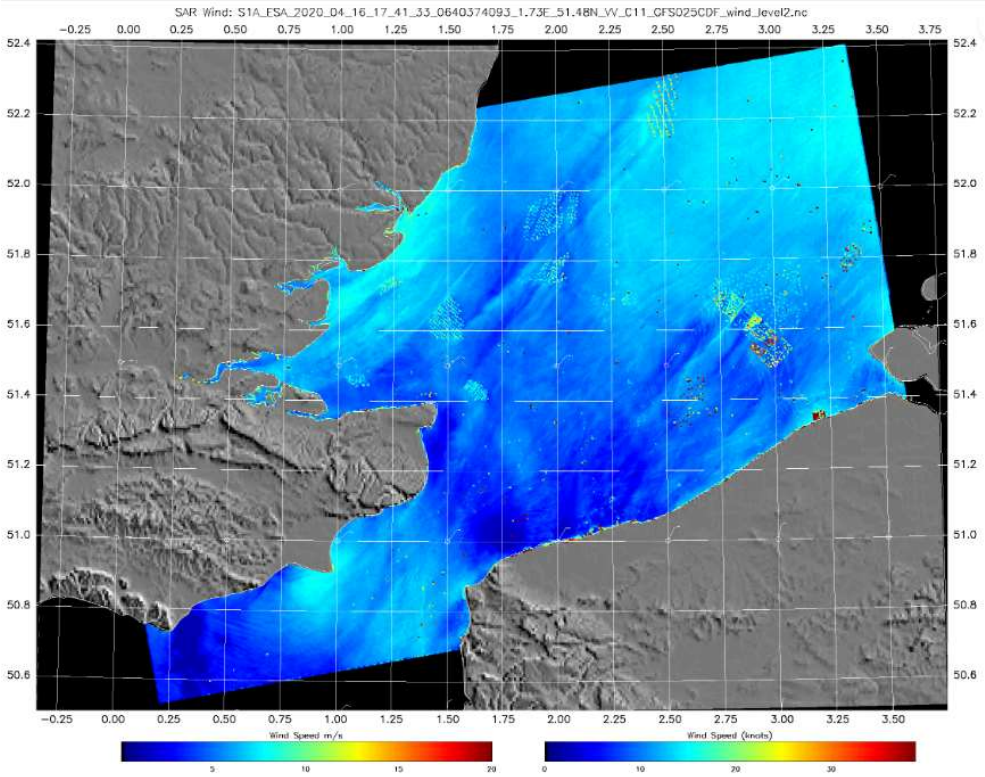
21-09-19 (17:24:58): wake length and interaction with strong background wind



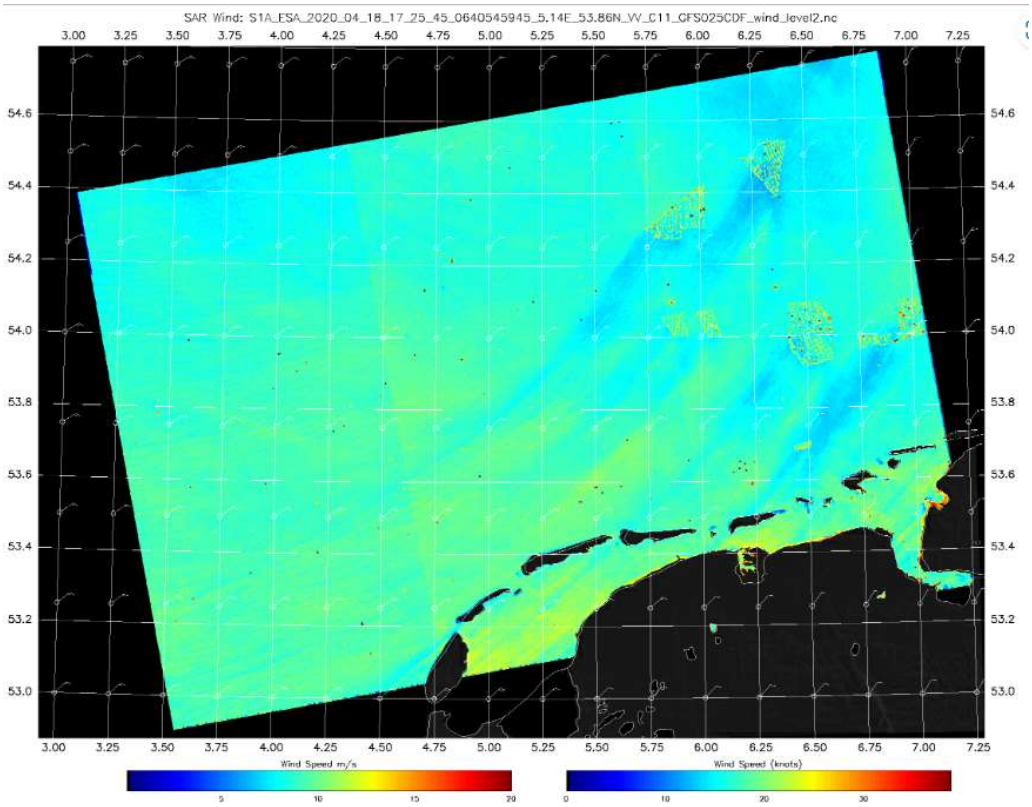
03-03-20 (05:58:36): wake length



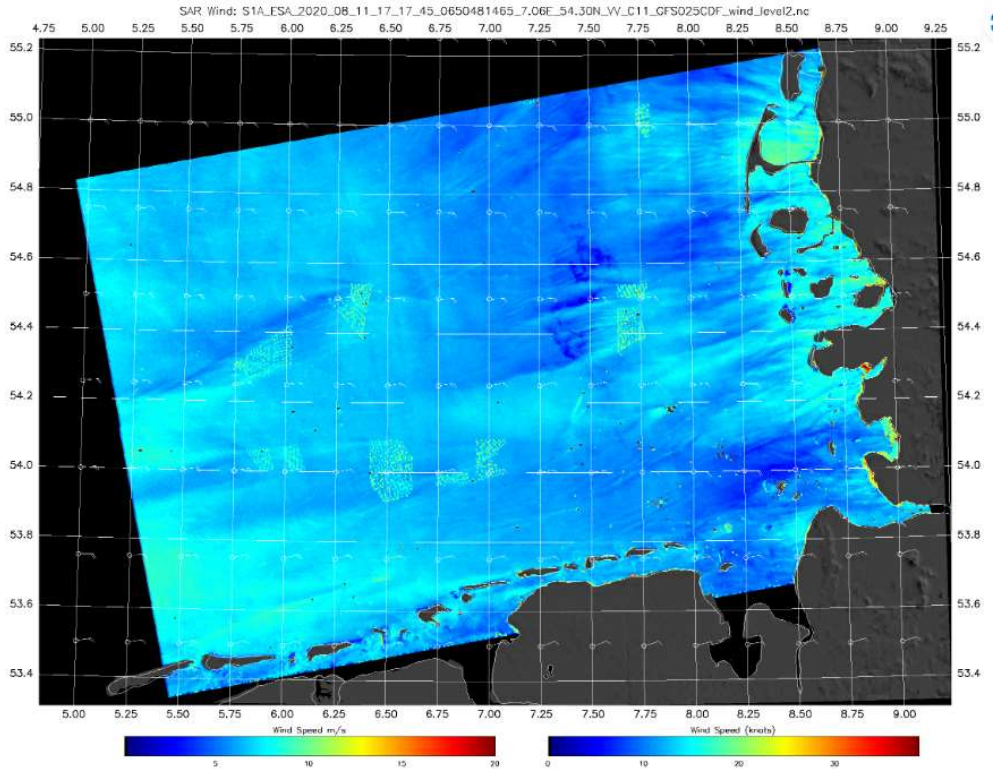
06-04-20 (17:25:45): interacting wakes



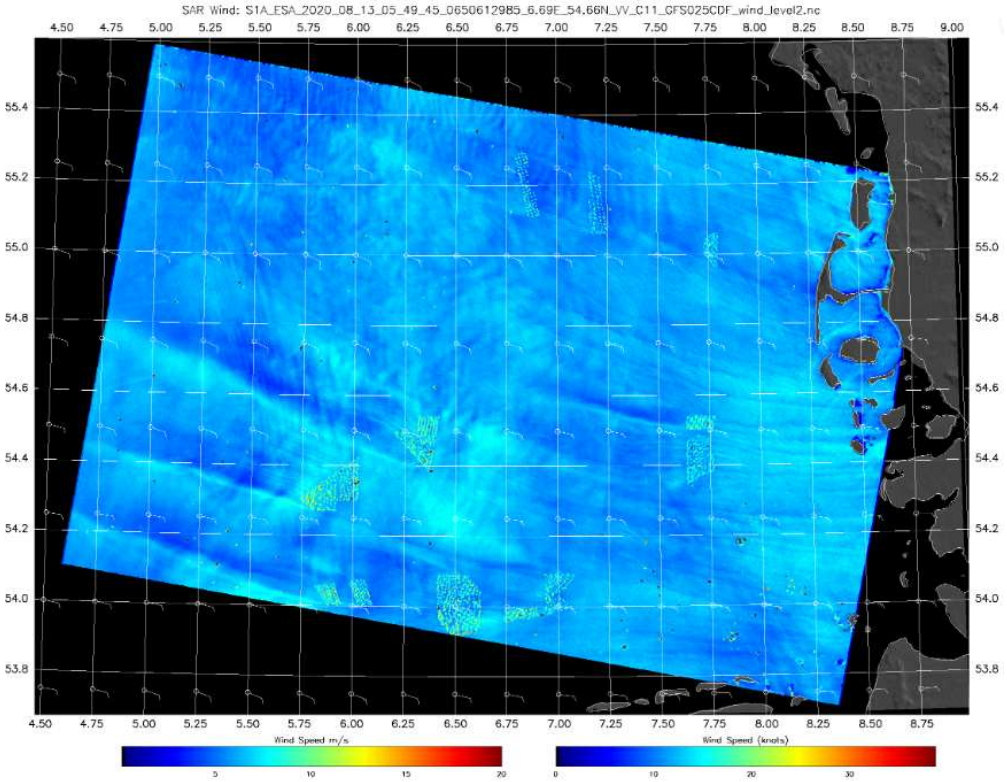
16-04-20 (17:41:33): wake length and interaction



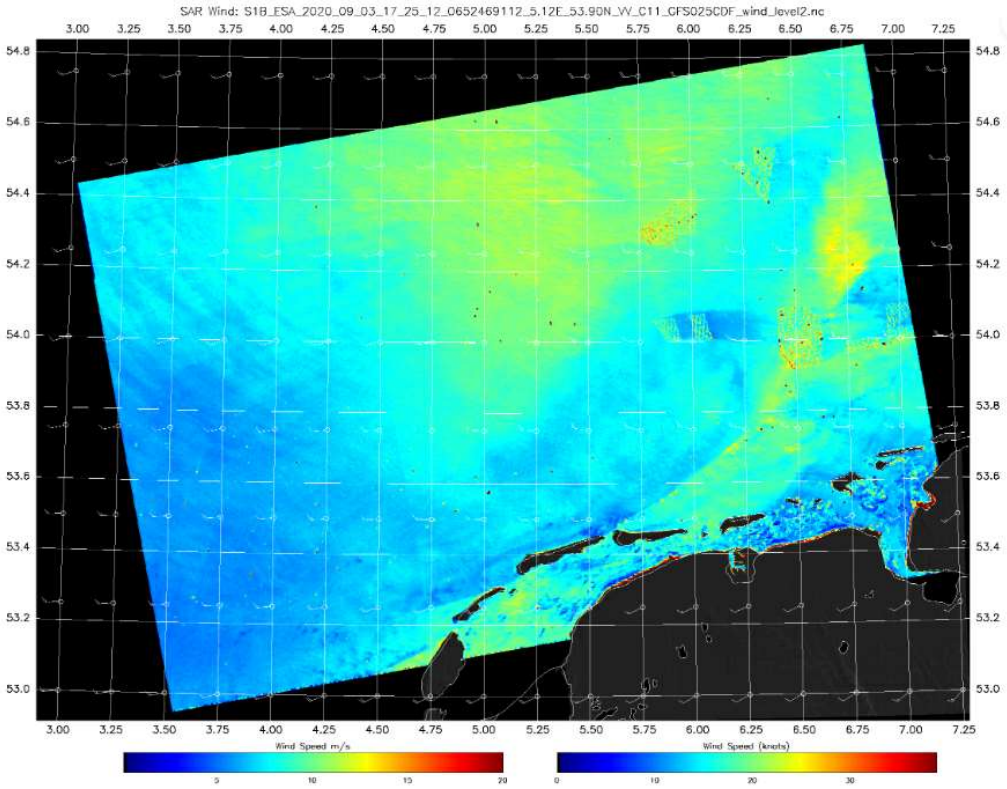
18-04-20 (17:25:45): wake length



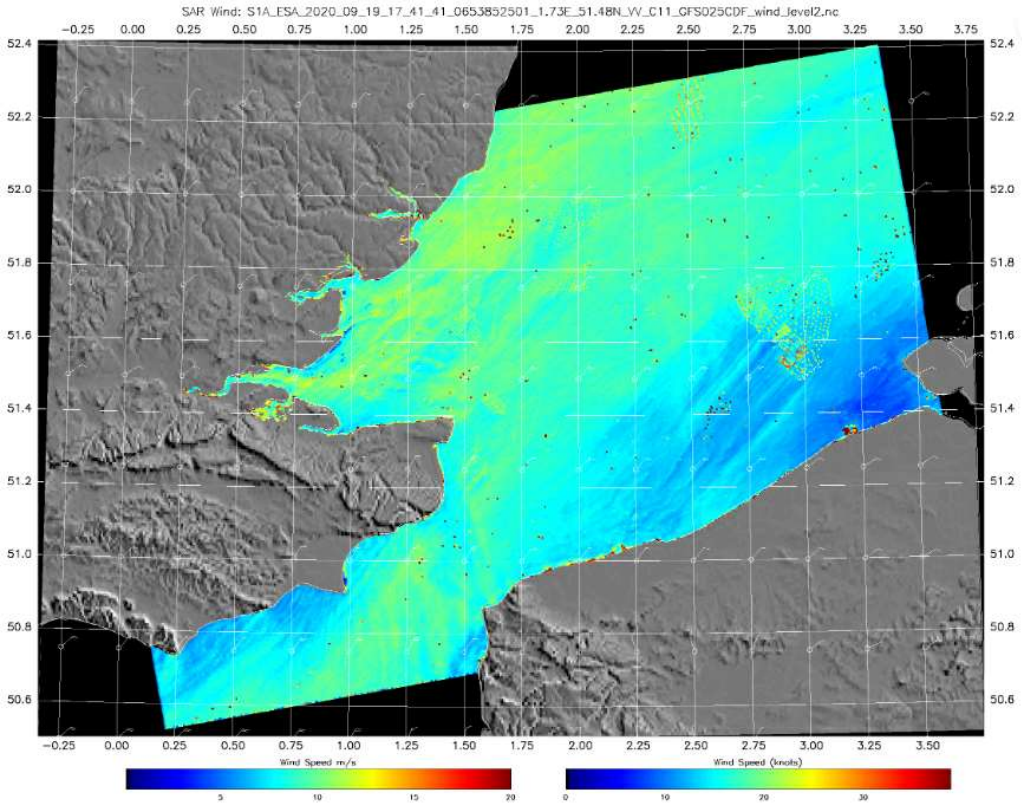
11-08-20 (17:17:45): wake length and interaction



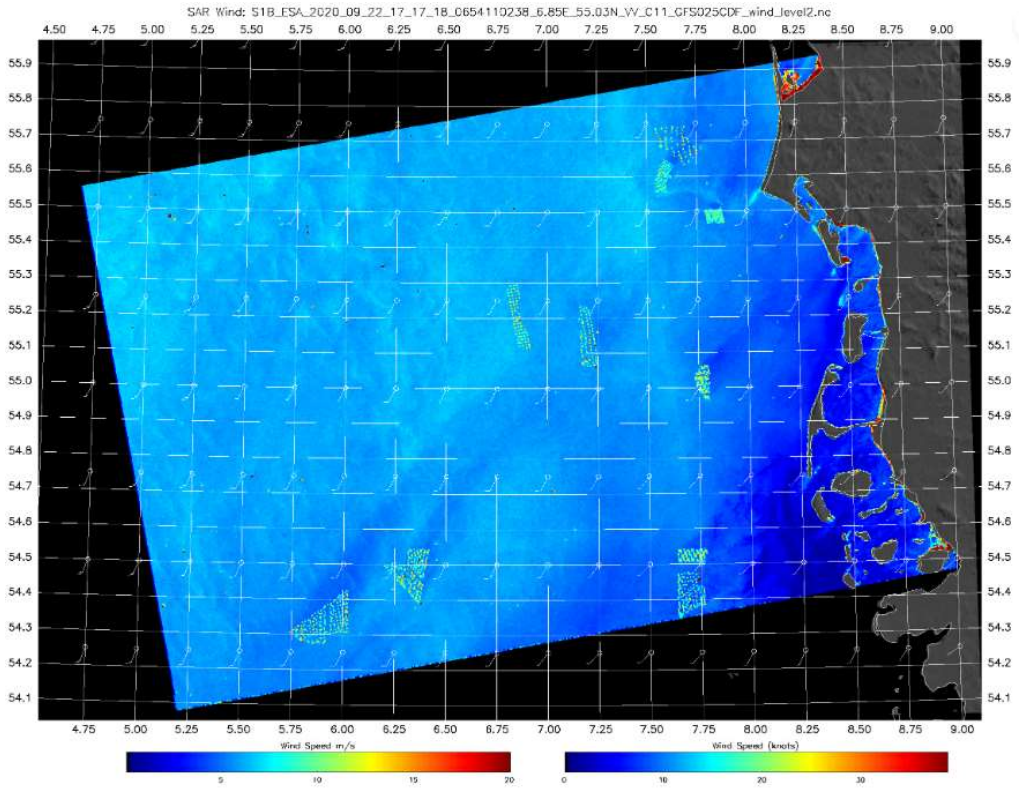
13-08-20 (05:49:45): wake length and interaction



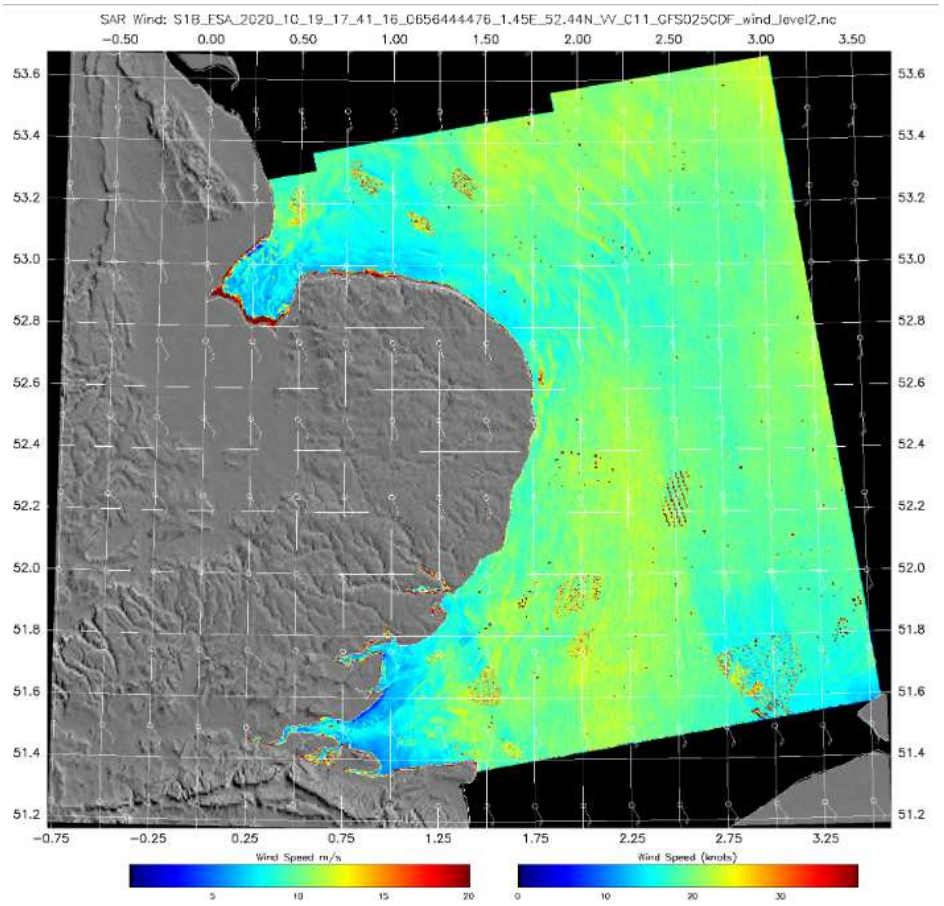
03-09-20 (17:25:12): wake length and interaction Gemini



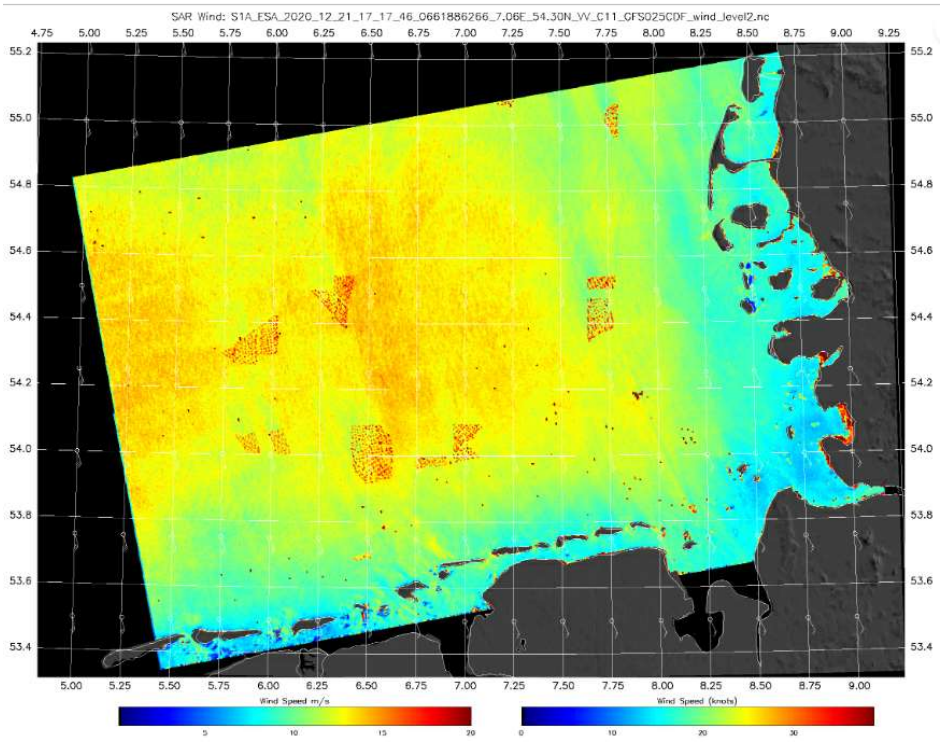
19-09-20 (17:41:41): wake length and interaction



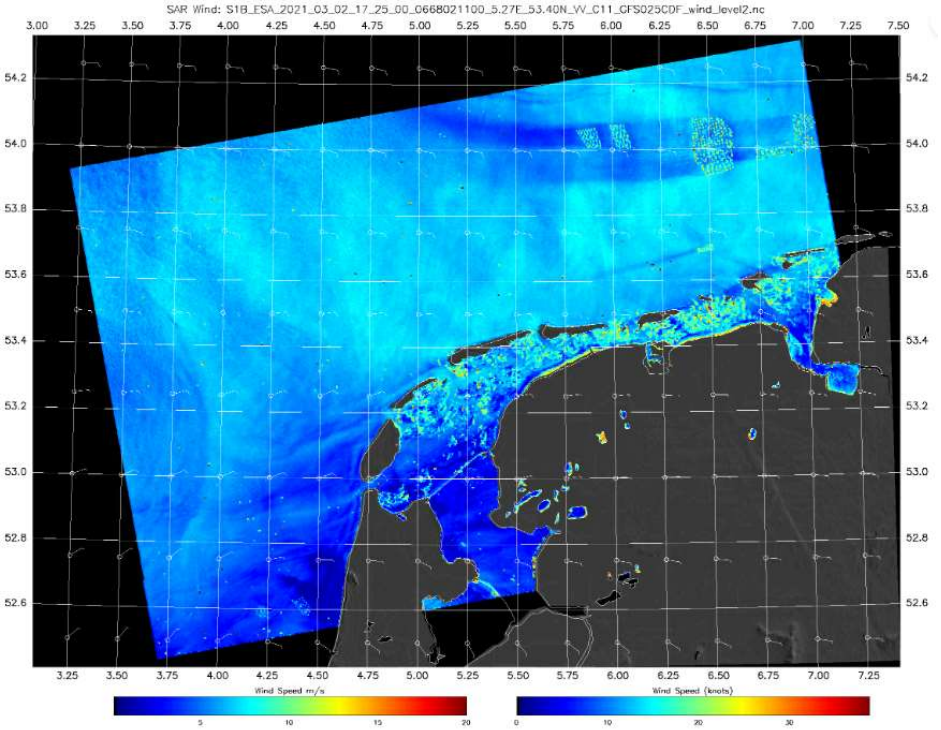
22-09-20 (17:17:18): wake length



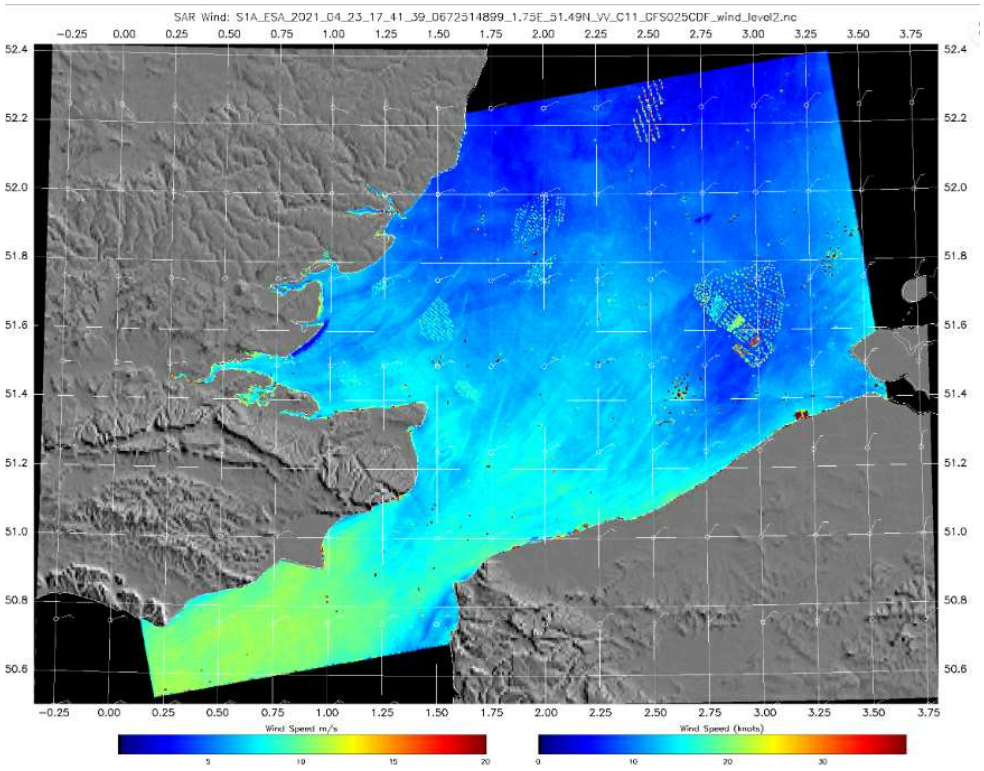
19-10-20 (17:41:16): wake length with strong background wind



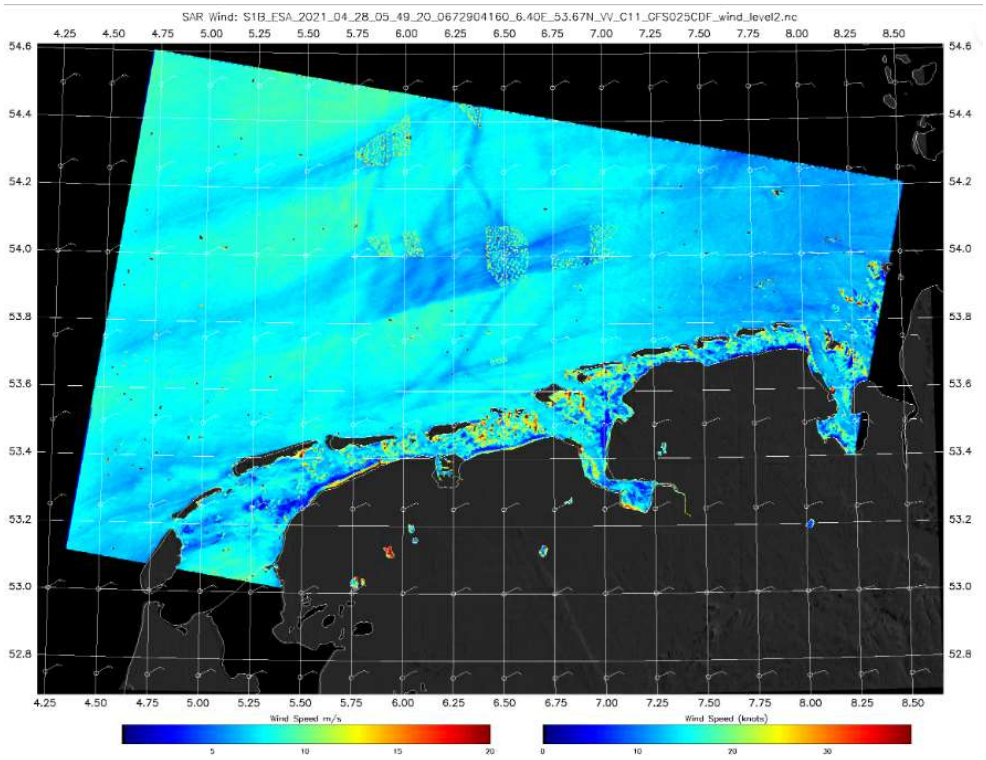
21-12-20 (17:17:46): wake length with strong background wind



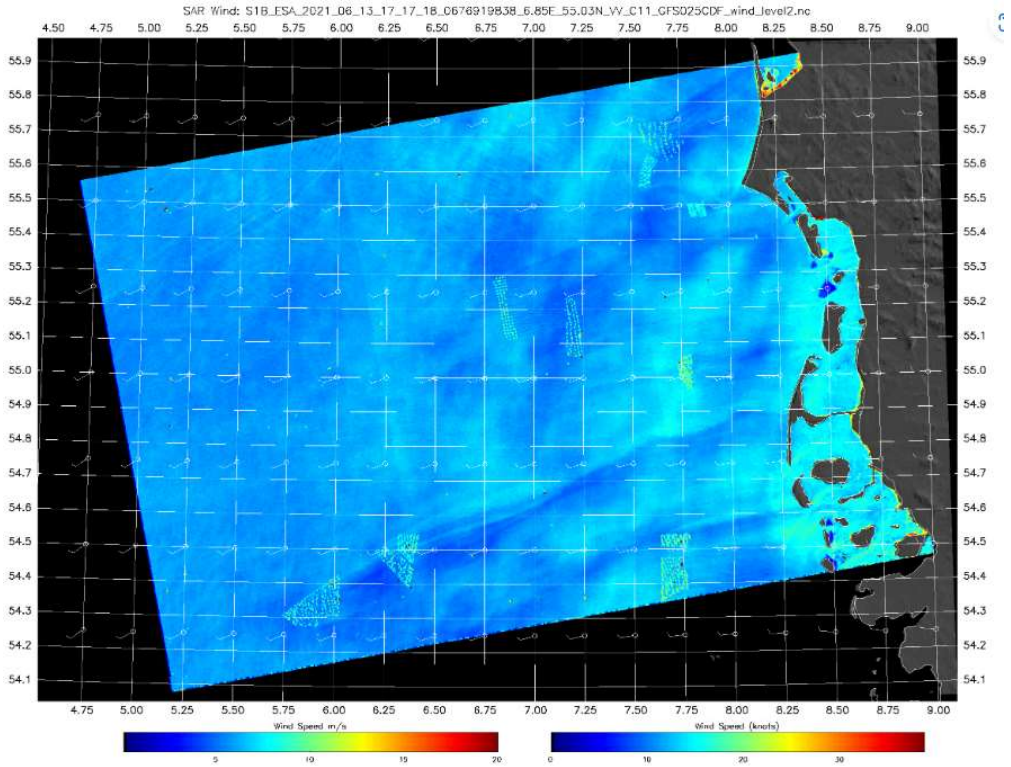
02-03-21 (17:25:00): wake length



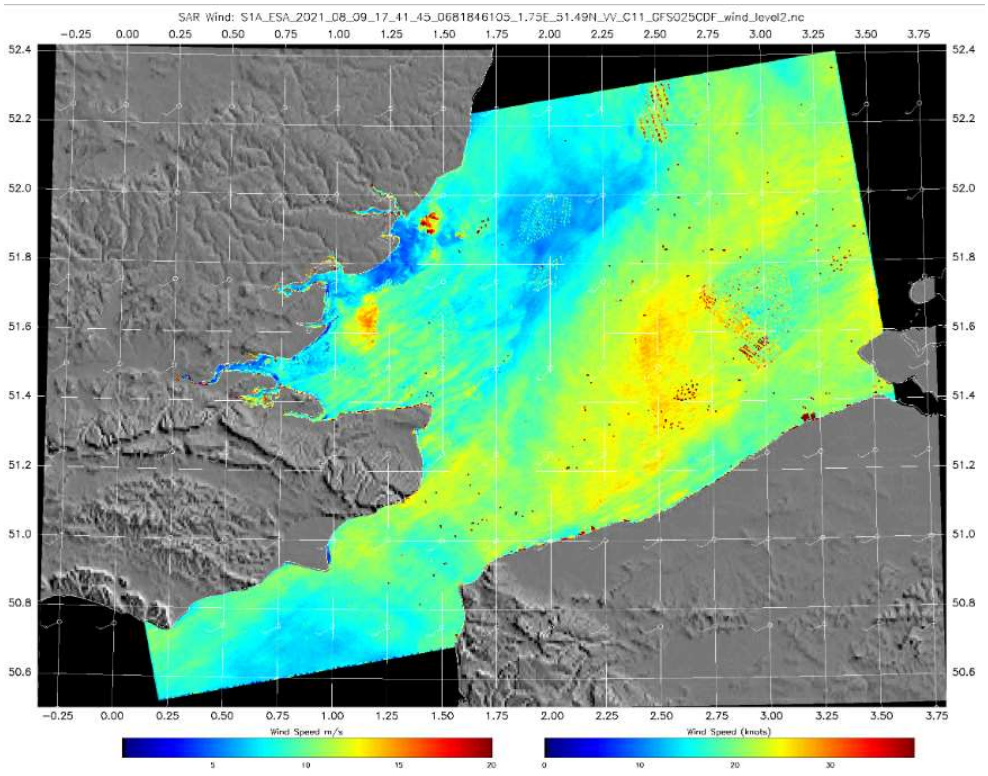
23-4-21 (17:41:39): wake length



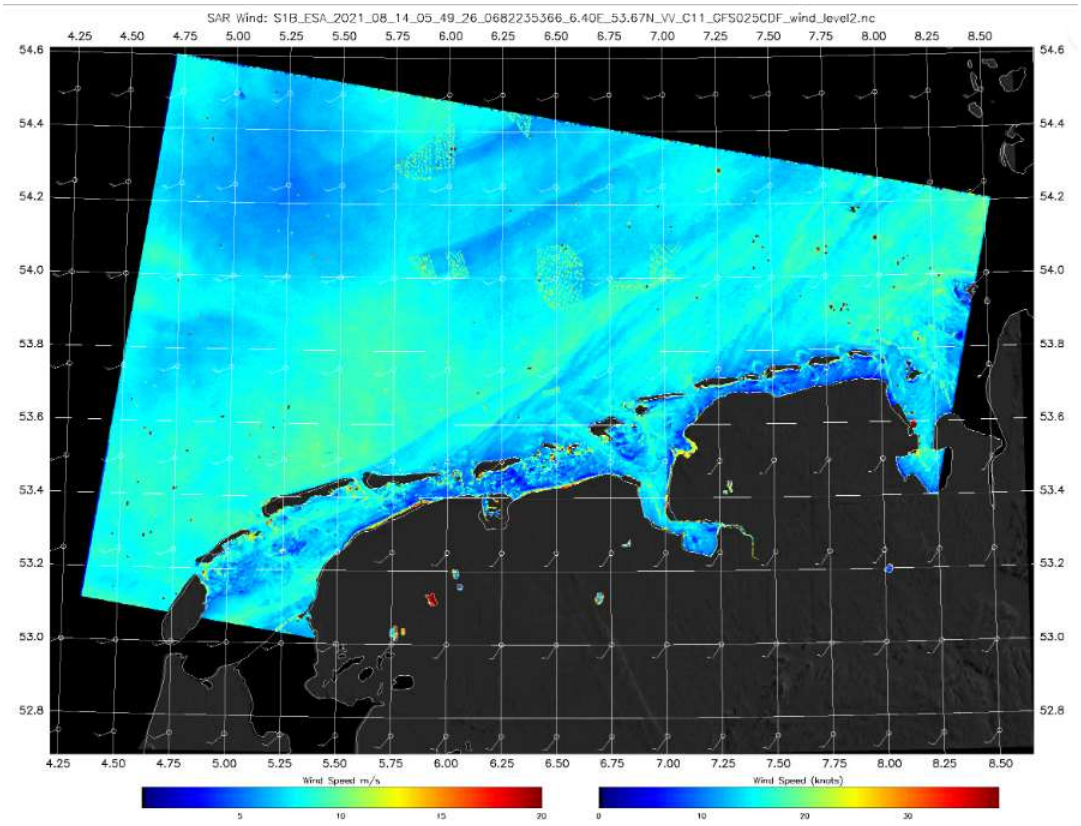
28-4-21 (05:49:20): wake length and interaction



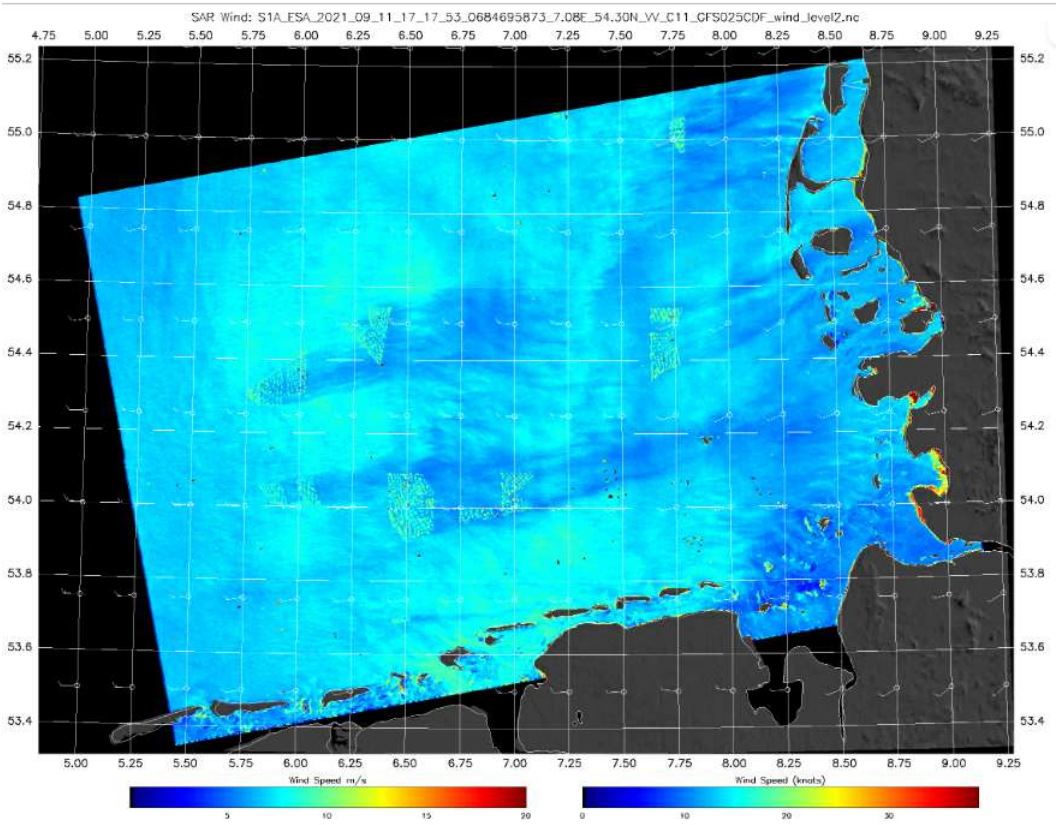
13-06-21 (17:17:18): wake length and interaction



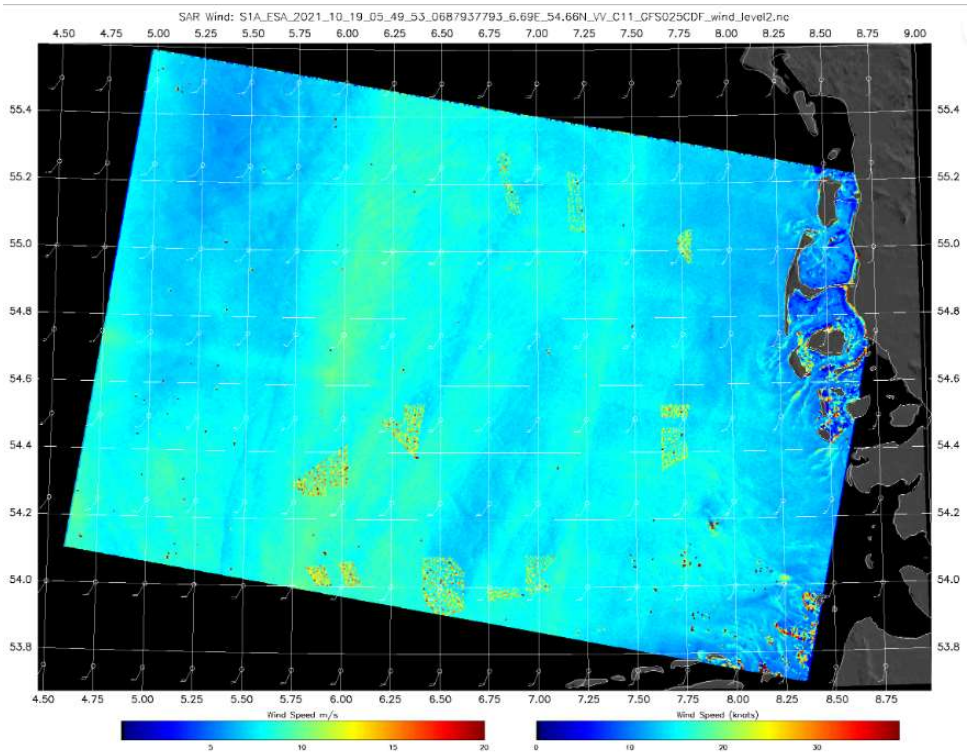
09-08-21 (17:41:45): wake length



14-08-21 (05:49:26): wake length and interaction

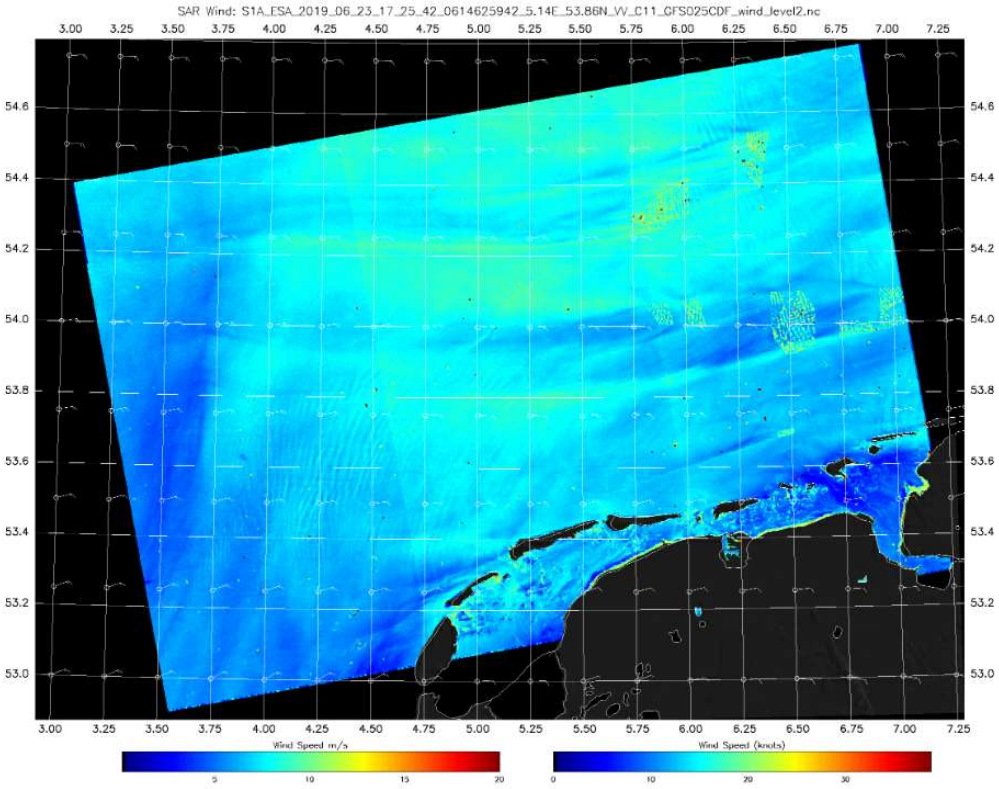


11-09-21 (17:17:53): wake length and interaction

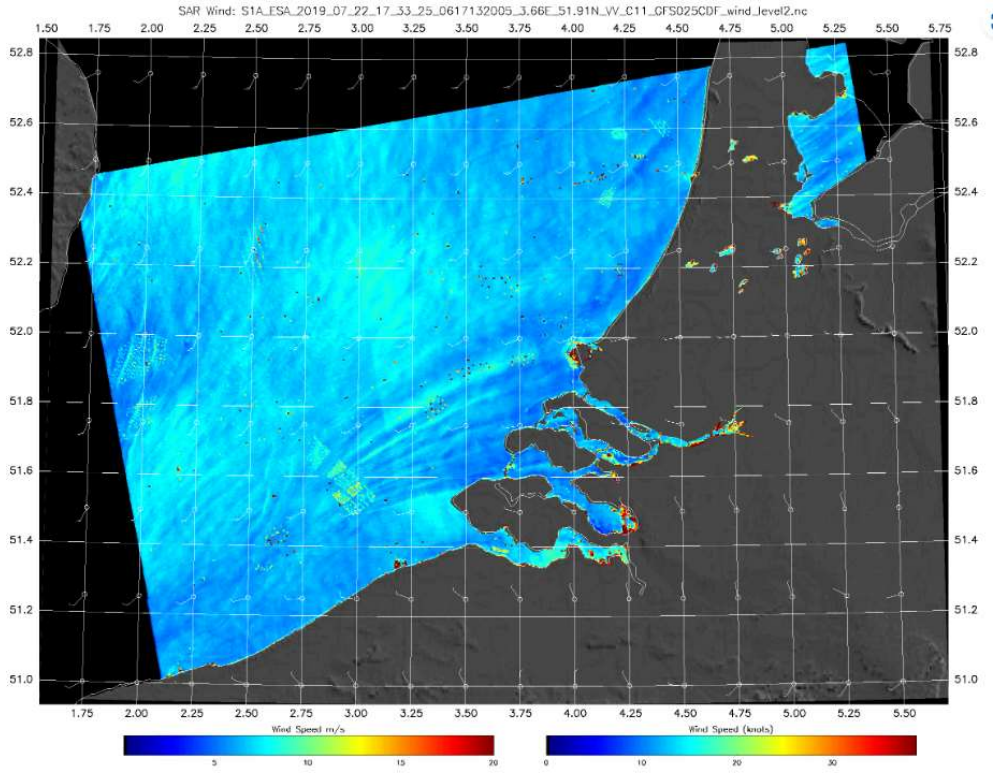


19-10-21 (05:49:53): wake length

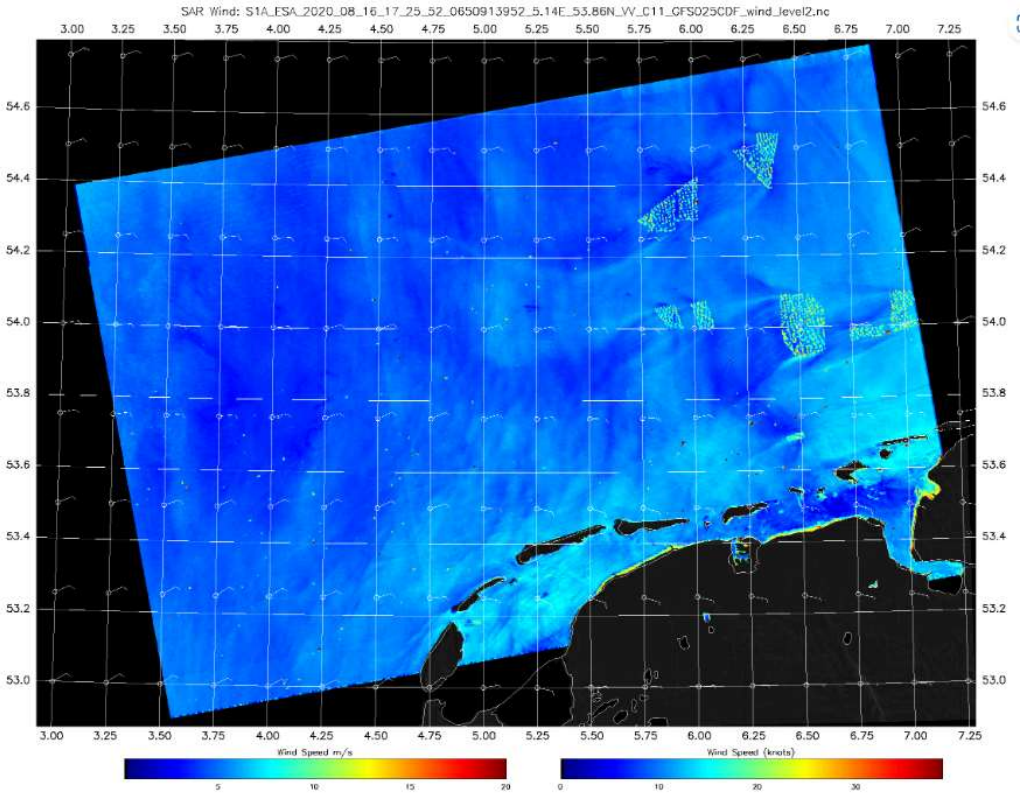
5.2. Turning wakes (all cases = 4 selected)



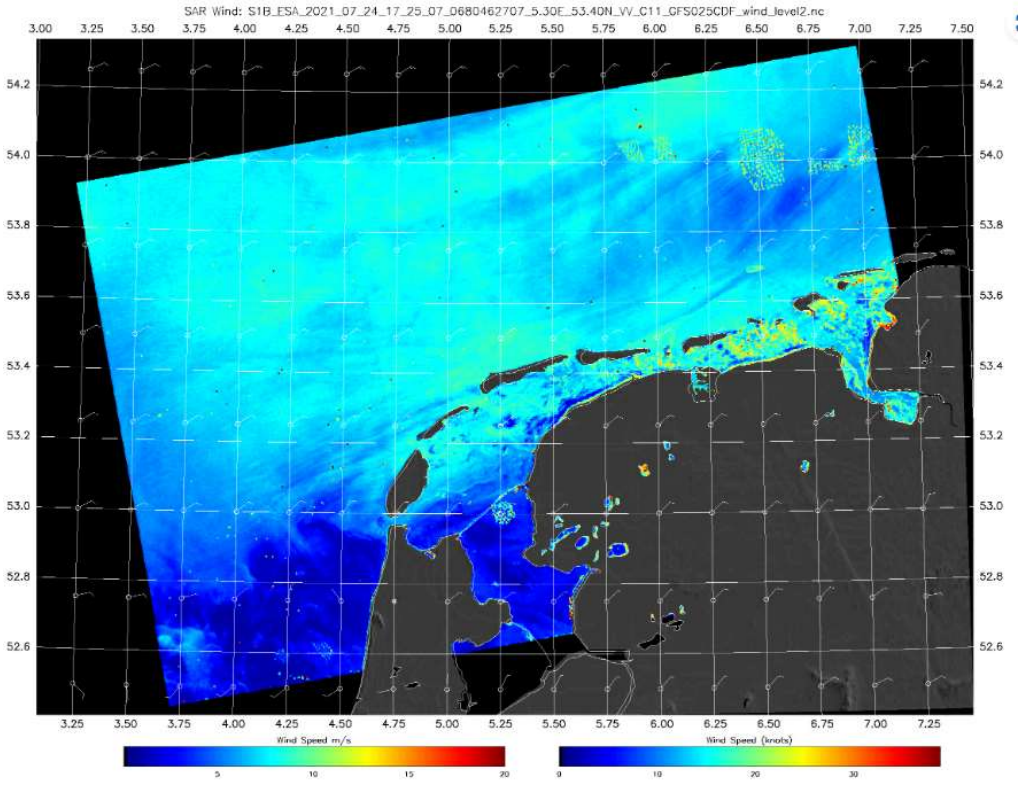
23-06-19 (17:25:42): turning wakes



22-07-19 (17:33:25): turning wakes

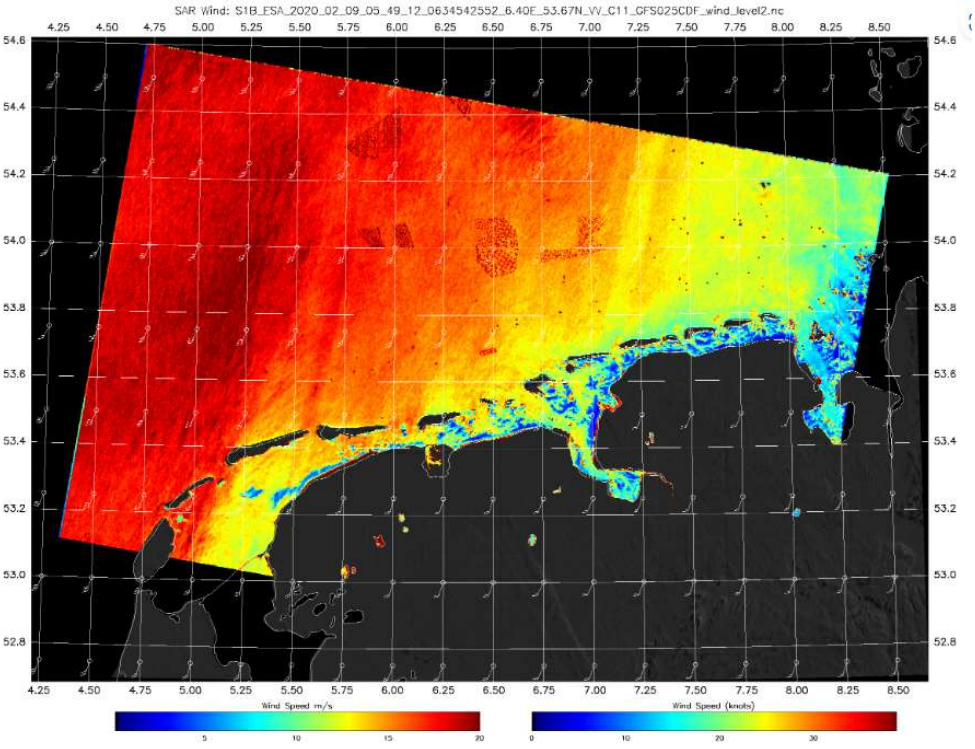


16-08-20 (17:25:52): turning wakes

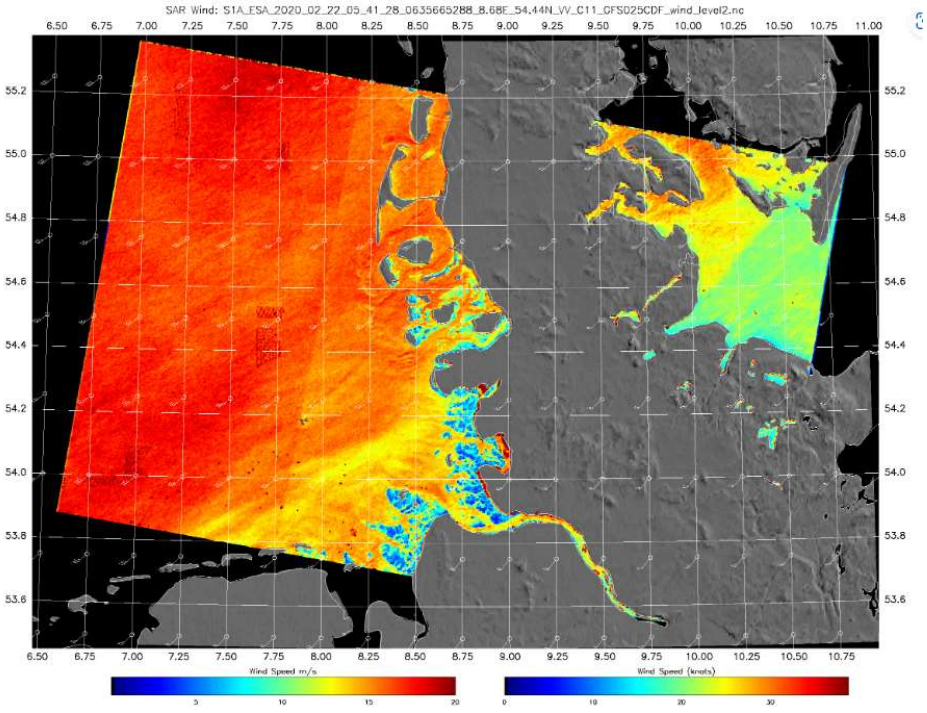


24-07-21 (17:25:07): turning wakes

5.3 Storms (all cases = 3 selected)

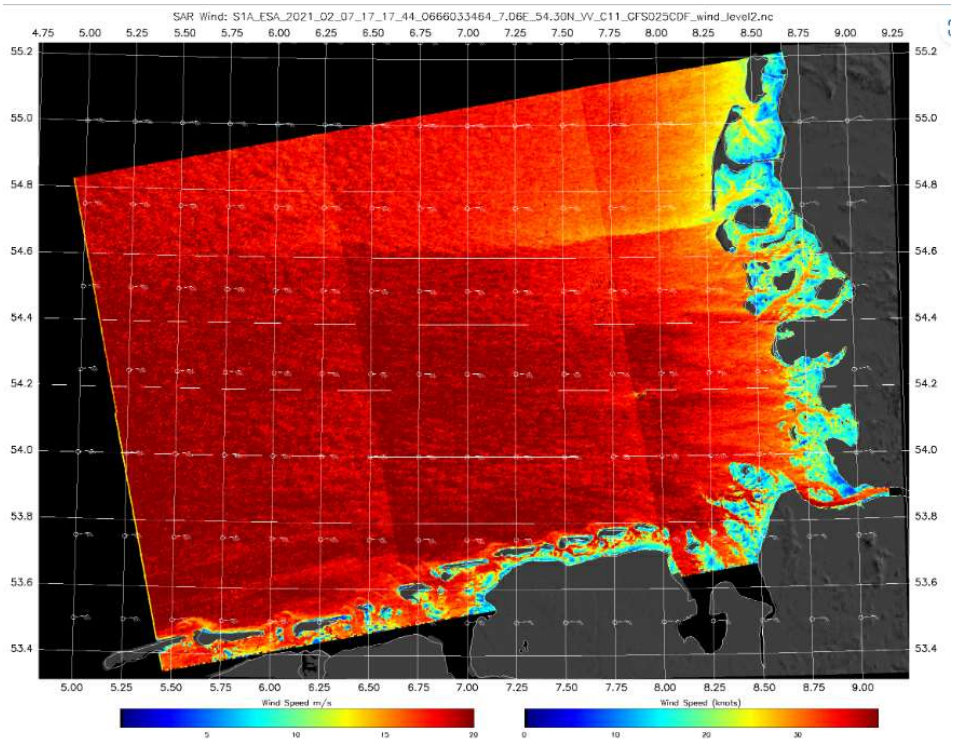


09-02-20 (05:49:12): Ciara[15][16]



22-02-20 (05:41:28): Dennis[17]

[15] Storm Ciara - Wikipedia
[16] https://www.knmi.nl/nederland-nu/klimatologie/lijsten/zwarestormen
[17] 22 feb 2020 storm - Zoeken (bing.com)

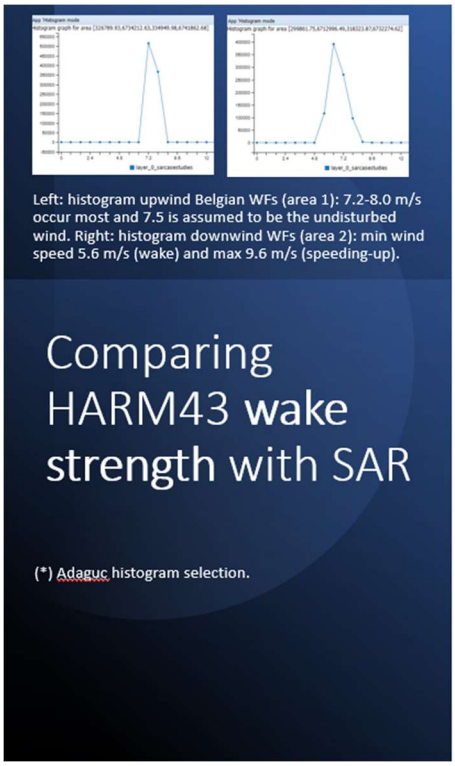


07-02-21 (17:17:44): Darcy[18] with snow and E'ly winds

[18] https://www.knmi.nl/over-het-knmi/nieuws/code-rood-voor-seeuwstorm-darcy

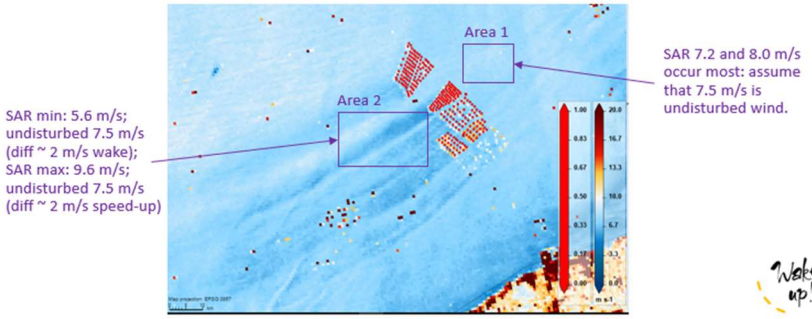
6. Appendix B: Method SAR validation

For the SAR validation, Adaguc-viewer was used[19]. With this publicly available viewer information can be easily combined in space and time.



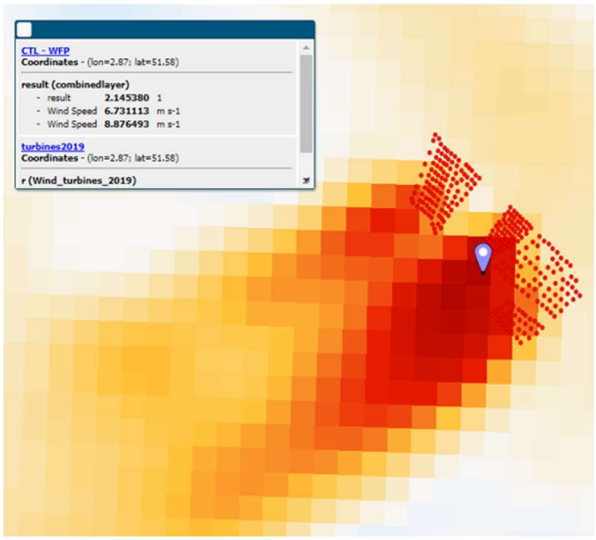
Comparing SAR and HARM43 (a):

- SAR biases can be high, but are the same inside and outside the wake when flow is uniform (e.g. no fronts): that is why we validate windspeed difference inside and outside the wake.
- Select (*) two areas: area 1 upstream wind farm (where wind should be comparable to CTL, so area 1 should be outside wake of another wind farm) and area 2 downstream the wind farm (where wind should be comparable to WFP)
- Area 1: assume (average) of most occurring wind speeds as undisturbed wind
- Area 2: max wake strength = difference between undisturbed wind and lowest wind speed in histogram (> 0 cases included).
- Area 2: max speed-up = difference between undisturbed wind and highest wind speed in histogram (> 0 cases included). Left or right side: looking downwind.



Comparing SAR and HARM43 (b):

- Select max CTL-WFP using Agaduc AutoWMS selection: select gridbox with highest difference (here 8.8-6.7 = 2.1 m/s).

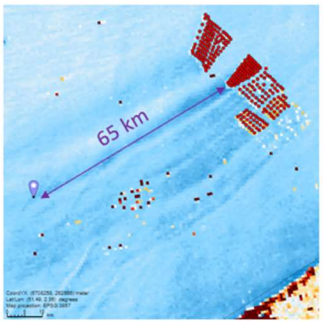


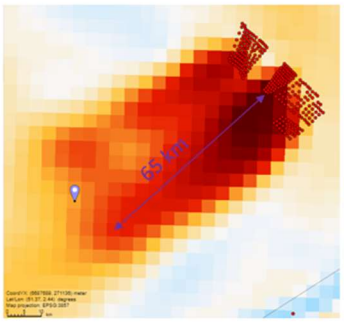
[19] ADAGUC Viewer (knmi.nl)

Comparing HARM43 **wake length** with SAR

Method of comparing wake length in SAR and HARM43:

- Assume max wake length is where difference between wind speed in the wake and the undisturbed wind becomes less than 1 m/s
- Set pointer to max wake length in SAR-image (where wind speed is 1 m/s lower than the undisturbed wind) and compare to max wake length according to CTL-WFP (where CTL-WFP becomes <1 m/s).
- Max wake length ~ 65 km (SAR) and ~ 65 km (CTL-WFP)





Undisturbed wind: 7.5 m/s.
At pointer SAR wind speed 6.5 m/s.
Wake length: ~ 65 km

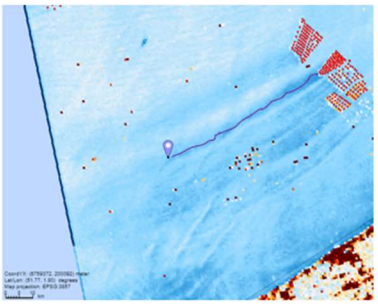
Comparing HARM43 **wake length&strength** with SAR

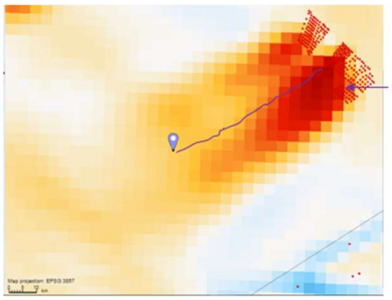
5-4-2019: only Belgian wind farms; the first Borssele wind turbine (Borssele I/II) was built in April 2020.

(*) https://vasab.org/wp-content/uploads/2018/06/BalticLINes_CapacityDensityStudy_June2018-1.pdf

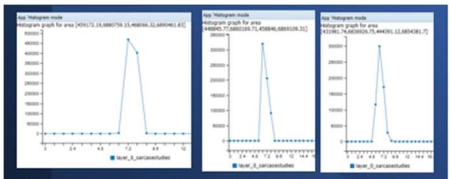
Comparison SAR and CTL-WFP: (**5-4-2019** 17:33:20 UTC & 17:00:00 UTC)

- Max wake length (from Northwind): ~ 65 km (SAR) and ~ 65 km (CTL-WFP)
- Max wake strength: 7.5-5.6 ~ 1.9 m/s (SAR) and ~ 2 m/s (CTL-WFP)
- Max speed-up: 9.6-7.5 ~ 2 m/s on left side of wake (SAR)





- Note: wake length&strength in WFP accurate, but there are differences in wake propagation (turning of wake)
- Note: wake strongest behind wind farm with highest power density: Northwind: 16.9 MW/km² (*)

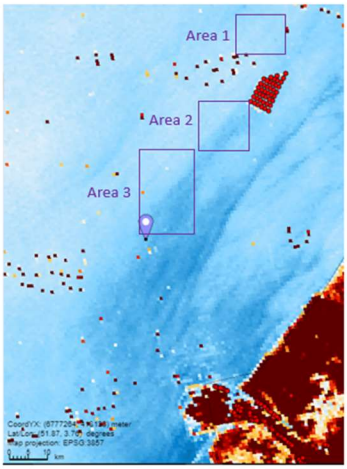


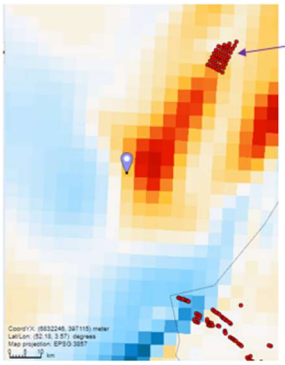
Left: histogram upwind wind farm (area 1): 7.2-8.0 m/s occur most and 7.5 is assumed to be the undisturbed wind. Middle/right: histogram downwind wind farm. Middle (area 2): min wind speed 6.4 m/s (wake) and max 8.0 m/s (speeding-up). Right (area 3): min 5.6 m/s.

Comparing HARM43 wake length&strength with SAR

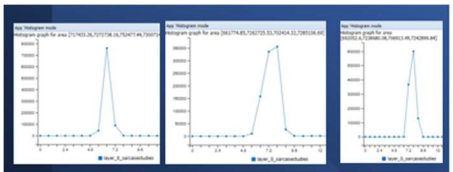
Comparison SAR and CTL-WFP: (**5-4-2019** 17:33:20 UTC & 17:00:00 UTC)

- Max wake length (from Luchterduinen): ~ 40 km (SAR) and ~ 40 km (CTL-WFP)
- Max wake strength: 7.5-5.6 ~ **1.9 m/s** (SAR) and ~ **1.2 m/s** (CTL-WFP)
- Max speed-up: 8.0-7.5 ~ 0.5 m/s (not significant) (SAR)



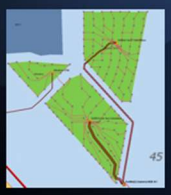


Note:
- Pointer indicates wake length SAR (where wake strength SAR is 1 m/s)
- Wake stronger further from WF



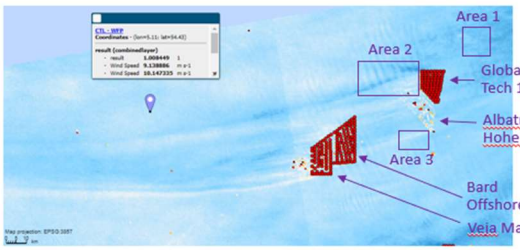
Left: histogram upwind wind farm (area 1): 6.4 m/s. Middle: histogram downwind wind farm (area 2): min wind speed 5.6 m/s (wake) and max 12.0 m/s (max in Albatros/Hohe See, so excluded from analyses). Right: clear speed up left side of wake Hohe See (area 3): max 8.8 m/s

Comparing HARM43 wake length&strength with SAR

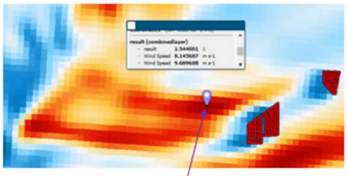


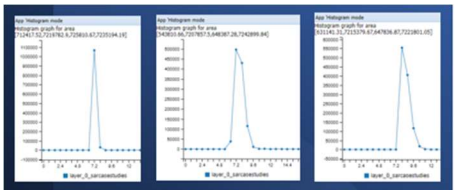
Comparison SAR and CTL-WFP: (**23-6-2019** 17:25:42 UTC & 17:00:00 UTC)

- Max wake length (from Global Tech 1): ~ **x km** (SAR) and ~ **135 km** (CTL-WFP)
- Max wake strength: 6.4 – 5.6 ~ 0.8 m/s (SAR) and ~ 1.5 m/s (CTL-WFP)
- Max speed-up: 8.8-6.4 ~ 2.4 m/s on left side of wake (SAR)



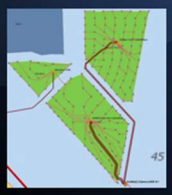
- Wake length cannot be determined from SAR (wake strength mostly less than 1 m/s). Pointer in SAR-figure above = where CTL-WFP ~ 1 m/s
- Some turbines in Albatros and Hohe See WF in SAR, but not yet in WFP 2019 (turbines are added once a year, on the 1st of January).
- Note the strange abrupt end of wake in CTL-WFP





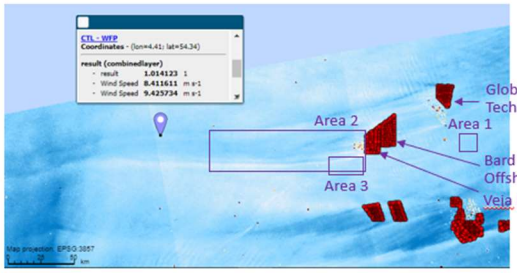
Left: histogram upwind wind farms (area 1): 7.2 m/s. Middle: histogram downwind wind farms (area 2): min wind speed 6.4 m/s (wake) and max 15.2 m/s (max in Deutsche Bocht, so excluded from analyses). Right: clear speed up left side of wake (area 3): max 11.2 m/s

Comparing HARM43 wake length&strength with SAR

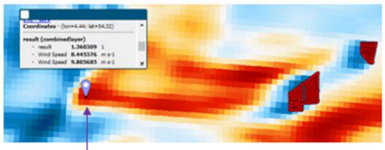


Comparison SAR and CTL-WFP: (**23-6-2019** 17:25:42 UTC & 17:00:00 UTC)

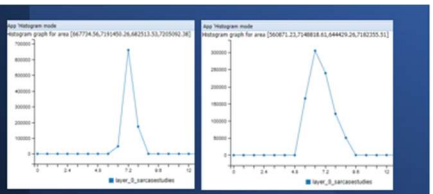
- Max wake length (from Veija Mate): ~ **x km** (SAR) and ~ **150 km** (CTL-WFP)
- Max wake strength: 7.2-6.4 ~ 0.8 m/s (SAR) and ~ 1.4 m/s (CTL-WFP)
- Max speed-up: 11.2-7.2 ~ 4.0 m/s on left side of wake (SAR)



- Wake length cannot be determined from SAR (wake strength mostly less than 1 m/s). Pointer in SAR-figure above = where CTL-WFP ~ 1 m/s
- Some turbines in Deutsche Bucht WF in SAR, but not yet in WFP (turbines are added once a year, on the 1st of January).
- Note the strange abrupt end of wake in CTL-WFP



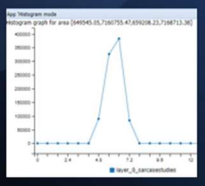
Location where CTL-WFP has max value (1.4 m/s)



Left: histogram upwind wind farms (area 1): 7.2 m/s occurs most and is assumed to be the undisturbed wind. Right: histogram downwind wind farms (area 2): min wind speed 5.6 m/s (wake) and max 9.6 m/s (speeding-up).

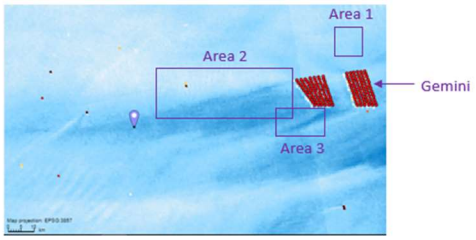
Comparing HARM43 wake length&strength with SAR

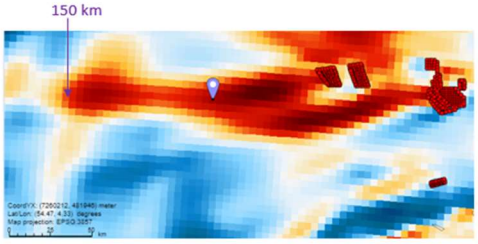
Area 3: min 4.8, max 7.2 (strongest wake effect, but no speed-up)

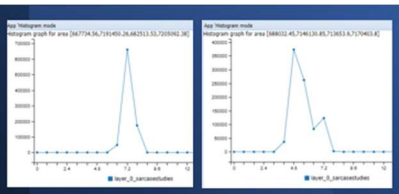


Comparison SAR and CTL-WFP: (**23-6-2019** 17:25:42 UTC & 17:00:00 UTC)

- Max wake length (from Gemini): ~ **70 km** (SAR) and ~ **150 km** (CTL-WFP)
- Max wake strength: 7.2 -4.8 ~ 2.4 m/s (SAR) and ~ 2.1 m/s (CTL-WFP)
- Max speed-up: 9.6-7.2 ~ 2.4 m/s on right side of wake (SAR)







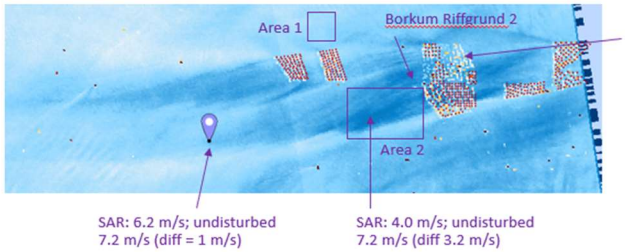
Left: histogram upwind wind farms (area 1): 7.2 m/s occurs most and is assumed to be the undisturbed wind. Right: histogram downwind wind farms (area 2): min wind speed 4.0 m/s (wake) and max 8.0 m/s (speeding-up).

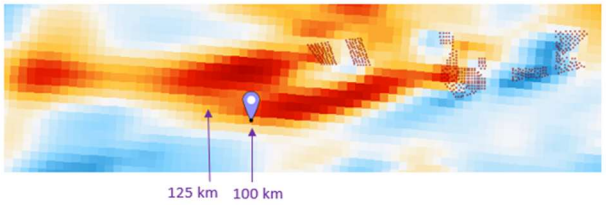
Comparing HARM43 wake length&strength with SAR

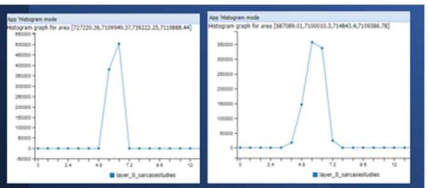
56th wind group 21-09-2023

Comparison SAR and CTL-WFP: (**23-6-2019** 17:25:42 UTC & 17:00:00 UTC)

- Max wake length (from B. Riffgrund 2): ~ **100 km** (SAR) and ~ **125 km** (CTL-WFP)
- Max wake strength: 7.2-4.0 ~ **3.2 m/s** (SAR) and ~ **2.0 m/s** (CTL-WFP)
- Max speed-up: 8.0-7.2 ~ 0.8 m/s (not significant) (SAR)





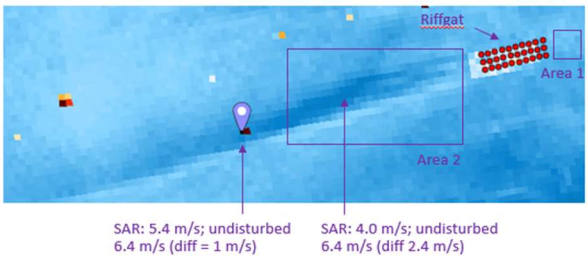


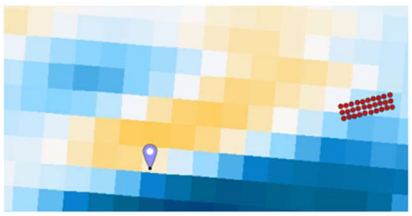
Left: histogram upwind wind farm (area 1): 5.6 and 6.4 m/s occur most and 6.0 m/s is assumed to be the undisturbed wind. Right: histogram downwind wind farm (area 2): min wind speed 4.0 m/s (wake) and max 7.2 m/s (speeding-up).

Comparing HARM43 wake length&strength with SAR

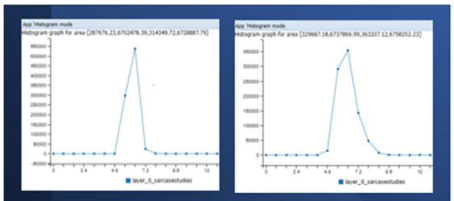
Comparison SAR and CTL-WFP: (**23-6-2019** 17:25:42 UTC & 17:00:00 UTC)

- Max wake length (from Riffgat): ~ **30 km** (SAR) and ~ **x km**(CTL-WFP)
- Max wake strength: 6.0-4.0 ~ **2.0 m/s** (SAR) and ~ **0.5 m/s** (CTL-WFP)
- Max speed-up: 7.2-6.0 ~ 1.2 m/s on left side of wake (SAR)





Note: wake in WFP too far north.

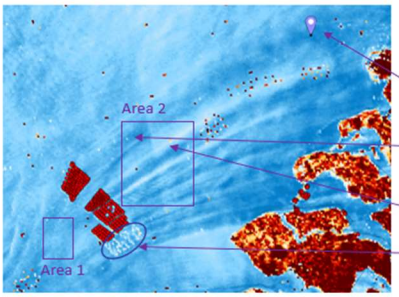


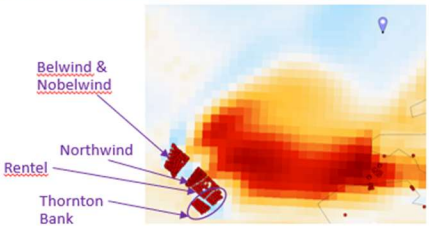
Left: histogram upwind wind farms (area 1): 5.6-6.4 m/s occur most and 6.2 is assumed to be the undisturbed wind. Right: histogram downwind wind farms (area 2): min wind speed 4.8 m/s (wake) and max 9.6 m/s (speeding-up).

Comparing HARM43 wake length&strength with SAR

Comparison SAR and CTL-WFP: (**22-7-2019** 17:33:25 UTC & 17:00:00 UTC)

- Max wake length (from Belgian WFs): ~ **100 km** (SAR) and ~ **30 km** (CTL-WFP)
- Max wake strength: 6.2-4.8 ~ 1.4 m/s (SAR) and ~ 1.4 m/s (CTL-WFP)
  - Max speed-up 9.6-6.2 ~ 3.4 m/s on left side of wake (SAR)

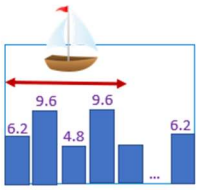




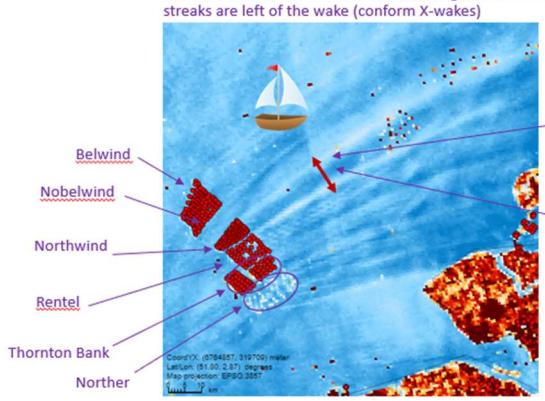
Comparing HARM43 wake length&strength with SAR

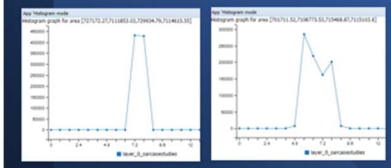
Comparison SAR and CTL-WFP: (**22-7-2019** 17:33:25 UTC & 17:00:00 UTC)

- Max wake length (from Belgian WFs): ~ **100 km** (SAR) and ~ **30 km** (CTL-WFP)
- Max wake intensity: 6.2-4.8 ~ 1.4 m/s (SAR) and ~ 1.4 m/s (CTL-WFP)
- Max speed-up ~ 3.3 m/s on left side of wake (SAR)



Ship experiences a change in wind speed of almost 5 m/s at least twice within 15 km. Note that looking downwind TI-streaks are left of the wake (conform X-wakes)



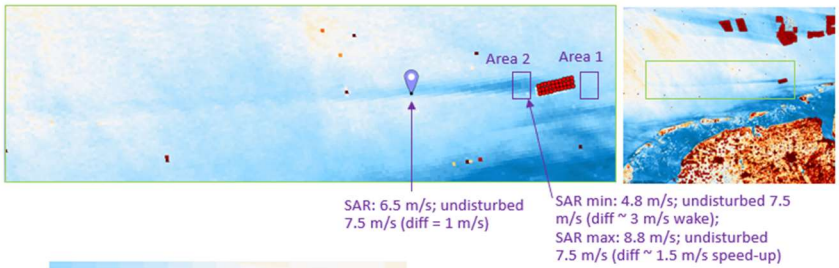


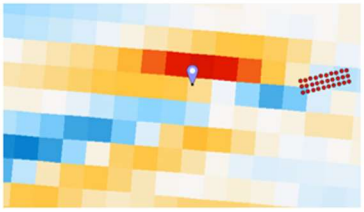
Left: histogram upwind wind farm (area 1): 7.2-8.0 m/s occur most and 7.5 is assumed to be the undisturbed wind. Right: histogram downwind wind farm (area 2): min wind speed 4.8 m/s (wake) and max 8.8 m/s (speeding-up).

Comparing HARM43 wake length&strength with SAR

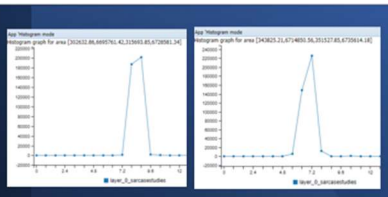
Comparison SAR and CTL-WFP: (**21-9-2019** 17:24:58 UTC & 17:00:00 UTC)

- Max wake length (from Riffgat): ~ 20 km (SAR) and ~ 20 km (CTL-WFP)
- Max wake strength: 7.5-4.8 ~ **2.7 m/s** (SAR) and ~ **1.1 m/s** (CTL-WFP)
- Max speed-up: 8.8-7.5 ~ 1.3 m/s on left side of wake (SAR)





Note: wake in WFP too far north.

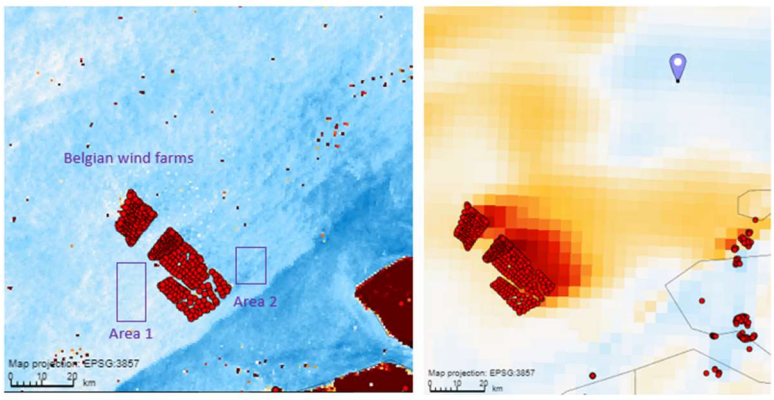


Left: histogram upwind wind farms (area 1): 8.0 and 8.8 m/s occur most and 8.5 m/s assumed to be the undisturbed wind. Right: histogram downwind wind farms (area 2): min wind speed 5.6 m/s (wake) and max 8.8 m/s (no speeding-up).

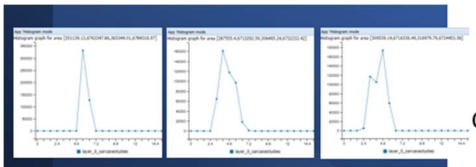
Comparing HARM43 wake length&strength with SAR

Comparison SAR and CTL-WFP: (**3-3-2020** 05:58:36 UTC & 05:00:00 UTC)

- Max wake length (from Belgian WFs): ~ **80 km** (SAR) and ~ **10 km** (CTL-WFP)
- Max wake strength: 8.5-5.6 ~ **2.9 m/s** (SAR) and ~ **1.5 m/s** (CTL-WFP)
- Max speed-up: 8.8-8.5 ~ 0.3 m/s (not significant) (SAR)



Note:
- Pointer indicates wake length SAR (where wake strength is 1 m/s)

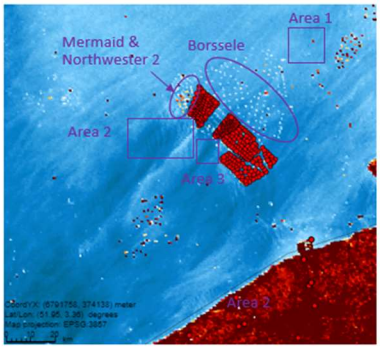


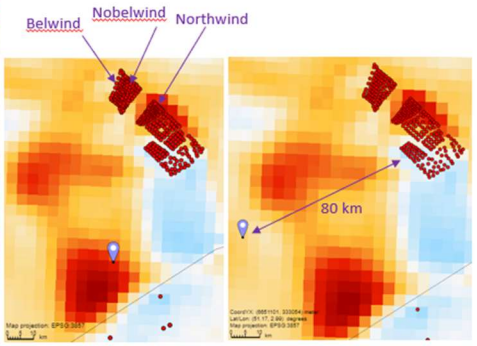
Left: histogram upwind wind farms (area 1): 5.6 m/s occurs most and is assumed to be the undisturbed wind. Middle/right: histogram downwind wind farm. Middle (area 2): min wind speed 3.2 m/s (wake) and max 7.2 m/s (speeding-up). Right (area 3): min 2.4 m/s.

Comparing HARM43 wake length&strength with SAR

Comparison SAR and CTL-WFP: (**16-4-2020** 17:41:33 UTC & 17:00:00 UTC)

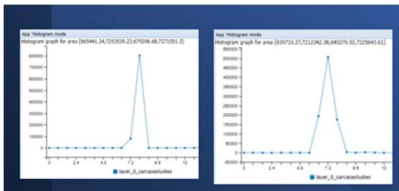
- Max wake length (from Belgian WFs): ~ **80 km** (SAR) and ~ **75 km** (CTL-WFP)
- Max wake strength: 5.6-2.4 ~ **3.2 m/s** (SAR) and ~ **1.5 m/s** (CTL-WFP)
- Max speed-up: 7.2-5.6 ~ 1.6 m/s on left side of wake Nobelwind (SAR)





Note:

- On 16-4-2020 some turbines in Mermaid/Northwester 2 and Borssele I/II visible in SAR, but not yet in WFP (turbines are added once a year, on the 1st of January). First Borssele I/II turbines built April 2020; first turbine delivers power 28-4-20; fully operational 27-11-20
- Wake strongest behind Northwind with highest power density: 16.9 MW/km²
- Pointers indicate wake length SAR (where wake strength is 1 m/s)

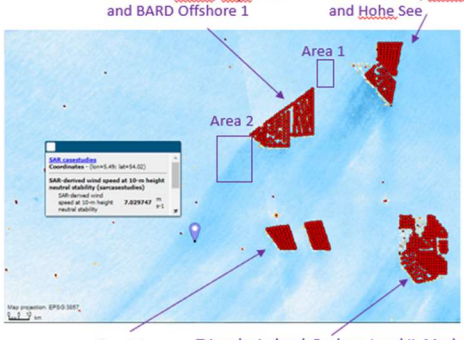


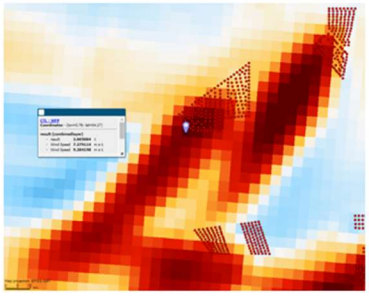
Left: histogram upwind wind farms (area 1): 8.0 m/s occurs most and is assumed to be the undisturbed wind. Right: histogram downwind wind farms (area 2): min wind speed 6.4 m/s (wake) and max 8.8 m/s (speeding-up).

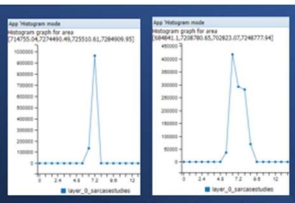
Comparing HARM43 wake length&strength with SAR

Comparison SAR and CTL-WFP: (**18-4-2020** 17:25:45 UTC & 17:00:00 UTC)

- Max wake length (from Deutsche Bucht): ~ **60 km** (SAR) and ~ **80 km** (CTL-WFP)
- Max wake strength: 8.0-6.4 ~ **1.6 m/s** (SAR) and ~ **2.0 m/s** (CTL-WFP)
- Max speed-up: 8.8-8.0 ~ 0.8 m/s (not significant) (SAR)





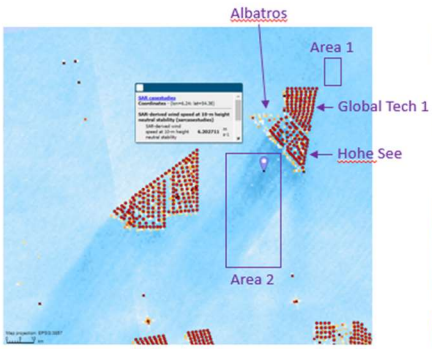


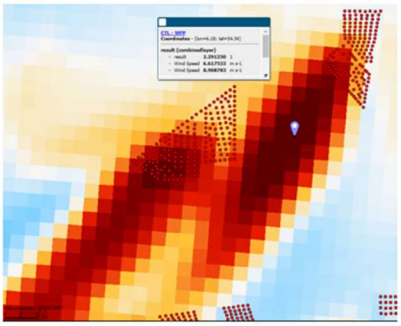
Left: histogram upwind wind farms (area 1): 7.2 m/s occurs most and is assumed to be the undisturbed wind. Right: histogram downwind wind farms (area 2): min wind speed 5.6 m/s (wake) and max 8.8 m/s (speeding-up).

Comparing HARM43 wake length&strength with SAR

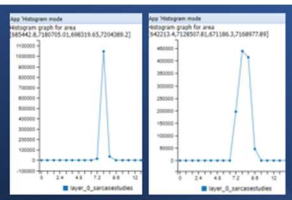
Comparison SAR and CTL-WFP: (**18-4-2020** 17:25:45 UTC & 17:00:00 UTC)

- Max wake length (from Hohe See): ~ **10 km** (SAR) and ~ **65 km** (CTL-WFP)
- Max wake strength: 7.2-5.6 ~ **1.6 m/s** (SAR) and ~ **2.3 m/s** (CTL-WFP)
- Max speed-up: 8.8-7.2 ~ 1.6 m/s on left side of wake (SAR)





Note: on 18-4-2020 some turbines in Albatros WF are visible in SAR, but are not yet included in HARMONIE-WFP (turbines are added once a year, on the 1st of January).

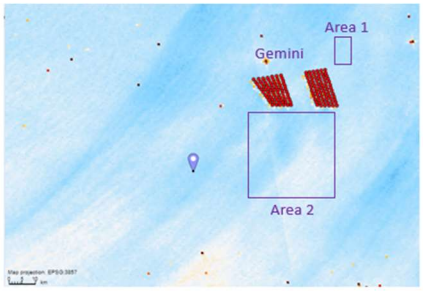


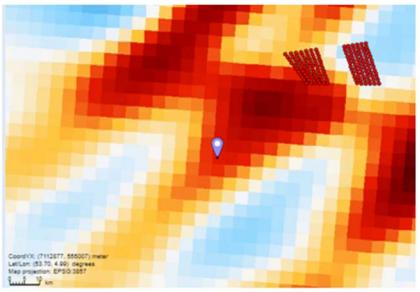
Left: histogram upwind wind farms (area 1): 8.0 m/s occurs most and is assumed to be the undisturbed wind. Right: histogram downwind wind farms (area 2): min wind speed 7.2 m/s (wake) and max 9.6 m/s (speeding-up).

Comparing HARM43 wake length&strength with SAR

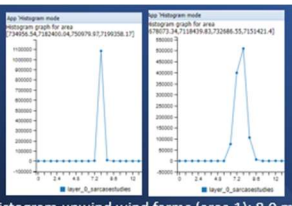
Comparison SAR and CTL-WFP: (**18-4-2020** 17:25:45 UTC & 17:00:00 UTC)

- Max wake length (from Gemini): ~ **x km** (SAR) and ~ **40 km** (CTL-WFP)
- Max wake strength: 8.0-7.2 ~ **0.8 m/s** (SAR) and ~ **1.7 m/s** (CTL-WFP)
- Max speed-up: 9.6-8.0 ~ 1.6 m/s on left side of wake (SAR)





Note: wake length cannot be determined from SAR (wake strength mostly less than 1 m/s). Pointer in SAR-figure above = where CTL-WFP ~ 1 m/s



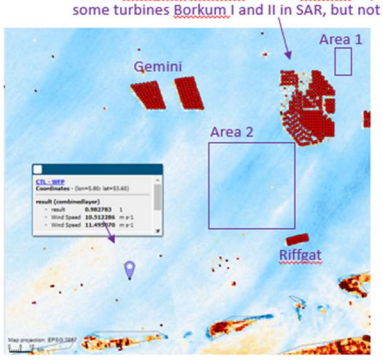
Left: histogram upwind wind farms (area 1): 8.0 m/s occurs most and is assumed to be the undisturbed wind. Right: histogram downwind wind farms (area 2): min wind speed 6.4 m/s (wake) and max 9.6 m/s (speeding-up).

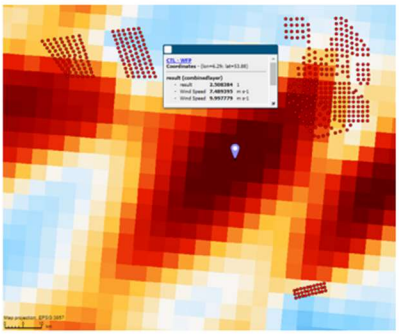
Comparing HARM43 wake length&strength with SAR

Comparison SAR and CTL-WFP: (**18-4-2020** 17:25:45 UTC & 17:00:00 UTC)

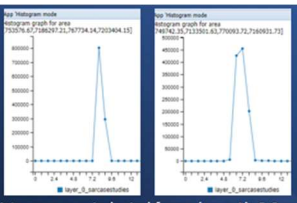
- Max wake length (from B. Riffgrund 2): ~ **30 km** (SAR) and ~ **95 km** (CTL-WFP)
- Max wake strength: 8.0-6.4 ~ **1.6 m/s** (SAR) and ~ **2.5 m/s** (CTL-WFP)
- Max speed-up: 9.6-8.0 ~ 1.6 m/s on left side of wake (SAR)

Trianel windpark Borkum I and II, Merkur, Alpha Ventus, Borkum Riffgrund I and II; some turbines Borkum I and II in SAR, but not yet in WFP





Note: pointer in SAR-figure = where CTL-WFP ~ 1 m/s

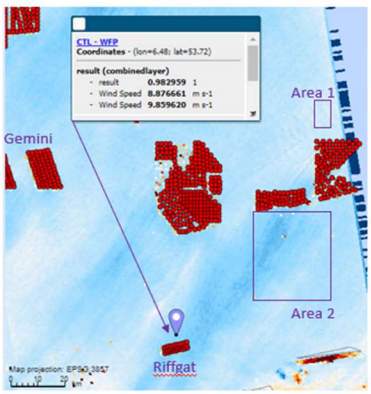


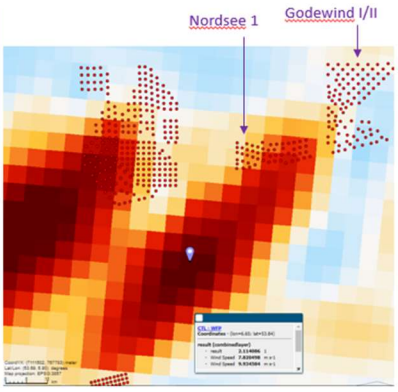
Left: histogram upwind wind farms (area 1): 8.0 m/s occurs most and is assumed to be the undisturbed wind. Right: histogram downwind wind farms (area 2): min wind speed 5.6 m/s (wake) and max 10.4 m/s (speeding-up).

Comparing HARM43 wake length&strength with SAR

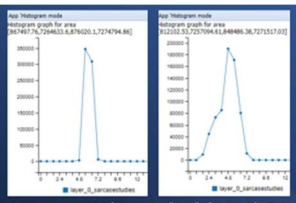
Comparison SAR and CTL-WFP: (**18-4-2020** 17:25:45 UTC & 17:00:00 UTC)

- Max wake length (from Nordsee 1): ~ 30 km (SAR) and ~ 30 km (CTL-WFP)
- Max wake strength: 8.0-5.6 ~ **2.6 m/s** (SAR) and ~ **2.0 m/s** (CTL-WFP)
- Max speed-up: 10.4-8.0 ~ 2.4 m/s on left side of wake Godewind I/II (SAR)



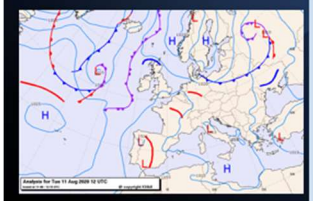


Note: pointer in SAR-figure = where CTL-WFP ~ 1 m/s



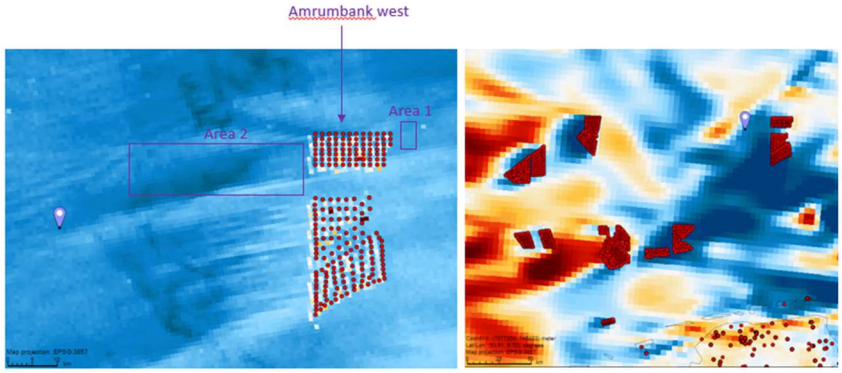
Left: histogram upwind Amrumbank (area 1): 5.6 and 6.4 occur most and 6.0 is assumed to be the undisturbed wind. Right: histogram downwind Amrumbank (area 2): min wind speed 1.6 m/s (wake) and max 7.2 m/s (speeding-up).

Comparing HARM43 wake length&strength with SAR

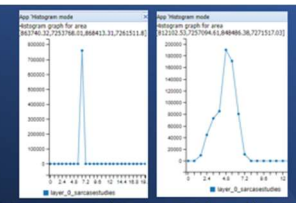


Comparison SAR and CTL-WFP: (**11-08-2020** 17:17:45 UTC & 17:00:00 UTC)

- Max wake length (from Amrumbank W): ~ **30 km** (SAR) and ~ **x km** (CTL-WFP)
- Max wake strength: 6.0-1.6 ~ **4.4 m/s** (SAR) and ~ **x m/s** (CTL-WFP)
- Max speed-up: 7.2-6.0 ~ 1.2 m/s on left side of wake Amrumbank W (SAR)

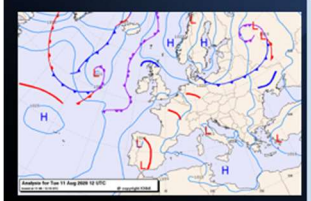


Note:
- There is no wake in CTL-WFP?
- Pointer in CTL-WFP-figure where wake in SAR for Amrumbank = max



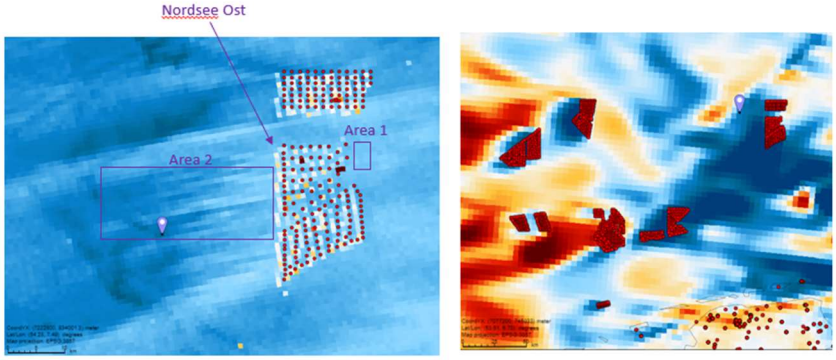
Left: histogram upwind Nordsee Ost (area 1): 6.4 occurs most and assumed to be the undisturbed wind. Right: histogram downwind Nordzee Ost (area 2): min wind speed 2.4 m/s (wake) and max 7.2 m/s (speeding-up).

Comparing HARM43 wake length&strength with SAR

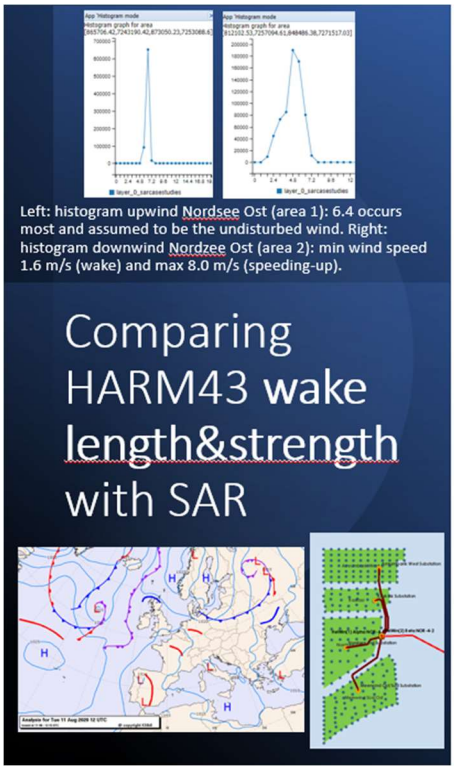


Comparison SAR and CTL-WFP: (**11-08-2020** 17:17:45 UTC & 17:00:00 UTC)

- Max wake length (from Nordsee Ost): ~ **40 km** (SAR) and ~ **x km** (CTL-WFP)
- Max wake strength: 6.4-2.4 ~ **4.0 m/s** (SAR) and ~ **x m/s** (CTL-WFP)
- Max speed-up: 7.2-6.4 ~ 0.8 m/s (not significant) (SAR)

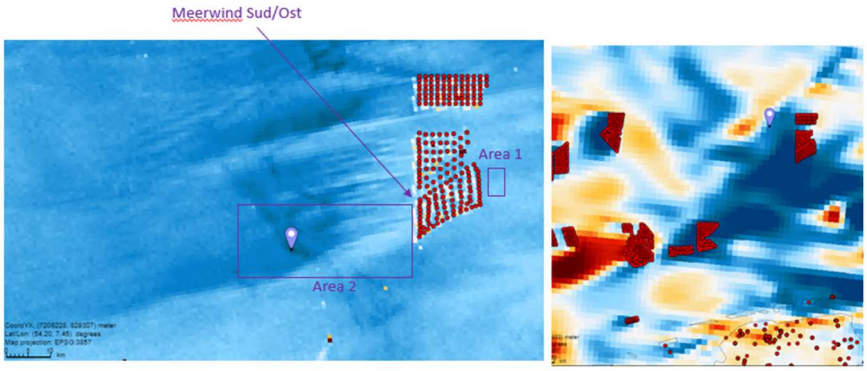


Note:
- There is no wake in CTL-WFP?
- Pointer in CTL-WFP-figure where wake in SAR for Amrumbank = max

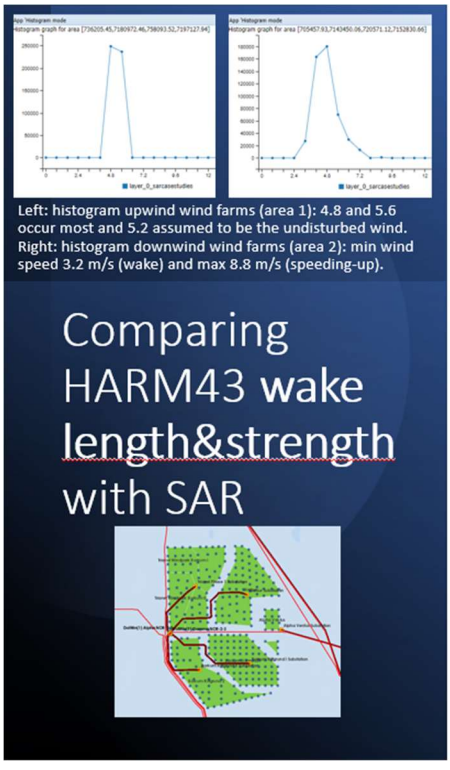


Comparison SAR and CTL-WFP: (**11-08-2020** 17:17:45 UTC & 17:00:00 UTC)

- Max wake length (from Meerwind Sud/Ost): ~ **60 km** (SAR) and ~ **x km** (CTL-WFP)
- Max wake strength: 6.4-1.6 ~ **4.8 m/s** (SAR) and ~ **x m/s** (CTL-WFP)
- Max speed-up: 8.0-6.4 ~ 1.6 m/s left of the wake Meerwind Sud/Ost (SAR)

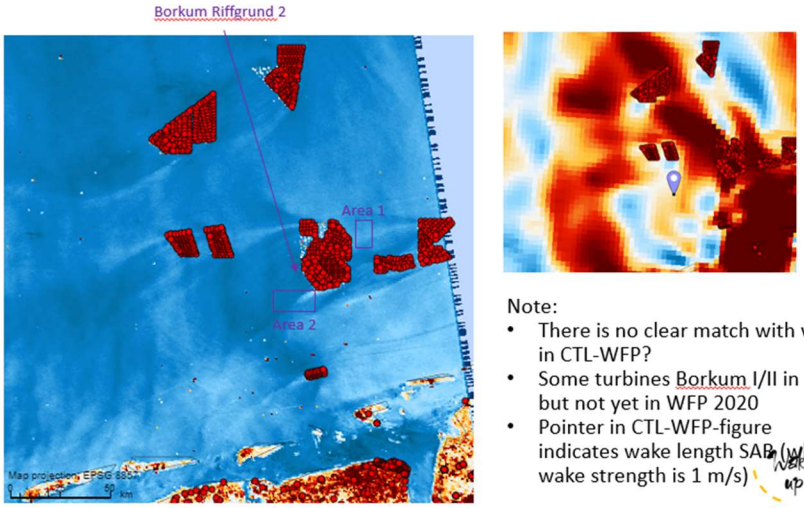


Note:
- There is no wake in CTL-WFP?
- Pointer in CTL-WFP-figure where wake in SAR for Amrumbank = max

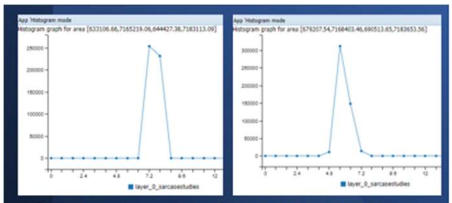


Comparison SAR and CTL-WFP: (**16-08-2020** 17:25:52 UTC & 17:00:00 UTC)

- Max wake length (from B.Riffgrund 2): ~ **45 km** (SAR) and ~ **20? km** (CTL-WFP)
- Max wake strength: 5.2-3.2 ~ **3.0 m/s** (SAR) and ~ **2.7? m/s** (CTL-WFP)
- Max speed-up: 8.8-5.2 ~ 3.6 m/s left of the wake B. Riffgrund 2 (SAR)



Note:
- There is no clear match with wake in CTL-WFP?
- Some turbines Borkum I/II in SAR, but not yet in WFP 2020
- Pointer in CTL-WFP-figure indicates wake length SAR (where wake strength is 1 m/s)

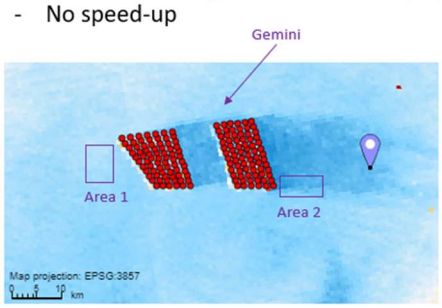


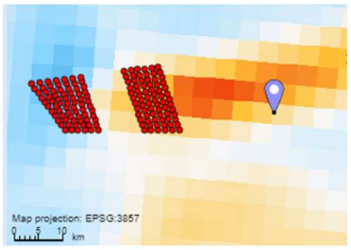
Left: histogram upwind wind farms (area 1): 7.2 and 8.0 occur most and 7.5 assumed to be the undisturbed wind. Right: histogram downwind wind farms (area 2): min wind speed 4.8 m/s (wake) and max 7.2 m/s (no speeding-up).

Comparing HARM43 wake length&strength with SAR

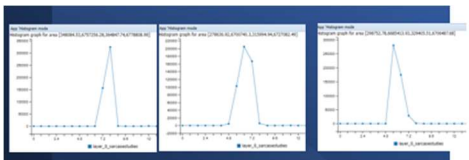
Comparison SAR and CTL-WFP: (**03-09-2020** 17:25:12 UTC & 17:00:00 UTC)

- Max wake length (from Gemini): ~ **30 km** (SAR) and ~ **x km** (CTL-WFP)
- Max wake strength: 7.5-4.8 ~ **2.7 m/s** (SAR) and ~ < **1 m/s** (CTL-WFP)
- No speed-up





Note:
- Pointer indicates wake length SAR (where wake strength is 1 m/s)
- CTL-WFP is 0.9 at most (too weak to establish wake length)



Left: histogram upwind wind farms (area 1): 8.0 occurs most and is assumed to be the undisturbed wind. Middle (area 2) /right (area 3): histogram downwind wind farms: min wind speed 4.8 m/s (area 2) and 5.6 m/s (area 3). Max 8.0 m/s (both areas) so no speeding-up.

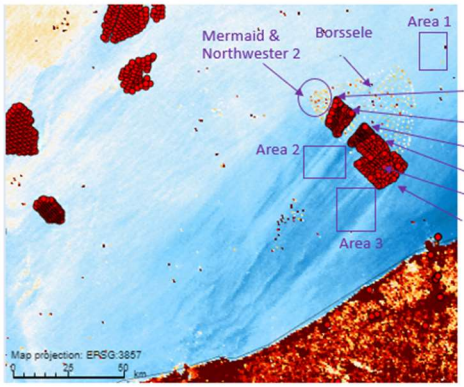
Comparing HARM43 wake length&strength with SAR

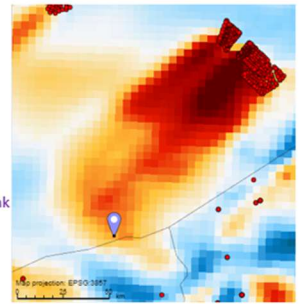
First Borssele I/II turbines are built April 2020; first turbine delivers power 28-4-20; fully operational 27-11-20.

First Borssele III/IV turbine built 28-5-20; first turbine delivers power 10-8-20; fully operational 6-1-21

Comparison SAR and CTL-WFP: (**19-09-2020** 17:41:41 UTC & 17:00:00 UTC)

- Max wake length (from Belgian WFs): ~ **110 km** (SAR) and ~ **90 km** (CTL-WFP)
- Max wake strength: 8.0-4.8 ~ **3.2 m/s** (SAR) and ~ **2.3 m/s** (CTL-WFP)
- No speed-up (compared to undisturbed wind)

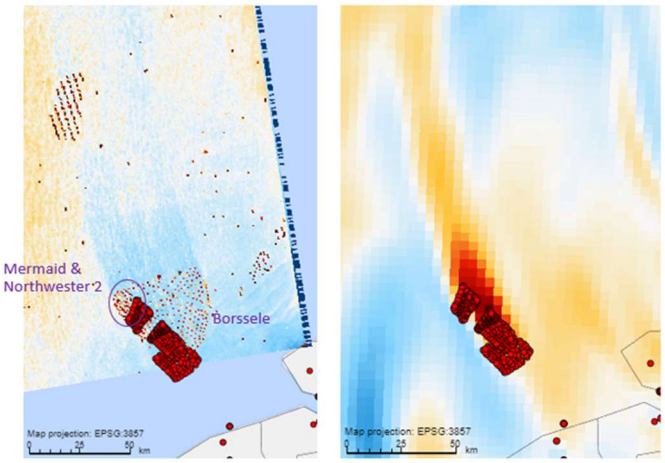




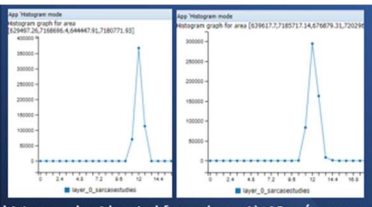
Note:
- Some (all?) turbines Mermaid, Northwester 2 and Borssele in SAR, but not yet in WFP 2020.
- Pointer indicates wake length SAR (where wake strength SAR is 1 m/s)

Comparing HARM43 wake length&strength with SAR

Comparison SAR and CTL-WFP: (**19-10-2020** 17:41:16 UTC & 17:00:00 UTC)



Decided not to include this case study in validation: on 19-10-2020 Borssele I/II almost fully operational (on 27-11). First turbine Borssele III/IV built 28-5-20; first turbine delivers power 10-8-20; fully operational 6-1-21. Borssele, Mermaid and Northwester 2 in SAR, but not yet in WFP (but Borssele III/IV is included in the 2021 WFP run despite not being fully operational on 1-1-2021)

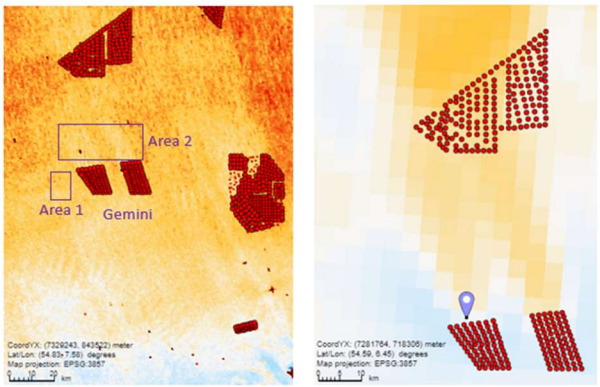


Left: histogram beside wind farms (area 1): 12 m/s occurs most and is assumed to be the undisturbed wind. Right: histogram downwind wind farms (area 2): min wind speed 10.4 m/s (wake) and max 14.4 m/s (speeding-up).

Comparing HARM43 wake length&strength with SAR

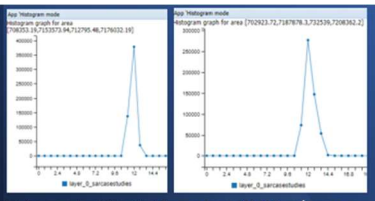
Comparison SAR and CTL-WFP: (**21-12-2020** 17:17:46 UTC & 17:00:00 UTC)

- Max wake length (from Gemini): ~ **1 km** (SAR) and ~ **x km** (CTL-WFP)
- Max wake strength: 12.0-10.4 ~ **1.6 m/s** (SAR) and ~ **0.3 m/s** (CTL-WFP)
- Max speed-up: 14.4-12.0 ~ 2.4 m/s both sides of the wake Gemini (SAR)



Note:

- Histogram beside Gemini used to derive undisturbed wind (instead of upwind) to exclude effect that wind increases further from coast
- Pointer indicates wake length SAR (where wake strength SAR is 1 m/s)

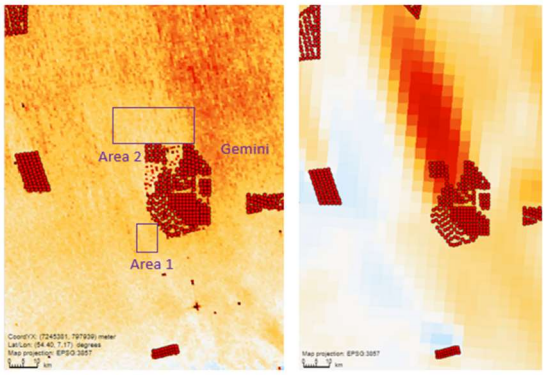


Left: histogram beside wind farms (area 1): 12 m/s occurs most and is assumed to be the undisturbed wind. Right: histogram downwind wind farms (area 2): min wind speed 11.2 m/s (wake) and max 14.4 m/s (speeding-up).

Comparing HARM43 wake length&strength with SAR

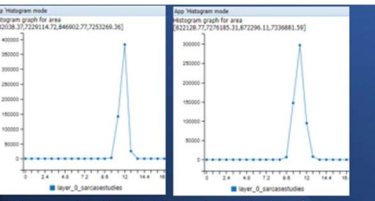
Comparison SAR and CTL-WFP: (**21-12-2020** 17:17:46 UTC & 17:00:00 UTC)

- Max wake length (from Borkum): ~ **x km** (SAR) and ~ **40 km** (CTL-WFP)
- Max wake strength: 12.0-11.2 ~ **0.8 m/s** (SAR) and ~ **1.2 m/s** (CTL-WFP)
- Max speed-up: 14.4-12.0 ~ 2.4 m/s right side of the wake Borkum (SAR)



Note:

- Histogram beside Borkum Riffgrund 2 (outside wake Riffgat) used to derive undisturbed wind (instead of upwind) to exclude effect that wind increases further from coast
- Some turbines Borkum I/II in SAR, but not yet in WFP 2020

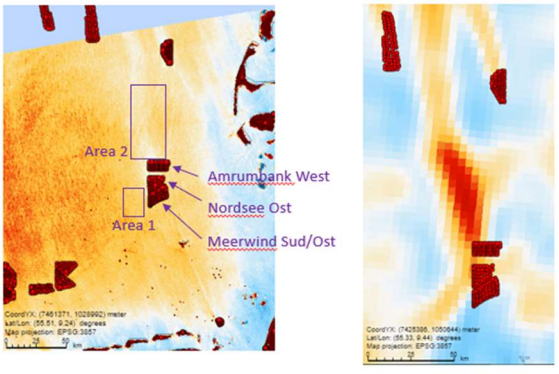


Left: histogram beside wind farms (area 1): 12 m/s occurs most and is assumed to be the undisturbed wind. Right: histogram downwind wind farms (area 2): min wind speed 8.8 m/s (wake) and max 12.8 m/s (speeding-up).

Comparing HARM43 wake length&strength with SAR

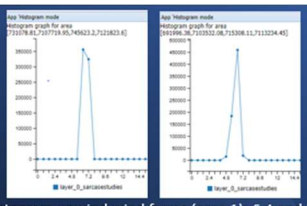
Comparison SAR and CTL-WFP: (**21-12-2020** 17:17:46 UTC & 17:00:00 UTC)

- Max wake length (from Amrumbank W): **> 120 km** (SAR) and ~ **60 km** (CTL-WFP)
- Max wake strength: 12.0-8.8 ~ **3.2 m/s** (SAR) and ~ **1.2 m/s** (CTL-WFP)
- No significant (< 1.0) speed-up (compared to undisturbed wind)



Note:

- Histogram beside Meerwind S/O used to derive undisturbed wind (instead of upwind) to exclude effect that wind increases further from coast
- Wake strength still just > 1 m/s at the edge of the SAR-image (at 120 km from Amrumbank West)

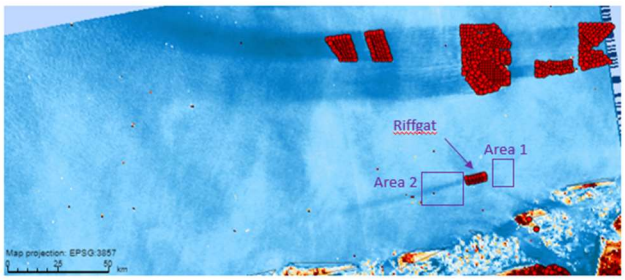


Left: histogram upwind wind farms (area 1): 6.4 and 7.2 occur most and 7.0 is assumed to be the undisturbed wind. Right: histogram downwind wind farms (area 2): min wind speed 4.8 m/s (wake) and max 7.2 m/s (no speeding-up).

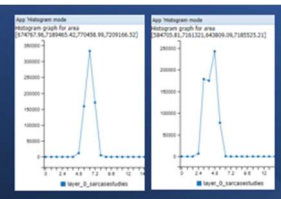
Comparing HARM43 wake length&strength with SAR

Comparison SAR and CTL-WFP: (**02-03-2021** 17:25:00 UTC & 17:00:00 UTC)

- Max wake length (from Riffgat): ~ **60 km** (SAR) and ~ **30 km** (CTL-WFP)
- Max wake strength: 7.0-4.8 ~ **2.2 m/s** (SAR) and ~ **1.0 m/s** (CTL-WFP)
- No speed-up (compared to undisturbed wind)



Note:
- Pointer indicates wake length SAR (where wake strength SAR is 1 m/s)

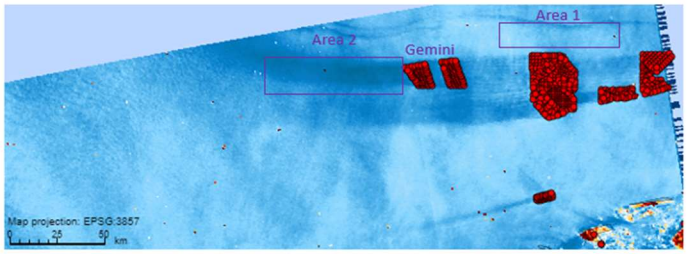


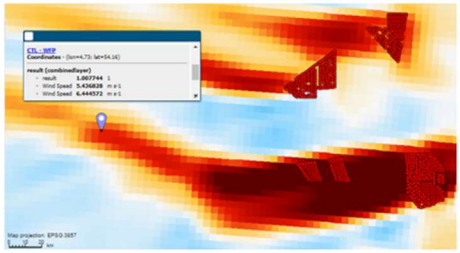
Left: histogram upwind wind farms (area 1): 6.4 occurs most and is assumed to be the undisturbed wind. Right: histogram downwind wind farms (area 2): min wind speed 2.4 m/s (wake) and max 6.4 m/s (no speeding-up).

Comparing HARM43 wake length&strength with SAR

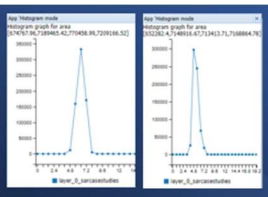
Comparison SAR and CTL-WFP: (**02-03-2021** 17:25:00 UTC & 17:00:00 UTC)

- Max wake length (from Gemini): **> 100 km** (SAR) and **~ 120 km** (CTL-WFP)
- Max wake strength: 6.4-2.4 ~ **4.0 m/s** (SAR) and ~ **2.9 m/s** (CTL-WFP)
- No speed-up (compared to undisturbed wind)





Note:
- Wake strength still just > 1 m/s at the edge of the SAR-image (at 100 km from Gemini)

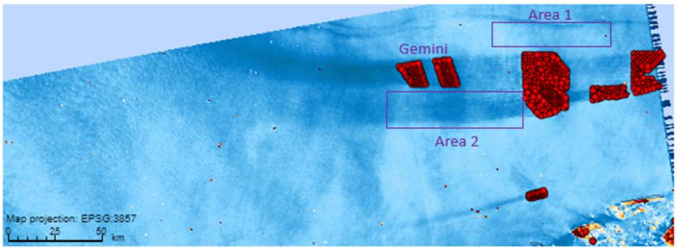


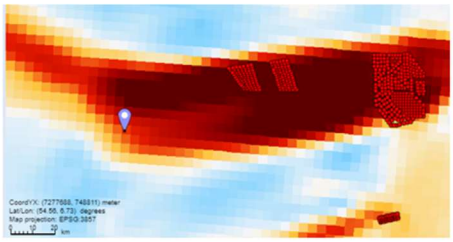
Left: histogram upwind wind farms (area 1): 6.4 occurs most and is assumed to be the undisturbed wind. Right: histogram downwind wind farms (area 2): min wind speed 4.0 m/s (wake) and max 8.0 m/s (speeding-up).

Comparing HARM43 wake length&strength with SAR

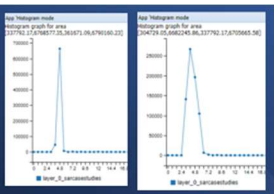
Comparison SAR and CTL-WFP: (**02-03-2021** 17:25:00 UTC & 17:00:00 UTC)

- Max wake length (Borkum Riffgrund 2): **~ 110 km** (SAR) and **~ 105 km** (CTL-WFP)
- Max wake strength: 6.4-4.0 ~ **2.4 m/s** (SAR) and ~ **2.9 m/s** (CTL-WFP)
- Max speed-up: 8.0 -6.4 ~ 1.6 m/s on left side of wake Borkum Riffgrund 2 (SAR)





Note:
- Pointer indicates wake length SAR (where wake strength SAR is 1 m/s)

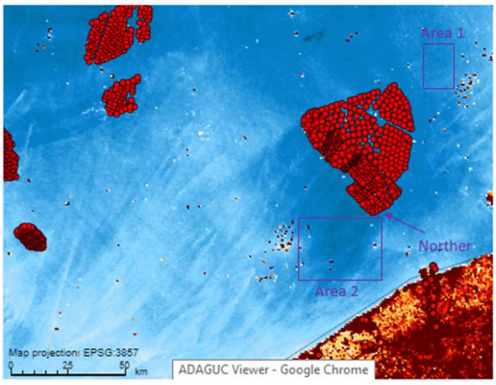


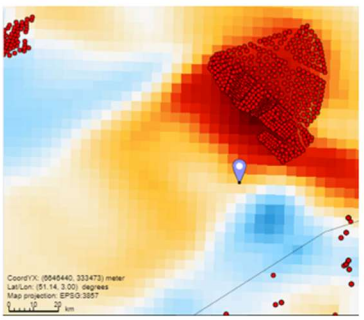
Left: histogram upwind wind farms (area 1): 4.8 occurs most and is assumed to be the undisturbed wind. Right: histogram downwind wind farms (area 2): min wind speed 3.2 m/s (wake) and max 7.2 m/s (speeding-up).

Comparing HARM43 wake length&strength with SAR

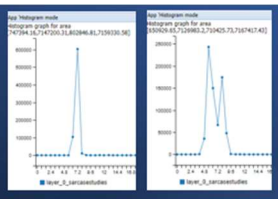
Comparison SAR and CTL-WFP: (**23-04-2021** 17:41:39 UTC & 17:00:00 UTC)

- Max wake length (from Belgian WFs): ~ **20 km** (SAR) and **< 10 km** (CTL-WFP)
- Max wake strength: 4.8-3.2 ~ 1.6 m/s (SAR) and ~ 1.7 m/s (CTL-WFP)
- Max speed-up: 7.2-4.8 ~ 2.6 m/s on left side of wake Norther (SAR)





Note:
- Pointer in CTL-WFP-figure indicates wake length SAR (where wake strength is 1 m/s)

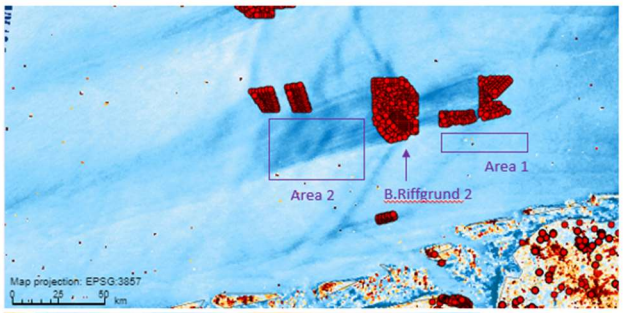


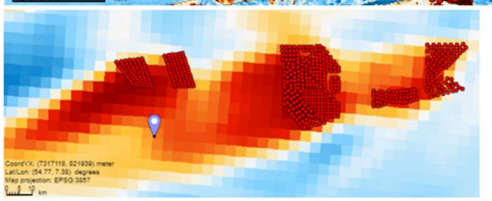
Left: histogram upwind wind farms (area 1): 7.2 m/s occurs most and is assumed to be the undisturbed wind. Right: histogram downwind wind farms (area 2): min wind speed 4.0 m/s (wake) and max 11.2 m/s (speeding-up).

Comparing HARM43 wake length&strength with SAR

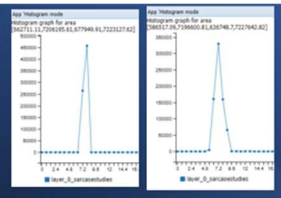
Comparison SAR and CTL-WFP: (**28-04-2021** 05:49:20 UTC & 05:00:00 UTC)

- Max wake length (from B. Riffgrund 2): ~ **45 km** (SAR) and ~ **20 km** (CTL-WFP)
- Max wake strength: 7.2-4.0 **~ 3.2 m/s** (SAR) and **~ 1.4 m/s** (CTL-WFP)
- Max speed-up: 11.2-7.2 ~ 4.0 m/s on left side of wake B.Riffgrund (SAR)





Note:
- Pointer in CTL-WFP-figure indicates wake length SAR (where wake strength is 1 m/s)

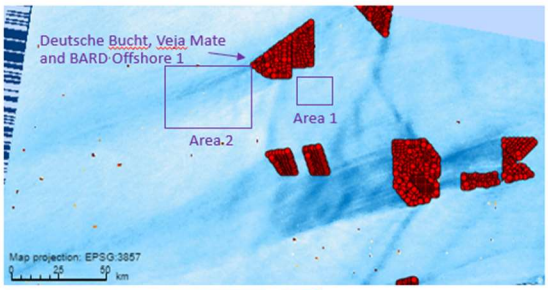


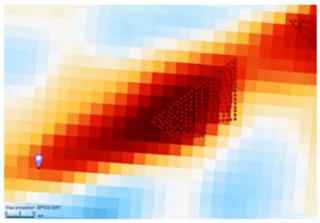
Left: histogram upwind wind farms (area 1): 8.0 m/s occurs most and is assumed to be the undisturbed wind. Right: histogram downwind wind farms (area 2): min wind speed 5.6 m/s (wake) and max 12.8 m/s (speeding-up).

Comparing HARM43 wake length&strength with SAR

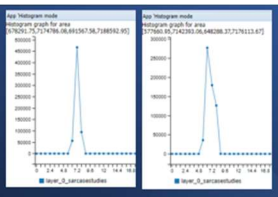
Comparison SAR and CTL-WFP: (**28-04-2021** 05:49:20 UTC & 05:00:00 UTC)

- Max wake length (from Veja Mate): ~ 45 km (SAR) and ~ 45 km (CTL-WFP)
- Max wake strength: 8.0-5.6 **~ 2.4 m/s** (SAR) and **~ 2.0 m/s** (CTL-WFP)
- Max speed-up: 12.8 -8.0 ~ 4.8 m/s on left side of wake Veja Mate (SAR)





Note:
- Pointer in CTL-WFP-figure indicates wake length SAR (where wake strength is 1 m/s)

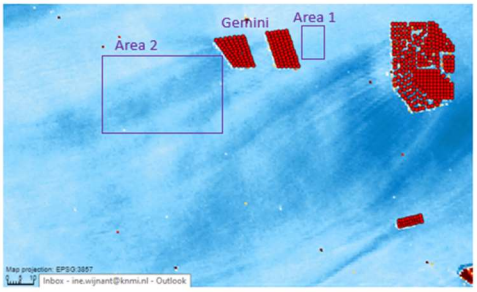


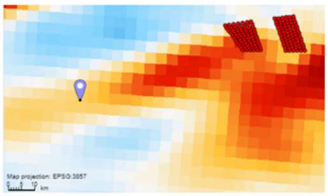
Left: histogram upwind wind farms (area 1): 7.2 m/s occurs most and is assumed to be the undisturbed wind. Right: histogram downwind wind farms (area 2): min wind speed 5.6 m/s (wake) and max 8.8 m/s (speeding-up).

Comparing HARM43 wake length&strength with SAR

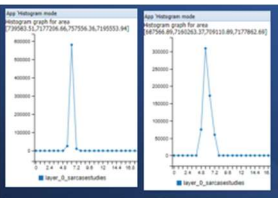
Comparison SAR and CTL-WFP: (**24-07-2021** 17:25:07 UTC & 17:00:00 UTC)

- Max wake length (Gemini): **~ 60 km** (SAR) and **~ 35 km** (CTL-WFP)
- Max wake strength: 7.2-5.6 **~ 1.4 m/s** (SAR) and **~ 1.0 m/s** (CTL-WFP)
- Max speed-up: 8.8 -7.2 ~ 0.7 m/s on both sides of wake Gemini (SAR)





Note:
- Pointer in CTL-WFP-figure indicates wake length SAR (where wake strength is 1 m/s)

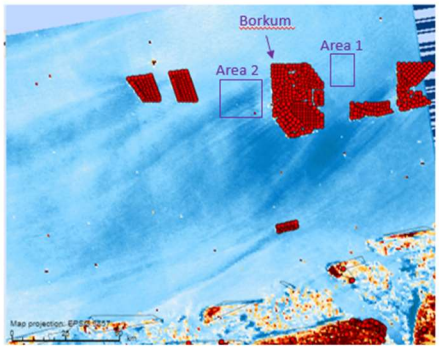


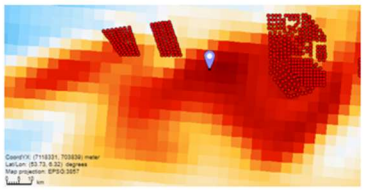
Left: histogram upwind wind farms (area 1): 6.4 m/s occurs most and is assumed to be the undisturbed wind. Right: histogram downwind wind farms (area 2): min wind speed 4.8 m/s (wake) and max 8.0 m/s (speeding-up).

Comparing HARM43 wake length&strength with SAR

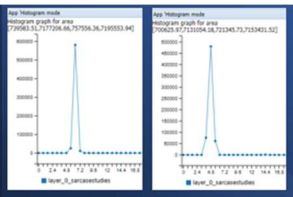
Comparison SAR and CTL-WFP: (**24-07-2021** 17:25:07 UTC & 17:00:00 UTC)

- Max wake length (Borkum): **~ 30 km** (SAR) and **~ 60 km** (CTL-WFP)
- Max wake strength: 6.4-4.8 ~ 1.6 m/s (SAR) and ~ 1.6 m/s (CTL-WFP)
- Max speed-up: 8.0 -6.4 ~ 1.6 m/s on both sides of wake Borkum (SAR)





Note:
- Pointer in CTL-WFP-figure indicates wake length SAR (where wake strength is 1 m/s)

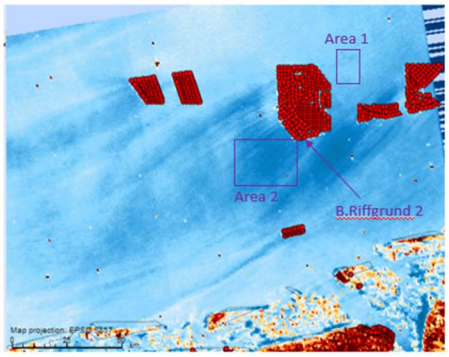


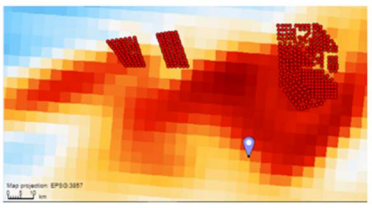
Left: histogram upwind wind farms (area 1): 6.4 m/s occurs most and is assumed to be the undisturbed wind. Right: histogram downwind wind farms (area 2): min wind speed 4.0 m/s (wake) and max 5.6 m/s (no speeding-up).

Comparing HARM43 wake length&strength with SAR

Comparison SAR and CTL-WFP: (**24-07-2021** 17:25:07 UTC & 17:00:00 UTC)

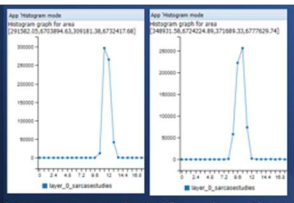
- Max wake length (B.Riffgrund 2): ~ 30 km (SAR) and ~ 30 km (CTL-WFP)
- Max wake strength: 6.4-4.0 **~ 2.4 m/s** (SAR) and **~ 1.3 m/s** (CTL-WFP)
- No speed-up (compared to undisturbed wind)





Note:

- Pointer in CTL-WFP-figure indicates wake length SAR (where wake strength is 1 m/s)

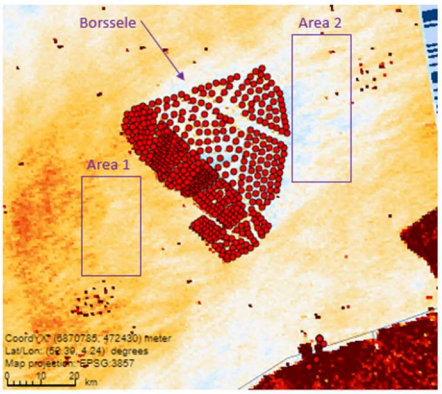


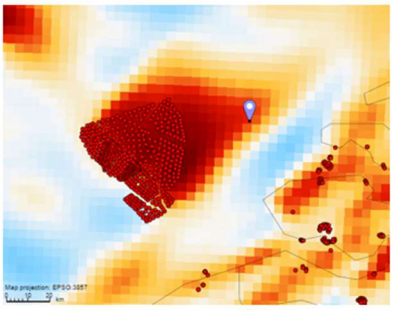
Left: histogram upwind wind farms (area 1): 11.2 and 12.0 m/s occur most and 11.5 m/s is assumed to be the undisturbed wind. Right: histogram downwind wind farms (area 2): min wind speed 8.0 m/s (wake) and max 16.8 m/s (speeding-up).

Comparing HARM43 wake length&strength with SAR

Comparison SAR and CTL-WFP: (**09-08-2021** 17:41:45 UTC & 17:00:00 UTC)

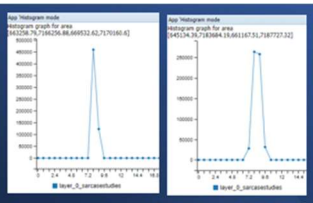
- Max wake length (Borssele): ~ 30 km (SAR) and ~ 30 km (CTL-WFP)
- Max wake strength: 11.5-8.0 **~ 3.5 m/s** (SAR) and **~ 1.7 m/s** (CTL-WFP)
- Max speed-up: 16.8 -11.5 ~ 5.3 m/s in middle of wake Borssele (SAR)





Note:

- Pointer in CTL-WFP-figure indicates wake length SAR (where wake strength is 1 m/s)

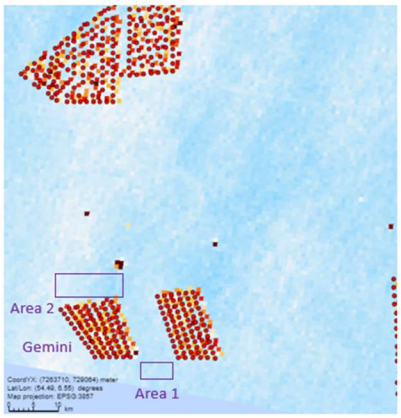


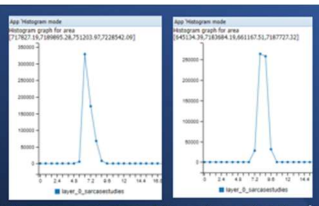
Left: histogram upwind wind farms (area 1): 8.0 m/s occurs most and is assumed to be the undisturbed wind. Right: histogram downwind wind farms (areas 2): min wind speed 7.2 m/s (wake) and max 9.6 m/s (speeding-up).

Comparing HARM43 wake length&strength with SAR

Comparison SAR and CTL-WFP: (**19-10-2021** 05:49:53 UTC & 05:00:00 UTC)

- Max wake length (Gemini): **~ x km** (SAR) and **~ 15 km** (CTL-WFP)
- Max wake strength: 8.0-7.2 **~ 0.8 m/s** (SAR) and **~ 1.4 m/s** (CTL-WFP)
- Max speed-up: 9.6 -8.0 ~ 1.6 m/s at left of wake Gemini (SAR)



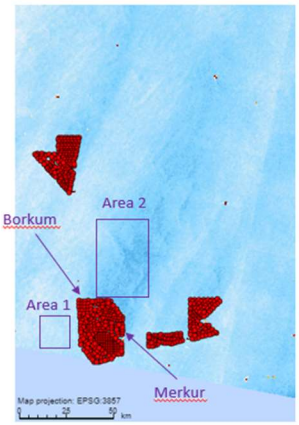


Left: histogram upwind wind farms (area 1): 8.0 m/s occurs most and is assumed to be the undisturbed wind. Right: histogram downwind wind farms (areas 2): min wind speed 5.6 m/s (wake) and max 8.8 m/s (no speeding-up).

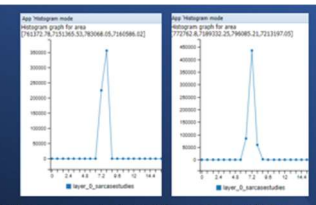
Comparing HARM43 wake length&strength with SAR

Comparison SAR and CTL-WFP: (**19-10-2021** 05:49:53 UTC & 05:00:00 UTC)

- Max wake length (Borkum/Merkur): **~ 100 km** (SAR) and **~ 80 km** (CTL-WFP)
- Max wake strength: 8.0-5.6 **~ 2.4 m/s** (SAR) and **~ 3.2 m/s** (CTL-WFP)
- Max speed-up: 8.8 -8.0 ~ 0.8 m/s (not significant) (SAR)



Note:
- Pointer in CTL-WFP-figure indicates wake length SAR (where wake strength is 1 m/s)



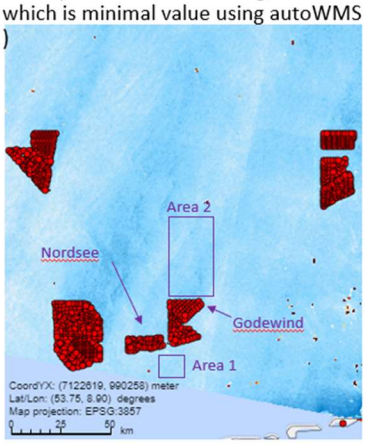
Left: histogram upwind wind farms (area 1): 7.2 and 8.0 m/s occur most and 7.5 m/s is assumed to be the undisturbed wind. Right: histogram downwind wind farms (areas 2): min wind speed 6.4 m/s (wake) and max 8.8 m/s (speeding-up).

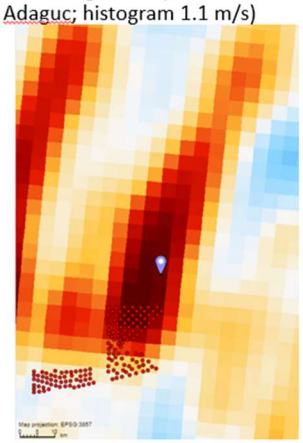
Comparing HARM43 wake length&strength with SAR

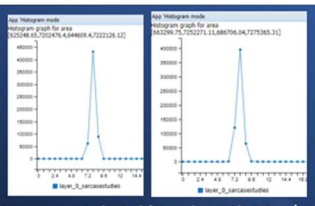
Comparison SAR and CTL-WFP: (**19-10-2021** 05:49:53 UTC & 05:00:00 UTC)

- Max wake length (Godewind): **~ 10 km** (SAR) and **~ 50 km** (CTL-WFP)
- Max wake strength: 7.5-6.4 **~ 1.1 m/s** (SAR) and **~ 2.2 m/s** (CTL-WFP)
- Max speed-up: 8.8 -7.5 ~ 1.3 m/s on right side of wake Godewind (SAR); left side in wake Nordsee WF!

Note: pointer in CTL-WFP-figure indicates wake length SAR (where wake strength is 0.9 m/s which is minimal value using autoWMS in Adaguc; histogram 1.1 m/s)
)







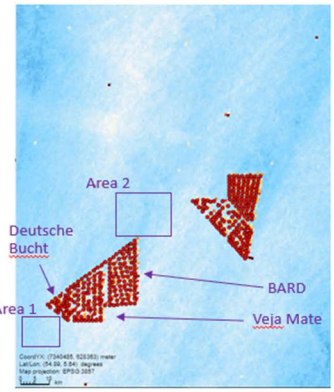
Left: histogram upwind wind farms (area 1): 8.0 m/s occurs most and is assumed to be the undisturbed wind. Right: histogram downwind wind farms (areas 2): min wind speed 6.4 m/s (wake) and max 9.6 m/s (speeding-up).

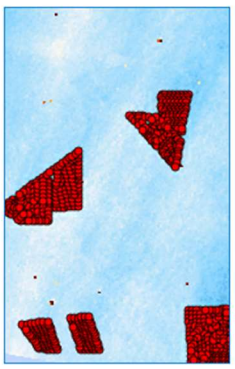
Comparing HARM43 wake length&strength with SAR

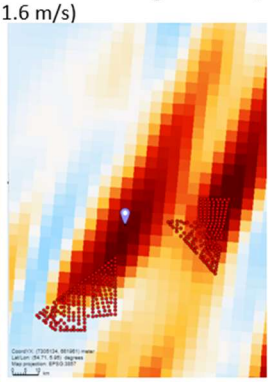
Comparison SAR and CTL-WFP: (**19-10-2021** 05:49:53 UTC & 05:00:00 UTC)

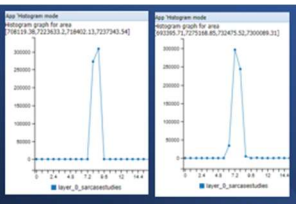
- Max wake length (BARD): **~ 15 km** (SAR) and **~ 60 km** (CTL-WFP)
- Max wake strength: 8.0-6.4 **~ 1.6 m/s** (SAR) and **~ 2.0 m/s** (CTL-WFP)
- Max speed-up: 9.6 -6.0 ~ 3.6 m/s on right side of wake BARD (SAR); speed-up starts left side wake Gemini!

Note: pointer in CTL-WFP-figure indicates wake length SAR (where wake strength is 0.9 m/s which is minimal value using autoWMS in Adaguc; histogram 1.6 m/s)









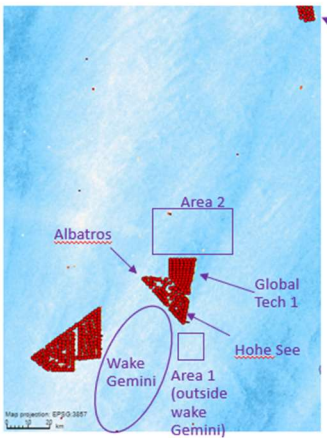
Left: histogram upwind wind farms (area 1): 8.0 and 8.8 m/s occur most and 8.5 m/s is assumed to be the undisturbed wind. Right: histogram downwind wind farms (areas 2): min wind speed 6.4 m/s (wake) and max 10.4 m/s (speeding-up).

Comparing HARM43 wake length&strength with SAR

Comparison SAR and CTL-WFP: (**19-10-2021** 05:49:53 UTC & 05:00:00 UTC)

- Max wake length (Global Tech 1): **~ x km** (SAR) and **~ 75 km** (CTL-WFP)
- Max wake strength: 8.5-6.4 **~ 2.1 m/s** (SAR) and **~ 2.3 m/s** (CTL-WFP)
- Max speed-up: 10.4-8.5 ~ 1.9 m/s on both sides of wake Global Tech 1 (SAR)

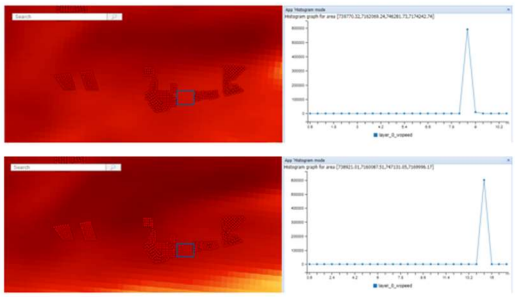
Note: pointer in CTL-WFP-figure (125 km from Global Tech 1): wake strength still > 1 m/s, but beginning of Sandbank WF

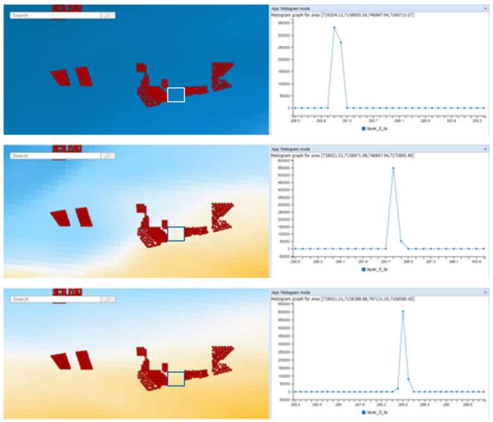


Date/time	Wind Farm	Max wake length	Max wake length	Max wake strength	Max wake strength	Max speed-up	Speed-up
		SAR [km]	CTL-WFP [km]	SAR [m/s]	CTL-WFP [m/s]	SAR [m/s]	
05-04-2019 17UTC	Northwind	65	65	1,9	2	2	left
05-04-2019 17UTC	Luchterduinen	40	40	1,9	1,2	x	x
23-06-2019 17 UTC	Global Tech 1	x	135	0,8	1,5	2,4	left
23-06-2019 17 UTC	Veja Mate	x	150	0,8	1,4	4	left
23-06-2019 17 UTC	Gemini	70	150	2,4	2,1	2,4	right
23-06-2019 17 UTC	Borkum Riffgrund 2	100	125	3,2	2	x	x
23-06-2019 17 UTC	Riffgat	30	x	2	0,5	1,2	left
22-07-2019 17 UTC	Belgian Wind Farms (*)	100	30	1,4	1,4	3,4	left
21-09-2019 17 UTC	Riffgat	20	20	2,7	1,1	1,3	left
03-03-2020 05 UTC	Belgian Wind Farms	80	10	2,9	1,5	x	x
16-04-2020 17 UTC	Belgian Wind Farms	80	75	3,2	1,5	1,6	left
18-04-2020 17UTC	Deutsche Bucht	60	80	1,6	2	x	x
18-04-2020 17UTC	Hohe See (*)	10	65	1,6	2,3	1,6	left
18-04-2020 17UTC	Gemini	x	40	0,8	1,7	1,6	left
18-04-2020 17UTC	Borkum Riffgrund 2	30	95	1,6	2,5	1,6	left
18-04-2020 17UTC	Nordsee 1	30	30	2,6	2	2,4	left (Godewind)
11-08-2020 17 UTC	Amrumbank West	30	x	4,4	x	1,2	left
11-08-2020 17 UTC	Nordsee Ost	40	x	4	x	x	x
11-08-2020 17 UTC	Meerwind Sud/Ost	60	x	4,8	x	1,6	left
16-08-2020 17 UTC	Borkum Riffgrund 2	45	x (20?)	3	x (2,7?)	3,6	left
03-09-2020 17 UTC	Gemini	30	x	2,7	< 1	x	x
19-9-2020 17 UTC	Belgian Wind Farms	110	90	3,2	2,3	x	x
19-10-2020 17 UTC	Belgian Wind Farms	x	x	x	x	x	x
21-12-2020 17 UTC	Gemini	1	x	1,6	0,3	2,4	both
21-12-2020 17 UTC	Borkum	x	40	0,8	1,2	2,4	right
21-12-2020 17 UTC	Amrumbank West	x (>120)	60	3,2	1,2	x	x
02-03-2021 17 UTC	Riffgat	60	30	2,2	1	x	x
02-03-2021 17 UTC	Gemini	x (> 100)	120	4	2,9	x	x
02-03-2021 17 UTC	Borkum Riffgrund 2	110	105	2,4	2,9	1,6	left
23-04-2021 17 UTC	Belgian Wind Farms	20	10	1,6	1,7	2,6	left (Norther)
28-04-2021 05 UTC	Borkum Riffgrund 2	45	20	3,2	1,4	4	left
28-04-2021 05 UTC	Veija Mate	45	45	2,4	2	4,8	left
24-07-2021 17 UTC	Gemini	60	35	1,5	1	0,5	both
24-07-2021 17 UTC	Borkum	30	60	1,6	1,6	1,5	both
24-07-2021 17 UTC	Borkum Riffgrund 2	30	30	2,4	1,3	x	x
09-08-2021 17 UTC	Borssele	30	30	3,5	1,7	5,3	middle
19-10-2021 05 UTC	Gemini	x	15	0,8	1,4	1,6	left
19-10-2021 05 UTC	Borkum/Merkur	100	80	2,4	3,2	x	x
19-10-2021 05 UTC	Godewind	x (10?)	50	1,1	2,2	1,3	right
19-10-2021 05 UTC	BARD	x (15?)	60	1,6	2	3,6	right
19-10-2021 05 UTC	Global Tech 1	x (> 125)	75	2,1	2,3	1,9	both

Date/time	Wind Farm	x means:
05-04-2019 17UTC	Northwind	
05-04-2019 17UTC	Luchterduinen	No (significant) speed-up (compared to undisturbed wind)
23-06-2019 17 UTC	Global Tech 1	Max wake lenght = where diff wake and undisturbed = 1 (so cannot be determined in SAR)
23-06-2019 17 UTC	Veja Mate	Max wake lenght = where diff wake and undisturbed = 1 (so cannot be determined in SAR)
23-06-2019 17 UTC	Gemini	
23-06-2019 17 UTC	Borkum Riffgrund 2	No (significant) speed-up (compared to undisturbed wind)
23-06-2019 17 UTC	Riffgat	Max wake lenght = where diff wake and undisturbed = 1 (so cannot be determined based on CTL-WFP)
22-07-2019 17 UTC	Belgian Wind Farms (*)	
21-09-2019 17 UTC	Riffgat	
03-03-2020 05 UTC	Belgian Wind Farms	No (significant) speed-up (compared to undisturbed wind)
16-04-2020 17 UTC	Belgian Wind Farms	
18-04-2020 17UTC	Deutsche Bucht	No (significant) speed-up (compared to undisturbed wind)
18-04-2020 17UTC	Hohe See (*)	
18-04-2020 17UTC	Gemini	Max wake lenght = where diff wake and undisturbed = 1 (so cannot be determined in SAR)
18-04-2020 17UTC	Borkum Riffgrund 2	
18-04-2020 17UTC	Nordsee 1	
11-08-2020 17 UTC	Amrumbank West	WFP does not pick up wake
11-08-2020 17 UTC	Nordsee Ost	WFP does not pick up wake. No (significant) speed-up (compared to undisturbed wind)
11-08-2020 17 UTC	Meerwind Sud/Ost	WFP does not pick up wake
16-08-2020 17 UTC	Borkum Riffgrund 2	WFP does not pick up wake properly
03-09-2020 17 UTC	Gemini	Max wake lenght = where diff wake and undisturbed = 1 (so cannot be determined based on CTL-WFP). No (significant) speed-up (compared to undisturbed wind)
19-9-2020 17 UTC	Belgian Wind Farms	No (significant) speed-up (compared to undisturbed wind)
19-10-2020 17 UTC	Belgian Wind Farms	
21-12-2020 17 UTC	Gemini	Max wake lenght = where diff wake and undisturbed = 1 (so cannot be determined based on CTL-WFP).
21-12-2020 17 UTC	Borkum	Max wake lenght = where diff wake and undisturbed = 1 (so cannot be determined in SAR)
21-12-2020 17 UTC	Amrumbank West	Wake strenght at edge SAR image still just > 1 m/s. No (significant) speed-up (compared to undisturbed wind)
02-03-2021 17 UTC	Riffgat	No (significant) speed-up (compared to undisturbed wind)
02-03-2021 17 UTC	Gemini	Wake strenght at edge SAR image still just > 1 m/s. No (significant) speed-up (compared to undisturbed wind)
02-03-2021 17 UTC	Borkum Riffgrund 2	
23-04-2021 17 UTC	Belgian Wind Farms	
28-04-2021 05 UTC	Borkum Riffgrund 2	
28-04-2021 05 UTC	Veija Mate	
24-07-2021 17 UTC	Gemini	
24-07-2021 17 UTC	Borkum	
24-07-2021 17 UTC	Borkum Riffgrund 2	No (significant) speed-up (compared to undisturbed wind)
09-08-2021 17 UTC	Borssele	
19-10-2021 05 UTC	Gemini	Max wake lenght = where diff wake and undisturbed = 1 (so cannot be determined in SAR)
19-10-2021 05 UTC	Borkum/Merkur	No (significant) speed-up (compared to undisturbed wind)
19-10-2021 05 UTC	Godewind	In Adaguc autoWMS difference with undisturbed wind remains < 1 m/s (with histogram 1.1), so cannot use 'normal' method to determine max wake length
19-10-2021 05 UTC	BARD	In Adaguc autoWMS difference with undisturbed wind remains < 1 m/s (with histogram 1.6), so cannot use 'normal' method to determine max wake length.
19-10-2021 05 UTC	Global Tech 1	Max wake lenght = where diff wake and undisturbed = 1 (so cannot be determined in SAR, because where next wind farm (Sandbank) starts, wake strenght still > 1 m/s
		Blue: comparison wake lenght + strenght
		Red: only comparison wake strenght
		Purple: discrepancy WF's in SAR and WFP (*: does not affect max wake strength/length)

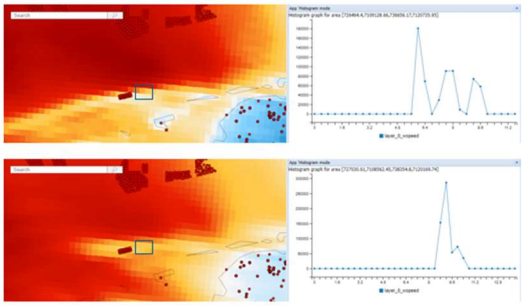
7. Appendix C: Stability Assessment

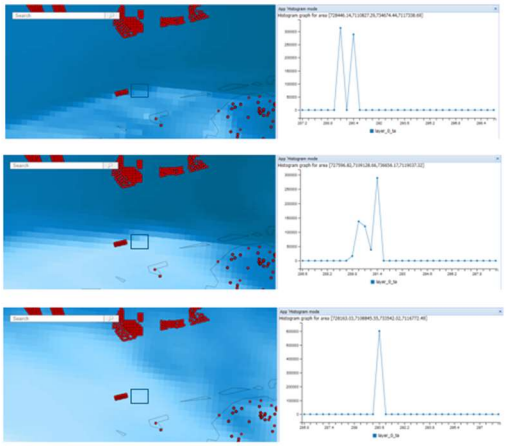




(**23-6-2019** 17:25:42 UTC & 17:00:00 UTC)

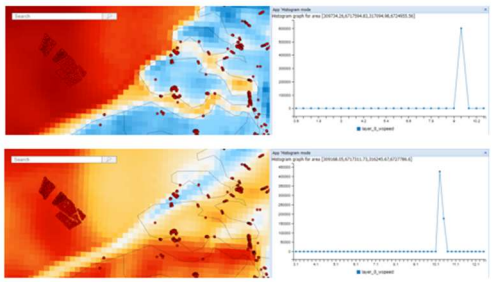
Wind (10m) from SAR: 7.2 m/s
Wind (10m) from CTL: 8.6 m/s
Wind (100m) from CTL: 14.4 m/s
Temp (10m) from CTL: 290.3 K (17.15 °C)
Temp (100m) from CTL: 294.3 K (21.15°C)
Temp (200m) from CTL: 294.8 K (21.65°C)

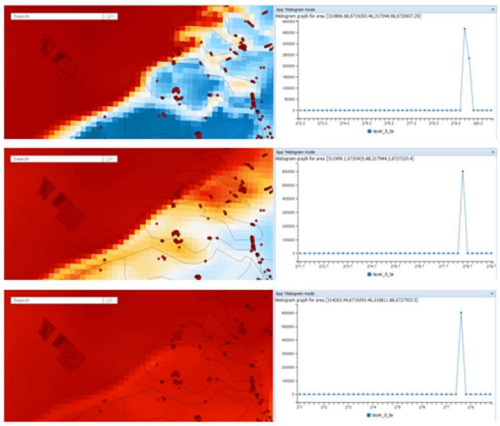




(**21-9-2019** 17:24:58 UTC & 17:00:00 UTC)

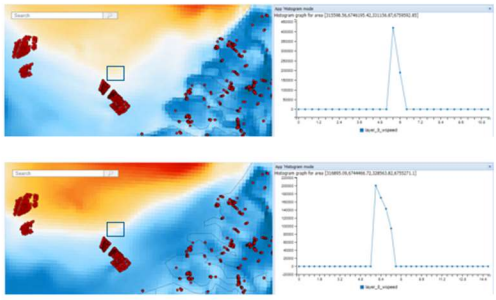
Wind (10m) from SAR: 7.5 m/s
Wind (10m) from CTL: 7.5 m/s (spread 6-9 m/s)
Wind (100m) from CTL: 9.2 m/s
Temp (10m) from CTL: 290 K (16.85 °C) [spread 289.6 (16.45°C) and 290.4 (17.25°C)]
Temp (100m) from CTL: 290.9 K (17.75°C) [spread 290.4 (17.25 °C) and 291.4 (18.25 °C)]
Temp (200m) from CTL: 290.6 K (17.45 °C)

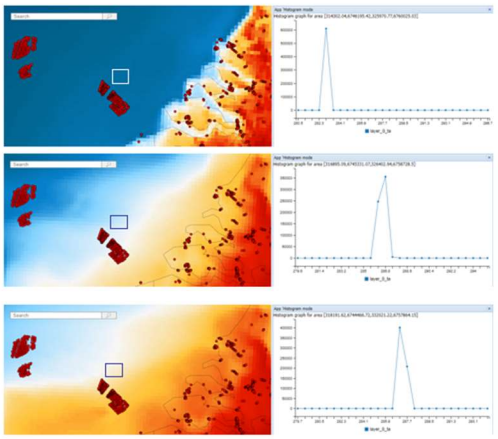




(**3-3-2020** 05:58:36 UTC & 05:00:00 UTC)

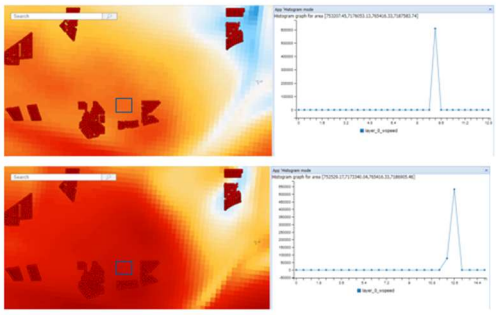
Wind (10m) from SAR: 8.5 m/s
Wind (10m) from CTL: 9.4 m/s
Wind (100m) from CTL: 10.3 m/s
Temp (10m) from CTL: 279.8 K (6.65 °C)
Temp (100m) from CTL: 278.5 K (5.35°C)
Temp (200m) from CTL: 277.6 K (4.45 °C)

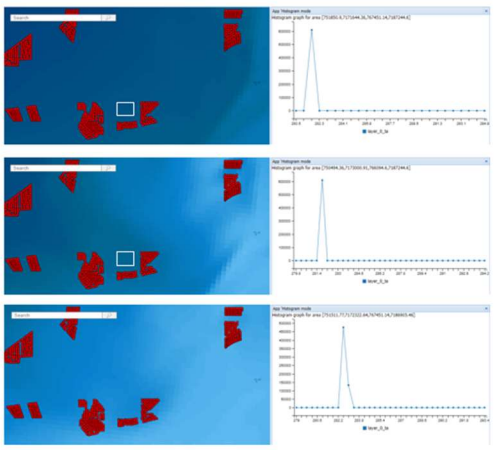




(16-4-2020 17:41:33 UTC & 17:00:00 UTC)

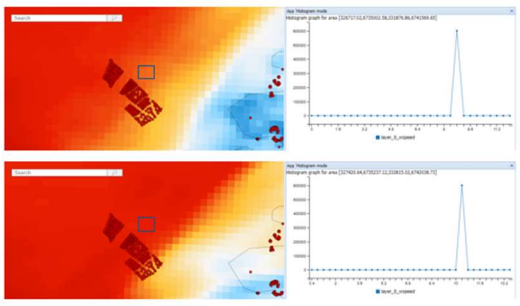
Wind (10m) from SAR: 5.6 m/s
Wind (10m) from CTL: 5.6 m/s
Wind (100m) from CTL: 6.2 m/s
Temp (10m) from CTL: 282.9 K (9.75 °C)
Temp (100m) from CTL: 286.5 K (13,35°C)
Temp (200m) from CTL: 287.1 K (13,95 °C)

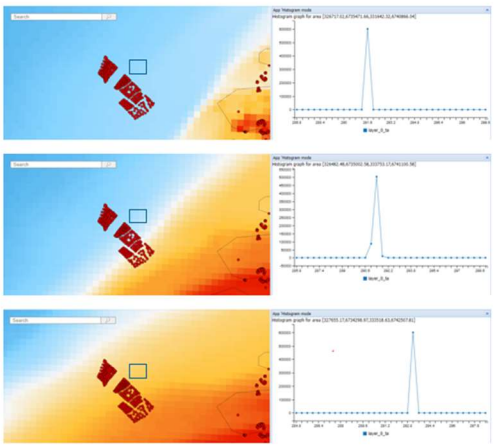




(18-4-2020 17:25:45 UTC & 17:00:00 UTC)

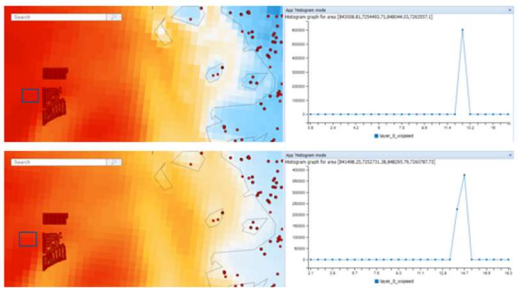
Wind (10m) from SAR: 8.0 m/s
Wind (10m) from CTL: 9.2 m/s
Wind (100m) from CTL: 12.6 m/s
Temp (10m) from CTL: 281.7 K (8.55 °C)
Temp (100m) from CTL: 281.8 K (8.65°C)
Temp (200m) from CTL: 282.6 K (9,45 °C)

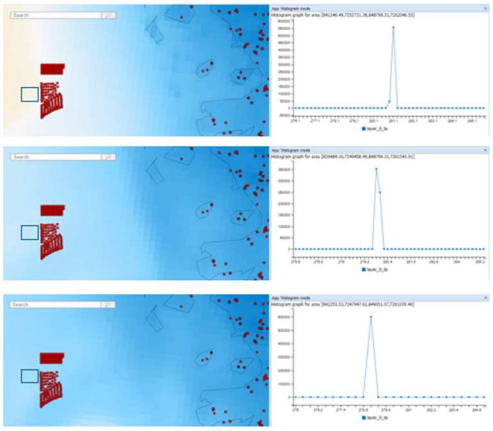




(19-09-2020 17:41:41 UTC & 17:00:00 UTC)

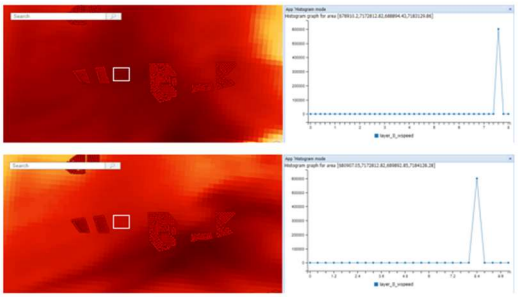
Wind (10m) from SAR: 8.0 m/s
Wind (10m) from CTL: 8.8 m/s
Wind (100m) from CTL: 10.4 m/s
Temp (10m) from CTL: 291.6 K (18.45°C)
Temp (100m) from CTL: 291.4 K (18.25°C)
Temp (200m) from CTL: 293.2 K (20.05°C)

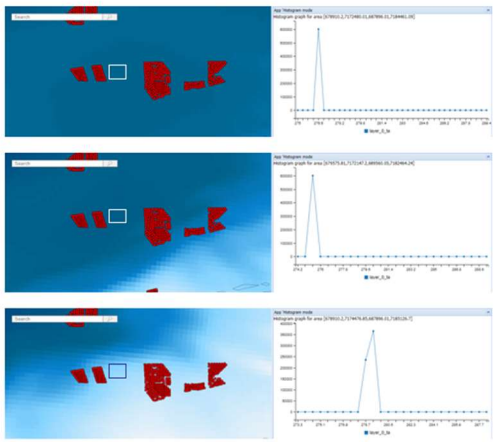




(**21-12-2020** 17:17:46 UTC & 17:00:00 UTC)

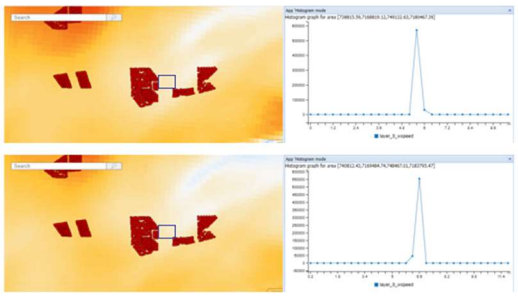
Wind (10m) from SAR: 12 m/s
Wind (10m) from CTL: 12.6 m/s
Wind (100m) from CTL: 14.5 m/s
Temp (10m) from CTL: 281.1 K (7.95°C)
Temp (100m) from CTL: 279.9 K (6.75°C)
Temp (200m) from CTL: 279 K (5.85°C)

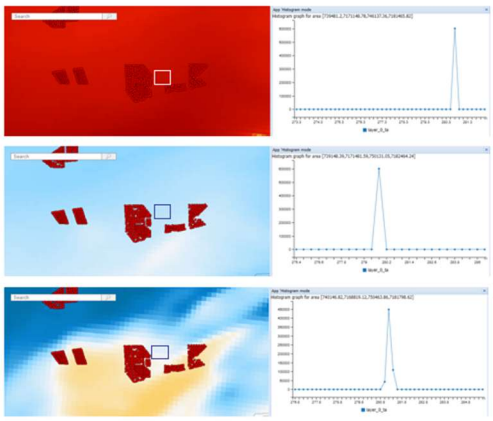




(**02-03-2021** 17:25:00 UTC & 17:00:00 UTC)

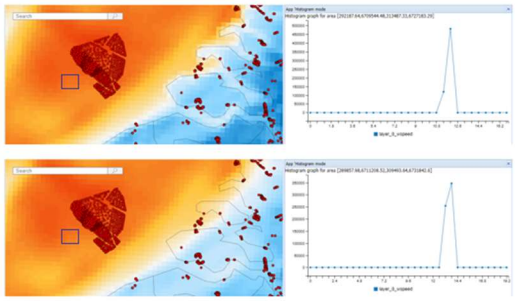
Wind (10m) from SAR: 6.4 m/s
Wind (10m) from CTL: 7.6 m/s
Wind (100m) from CTL: 8.4 m/s
Temp (10m) from CTL: 276.6 K (3.45°C)
Temp (100m) from CTL: 275.4 K (2.25°C)
Temp (200m) from CTL: 279.1 (5.95°C)

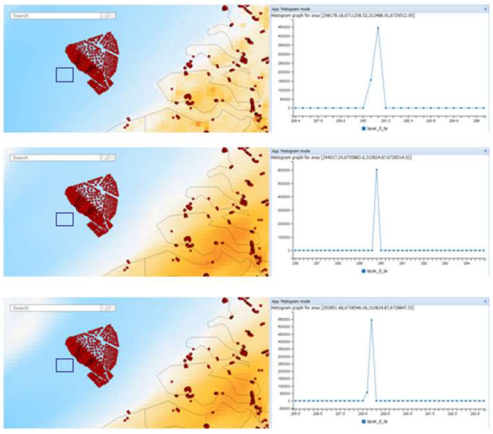




(**28-04-2021** 05:49:20 UTC & 05:00:00 UTC)

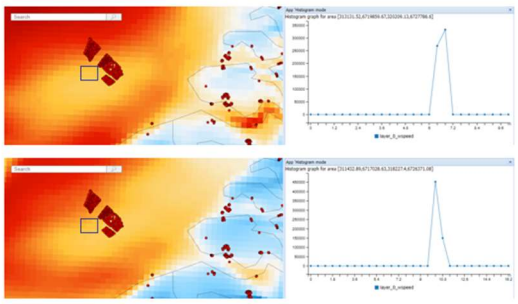
Wind (10m) from SAR: 7.2 m/s
Wind (10m) from CTL: 5.6 m/s
Wind (100m) from CTL: 6.6 m/s
Temp (10m) from CTL: 280.7 K (7.55°C)
Temp (100m) from CTL: 279.8 K (6.65°C)
Temp (200m) from CTL: 281.2 K (8.05°C)

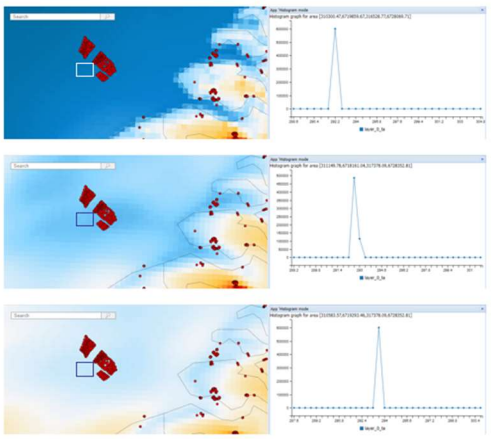




(**09-08-2021** 17:41:45 UTC & 17:00:00 UTC)

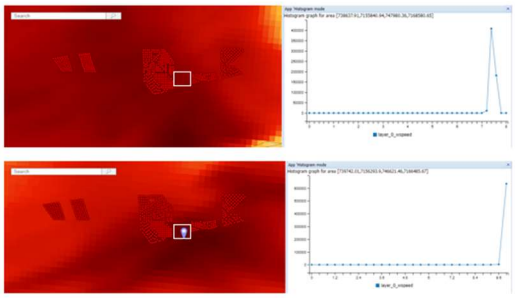
Wind (10m) from SAR: 11.5 m/s
Wind (10m) from CTL: 12 m/s
Wind (100m) from CTL: 13.6 m/s
Temp (10m) from CTL: 290.8 K (17.65°C)
Temp (100m) from CTL: 289.8 K (16.65°C)
Temp (200m) from CTL: 288.9 K (15.75°C)

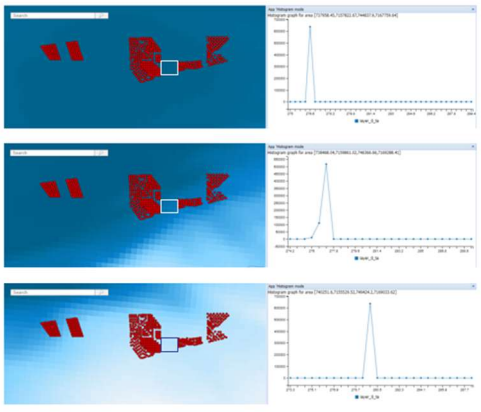




(**22-7-2019** 17:33:25 UTC & 17:00:00 UTC)

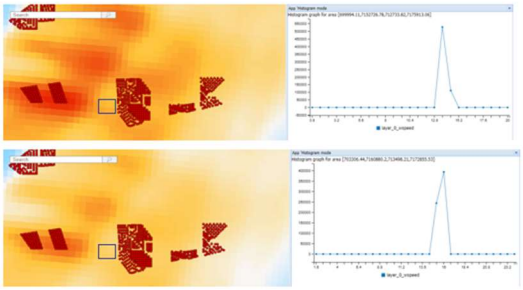
Wind (10m) from SAR: 6.2 m/s
Wind (10m) from CTL: 6.7 m/s
Wind (100m) from CTL: 10.4 m/s
Temp (10m) from CTL: 292.2 K (19.05°C)
Temp (100m) from CTL: 292.6 K (19.45°C)
Temp (200m) from CTL: 293.6 K (20.45°C)

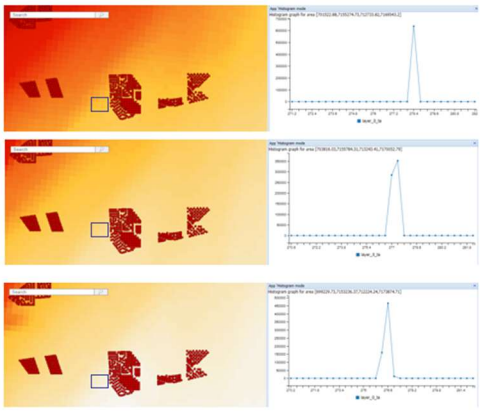




(**02-03-2021** 17:25:00 UTC & 17:00:00 UTC)

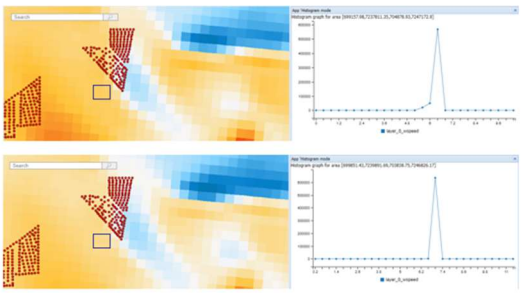
Wind (10m) from SAR: 6.4 m/s
Wind (10m) from CTL: 7.4 m/s
Wind (100m) from CTL: 10 m/s
Temp (10m) from CTL: 276.6 K (3.45°C)
Temp (100m) from CTL: 277.2 K (4.05°C)
Temp (200m) from CTL: 279.9 K (6.75°C)

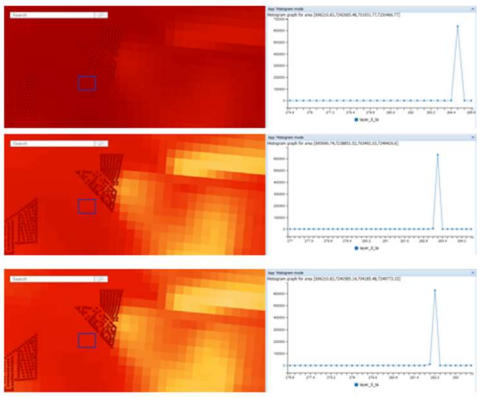




(**19-10-2021** 05:49:53 UTC & 05:00:00 UTC)

Wind (10m) from SAR: 8 m/s
Wind (10m) from CTL: 13.6 m/s
Wind (100m) from CTL: 15.8 m/s
Temp (10m) from CTL: 278.4 K (5.25°C)
Temp (100m) from CTL: 277.2 K (4.05°C)
Temp (200m) from CTL: 276.6 K (3.45°C)





Wind (10m) from SAR: 8.5 m/s
Wind (10m) from CTL: 6.4 m/s
Wind (100m) from CTL: 7 m/s
Temp (10m) from CTL: 284.8 K (11.65°C)
Temp (100m) from CTL: 283.2 K (10.05°C)
Temp (200m) from CTL: 282.2 K (9.05°C)