A statistical framework for quantifying impact regions of offshore wind farms

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Outline

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- Datasets
- Methods
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- Discussion
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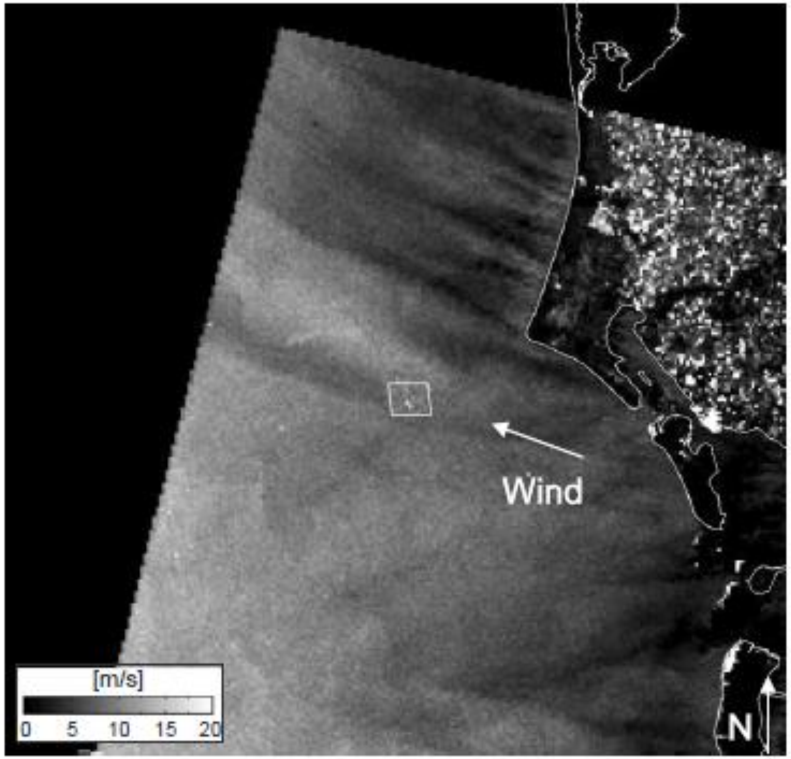
Introduction

Within 1 -2 km downwind:

- Wind speed deficit: 8-9%
- 0.5 - 1.5 m/s (Chistiansen and Hasager, 2005)

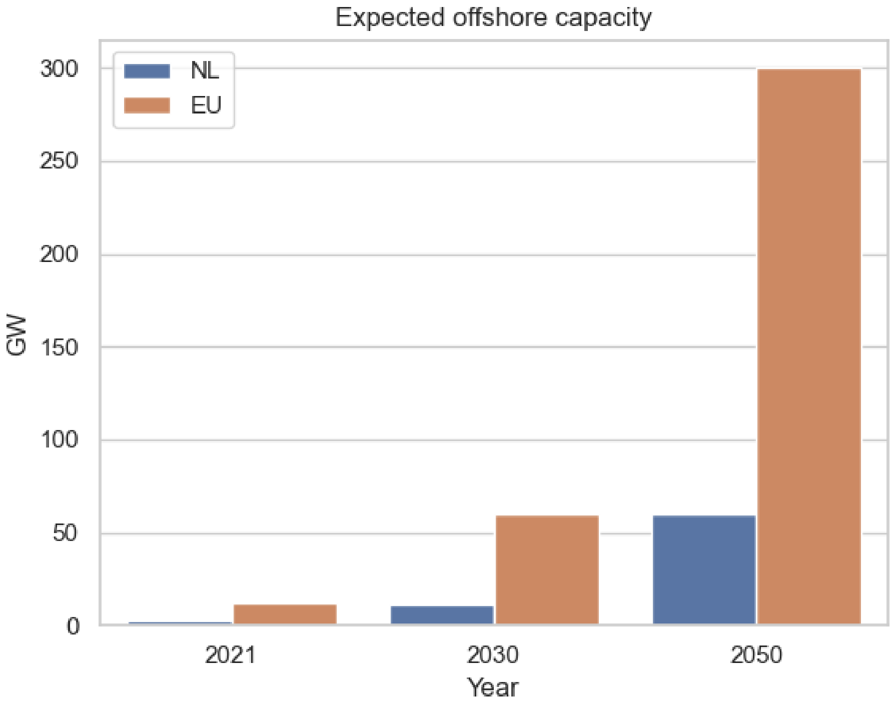
Wake length depending on:

- Wind speed
- Atmospheric stability (Cañadillas et al., 2020)
- Can exceed 50 km

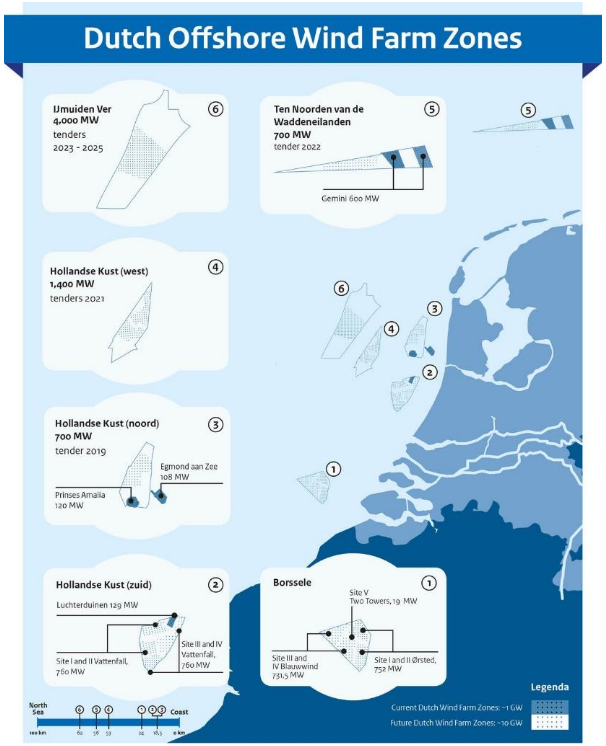


(Chistiansen and Hasager, 2005)

Introduction



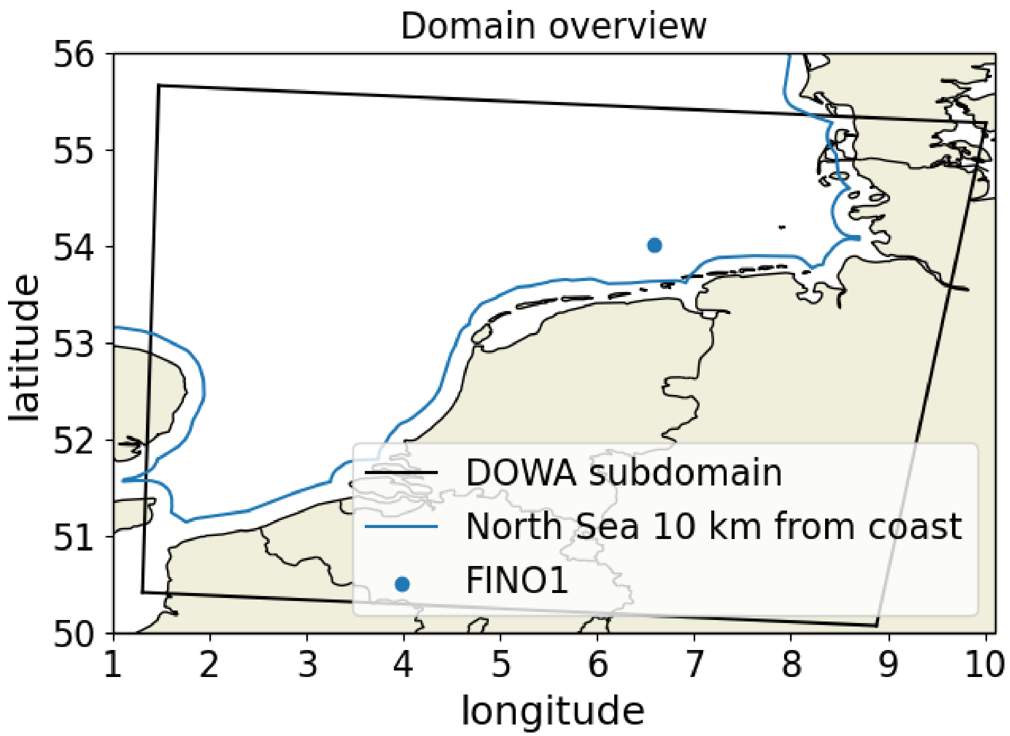
(EU,2021)
(Rijksoverheid, 2021)



(Rijksoverheid, 2021)

Research questions

1) Where does the wind regime change because of wind farm impact?
2) Where is this impact significant?



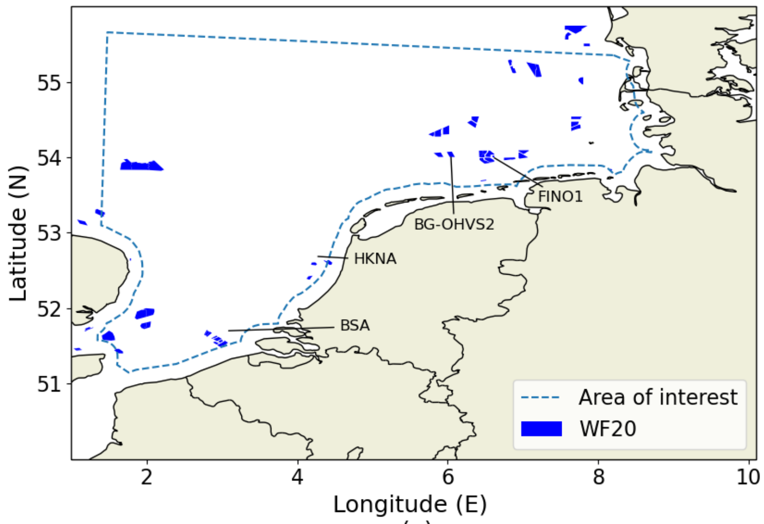
Datasets

WINS50:

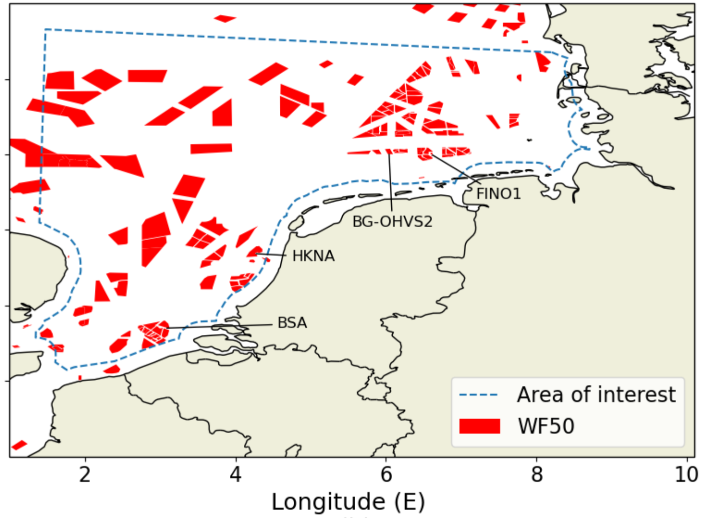
- HARMONIE cycle 43h2.1
- Wind farm parameterization
- 3 experiments for 2020:
  - No wind farms (CTL)
  - Wind farms up to 2020 (WF20)
  - Wind farms up to 2050 (WF50)

DOWA (Wijnant et al., 2019):

- HARMONIE cycle 40h1.2.tg2
- 2008 - 2018



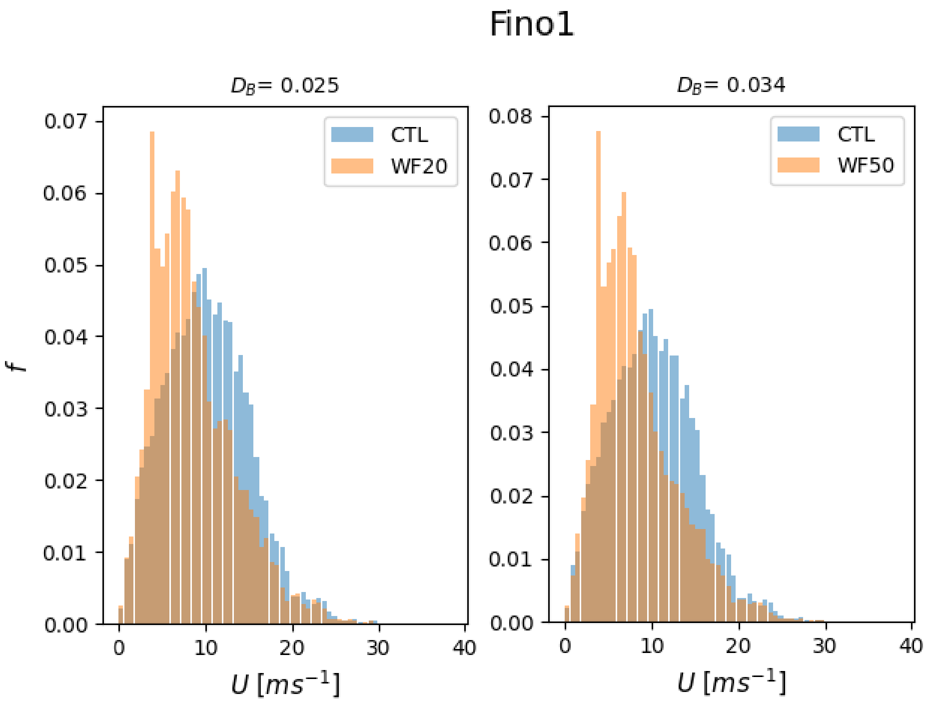
(a)



(b)

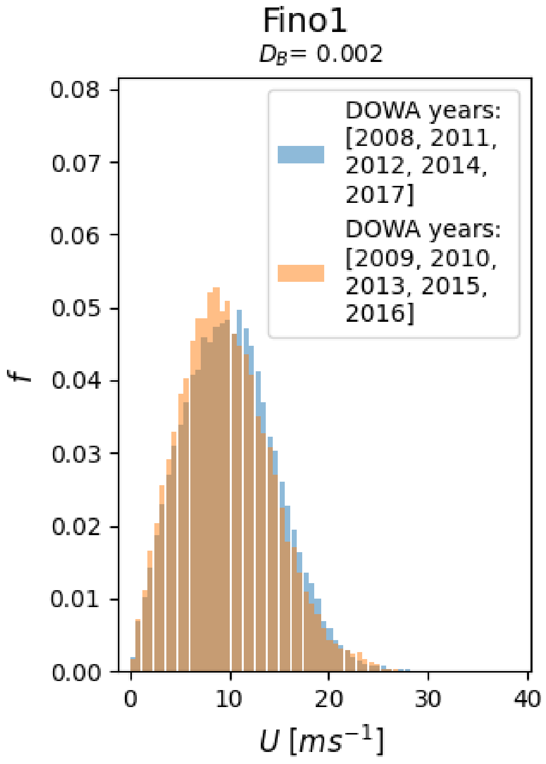
Methods: Bhattacharyya distance

- Measure of overlap between 2 probability distributions *p* and *q*
- $D_B = -\ln(\sum_{x \in X} \sqrt{p(x)q(x)})$
- $D_B = 0$, when *p* and *q* are similar
- $D_B = \infty$, when *p* and *q* have no overlap

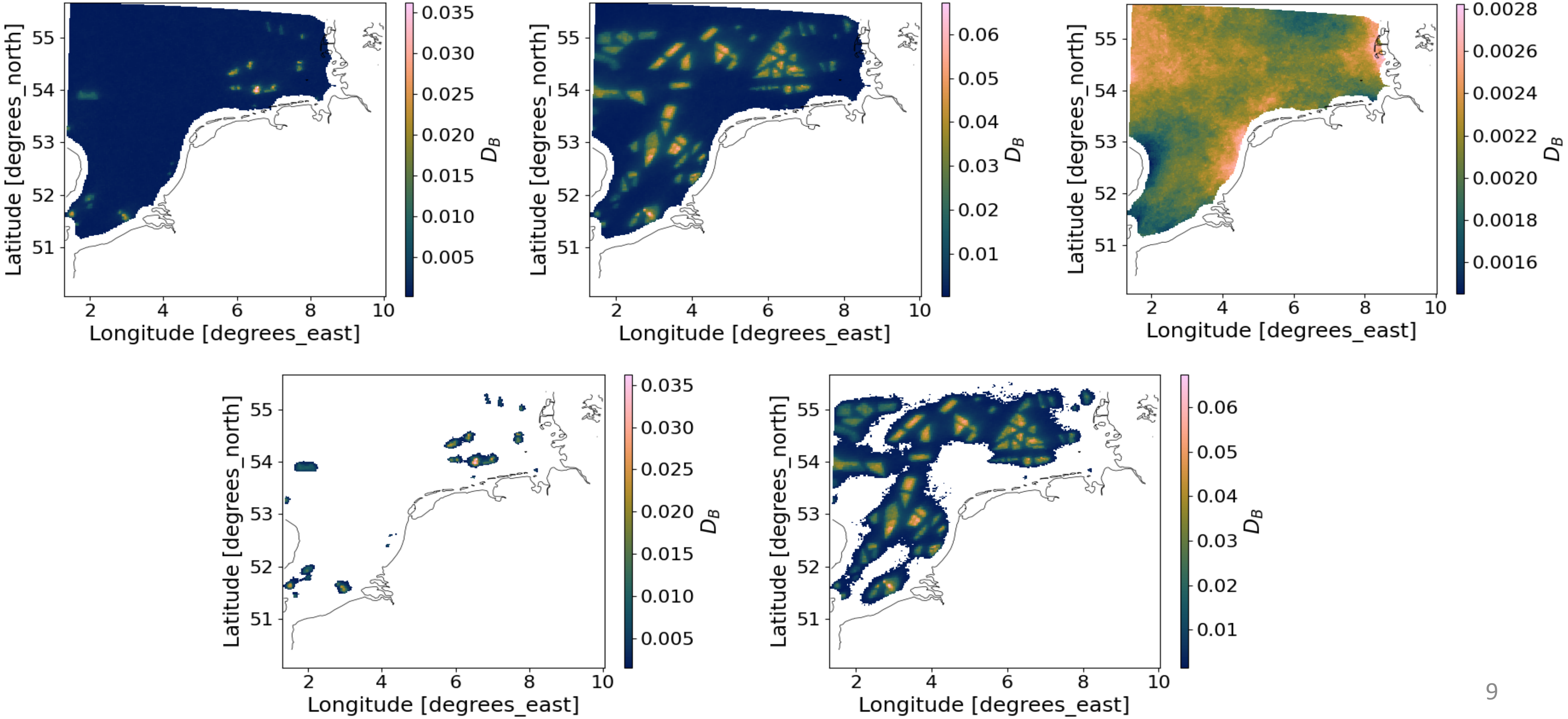


Methods: thresholding

- Represents the natural variability on every location
- 10 years of DOWA data
- D_B between 2 selected groups of 5 years
- 126 unique comparisons
- Threshold is 95th quantile



Results: Wind speed 100 m



Methods: filtering

- To wind direction:

  1) N: 315 – 45

  2) E: 45 – 135

  3) S: 135 – 225

  4) W: 225 – 315

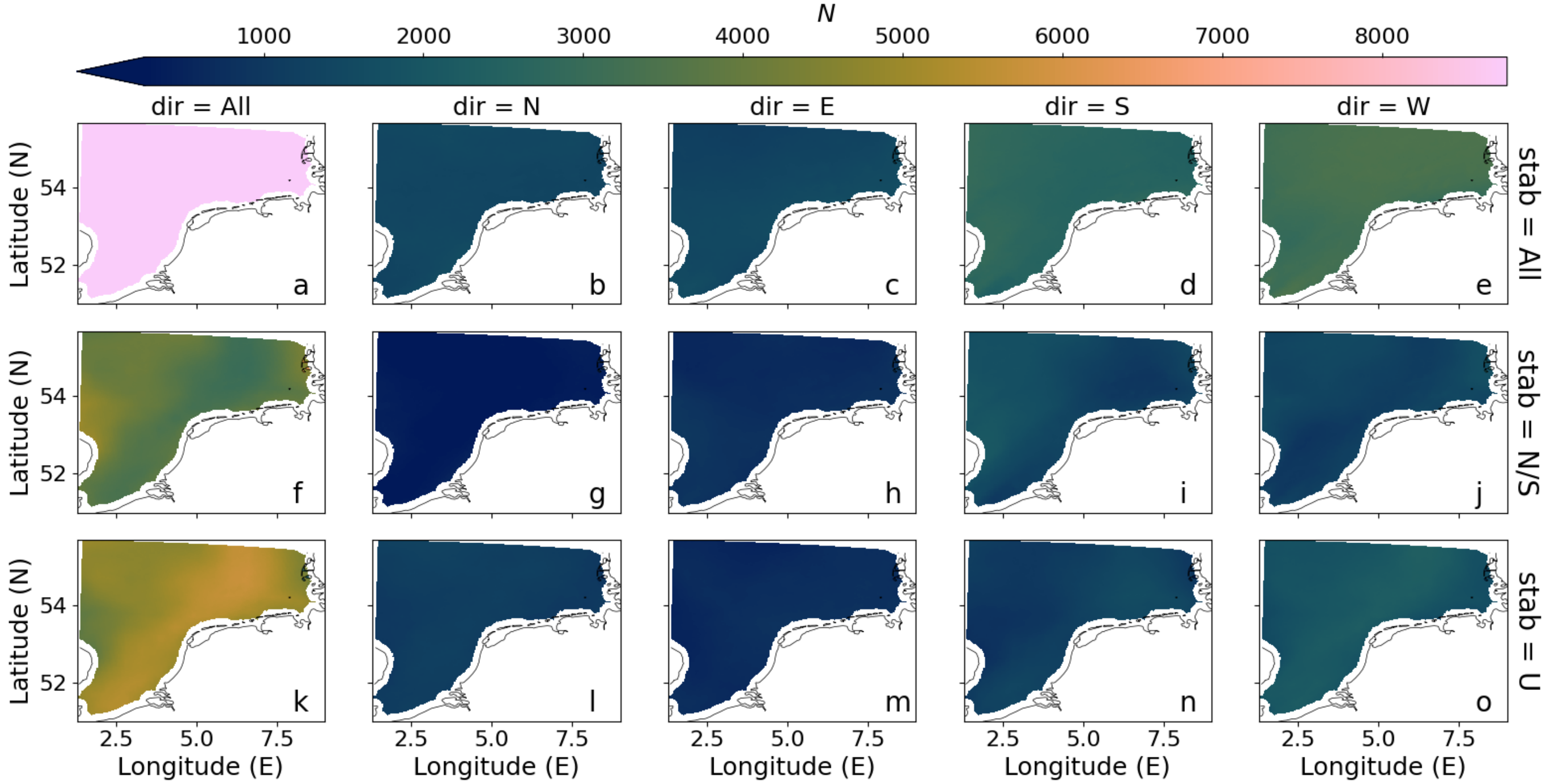
- To air surface temperature difference (ASTD):

  $$ASTD = T\_100 - T\_10 + 0.9$$

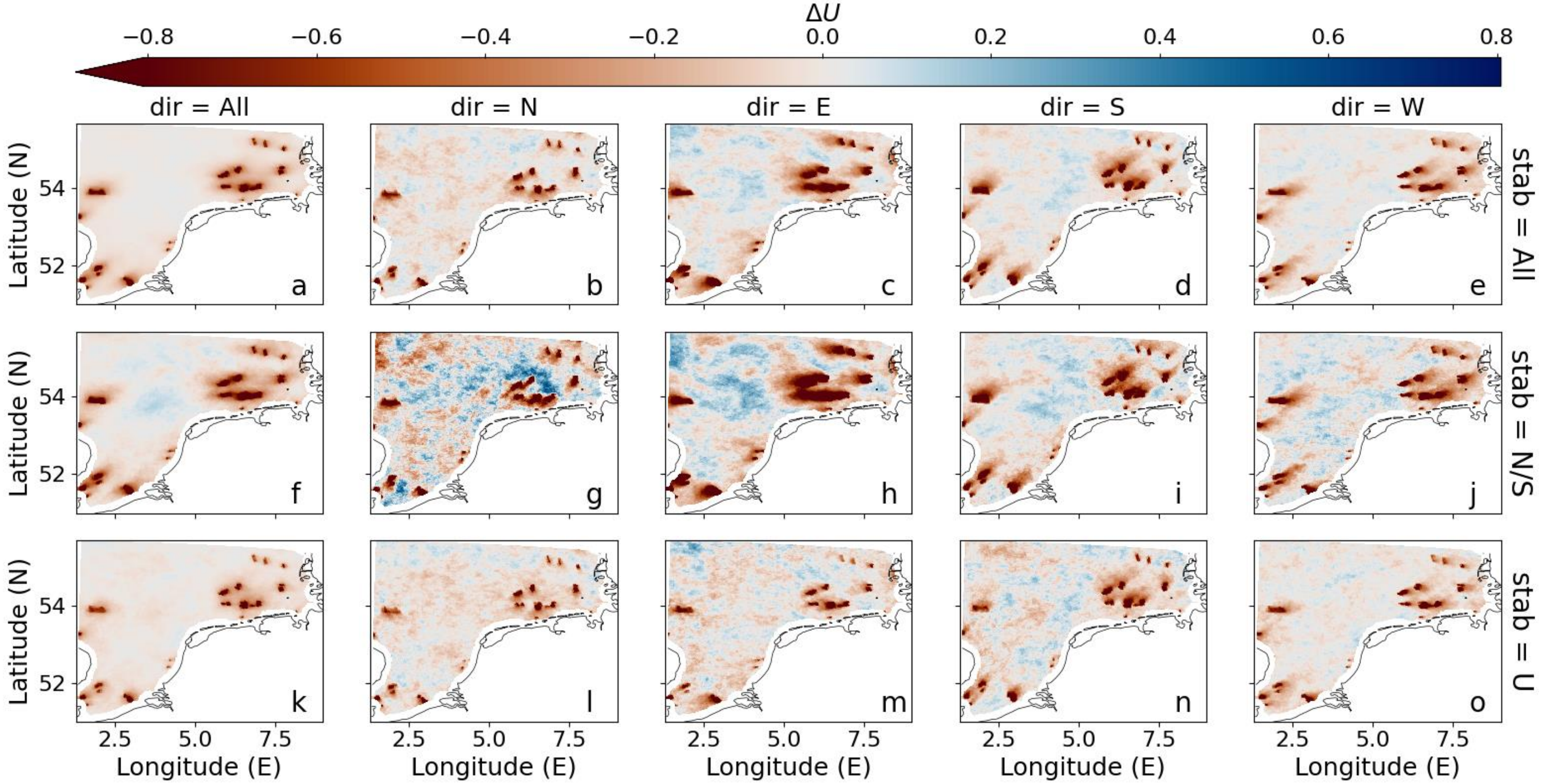
  1) Neutral/Stable: $ASTD \geq 0$

  2) Unstable: $ASTD < 0$

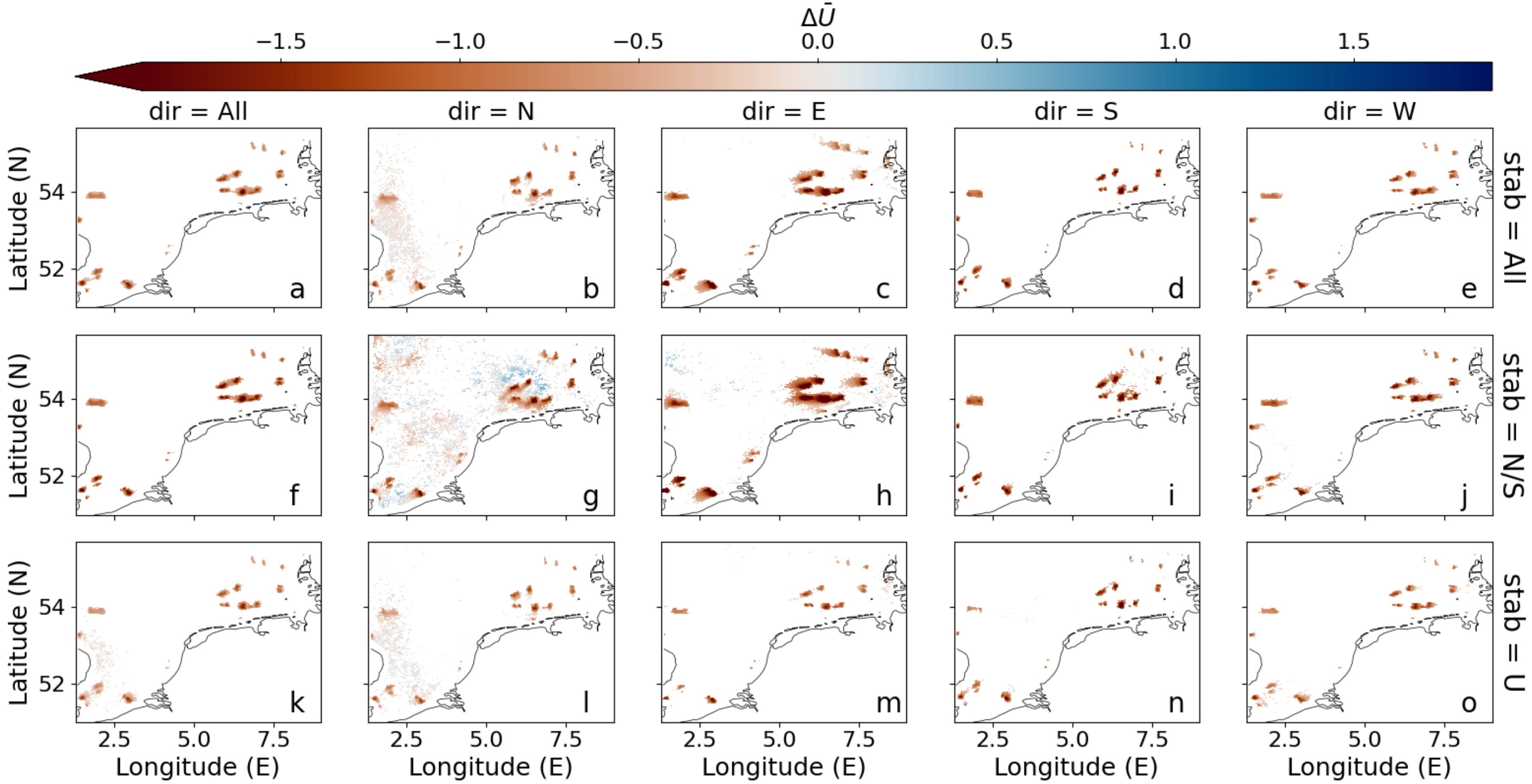
Results: N WF20



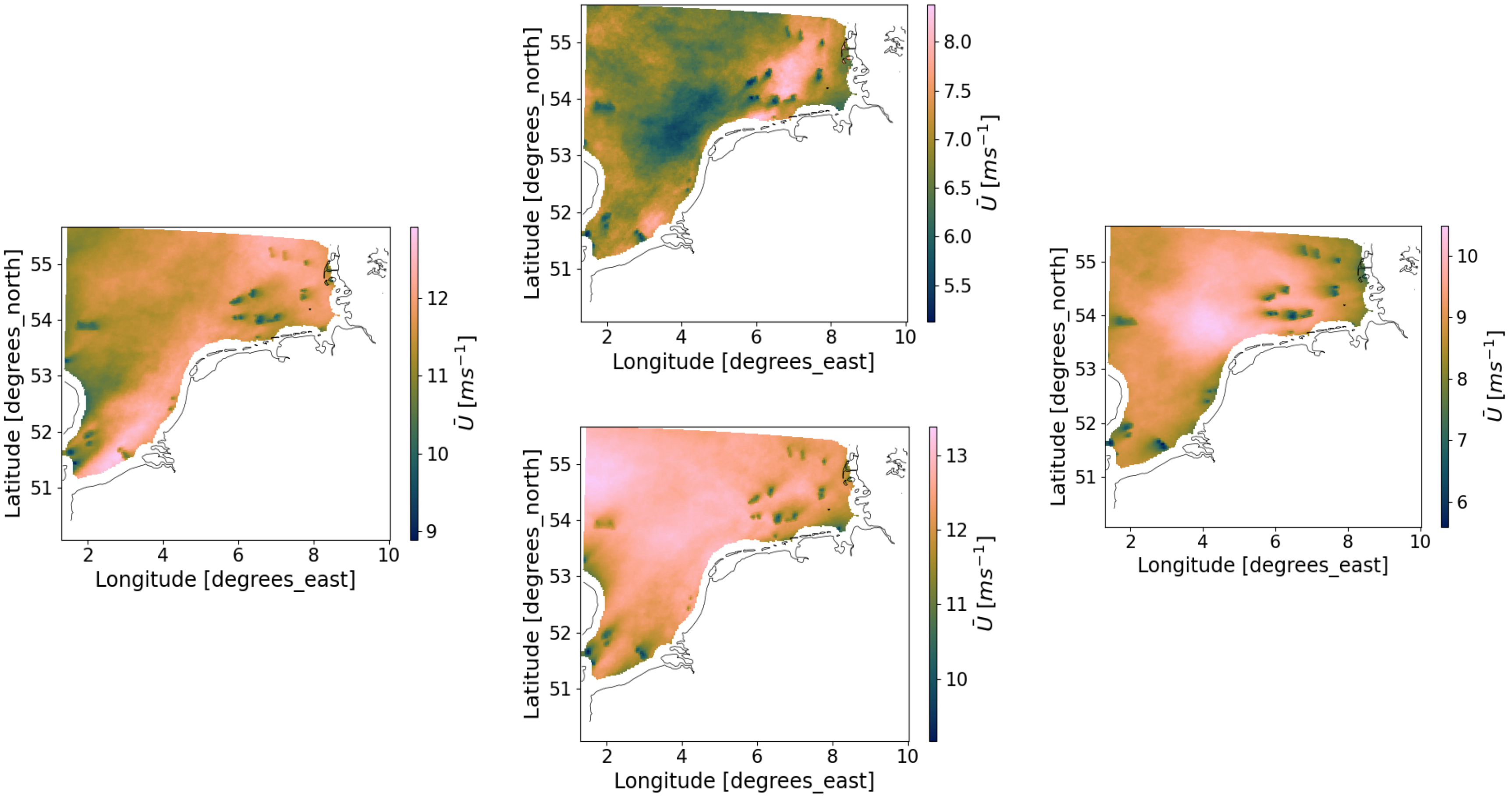
Results: mean wind speed difference WF20



Results: Where D_B > threshold



Results: mean wind speed N/S conditions

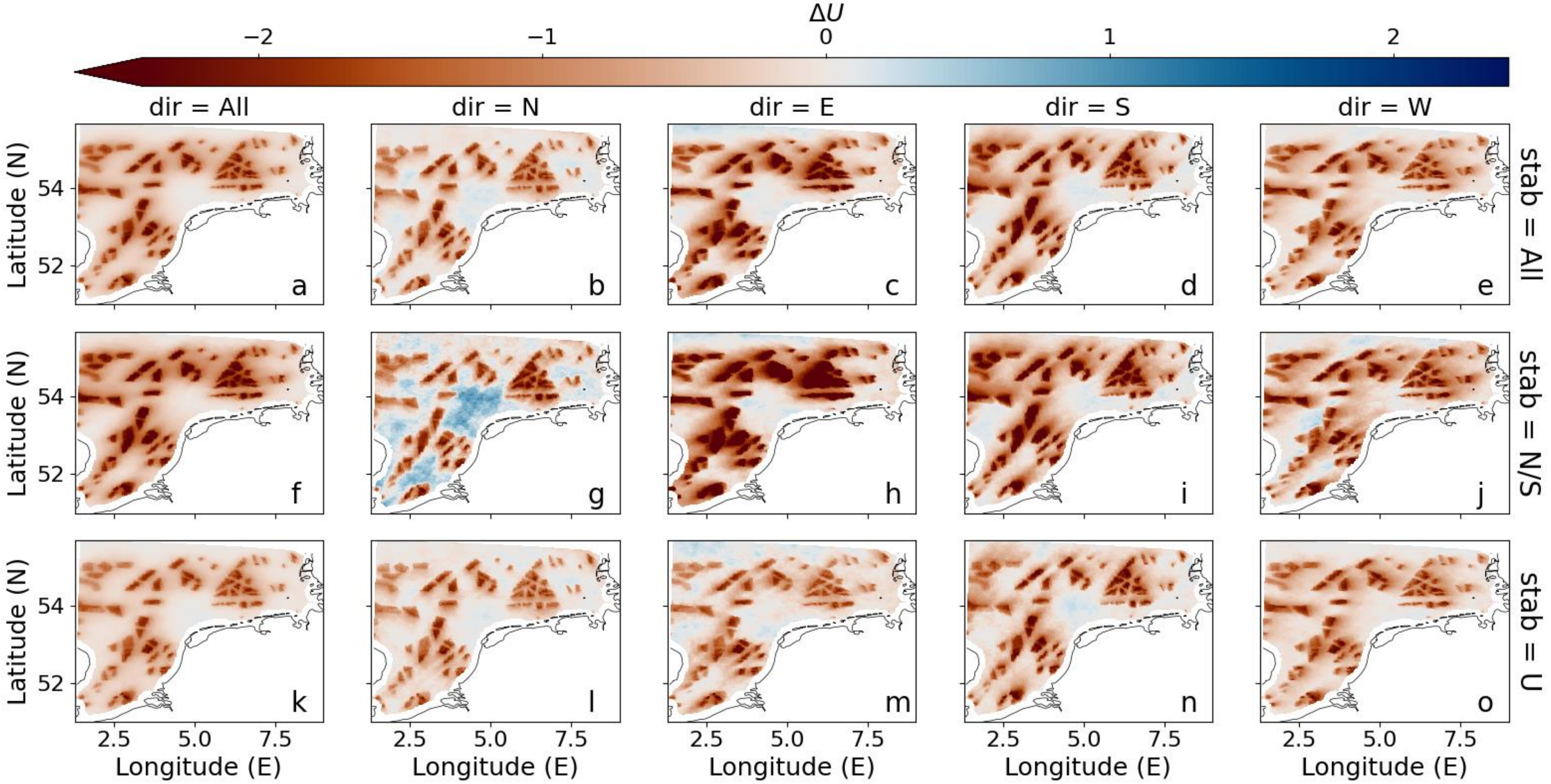


Results: normalized impact area WF20

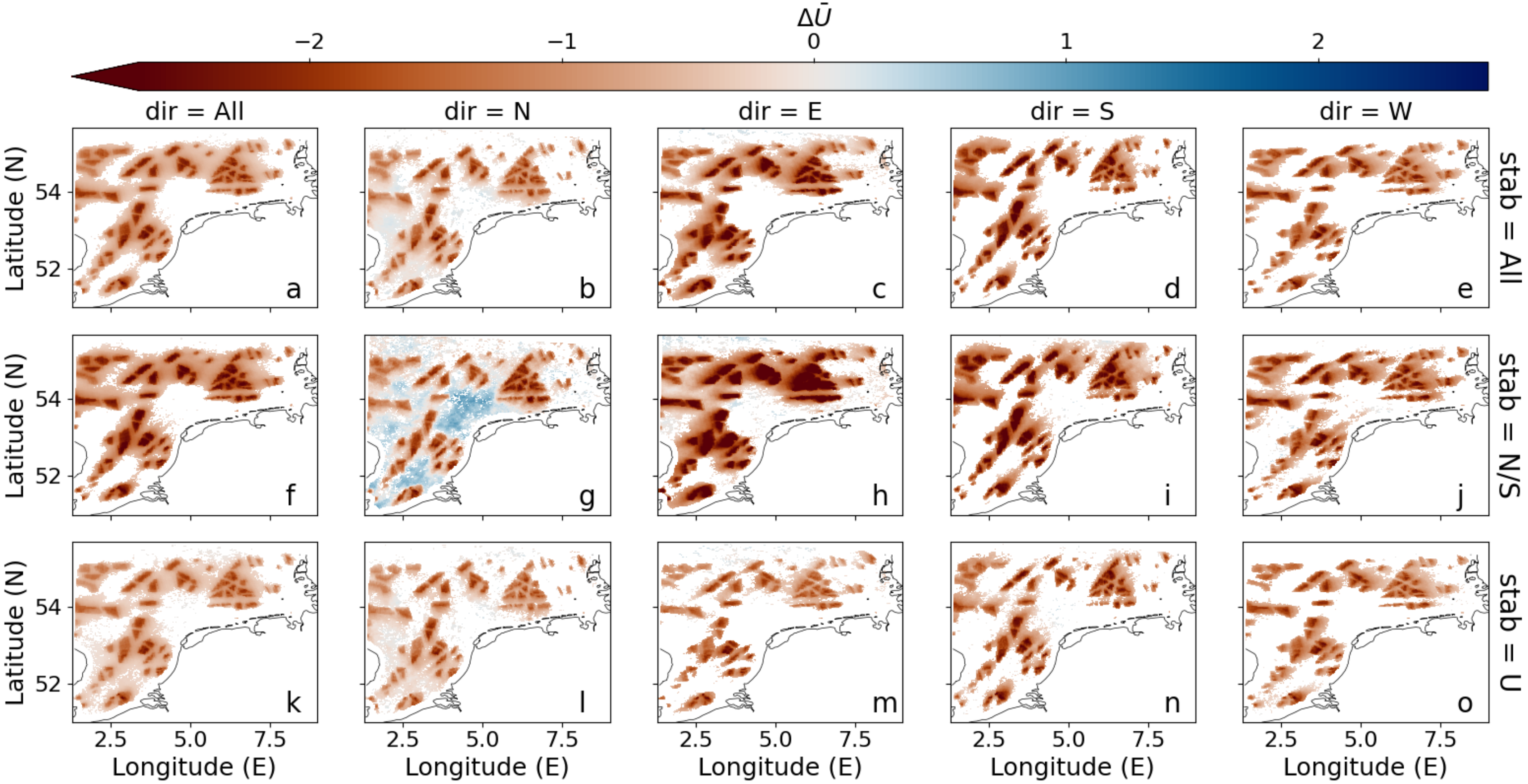
Area region of interest = ~140 000 km^2
Turbine area = 3113 km^2
Normalized area region of interest = ~45

	All	N	E	S	W
All	2.0	5.8	3.5	1.3	1.6
N/S	1.9	12.7	6.0	1.9	2.1
U	2.6	4.1	1.3	1.3	1.6

Results: mean wind speed difference WF50



Results: Where D_B > threshold



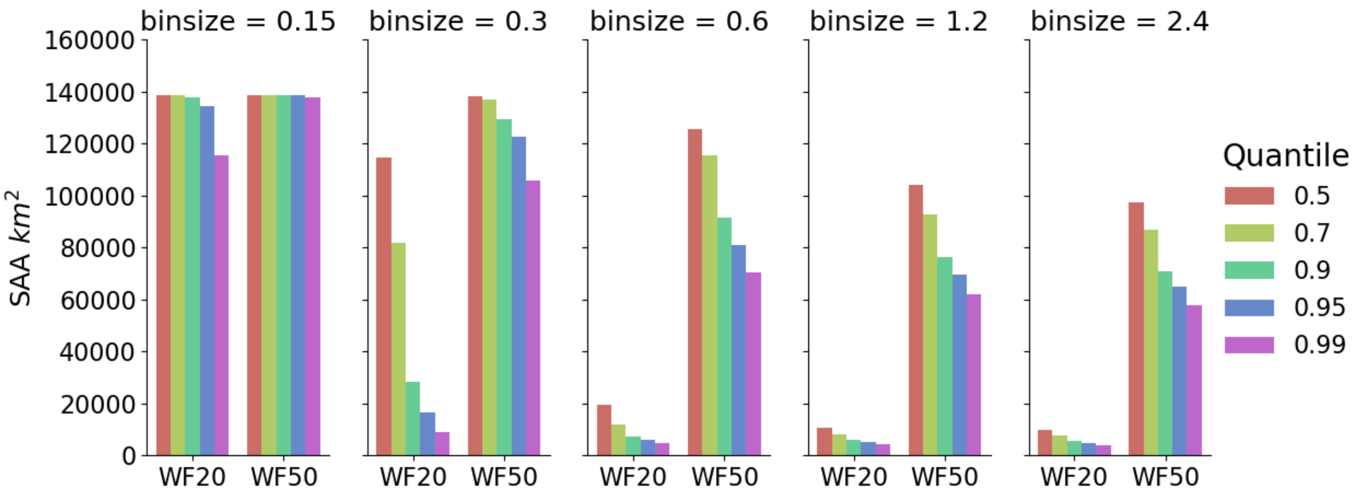
Results: normalized impact area WF50

Area region of interest = ~140 000 km^2
Turbine area = 21490 km^2
Normalized area region of interest = ~6.5

	All	N	E	S	W
All	3.8	3.8	3.9	2.7	2.6
N/S	3.8	5.0	4.6	3.3	3.1
U	3.8	3.4	2.3	2.6	2.5

Discussion

- Dependency on bin width and choosen threshold quantile



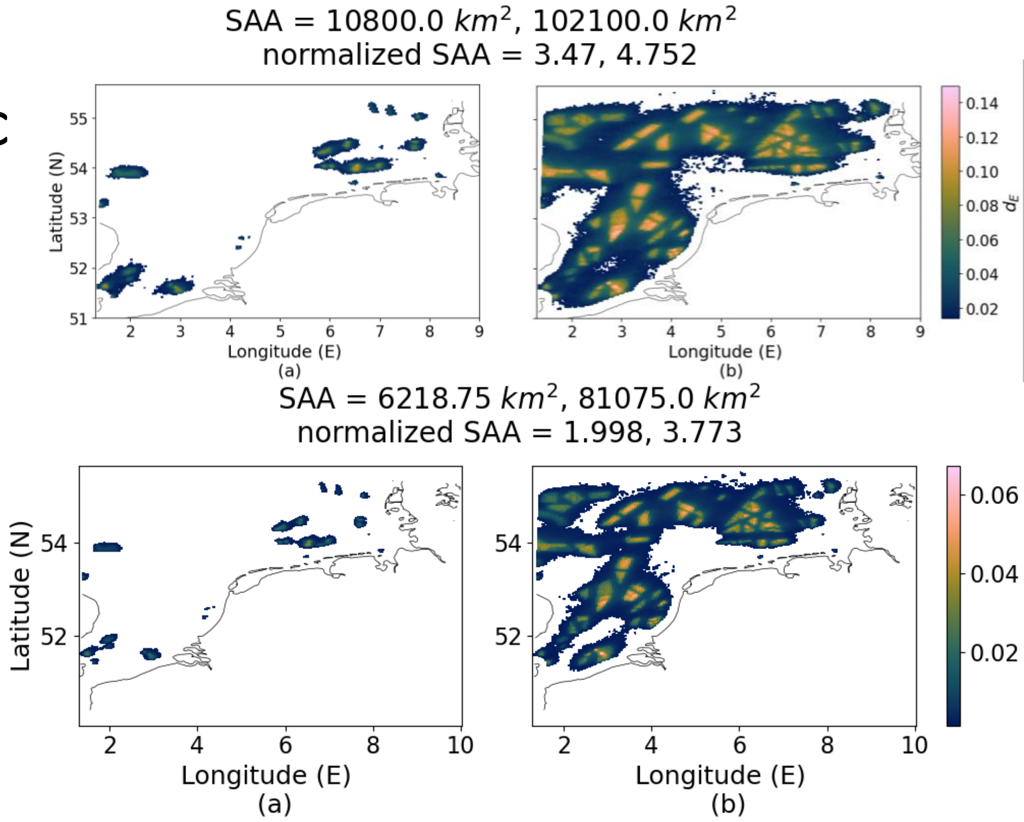
Discussion

- Dependency on distance metric
- Euclidean distance:

$$D_E = \sqrt{\sum_{i}^{d} |P_i - Q_i|^2}$$

- Bhattacharyya distance:

$$D_B = -\ln\left(\sum_{x \in X} \sqrt{p(x)q(x)} \right)$$



Conclusion

We developed a method to analyze wind farm impact that:

- Takes natural variability into account
- Captures the wake effect

With this framework we see:

- The wake effect is largests during East wind under non-convective boundary layers
- The normalized impact area does not increase linearly with increasing turbine area
- In the WF50 scenario the wake effect is less dependent on wind direction

Outlook

- Other variables
- WF20 2019 and 2021
- Look into power production
- Compare WFPs

Sources

Cañadillas, B., Foreman, R., Barth, V., Siedersleben, S., Lampert, A., Platis, A., . . .others (2020). Offshore wind farm wake recovery: Airborne measurements andits representation in engineering models.Wind Energy,23(5), 1249–1265.

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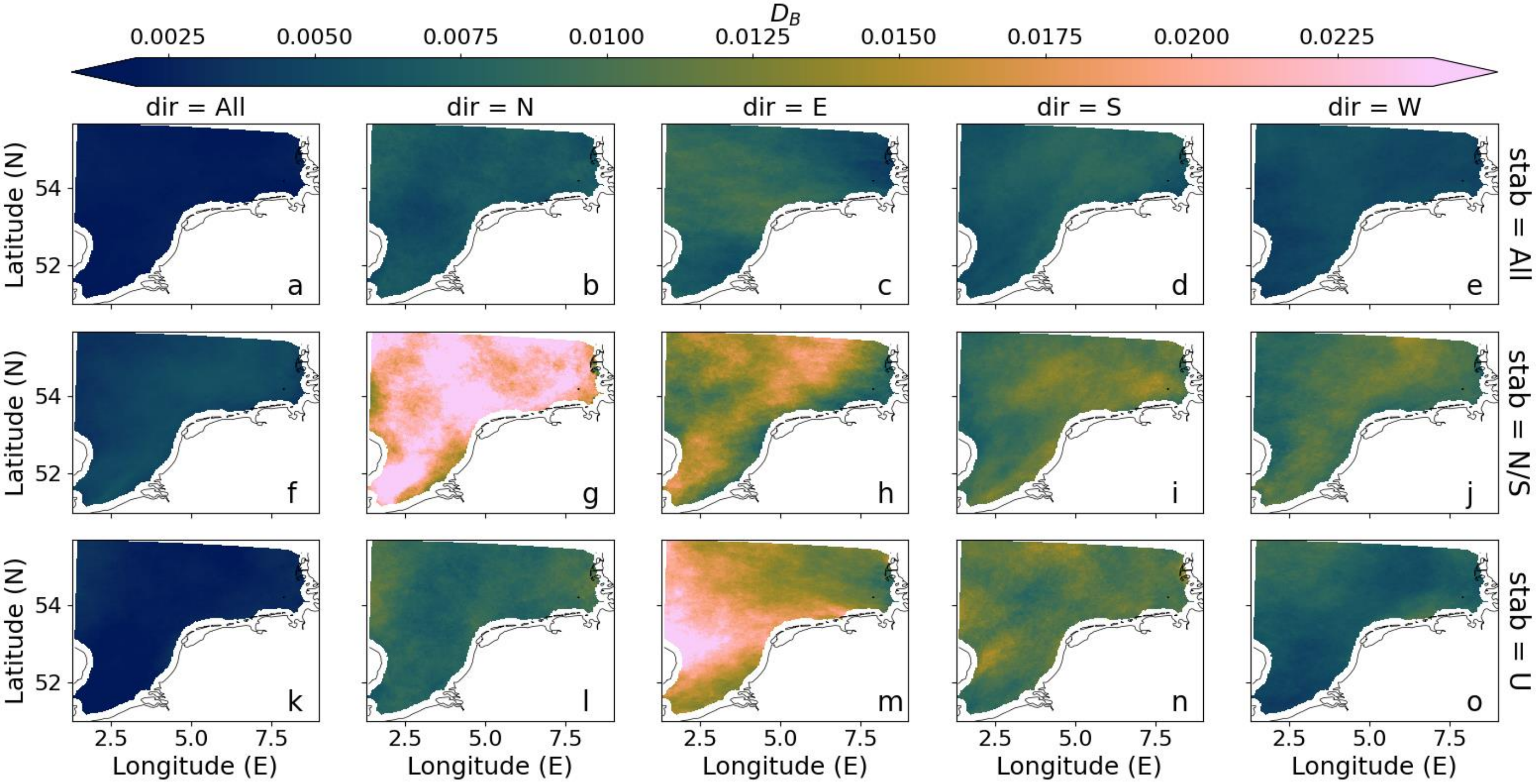
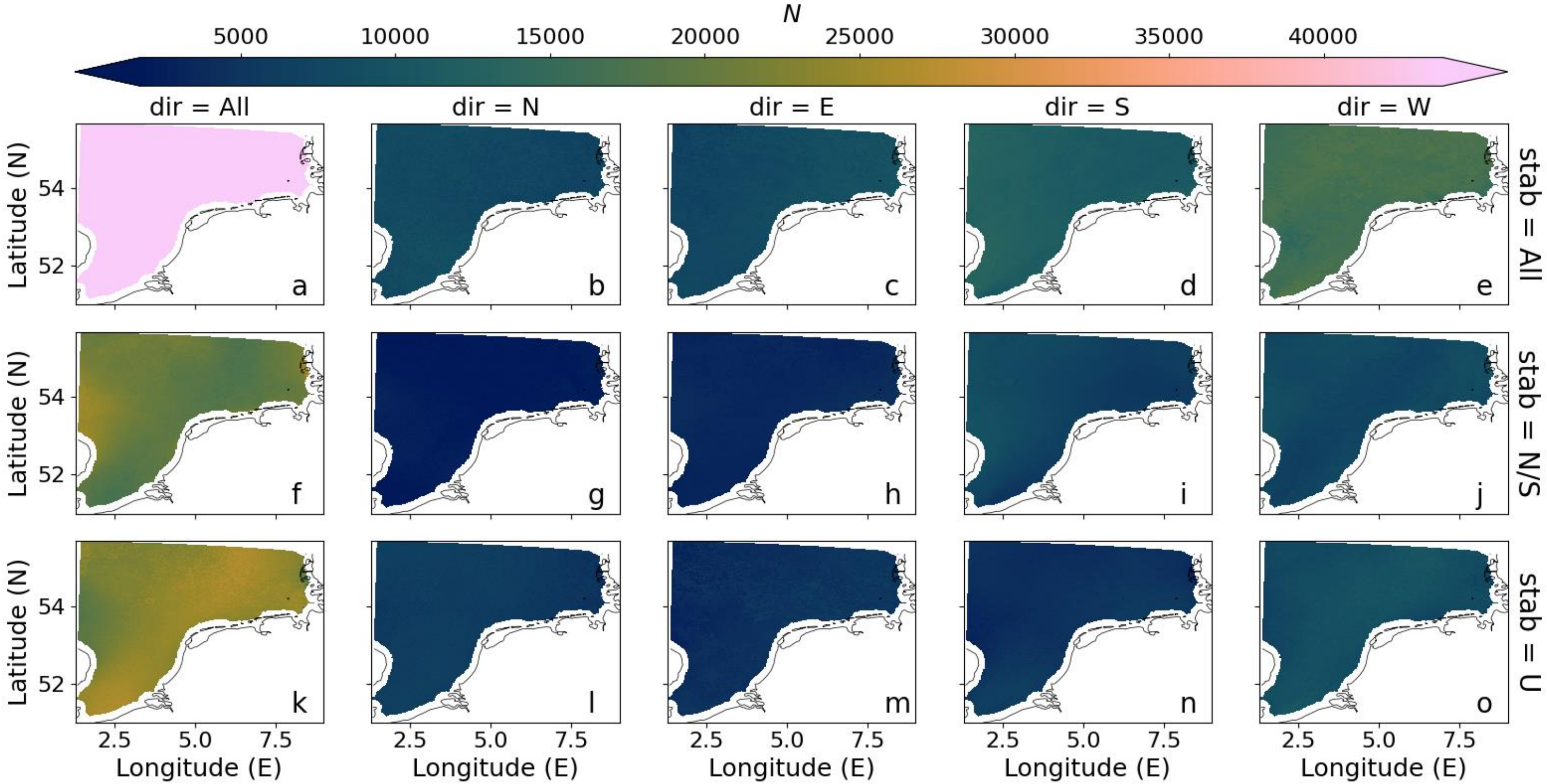
Wijnant, I., van Ulft, B., van Stratum, B., Barkmeijer, J., Onvlee, J., de Valk, C.,. . . Stepek, A. (2019).The dutch offshore wind atlas (dowa): Description ofthe dataset(Tech. Rep.). KNMI Tech. Rep. 2019, TR-380.

DOWA threshold

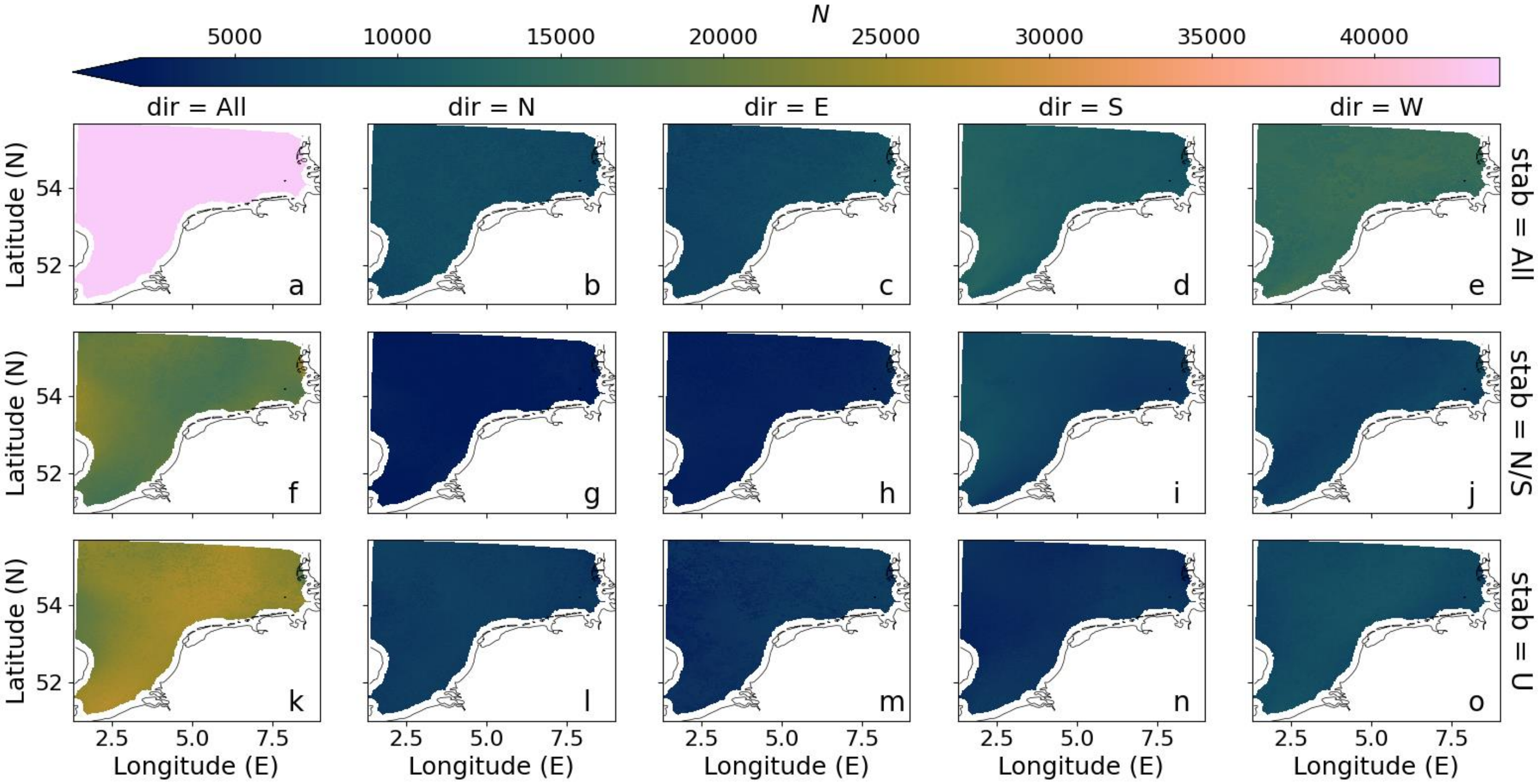


DOWA N years



N
5000
10000
15000
20000
25000
30000
35000
40000
dir = All
dir = N
dir = E
dir = S
dir = W
stab = All
stab = N/S
stab = U
Latitude (N)
54
52
Longitude (E)
2.5
5.0
7.5
a
b
c
d
e
f
g
h
i
j
k
l
m
n
o

DOWA other years



WFP equations

Thrust force:

$$\vec{F}_{\text{thrust}} = -\frac{1}{2}\rho C_{\text{T}}|\vec{V}|\vec{V}A_T, \qquad [\text{N}] \quad (2.1)$$

Rate loss of kinetic energy (KE):

$$\left.\frac{\partial \text{KE}}{\partial t}\right|_{\text{drag}} = -\frac{1}{2}\rho C_{\text{T}}|\vec{V}|^3 A_T. \qquad [\text{J s}^{-1}] \quad (2.2)$$

Total change in KE of a single grid cell with volume delta_k:

$$\left.\frac{\partial \text{KE}_{\text{k}}}{\partial t}\right|_{\text{cell}} = \frac{\partial}{\partial t}\left(\frac{1}{2}\rho_k|\vec{V}_k|^2\right)\Delta_k = \rho_k|\vec{V}_k|\frac{\partial|\vec{V}_k|}{\partial t}\Delta_k. \qquad [\text{J s}^{-1}] \quad (2.3)$$

Re-arranging with 2.2=2.3:

$$\frac{\partial|\vec{V}_k|}{\partial t} = -\frac{1}{2}C_{\text{T}}\,|\vec{V}_k|^2\,A_k\,\Delta_k^{-1}, \qquad [\text{m s}^{-2}] \quad (2.5)$$

Assuming $C_{\text{TKE}} = C_{\text{T}} - C_{\text{P}}$, the production rate of turbulent kinetic engergy (TKE):

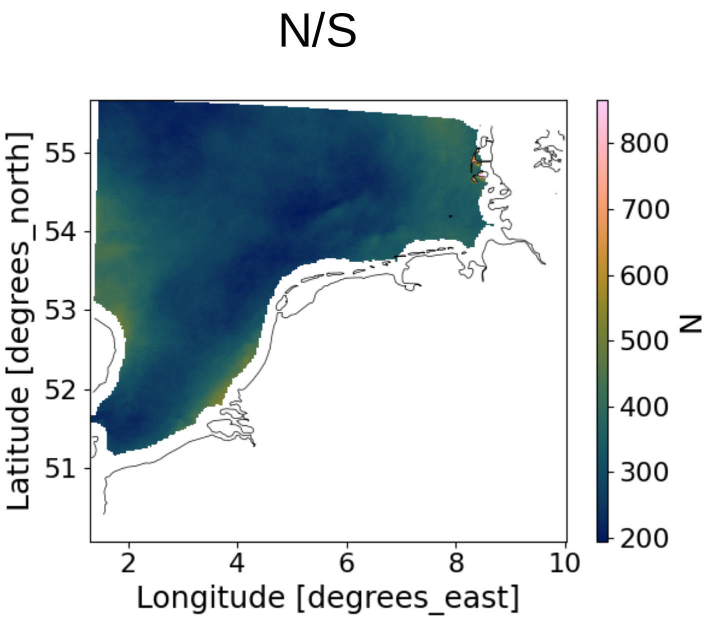
$$\frac{\partial \text{TKE}_{\text{k}}}{\partial t} = \frac{1}{2}C_{\text{TKE}}\,|\vec{V}_k|^3\,A_k\,\Delta_k^{-1}. \qquad [\text{m}^2\,\text{s}^{-2}\,\text{s}^{-1}] \quad (2.8)$$

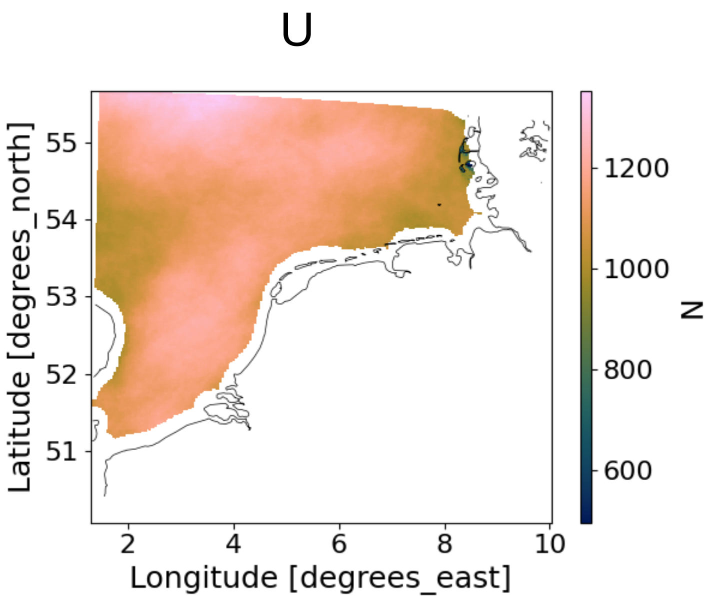
Electrical power produce by the wind tubines:

$$\text{P} = \frac{1}{2}\rho C_{\text{P}}\,A_T\,|\vec{V}_{\text{hub}}|^3 \qquad [\text{W}] \quad (2.9)$$

(Stratum et al., 2019)

Results: zoom N for North winds





Scott's Rule

$$h = 3.5\sigma N^{-1/3}$$