Wind-turbine wakes responding to diurnal cycle-driven boundary-layer flow over homogeneous and complex terrain: A numerical modelling study

Antonia Englberger and Andreas Dörnbrack

German Aerospace Center - DLR

28.-30. May 2018

Motivation

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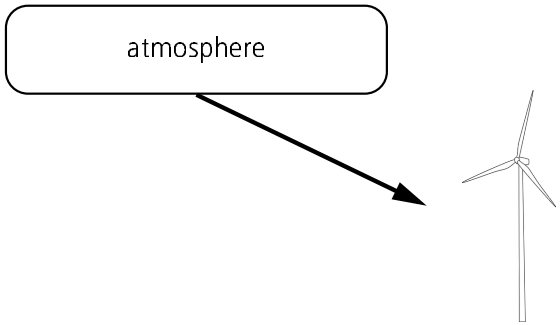

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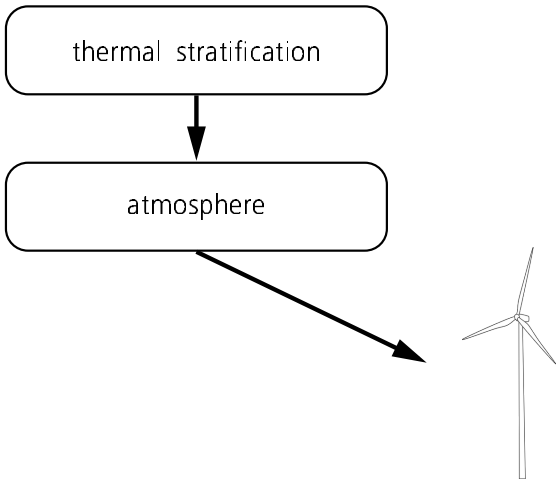
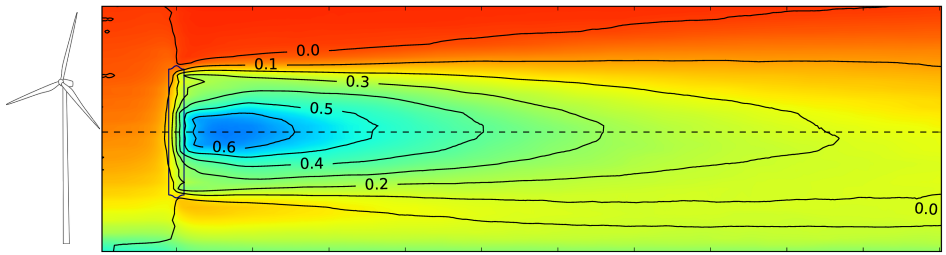


Motivation

thermal stratification

atmosphere



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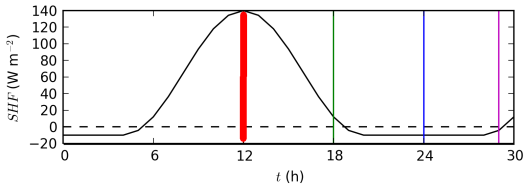

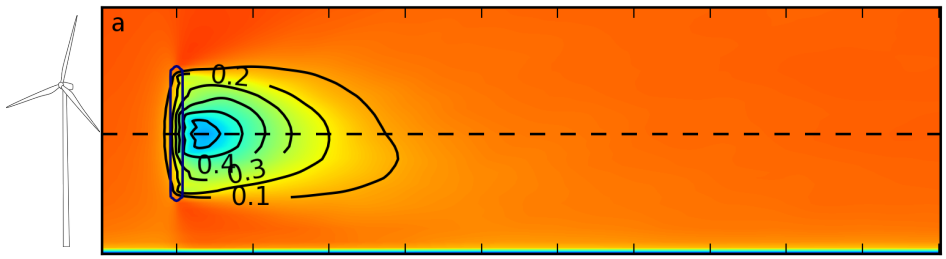

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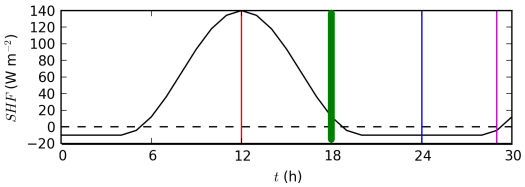

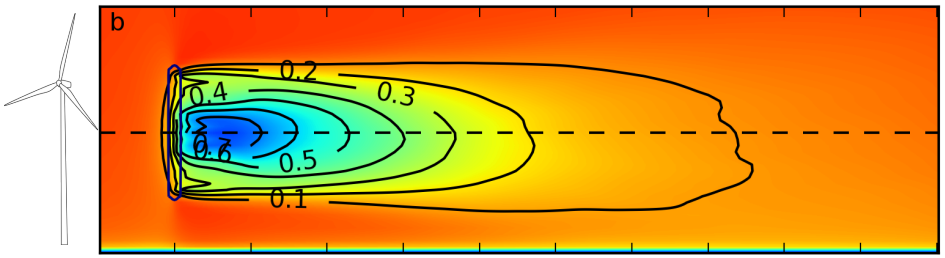

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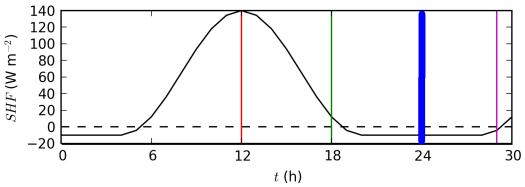

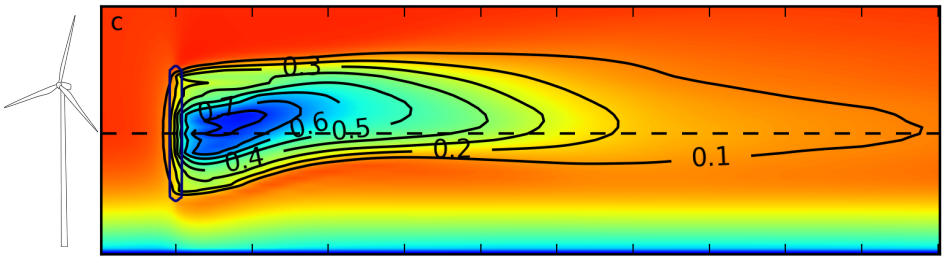

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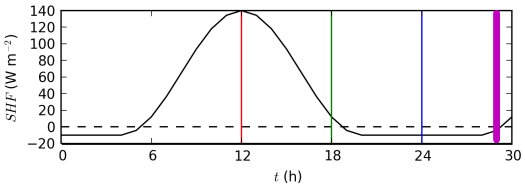
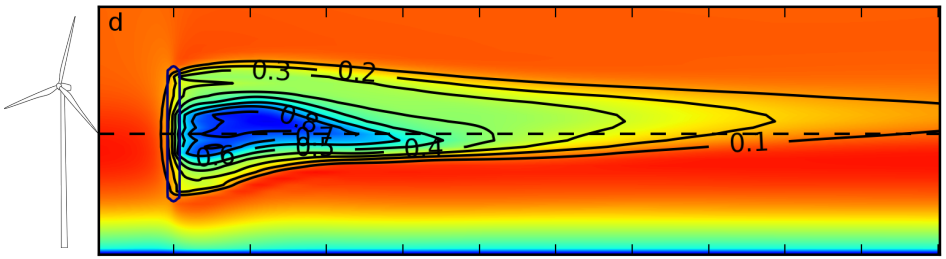


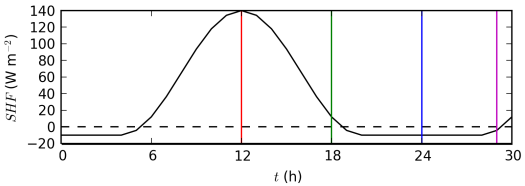


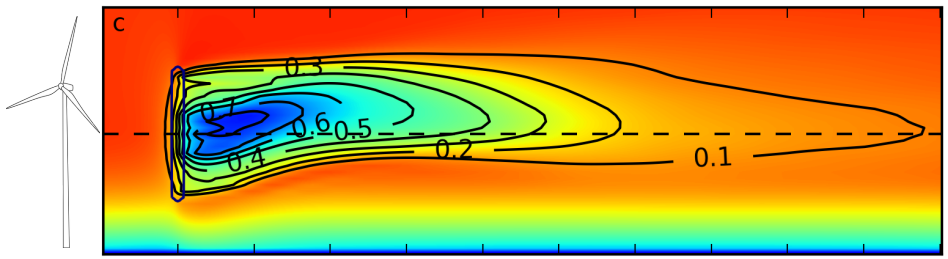
Motivation

stably stratified flow

thermal stratification

atmosphere





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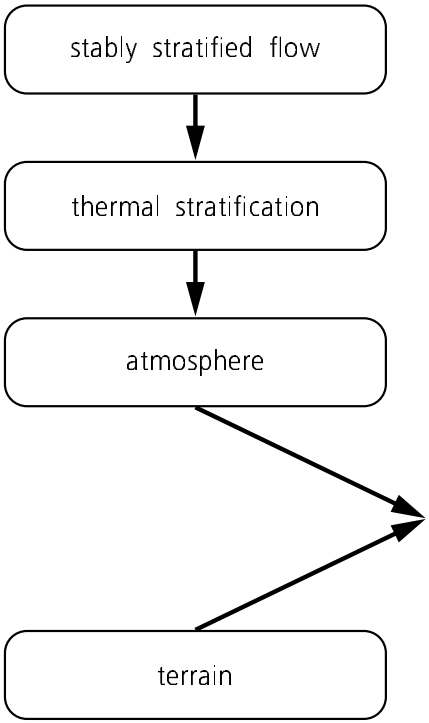
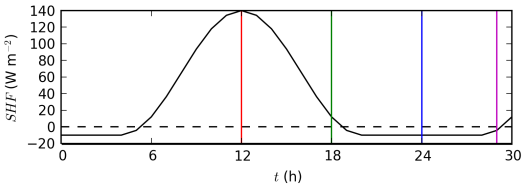

stably stratified flow
thermal stratification
atmosphere
terrain


SHF (W m⁻²)
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12
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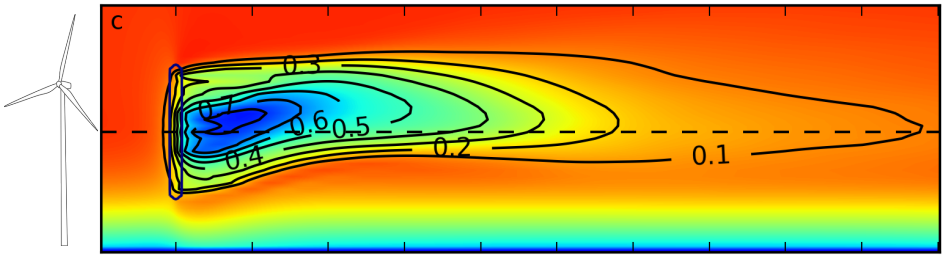
t (h)


c
0.3
0.7
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0.4
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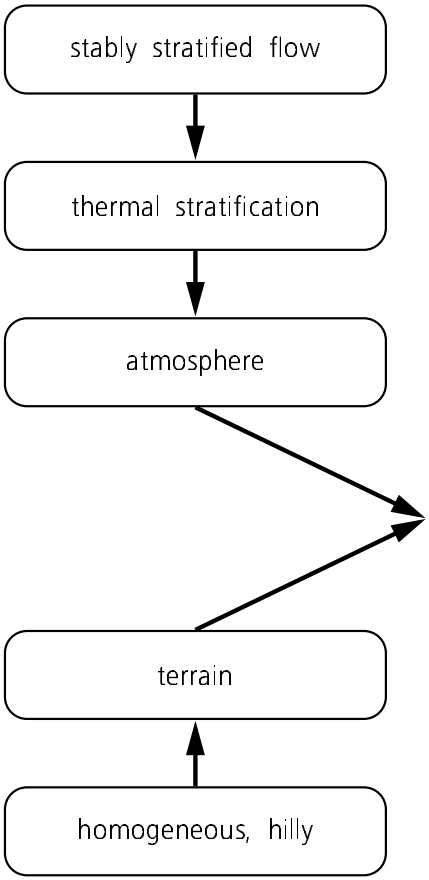
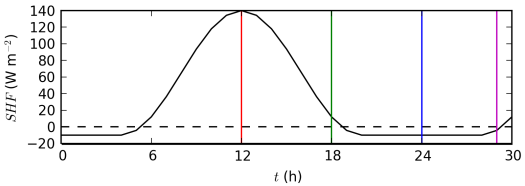
0.1

Motivation


stably stratified flow
thermal stratification
atmosphere
terrain
homogeneous, hilly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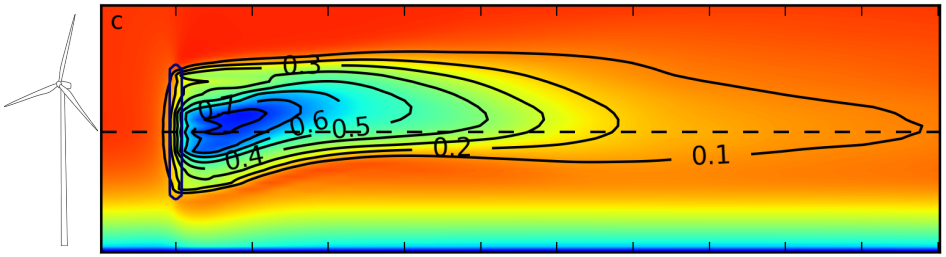
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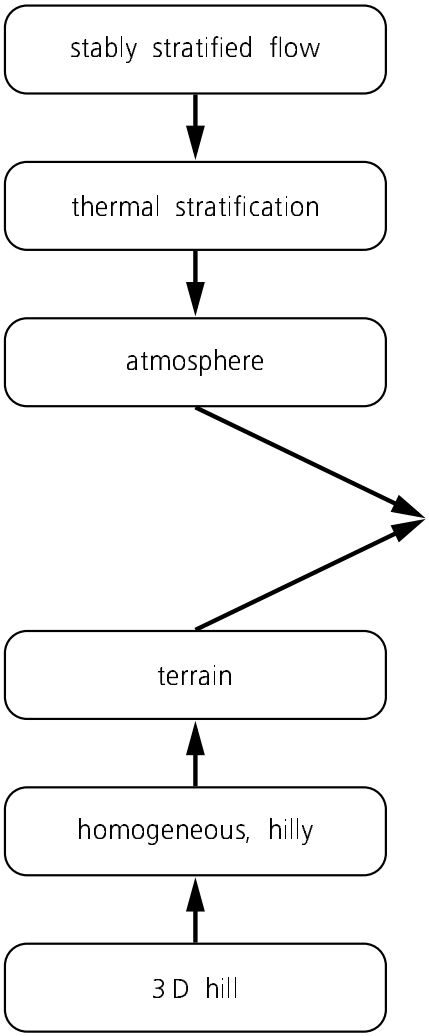
stably stratified flow
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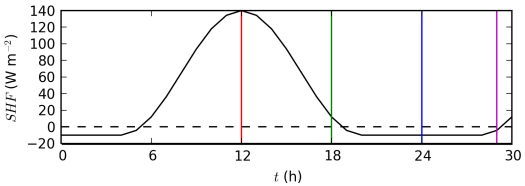
3 D hill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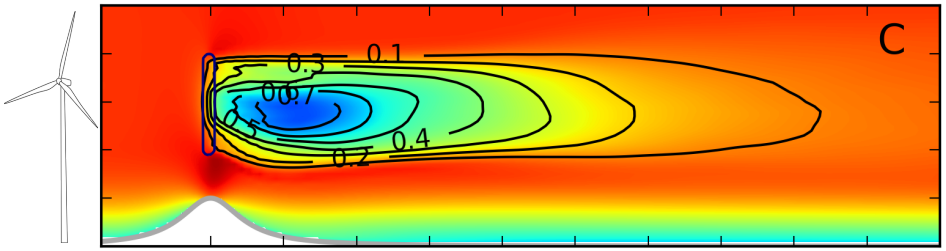
C
0.1
0.3
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Motivation

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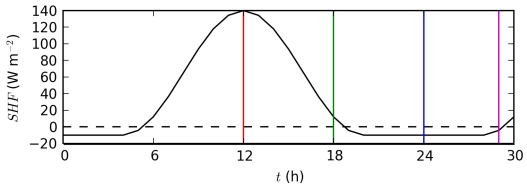
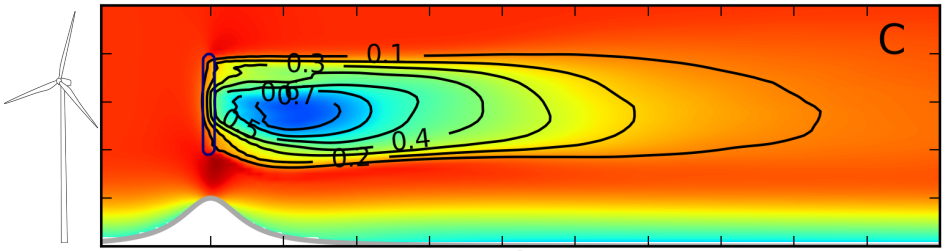
3 D hill





ATMOSPHERE & TERRAIN

Overview

Turbulent inflow Diurnal cycle precursor simulation

Homogeneous surface Wind-turbine simulations representing different atmospheric stratifications (CBL, EBL, SBL, MBL)

3 D hill Simulations of a hill-top wind turbine representing different stably stratified flow regimes

Complex terrain Nighttime flow simulation though a wind-turbine in Perdigão (Portugal)

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Mandatory for realistic wake recovery

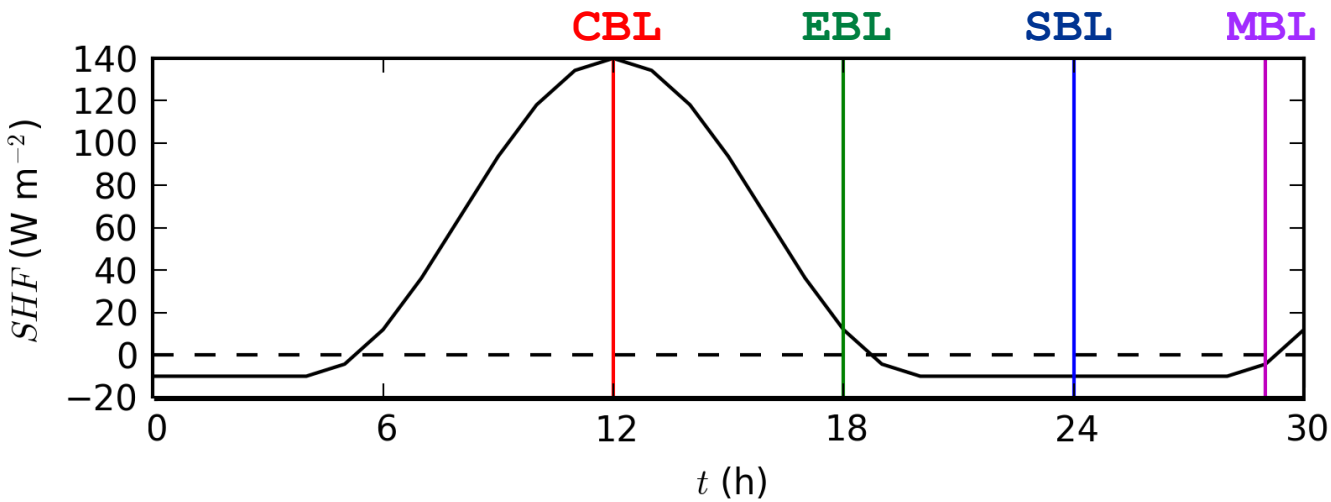
Problem Wind-turbine simulations with open streamwise boundary conditions

→ Permanent data input required

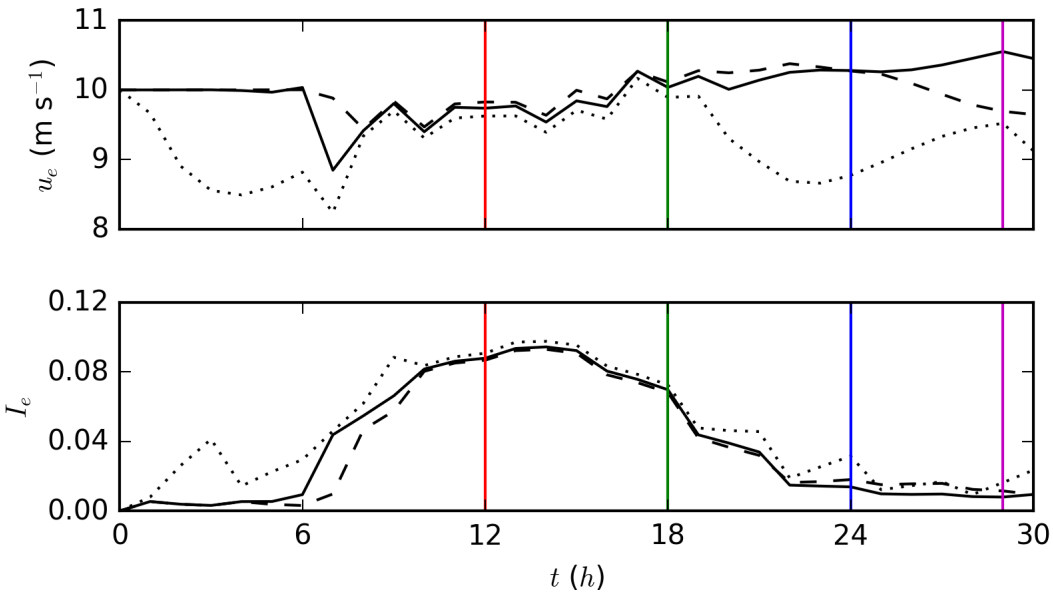
→ Diurnal cycle precursor simulation

- forcing via sensible heat flux
- 31 h simulation to represent all relevant stratifications during a diurnal cycle

12 h CBL (convective boundary layer)
18 h EBL (evening boundary layer)
24 h SBL (stable boundary layer)
29 h MBL (morning boundary layer)

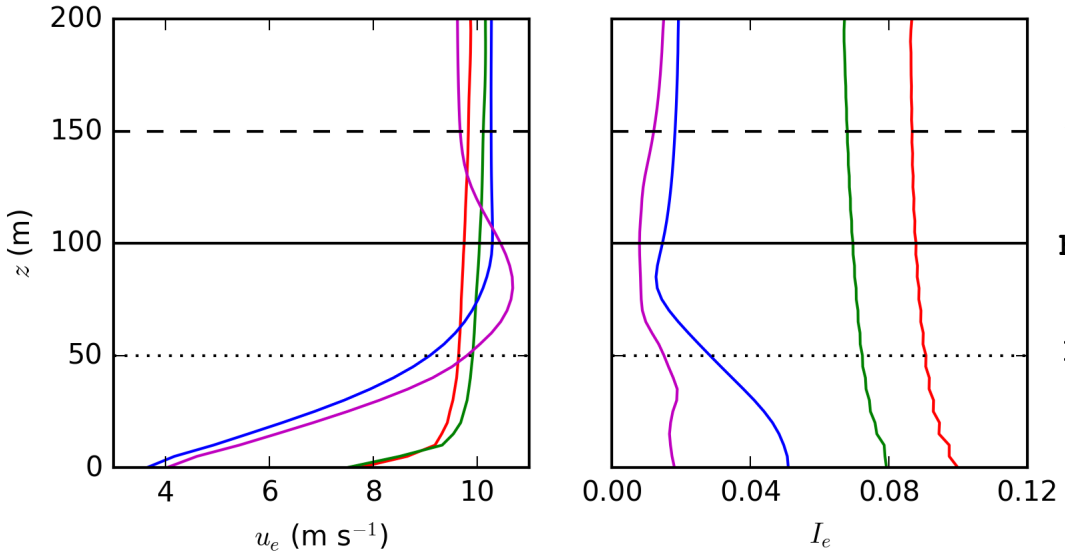


Diurnal cycle precursor simulation



horizontal wind

turbulent intensity



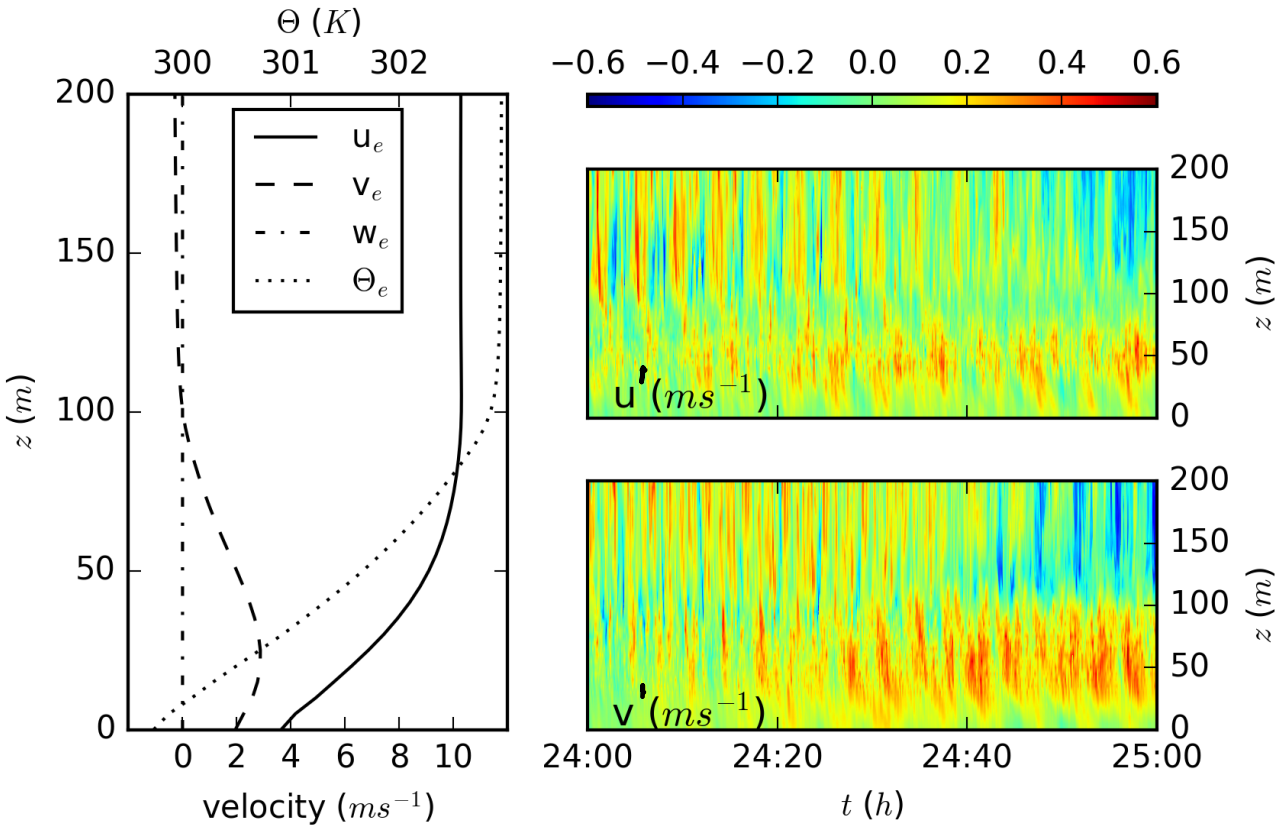
top tip height

hub height

bottom tip height

Simulation strategy

- diurnal cycle precursor simulation for wind-turbine simulations (wind turbine: $D = z_{hub} = 100$ m)
  - ⇒ initial and background conditions
  - ⇒ synchronized coupling during the simulation



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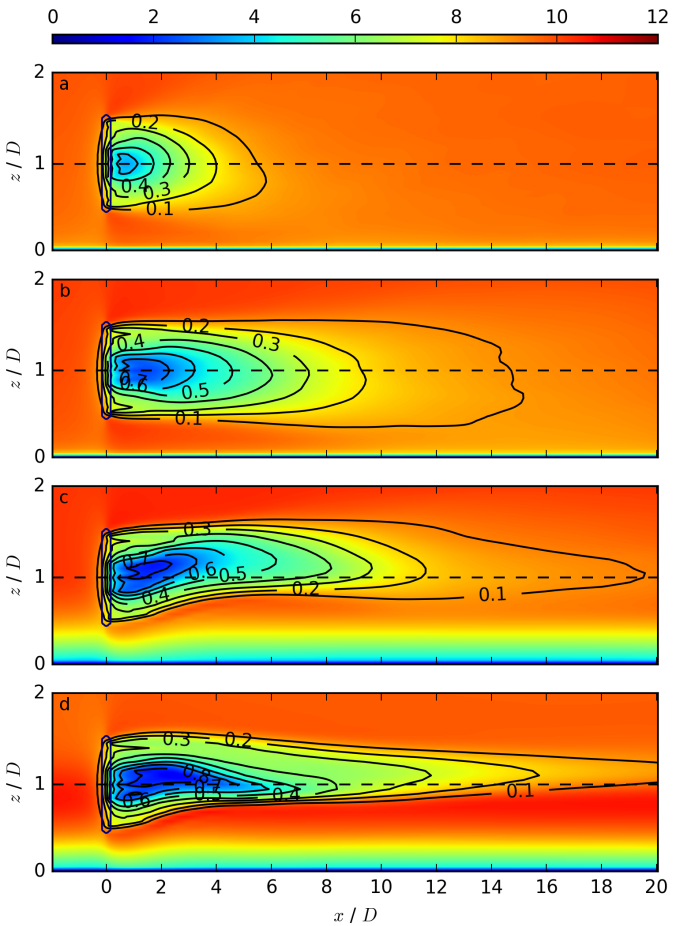
Wind-turbine simulations over homogeneous surface

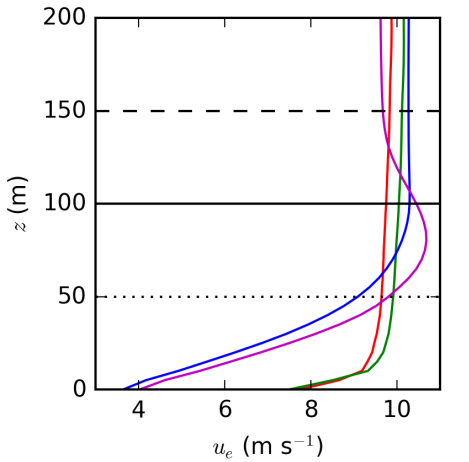
CBL

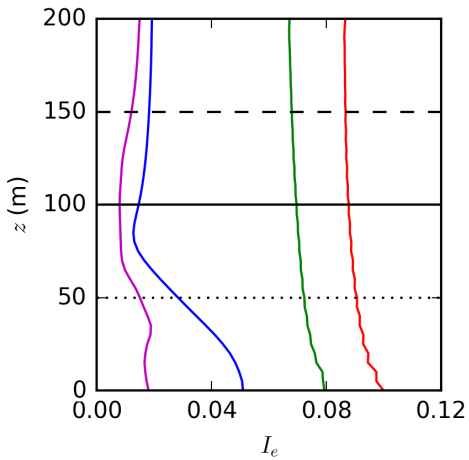
EBL

SBL

MBL







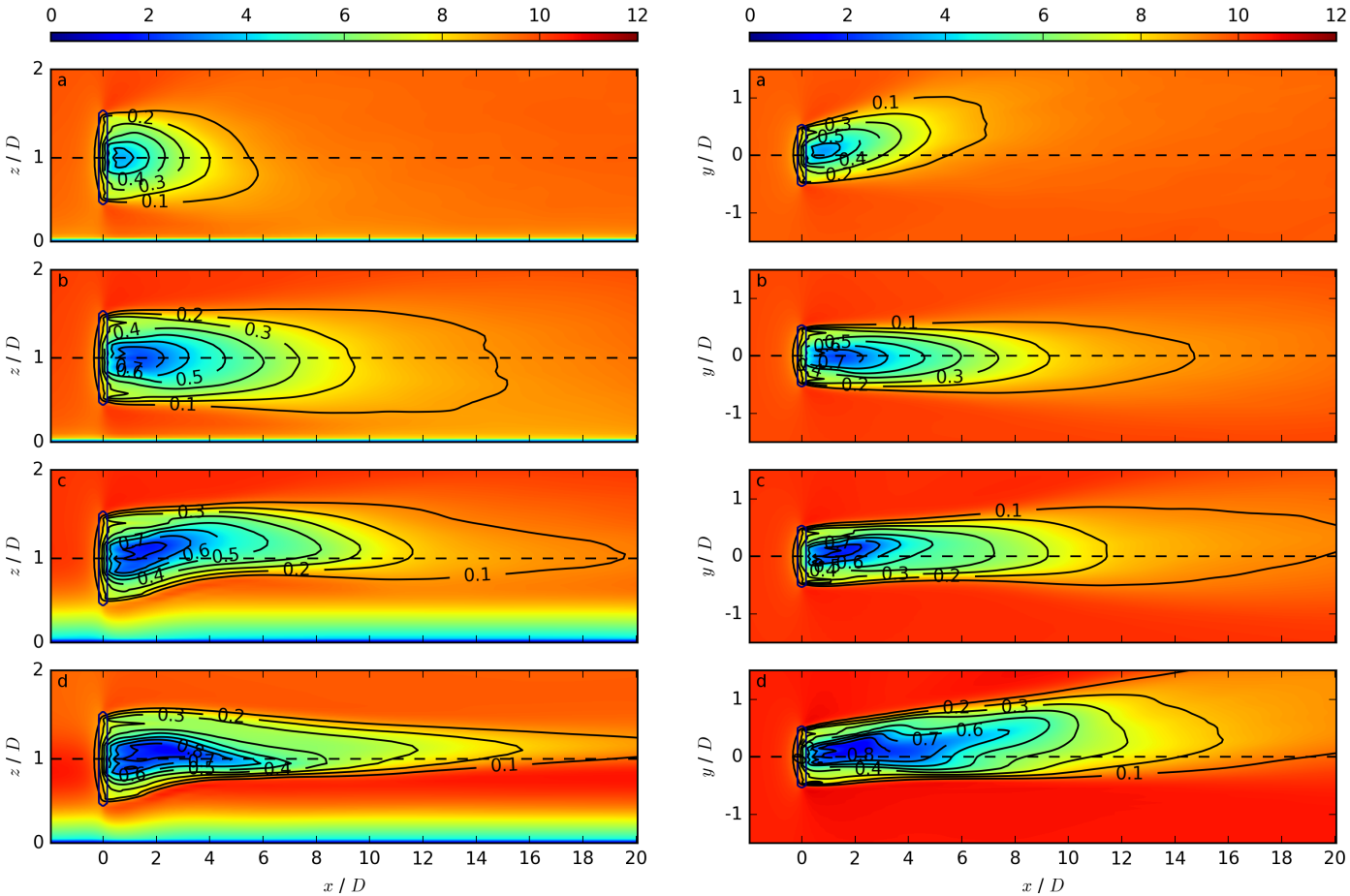
Wind-turbine simulations over homogeneous surface

CBL

EBL

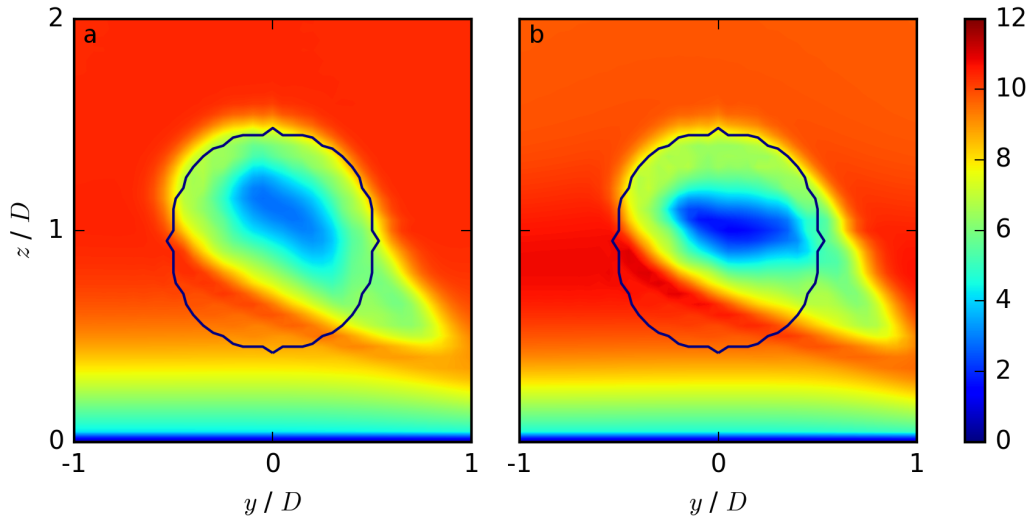
SBL

MBL

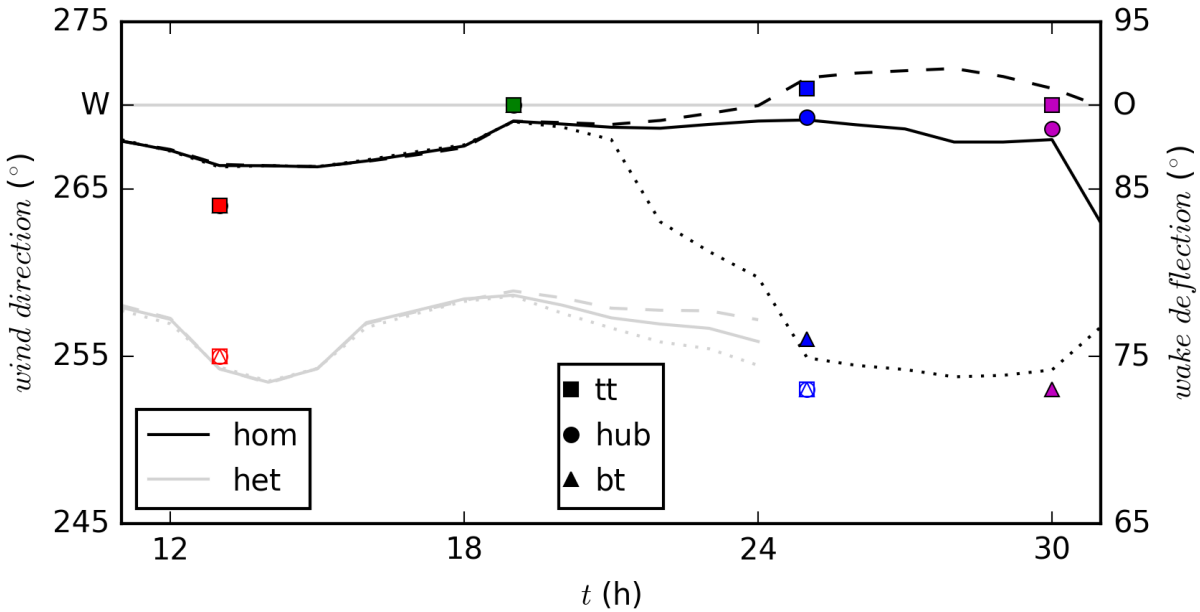


Wind-turbine simulations over homogeneous surface

SBL



MBL



WIND vertical wake structure

TURBULENCE streamwise wake extension

⇓

WIND & TURBULENCE

characterize the

ATMOSPHERE

both are important to investigate the wind-turbine wake response for different thermal stratifications

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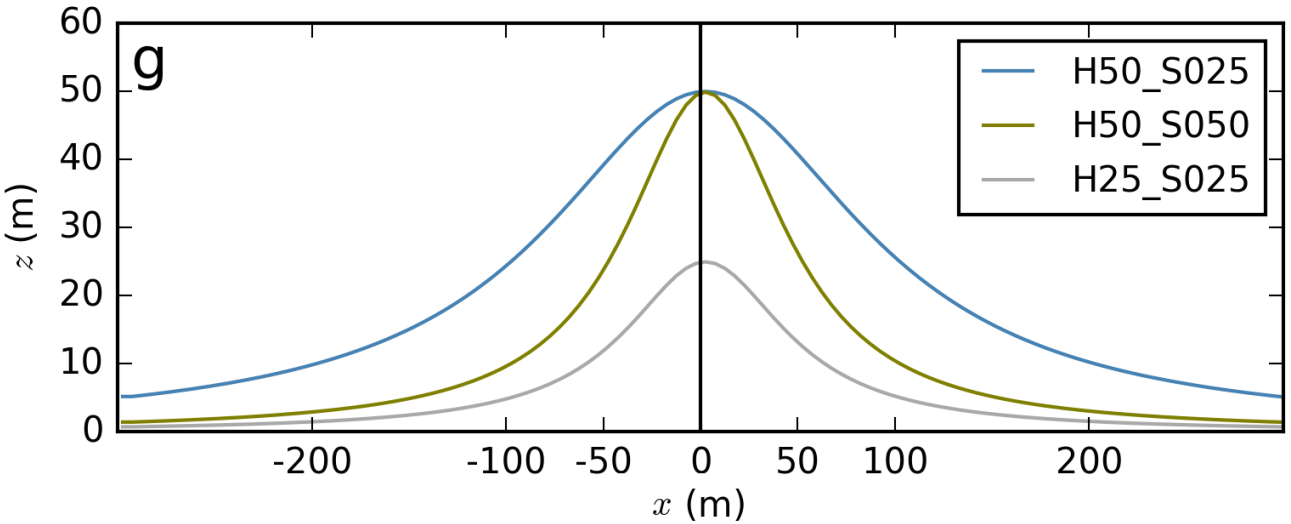
- terrain representation

  $\Rightarrow$ 3 D isolated hill ($H = 25$ - 50 m; $S = 0.25$ - 0.50)

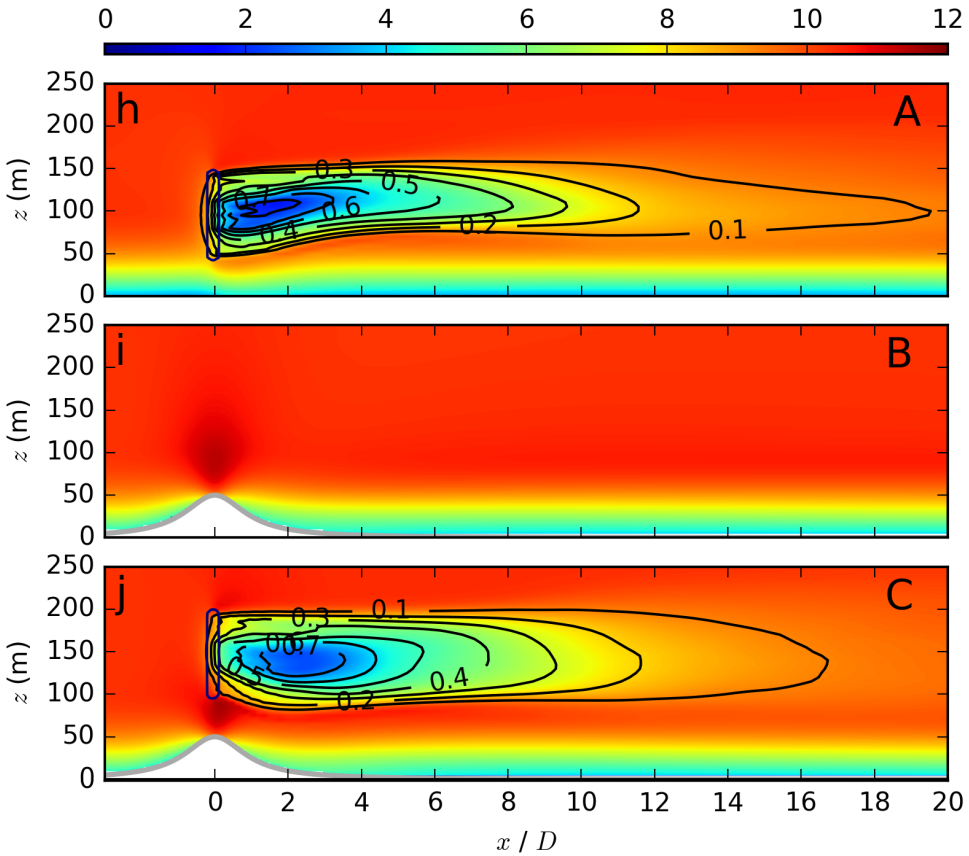


Performed simulations

Type A Stably stratified flow over a homogeneous surface with a wind turbine.

Type B Stably stratified flow over a 3 D hill without a wind turbine.

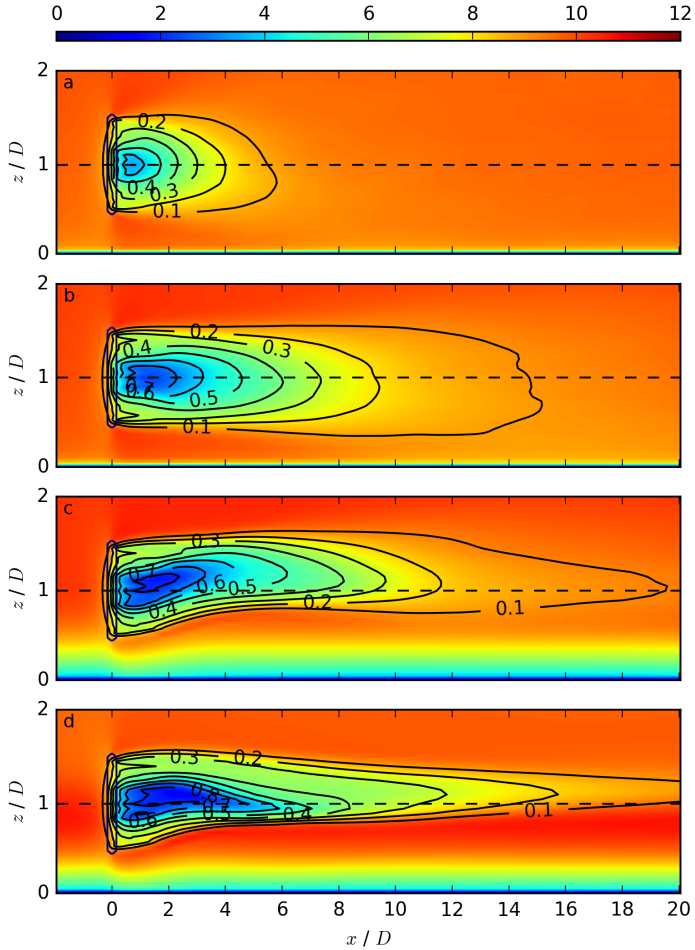
Type C Stably stratified flow over a 3 D hill with a wind turbine on its top.



3 D hill: ATMOSPHERE - Type A simulations

WIND & TURBULENCE

⇒ ATMOSPHERE



3 D hill: TERRAIN - Type B simulations

Froude number:

$$F_* = \frac{u_*}{NH}$$

$$F_H = \frac{\overline{u_H}}{NH}$$

$$F_L = \frac{\overline{u_H}}{NL}$$

	F_*	F_H	F_L
neutral	$>> 1$	$>> 1$	$>> 1$
weakly stable	≤ 1	$>> 1$	$>> 1$
moderately stable	$<< 1$	> 1	≤ 1
strongly stable	$<< 1$	≤ 1	$<< 1$

3 D hill: TERRAIN - Type B simulations

Froude number:

$$F_* = \frac{u_*}{NH}$$

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ABL	H / m	L / m	F_*	F_H	F_L
SBL	50	50	~ 0	3.8	3.8
SBL	50	100	~ 0	3.8	1.9
SBL	25	50	~ 0	6.1	3.1
MBL	50	50	~ 0	5.0	5.0
MBL	50	100	~ 0	5.0	2.5
MBL	25	50	~ 0	9.4	4.7
EBL	50	50	0.20	13.3	13.3
EBL	50	100	0.20	13.3	6.6
EBL	25	50	0.28	18.6	8.9

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weakly stably stratified

$\Downarrow$

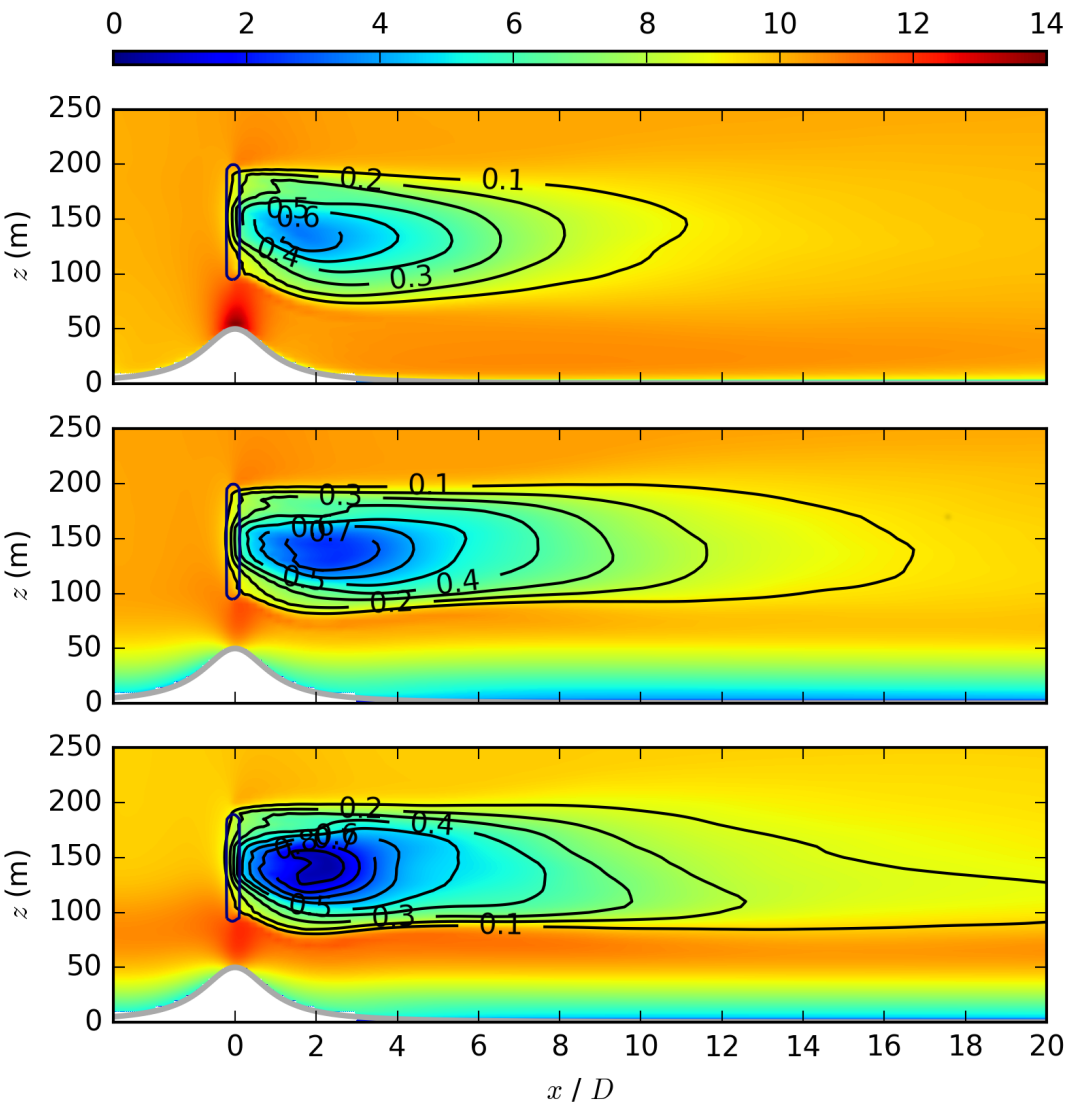
minor wake impact expected

3D hill: ATMOSPHERE & TERRAIN - Type C simulations

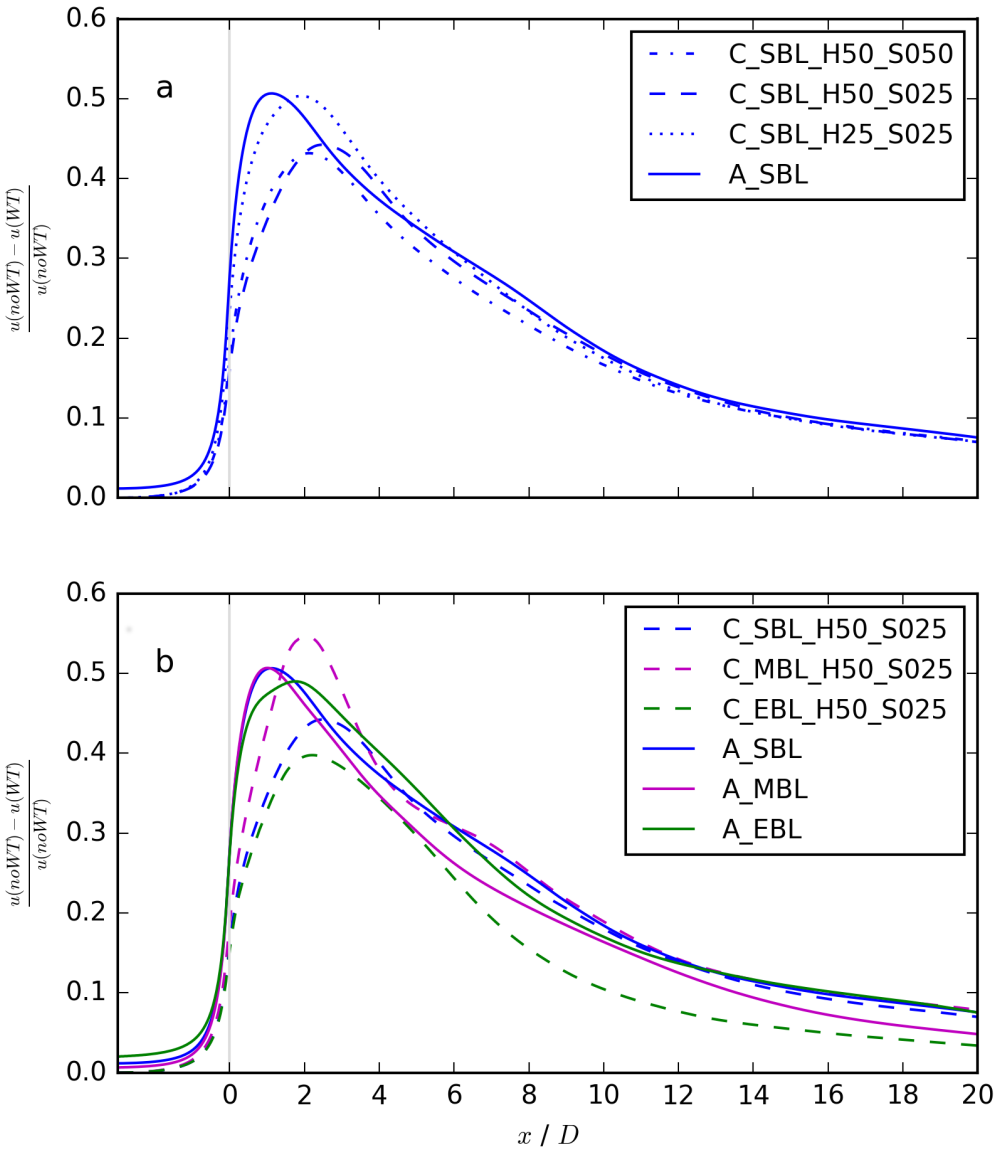
EBL

SBL

MBL



3D hill: Summary



TERRAIN

⇓

only near wake impact

ATMOSPHERE

⇓

near and far wake impact

3D hill: Conclusion

- classification only via dimensionless Froude number not applicable on its own for wind-turbine applications between 50 m and 150 m
- turbulent intensity of upstream wind field is essential

⇓

ATMOSPHERE & TERRAIN

both are important to investigate the wind-turbine wake response towards stably stratified flow over a hill

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Complex terrain: Wind-turbine simulation of Perdigão

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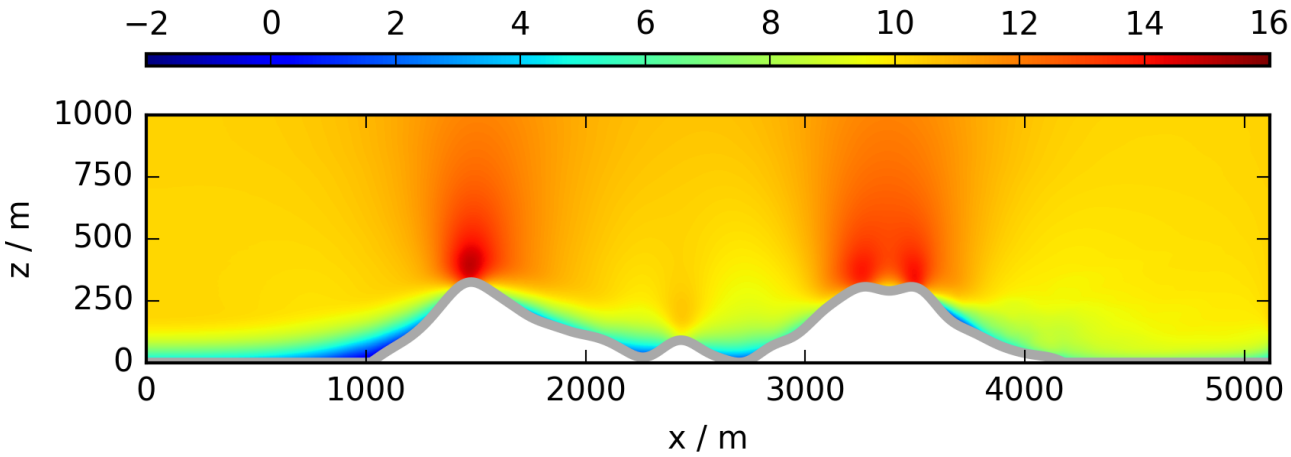

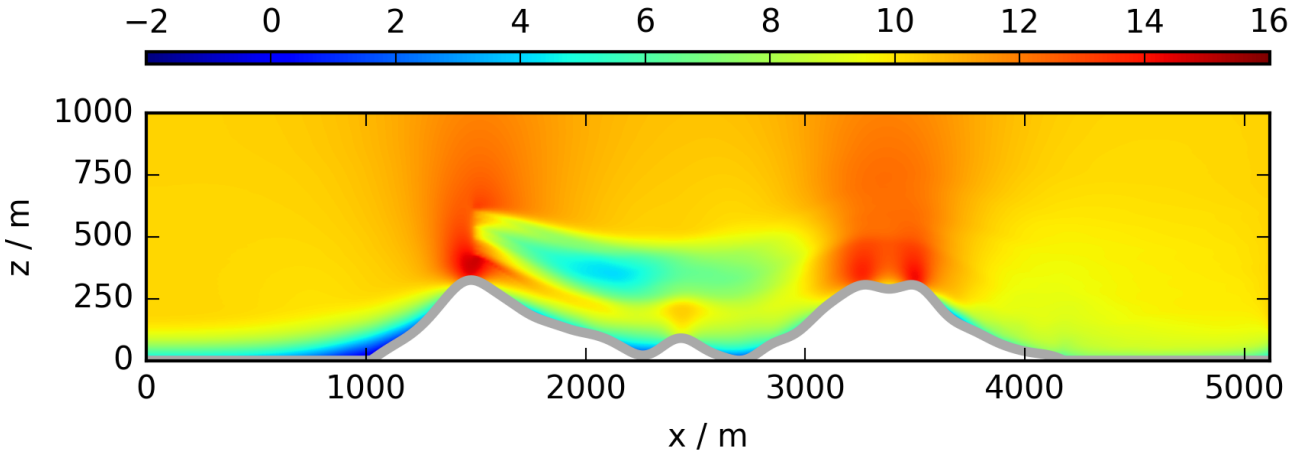

Complex terrain: Conclusion

realistic features:

- reversed flow
- speed up above hill
- much more structured wake due to more complex terrain

improvable:

- open spanwise boundary conditions
- 3 D dependence of background wind and turbulence fields

Final Conclusion

Turbulent inflow Diurnal cycle precursor simulation is necessary

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Homogeneous surface Wind and turbulence determine the wake characteristics

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Complex terrain Complexity of terrain significantly impacts the wake structure

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Thank you for your attention!

Englberger A, Dörnbrack A (2017) Impact of neutral boundary-layer turbulence on wind-turbine wakes: A numerical modelling study. Boundary-Layer Meteorol 162(3):427-449

Englberger A, Dörnbrack A (2018) Impact of the diurnal cycle of the atmospheric boundary layer on on wind-turbine wakes: A numerical modelling study. Boundary-Layer Meteorol pp 1-26

Englberger A, Dörnbrack A (2018) A numerically efficient parametrization of turbulent wind-turbine flows for LES of different thermal stratifications. Boundary-Layer Meteorol, ~~under review~~ Accepted

Englberger A, Dörnbrack A (2018) Wind-turbine wakes responding to stably stratified flow over complex terrain. J. Phys.: Conf. Series, ~~under review~~ Accepted