FLORIS: A Brief Tutorial

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5th Wind Energy Systems Engineering Workshop

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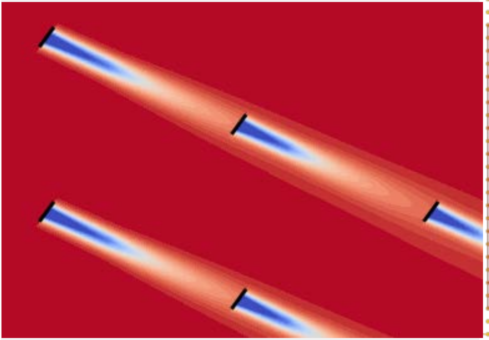
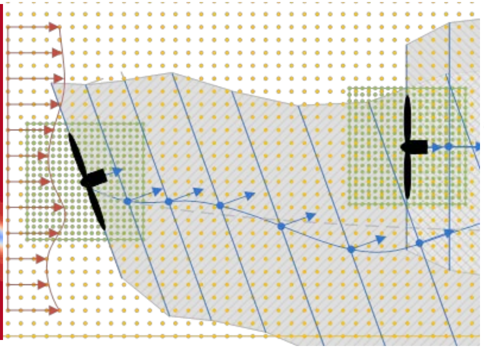
Modeling Tools at NREL

FLORIS



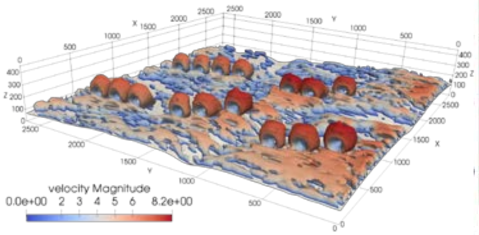
- Control-oriented model
- **Runs in fractions of seconds**
- Can be used to find optimal control settings and analyze across wind rose to estimate AEP

FAST.FARM



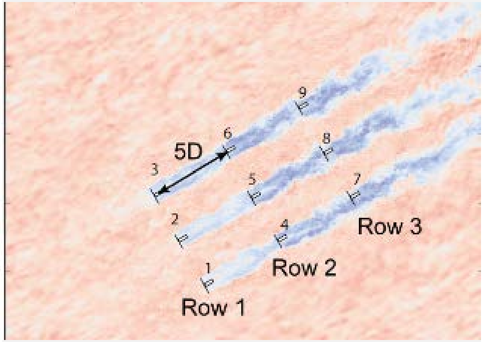
- New code which overlays DWM wakes
- Includes embedded FAST models of turbines
- **Runs on few cores**, near real time, allowing load suite analysis

WindSE



- Solves the steady/unsteady 2D/3D RANS equations
- Adjoints included for large-scale optimizations
- **Runs in serial or in parallel**, in minutes

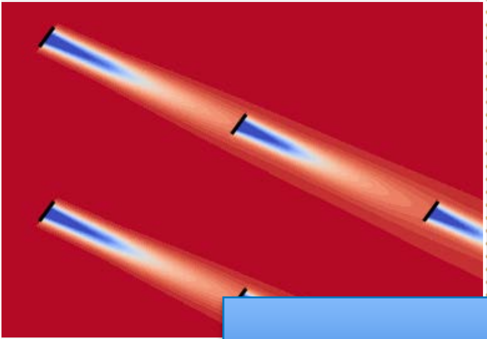
SOWFA



- Wind farm simulator based on large-eddy simulation
- Allows detailed investigation of wake physics, but **requires many cores and time to run simulations**

Modeling Tools at NREL

FLORIS



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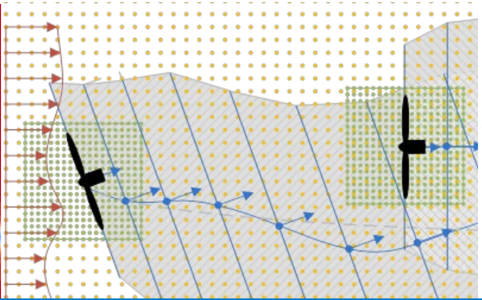
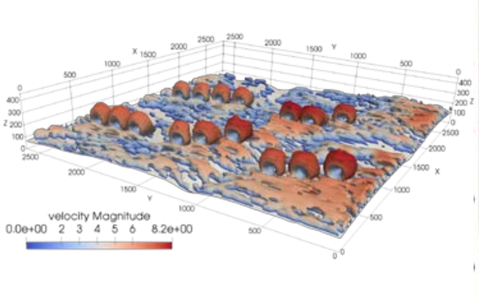


overlays DWM wakes

- Includes embedded FAST models of turbines
- **Runs on few cores**, near real time, allowing load suite analysis

WindSE



steady/unsteady 2D/3D RANS equations

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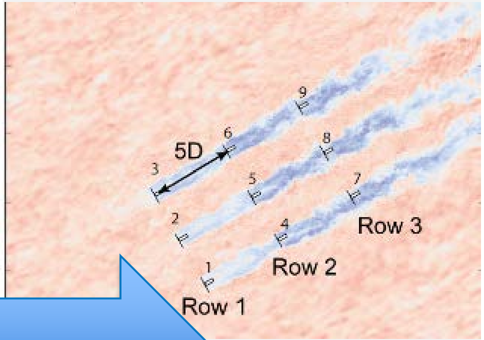
SOWFA



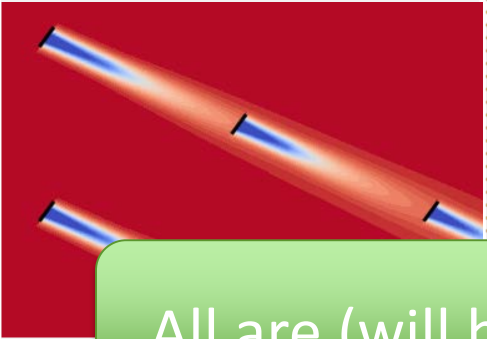
farm simulator based on large-eddy simulation

- Allows detailed investigation of wake physics, but **requires many cores and time to run simulations**

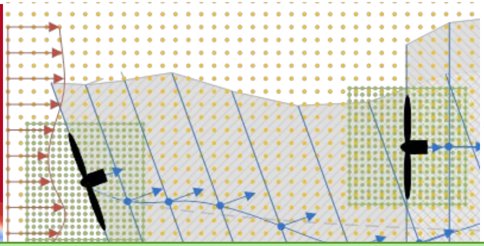
Increasing Flow Physics

Modeling Tools at NREL

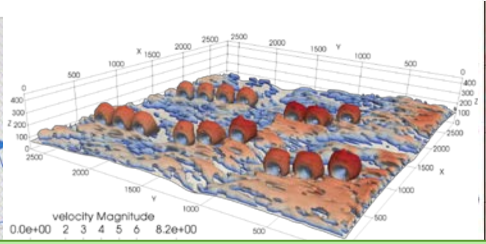
FLORIS



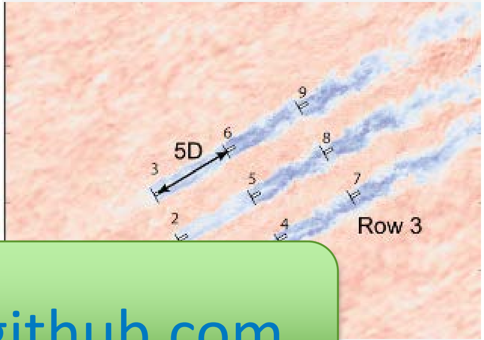
FAST.FARM



WindSE



SOWFA



All are (will be) available open source on www.github.com

- model
- **Runs in fractions of seconds**
- Can be used to find optimal control settings and analyze across wind rose to estimate AEP

- overlays DWM wakes
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- Allows detailed investigation of wake physics, but **requires many cores and time to run simulations**

FLORIS: Controls-oriented wind farm model

- Computationally inexpensive (<1s for 100 turbines)
- https://github.com/NREL/floris

Models

- Wake models
- ”Turbulence Models”
- Turbine models

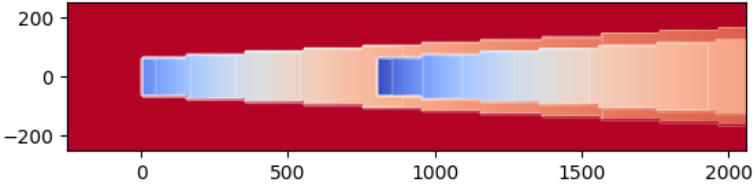
Tools

- Visualization
- Optimization
- Analysis

Wake Models

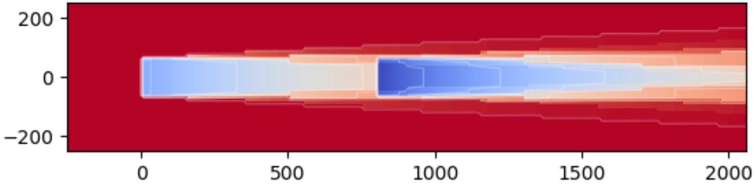
- Jensen (Park) Model – 0.0018 s

  Jensen, Niels Otto. *A note on wind generator interaction*. 1983.



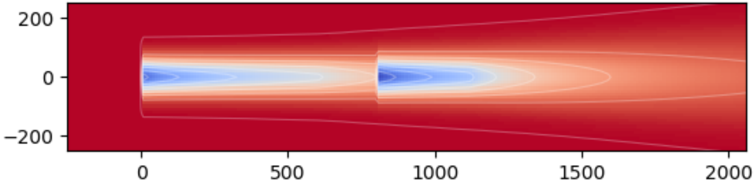
- Multi-zone wake model – 0.0019 s

  Gebraad, P. M. O., et al. Wind plant power optimization through yaw control using a parametric model for wake effects—a CFD simulation study. *2016.*



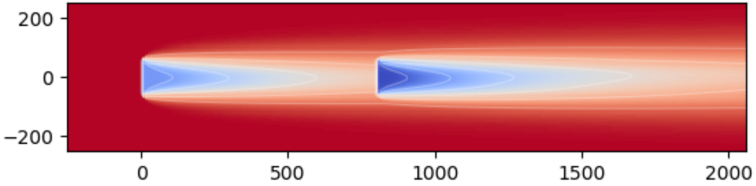
- Gaussian wake model – 0.0025 s

  Niayifar, A. and Porté-Agel, F.: A new analytical model for wind farm power prediction, 2015.
  Dilip, D. and Porté-Agel, F.: Wind Turbine Wake Mitigation through Blade Pitch Offset, 2017.
  Abkar, M. and Porté-Agel, F.: Influence of atmospheric stability on wind-turbine wakes: A large-eddy simulation study, 2015.
  Bastankhah, M. and Porté-Agel, F.: A new analytical model for wind-turbine wakes, 2014.
  Bastankhah, M. and Porté-Agel, 5 F.: Experimental and theoretical study of wind turbine wakes in yawed conditions, 2016.



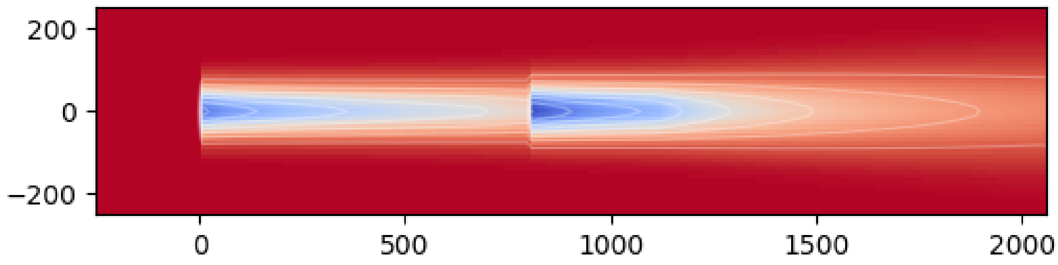
- Curl model – 1.6 s

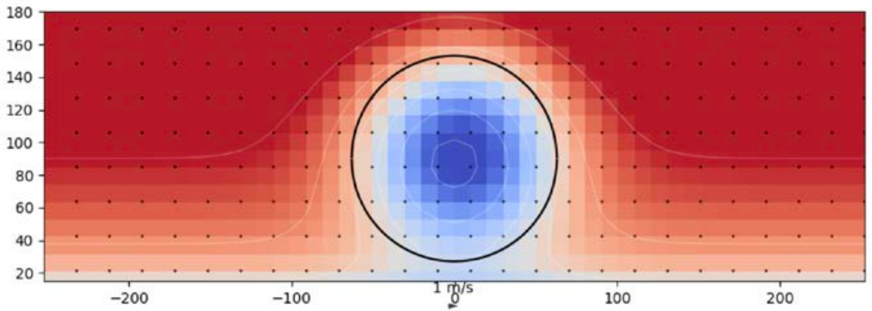
  Martínez-Tossas, L. A., Annoni, J., Fleming, P. A., and Churchfield, M. J.: The aerodynamics of the curled wake: a simplified model in view of flow control, 2019.



Wake Models - Gaussian

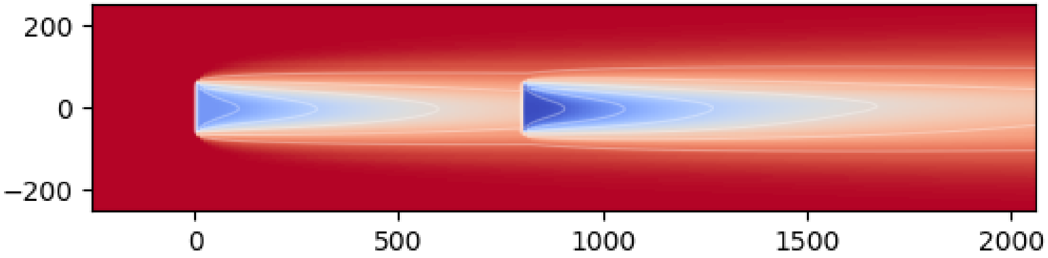
- Analytical solution to the simplified linearized Navier-Stokes equations
- Dependent on physical parameters that can be measured in the field
  - Ambient turbulence intensity
  - Shear
  - Veer
- Only 4 tuning parameters
- Good for normal turbine operation

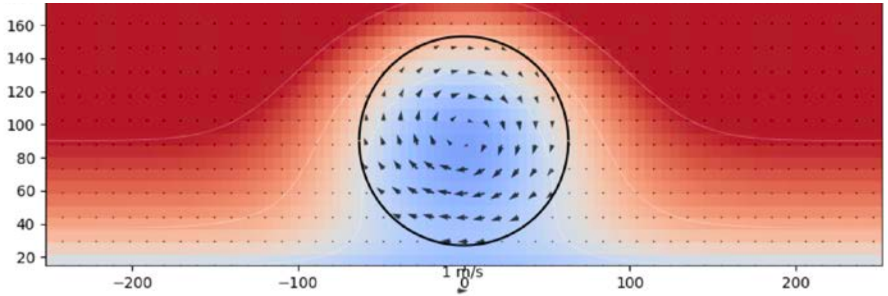




Wake Models - Curl

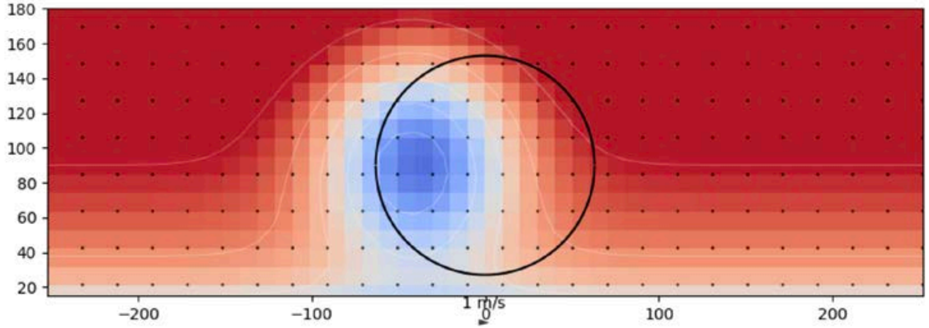
- Solves the linearized Navier-Stokes equations in time marching fashion
- Dependent on physical parameters that can be measured in the field
  - Ambient turbulence intensity
  - Shear
  - Veer
- Only 2 tuning parameters
- Good for wake steering analysis



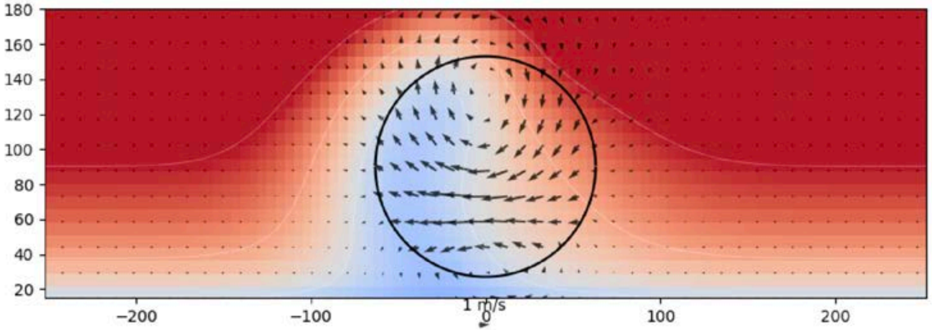


Deflection Models

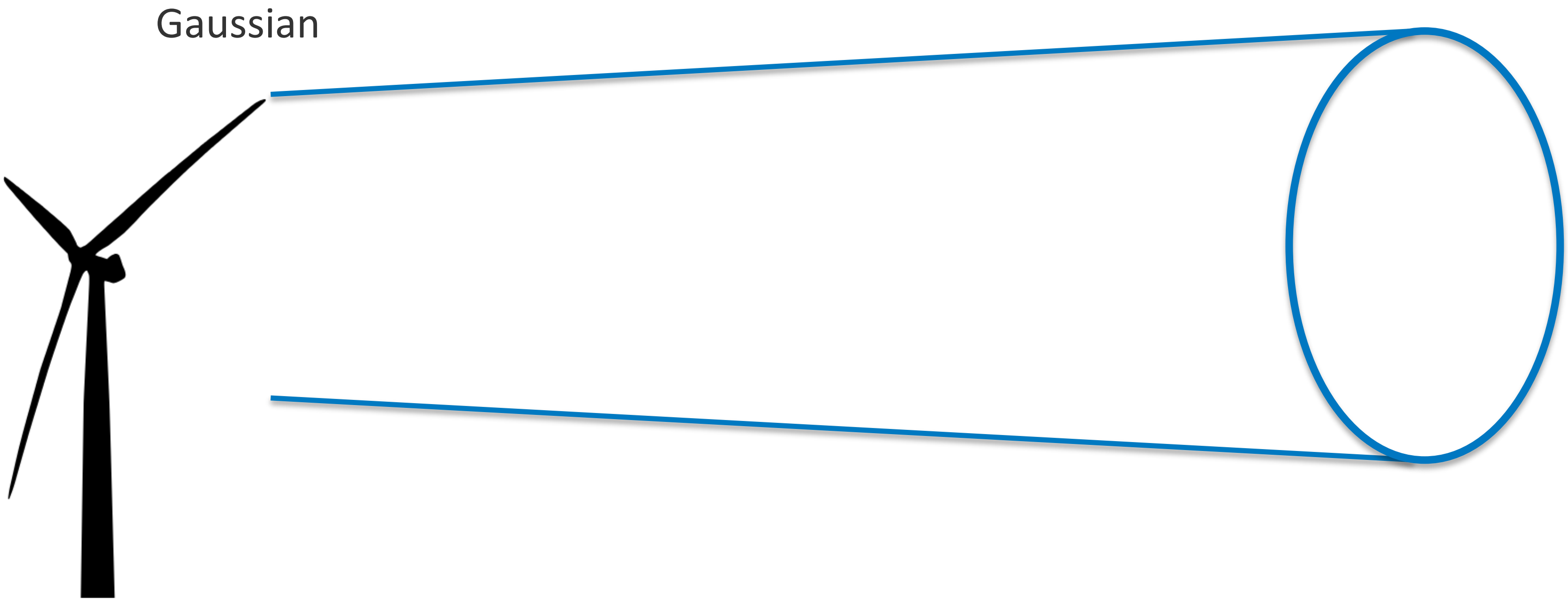
- Gaussian model deflection
  - Wake is offset from centerline



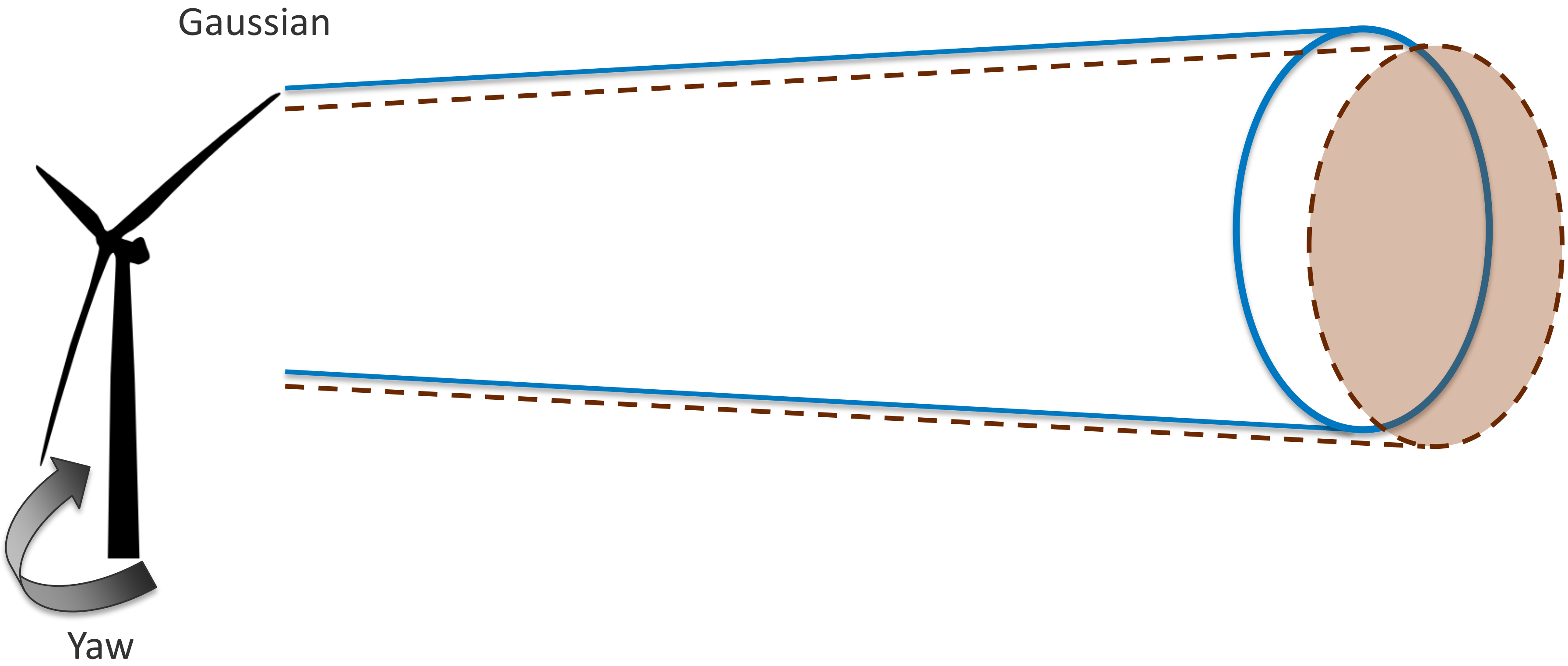
- Curl model deflection
  - Counter-rotating vortices
  - Wake rotation
  - Secondary steering



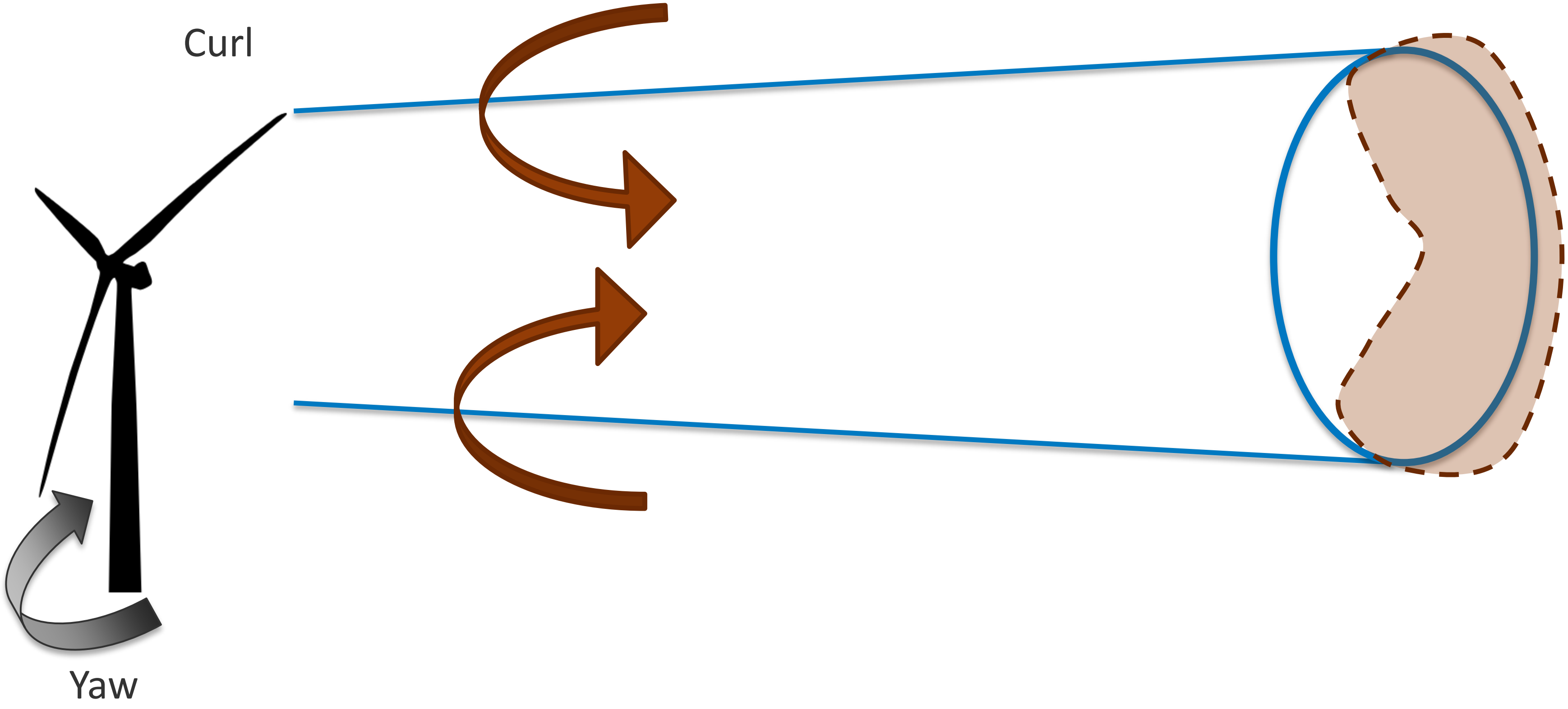
Gaussian Model



Gaussian Model



Aerodynamics of Wake Steering



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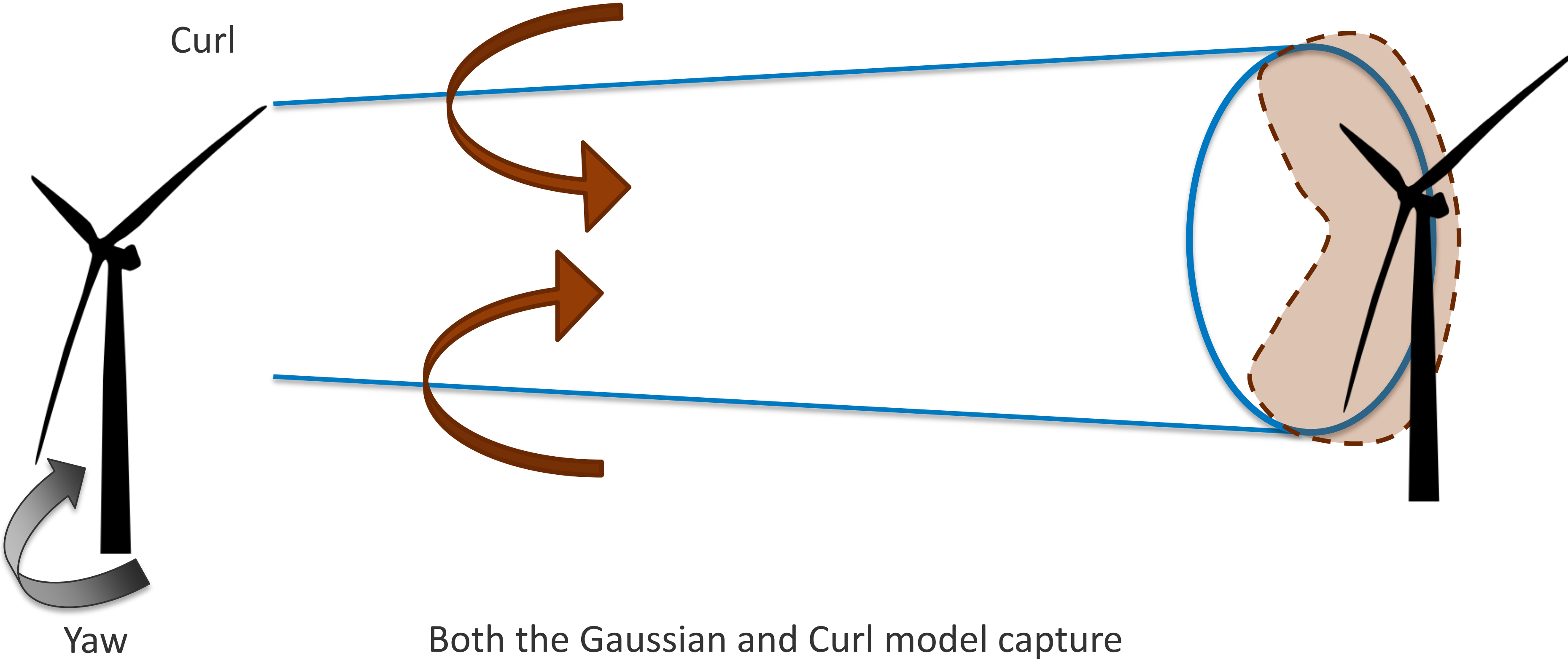
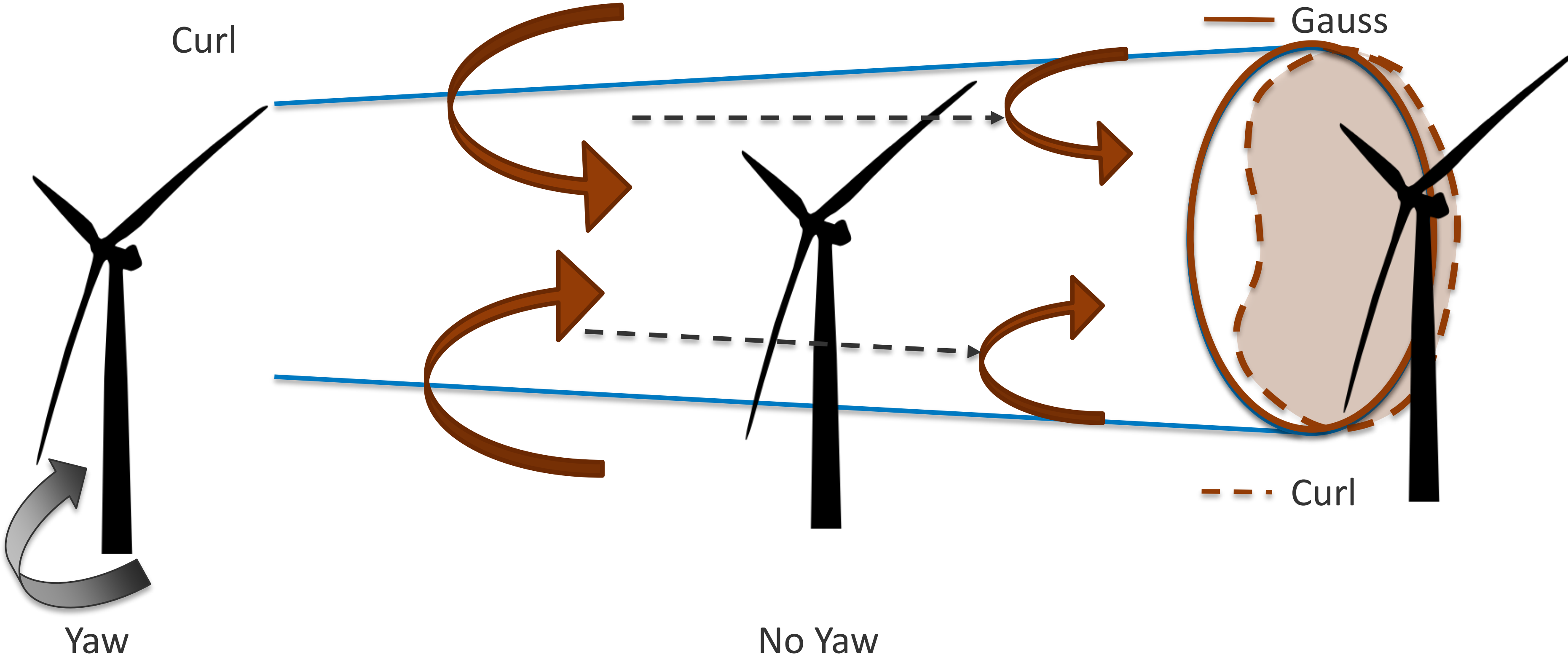


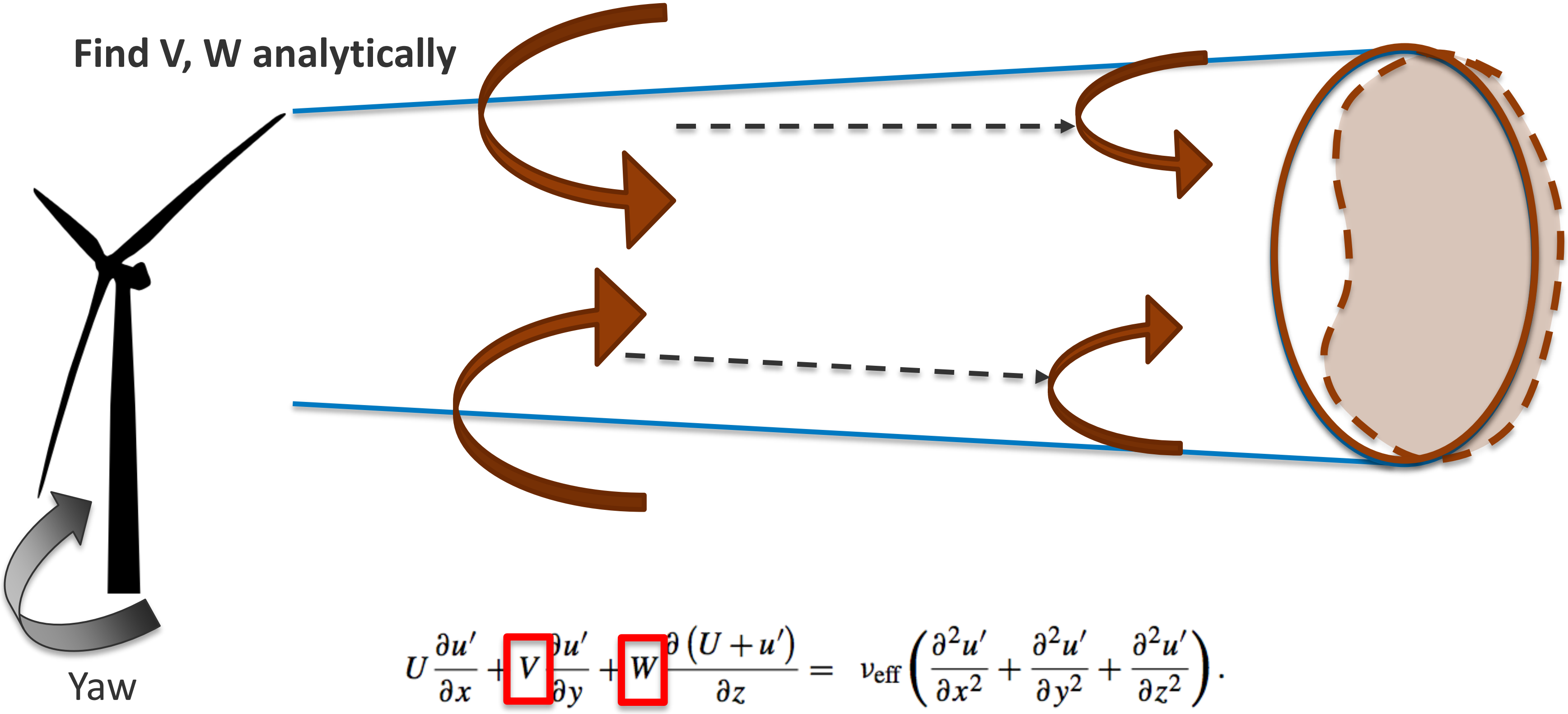
Both the Gaussian and Curl model capture
2 turbine effects very well

Aerodynamics of Wake Steering



Overview of the Curl Model

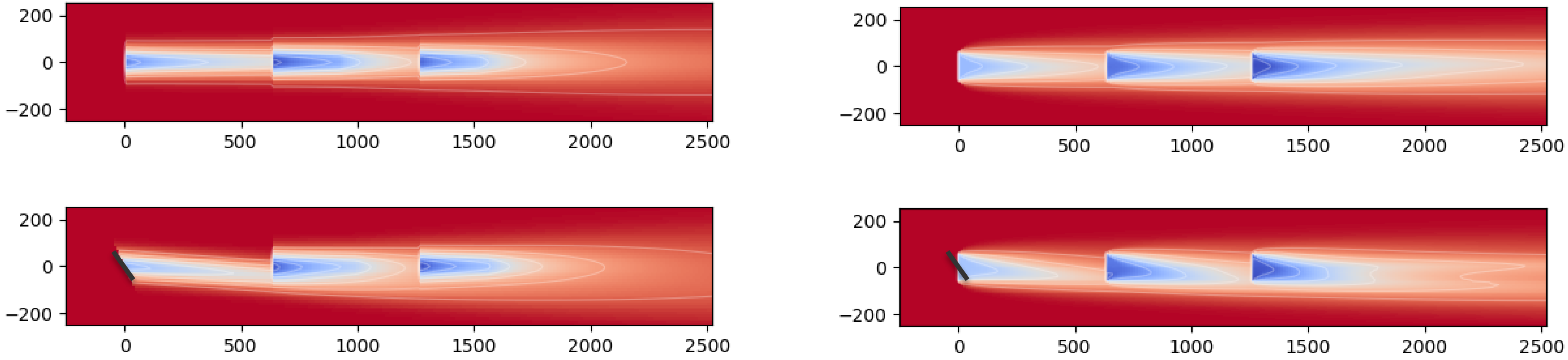
Find V, W analytically



$$U\frac{\partial u'}{\partial x}+\boxed{V}\frac{\partial u'}{\partial y}+\boxed{W}\frac{\partial (U+u')}{\partial z}=\nu_{\mathrm{eff}}\left(\frac{\partial^2 u'}{\partial x^2}+\frac{\partial^2 u'}{\partial y^2}+\frac{\partial^2 u'}{\partial z^2}\right).$$

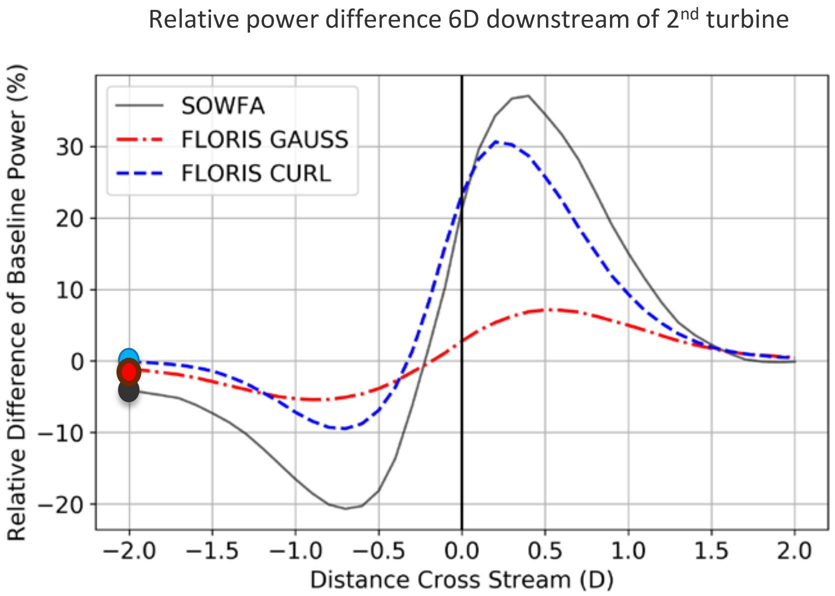
Martínez-Tossas, L. A., Annoni, J., Fleming, P. A., and Churchfield, M. J.: The aerodynamics of the curled wake: a simplified model in view of flow control, Wind Energ. Sci., 4, 127-138, https://doi.org/10.5194/wes-4-127-2019, 2019.

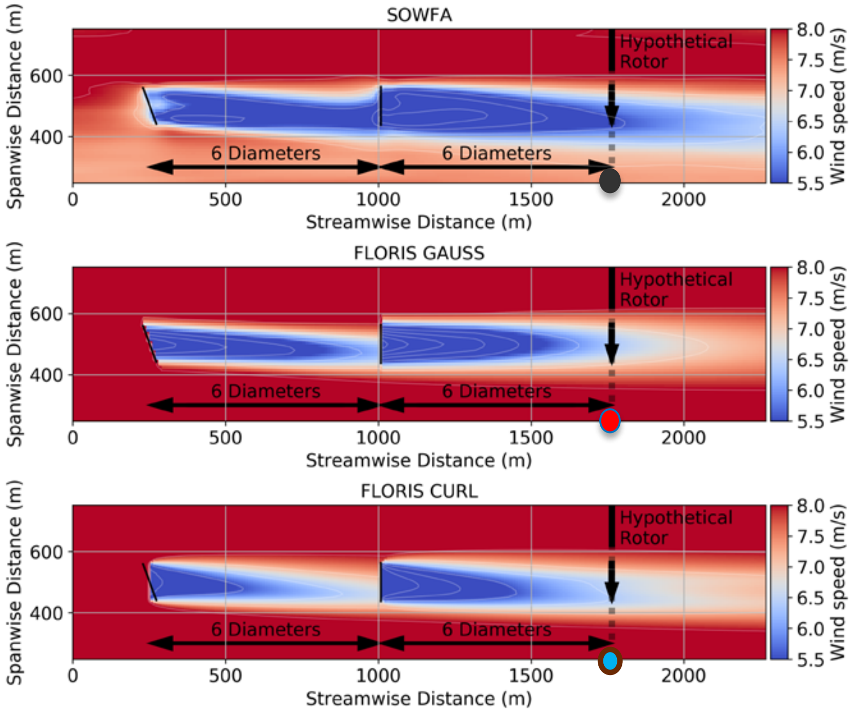
Secondary Steering



Turbines can work together to help build larger vortex-structures, developing flow control strategies throughout the farm

Compare Wake Steering



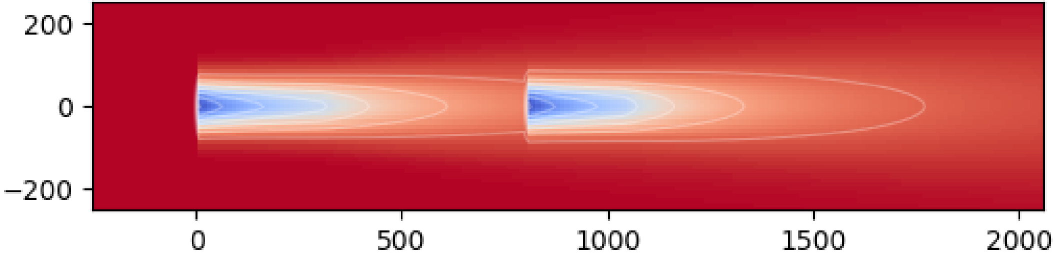


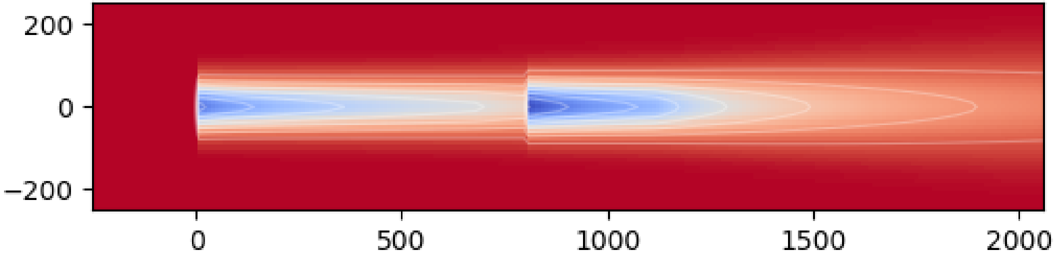
“Turbulence” Models

- **Wake expansion** dependent on ambient turbulence intensity

- **Added turbulence** due to turbine operation
    - As Ct increases, wake expansion increases

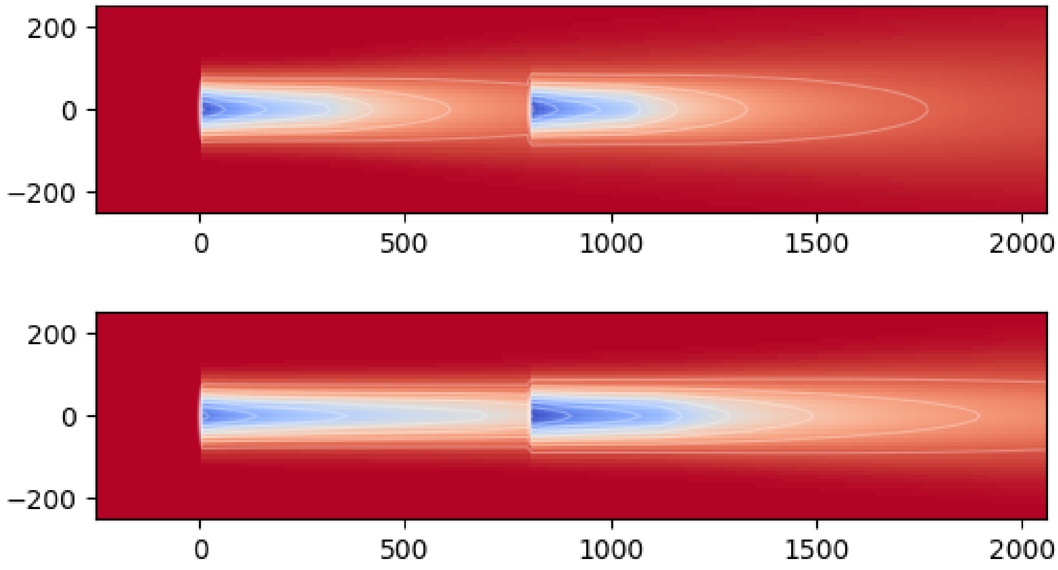
- Very important for investigating **deep array effects** (ongoing work)





Turbine Model - Cp/Ct Tables

- Turbine represented as **Actuator Disks**
- Generate **Cp/Ct tables** by:
  - *FAST* – Aeroelastic code
  - *CCBlade* – steady/state BEM coupled to FLORIS



Code Examples

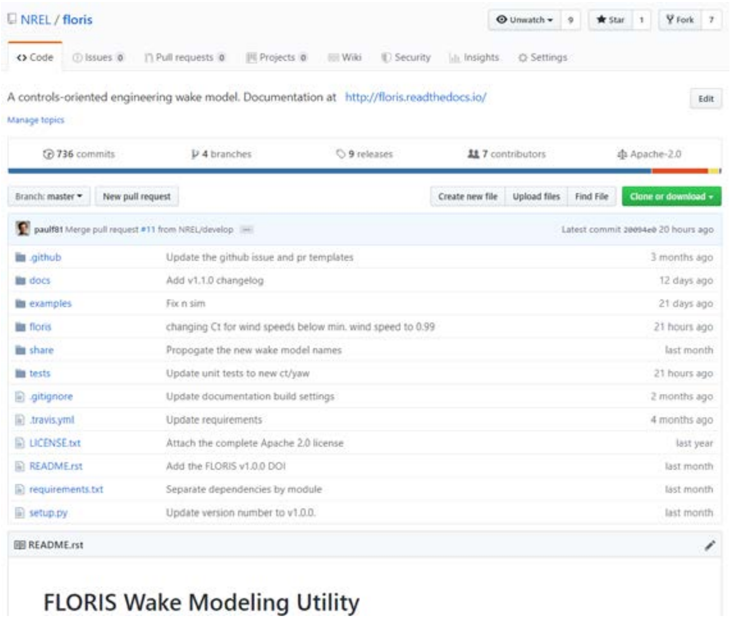
FLORIS: Open-source and Collaborative

Available at: https://github.com/NREL/floris

Divided into two packages:

- simulation:
  - Contains code for FLORIS models
- tools:
  - Modules for interacting with FLORIS models and data

Documentation and examples available at: https://floris.readthedocs.io/en/develop/index.html



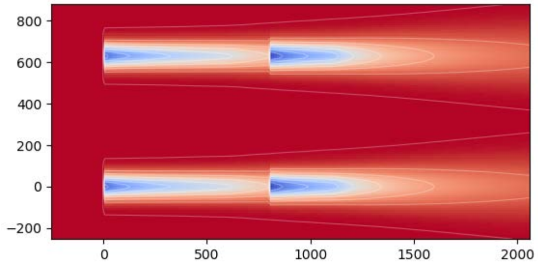
Example 0000: Open and Visualize FLORIS

Tools module allows for easy and intuitive interaction with FLORIS models.

All in python using open-source python modules.

- Line 15: import the FLORIS tools module
- Line 18: create FLORIS interface
- Line 21: calculate the wake
- Line 24: capture a horizontal cut-plane of the flow
- Line 31: use visualization module plot horizontal cut-plane

```
14  import matplotlib.pyplot as plt
15  import floris.tools as wfct
16
17  # Initialize the FLORIS interface fi
18  fi = wfct.floris_utilities.FlorisInterface("example_input.json")
19
20  # Calculate wake
21  fi.calculate_wake()
22
23  # Initialize the horizontal cut
24  hor_plane = wfct.cut_plane.HorPlane(
25      fi.get_flow_data(),
26      fi.floris.farm.turbines[0].hub_height
27  )
28
29  # Plot and show
30  fig, ax = plt.subplots()
31  wfct.visualization.visualize_cut_plane(hor_plane, ax=ax)
32  plt.show()
```



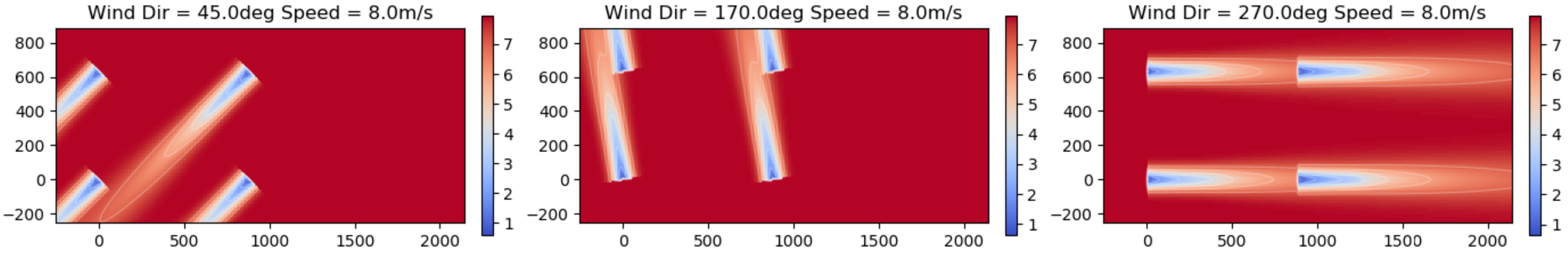
Example 0005: Changing Locations/Wind Direction

Programmatically change turbine and environmental parameters without re-loading the input file.

- Line 28: change turbine layout
- Line 63: change wind speed and direction

```
24    # set turbine locations to 4 turbines in a row - demonstrate how to change coordinates
25    D = fi.floris.farm.flow_field.turbine_map.turbines[0].rotor_diameter
26    layout_x = [0, 7*D, 0, 7*D]
27    layout_y = [0, 0, 5*D, 5*D]
28    fi.reinitialize_flow_field(layout_array=(layout_x, layout_y))
```

```
52    ws = np.linspace(6, 8, 3)
53    wd = [45.0, 170.0, 270.]
54
55    # Plot and show
56    fig, ax = plt.subplots(3, 3, figsize=(15, 15))
57    power = np.zeros((len(ws), len(wd)))
58    for i, speed in enumerate(ws):
59        for j, wdir in enumerate(wd):
60            print('Calculating wake: wind direction = ',
61                  wdir, 'and wind speed = ', speed)
62
63            fi.reinitialize_flow_field(wind_speed=speed, wind_direction=wdir)
```



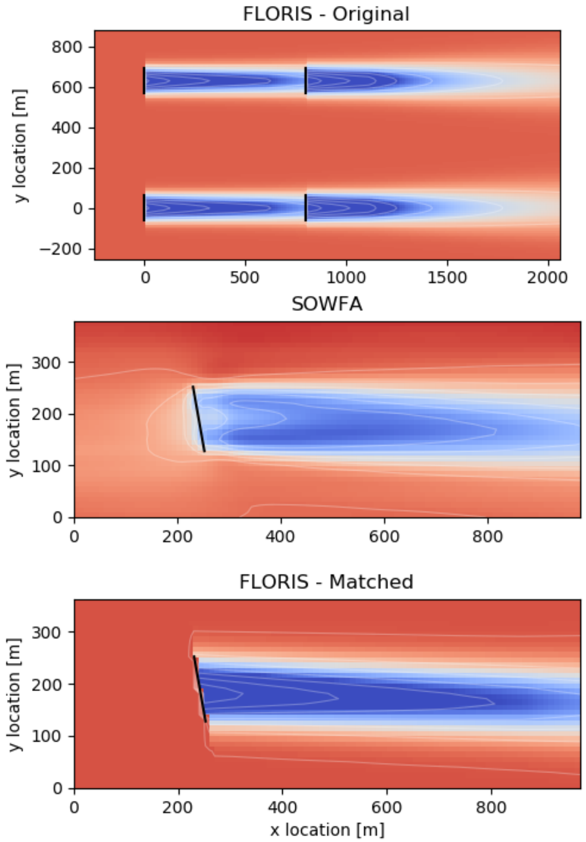
Example 0015: Compare with SOWFA

Module to load and interact with SOWFA data for analysis and comparison

- Line 27: use SOWFA interface to load SOWFA data
- Lines 55 & 61: set the relevant FLORIS model parameters to be equal to the SOWFA conditions

```
26  # Load the SOWFA case in
27  si = wfct.sowfa_utilities.SowfaInterface('sowfa_example')
```

```
54  # Set the relevant FLORIS parameters to equal the SOWFA case
55  fi.reinitialize_flow_field(wind_speed=si.precursor_wind_speed,
56                             wind_direction=si.precursor_wind_dir,
57                             layout_array=(si.layout_x, si.layout_y)
58                             )
59
60  # Set the yaw angles
61  fi.calculate_wake(yaw_angles=si.yaw_angles)
```



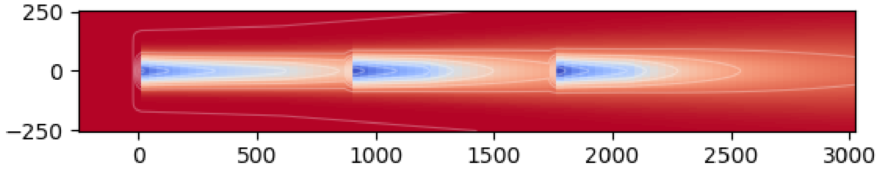
Example 0010: Optimization

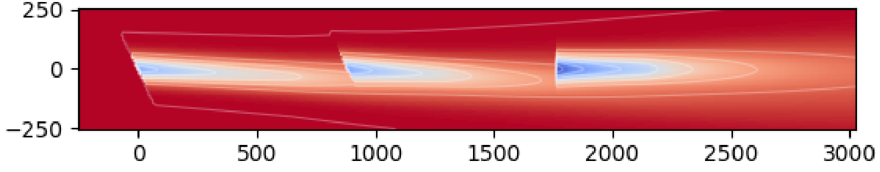
Perform yaw optimizations to investigate wake steering power gains.

- Line 59: create optimization object with min. and max. yaw angles
- Line 64: perform yaw optimization

```
54  # Set bounds for allowable wake steering
55  min_yaw = 0.0
56  max_yaw = 25.0
57
58  # Instantiate the Optimization object
59  yaw_opt = YawOptimizationOneWD(fi,
60                                 minimum_yaw_angle=min_yaw,
61                                 maximum_yaw_angle=max_yaw)
62
63  # Perform optimization
64  yaw_angles = yaw_opt.optimize()
```

```
=====================================================
Optimizing wake redirection control...
Number of parameters to optimize =  3
=====================================================
yaw angles =
Turbine  0 = 24.892413743776544  deg
Turbine  1 = 24.77131815924147  deg
Turbine  2 = 1.8695304301172757e-05  deg
=========================================
Total Power Gain = 8.2%
=========================================
```





Ongoing Developments of FLORIS

- Incorporate **local effects** (currently: one wind speed/direction)
- **Deep-array effects** through better turbulence modeling
- Blade/Rotor **loads** calculations – using CCBlade from WISDEM
- Analytic **gradients** for large-scale optimizations (many turbines)
- Combinations of **optimizations –** Layout/Yaw/Thrust/Loads
- **FLORIS is a living code** – please let us know any suggestions on how we can address critical research questions in FLORIS to benefit the wind energy community.