

# WindSim尾流模型及湍 流模型的对比分析

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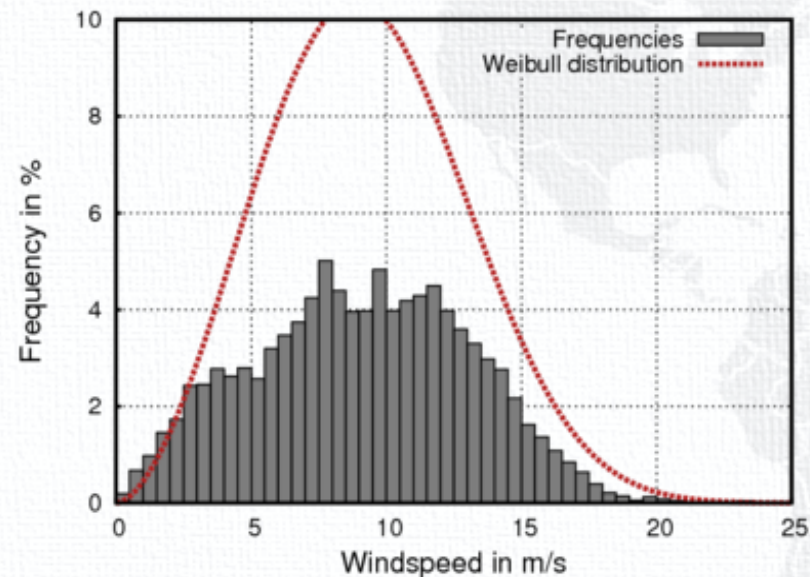
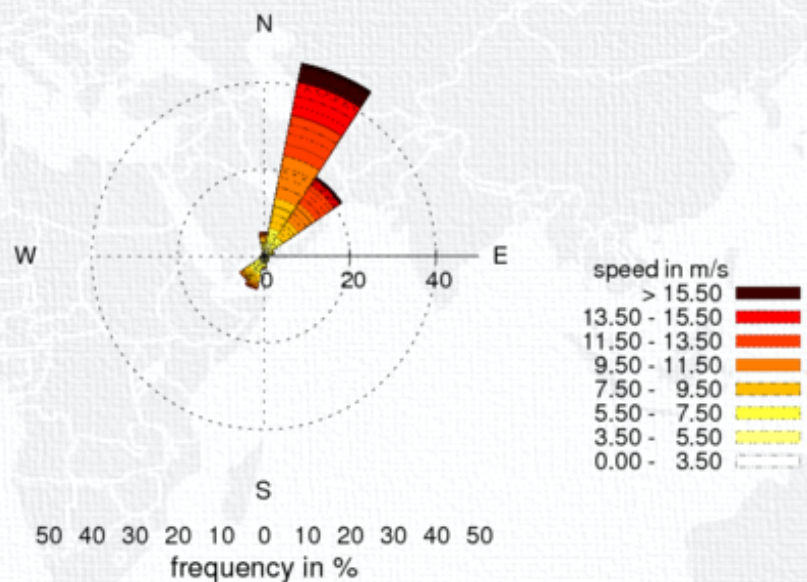
## 目录:

- 一、WindSim尾流模型对比
- 二、WindSim湍流模型对比
- 三、结论与探讨

# 一、WindSim尾流模型对比

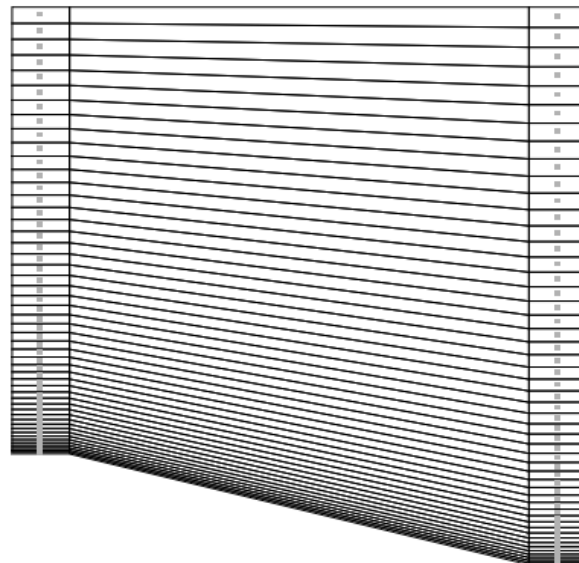
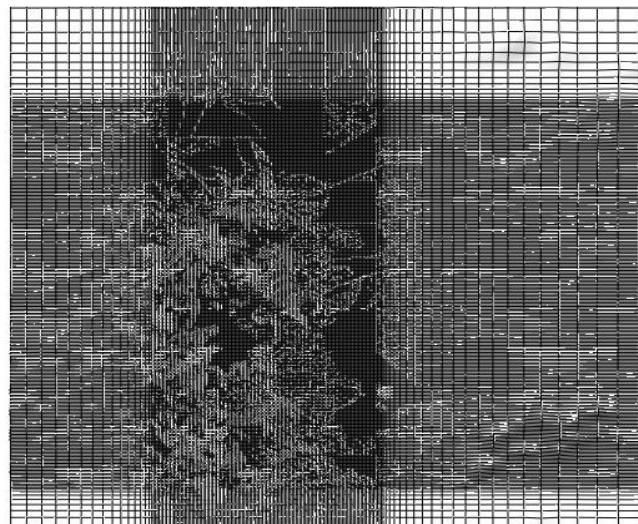
## 1.项目简介

其它条件相同，仅采用不同的尾流模型，在某近海区域内探讨尾流模型与年发电量和尾流损耗的影响关系。



80m高度处，测风塔在一年内测量结果的平均风速是9.1m/s。

## 2.WindSim计算设置

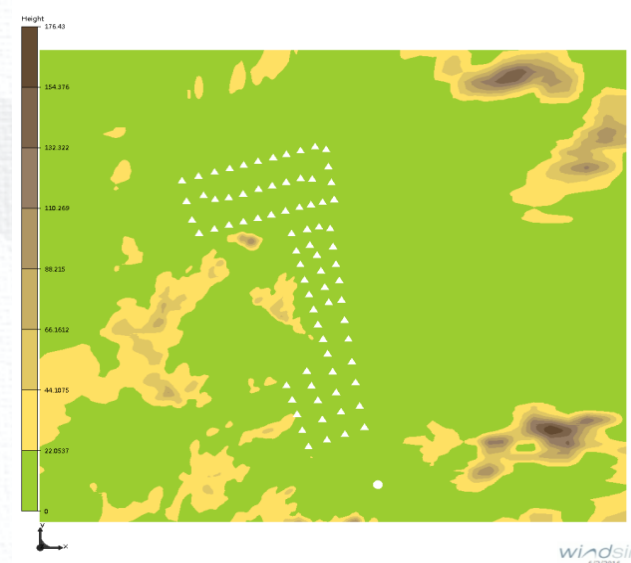


网格划分

|                  | Easting    | Northing   | z        | Total   |
|------------------|------------|------------|----------|---------|
| Grid spacing (m) | 73.2-855.9 | 73.0-543.0 | Variable | -       |
| Number of cells  | 161        | 247        | 50       | 1988350 |

|                 | 1   | 2   | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10   |
|-----------------|-----|-----|------|------|------|------|------|------|------|------|
| z-dist. max (m) | 1.5 | 4.6 | 8.3  | 12.6 | 17.4 | 22.7 | 28.5 | 34.9 | 41.8 | 49.3 |
| z-dist. min (m) | 1.8 | 5.8 | 10.4 | 15.7 | 21.7 | 28.3 | 35.6 | 43.6 | 52.2 | 61.5 |

保证流场计算条件设定不变，仅改变尾流模型，采用76台海装H127-5.0MW机组进行计算。



风机和测风塔位置

|                                  |           |
|----------------------------------|-----------|
| Height of boundary layer (m)     | 500.0     |
| Speed above boundary layer (m/s) | 10.0      |
| Boundary condition at the top    | fix pres. |
| Potential temperature            | No        |
| Turbulence model                 | Standard  |
| Solver                           | GCV       |
| Maximum iterations               | 2000      |

### 3.结果对比

#### Wake model 1

| Turbine Type | Hub Height (m) | No. of turbines | Capacity (MW) | Gross AEP (GWh/y) | Average wind speed (m/s) | Wake losses (%) | AEP with wake losses (GWh/y) | Full load hours (hours) | Capacity factor(%) |
|--------------|----------------|-----------------|---------------|-------------------|--------------------------|-----------------|------------------------------|-------------------------|--------------------|
| H127-5.0MW   | 85.0           | 76              | 380.0         | 1751.9            | 9.3                      | 5.1             | 1663.2                       | 4376.7                  | 50.0               |

#### Wake model 2

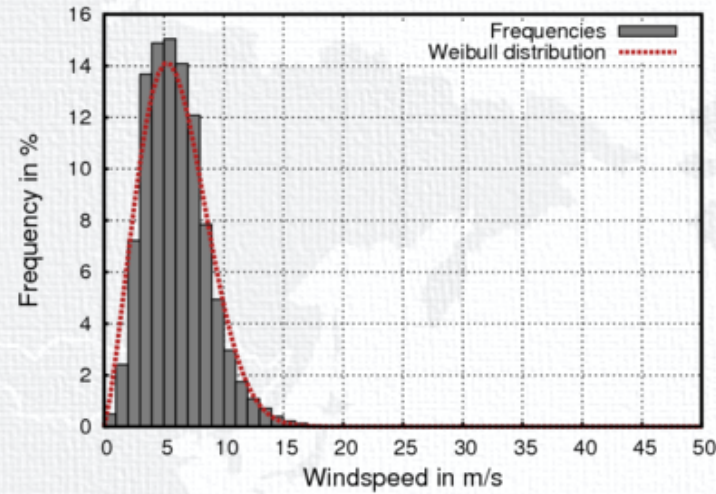
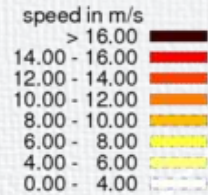
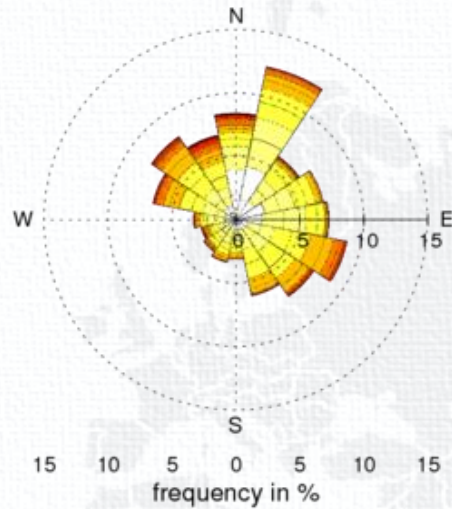
| Turbine Type | Hub Height (m) | No. of turbines | Capacity (MW) | Gross AEP (GWh/y) | Average wind speed (m/s) | Wake losses (%) | AEP with wake losses (GWh/y) | Full load hours (hours) | Capacity factor(%) |
|--------------|----------------|-----------------|---------------|-------------------|--------------------------|-----------------|------------------------------|-------------------------|--------------------|
| H127-5.0MW   | 85.0           | 76              | 380.0         | 1751.9            | 9.3                      | 3.5             | 1690.9                       | 4449.7                  | 50.8               |

#### Wake model 3

| Turbine Type | Hub Height (m) | No. of turbines | Capacity (MW) | Gross AEP (GWh/y) | Average wind speed (m/s) | Wake losses (%) | AEP with wake losses (GWh/y) | Full load hours (hours) | Capacity factor(%) |
|--------------|----------------|-----------------|---------------|-------------------|--------------------------|-----------------|------------------------------|-------------------------|--------------------|
| H127-5.0MW   | 85.0           | 76              | 380.0         | 1751.9            | 9.3                      | 5.5             | 1655.9                       | 4357.5                  | 49.7               |

通过基于相同流场计算结果的年发电量对比，可以看出，相对而言，WindSim软件中尾流模型3算得的风场整体年发电量损耗最大，尾流模型1的结果与之相近，略有偏小，尾流模型2算得的损耗最小；满载小时数等计算结果随尾流损耗计算的不同而负相关浮动。

# 4.不同项目的计算结果比较

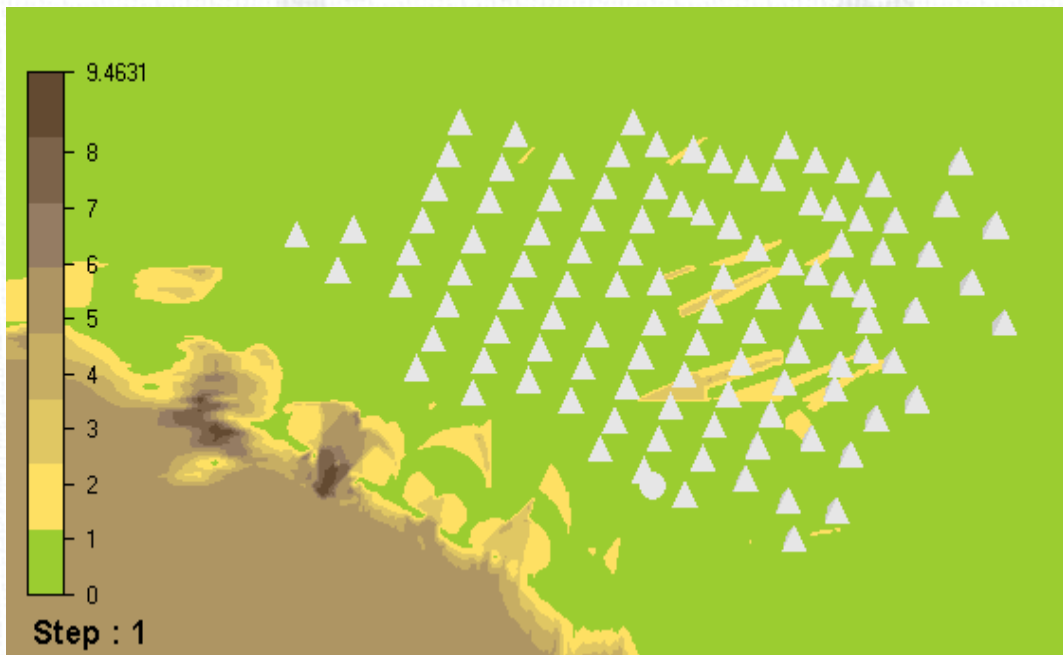


|                                  |           |
|----------------------------------|-----------|
| Height of boundary layer (m)     | 500.0     |
| Speed above boundary layer (m/s) | 10.0      |
| Boundary condition at the top    | fix pres. |
| Potential temperature            | No        |
| Turbulence model                 | Standard  |
| Solver                           | GCV       |
| Maximum iterations               | 500       |

|                  | Easting      | Northing     | z        | Total  |
|------------------|--------------|--------------|----------|--------|
| Grid spacing (m) | 56.7 - 614.1 | 56.7 - 402.5 | Variable | -      |
| Number of cells  | 299          | 176          | 19       | 999856 |

|                 | 1  | 2  | 3  | 4  | 5  | 6     | 7     | 8     | 9     | 10    |
|-----------------|----|----|----|----|----|-------|-------|-------|-------|-------|
| z-dist. max (m) | 10 | 30 | 50 | 70 | 90 | 111.4 | 136.2 | 165.2 | 198.4 | 235.8 |
| z-dist. min (m) | 10 | 30 | 50 | 70 | 90 | 111.5 | 136.7 | 166.1 | 199.8 | 237.8 |

某近海项目，97m高度处，测风塔在一年内测量结果的平均风速是6.01m/s。



风机和测风塔位置

由计算结果可得，尾流模型2的尾流损失最小。

### Wake model 1

| Turbine Type | Hub Height (m) | No. of turbines | Capacity (MW) | Gross AEP (GWh/y) | Average wind speed (m/s) | Wake losses (%) | AEP with wake losses (GWh/y) | Full load hours (hours) | Capacity factor(%) |
|--------------|----------------|-----------------|---------------|-------------------|--------------------------|-----------------|------------------------------|-------------------------|--------------------|
| H151-5.0MW   | 97.0           | 109             | 545.0         | 1328.054          | 6.09                     | 17.72           | 1092.778                     | 2005.1                  | 22.9               |

### Wake model 2

| Turbine Type | Hub Height (m) | No. of turbines | Capacity (MW) | Gross AEP (GWh/y) | Average wind speed (m/s) | Wake losses (%) | AEP with wake losses (GWh/y) | Full load hours (hours) | Capacity factor(%) |
|--------------|----------------|-----------------|---------------|-------------------|--------------------------|-----------------|------------------------------|-------------------------|--------------------|
| H151-5.0MW   | 97.0           | 109             | 545.0         | 1328.054          | 6.09                     | 13.07           | 1154.541                     | 2118.4                  | 24.2               |

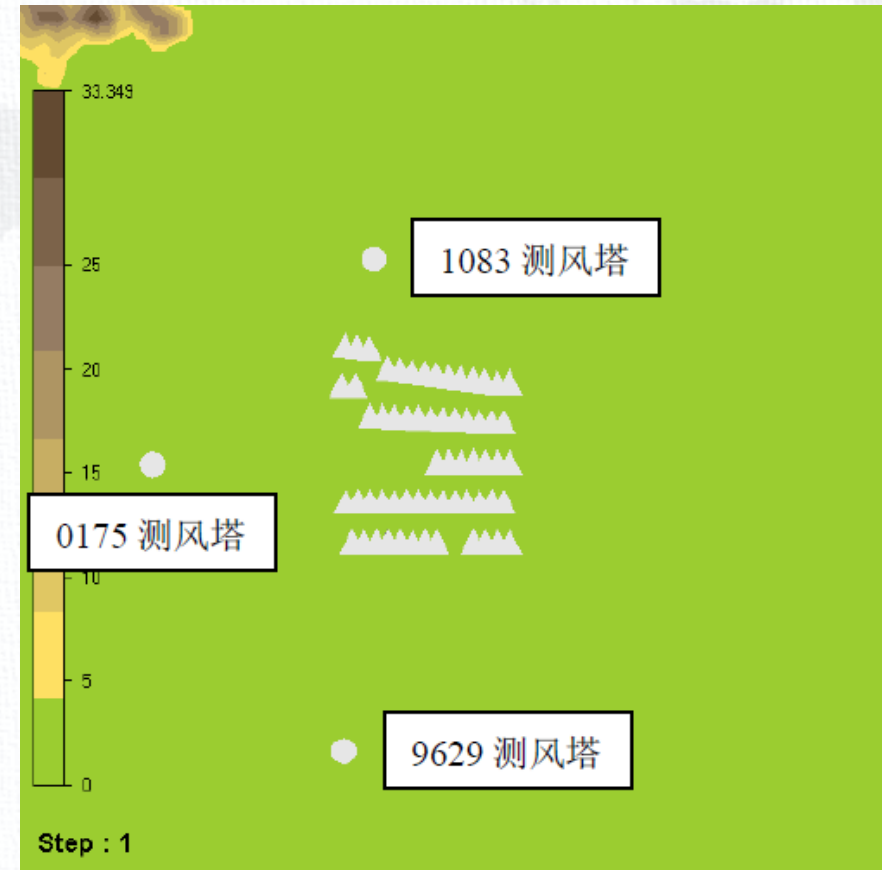
### Wake model 3

| Turbine Type | Hub Height (m) | No. of turbines | Capacity (MW) | Gross AEP (GWh/y) | Average wind speed (m/s) | Wake losses (%) | AEP with wake losses (GWh/y) | Full load hours (hours) | Capacity factor(%) |
|--------------|----------------|-----------------|---------------|-------------------|--------------------------|-----------------|------------------------------|-------------------------|--------------------|
| H151-5.0MW   | 97.0           | 109             | 545.0         | 1328.054          | 6.09                     | 17.03           | 1101.908                     | 2021.8                  | 23.1               |

## 二、WindSim湍流模型对比

### 1.项目简介

基于某海上风电项目，通过采用不同的湍流模型对计算结果进行了对比，并通过不同测风塔之间的交叉检验对湍流模型进行了实用性初步评价。所有算例网格及各模块计算参数设置均相同，仅对风场模块的湍流模型进行了修改。



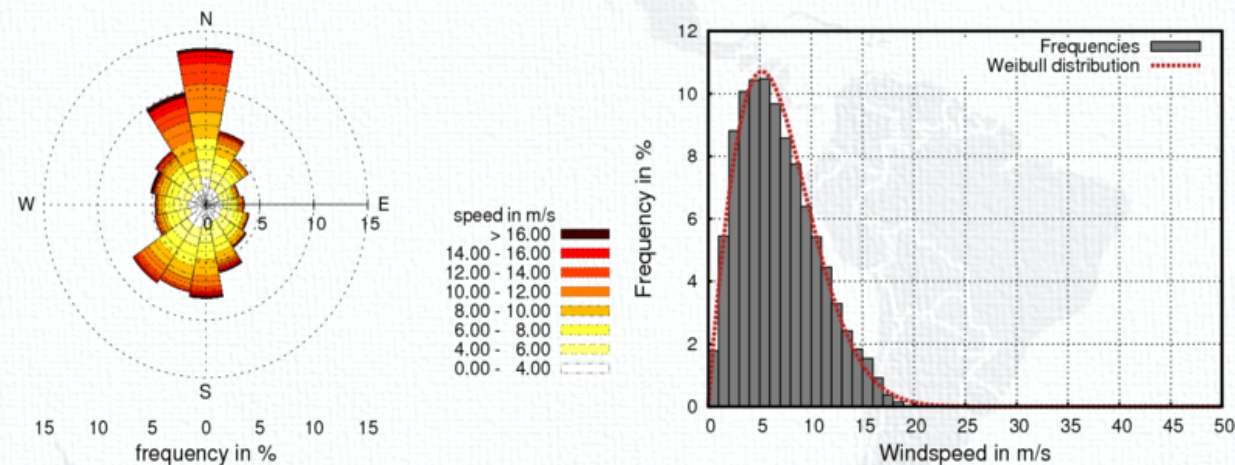
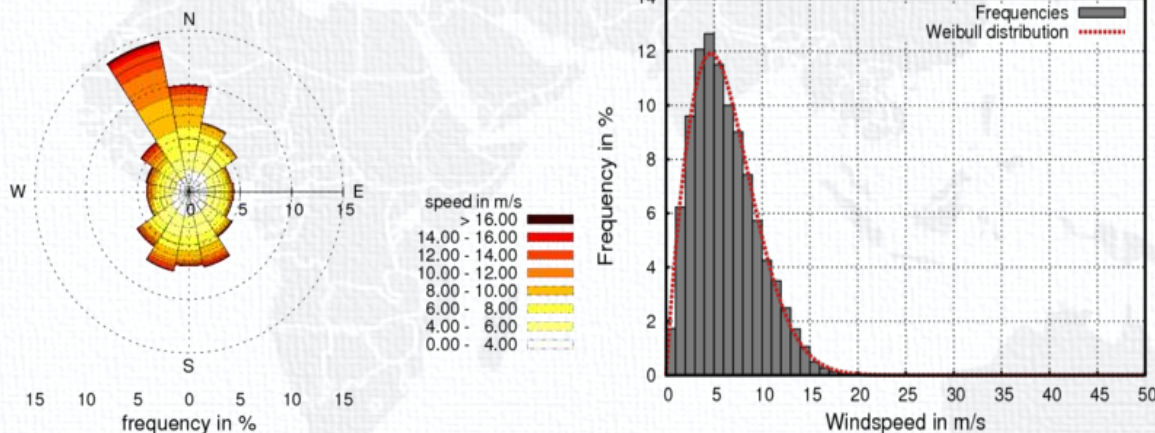
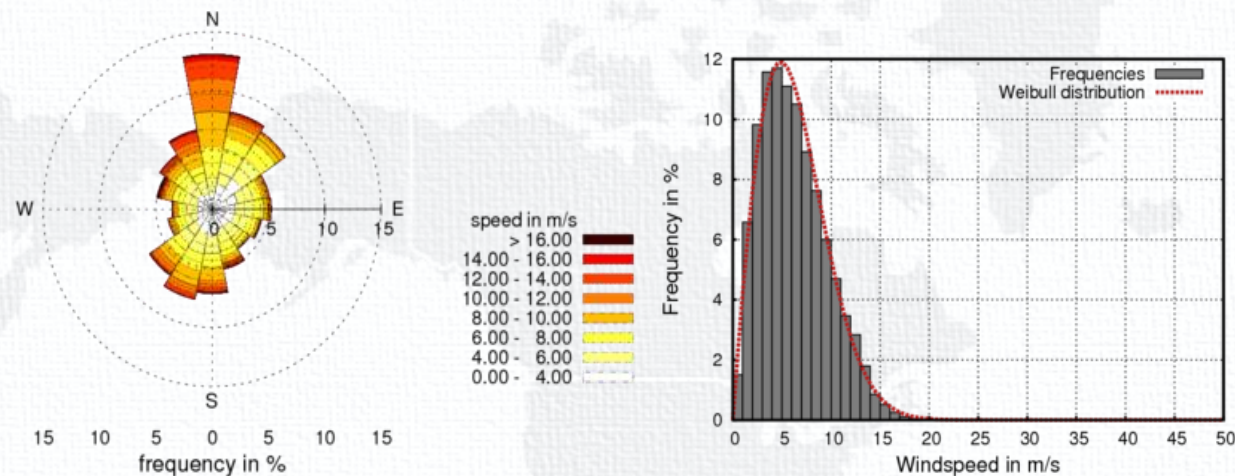
风机和测风塔位置

采用61台风机，其中60台为H171-5.0MW，1台为H151-5.0MW。

## 2.测风塔数据

测风塔主要参数

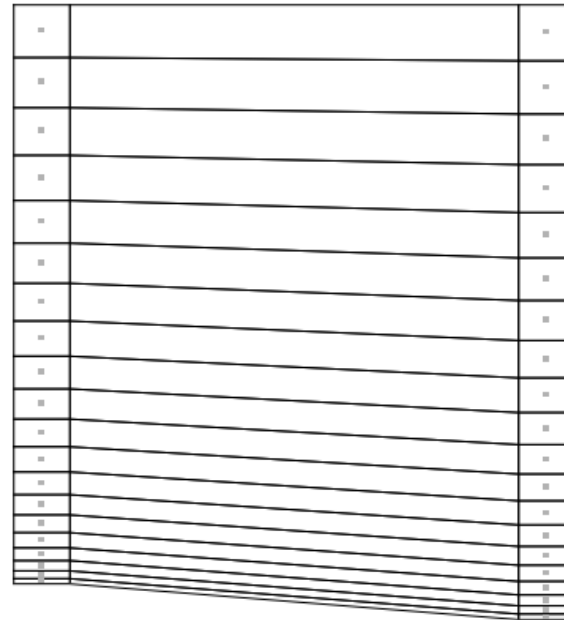
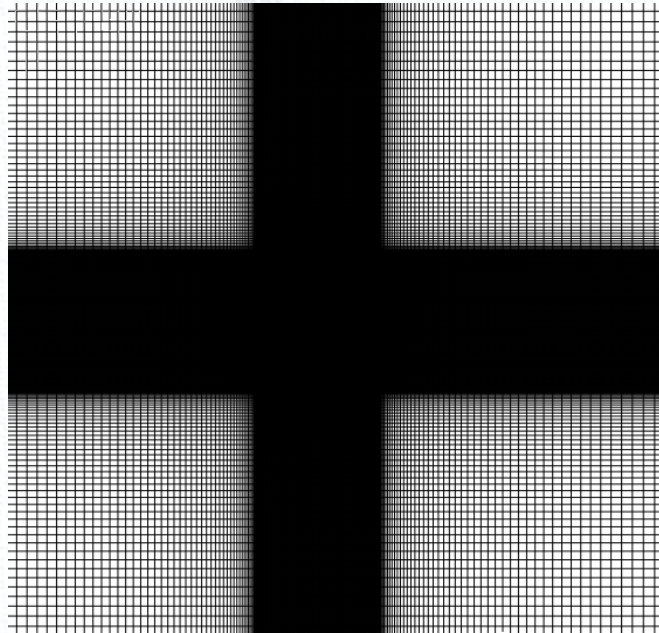
| Climatology | Average wind speed | Weibull k, | Weibull A |
|-------------|--------------------|------------|-----------|
| 1083        | 6.14               | 1.90       | 6.95      |
| 0175        | 6.20               | 1.95       | 7.08      |
| 9629        | 6.80               | 1.90       | 7.74      |



1083测风塔风玫瑰图和风速频率分布

9629测风塔风玫瑰图和风速频率分布

### 3.WindSim计算设置



网格划分

|                                  |           |
|----------------------------------|-----------|
| Height of boundary layer (m)     | 500.0     |
| Speed above boundary layer (m/s) | 10.0      |
| Boundary condition at the top    | fix pres. |
| Potential temperature            | No        |
| Solver                           | GCV       |
| Maximum iterations               | 2000      |

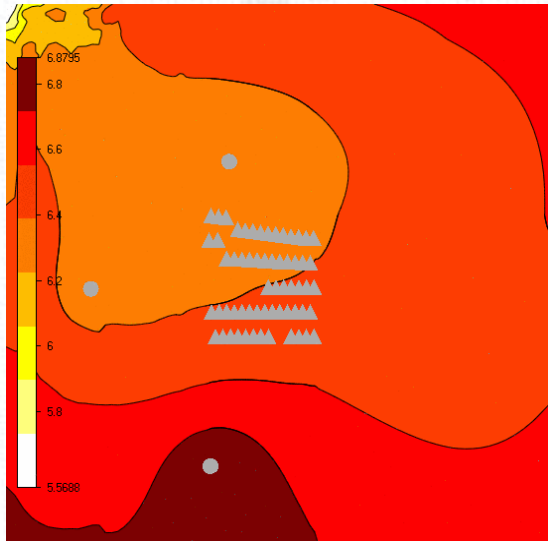
流场计算条件设定

|                  | Easting    | Northing   | z        | Total   |
|------------------|------------|------------|----------|---------|
| Grid spacing (m) | 28.4-713.0 | 28.2-683.3 | Variable | -       |
| Number of cells  | 366        | 409        | 20       | 2993880 |

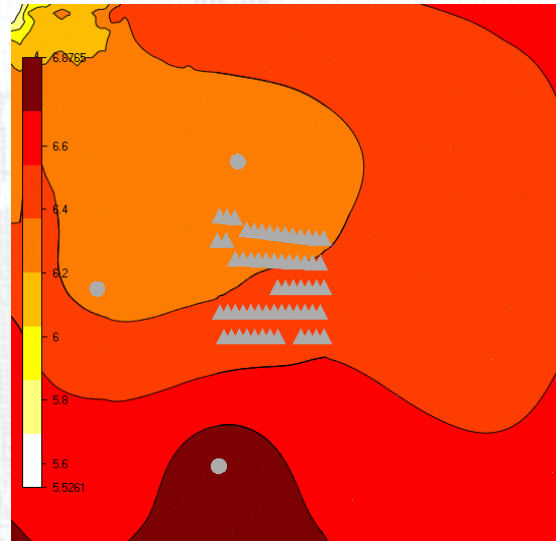
|                 | 1   | 2    | 3    | 4    | 5    | 6    | 7     | 8     | 9     | 10    |
|-----------------|-----|------|------|------|------|------|-------|-------|-------|-------|
| z-dist. max (m) | 3.6 | 12.6 | 25.1 | 41.0 | 60.3 | 83.1 | 109.3 | 138.9 | 172.1 | 208.6 |
| z-dist. min (m) | 3.9 | 13.4 | 26.6 | 43.5 | 64.0 | 88.2 | 116.0 | 147.5 | 182.7 | 221.5 |

密度统一采用固定值  
1.238kg/m<sup>3</sup>，尾流模型均采用Wake model 1。

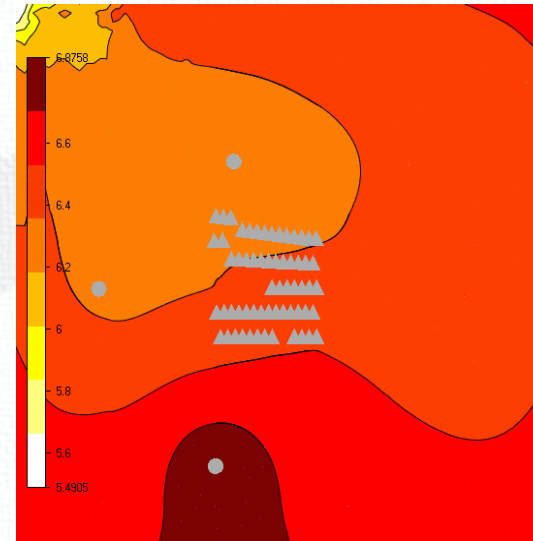
## 4. 结果对比



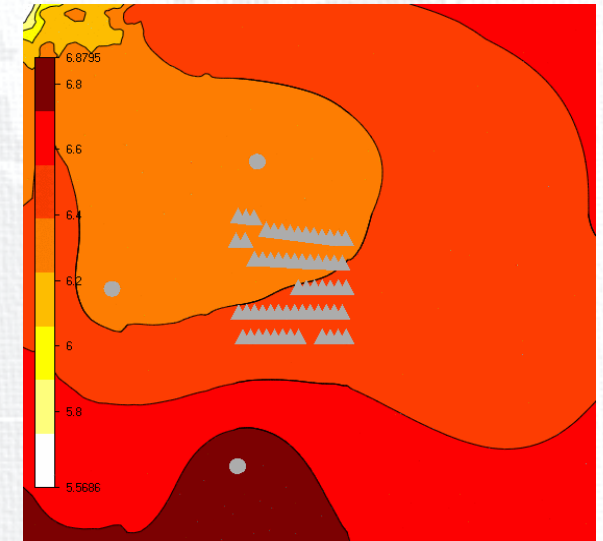
Standard k-ε湍流模型算得的风资源图谱



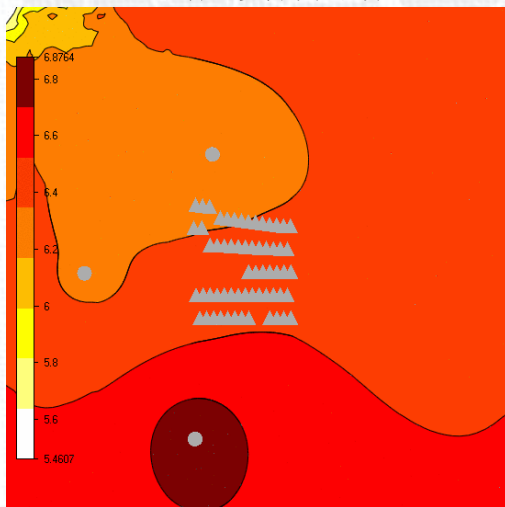
Modified湍流模型算得的风资源图谱



RNG k-ε湍流模型算得的风资源图谱



k-ε with YAP Correction湍流模型算得的风资源图谱



k-omega湍流模型算得的风资源图谱

从速度等值线包络的范围可以看出，Standard k-ε湍流模型与k-ε with YAP Correction湍流模型的计算结果非常相近，k-omega湍流模型计算风资源图谱的风速等值线与其他模型结果差异很大。

| Climatology name | Turbulence Model | Gross AEP (GWh/y) | AEP with wake losses (GWh/y) | Wake losses (GWh/y) | Wake losses (%) |
|------------------|------------------|-------------------|------------------------------|---------------------|-----------------|
| 1083             | Standard k-ε     | 972.806           | 882.369                      | 90.437              | 9.297           |
|                  | Modified k-ε     | 978.727           | 888.415                      | 90.312              | 9.227           |
|                  | RNG k-ε          | 984.837           | 894.819                      | 90.018              | 9.140           |
|                  | YAP Correction   | 972.773           | 882.341                      | 90.432              | 9.296           |
|                  | k-omega          | 989.391           | 900.125                      | 89.267              | 9.022           |
| 0175             | Standard k-ε     | 1016.443          | 926.589                      | 89.853              | 8.840           |
|                  | Modified k-ε     | 1012.216          | 922.466                      | 89.750              | 8.867           |
|                  | RNG k-ε          | 1009.645          | 918.998                      | 90.647              | 8.978           |
|                  | YAP Correction   | 1016.447          | 926.597                      | 89.850              | 8.840           |
|                  | k-omega          | 1008.097          | 917.099                      | 90.998              | 9.027           |
| 9629             | Standard k-ε     | 1143.878          | 1057.844                     | 86.034              | 7.521           |
|                  | Modified k-ε     | 1146.663          | 1059.460                     | 87.203              | 7.605           |
|                  | RNG k-ε          | 1149.779          | 1062.600                     | 87.179              | 7.582           |
|                  | YAP Correction   | 1143.892          | 1057.855                     | 86.037              | 7.521           |
|                  | k-omega          | 1158.035          | 1071.762                     | 86.273              | 7.450           |
| All              | Standard k-ε     | 1033.442          | 944.687                      | 88.755              | 8.588           |
|                  | Modified k-ε     | 1035.488          | 946.462                      | 89.026              | 8.598           |
|                  | RNG k-ε          | 1038.104          | 948.958                      | 89.146              | 8.587           |
|                  | YAP Correction   | 1033.435          | 944.681                      | 88.753              | 8.588           |
|                  | k-omega          | 1041.927          | 953.232                      | 88.694              | 8.513           |

从计算结果可以看出，Standard k-ε模型和k-ε with YAP Correction模型的发电量和平均尾流损失非常接近，与风速等值线结果吻合。k-omega模型计算结果的平均尾流损失相对最小，平均发电量相对较高。

# 不同湍流模型下风速的交叉检验结果

## Modified模型风速交叉检验

|      | Target climatology | Concurrent records | Reference measured | Target measured | Target Modeled | Error (%) |
|------|--------------------|--------------------|--------------------|-----------------|----------------|-----------|
| 1083 | 0175               | 42328              | 7.10               | 6.51            | 7.05           | 8.38      |
| 1083 | 9629               | 42472              | 7.10               | 7.64            | 7.12           | -6.92     |
| 0175 | 1083               | 42177              | 7.18               | 6.51            | 7.21           | 10.70     |
| 0175 | 9629               | 42177              | 7.18               | 7.17            | 7.25           | 1.15      |
| 9629 | 1083               | 43311              | 7.78               | 6.84            | 7.74           | 13.27     |
| 9629 | 0175               | 43171              | 7.78               | 6.48            | 7.70           | 18.84     |

## RNG k-ε模型风速交叉检验

|      | Target climatology | Concurrent records | Reference measured | Target measured | Target Modeled | Error (%) |
|------|--------------------|--------------------|--------------------|-----------------|----------------|-----------|
| 1083 | 0175               | 42328              | 7.10               | 6.51            | 7.08           | 8.80      |
| 1083 | 9629               | 42472              | 7.10               | 7.64            | 7.15           | -6.47     |
| 0175 | 1083               | 42177              | 7.18               | 6.51            | 7.17           | 10.05     |
| 0175 | 9629               | 42177              | 7.18               | 7.17            | 7.22           | 0.72      |
| 9629 | 1083               | 43311              | 7.78               | 6.84            | 7.72           | 12.95     |
| 9629 | 0175               | 43171              | 7.78               | 6.48            | 7.72           | 19.15     |

## Standard k-ε 模型风速交叉检验

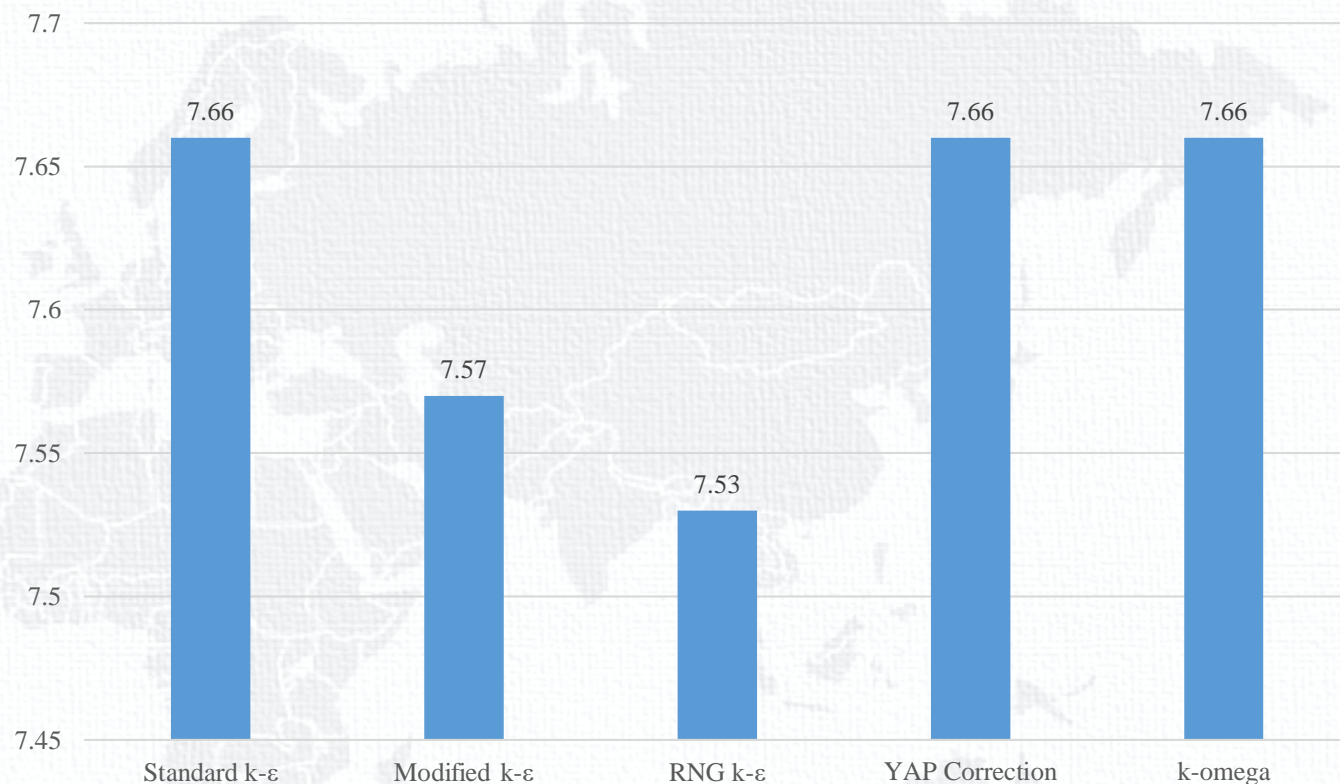
|      | Target climatology | Concurrent records | Reference measured | Target measured | Target Modeled | Error (%) |
|------|--------------------|--------------------|--------------------|-----------------|----------------|-----------|
| 1083 | 0175               | 42328              | 7.10               | 6.51            | 7.02           | 7.91      |
| 1083 | 9629               | 42472              | 7.10               | 7.64            | 7.09           | -7.25     |
| 0175 | 1083               | 42177              | 7.18               | 6.51            | 7.27           | 11.58     |
| 0175 | 9629               | 42177              | 7.18               | 7.17            | 7.28           | 1.52      |
| 9629 | 1083               | 43311              | 7.78               | 6.84            | 7.77           | 13.68     |
| 9629 | 0175               | 43171              | 7.78               | 6.48            | 7.68           | 18.52     |

## YAP Correction模型风速交叉检验

|      | Target climatology | Concurrent records | Reference measured | Target measured | Target Modeled | Error (%) |
|------|--------------------|--------------------|--------------------|-----------------|----------------|-----------|
| 1083 | 0175               | 42328              | 7.10               | 6.51            | 7.02           | 7.90      |
| 1083 | 9629               | 42472              | 7.10               | 7.64            | 7.09           | -7.25     |
| 0175 | 1083               | 42177              | 7.18               | 6.51            | 7.27           | 11.58     |
| 0175 | 9629               | 42177              | 7.18               | 7.17            | 7.28           | 1.52      |
| 9629 | 1083               | 43311              | 7.78               | 6.84            | 7.77           | 13.69     |
| 9629 | 0175               | 43171              | 7.78               | 6.48            | 7.68           | 18.52     |

## k-omega模型风速交叉检验

|      | Target climatology | Concurrent records | Reference measured | Target measured | Target Modeled | Error (%) |
|------|--------------------|--------------------|--------------------|-----------------|----------------|-----------|
| 1083 | 0175               | 42328              | 7.10               | 6.51            | 7.12           | 9.49      |
| 1083 | 9629               | 42472              | 7.10               | 7.64            | 7.13           | -6.77     |
| 0175 | 1083               | 42177              | 7.18               | 6.51            | 7.15           | 9.75      |
| 0175 | 9629               | 42177              | 7.18               | 7.17            | 7.17           | 0.05      |
| 9629 | 1083               | 43311              | 7.78               | 6.84            | 7.75           | 13.32     |
| 9629 | 0175               | 43171              | 7.78               | 6.48            | 7.78           | 20.10     |



风速交叉检验平均误差 (%)

从平均误差来看，RNG k-ε湍流模型在计算风场风速时的误差相对最小；从表格中 Reference measured、Target measured、Target Modeled三项的变化可以看出，不论参考测风塔和目标测风塔的风速差距大小，参考测风塔的风速测量值和目标测风塔的风速计算值普遍很接近，说明WindSim计算的风场中的风速变化要比实际风场中的风速变化更加和缓。这样，如果风场中两个测风塔的平均风速相差较大，在进行交叉检验时很容易出现误差较大的情况。

# 不同湍流模型下湍流强度的交叉检验结果

### Modified模型风速交叉检验

| Reference climatology | Target climatology | Concurrent records | Reference measured | Target measured | Target Modeled | Error (%) |
|-----------------------|--------------------|--------------------|--------------------|-----------------|----------------|-----------|
| 1083                  | 0175               | 281                | 0.58               | 0.90            | 0.59           | -34.31    |
| 1083                  | 9629               | 839                | 0.87               | 0.87            | 0.90           | 3.41      |
| 0175                  | 1083               | 345                | 0.68               | 0.91            | 0.65           | -28.87    |
| 0175                  | 9629               | 839                | 0.63               | 0.87            | 0.62           | -29.15    |
| 9629                  | 1083               | 345                | 0.95               | 0.91            | 0.89           | -1.76     |
| 9629                  | 0175               | 281                | 0.61               | 0.90            | 0.61           | -31.92    |

### RNG k-ε模型风速交叉检验

| Reference climatology | Target climatology | Concurrent records | Reference measured | Target measured | Target Modeled | Error (%) |
|-----------------------|--------------------|--------------------|--------------------|-----------------|----------------|-----------|
| 1083                  | 0175               | 281                | 0.58               | 0.90            | 0.59           | -34.55    |
| 1083                  | 9629               | 839                | 0.87               | 0.87            | 0.89           | 1.77      |
| 0175                  | 1083               | 345                | 0.68               | 0.91            | 0.65           | -28.35    |
| 0175                  | 9629               | 839                | 0.63               | 0.87            | 0.61           | -29.66    |
| 9629                  | 1083               | 345                | 0.95               | 0.91            | 0.91           | -0.09     |
| 9629                  | 0175               | 281                | 0.61               | 0.90            | 0.61           | -31.66    |

### Standard k-ε 模型风速交叉检验

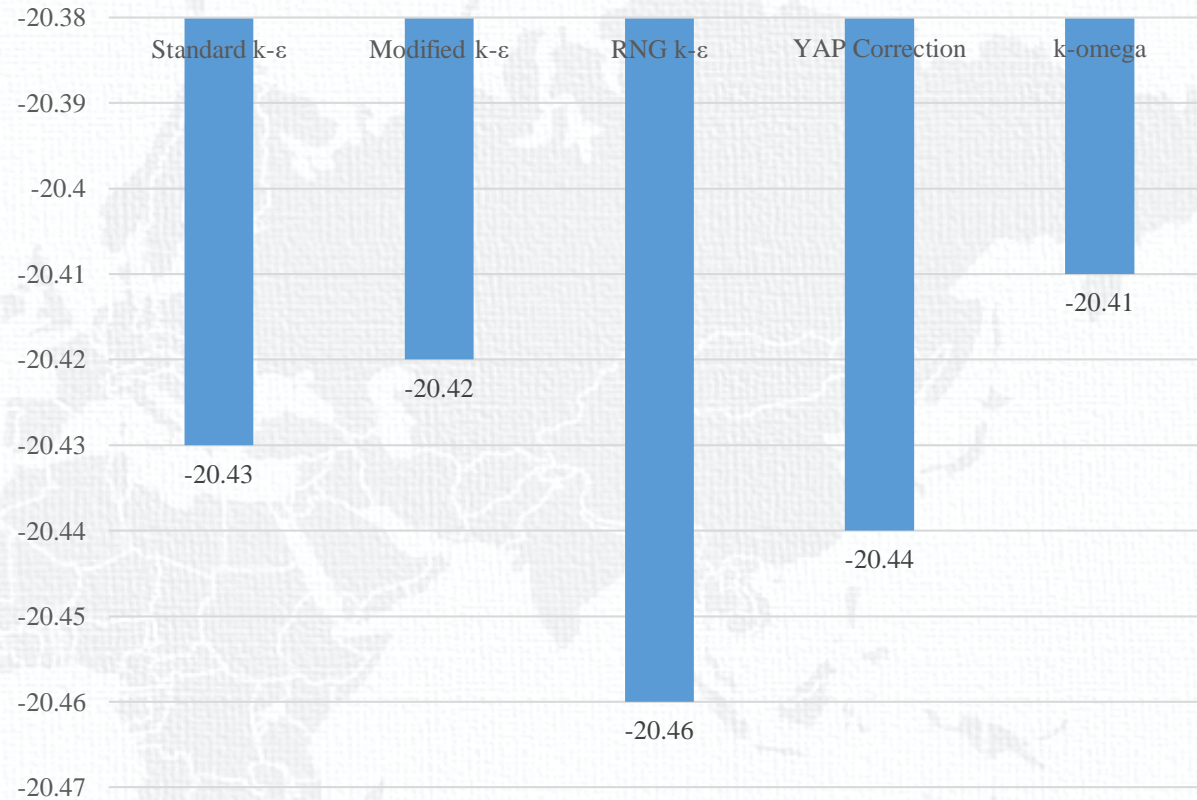
| Reference climatology | Target climatology | Concurrent records | Reference measured | Target measured | Target Modeled | Error (%) |
|-----------------------|--------------------|--------------------|--------------------|-----------------|----------------|-----------|
| 1083                  | 0175               | 281                | 0.58               | 0.90            | 0.59           | -34.47    |
| 1083                  | 9629               | 839                | 0.87               | 0.87            | 0.88           | 0.74      |
| 0175                  | 1083               | 345                | 0.68               | 0.91            | 0.65           | -28.32    |
| 0175                  | 9629               | 839                | 0.63               | 0.87            | 0.61           | -29.92    |
| 9629                  | 1083               | 345                | 0.95               | 0.91            | 0.92           | 0.68      |
| 9629                  | 0175               | 281                | 0.61               | 0.90            | 0.62           | -31.48    |

### YAP Correction模型风速交叉检验

| Reference climatology | Target climatology | Concurrent records | Reference measured | Target measured | Target Modeled | Error (%) |
|-----------------------|--------------------|--------------------|--------------------|-----------------|----------------|-----------|
| 1083                  | 0175               | 281                | 0.58               | 0.90            | 0.59           | -34.31    |
| 1083                  | 9629               | 839                | 0.87               | 0.87            | 0.90           | 3.42      |
| 0175                  | 1083               | 345                | 0.68               | 0.91            | 0.65           | -28.88    |
| 0175                  | 9629               | 839                | 0.63               | 0.87            | 0.62           | -29.15    |
| 9629                  | 1083               | 345                | 0.95               | 0.91            | 0.89           | -1.77     |
| 9629                  | 0175               | 281                | 0.61               | 0.90            | 0.61           | -31.92    |

### k-omega模型风速交叉检验

| Reference climatology | Target climatology | Concurrent records | Reference measured | Target measured | Target Modeled | Error (%) |
|-----------------------|--------------------|--------------------|--------------------|-----------------|----------------|-----------|
| 1083                  | 0175               | 281                | 0.58               | 0.90            | 0.59           | -34.70    |
| 1083                  | 9629               | 839                | 0.87               | 0.87            | 0.86           | -0.93     |
| 0175                  | 1083               | 345                | 0.68               | 0.91            | 0.66           | -27.97    |
| 0175                  | 9629               | 839                | 0.63               | 0.87            | 0.61           | -29.97    |
| 9629                  | 1083               | 345                | 0.95               | 0.91            | 0.93           | 2.51      |
| 9629                  | 0175               | 281                | 0.61               | 0.90            | 0.62           | -31.41    |



湍流强度交叉检验平均误差 (%)

从平均误差来看，k-omega湍流模型在计算风场湍流强度时的误差相对最小；从表格中 Reference measured、Target measured、Target Modeled 三项的变化可以看出，不论参考测风塔和目标测风塔的湍流强度差距大小，目标测风塔的湍流强度计算值和参考测风塔的湍流强度测量值普遍很接近，说明WindSim计算的风场中的湍流强度变化主要来源于导入的测风塔数据。测风塔数据的质量对微选阶段的计算结果影响甚大。

## 5.不同项目的计算结果比较

采用与尾流模型对比部分相同的项目，尾流模型固定设置为wake model 2，其他设置不变，只改变湍流模型进行发电量计算，结果如下：

| Climatology name | Turbulence Model | Gross AEP (GWh/y) | AEP with wake losses (GWh/y) | Wake losses (GWh/y) | Wake losses (%) |
|------------------|------------------|-------------------|------------------------------|---------------------|-----------------|
| Exported_97m     | Standard k-ε     | 1328.054          | 1154.541                     | 173.513             | 13.07           |
|                  | Modified         | 1326.288          | 1154.703                     | 171.585             | 12.94           |
|                  | k-ε with YAP     | 1327.953          | 1154.403                     | 173.55              | 13.07           |
|                  | RNG k-ε          | 1327.179          | 1157.367                     | 169.812             | 12.79           |
|                  | k-omega          | 1318.213          | 1153.117                     | 165.096             | 12.52           |

同样是k-omega模型平均尾流损失最小，但发电量偏低， Standard k-ε模型和k-ε with YAP Correction模型的发电量和平均尾流损失非常接近。

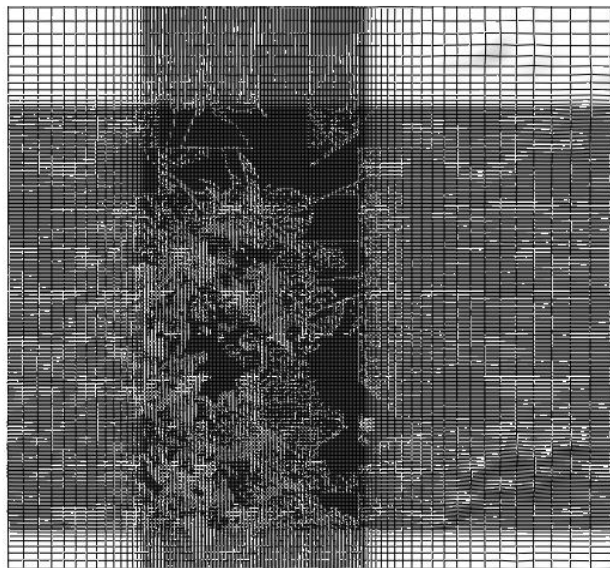
## 三、结论与探讨

### 1. 结论

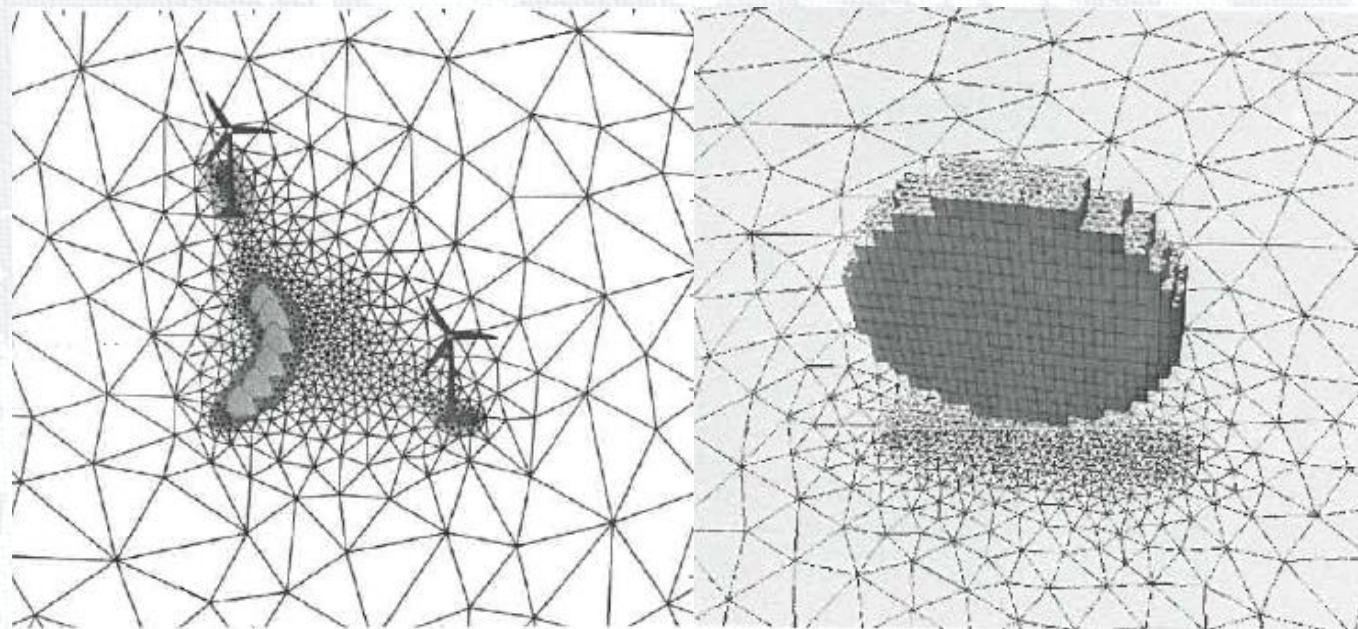
对于近海或海上风电项目，关于WindSim尾流模型，wake model 2算得的损耗最小，wake model 3算得的风场整体年发电量损耗与wake model 1的结果相近；

关于WindSim湍流模型，k-omega模型计算结果的平均尾流损失相对最小，平均发电量存在不确定性，Standard k-ε模型和k-ε with YAP Correction模型的发电量和平均尾流损失非常接近。

## 2.探讨



WindSim网格加密



ZephyScience网格加密

目前WindSim采用的网格加密方式加密区域过多，相同项目中会产生更多的网格数量，使得项目计算时间成本偏高。在不降低发电量计算准确度的情况下，WindSim是否有必要采用针对机位点和特定位置局部加密的方式，以降低项目计算的时间成本？

中国海装风电希望加强与各界的协作，共同促进行业的发展。



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