近20年来风电场（群）对气候的影响研究进展

第五届区域气候变化监测与检测研讨会

湖北省气象服务中心，武汉

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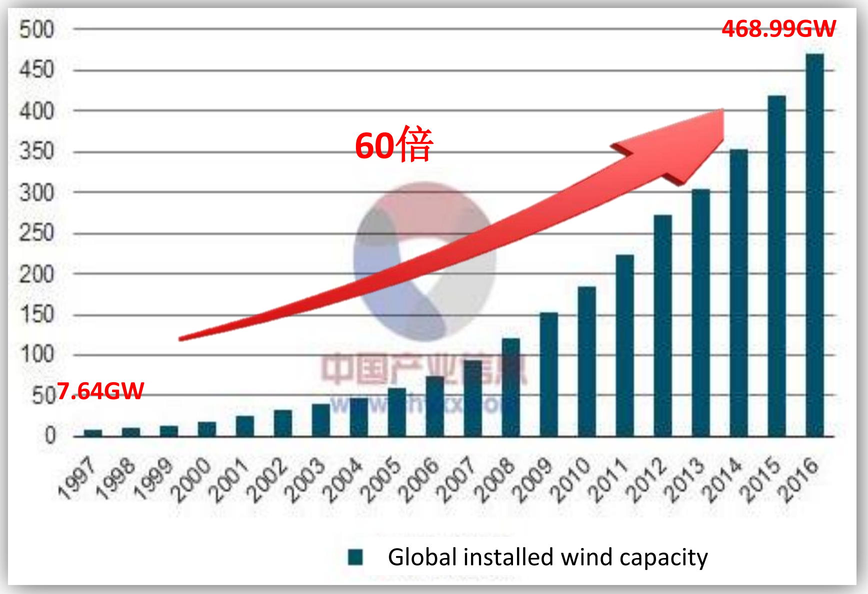
PAPT 01

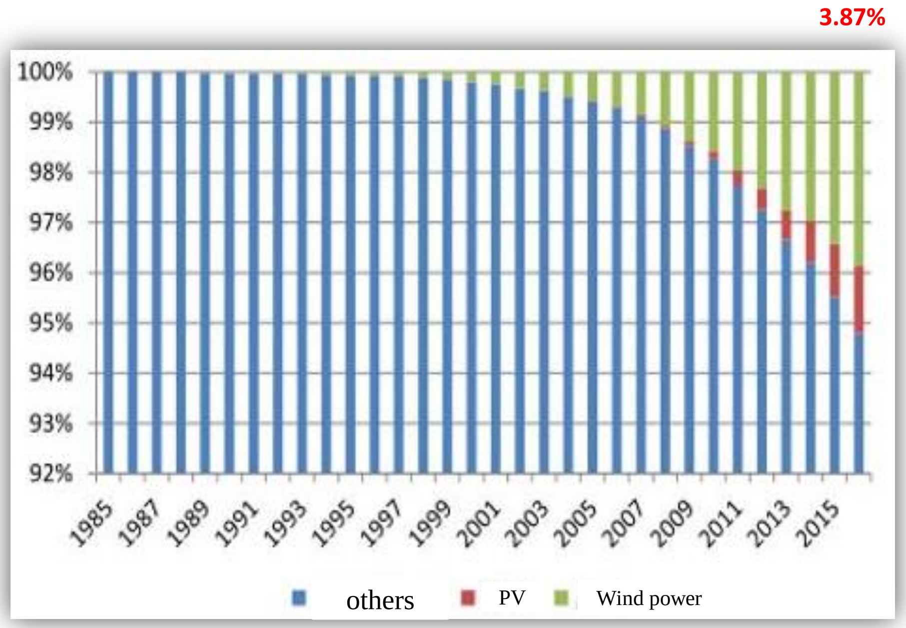
研究背景

研究背景

1. 风电场（群）的快速增加



Global cumulative installed wind capacity 1997-2016 (GW)



The proportion of global wind power generation (%)

研究背景

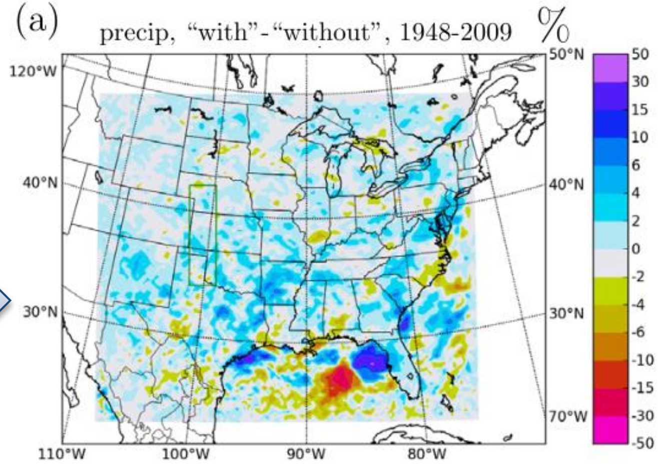
2.风电场（群）的负面影响

Noise

Interference with TV transmission signals

Visual, image flicker

Bird hits



Possible climatic impacts

研究进程

Studies mainly concentrated in the United States, Europe (Spain, England, Norway, Switzerland, Denmark) and Canada. Research on the impact of wind farms on climate has already started in China.

1970s	2000	2010
Environmental impacts of WFs	**Wind energy resources of WFs**	**Climatic impacts of WFs**
Step One	**Step Two**	**Step Three**
It was speculated that climate change will occur downstream of wind farms.	The wake experiment mainly focuses on the change of wind speed downstream of WFs.	Analysis and simulation the influence of WFs on local and global climate.
起步于环境影响研究	发展于风能资源研究	气候变化研究

表1 2000年以来风电场对气候的影响研究

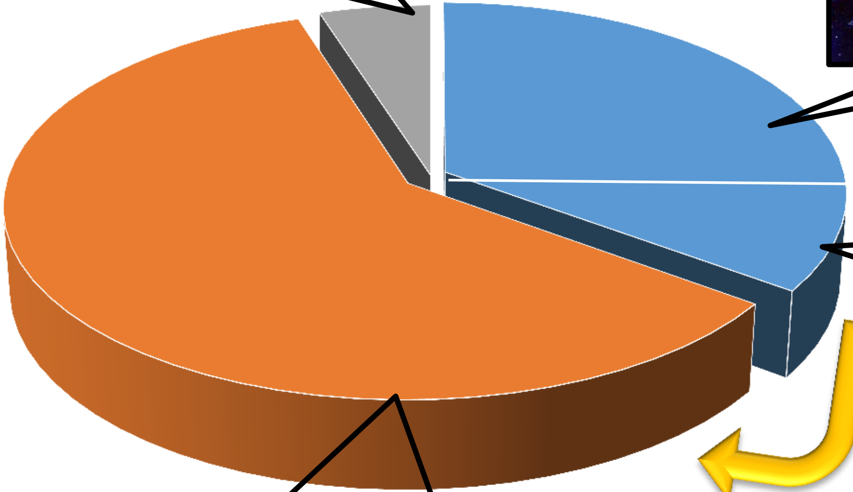
Authors	Methods	Research variables	Title
Roy et al [1]	RAMs	LST	Impacts of wind farms on surface air temperature
Zhou et al[2]	Remote sensing data	LST	Diurnal and seasonal variations of wind farm impacts on land surface temperature over western Texas
Thomas et al[3]	MODIS5 data	LST	Further evidence of impacts of large-scale wind farms on land surface temperature
Fitch et al[4]	WRF	Temperature	Mesoscale Influences of Wind Farms throughout a Diurnal Cycle
Rui et al[5]	MODIS5 data	Temperature	The impacts of Chinese wind farms on climate
Christiansen et al[6]	SAR	Wind speed	Using airborne and satellite SAR for mapping offshore
Hidalgo et al[7]	WRF	Wind speed	Impacts of a cluster of wind farms on wind resource availability and wind power production over complex terrain
Fitch et al [8]	WRF (V3.3)	Wind speed	Local and Mesoscale Impacts of Wind Farms as Parameterized in a Mesoscale NWP Model
Rhodes et al[9]	Doppler Lidar	Wind speed	The Effect of Wind-Turbine Wakes on Summertime US Midwest Atmospheric Wind Profiles as Observed with Ground-Based Doppler Lidar
Fiedler et al [10]	RCM and WRF	Precipitation	The effect of a giant wind farm on precipitation in a regional climate model
Roy et al [11]	RAMs	Thermal and dynamic effects	Can large wind farms affect local meteorology?
Smith et al [12]	Observational data	surface temperature profiles, turbulence intensity, wind shear	In situ observations of the influence of a large onshore wind farm on near-surface temperature, turbulence intensity and wind speed profiles
Rajewski et al [13]	Observational data	Wind speed, radiation, precipitation, fluxes	Changes in fluxes of heat, H_2O, and CO_2 caused by a large wind farm
Wang et al [14]	CCM3	Global effects	Protential climatic impacts and reliability of very large-scale wind farms
Keith et al [15]	numerical experiments	Global effects	The influence of large-scale wind power on global climate

PAPT 02

研究方法

研究方法

- 观测数据分析
- 数值模拟实验
- 风洞实验

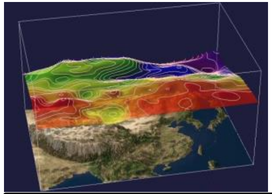


is limited by experimental conditions

Remote sensing data:
Effectiveness, long, large scale

Data of field campaign:
expensive, short, local

Data analysis:
①Post WFs-Pre WFs
②Data over the WFs- Data in nonWFs
③Data of WF is on – WF is off



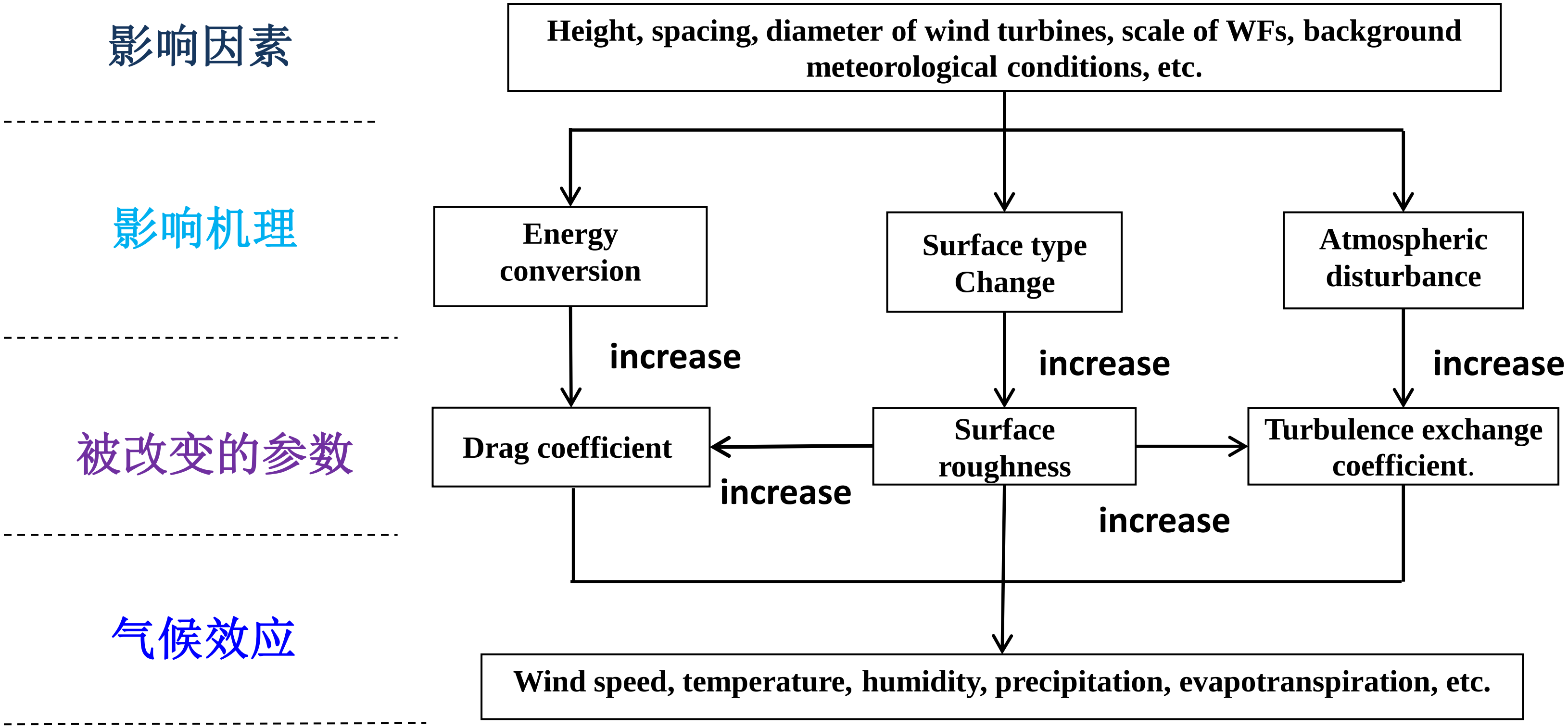
models: RAMS/BEM/LES/CCM5/RCM/WRF/
a fully coupled atmosphere-ocean-land system model
Set control and sensitive experiment in numerical models

The model can be verified by the measured data.

PAPT 03

影响机理

影响机理



影响因素
影响机理
被改变的参数
气候效应
Height, spacing, diameter of wind turbines, scale of WFs, background meteorological conditions, etc.
Energy conversion
Surface type Change
Atmospheric disturbance
increase
increase
increase
Drag coefficient
Surface roughness
Turbulence exchange coefficient.
increase
increase
Wind speed, temperature, humidity, precipitation, evapotranspiration, etc.

PAPT 04

局地气候效应

温度

风速

降水和湿度

风电场（群）对地表温度的影响

实地观测数据的分析结论 [1] Roy

A wind farm at San Gorgonio, California, consisted of 23-m-tall turbines with 8.5-m-long rotor blades arranged in 41 rows that were spaced 120 m apart.

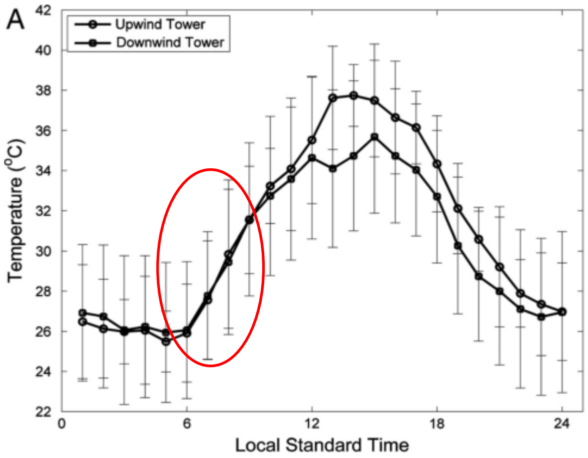


Fig.1 Near-surface air-temperature patterns during the field campaign.

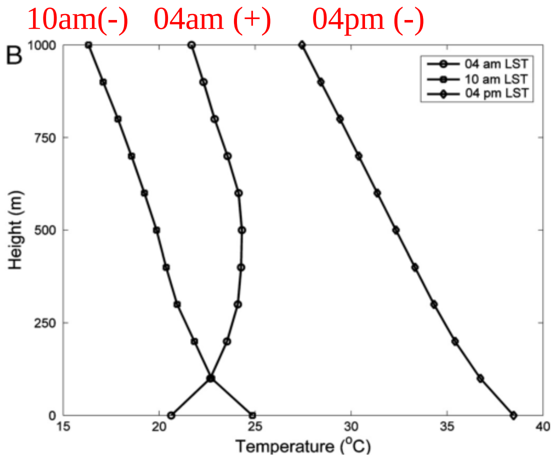


Fig.2 Vertical profiles of air temperature at Edwards Air Force Base during June–August 1989.

结果:

- ➢ Near-surface air temperatures downwind of the wind farm are higher than upwind regions during night and early morning hours, whereas the reverse holds true for the rest of the day.

可能的原因:

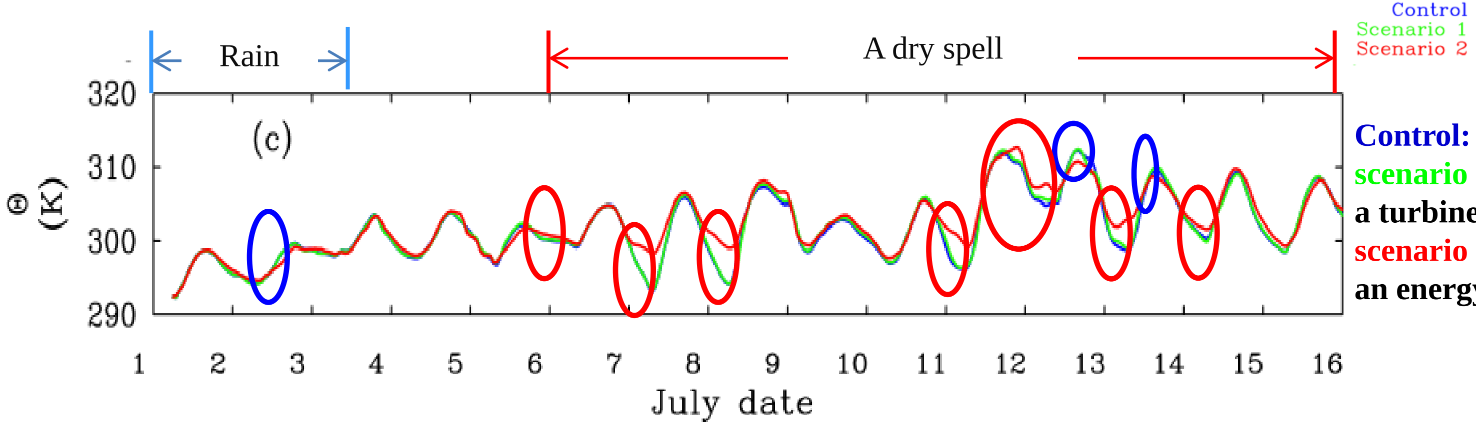
- Turbulence generated in the wake of the rotors enhance vertical mixing. In a stable atmosphere a warm layer overlies a cool layer, enhanced vertical mixing mixes warm air down and cold air up.

[1] Baidya Roy S, Traiteur J J. Impacts of wind farms on surface air temperature[J]. NAS, 2010, 107(42): 17899J17904, doi: 10.1073/pnas.1000493107

风电场（群）对地表温度的影响

数值模拟结果 [11] Roy

RAM: a virtual wind farm consisting of a 100 ×100 array of wind turbines spaced 1 km apart. Each turbine is 100 m tall (hub height) with 50m long rotor blades.



Control: no turbine

scenario 1:

a turbine is a sink of energy

scenario 2:

an energy sink + a source of turbulence

Figure.3 Time series of surface air Θ over the wind farm.

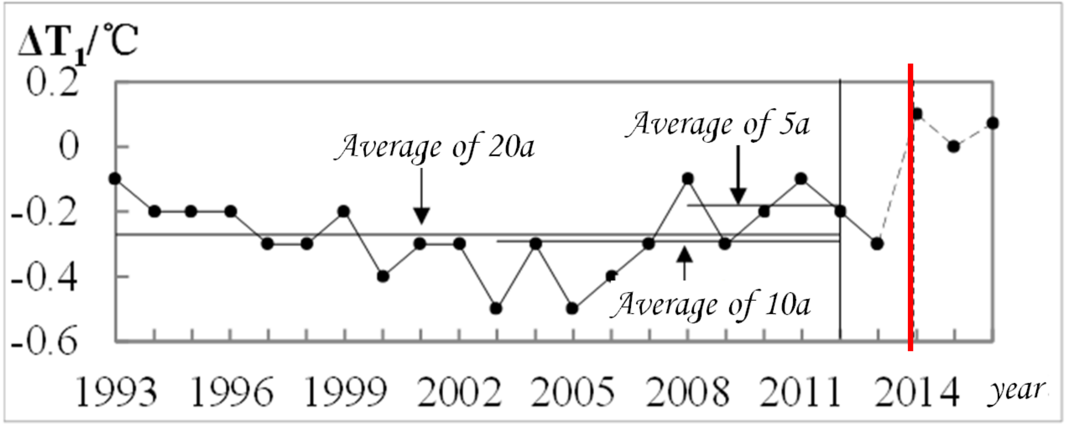
结果:

- Generally, Θ in scenario 2 is higher than the other cases and the effect peaks during the early mornings in the dry period.
- Occasionally, during daytime hours, a reduction in Θ in scenario 2 can also be observed.

[11] Baidya Roy S, Pacala SW, Walko RL. Can large wind farms affect local meteorology? [J] Geophys Res D: Atmos 2004; 109(D19101):1–6.

风电场（群）对地表温度的影响

课题组研究结果[*]Zhang 湖北省大悟山区风电场群



$\Delta T_1 = T_{Dawu} - T_{Hongan}$

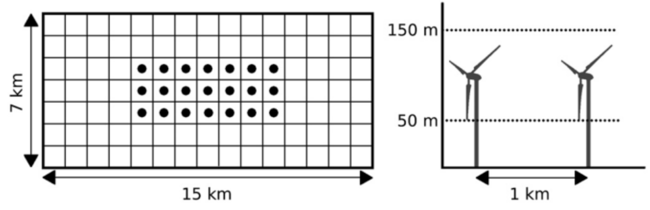
	2013
ΔT_1	0.001
	Affected significantly

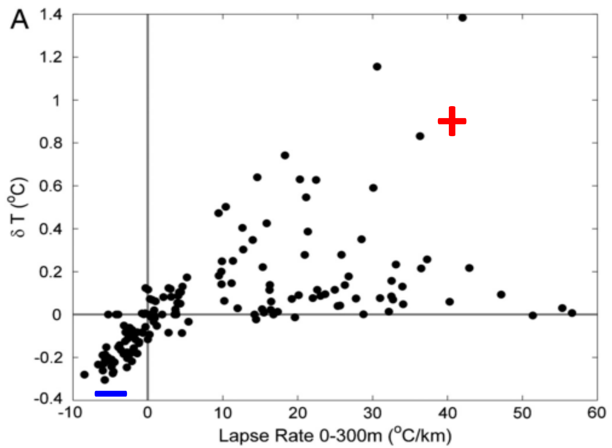
After 2014, ΔT_1 increases suddenly, the average value is 0.06 °C, 0.33 °C larger than average value of ΔT_1 from 1993 to 2012 (0.27 °C) .

风电场（群）对地表温度的影响

数值模拟验证 [1] Roy

RAMS model domain





δT: near-surface air temperature (wind farm–control)

Figure.4 Simulated change in near-surface air temperatures within the wind farm plotted as a function of 0–300 m potential temperature lapse rate at the beginning of the simulations

- Wind turbine rotors create a warming effect under positive lapse rates and a cooling effect under negative lapse rates.

  正的温度梯度下产生地表增暖效应；负的温度梯度下产生地表降温效应

[5] Baidya Roy S, Traiteur J J. Impacts of wind farms on surface air temperature[J]. NAS, 2010, 107(42): 17899J17904, doi: 10.1073/pnas.1000493107

地表温度的时空变化

昼夜变化[2] Zhou

MODIS DATA: a region in West-Central Texas that is home to four large wind projects.

Pixels with plus symbol have at least one wind turbine

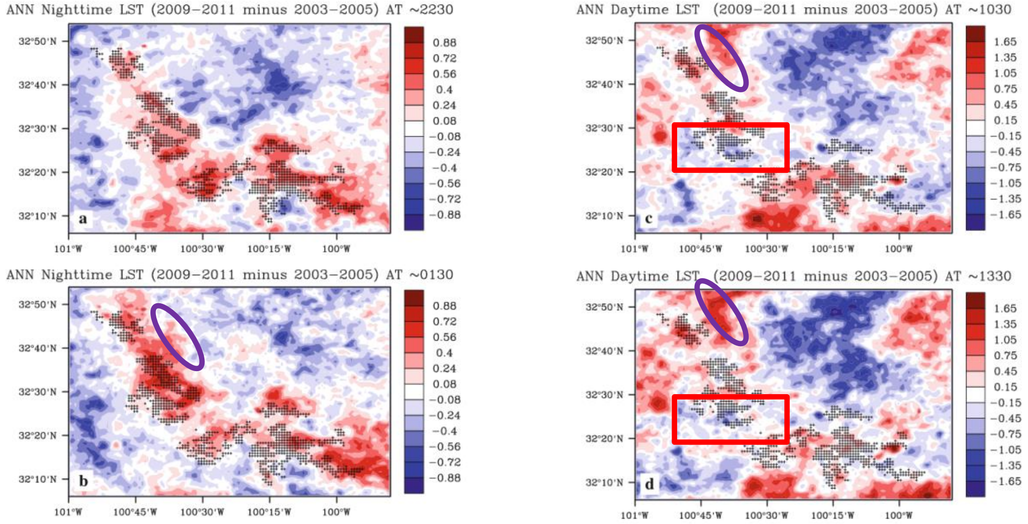
WFPs 风电场区域

(wind farm pixels）

NNWFPs 非风电场区域

(nearby non-wind-farm pixels)

夜间　　　　白天



(主导风向)

Figure.5 Annual mean LST differences (°C) (2009–2011 minus 2003–2005 averages) at nighttime and daytime.

- **WFPs are generally much warmer than NNWFPs, the warming is also observed downwind;风电场区域和下游 有增暖效应;**
- **there is a spatial coupling between the wind turbines and the warming over most WFPs in nighttime， the daytime LSTs show a much noisy warming effect over some WFPs；夜间增暖效应与风电场空间耦合较好，白天较为嘈杂。**

[2] Liming Zhou, Yuhong Tian, Baidya Roy S, et al. Diurnal and seasonal variations of wind farm impacts on land surface temperature over western Texas[J]. Clim Dyn 41: (2013) 307–326

地表温度的时空变化

季节变化[2] Zhou

冬季 夏季

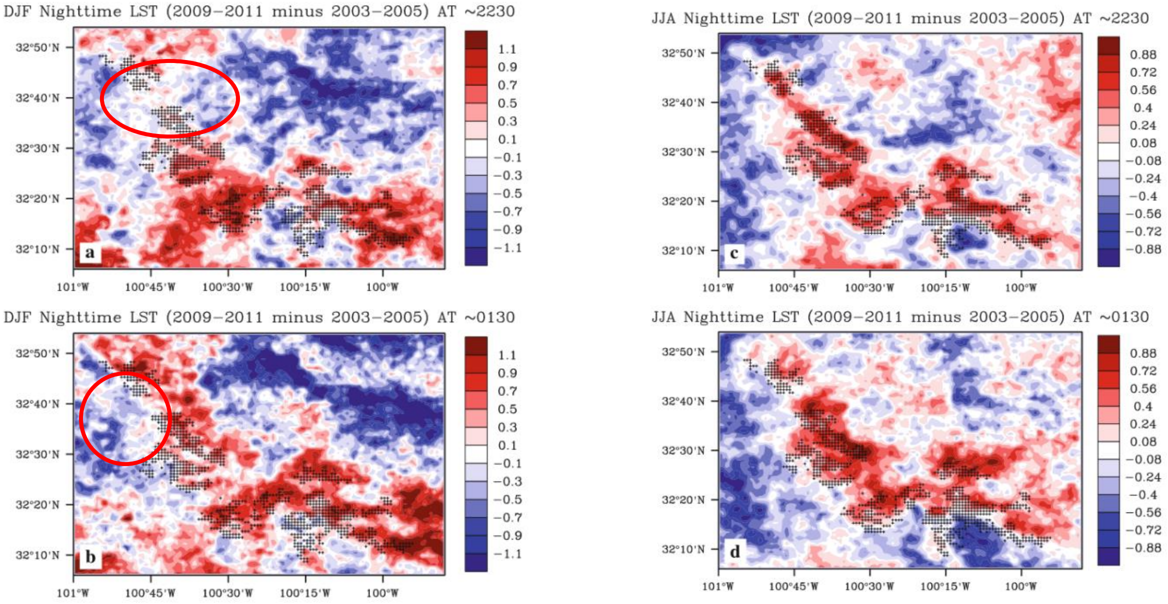


Figure. 6 DJF and JJA nighttime LST differences (℃) (2009–2011 minus 2003–2005 averages) at *22:30 (a, c) and *01:30 (b, d).

- The warming effect over WFPs is visible in both seasons but better coupled with the wind turbines and less noisy in summer than winter.
  夏季增暖效应与风机布设空间耦合较好，而冬季这种影响效应比较嘈杂

[7] Liming Zhou, Yuhong Tian, Baidya Roy S, et al. Diurnal and seasonal variations of wind farm impacts on land surface temperature over western Texas[J]. Clim Dyn 41: (2013) 307–326

地表温度的时空变化

季节变化[15]Chang 中国西北部瓜州（沙漠地区）

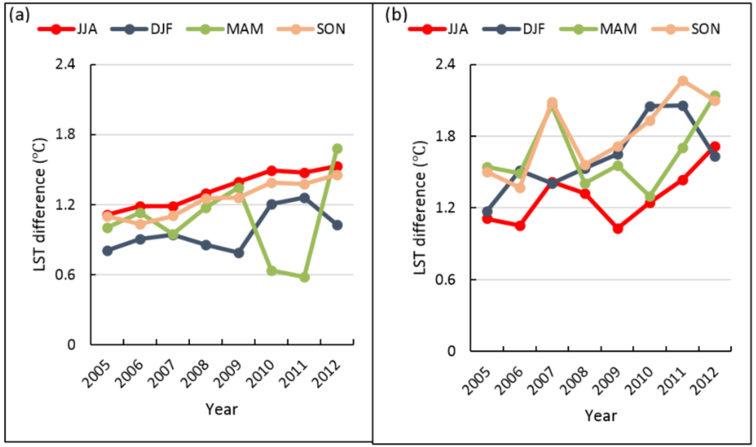


Figure 7. Inter-annual mean MODIS LST differences (°C) at nighttime for the period 2005–2012:(a) WFM-NNWF; (b)GZ -NNWF.

Table 1. LST trends of the areal mean differences between WFM (GZ) and NNWF pixels during the four seasons from MODIS data for the period 2005–2012.

		$LST_{WFM-NNWF}$ Trend		$LST_{GZ-NNWF}$ Trend
Nighttime	MAM	0.12 °C/8 years (R = 0.098)		0.30 °C/8 years (R = 0.302)
	JJA	**0.51 °C/8 years (R = 0.975)**		**0.51 °C/8 years (R = 0.670)**
	SON	**0.48 °C/8 years (R = 0.953)**	<	**0.80 °C/8 years (R = 0.748)**
	DJF	**0.38 °C/8 years (R = 0.665)**		**0.76 °C/8 years (R = 0.767)**
Daytime	MAM	0.13 °C/8 years (R = 0.197)		−0.03 °C/8 years (R = 0.014)
	JJA	0.08 °C/8 years (R = 0.112)		−0.46 °C/8 years (R = 0.532)
	SON	−0.25 °C/8 years (R = 0.324)		0.03 °C/8 years (R = 0.026)
	DJF	−0.67 °C/8 years (R = 0.323)		−0.35 °C/8 years (R = 0.161)

wind farm pixels (WFM); nearby non-wind farm pixels (NNWF);Guazhou county pixels (GZ);
R indicates the correlation coefficient

- The LST WFM-NNWF warming trend: summer>autumn>winter 夏天>秋天>冬天
- The LST impacts from wind farms are less than those from the urban area 风电场对地表温度影响效应小于城市效应

[4] Rui Chang, Rong Zhu, Peng Guo. A Case Study of Land-Surface-Temperature Impact from Large-Scale Deployment of Wind Farms in China from Guazhou[J]. Remote Sensing, 2016, 8(10):790

地表温度的时空变化

空间差异[3] Walsh-Thoma

San Gorgonio Wind Farm: wind farm consists of 3218 turbines which produce 615MW in California, arid low latitude desert (hot)

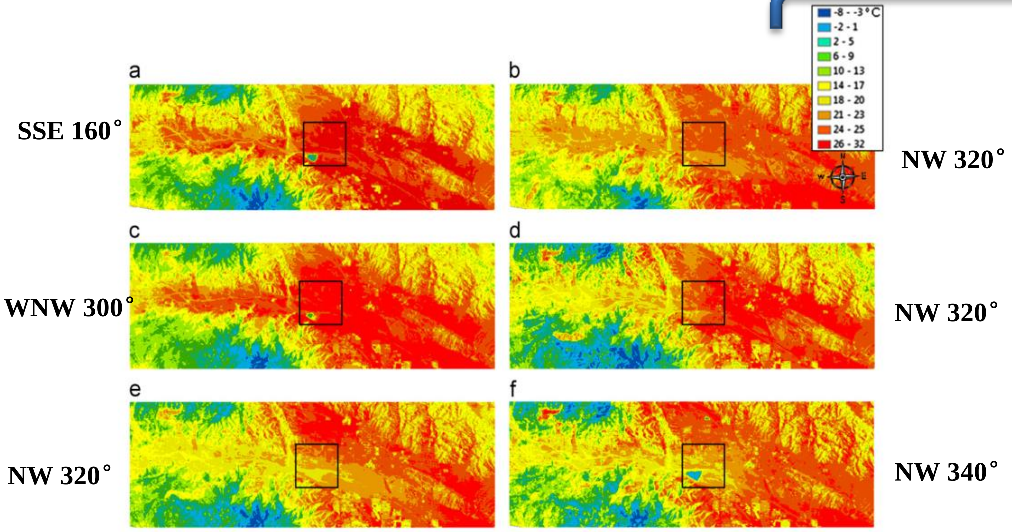


Fig. 8 Subset sample of temperature variation for the area of interest in the summer month

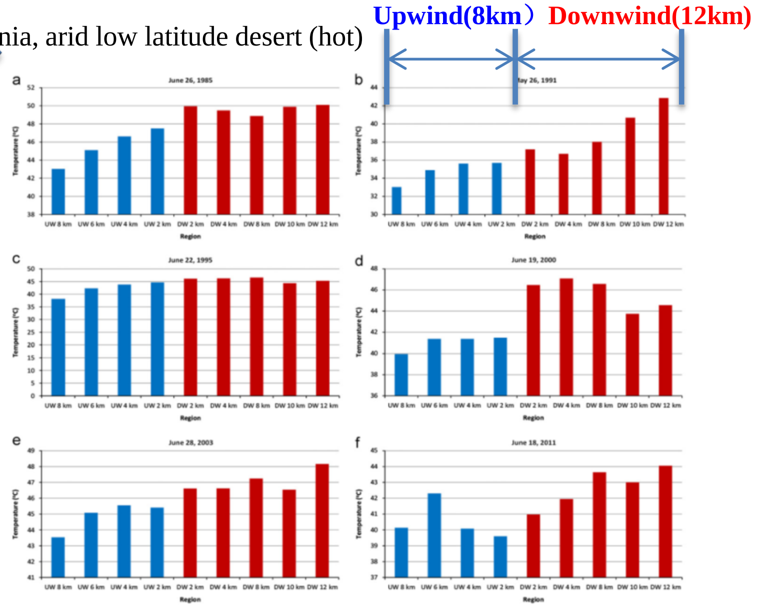


Fig. 9 Comparison of summer LST from upwind and downwind from wind farm as a function of distance

- The majority of the summer month images showing the similar warmer the downwind regions, downwind regions through 12 km are shown to be consistently 4~8℃ warmer than the observed upwind region through 8 km.

[3] Jenell M. Walsh-Thoma, Guido Cervone, Peggy Agouris, et al. Further evidence of impacts of large-scale wind farms on land surface temperature[J]. Renewable and Sustainable Energy Reviews 2012:16:6432–6437.

总结

- 大多研究结果显示风电场对地表温度在夜间有较明显的增暖效应，在白天有降温效应。夏季的增暖效应要强于冬季。
- 风电场群对地表温度的影响效应取决于近地大气层的稳定度。
- 对地表温度的增暖效应不仅发生在风电场区域，也发生在风电场的主导风向下游 。

风电场（群）对风速的影响

Nysted 风电场（丹麦大型海上风电场）观测数据的结论 [16] Frandsen

free stream wind speeds
between 8 and 9 m/s

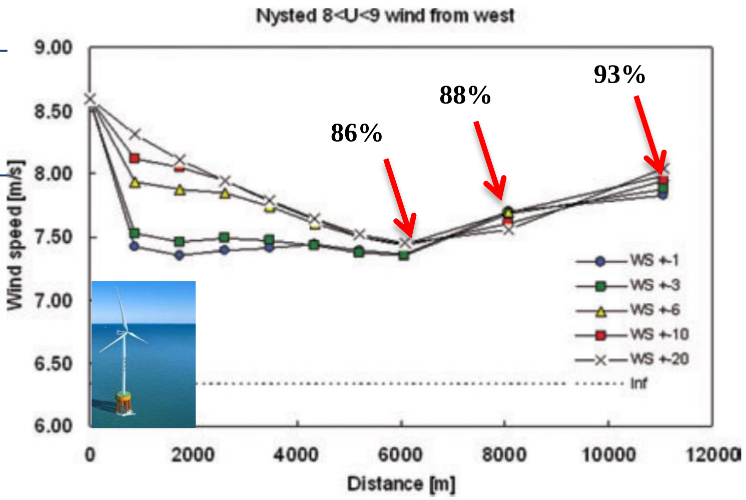


Figure 10. Variation of the mean wind speed through and behind the wind farm at Nysted, at a hub height of 70 m.

The different curves correspond to width of wind direction sectored entered into the averaging from ±1 °from the wake centre to ±20 °

[16] Frandsen S T, Jorgensen H E, Barthelmie R, et al. The making of a second generation wind farm efficiency model complex [J]. Wind Energy, 2009,12: 445-458.

风电场（群）对风速的影响

中尺度模型（KAMM）的模拟结果[16] Frandsen

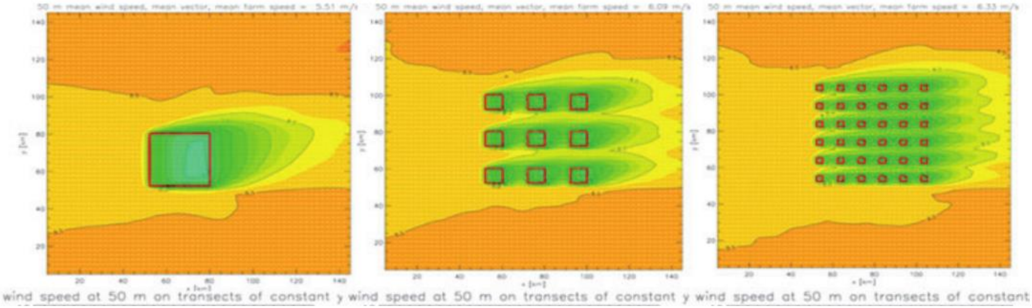


Table I. Configuration of the KAMM mesoscale model runs

Number of wind farms	Size of wind turbine group (km)	Distance between wind turbine groups (km)
1	30 × 30	—
9	10 × 10	10
36	5 × 5	5

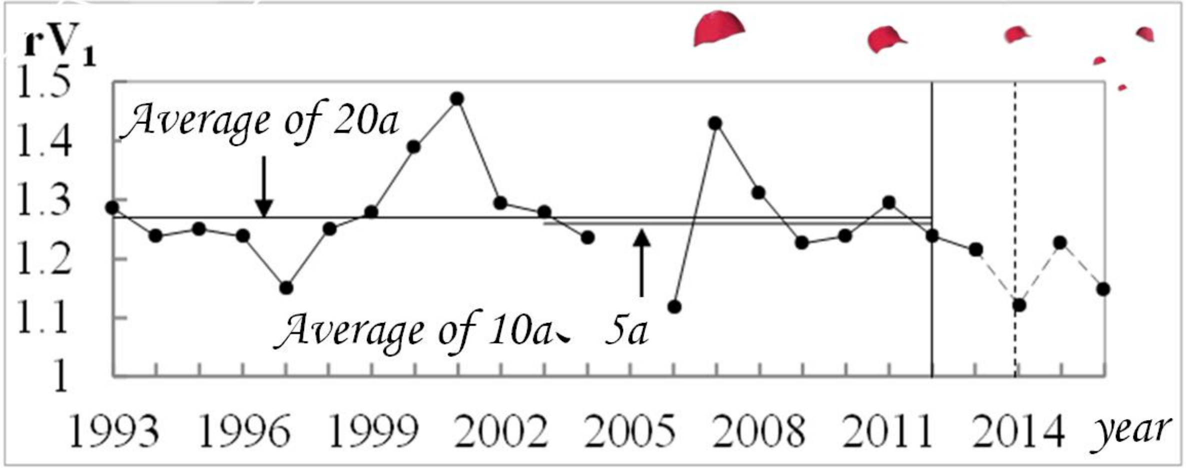
Figure 11. The mean wind speed for the three wind farm configurations along 61 northing transects.

- The downwind wind speed recovery or wake decay looks similar in all configurations.
- Recovery to flow speed upwind of the turbine groups takes approximately 30–60 km.
- When the distance between turbine groups is small, there is a reduced recovery.

[16] Frandsen S T, Jorgensen H E, Barthelmie R, et al. The making of a second generation wind farm efficiency model complex [J]. Wind Energy, 2009,12: 445-458.

风电场（群）对风速的影响

课题组研究结果[*]Zhang 湖北省大悟山区风电场群



rV₁

2012

0.05

small effect

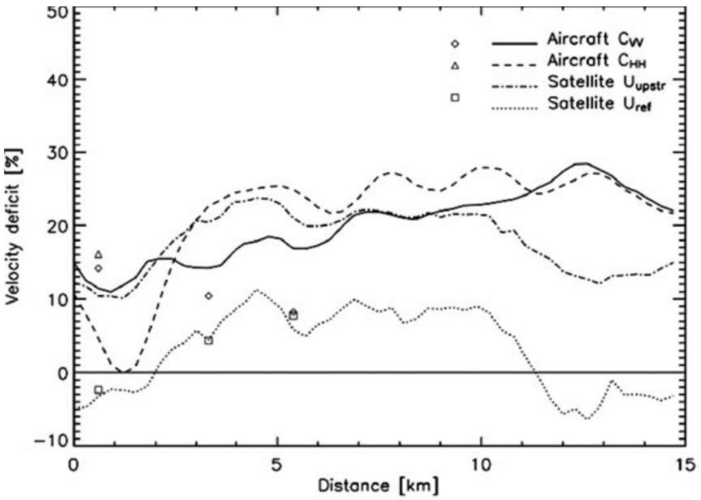
$$rV_1 = V_{Dawu}/V_{Huangpi}$$

The ratio of wind speed has changed since 2012.

风电场（群）对风速的影响

合成孔径雷达(SAR)观测结果［6］Christiansen

The aircraft SAR and the SAR on board the ERS-2 satellite:two large scale offshore wind farms : Horns Rev in the North Sea and Nysted in the Baltic.



$$\mathrm{VD} = \frac{U_{\text{freestream}} - U_{\text{wake}}}{U_{\text{freestream}}} \times 100\%$$

C vv and **C HH** are vertically and horizontally polarized C-band SAR measurements respectively.
U upstr indicates that SAR-retrieved wind speeds were normalized with the wind speed upstream of the wind farm；
U ref that a parallel reference transect was used for normalization

Figure.12 Average velocity deficit for wind-aligned tracks (line plots) and for the overlapping area of crosswind tracks

- Aircraft SAR suggested average velocity deficits of ~10% were found downstream of the large offshore WF
- Aircraft tracks showed : VD increased with downstream distance and fluctuations of the order of ±5% were seen.
- Towards the end of transects (10–15km) the satellite SAR data showed a decrease in VD, which was not observed for the air-craft SAR data.

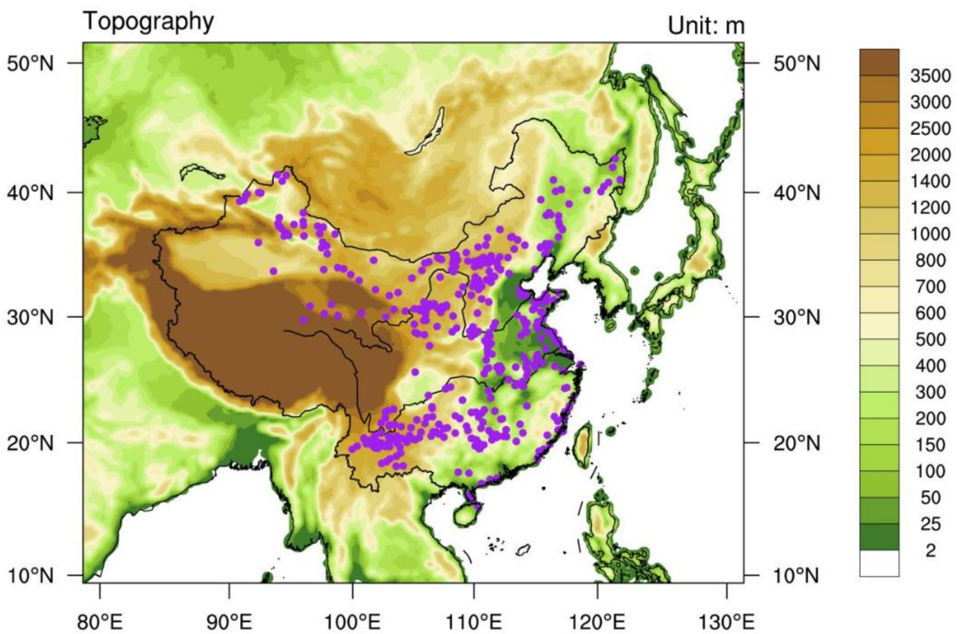
[6] Christiansen MB, Hasager CB. Using airborne and satellite SAR for mapping offshore[J]. Wind Energy 2006;9:437–55.

风电场（群）对风速的影响

主要是影响机理 [5] **Sun**

WRF model- A new wind farm fleet

CTL: no wind farms
SCEN1 (722WFs)
momentum sink
+TKE source
SCEN2 (722WFs)
momentum sink



2015

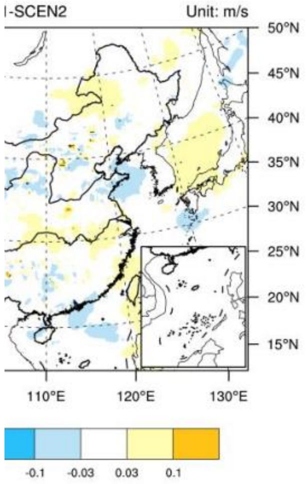


Figure 13. Dif **different simulations.**

Figure a and e shows statistically significant decreases of 100-m horizontal wind speed; whereas there is tiny changes in 100-m horizontal wind speed in Figure 3c

Tiny changes of 100-m horizontal wind speed in Figure 3c, (result from the redistribution of TKE), is much smaller than the changes of 100-m horizontal wind speed (result from the momentum sink) **动量吸收是影响风速的主要机理**

[5] Hongwei Sun, Yong Luo, Zongci Zhao, et al. The impacts of Chinese wind farms on climate. JGR-atmospheres. doi: 10.1029/2017JD028028. Online. .

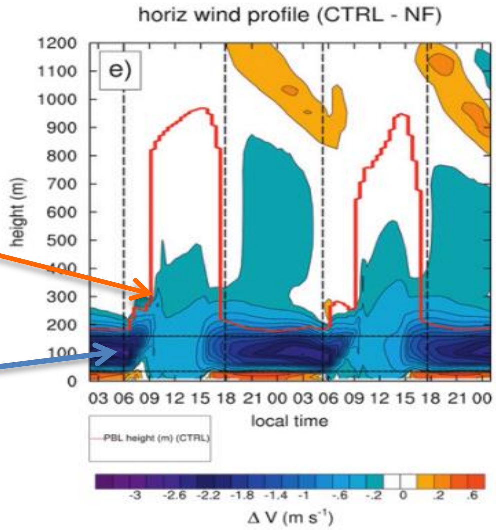
风速影响的时空变化

时间变化 [4] Fitch WRF:A large wind farm of size 10 km ×10 km is placed at the center of the fine grid, consisting of 100 turbines, each with a nominal power output of 5 MW. These turbines have a hub height of 100 m, and a blade diameter of 126 m.

Over the WF

1100LT:
0.2 m s^{-1} (3.5% off)

0600LT:
2.4 m s^{-1} (22% off)



CTRL: with a wind farm covering 10 kmx10km, consisting of 100 turbines, each with a nominal power output of 5 MW

NF: with no wind farm

Vertical dashed lines indicate sunrise and sunset times; **horizontal lines** indicate the extent of the rotor area.

Figure.14 Evolution of mean wind profiles and PBL height over the wind farm area: the difference in wind speed.

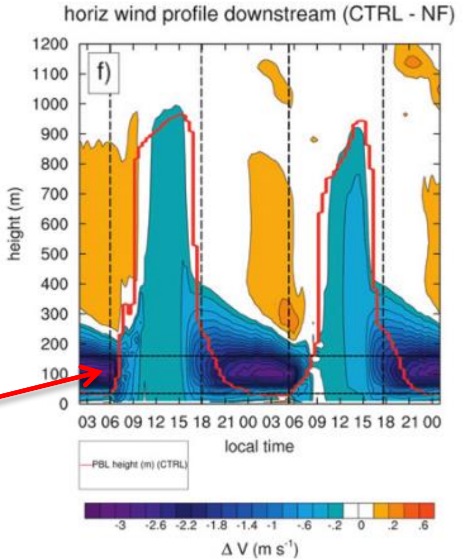
- **Periodism:** The greatest reduction in the wind is seen during the night. The wind reduction is smallest during the middle of the day.

[4] Fitch AC, Lundquist JK, Olson JB. Mesoscale Influences of Wind Farms throughout a Diurnal Cycle[J]. American Meteorological Society 2013;141:2173–98.

风速影响的时空变化

空间变化 [4]

10–20 km downwind of the WF



0600LT:
3.0m s $^{-1}$ (28% off)

Figure.15 Evolution of mean wind profiles and PBL height :the difference in wind speed.

- The greatest reduction of the wind at hub height is seen in the hours before dawn.
- The downwind reduction averaged over an area 10–20 km downwind is larger than that averaged over the area of the farm.

[4] Fitch AC, Lundquist JK, Olson JB. Mesoscale Influences of Wind Farms throughout a Diurnal Cycle[J]. American Meteorological Society 2013;141:2173–98.

总结

- 研究表明，风电场运行过程中，随着表面摩擦增加，风电场及下风区域存在风速亏损，风速恢复需要一定距离。

- 轮毂高度的风速亏损在夜间大于白天。

- 动量下降所造成的风速亏损远远大于湍流动能的产生（TKE）。

风电场（群）对降水的影响

对一年（1984）降水量的影响[10] Fiedler

WRF-A giant wind farm is covering 182700 km 2 in the central USA. The turbine density is 1.25 turbines per square kilometer, for a total of 228375 wind turbines. The 2.0 MW turbine with a 60 m hub height and a 76 m rotor diameter, resulting in an installed capacity of 0.457 TW.

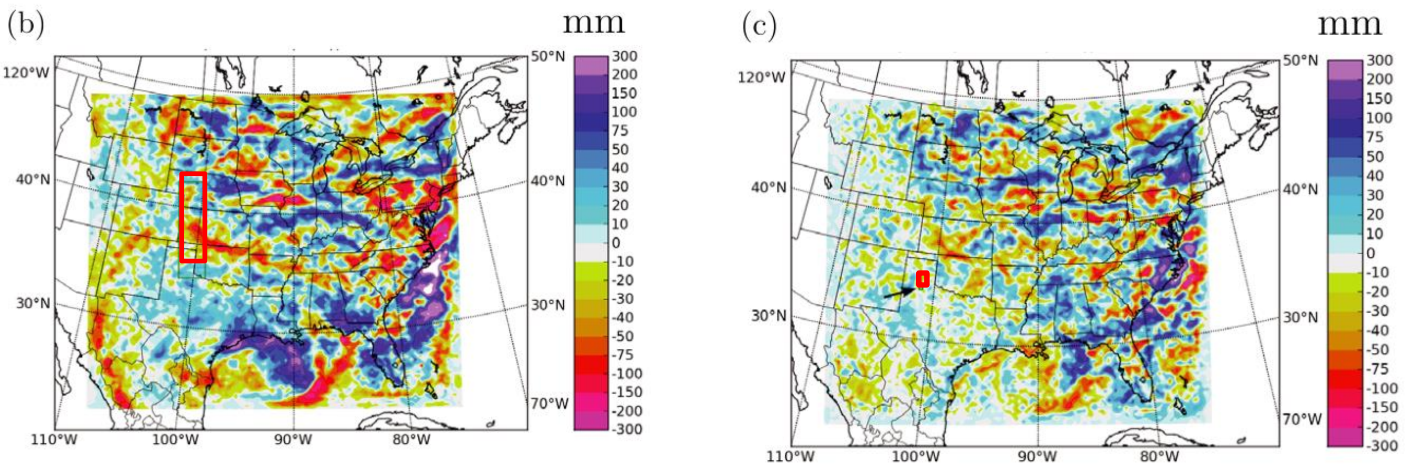


Figure 16. 1984 precipitation difference climatology: (b) warm season with giant wind farm (c) warm season with tiny (one-grid-point) wind farm.

- The presence of a wind farm can trigger the difference between drought and prcipitation for the season.
- figure 15(c) shows that a one-grid-point wind farm has an effect almost as large as the giant wind farm.

[10] Fiedler BH, Bukovsky MS. The effect of a giant wind farm on precipitation in a regional climate model[J]. Environ Res Lett 2011;6 7-7

风电场（群）对降水的影响

对62年降水量的影响 (1948-2009) [10] Fiedler

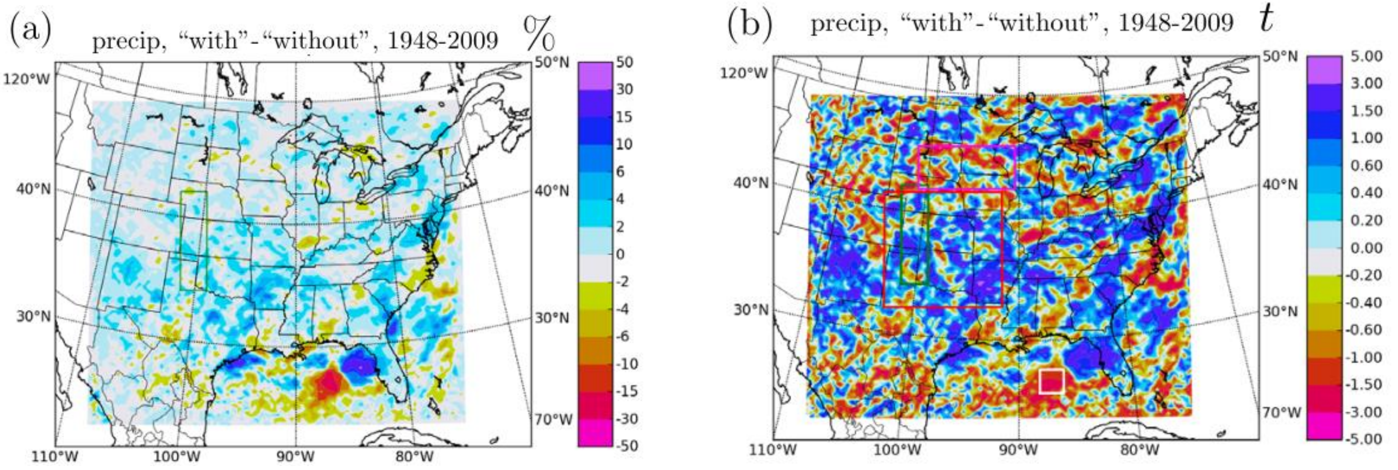


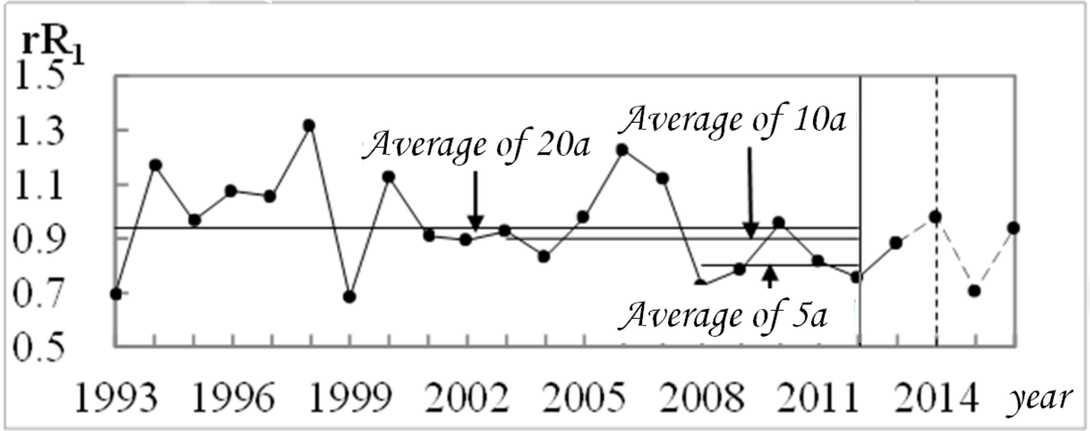
Figure 17. 62 yr precipitation differences as in figure 1(b), (a) as a percent (b) as a t -value from (4). The statistical significance of the average precipitation difference within the red, magenta and white box is investigated. [12].

- In the average precipitation of 62 warms seasons, there is a statistically significant 1.0% enhancement of precipitation surrounding and to the south-east(the red box) of the wind farm.
- The reason may be that the wind farm somewhat retards the advection of drier air from the northwest.

[10] Fiedler BH, Bukovsky MS. The effect of a giant wind farm on precipitation in a regional climate model[J]. Environ Res Lett 2011;6 7-7

风电场（群）对降水的影响

课题组研究结果[*]Zhang 湖北省大悟山区风电场群



$rR_1 = R_{Dawu}/R_{Hongan}$

rR_1

No mutation occurred after wind farms operation

no apparent impact

无显著影响！

The effect of wind farm group on precipitation is indistinctive.

风电场（群）对湿度的影响

现场观测数据的分析结果 [17] Armstrong Black Law Wind Farm, Scotland,comprises 54 turbines within 18.6 km^2. The turbine blade hub heights are approximately 70 m, the rotor diameter 82 m and the total capacity is 124 MW.

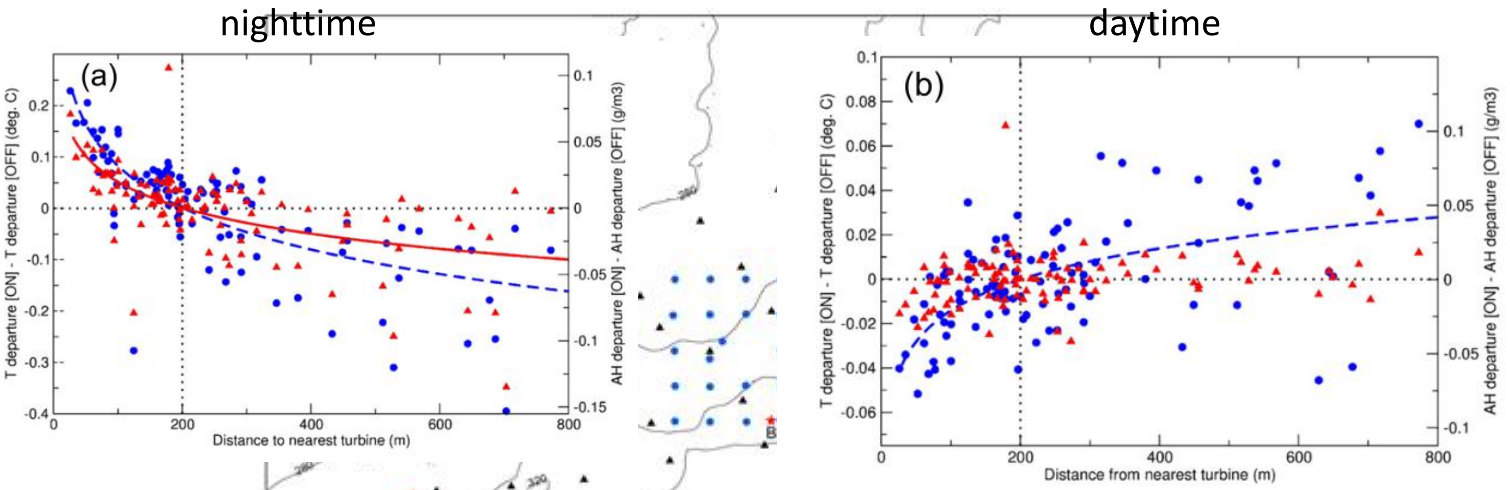


Figure 18. The effect of distance(x) from the nearest turbine on the temperature and AH departure

- During the night, air closer to a wind turbine was warmer and more moist, with TA departures reaching 0.25 ℃ and AH departures 0.1 g /m^3
- The daytime ΔAH cannot be approximated by a logarithmic function ($r < 0.2$).

[17] Alona Armstrong, Ralph R Burton, Susan E lee, *et al*. Ground-level climate at a peatland wind farm in Scotland is affected by wind turbine operation[J]. Environmental Research Letters, 2016, 11(4):044024.

风电场（群）对湿度的影响

现场数据的分析结果 [17] Armstrong

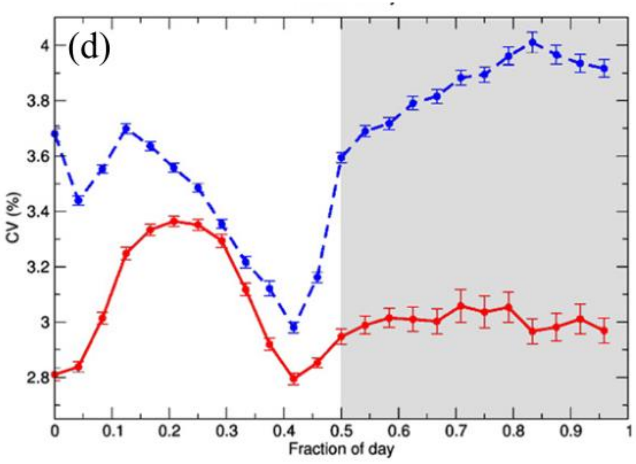


Figure 19. Diurnal variations in AH differ during wind farm operational and idle periods.

Table 1. Temperature and absolute humidity differences between sites downwind and not downwind from turbines for three direction sectors during the night time.

Direction sector	T, ON, Night		T, OFF, Night		AH, ON, Night		AH, OFF, Night	
	p	Difference	*p*	Difference	*p*	Difference	*p*	Difference
200–220	<0.01	0.18	ns	0.04	<0.01	0.03	ns	0.00
220–240	<0.01	0.16	ns	−0.03	ns	0.00	ns	−0.03
280–300	ns	−0.06	ns	0.05	ns	0.03	ns	0.04

- The difference in AH variability between the ON and OFF periods was greater during night than day.
- The AH of air downwind of the turbines was, on average, 0.03 g/m^3 greater during the ON period ($p < 0.01$) for the 200–220° direction sector (approximately the dominant wind direction).

[17] Alona Armstrong, Ralph R Burton, Susan E lee, *et al*. Ground-level climate at a peatland wind farm in Scotland is affected by wind turbine operation[J]. Environmental Research Letters, 2016, 11(4):044024.

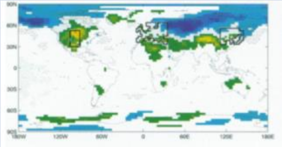
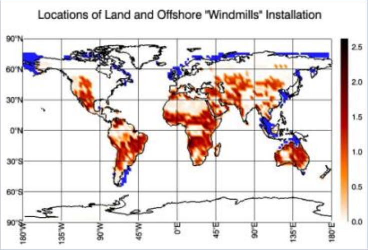
PAPT 05

全球气候效应

全球气候效应研究

风力发电场的全球气候变化数据难以获取，相关研究相对较少。问题如下:

- 风力发电场对气候有广泛的影响吗?
- 评价方法?
- 如何量化效果?

作者	研究方法	模拟情景	结论
David W. Keith [14]	alter surface drag coefficients in NCAR and GFDL	The array covers 10% of the global land surface. 	• The change in global-mean surface air temperature is negligible; • Regional peak-seasonal responses exceed ±2° C; • The climatic changes are too small to detect in the presence of other anthropogenic change and natural climate variability.
Maria [18]	Blade Element Momentum Model	Two scenarios are examined A: replace all fossil fuel energy globally in wind B:replace all onroad vehicles	• Relative energy losses in L1 above global land range from 0.06%–0.08%, and those above global land plus ocean range from 0.006%–0.008% • Such losses are also estimated to be at least an order of magnitude less than energy losses due to aerosol pollution and urbanization.
Chien. Wang Ronald G Prinn [13]	a fully coupled atmosphere-ocean-land system model (CCM3 with a mixed layer ocean)	Using wind turbines to meet 10% or more of global energy demand in 2100 	• The computed air temperature over the installation regions is elevated by more than 1 ◦ C in the lowest model layer (~30m thick at sea level) in many regions, but the increase, averaged over the entire global land surface, is only about 0.15 ◦ C. • Although the surface air temperature change is dominated by the increase over the wind turbine-installed areas ,the changes go well beyond these areas. • Although the changes in local convective and large-scale precipitation exceed 10% in some areas, the global average changes are not very large.

总结

- 全球平均值的变化是可以忽略不计的，然而一些地区的峰值-季节性可能是相当大的;
- 气候变化比其他人为变化和自然气候变化小得多。

PAPT 06

总结与讨论

目前研究存在的问题：

现有研究结果显示:

- 风电场对气候的影响不仅局限于风电场区域，还可能影响区域乃至全球气候。
- “低影响”风电发展可以从技术层面进行探讨。
- 大型风电场对气候变化影响的定量研究基于模型模拟，结果不确定。

展望

随着风电场的快速发展，风电场对气候的影响需要进一步研究，下一步研究方向可能是:

- 通过对引入机制的研究，建立了一种更合适的物理模型。
- 对观测数据进行实地调研和分析，进一步验证、修正数值模型中参数设置。
- 持续进行定量研究，探索全球风电发展的最大程度。

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谢谢!