The effect of a giant wind farm on precipitation in 62 years of WRF warm-season simulations

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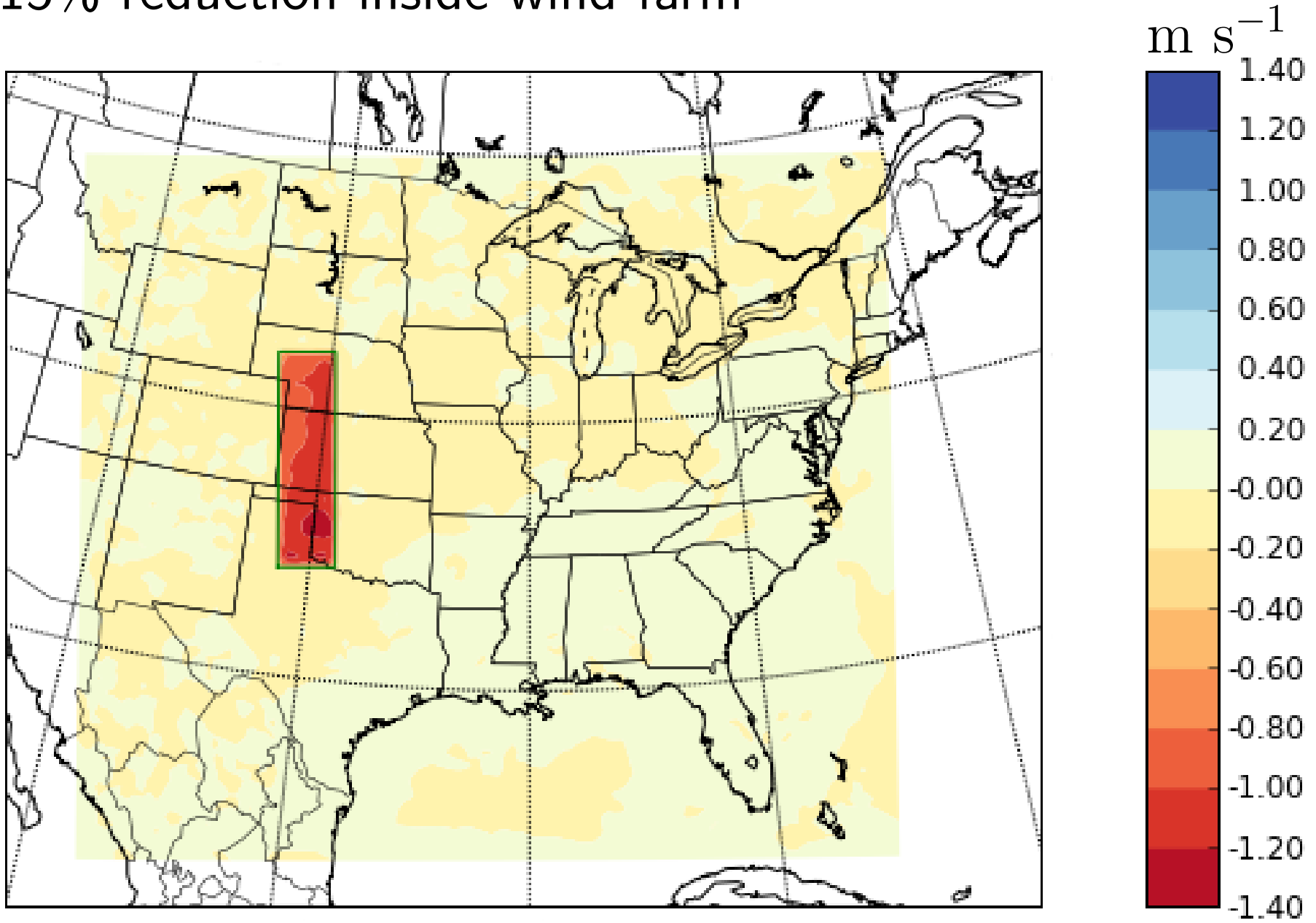
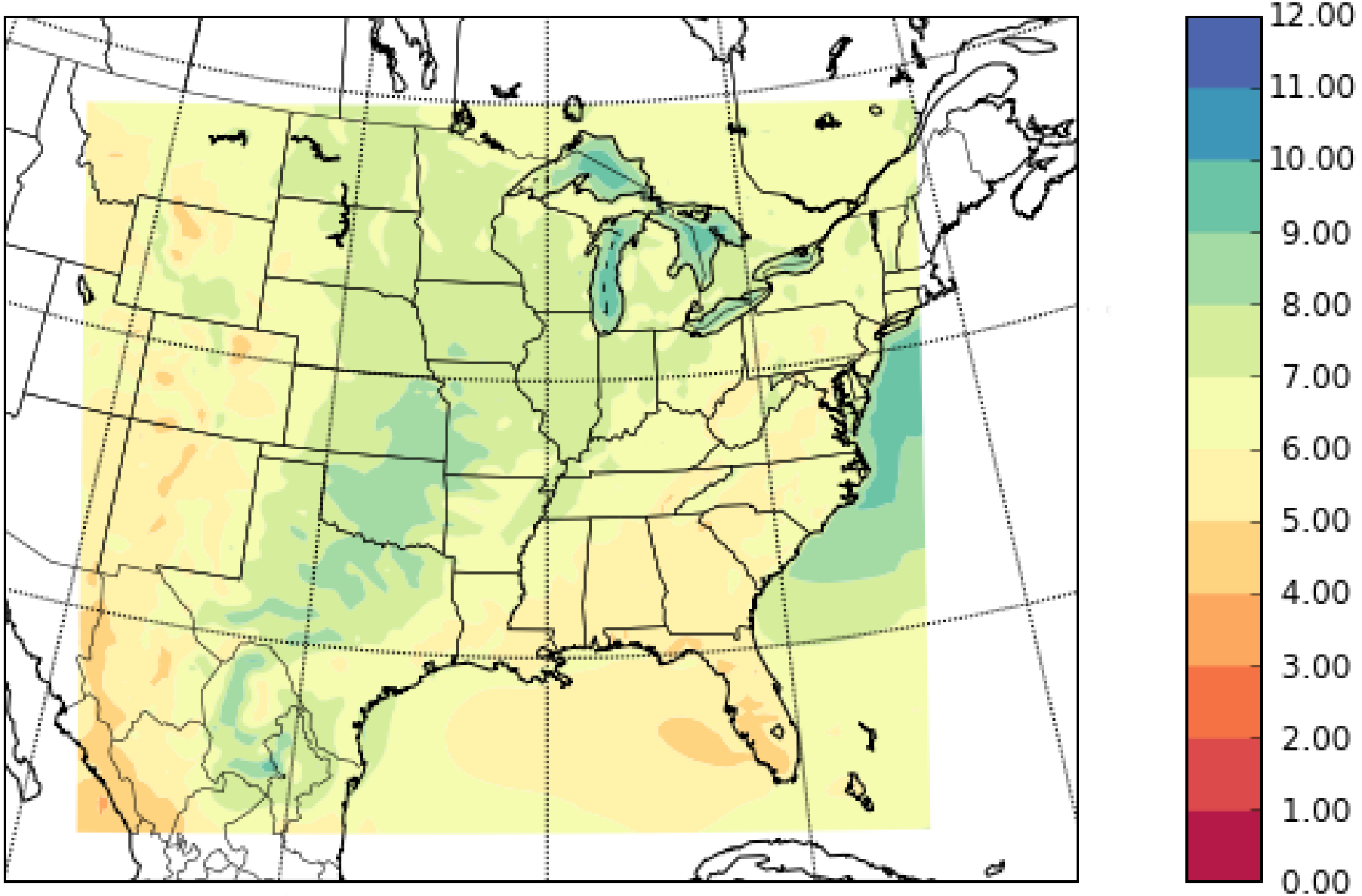
- WRF 30 km resolution
- Nested in May-June-July-August Reanalysis Data for 1948-2009
- Adams & Keith wind farm parameterization
- Bukovsky & Adams WRF configuration

1948-2009 average wind speed change at 100 m

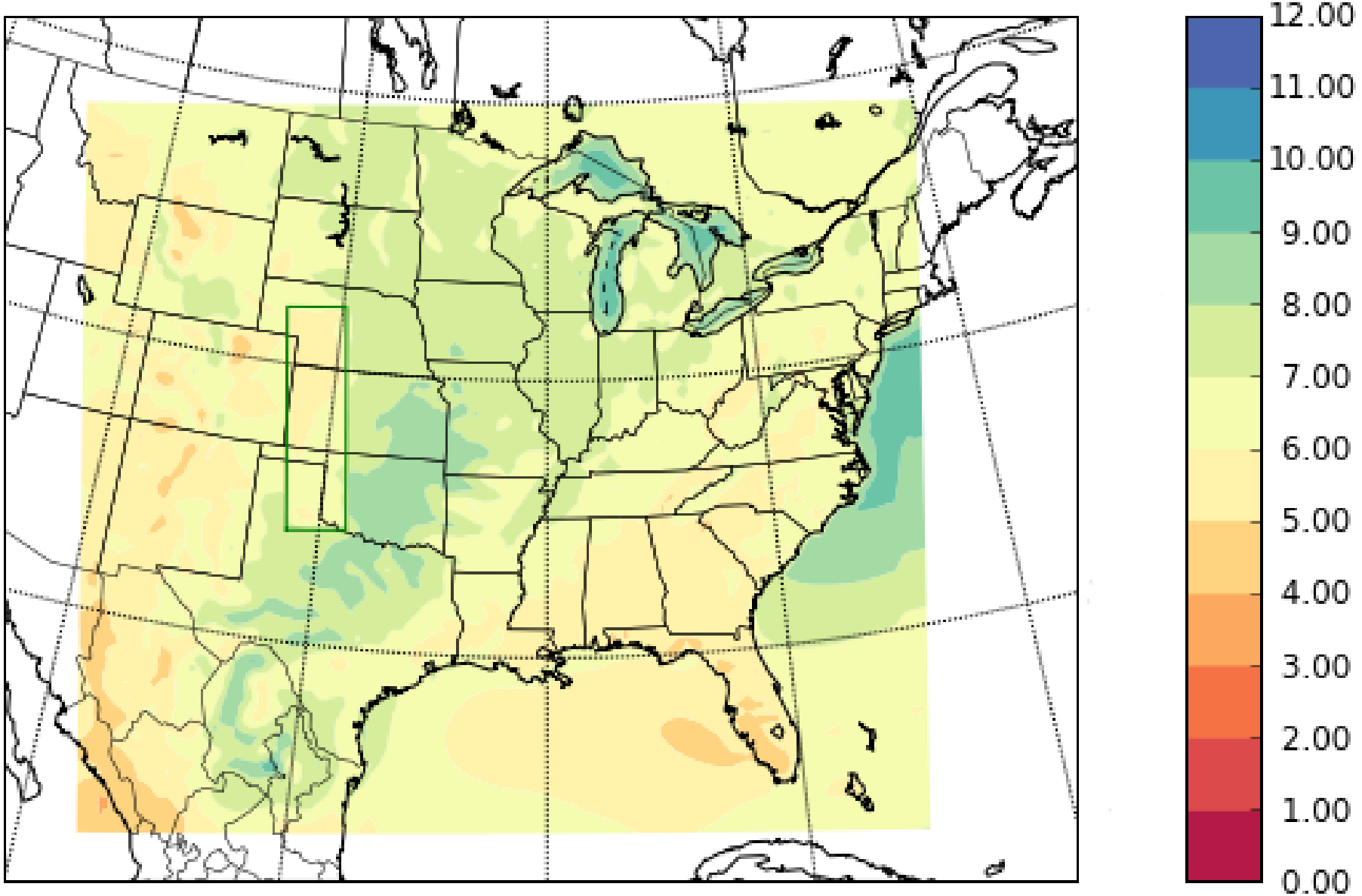
15% reduction inside wind farm



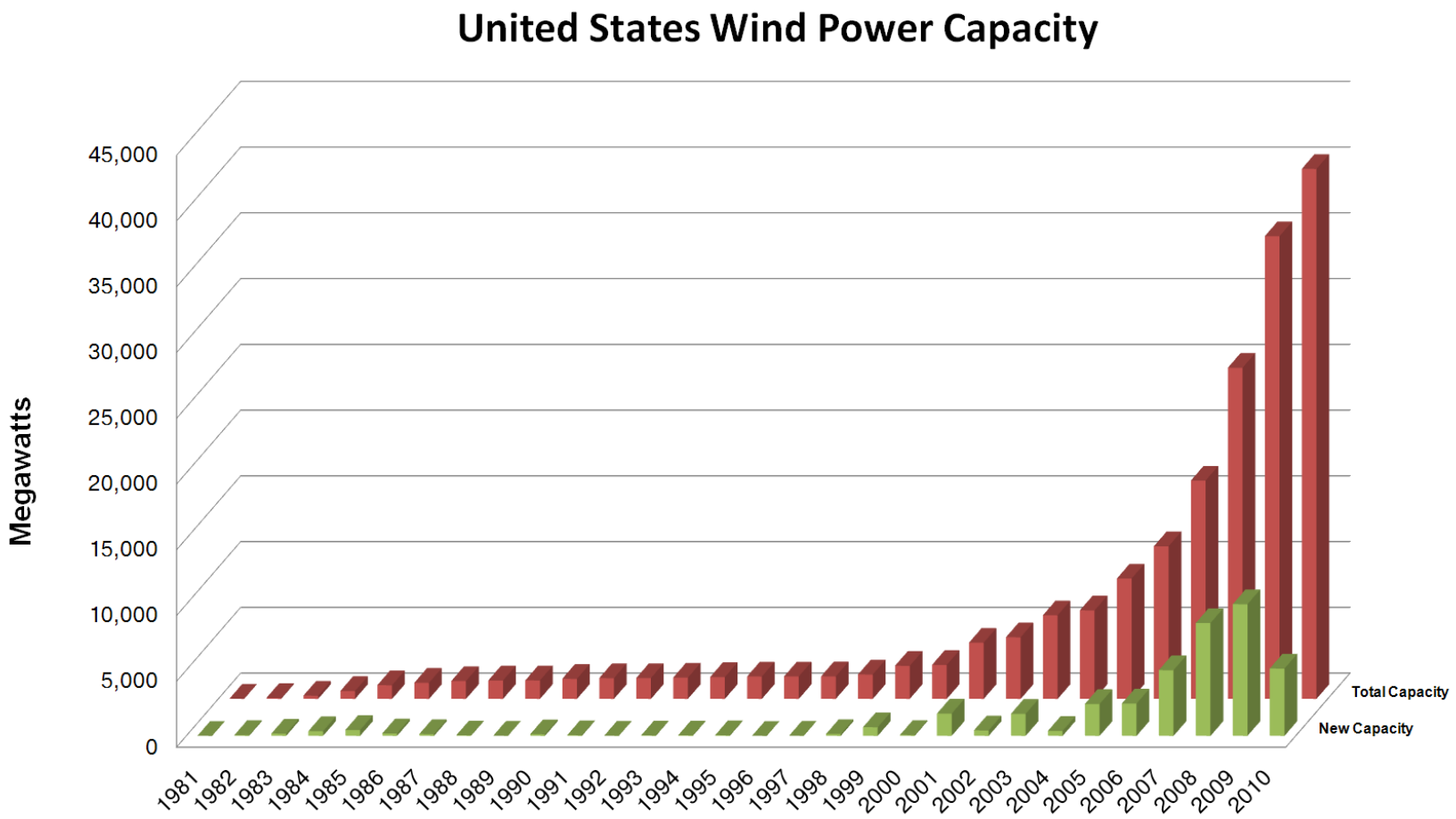
NO windfarm

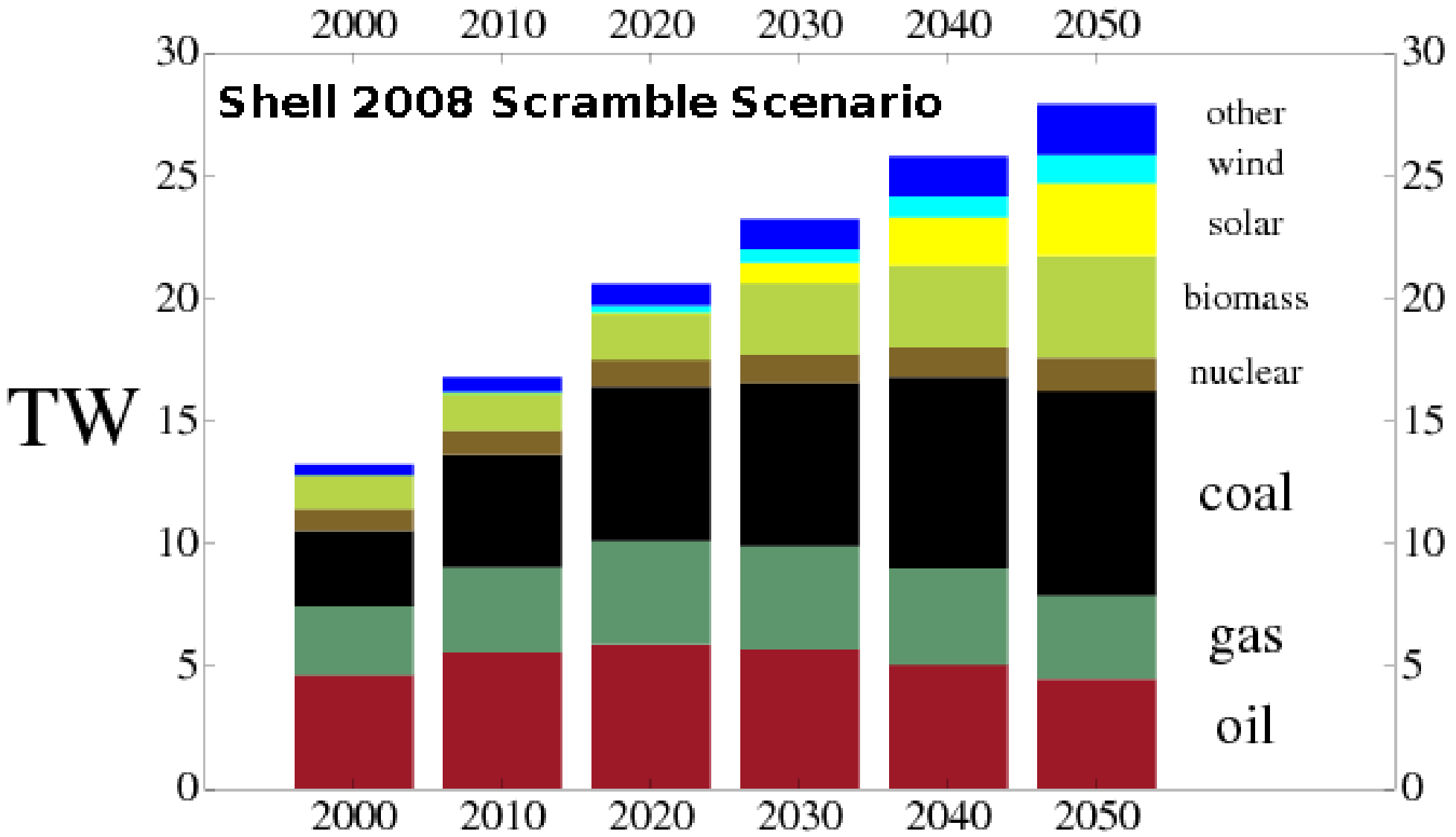


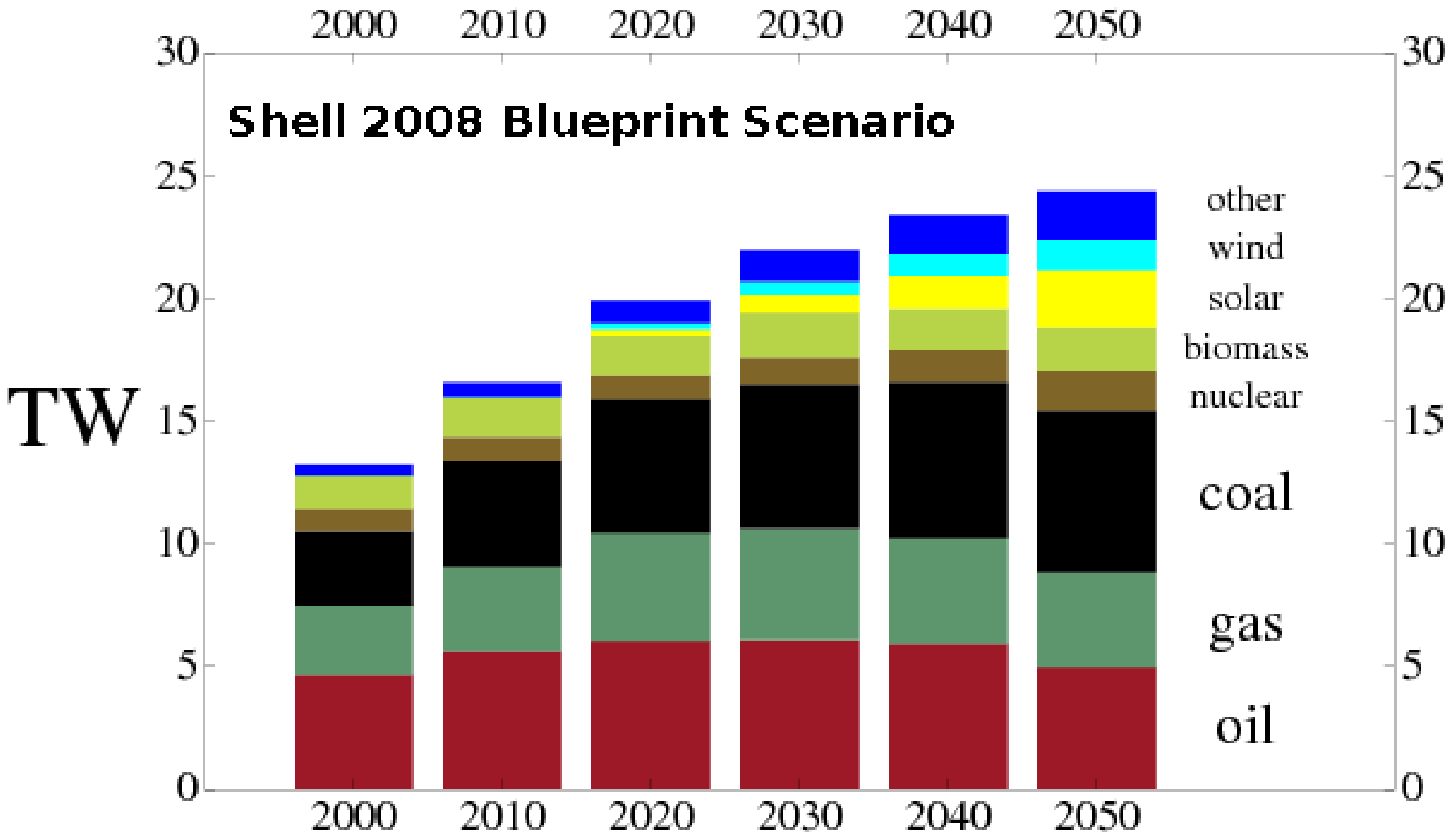
WITH windfarm



- 228,375 2.0 MW turbines = 0.457 TW capacity
- 1.25 turbines per km^2
- expected production 0.457 TW $\times$ 20% = 0.091 TW
- would supply 0.6% of the world's power of 15 TW
- at optimistic \$3 per MW, total cost is 1.3 trillion \$


United States Wind Power Capacity
Megawatts
45,000
40,000
35,000
30,000
25,000
20,000
15,000
10,000
5,000
0
1981
1982
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
Total Capacity
New Capacity


Shell 2008 Scramble Scenario
TW
2000
2010
2020
2030
2040
2050
0
5
10
15
20
25
30
other
wind
solar
biomass
nuclear
coal
gas
oil


Shell 2008 Blueprint Scenario
TW
2000
2010
2020
2030
2040
2050
0
5
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15
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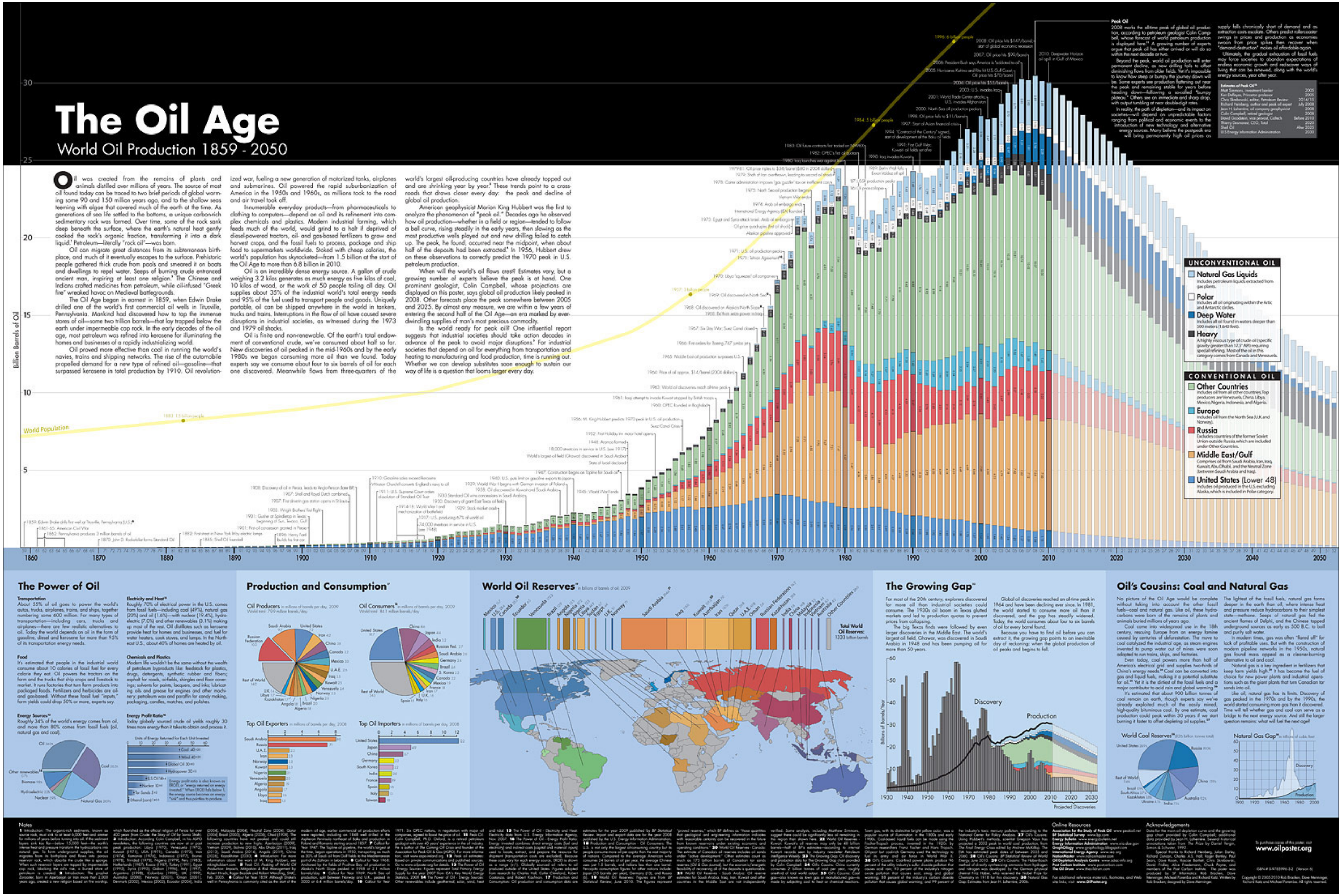
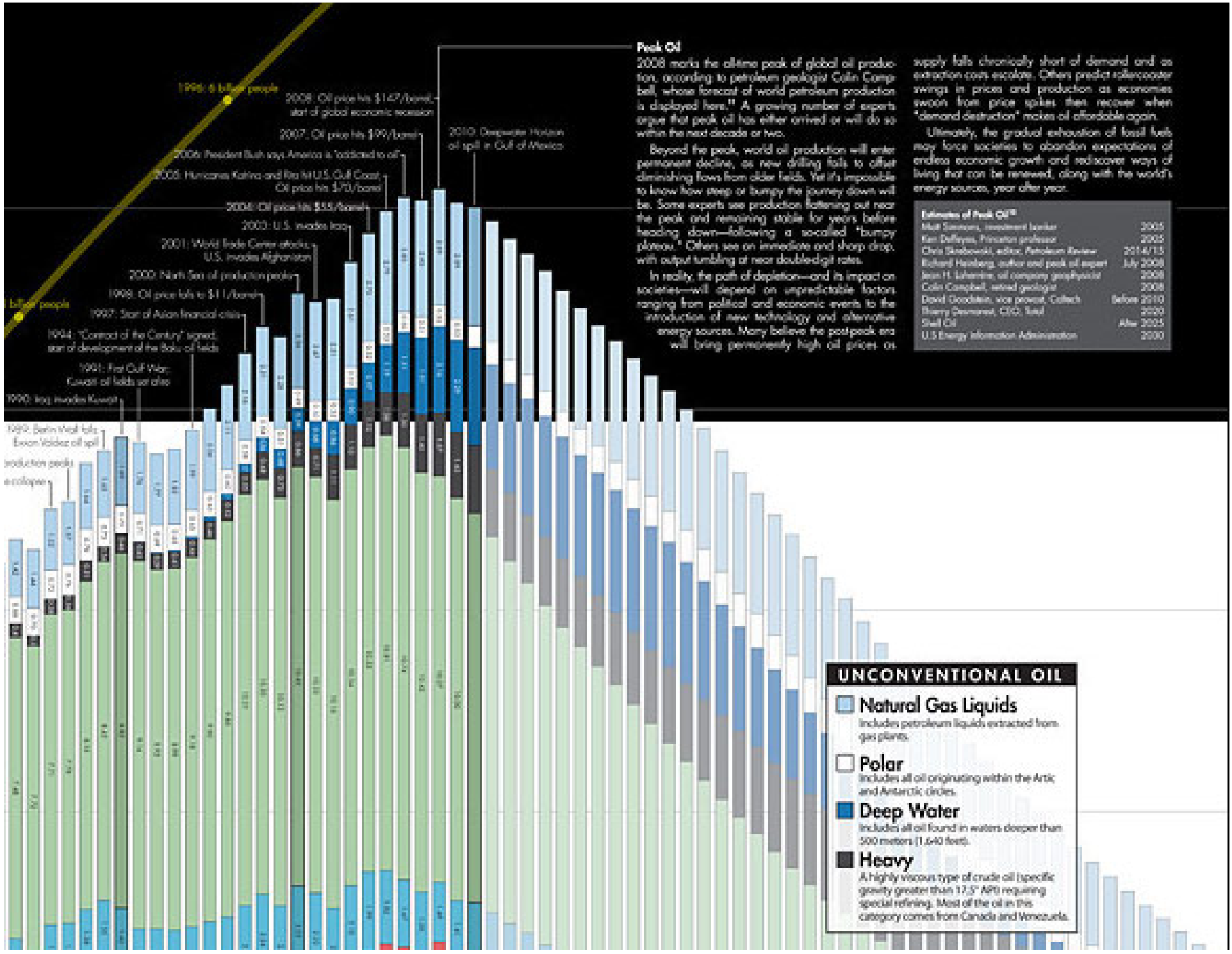
other
wind
solar
biomass
nuclear
coal
gas
oil



The Oil Age
World Oil Production 1859 - 2050
Oil was created from the remains of plants and animals distilled over millions of years. The source of most oil found today can be traced to two brief periods of global warming some 90 and 150 million years ago, and to the shallow seas teeming with algae that covered much of the earth at the time. As generations of sea life settled to the bottoms, a unique carbon-rich sedimentary rock was formed. Over time, some of the rock sank deep beneath the surface, where the earth's natural heat gently cooked the rock's organic fraction, transforming it into a dark liquid.[1] Petroleum—literally "rock oil"—was born.
Oil can migrate great distances from its subterranean birthplace, and much of it eventually escapes to the surface. Prehistoric people gathered thick crude from pools and smeared it on boats and dwellings to repel water. Seeps of burning crude entranced ancient man, inspiring at least one religion.[2] The Chinese and Indians crafted medicines from petroleum, while oil-infused "Greek fire" wreaked havoc on Medieval battlegrounds.
The Oil Age began in earnest in 1859, when Edwin Drake drilled one of the world's first commercial oil wells in Titusville, Pennsylvania. Mankind had discovered how to tap the immense stores of oil—some two trillion barrels—that lay trapped below the earth under impermeable cap rock. In the early decades of the oil age, most petroleum was refined into kerosene for illuminating the homes and businesses of a rapidly industrializing world.
Oil proved more effective than coal in running the world's navies, trains and shipping networks. The rise of the automobile propelled demand for a new type of refined oil—gasoline—that surpassed kerosene in total production by 1910. Oil revolutionized war, fueling a new generation of motorized tanks, airplanes and submarines. Oil powered the rapid suburbanization of America in the 1950s and 1960s, as millions took to the road and air travel took off.
Innumerable everyday products—from pharmaceuticals to clothing to computers—depend on oil and its refinement into complex chemicals and plastics. Modern industrial farming, which feeds much of the world, would grind to a halt if deprived of diesel-powered tractors, oil- and gas-based fertilizers to grow and harvest crops, and the fossil fuels to process, package and ship food to supermarkets worldwide. Stoked with cheap calories, the world's population has skyrocketed—from 1.5 billion at the start of the Oil Age to more than 6.8 billion in 2010.
Oil is an incredibly dense energy source. A gallon of crude weighing 3.2 kilos generates as much energy as five kilos of coal, 10 kilos of wood, or the work of 50 people toiling all day. Oil supplies about 35% of the industrial world's total energy needs and 95% of the fuel used to transport people and goods. Uniquely portable, oil can be shipped anywhere in the world in tankers, trucks and trains. Interruptions in the flow of oil have caused severe disruptions in industrial societies, as witnessed during the 1973 and 1979 oil shocks.
Oil is finite and non-renewable. Of the earth's total endowment of conventional crude, we've consumed about half so far. New discoveries of oil peaked in the mid-1960s and by the early 1980s we began consuming more oil than we found. Today experts say we consume about four to six barrels of oil for each one discovered. Meanwhile flows from three-quarters of the world's largest oil-producing countries have already topped out and are shrinking year by year.[3] These trends point to a crossroads that draws closer every day: the peak and decline of global oil production.
American geophysicist Marion King Hubbert was the first to analyze the phenomenon of "peak oil." Decades ago he observed how oil production—whether in a field or region—tended to follow a bell curve, rising steadily in the early years, then slowing as the most productive wells played out and new drilling failed to catch up. The peak, he found, occurred near the midpoint, when about half of the deposits had been extracted.[4] In 1956, Hubbert drew on these observations to correctly predict the 1970 peak in U.S. petroleum production.
When will the world's oil flows crest? Estimates vary, but a growing number of experts believe the peak is at hand. One prominent geologist, Colin Campbell, whose projections are displayed on this poster, says global oil production likely peaked in 2008. Other forecasts place the peak somewhere between 2005 and 2025. By almost any measure, we are within a few years of entering the second half of the Oil Age—an era marked by ever-dwindling supplies of man's most precious commodity.
Is the world ready for peak oil? One influential report suggests that industrial societies should take action decades in advance of the peak to avoid major disruptions.[5] For industrial societies that depend on oil for everything from transportation and heating to manufacturing and food production, time is running out. Whether we can develop substitutes soon enough to sustain our way of life is a question that looms larger every day.
Billion Barrels of Oil
World Population
Peak Oil
UNCONVENTIONAL OIL
Natural Gas Liquids
Polar
Deep Water
Heavy
CONVENTIONAL OIL
Other Countries
Europe
Russia
Middle East/Gulf
United States (Lower 48)
The Power of Oil
Production and Consumption
World Oil Reserves
The Growing Gap
Discovery
Production
Oil's Cousins: Coal and Natural Gas
Notes
Online Resources
Acknowledgements
www.oilposter.org



Peak Oil

2008 marks the all-time peak of global oil production, according to petroleum geologist Colin Campbell, whose forecast of world petroleum production is displayed here.** A growing number of experts argue that peak oil has either arrived or will do so within the next decade or two.

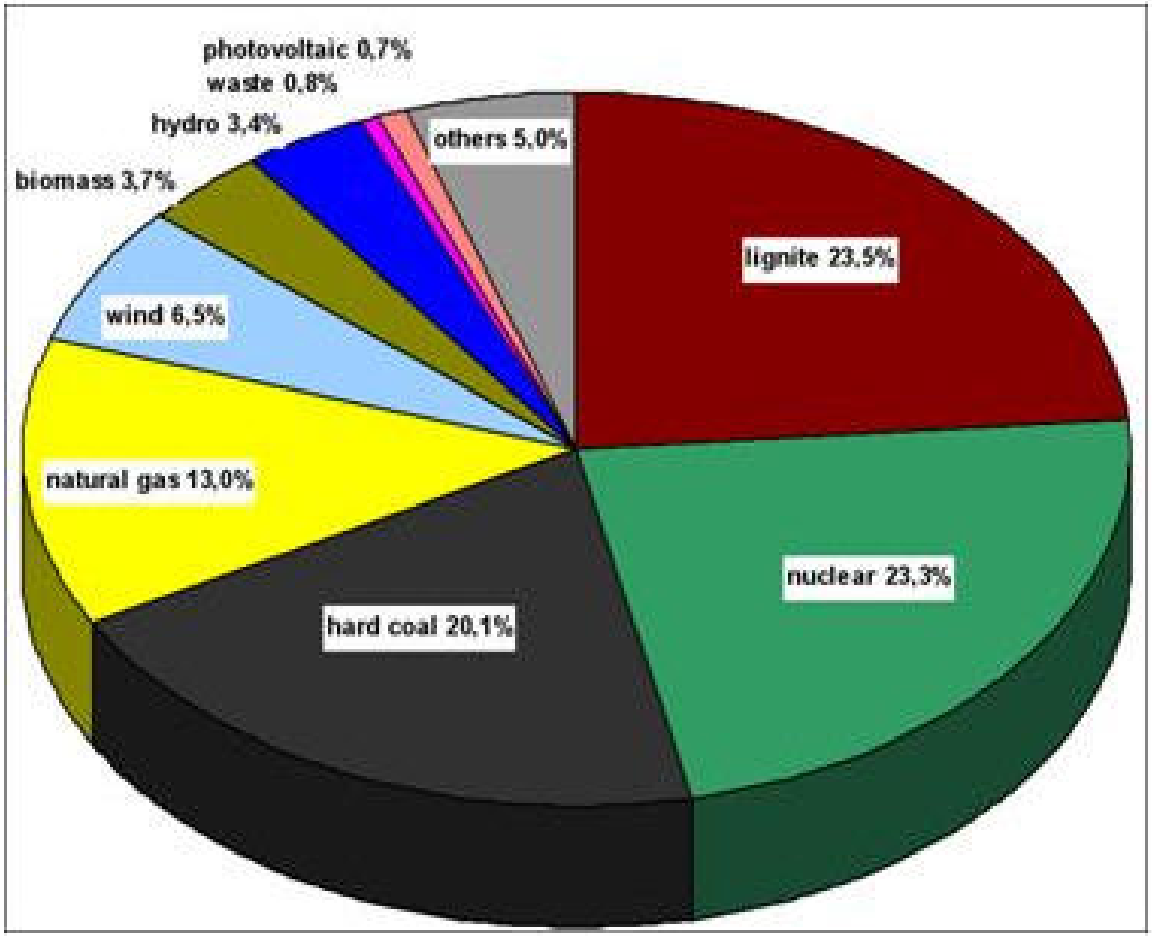
Beyond the peak, world oil production will enter permanent decline, as new drilling fails to offset diminishing flows from older fields. Yet it's impossible to know how steep or bumpy the journey down will be. Some experts see production flattening out near the peak and remaining stable for years before heading down—following a so-called "bumpy plateau." Others see an immediate and sharp drop, with output tumbling at near double-digit rates.

In reality, the path of depletion—and its impact on societies—will depend on unpredictable factors ranging from political and economic events to the introduction of new technology and alternative energy sources. Many believe the post-peak era will bring permanently high oil prices as supply falls chronically short of demand and as extraction costs escalate. Others predict rollercoaster swings in prices and production as economies swoon from price spikes then recover when "demand destruction" makes oil affordable again.

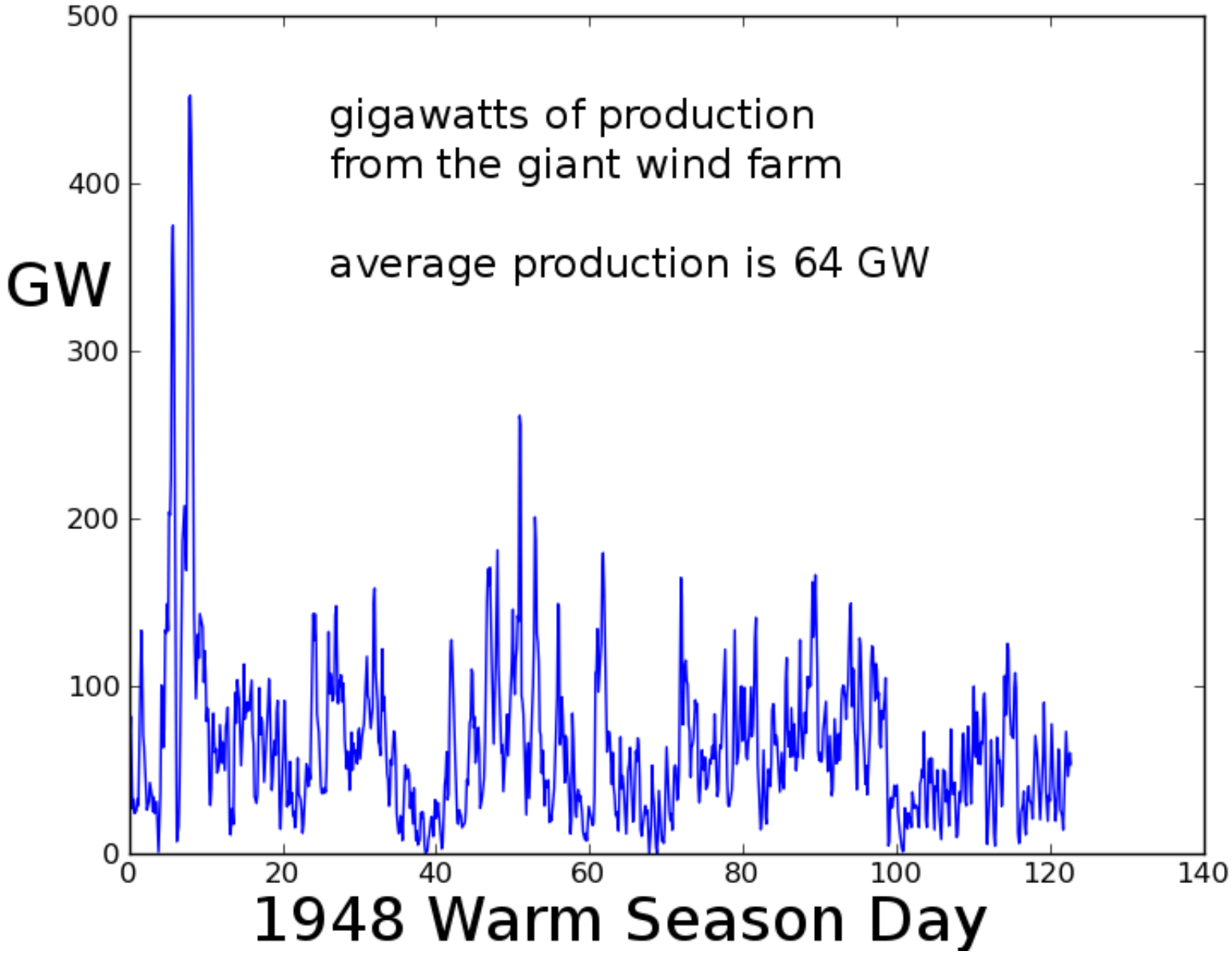
Ultimately, the gradual exhaustion of fossil fuels may force societies to abandon expectations of endless economic growth and rediscover ways of living that can be renewed, along with the world's energy sources, year after year.

Estimates of Peak Oil[1]

Matt Simmons, investment banker	2005
Ken Deffeyes, Princeton professor	2005
Chris Skrebowski, editor, *Petroleum Review*	2014/15
Richard Heinberg, author and peak oil expert	July 2008
Jean H. Laherrère, oil company geophysicist	2008
Colin Campbell, retired geologist	2008
David Goodstein, vice provost, Caltech	Before 2010
Thierry Desmarest, CEO, Total	2020
Shell Oil	After 2025
U.S Energy Information Administration	2030

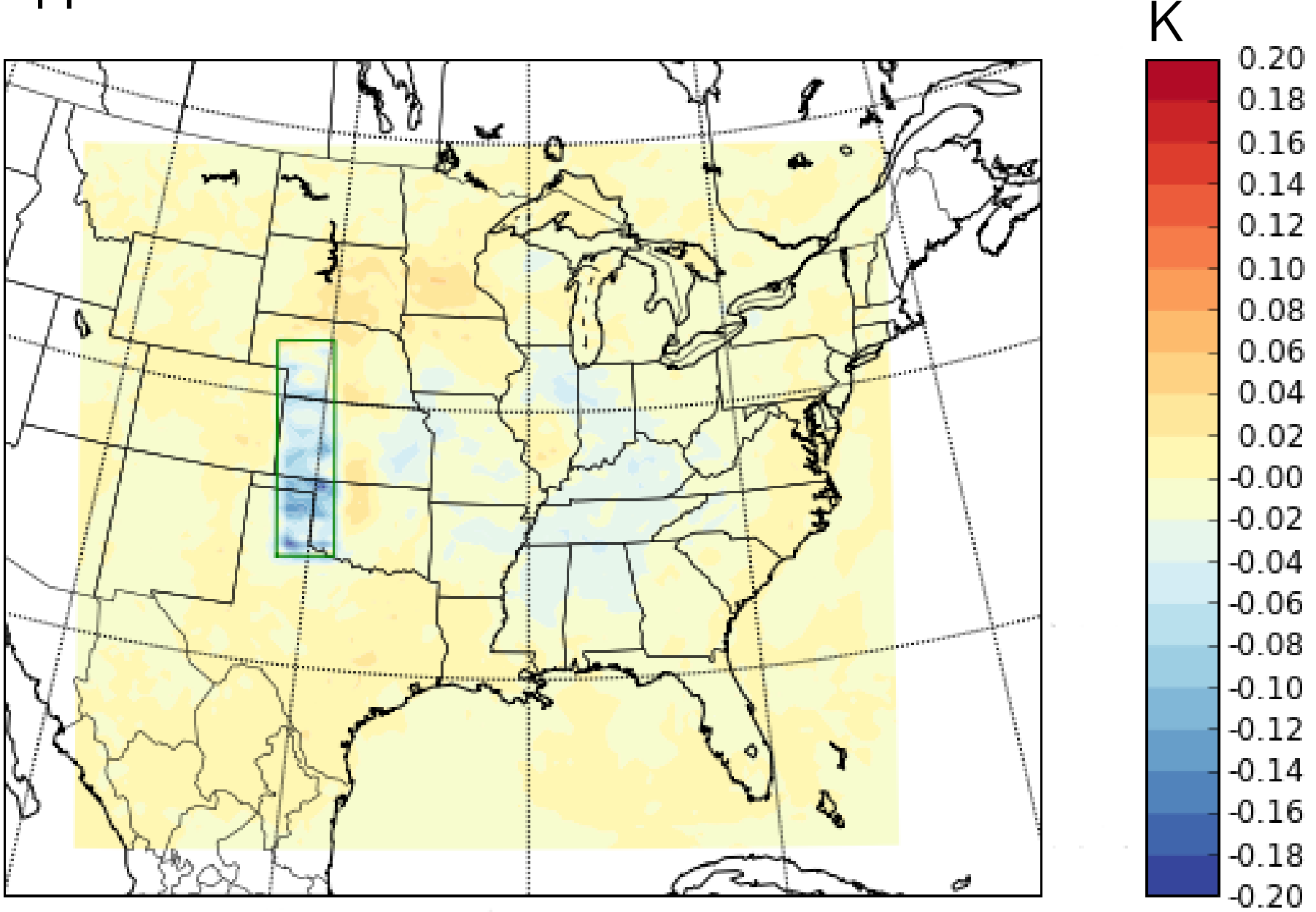


Electricity production by energy sources, Germany 2008


gigawatts of production
from the giant wind farm
average production is 64 GW
GW
500
400
300
200
100
0
0
20
40
60
80
100
120
140
1948 Warm Season Day

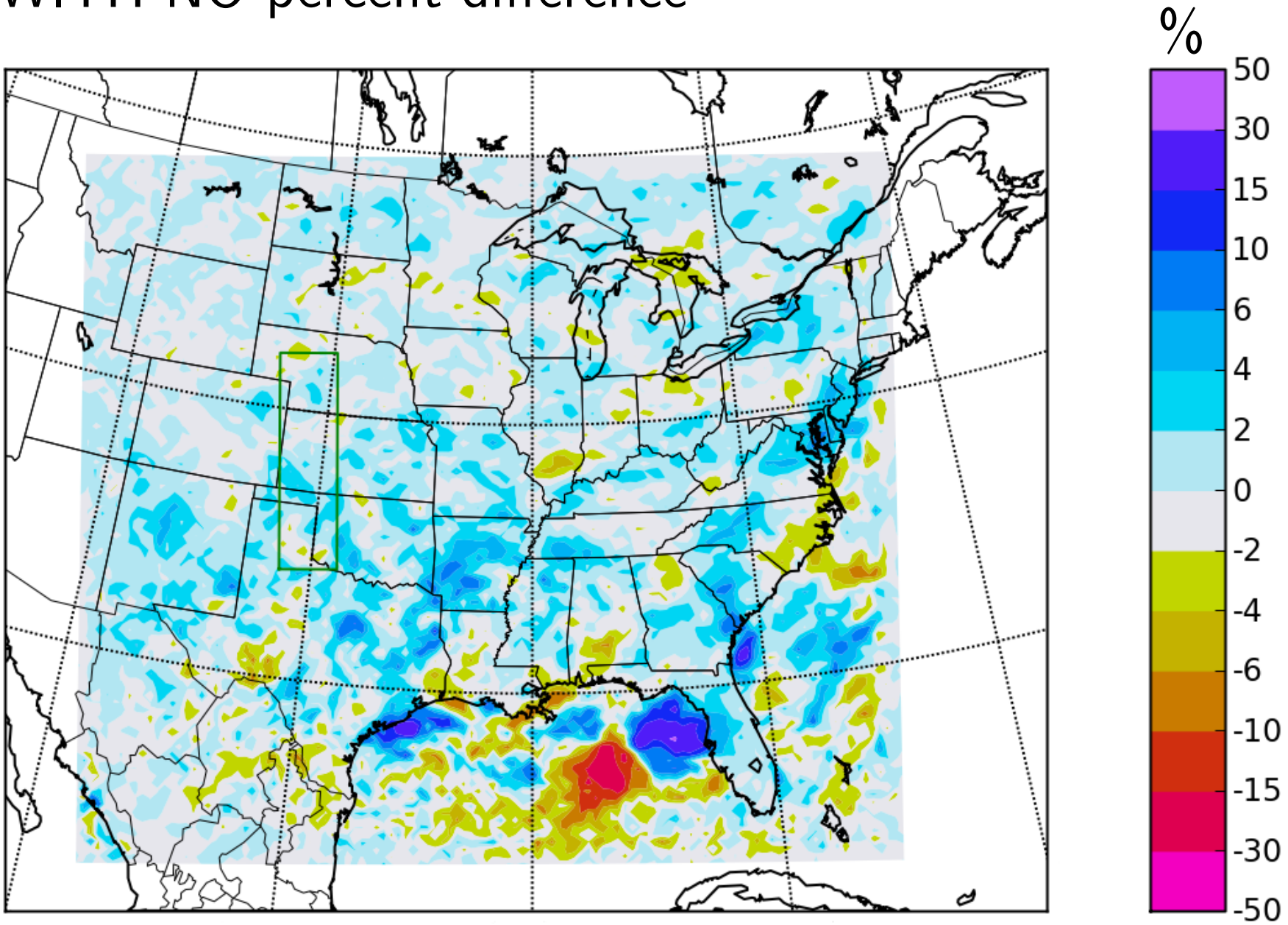
1948-2009 average temperature change at 2 m

Approximate 0.1 K reduction inside wind farm



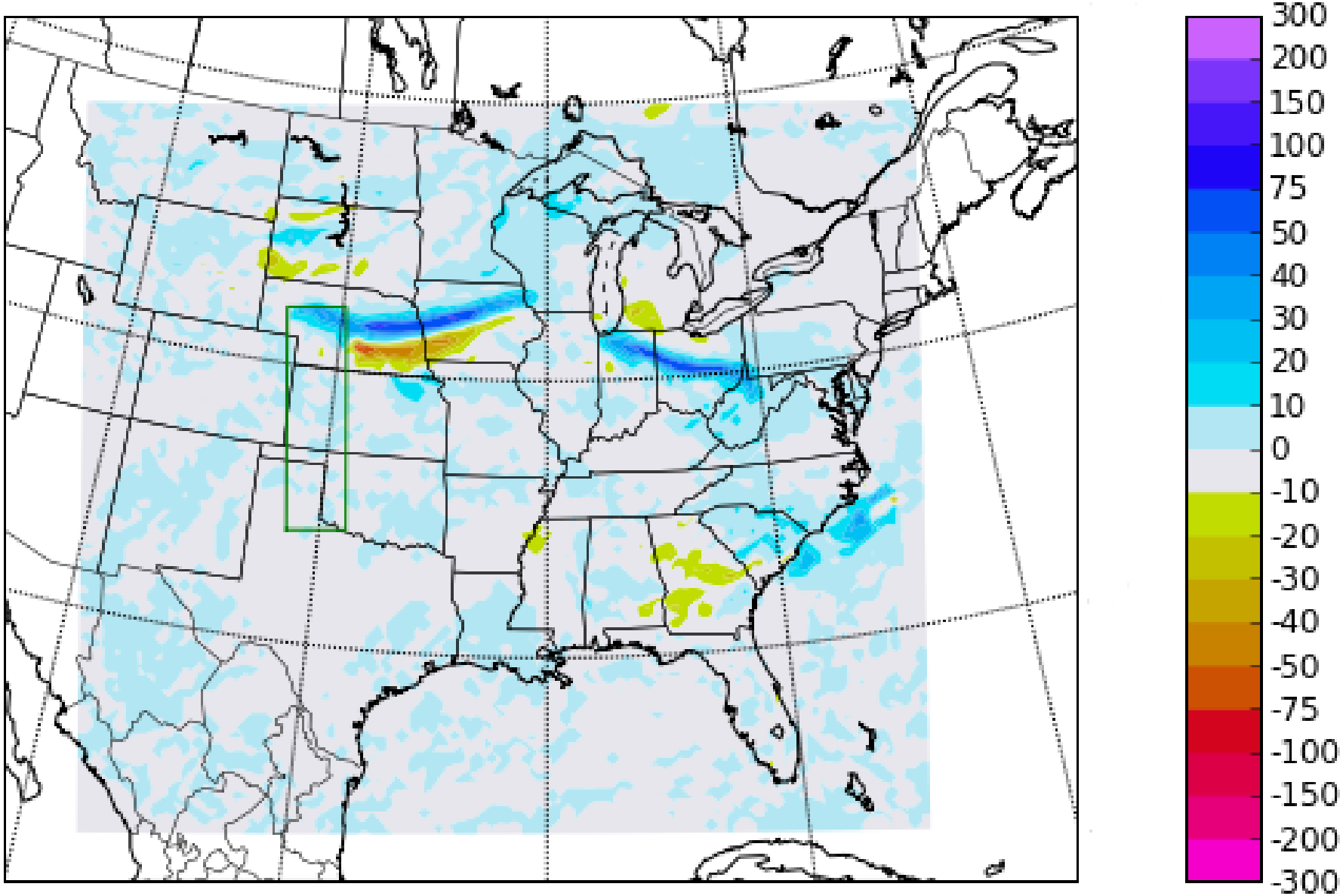
1948-2009 rainfall

WITH-NO percent difference



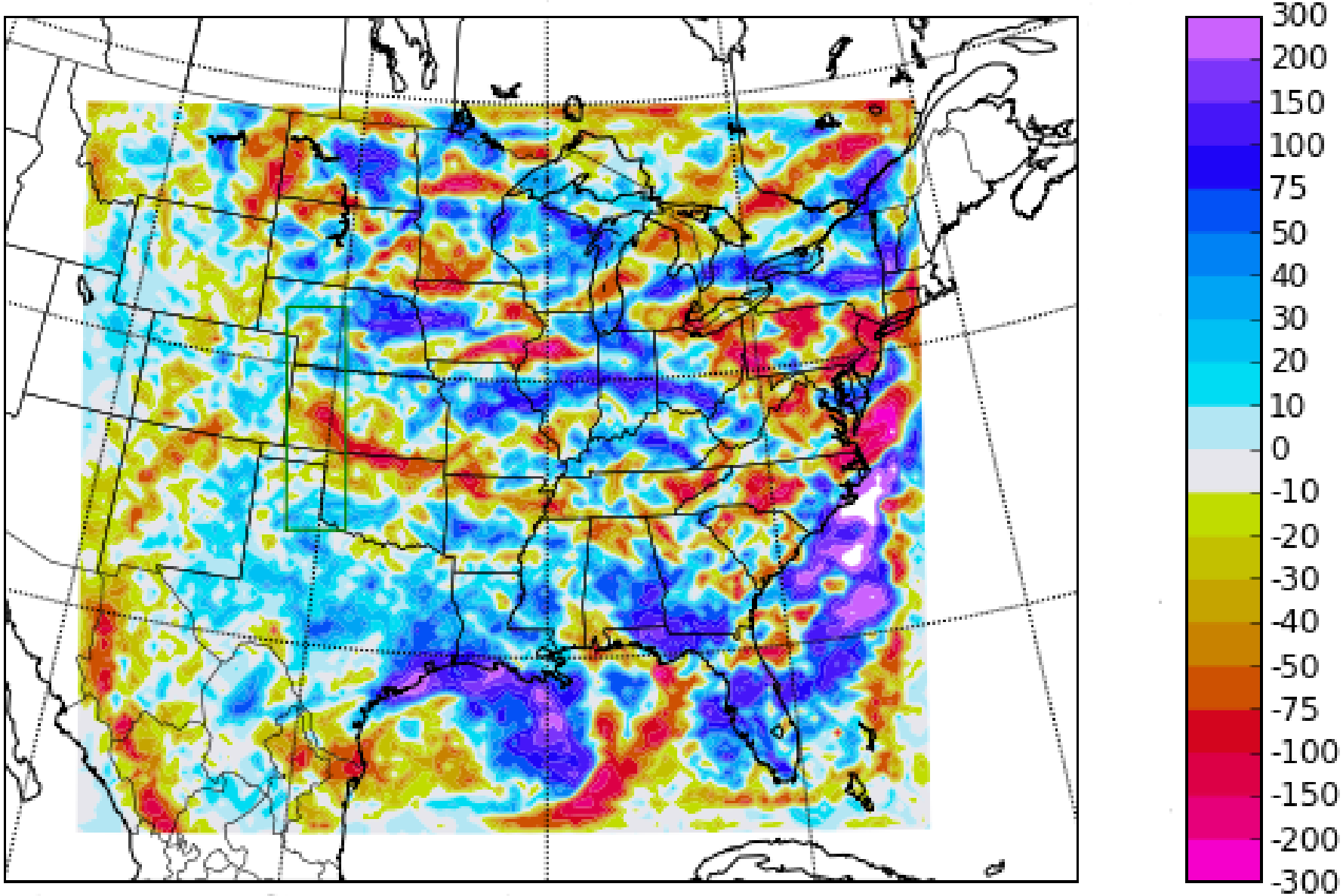
16 July 1948 rainfall

WITH-NO millimeter difference



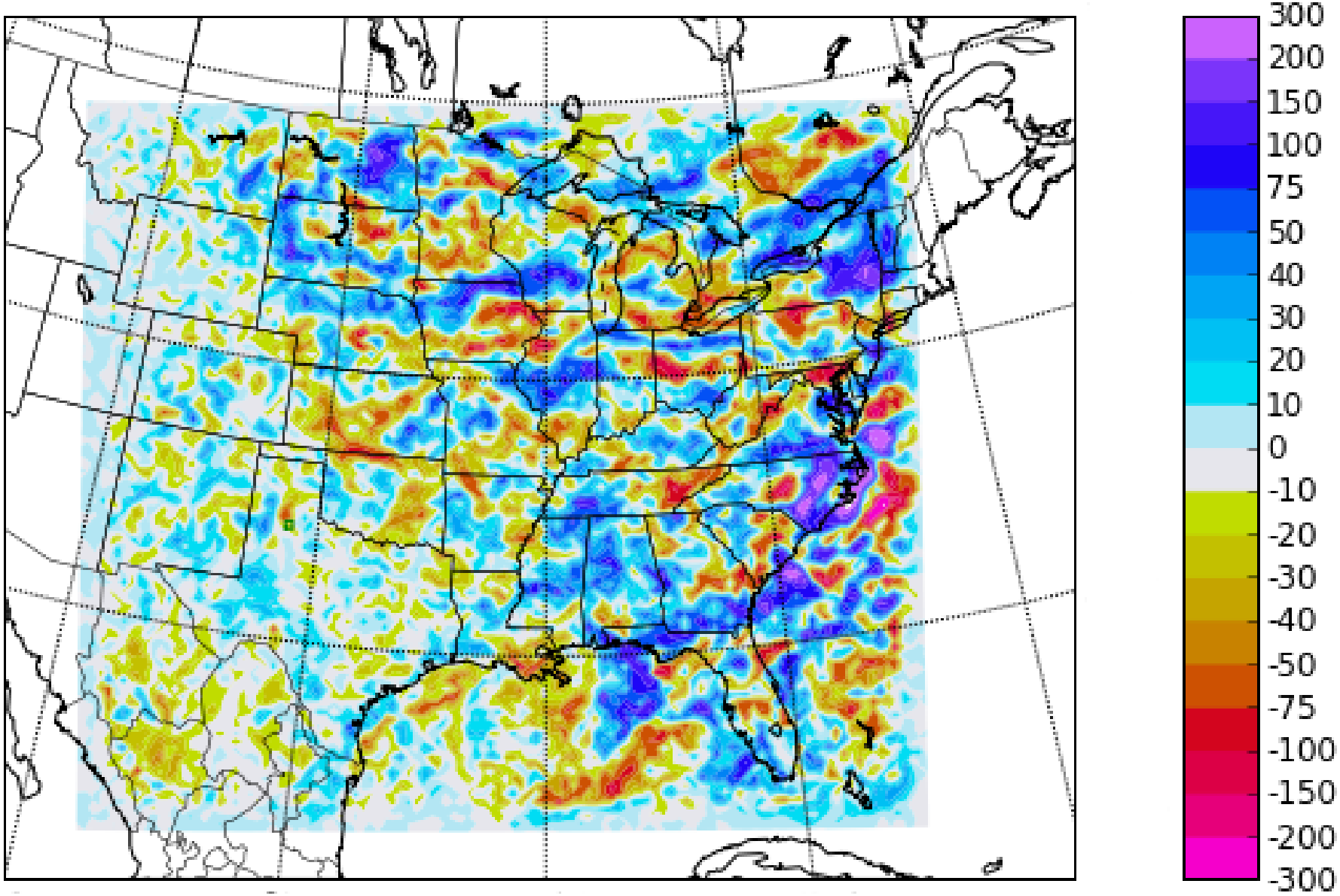
May-August 1948 rainfall

WITH-NO millimeter difference



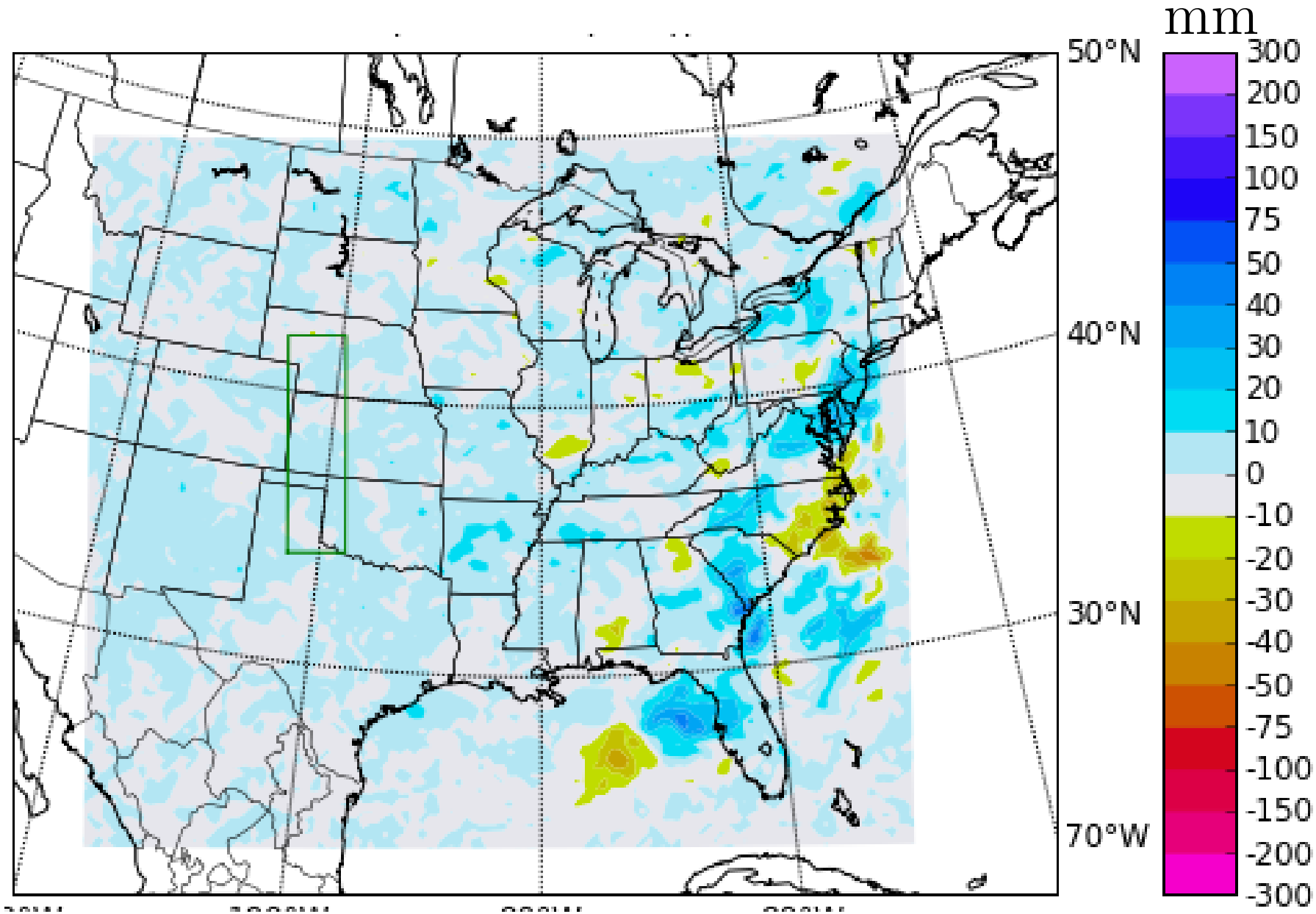
May-August 1948 rainfall TINY WINDFARM

WITH-NO millimeter difference



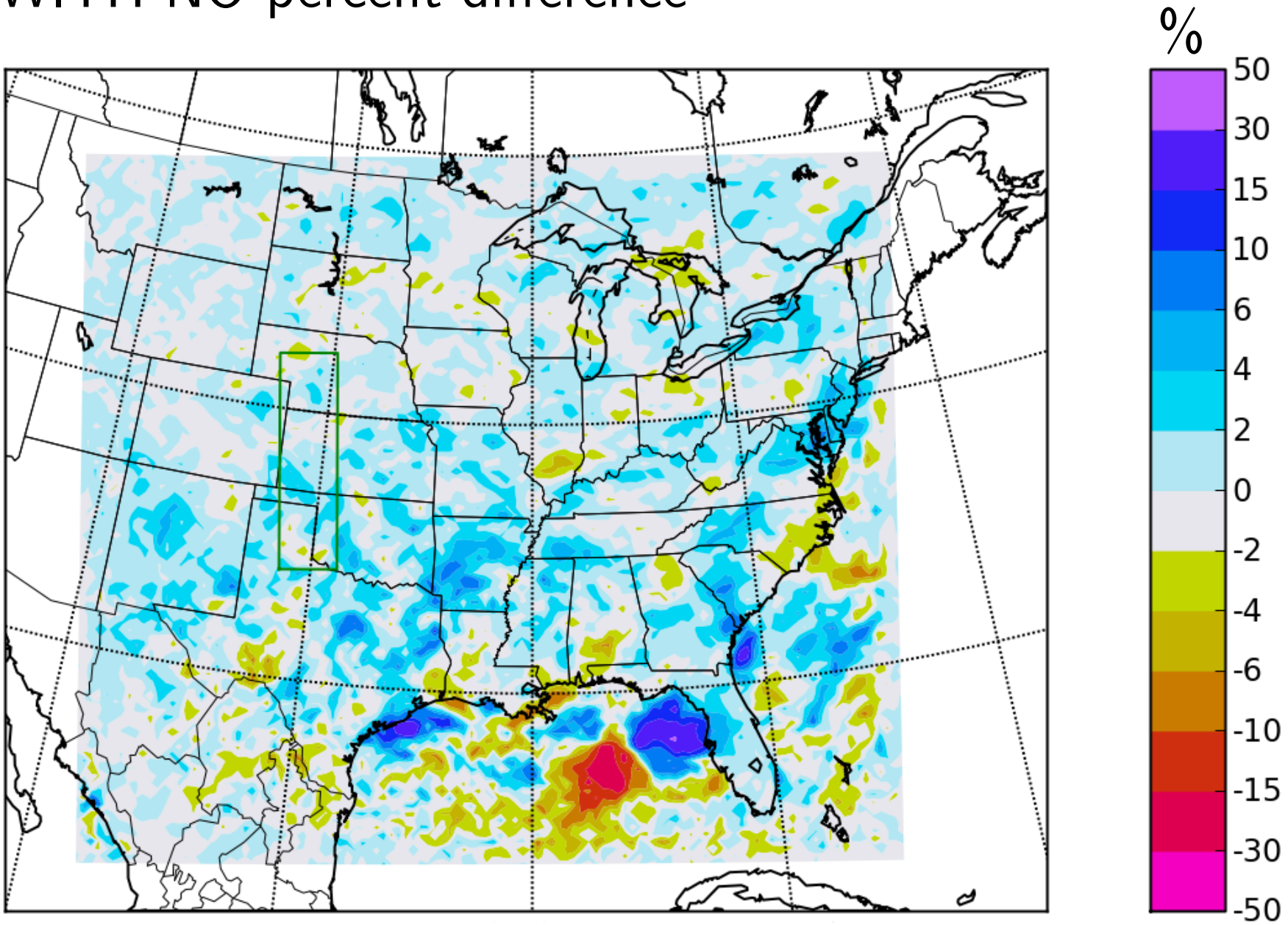
May-August 1948-2009 rainfall

WITH-NO millimeter difference



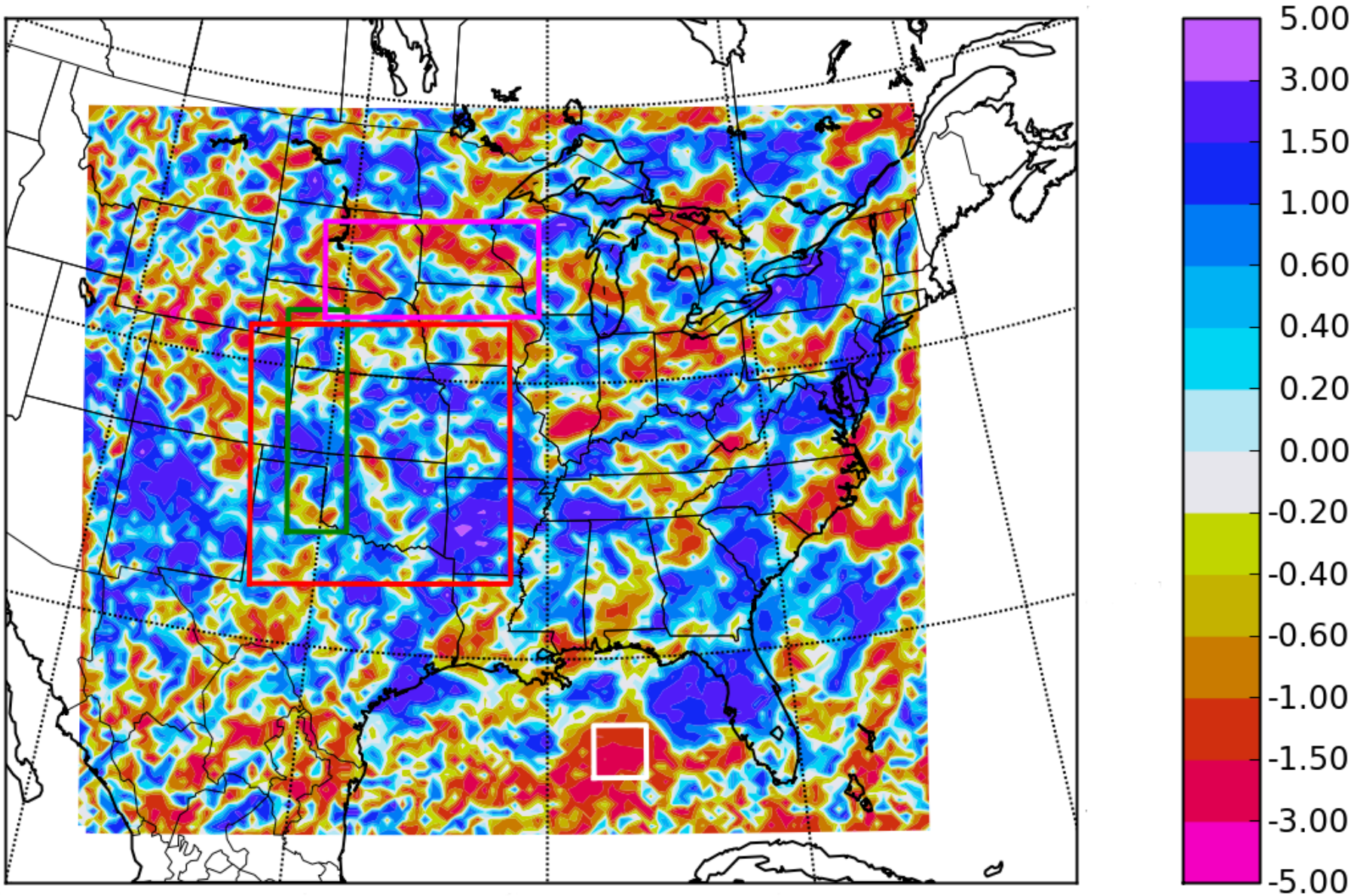
1948-2009 rainfall

WITH-NO percent difference



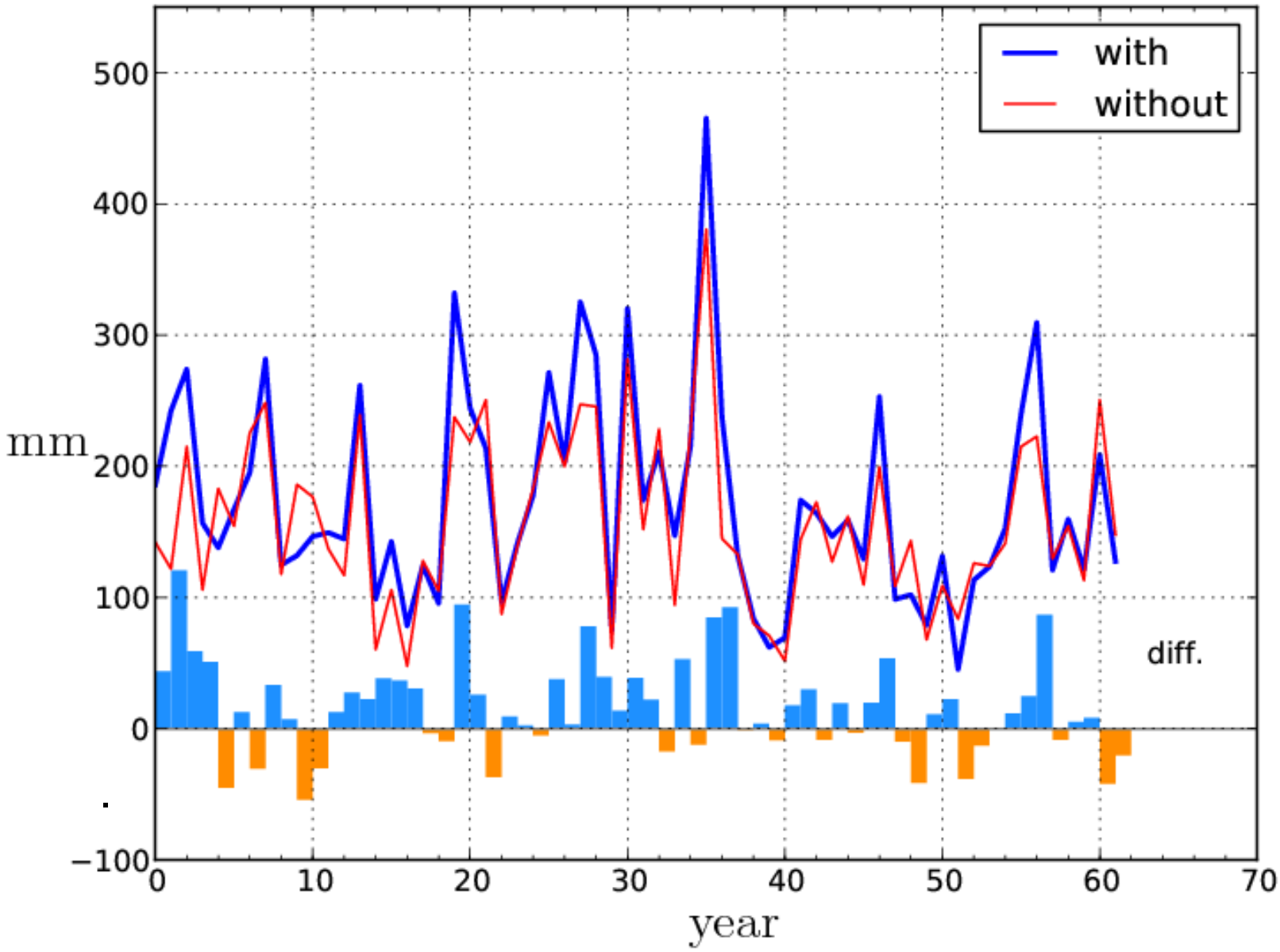
$$t = \sqrt{N}\frac{\bar{r}}{\sigma_r}$$

r is precipitation difference



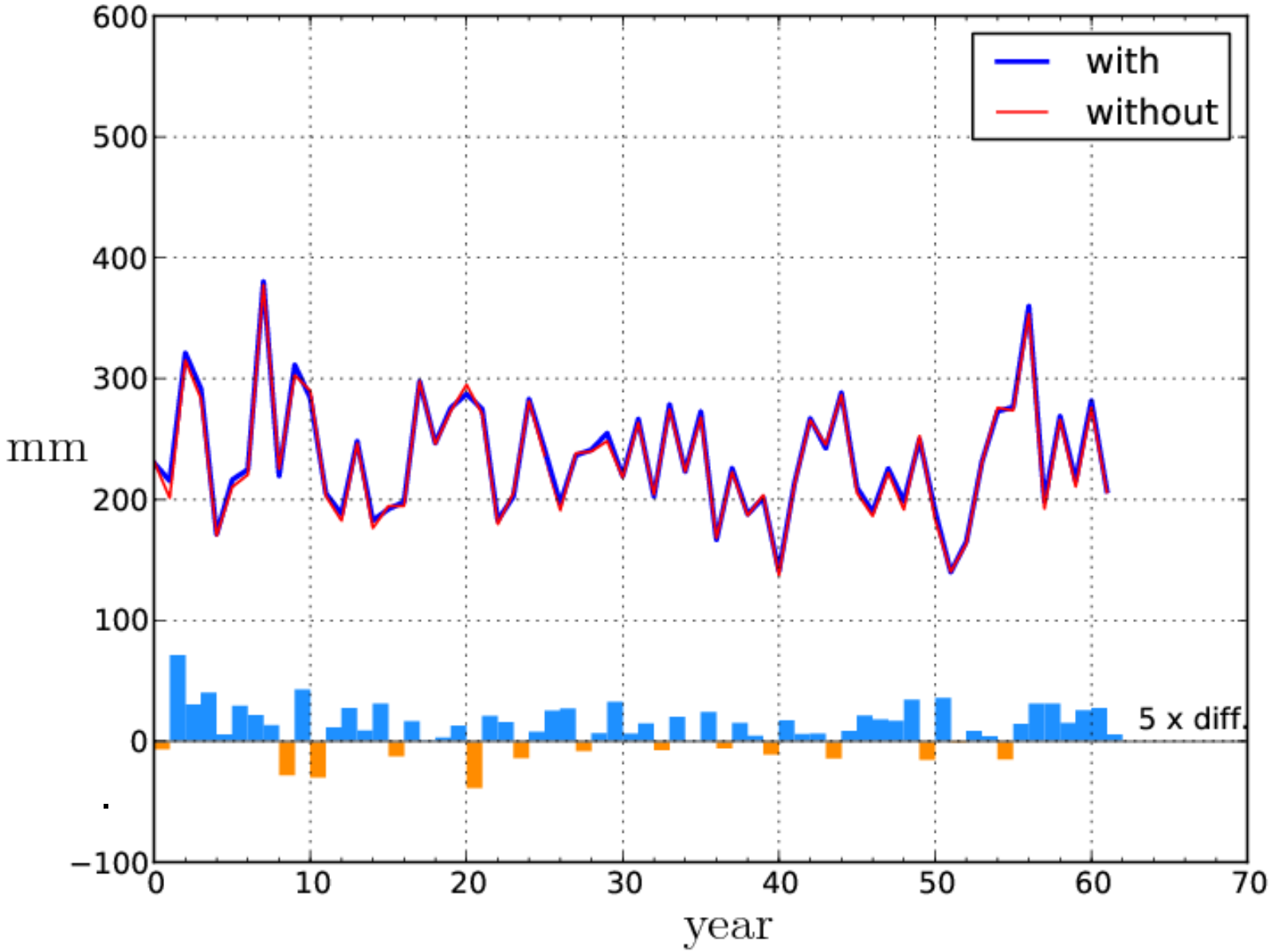
Arkansas point, fractional area is $f = .00009$

$t = 3.35$, $p = .00070$, $p = .00023$



Red box, fractional area is $f = .11$

$t = 4.71$, $p = .000008$, $p = .000002$

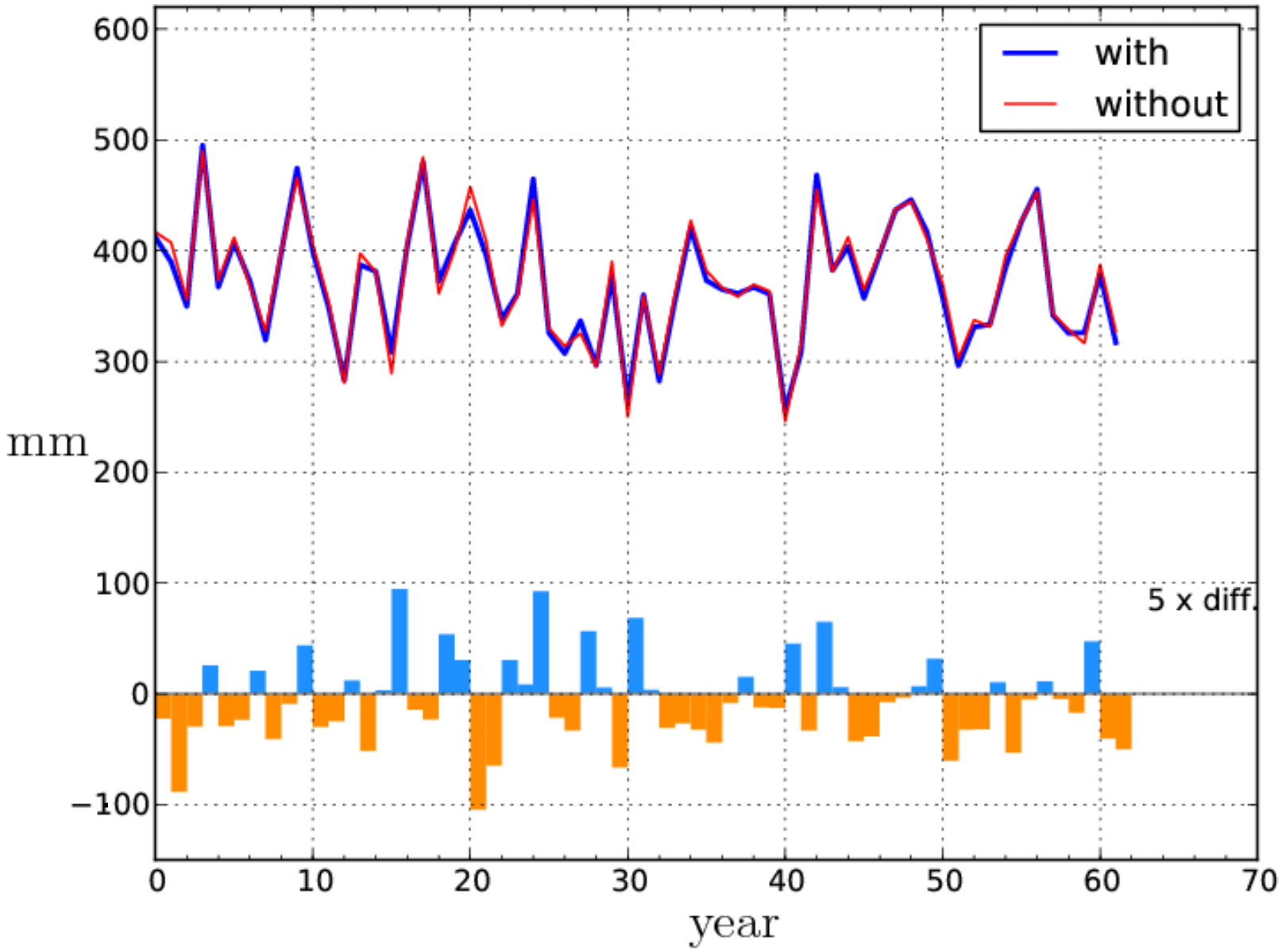


90% confidence that the model windfarm causes the true mean of precipitation to be between 0.64% and 1.33% enhancement within the red box.

A resampling-with-replacement method produces the identical 90% confidence interval.

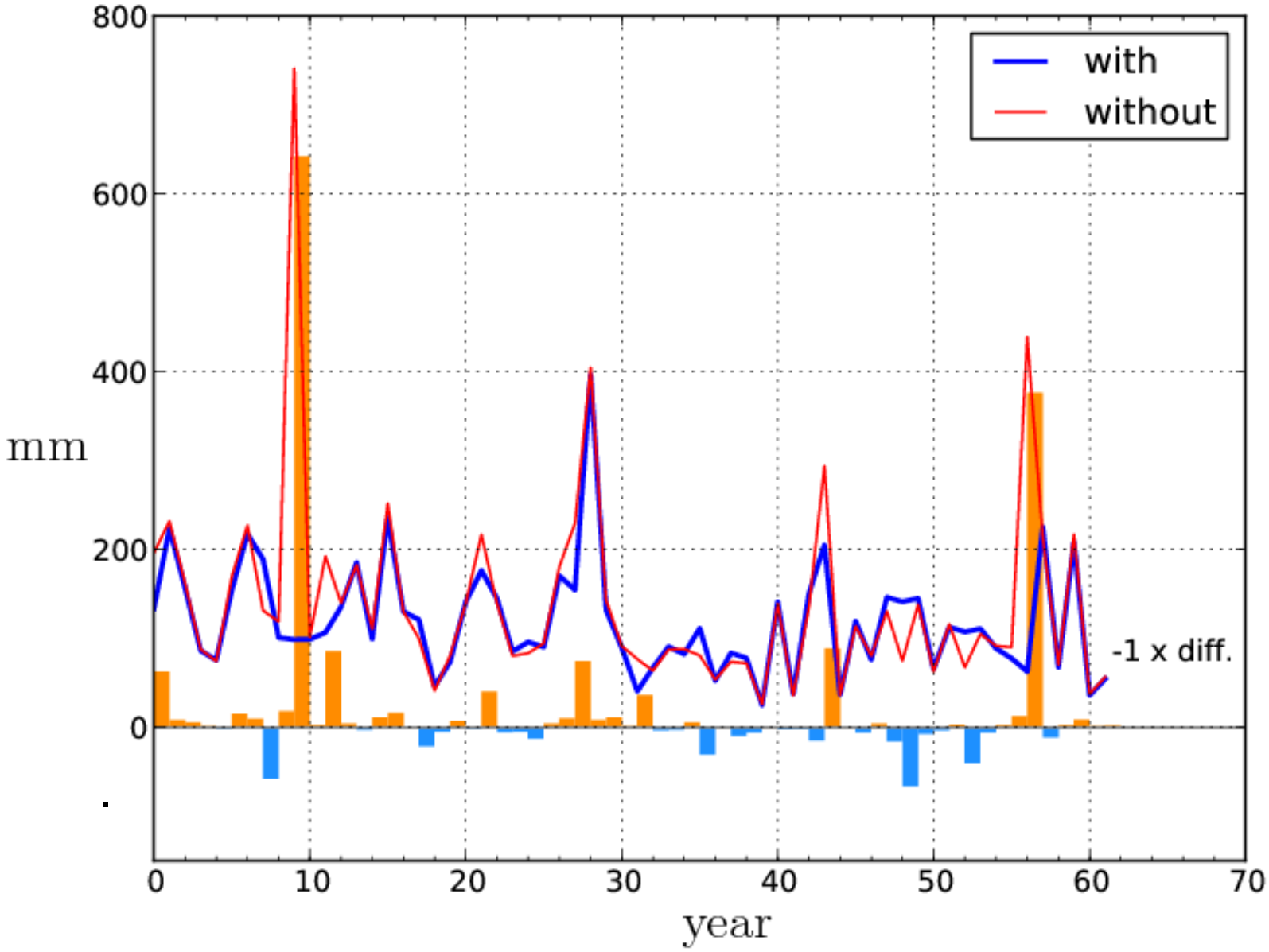
Magenta box, fractional area is $f = .0033$

$t = -1.5$, $p = .07$, $p = .07$



White box, fractional area is $f = .0043$

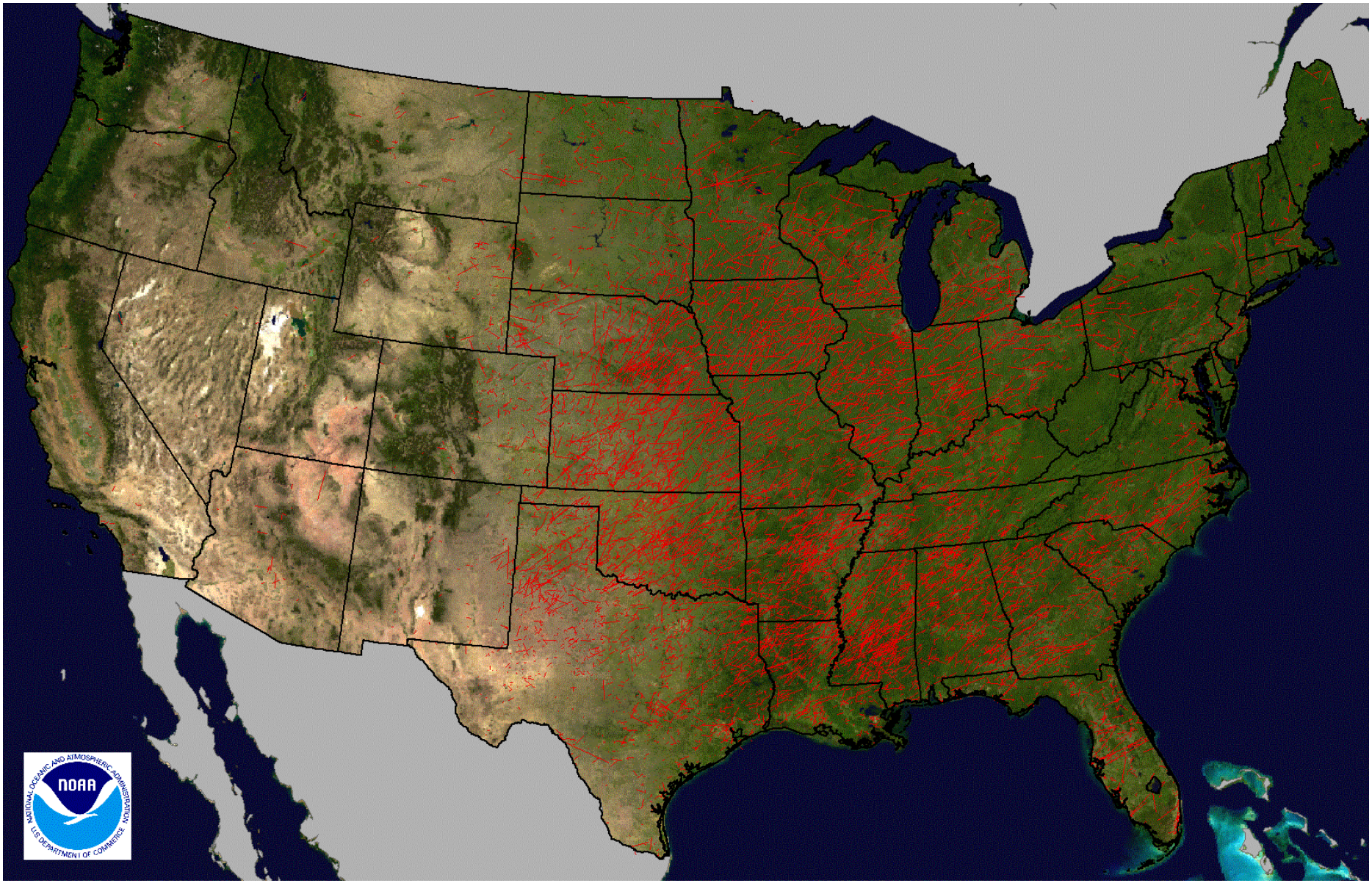
$t = -1.64$, $p = .053$, $p = .016$



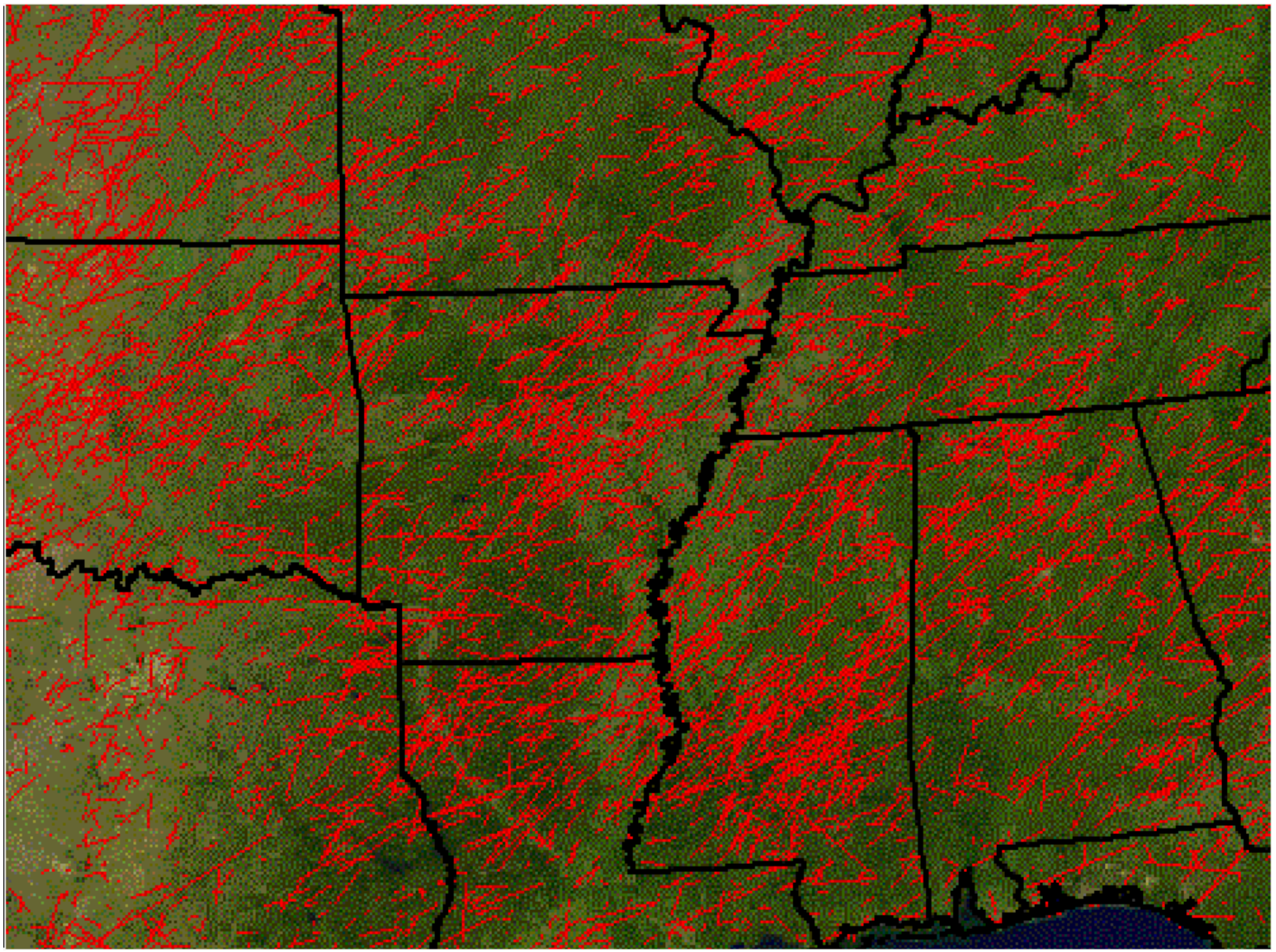
- Wind farms have a big effect on WRF weather
- Effect on WRF climate is small
- Effect on real climate?

- WRF simulations had $30\ \mathrm{km}$ resolution.
- What would happen at $1\ \mathrm{km}$ resolution?

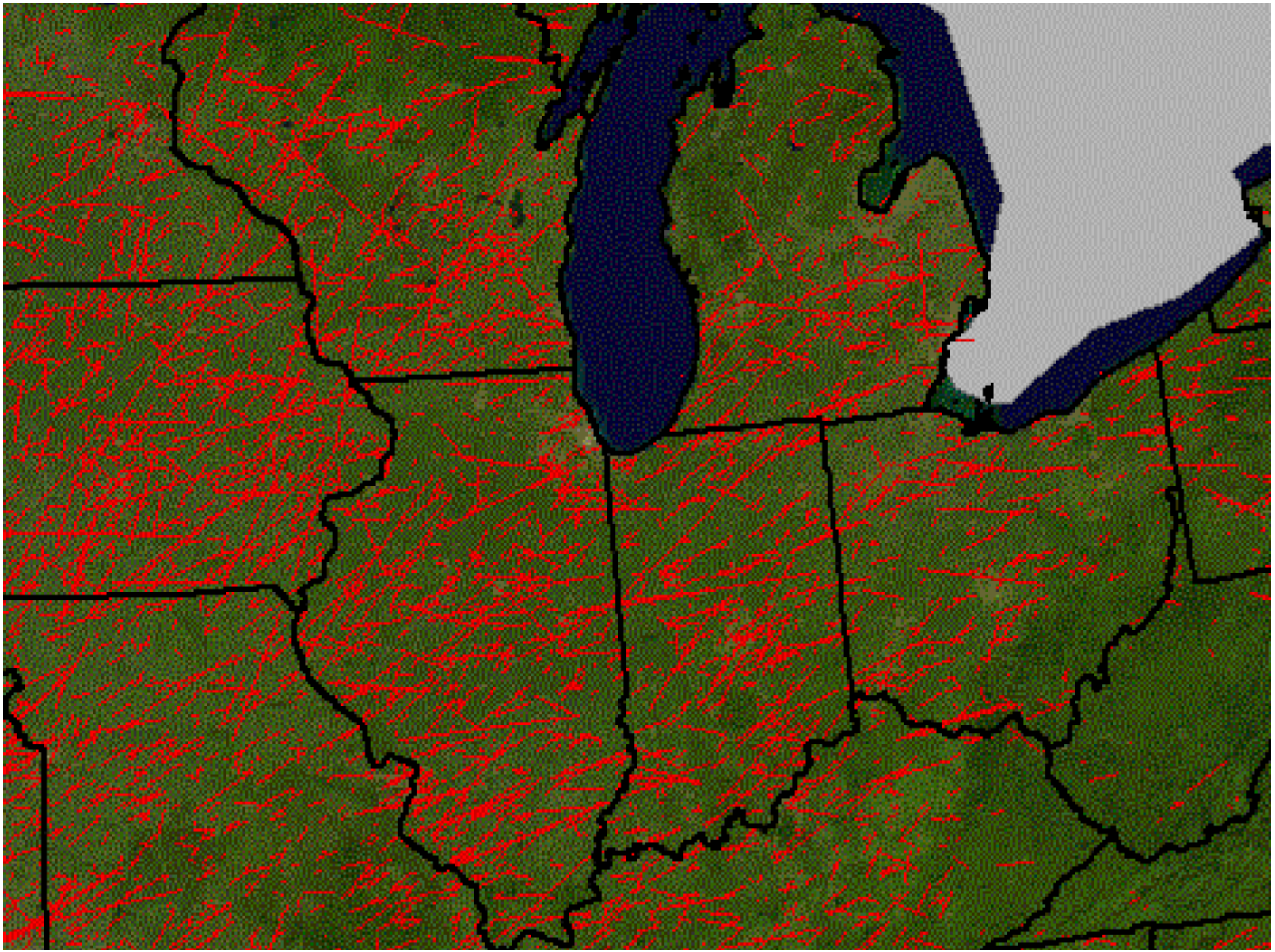
Tornado Tracks 1950-2010



Arkansas maximum at boundary with rough to west



Chicago minimum at boundary with rough to east



A larger perturbation than a "butterfly flapping its wings" will decrease the lead time for a significant effect and allow for greater potential of forecasting the event. *Possibly* a giant wind farm, with it's ability to have the blades furled by a command from a control room, provides the potential for advertent *forecastable* weather modification. Other human object may have similar magnitude of effect on weather, but urban heat islands can not be turned off, nor pasture reverted to forest, on the time scale required to change a forecastable weather event. This possibility of giant wind farms providing a choice for a weather event revives decades old scholarship about intentional weather modification, much of that written in the context of hurricane

modification, as opposed to the recent scholarship about the legal consequences of inadvertent climate change.

I agree that the statistical analysis used here is better than many current papers. This is primarily because the authors have performed 62 runs. In this respect this paper clearly sets new standards for ensemble mesoscale modeling because current papers use much smaller ensembles. But I still have 2 questions. First, is t-test a good test? The Gaussian distribution assumption required for t-test does not hold as the authors point out later. So, why not use a non-parametric test that does not have a distribution assumption? This will be relatively easy because many canned packages and freeware codes are available for standardized tests.

I find this paper very suitable for the focus issue 'Environmental Impacts of Wind Energy'. It was papers like this I was hoping for, when I proposed this focus issue. It is thought provoking and will generate some discussion.

I agree with the comments of the referee, essentially saying that this is an important paper of high quality, but it needs some modifications and some parts should be reduced, others expanded.

Discover Magazine, June 2011:

Tom Brokaw: We know that 2010 was tied for the hottest year on record, but were sitting here now in snowy New Haven. Its been a long, cold winter in New England and across much of America. How does this fact relate to climate change?

Rajendra Pachauri: The reality is that what we see today is not merely a smooth and steady increase in temperatures. We're really disrupting the well-balanced climate system of the globe, and this leads to an increase in floods and droughts, heat waves and extreme precipitation.