TECHNISCHE UNIVERSITÄT BERLIN
Fachgebiet Digitaler Wandel in Energiesystemen

8 May 2024

Advancing research at the intersection of wind energy and the geophysical sciences

Ken Caldeira

kcaldeira@carnegiescience.edu
Carnegie Institution for Science, Dept. of Global Ecology
Gates Ventures

2012

nature climate change LETTERS
PUBLISHED ONLINE: 9 SEPTEMBER 2012 | DOI:10.1038/NCLIMATE1683

Geophysical limits to global wind power

Kate Marvel[1]*, Ben Kravitz[2] and Ken Caldeira[2]

2017

JOURNAL OF CLIMATE

Spatial Distribution of Generation of Lorenz's Available Potential Energy in a Global Climate Model

EVA AHBE AND KEN CALDEIRA

2017

Geophysical potential for wind energy over the open oceans

Anna Possner[a,1] and Ken Caldeira[a]

PNAS | October 24, 2017

2021

Applied Energy 281 (2021) 116048
Contents lists available at ScienceDirect
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Applied Energy
journal homepage: www.elsevier.com/locate/apenergy

Atmospheric pressure gradients and Coriolis forces provide geophysical limits to power density of large wind farms

Enrico G.A. Antonini*, Ken Caldeira

2021

Spatial constraints in large-scale expansion of wind power plants

Enrico G. A. Antonini[a,1] and Ken Caldeira[a]

PNAS 2021 Vol. 118 No. 27 e2103875118

2024

communications earth & environment Article
https://doi.org/10.1038/s43247-024-01260-7

Identification of reliable locations for wind power generation through a global analysis of wind droughts

Check for updates

Enrico G. A. Antonini[1,2,3], Edgar Virgüez[1], Sara Ashfaq[1,4], Lei Duan[1,5], Tyler H. Ruggles[1] & Ken Caldeira[1,6]

Communications Earth & Environment | (2024)5:103

nature climate change

LETTERS

PUBLISHED ONLINE: 9 SEPTEMBER 2012 | DOI:10.1038/NCLIMATE1683

Geophysical limits to global wind power

Kate Marvel[1]*, Ben Kravitz[2] and Ken Caldeira[2]

We distributed representations of wind turbines, at different densities,

- Across the entire surface of the Earth
- Throughout the volume of the atmosphere

How much power can be produced?
What are the effects on climate?

I would like to hire a postdoc to continue this work, looking at smaller spatial scales.

nature climate change
LETTERS
PUBLISHED ONLINE: 9 SEPTEMBER 2012 | DOI:10.1038/NCLIMATE1683

Geophysical limits to global wind power

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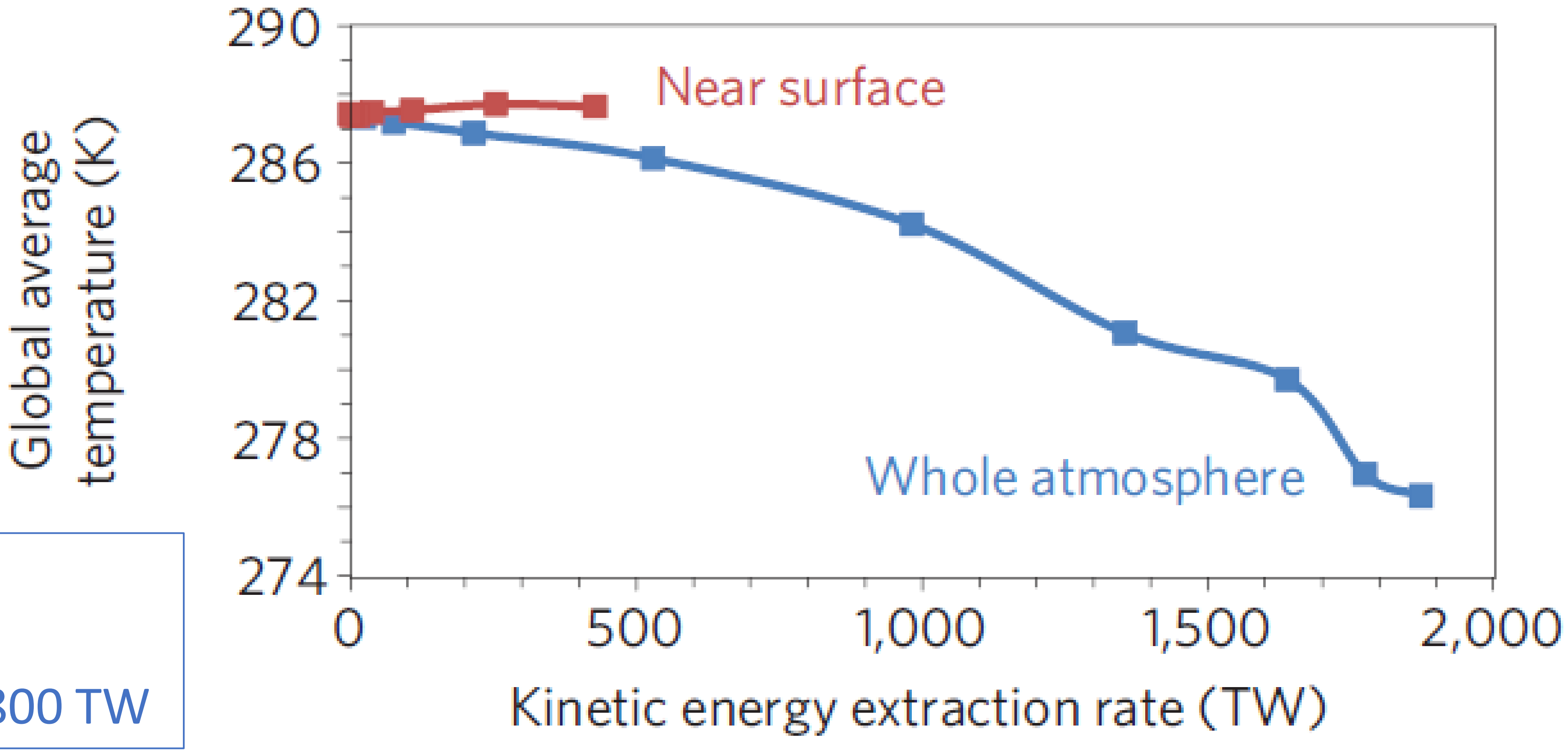

Geophysical potential:
Near surface > 400 TW
Whole atmosphere > 1800 TW

nature climate change
LETTERS
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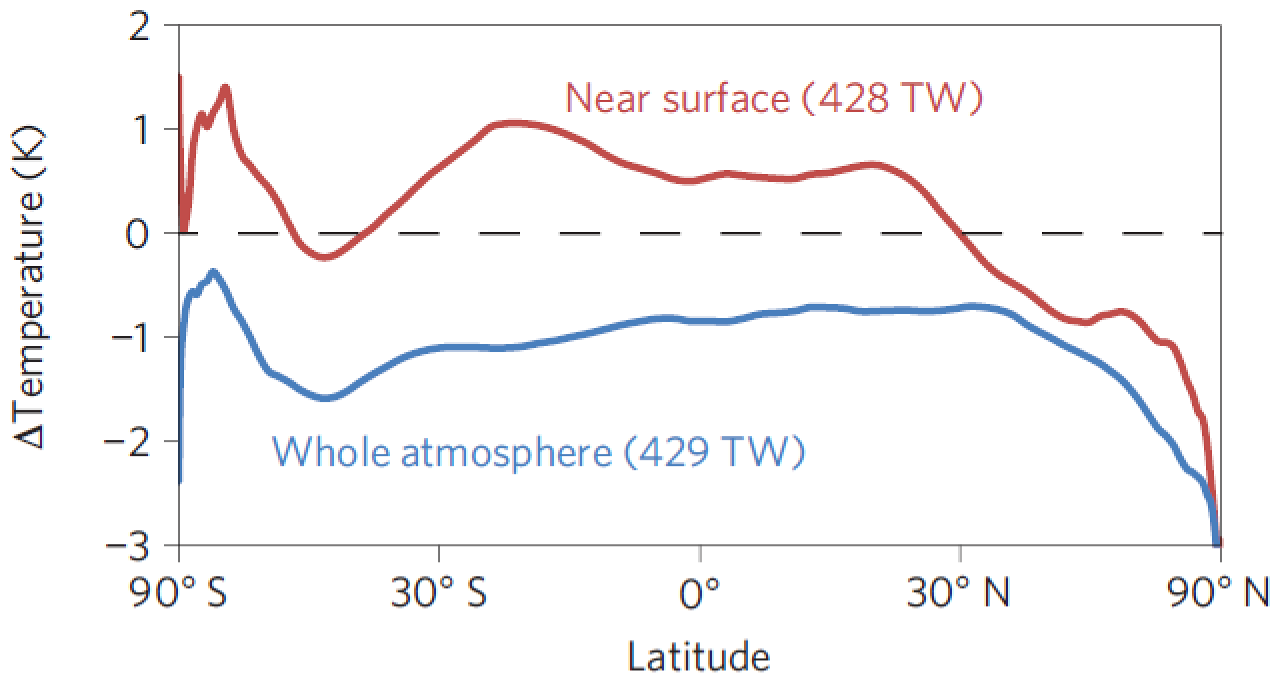
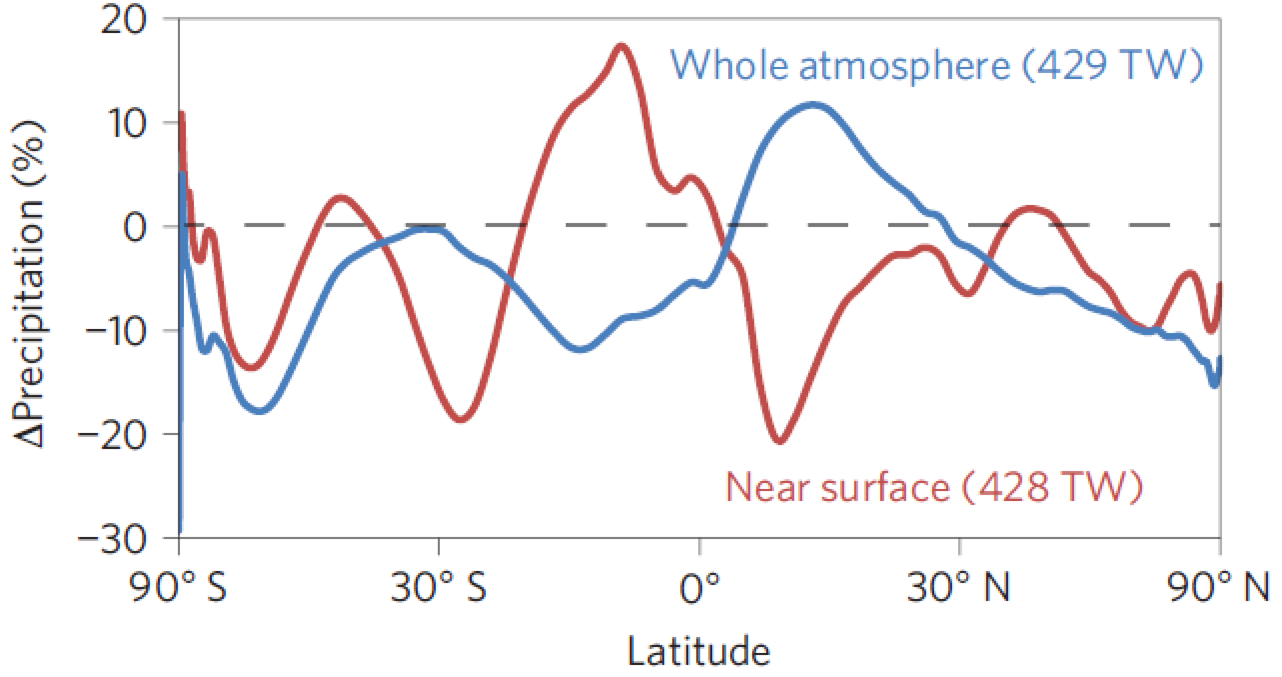
Geophysical limits to global wind power

Kate Marvel[1]*, Ben Kravitz[2] and Ken Caldeira[2]

Zonal mean temperature changes are < 0.1 K/TW
Zonal mean precipitation changes are < 0.1%/TW





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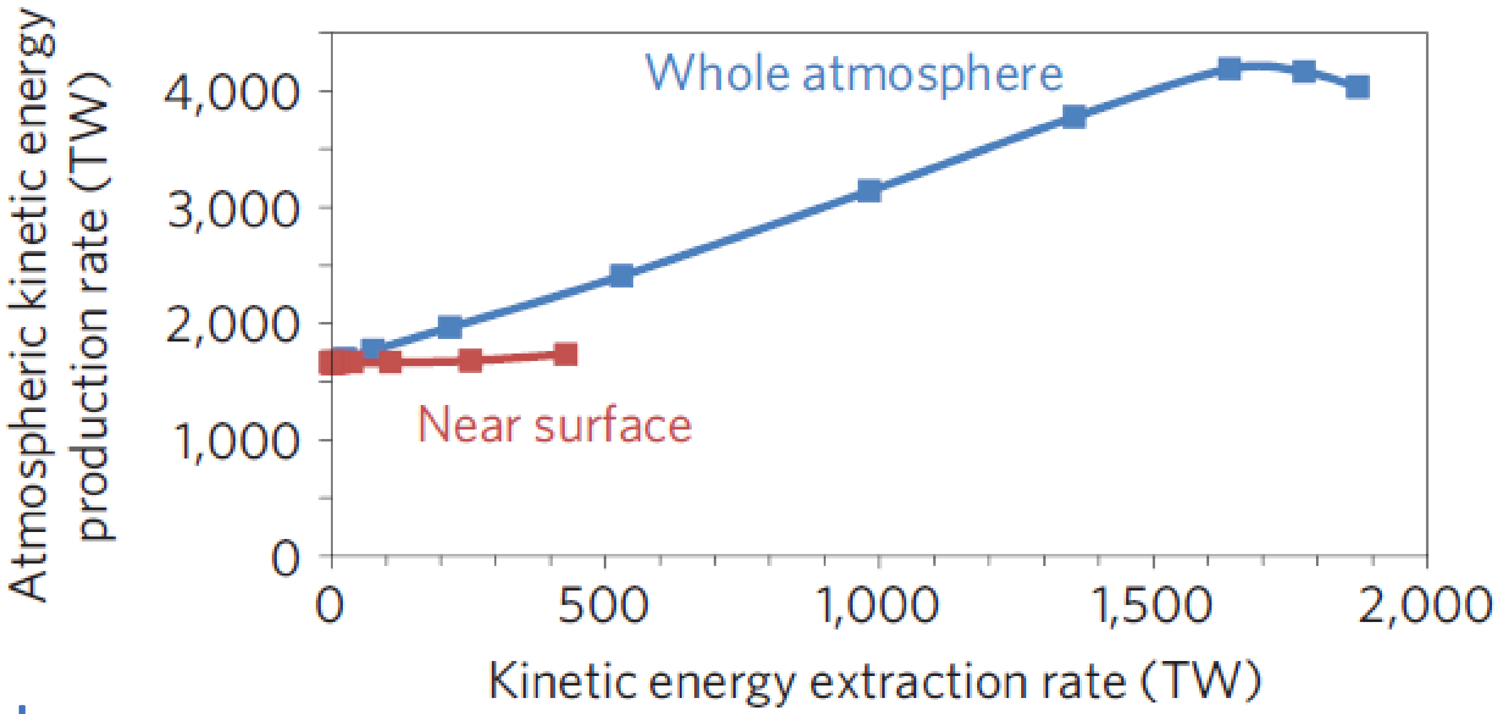


Wind turbines near surface affect where kinetic energy gets dissipated.

High-altitude wind turbines affect how much kinetic energy gets produced and dissipated.

Spatial Distribution of Generation of Lorenz's Available Potential Energy in a Global Climate Model

EVA AHBE AND KEN CALDEIRA

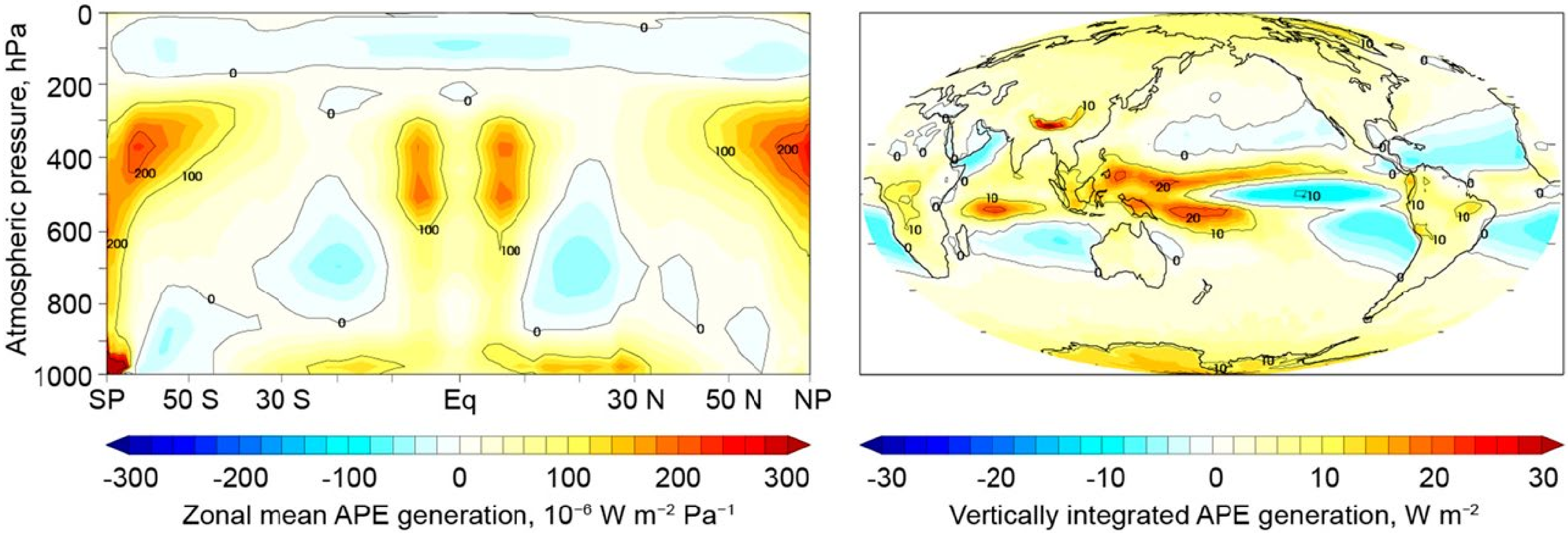


FIG. 3. As in Fig. 2, but for distribution of annual mean dry APE generation in units of (left) 10^{-6} W m^{-2} Pa^{-1} and (right) W m^{-2}. APE generation is greatest near the tropics in the ITCZ where air with relatively warm potential temperatures is heated largely by condensing water vapor and near the poles where air with relatively low potential temperatures is radiatively cooling, resulting in longwave radiation to space.

Geophysical potential for wind energy over the open oceans

Anna Possner[a,1] and Ken Caldeira[a]

PNAS | October 24, 2017

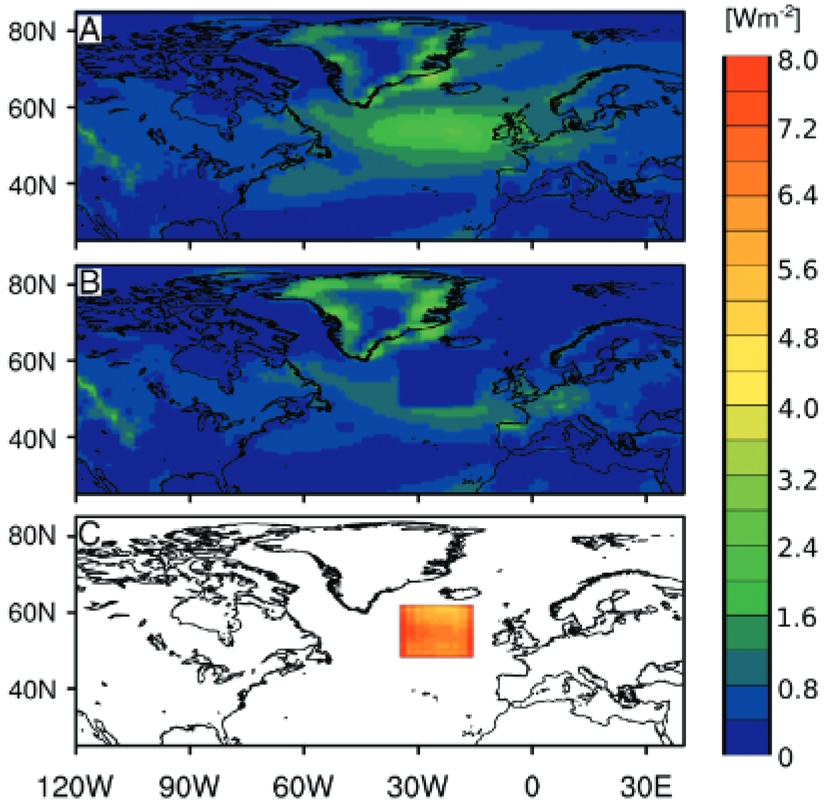


Fig. 3. Annual mean near-surface kinetic energy (KE) dissipation caused by drag (*A*) in the preindustrial climate and (*B*) for the largest simulated wind farm in the Atlantic with an area of 1.9 Mkm^2. (*C*) Kinetic energy extraction (KEE) within the largest wind farm in the North Atlantic. KE extracted by wind turbines is partially compensated for by a reduction in KE dissipation into the boundary layer caused by surface drag. Surplus energy extracted locally is compensated for by a regional decrease of KE dissipation into the boundary layer outside the wind farm.

About ~10 W/m^2 for the best parts of the North Atlantic compared with 2 or 3 W/m^2 for the best parts of North America.

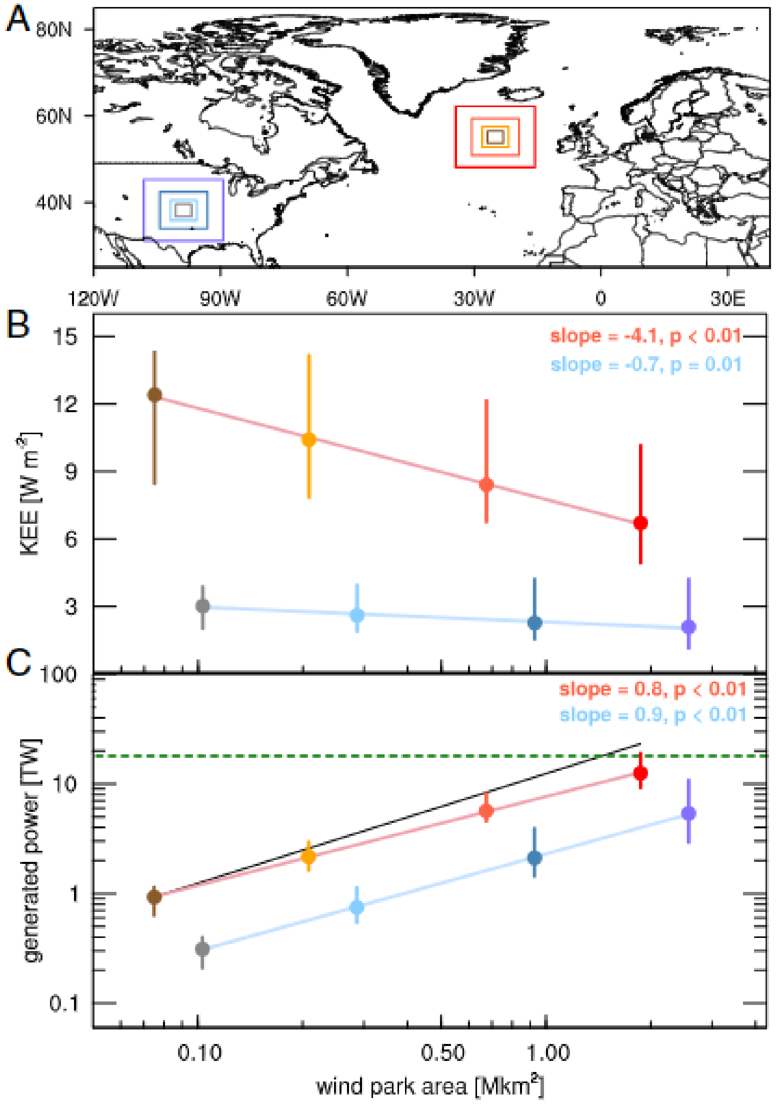


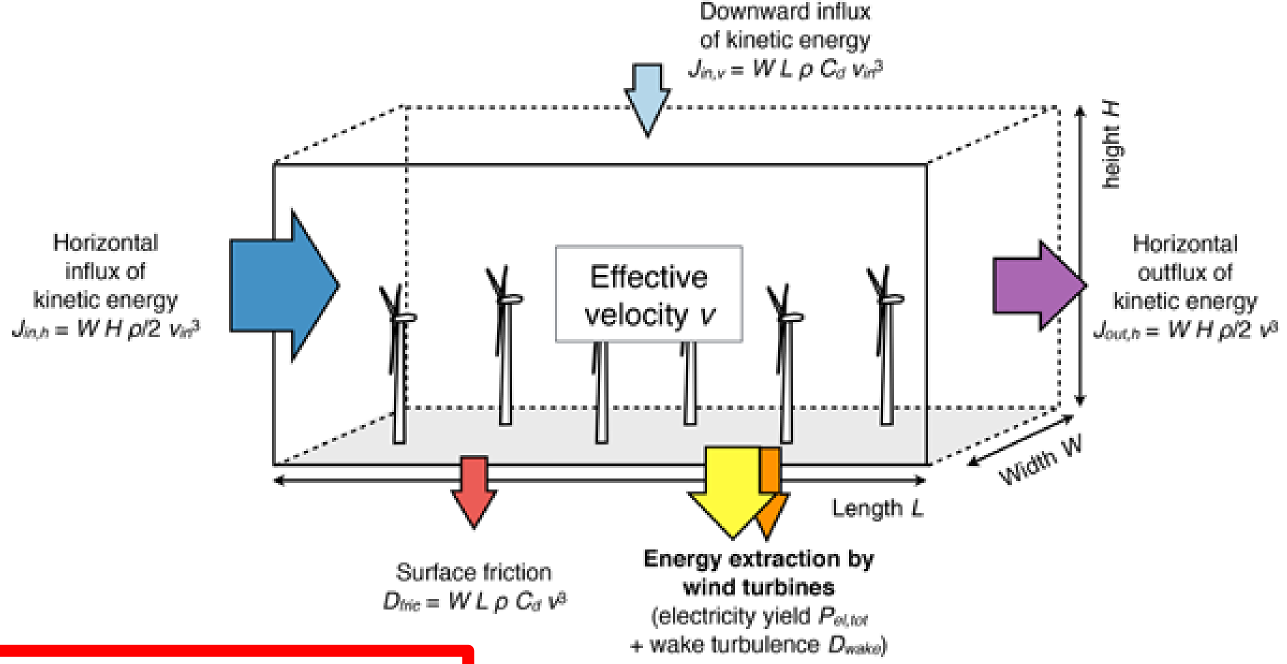
Fig. 2. (*A*) Map of wind farm locations. (*B* and *C*) Regional medians (•) and minimum–maximum ranges (lines) of annual mean kinetic energy extraction (KEE) in (*B*) watts meter^{-2} and (*C*) terawatts as function of wind farm area. Linear regression is fitted through the median KEE points against the common logarithm of the wind farm areas in the North Atlantic (salmon) and North America (light blue). Slopes and *P* values of fit are given. Precise KEE values and areas are in Table S1.

Geosci. Model Dev., 13, 4993–5005, 2020
https://doi.org/10.5194/gmd-13-4993-2020

Geoscientific Model Development
Open Access
EGU

The Kinetic Energy Budget of the Atmosphere (KEBA) model 1.0: a simple yet physical approach for estimating regional wind energy resource potentials that includes the kinetic energy removal effect by wind turbines

Axel Kleidon[1] and Lee M. Miller[2]



An incorrect view that I shared:

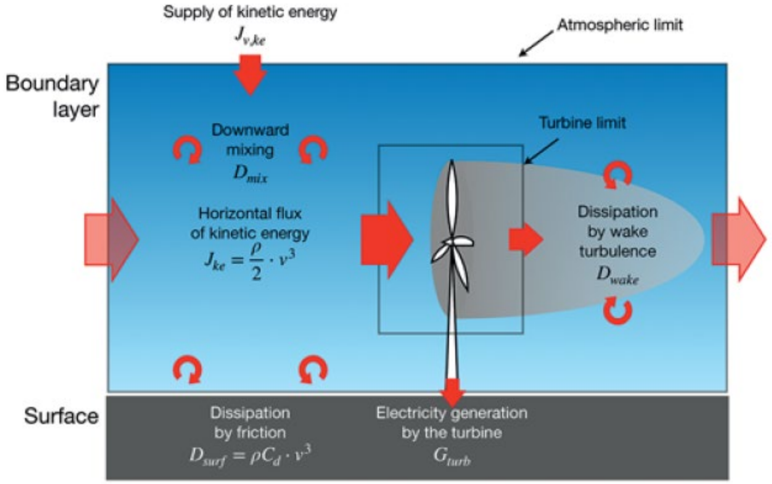
Kinetic energy removed from the near-surface boundary is replenished by a downward influx of kinetic energy from above.

Meteorol. Z. (Contrib. Atm. Sci.), Vol. **30**, No. 3, 203–225 (published online March 9, 2021)

Review Paper

Physical limits of wind energy within the atmosphere and its use as renewable energy: From the theoretical basis to practical implications

Axel Kleidon*



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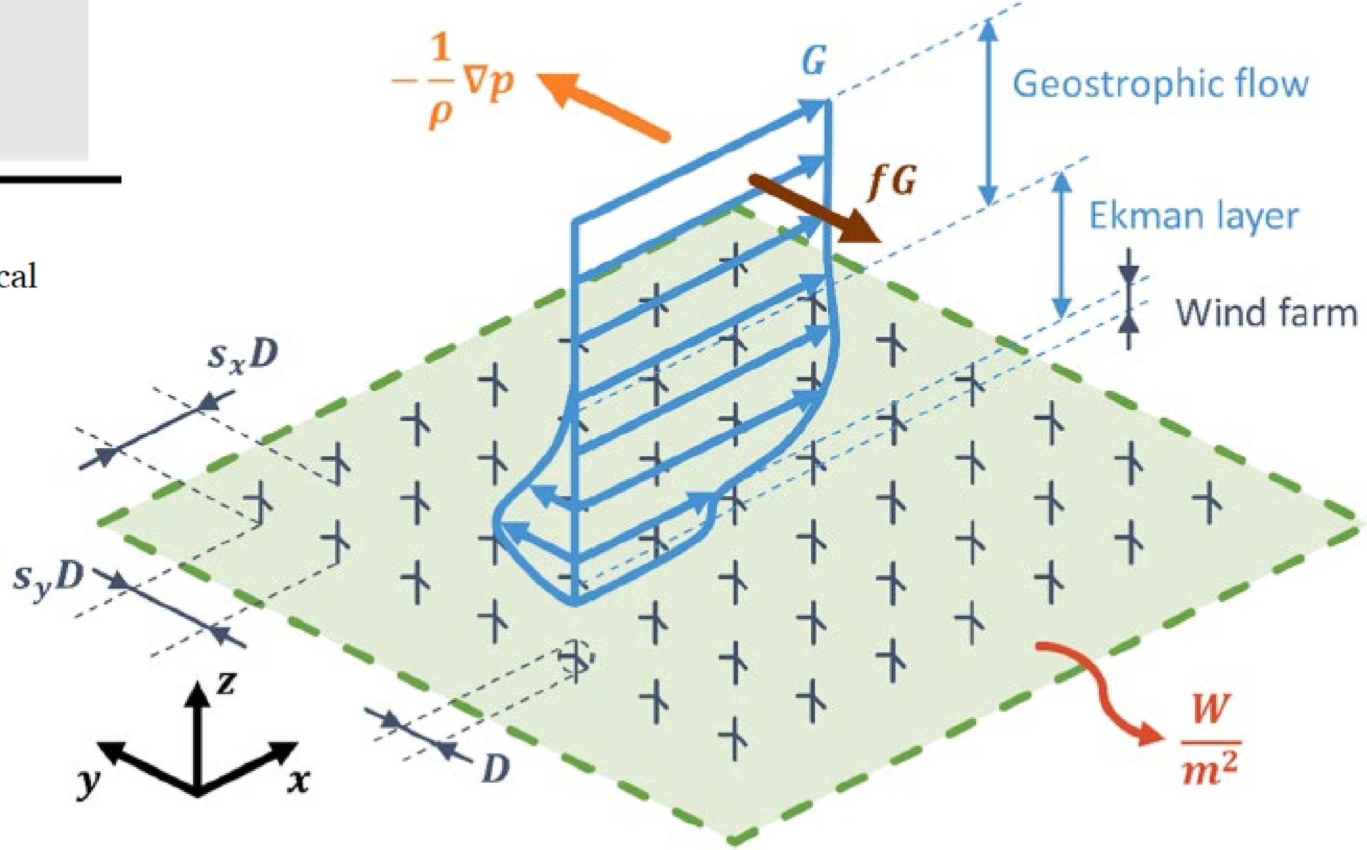

A better perspective:

1. Near surface winds represent a balance between pressure gradient forces and (apparent) Coriolis forces.

2. When winds are slowed by wind turbines, Coriolis forces diminishes, result in an acceleration of air parcels by large-scale pressure gradient forces.

3. Thus, kinetic energy removed from the atmosphere is replaced by large-scale potential energy gradients in the atmosphere.

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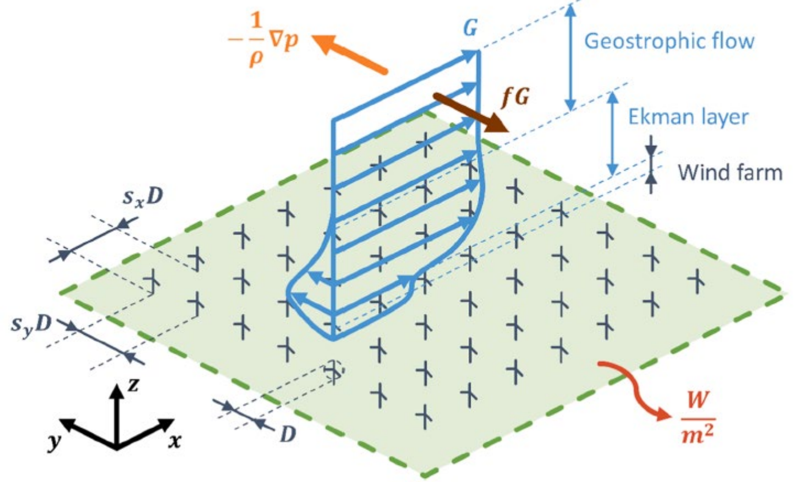

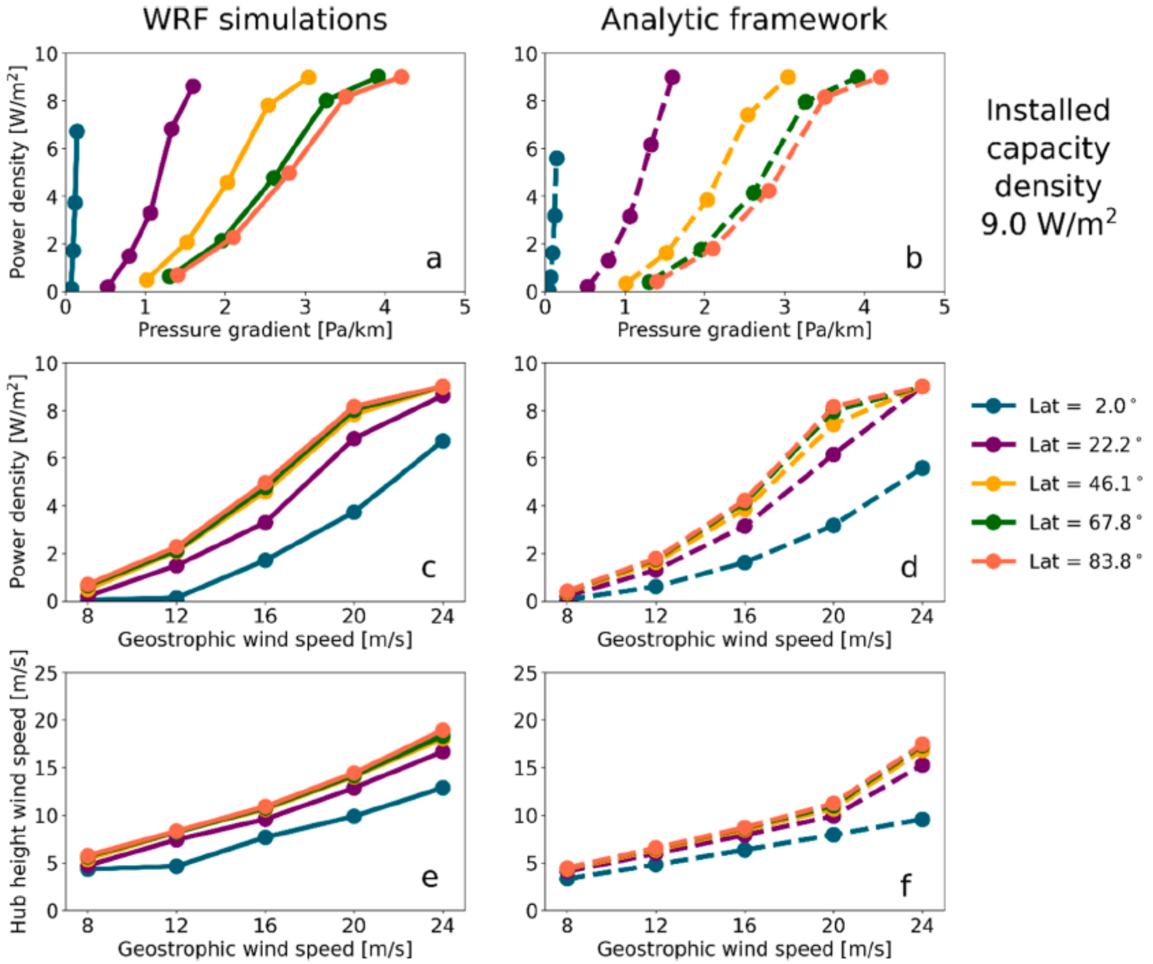

An analytic framework based on well-established theory produces results that are largely in agreement with results from fluid-dynamical model simulations.

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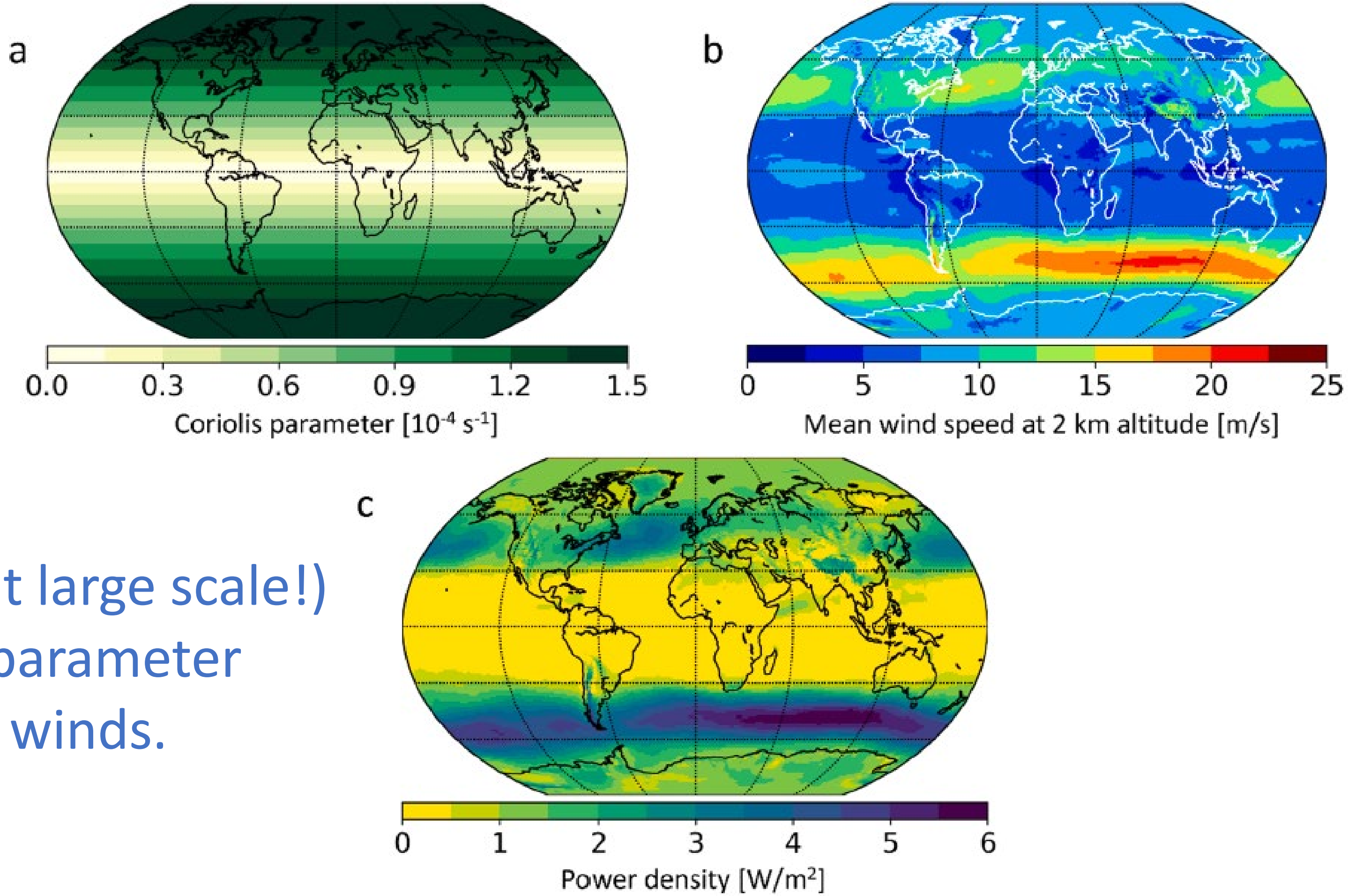
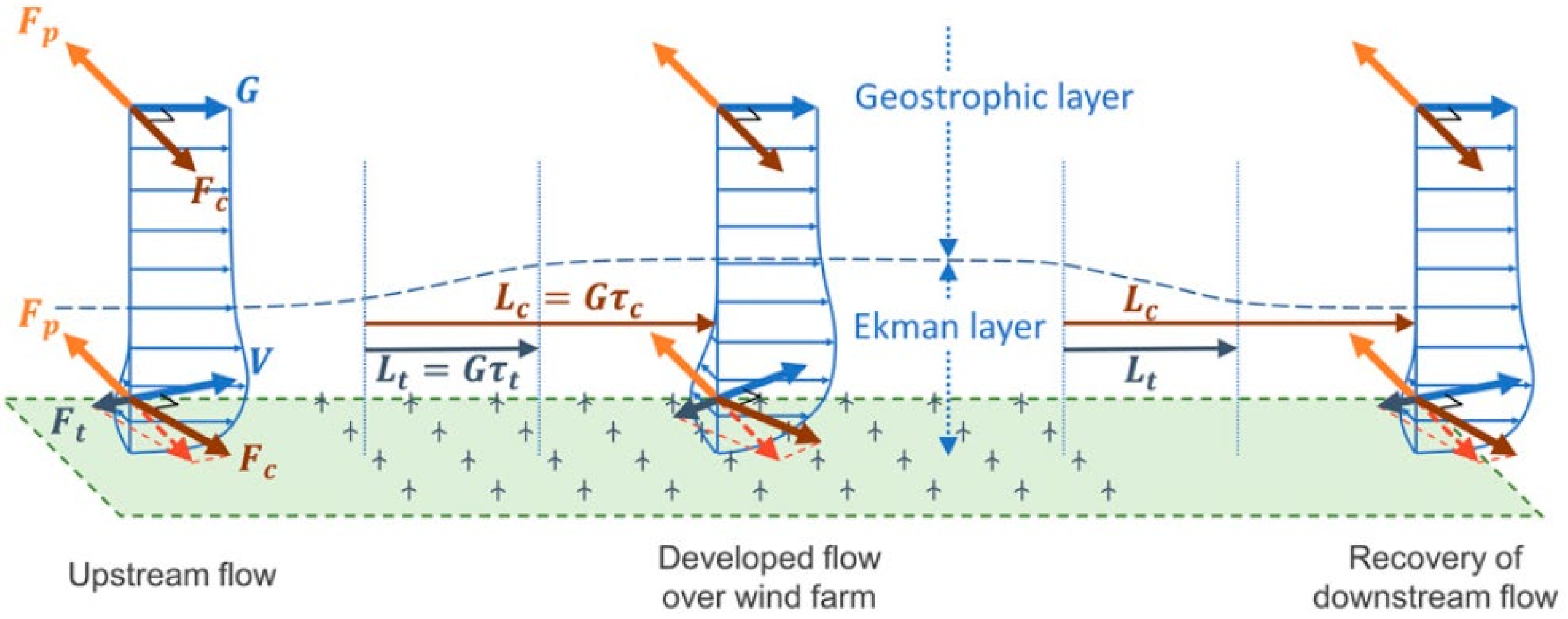


Maximum wind power extraction (at large scale!) can be estimated from the Coriolis parameter and the strength of the geostrophic winds.

Spatial constraints in large-scale expansion of wind power plants

Enrico G. A. Antonini[a,1] and Ken Caldeira[a]

PNAS 2021 Vol. 118 No. 27 e2103875118



$$L \propto \frac{G}{f} \propto \frac{\frac{d\Phi}{dx}}{f}$$

Transition length scale (L) is proportional to:
geostrophic winds (G) divided by Coriolis parameter (f),
which is proportional to
the horizontal pressure gradient (d Φ / d x) divided by the Coriolis parameter (f).

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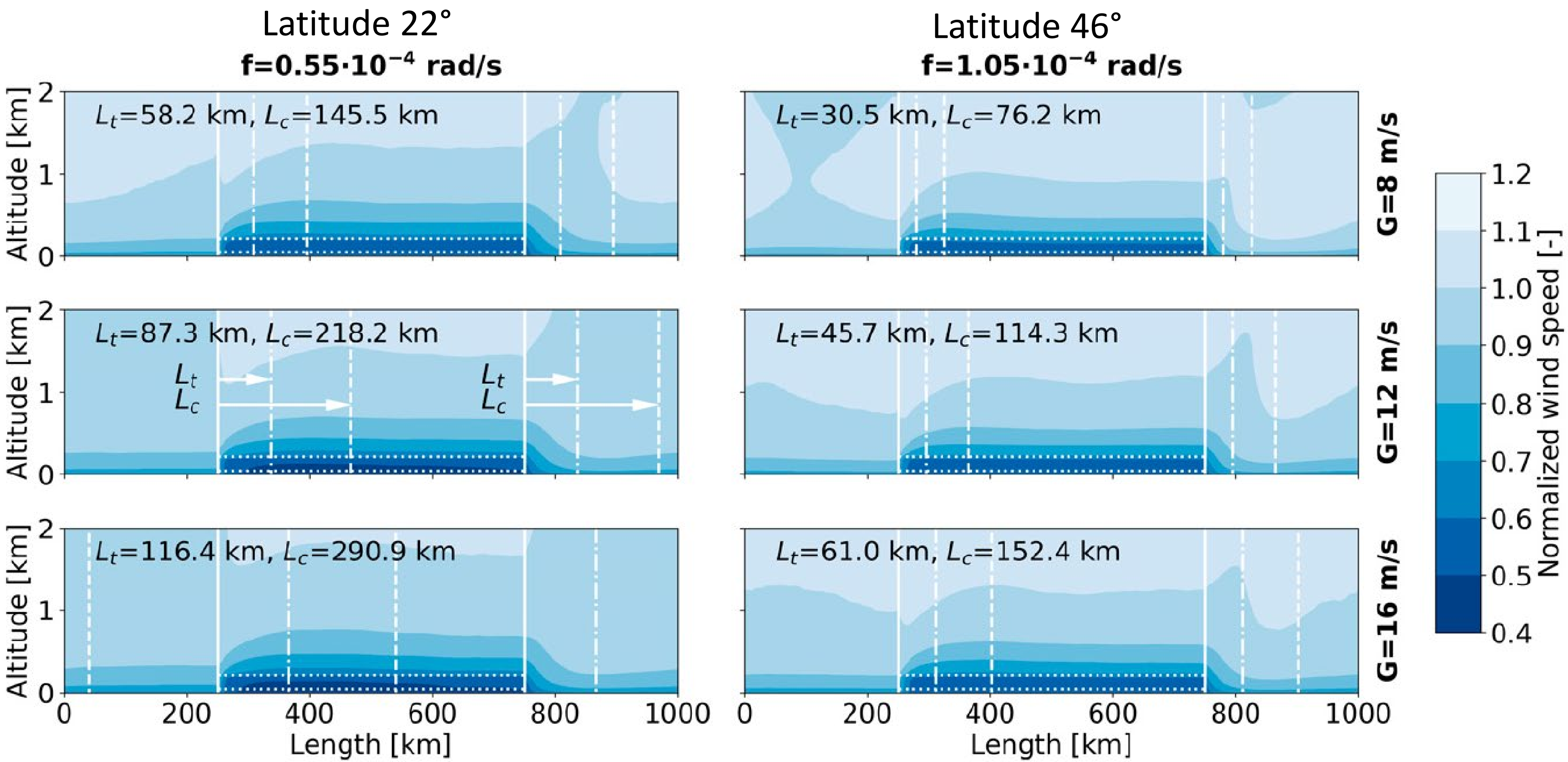

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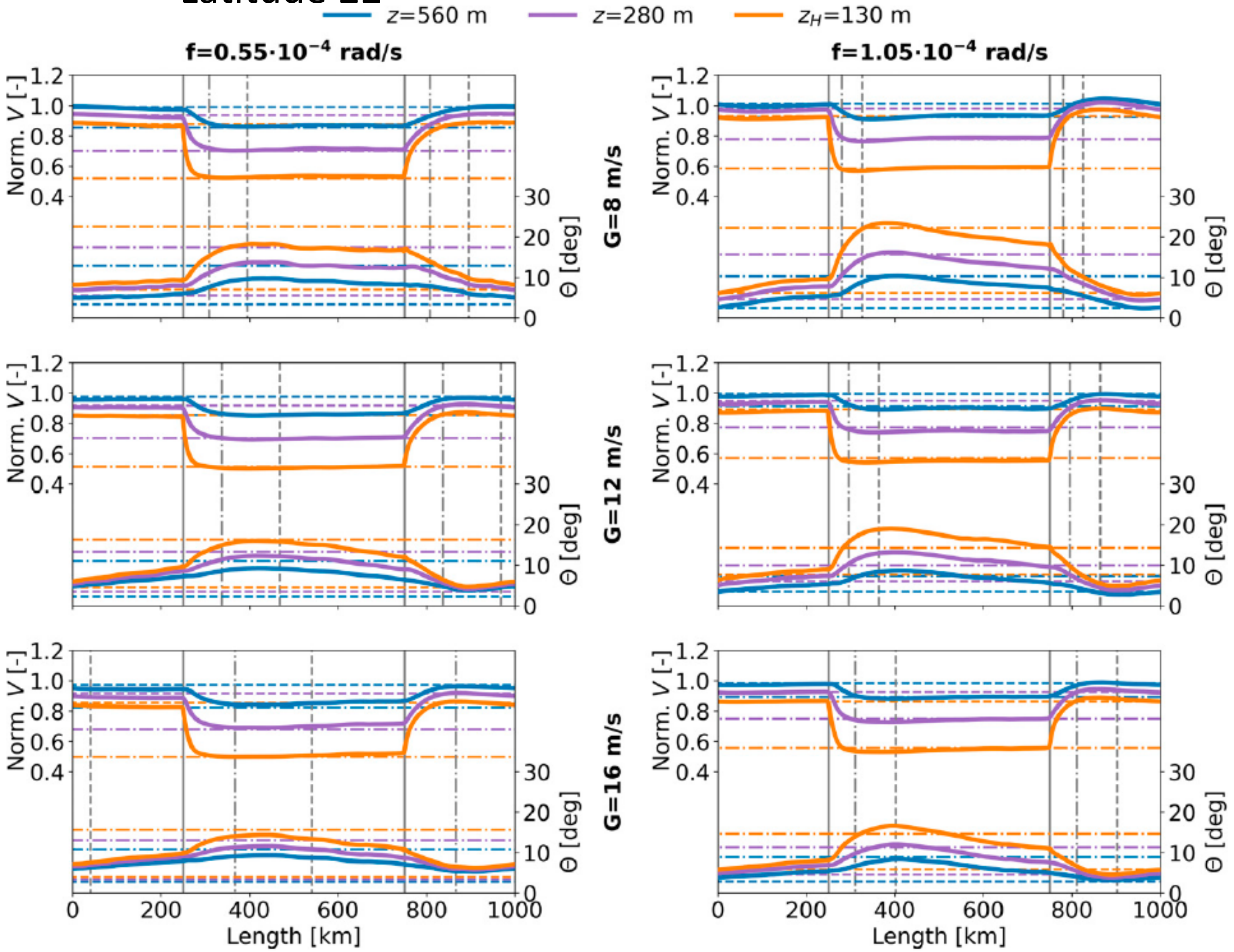
PNAS 2021 Vol. 118 No. 27 e2103875118

Latitude 22°

Latitude 46°



Wind speeds at hub height drop to ~0.6 by the turbulent length scale, which means wind power drops by 80%.

communications earth & environment   **Article**

https://doi.org/10.1038/s43247-024-01260-7

Identification of reliable locations for wind power generation through a global analysis of wind droughts

Check for updates

Enrico G. A. Antonini[1,2,3], Edgar Virgüez[1], Sara Ashfaq[1,4], Lei Duan[1,5], Tyler H. Ruggles[1] &
Ken Caldeira[1,6]

Communications Earth & Environment | (2024)5:103

What can we usefully say about wind resources from a purely geophysical perspective, without taking cost, current demand, etc, into consideration?

Goal: Identify locations with –

- High mean wind-power density
- Low seasonal variability
- Low weather variability

How do we reasonably combine disparate metrics (power density, variability) into a single metric?

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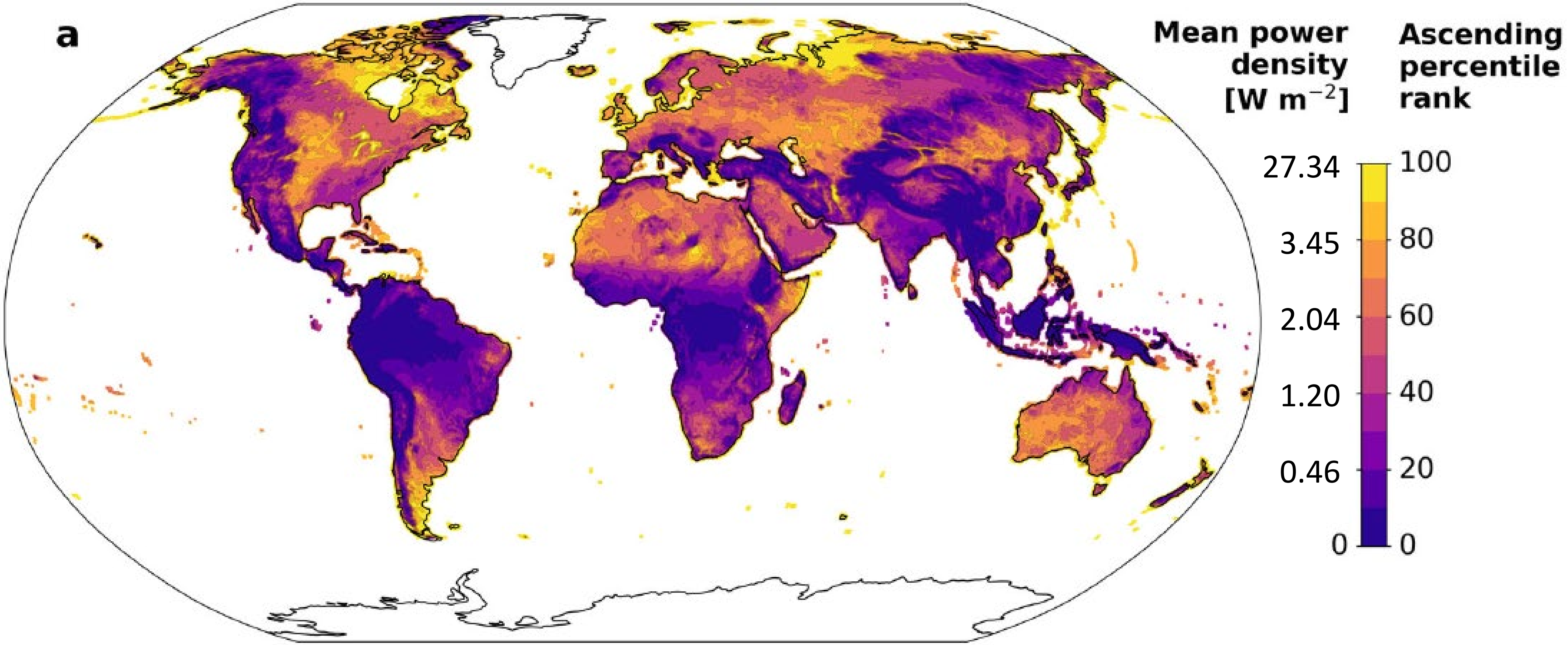
Power density



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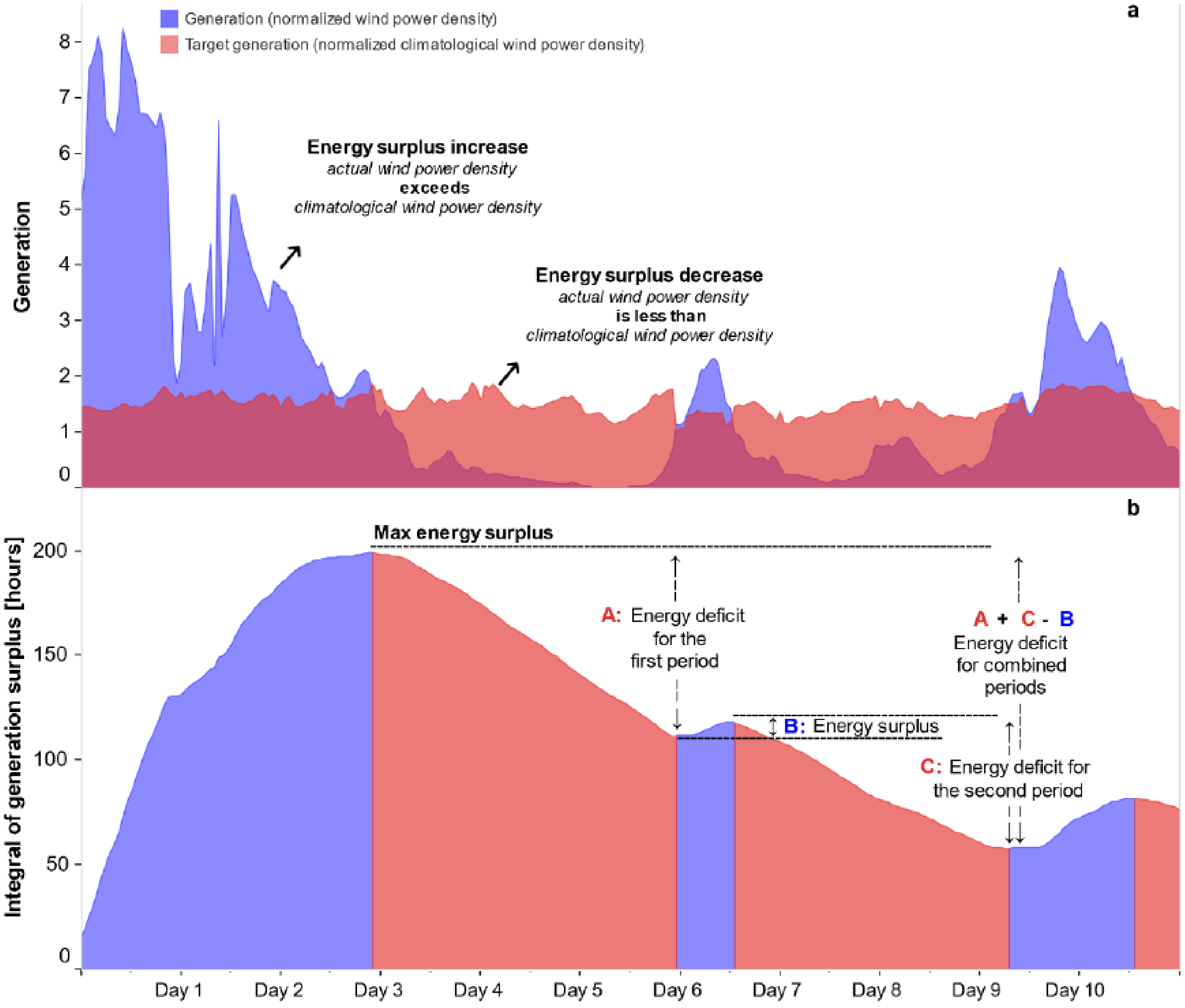
Energy deficit variability metrics

- **Seasonal variability**
  Difference between hourly climatological average wind power and constant mean average

- **Weather variability**
  Difference between hourly reanalysis wind power and hourly climatological averages



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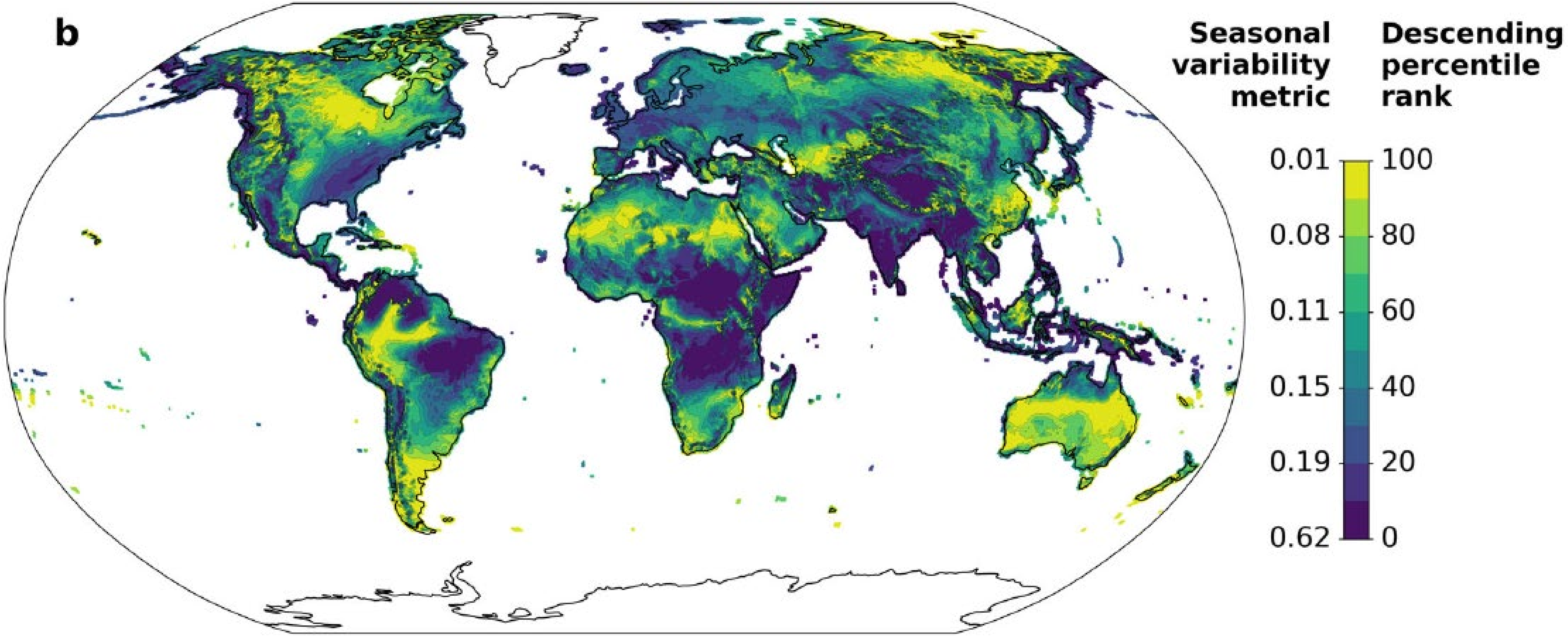
Seasonal variability



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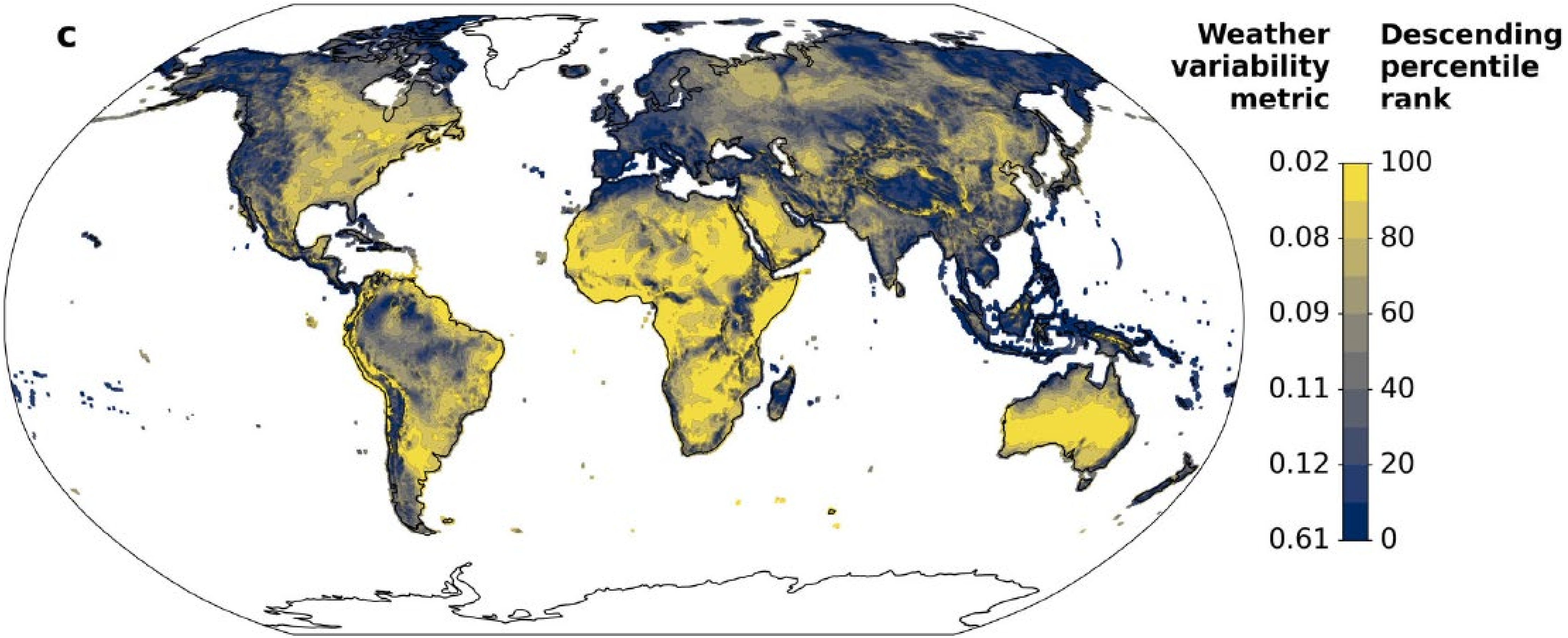
Weather variability



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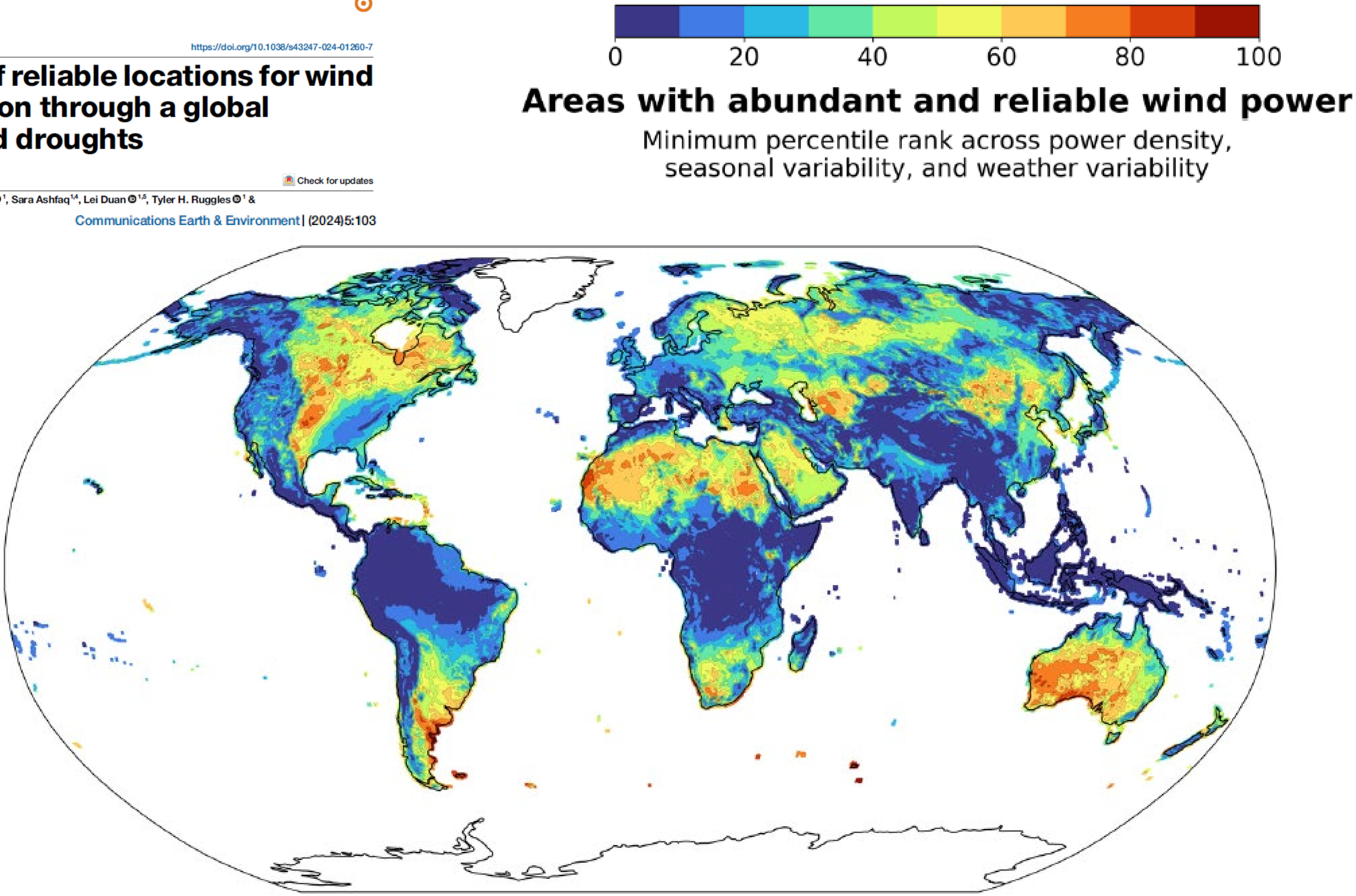

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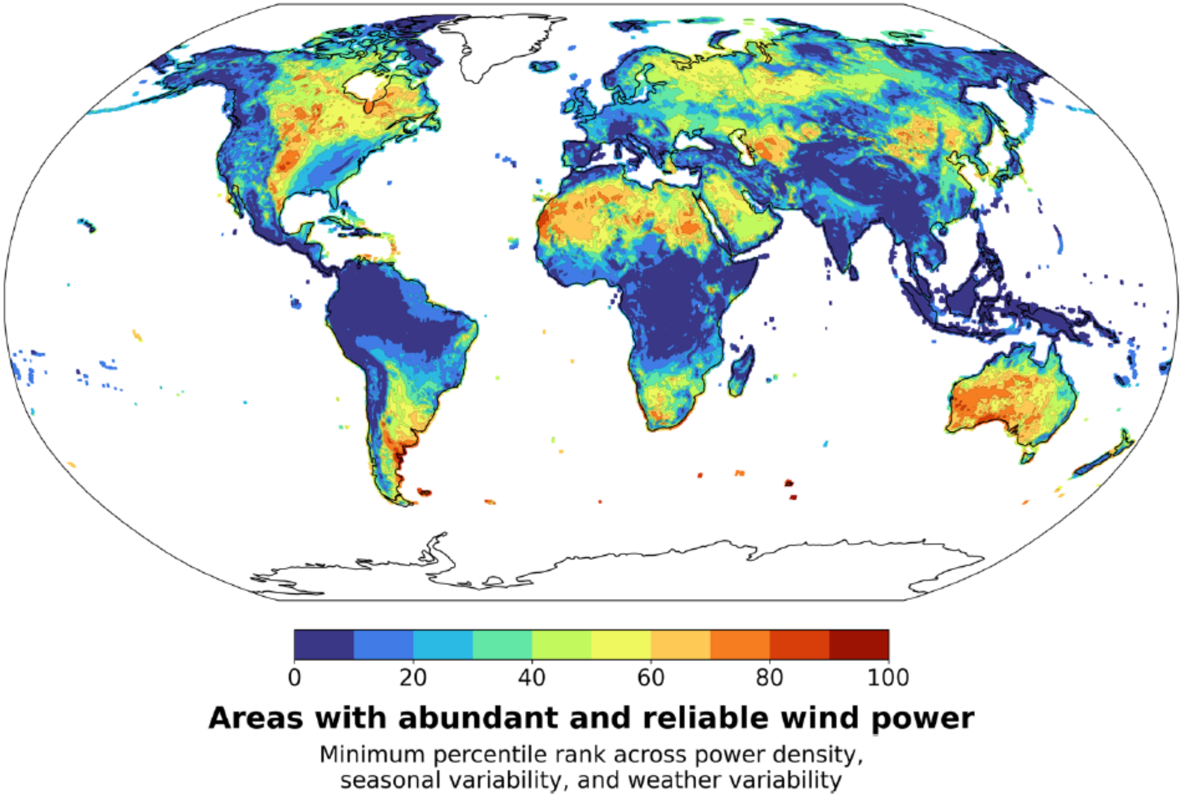

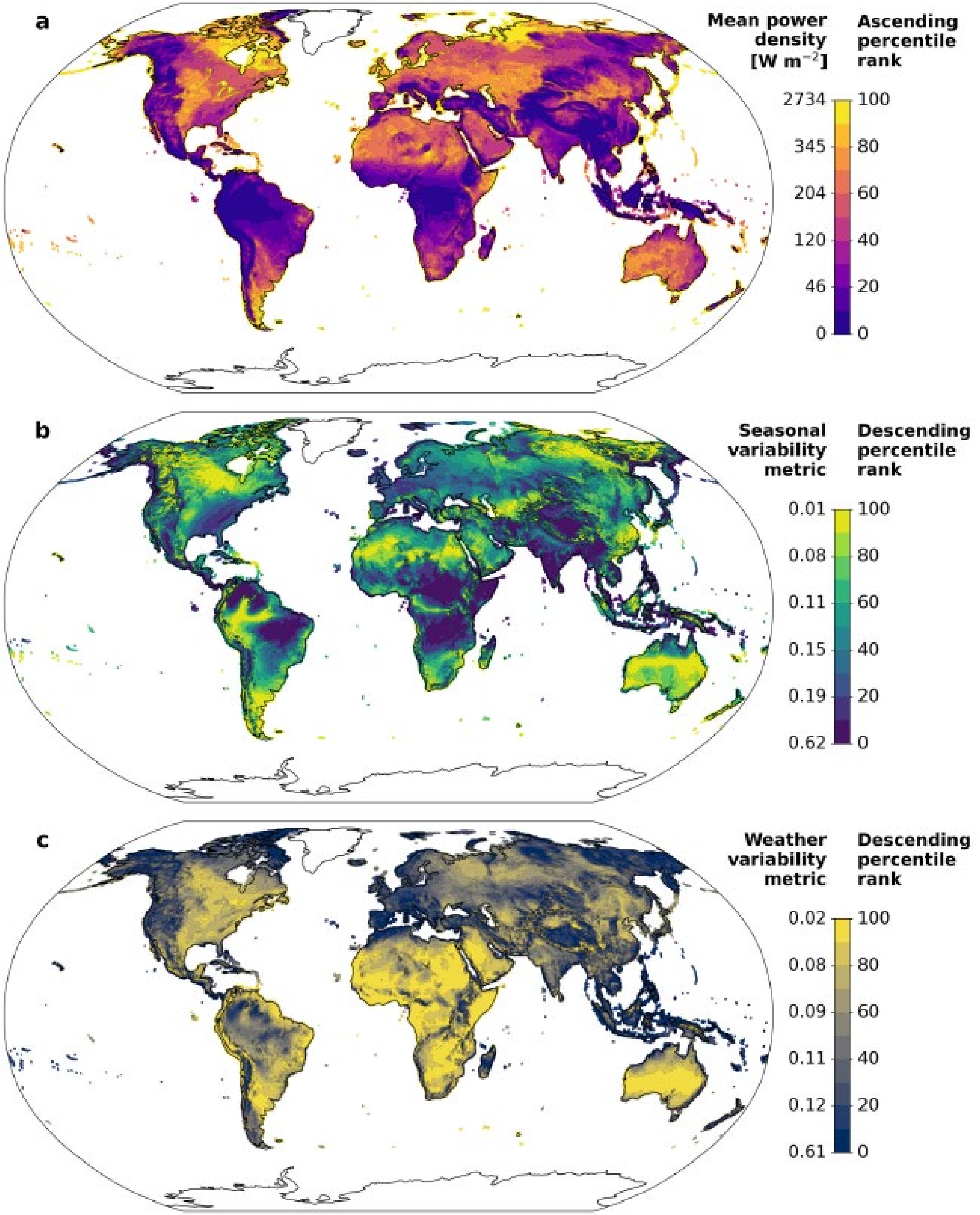

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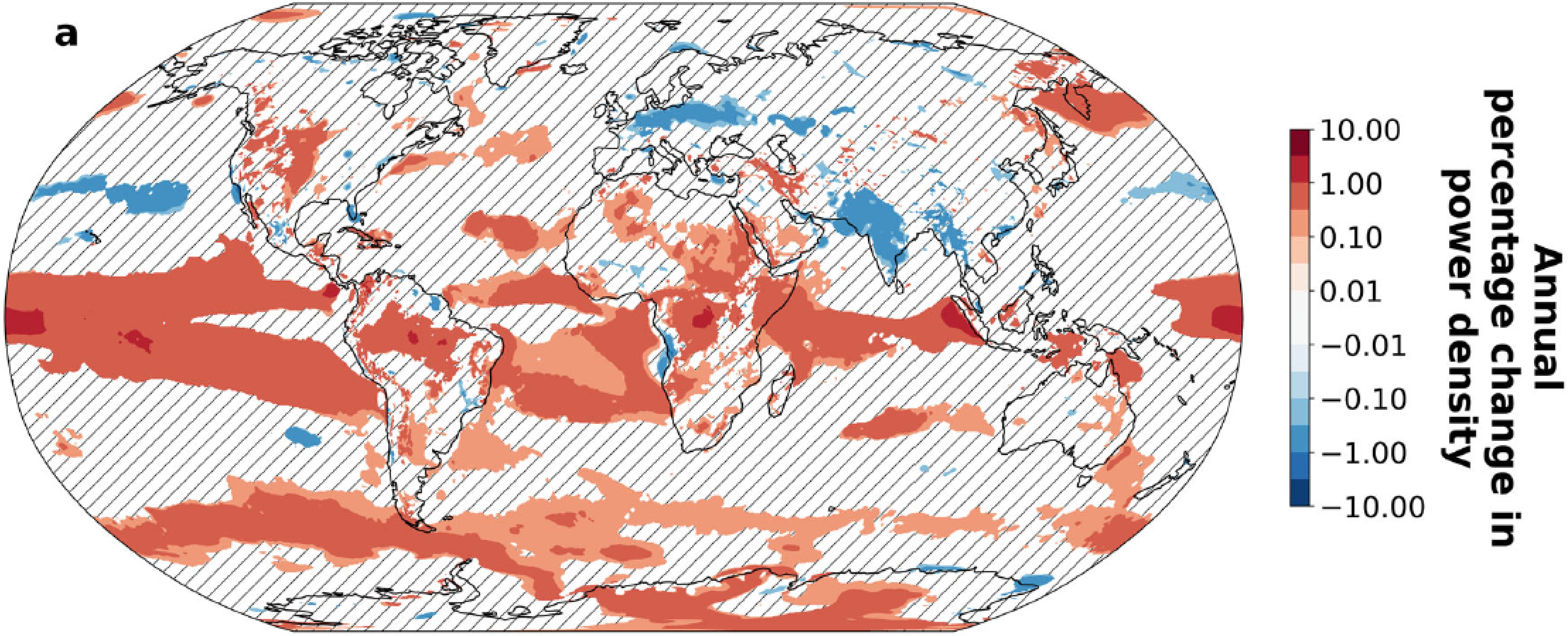
Historical temporal trends in power density



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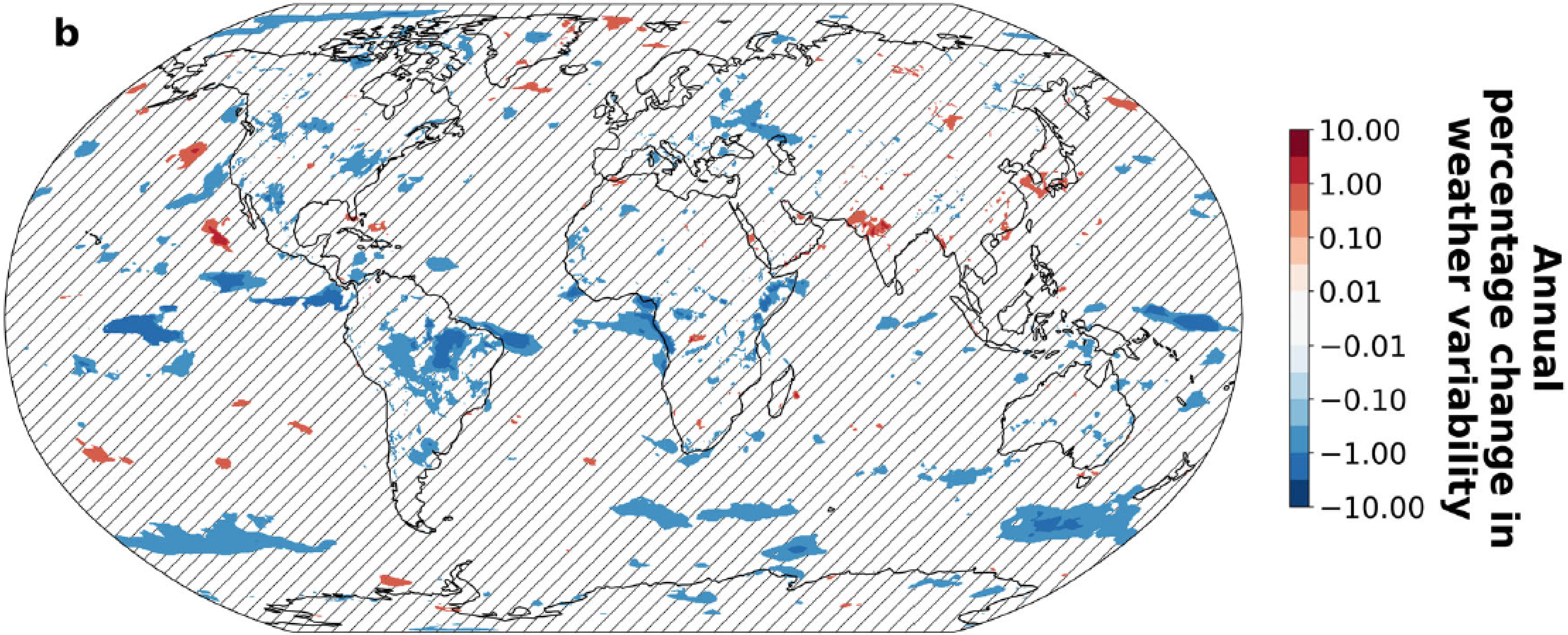
Historical temporal trends in weather variability



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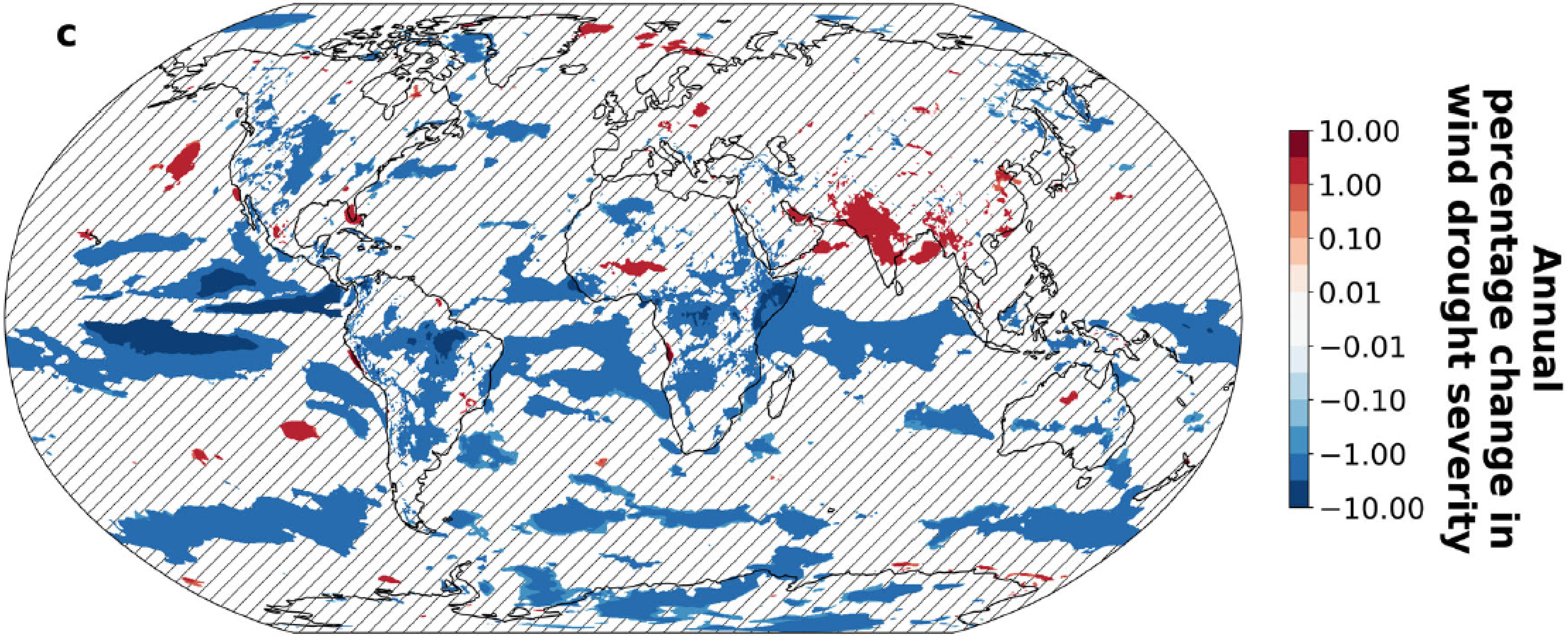
Historical temporal trends in wind drought severity



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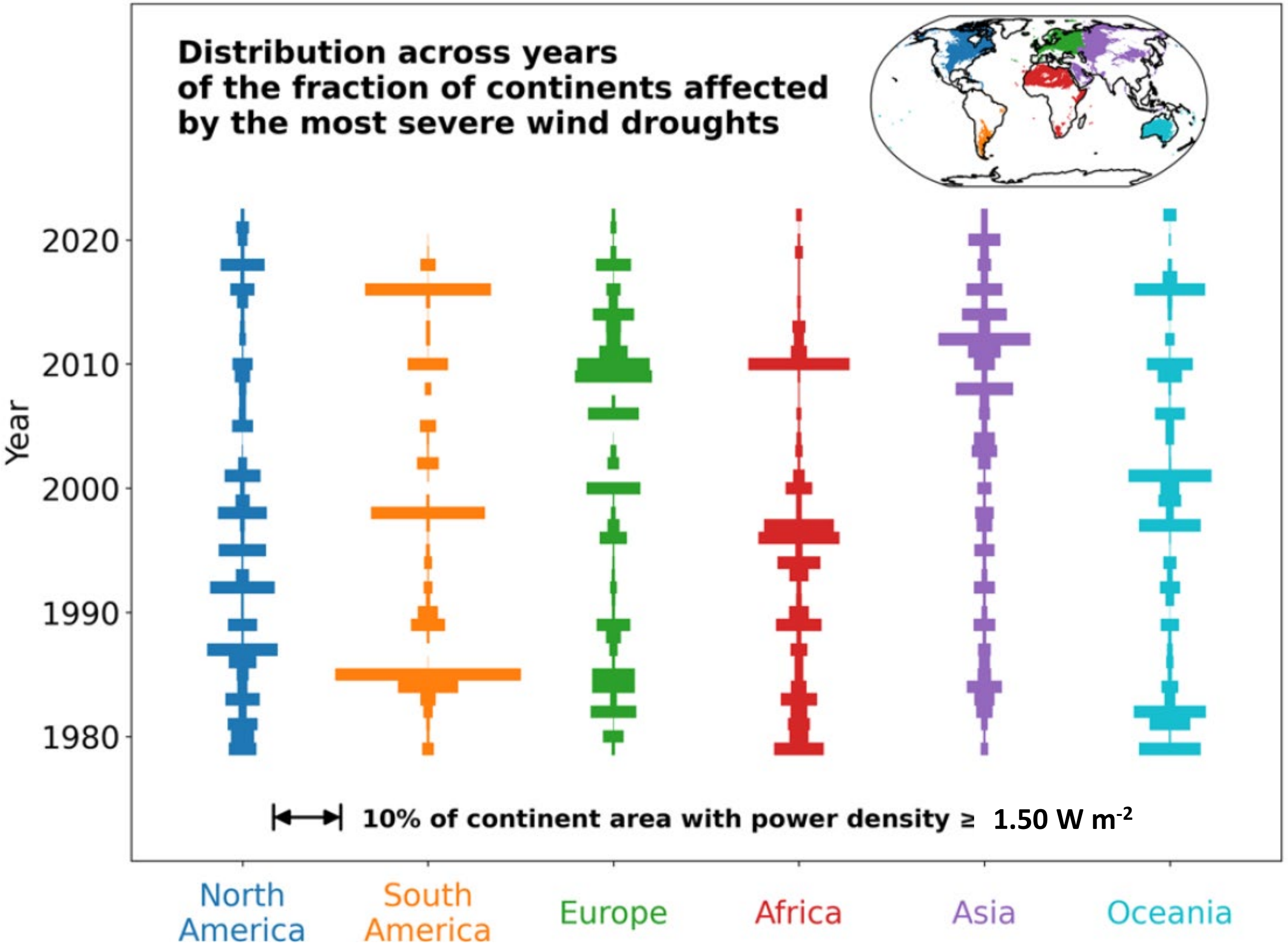
Historical temporal trends in wind drought area



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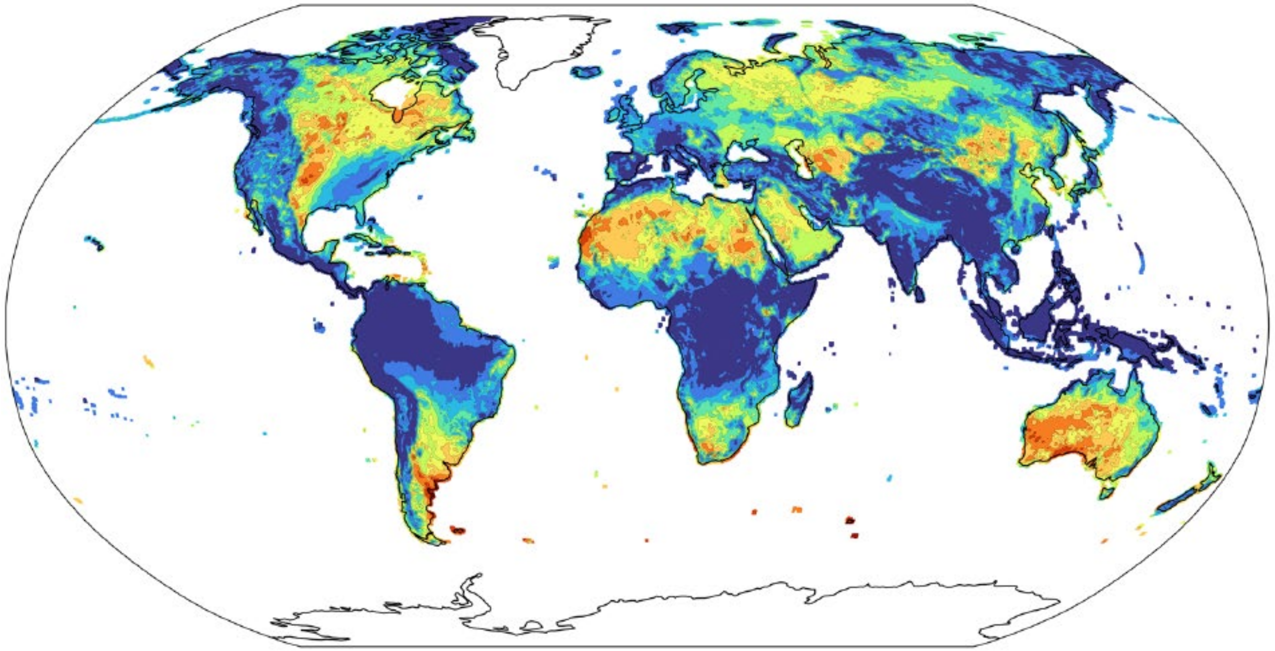
Thanks to Kate Marvel, Eva Ahbe, Anna Possner, and, especially, Enrico Antonini, for advancing this research at the intersection of wind energy and the geophysical sciences

(and thanks Gates Ventures for funding)

Conclusions



- There are a lot of places with strong, reliable winds, but not everywhere
- At regional scale in good places, 2 W/m^2 = 2 MW/km^2 is a reasonable expectation
- This value is limited by the ability of large-scale pressure forces to replenish energy removed by wind turbines
  - The length scale for replenishment is proportional to wind speeds and inversely proportional to the Coriolis parameter (and so shorter at high latitudes), but is typically some 10s of km

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nature climate change
LETTERS
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https://www.nature.com/articles/nclimate1683

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JOURNAL OF CLIMATE

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