How much kinetic energy can the large-scale atmospheric circulation at best generate?

Axel Kleidon
Max-Planck-Institut für Biogeochemie
akleidon@bgc-jena.mpg.de

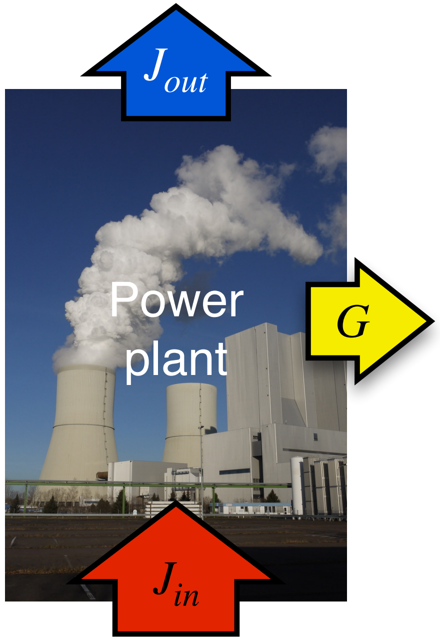
www.earthsystem.org

EGU General Assembly 2022

Image: NASA

The Earth operates like a power plant

Cooling
by water



Heating
by combustion

Electricity
generation
(free energy)

First law:
(energy conservation)

$$J_{in} = J_{out} + G$$

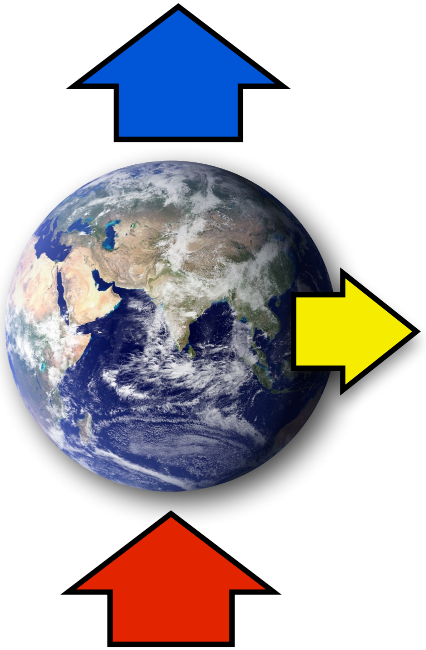
Second law:
(entropy cannot decrease)

$$\frac{J_{out}}{T_{out}} \geq \frac{J_{in}}{T_{in}}$$

Combination yields Carnot limit:

$$G \leq J_{in} \cdot \frac{T_{in} - T_{out}}{T_{in}}$$

Cooling
by emission



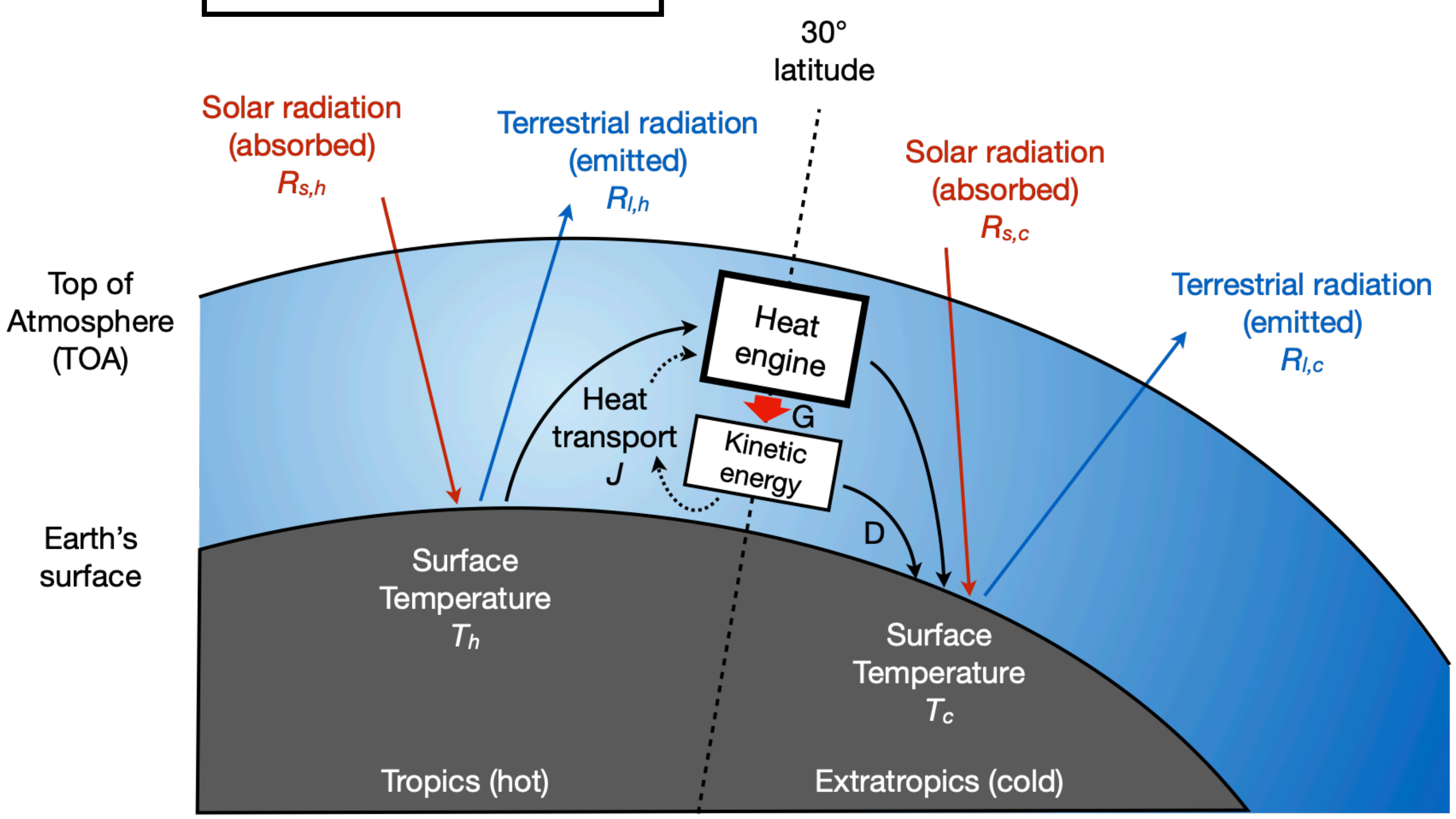
Heating
by sunlight

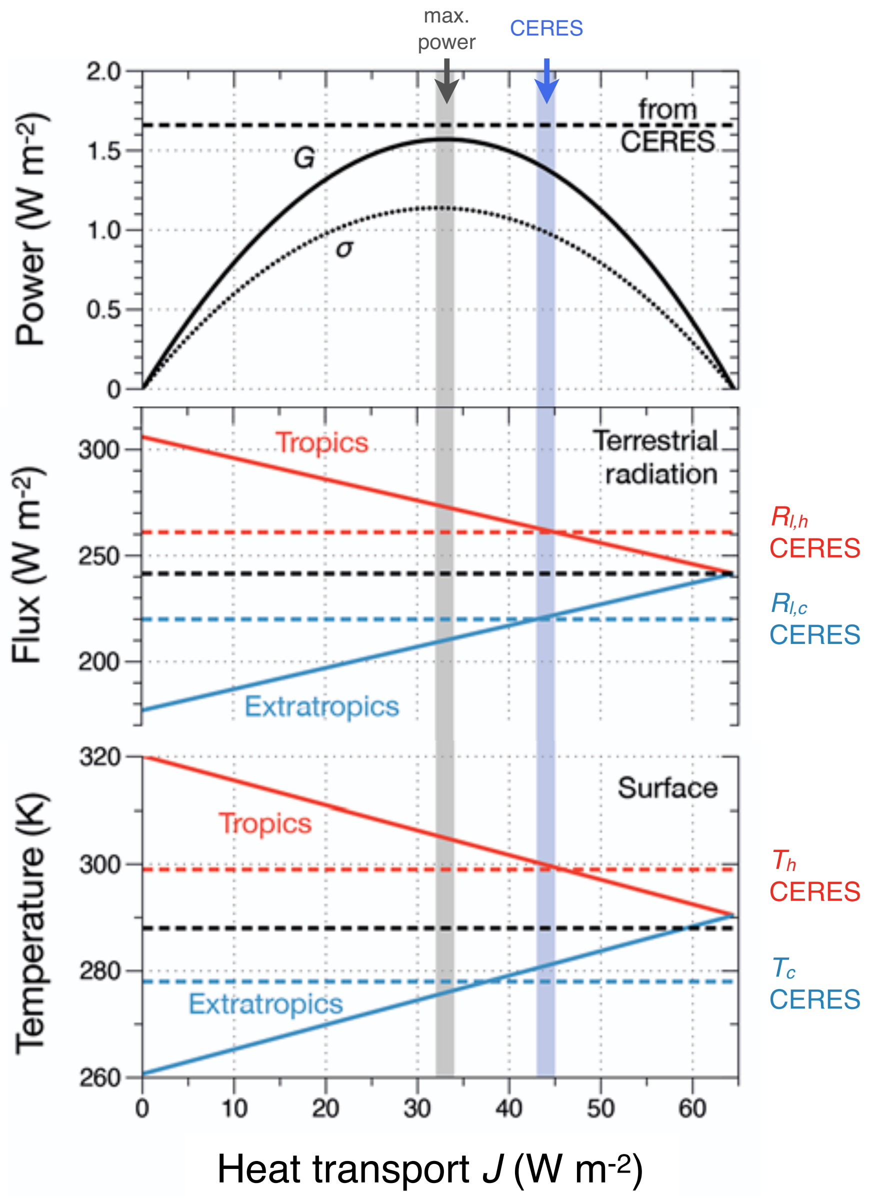
Image: NASA

Power
= Work/time
(free energy)

Thermodynamics limits kinetic energy generation

$\Delta R_s \rightarrow \Delta T \rightarrow G \rightarrow KE$



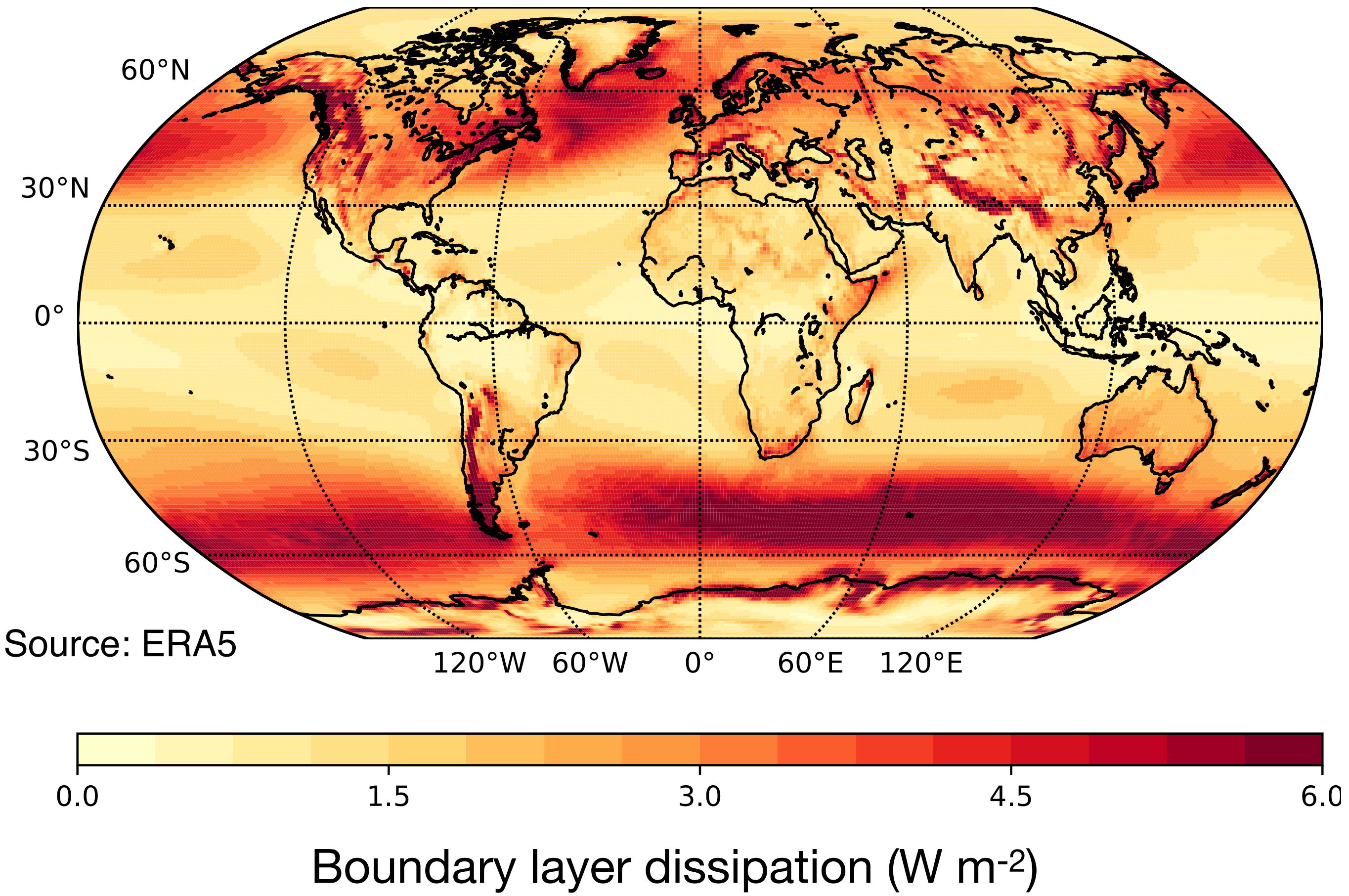


$$G = J \cdot \frac{T_h - T_c}{T_h}$$

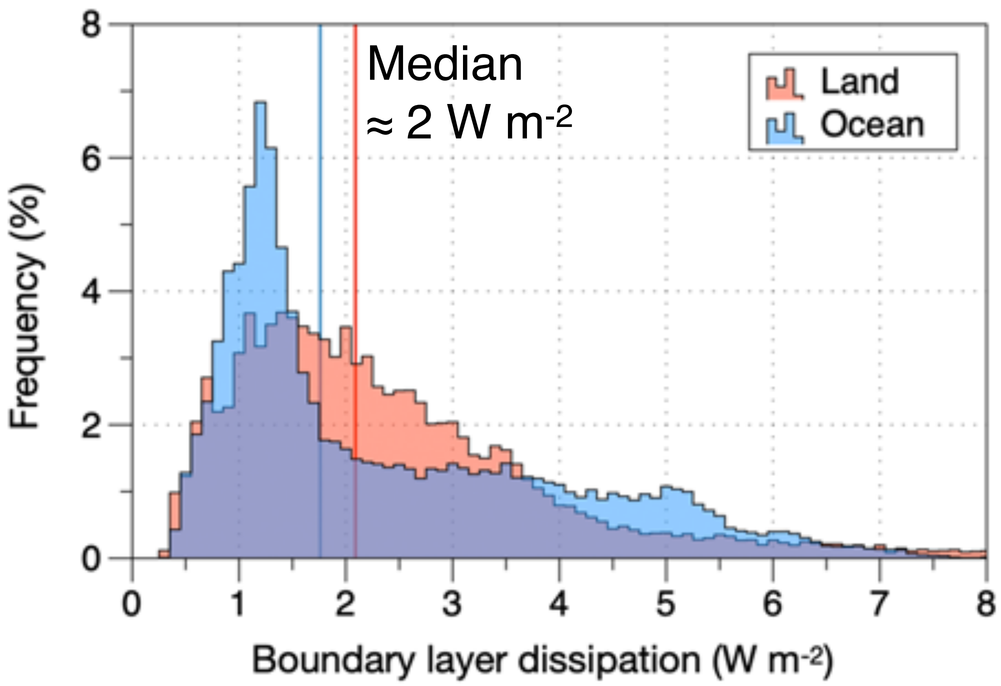
Kleidon (2021) *Met Z*

Thermodynamics limits frictional dissipation

$\Delta R_s \rightarrow \Delta T \rightarrow G \rightarrow KE \rightarrow D$



Source: ERA5



Kleidon (2021) *Met Z*

Link to MEP and Available Potential Energy (APE)

Maximum Entropy Production (MEP)

$\Delta R_s \rightarrow \Delta T \rightarrow G \rightarrow KE \rightarrow D$

Entropy production, σ,
by frictional dissipation, D:

$$\sigma = \frac{D}{T_c} = J \cdot \frac{T_h - T_c}{T_h \cdot T_c}$$

Carnot limit

Maximum power G
≈
Maximum Entropy Production σ
but more specific

MEP: Paltridge (1975) *QJRMS*, …

Lorenz Energy Cycle

$\Delta T \rightarrow \Delta PE \rightarrow APE \rightarrow KE \rightarrow D$

Difference in
Potential Energy, PE:

$$\Delta U_{pe} \approx \frac{p_s}{g} R \cdot \Delta T$$

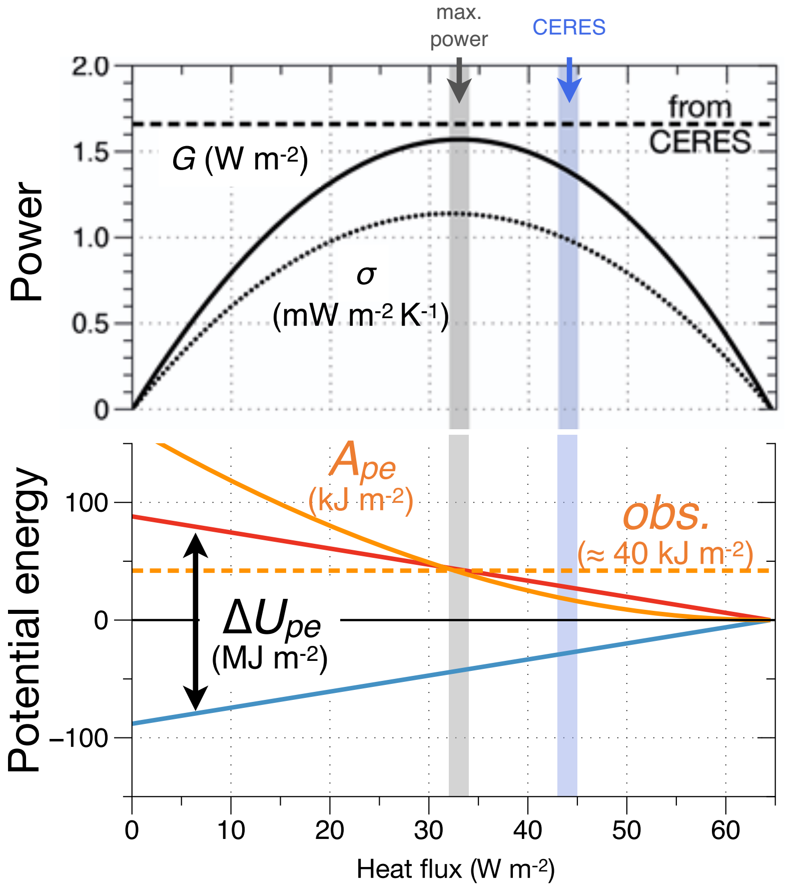
Available Potential Energy, APE:

$$A_{pe} \approx \frac{1}{2} \cdot \frac{p_s R}{g} \cdot \Delta T \cdot \frac{\Delta T}{T_h}$$

ΔU_{pe} Carnot efficiency

LEC: Lorenz (1955)

Two box model



Kleidon (2021)

How much kinetic energy can the atmosphere generate?

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*

Max-Planck-Institute for Biogeochemistry, Jena, Germany

(Manuscript received September 29, 2020; in revised form February 5, 2021; accepted February 15, 2021)

Abstract

How much wind energy does the atmosphere generate, and how much of it can at best be used as renewable energy? This review aims to give physically-based answers to both questions, providing first-order estimates and sensitivities that are consistent with those obtained from numerical simulation models. The first part describes how thermodynamics determines how much wind energy the atmosphere is physically capable of generating at large scales from the solar radiative forcing. The work done to generate and maintain large-scale atmospheric motion can be seen as the consequence of an atmospheric heat engine, which is driven by the difference in solar radiative heating between the tropics and the poles. The resulting motion transports heat, which depletes this differential solar heating and the associated, large-scale temperature difference, which drives this energy conversion in the first place. This interaction between the thermodynamic driver (temperature difference) and the resulting dynamics (heat transport) is critical for determining the maximum power that can be generated. It leads to a maximum in the global mean generation rate of kinetic energy of about 1.7 $W\,m^{-2}$ and matches rates inferred from observations of about 2.1–2.5 $W\,m^{-2}$ very well. This represents less than 1 % of the total absorbed solar radiation that is converted into kinetic energy. Although it would seem that the atmosphere is extremely inefficient in generating motion, thermodynamics shows that the atmosphere works as hard as it can to generate the energy contained in the winds. The second part focuses on the limits of converting the kinetic energy of the atmosphere into renewable energy. Considering the momentum balance of the lower atmosphere shows that at large-scales, only a fraction of about 26 % of the kinetic energy can at most be converted to renewable energy, consistent with insights from climate model simulations. This yields a typical resource potential in the order of 0.5 $W\,m^{-2}$ per surface area in the global mean. The apparent discrepancy with much higher yields of single wind turbines and small wind farms can be explained by the spatial scale of about 100 km at which kinetic energy near the surface is being dissipated and replenished. I close with a discussion of how these insights are compatible to established meteorological concepts, inform practical applications for wind resource estimations, and, more generally, how such physical concepts, particularly limits regarding energy conversion, can set the basis for doing climate science in a simple, analytical, and transparent way.

Keywords: Thermodynamics, Carnot limit, Maximum Entropy Production, maximum power limit, Lorenz energy cycle, Betz limit, wind energy, resource potential

1 Introduction

In the current transition to a sustainable energy system, renewable forms of energy, such as solar, wind energy, hydropower, and biofuels, play a central role. Wind energy, the use of the kinetic energy associated with atmospheric motion by wind turbines, is one of the more common forms of renewable energy that is used today. It has seen a rapid expansion in the recent two decades. In Europe, for instance, the installed capacity of wind turbines has more than doubled over the last decade from 77 GW at the end of 2009 to 205 GW at the end of 2019 (WINDEUROPE, 2020). Some scenarios expect wind energy to continue to grow, considering 450 GW of installed capacity in offshore areas of Europe alone in 2050, with about half to be installed in the North Sea (WINDEUROPE, 2019). In Germany, wind energy on land has roughly doubled during the last decade, with an increase in installed capacity from 25.7 GW at the end of 2009 to 53.3 GW at the end of 2019, contributing more than 40 % of the renewably generated electricity in Germany (BMWI, 2020). Scenarios for 2050 envision the installed capacity of onshore wind energy in Germany to increase to 102–178 GW, with additional 51 GW–60 GW installed offshore (BDI, 2019; WWF, 2019).

Such an anticipated increased use of wind energy in the future raises questions about the limits to wind energy use. How much can wind energy, at most, contribute to human energy needs? Can wind energy meet the entire energy needs of industrialized countries? Is wind energy so abundant that it can continuously power all human civilization, as some scientists have argued

*Corresponding author: Axel Kleidon, Max-Planck-Institute for Biogeochemistry, Hans-Knöll-Str. 10, 07745 Jena, Germany, akleidon@bgc-jena.mpg.de

DOI 10.1127/metz/2021/1062

Gebrüder Borntraeger Science Publishers, Stuttgart, www.borntraeger-cramer.com

- An atmospheric **heat engine** generates kinetic energy from differential radiative heating
- **Interaction** with energy balances yields a **maximum power limit**
- Maximum power of **≈ 2 $W\,m^{-2}$** compares to observations very well (+ associated APE)
- Link to MEP: power = dissipation, which produces entropy
- Link to LEC: $\Delta T \approx \Delta PE$, and $APE = \eta_{Carnot}\,\Delta PE$

The atmosphere works as hard as it can!

So what?

- Thermodynamic constraint on dynamics
- Reduced efficiency of wind turbines at larger scales

Kleidon (2021) Met Z
doi: 10.1127/metz/2021/1062