Seasonal and annual variability of global winds and wind power resources

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Seasonal and annual variability of global winds and wind power resources

Cristina L. Archer\textsuperscript{a} and Mark Z. Jacobson\textsuperscript{b}

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This paper provides global and regional wind resource estimates obtained with a 3-D numerical model that dynamically calculates the instantaneous wind power of a modern 5 MW wind turbine at its 100-m hub height each time step. The model was run at various horizontal resolutions (4x5, 2x2.5, and 1.5x1.5 degrees of latitude and longitude) for several years. Despite differences during the first two years, global wind power estimates from all runs effectively converged. Global delivered 100-m wind power at high-wind locations (≥7 m/s) over land, excluding both polar regions, including transmission, distribution, and wind farm array losses, but not considering landuse exclusions, is estimated to be 112-120 TW. Seasonal variations in global wind resources are significant, with 73-89 TW in June-July-August (JJA) versus 159-167 TW in December-January-February (DJF), with minima in September and maxima in January. The wind power over land in high-wind locations in the Northern Hemisphere (NH) is ~107 TW, over five times greater than that over the Southern Hemisphere (SH) (~19 TW) on average. The shallow-water offshore delivered wind power potential (excluding polar regions) is ~9 TW at 100 m, varying between 6.4 and 11.7 TW from JJA to DJF. The theoretical wind power over all land and ocean worldwide at all wind speeds, considering transmission, distribution, and array losses for typical wind farms, is ~1500 TW. Providing half the world’s energy for all purposes in 2030 from wind would consume <0.5% of the world’s wind power at 100 m, hardly affecting total power in the atmosphere.

1. Introduction

Wind energy is expected to play a major role in the transition from finite and polluting energy sources - fossil and fissile fuels - to a clean, sustainable, and perpetual renewable energy infrastructure\textsuperscript{1}. Although it is well known that the global wind resource is large\textsuperscript{2,3,4,5,6}, the exact magnitude of extractable wind power available worldwide is still under debate, mainly for four reasons: 1) the assumptions and definitions used in calculating global wind power are often inconsistent; 2) wind speed data at the hub height of modern wind turbines (~100 m) are few and sparse; 3) global model maps evaluated against data are not available at high resolution, either spatially or temporally; and 4) the conversion from wind speed to wind power is often calculated inconsistently because it requires assumptions about specific turbines and their efficiencies as well as transmission and wake losses.

First, the term “wind power potential” is not unequivocal. It can refer to one of four different types of potential\textsuperscript{7}, loosely defined as:
- Theoretical potential: the average kinetic energy in the winds at each instant at all levels in the atmosphere at all points, regardless of land cover, technology, efficiencies, or cost. As explained in section 3.2, a better measure of the theoretical wind power potential may be the added kinetic energy dissipation that does not introduce significant climatic effects.
- Technical potential: the fraction of the theoretical wind power potential that can be extracted with modern technologies (thus at hub height, over windy land and windy near-shore locations only, including limitations due to minimum and maximum wind speeds required to operate a turbine and array, transmission, and distribution losses).
- Practical potential: the wind power potential excluding areas with practical restrictions, such as conflicting land and water uses or remoteness.
- Economical potential: the fraction of practical wind power potential that can be harnessed after economic and financial considerations are included.

The need for clear, unequivocal definitions of wind power potentials has been addressed in Hoogwijk et al.\textsuperscript{3} and in GEA\textsuperscript{7}. Because such consistency in the definitions is still lacking in the literature, estimates of wind power potential can vary by orders of magnitude. Since the technical potential is possibly the most relevant, objective, and insensitive to market fluctuations, it is the primary focus of this study.

Second, the global technical wind power potential is challenging to evaluate because worldwide wind speed data are...
not available at the hub height of modern wind turbines (~100 m). As such, interpolation and extrapolations methods over hundreds of meters of altitude have been proposed, such as the Least Square Error method\textsuperscript{4,8} or the log- and power-laws\textsuperscript{9,10}. These techniques can be applied to both observational data and model results, but are approximate because they are based partly on theoretical and partly on empirical considerations\textsuperscript{10}. In this study, this limitation is overcome by using a 3-D atmospheric model with two layers with centers very close to 100 m, allowing a nearly precise model estimate of 100-m wind speeds.

In addition, global maps of the wind resource at hub height are not available at spatial and temporal resolutions that are fine enough to resolve significant local wind features or seasonal and monthly fluctuations of the global wind resource. Observation-based estimates, such as Archer and Jacobson\textsuperscript{2}, are limited by the sparse data in most regions of the globe. Fine-resolution maps are available for certain regions, such as the U.S. West Coast\textsuperscript{11,12}, but not for the entire globe, due to practical computational limitations. No study to date has addressed the seasonal and monthly fluctuations of wind power at the global scale. This study will address both issues – spatial and temporal resolution - by providing coarse, medium, and fine resolution maps of global wind power, season by season and month by month. A limitation of this study is that sub-grid scale topography could not be properly simulated at the resolutions modeled here. However, the model did treat subgrid soil and land use classes and calculated surface energy and moisture fluxes over each subgrid soil class every time step in the model. Running global simulations at higher-resolution than was done here was not possible given the computational resources available for this study.

Finally, the inconsistent methods of converting from wind speed to wind power is another reason for differences in wind power estimates in the literature. Previous model-based wind power mapping efforts estimated wind resources using data averaged over time from offline meteorological simulations, either by calculating the theoretical power available in the wind every 6 or 12 hours\textsuperscript{13,14}, applying a power curve to offline reanalyses of wind speeds every 6 hours\textsuperscript{15}, or using fitting equations to calculate the capacity factor from wind speeds averaged over one year\textsuperscript{15}. In this paper, wind power distributions were obtained by using the wind power curve of a selected wind turbine, the 5-MW model by REPower (http://www.repower.de/fileadmin/download/produkte/RE_PP_5 M_uk.pdf), directly in the meteorological model to calculate instantaneous power from instantaneous wind speed each model time step of 30 s in all simulations.

2. Methods

2.1 Implementation of a wind turbine power curve into the model

The model used for this study was GATOR-GCMOM, a one-way-nested (feeding information from coarser to finer domains) global-regional Gas, Aerosol, Transport, Radiation, General Circulation, Mesoscale, and Ocean Model that simulates climate, weather, and air pollution on all scales and has been evaluated extensively\textsuperscript{16,17,18}. In this paper, we further compare ocean wind speed data from the model with satellite data. The processes within the model have also been compared with those of other coupled climate-air pollution models in Zhang\textsuperscript{19}.

For this study, only the global domain was used, but at three horizontal resolutions. The model treated 47 vertical layers up to 60 km in each simulation, including 15 layers in the bottom 1 km. The four lowest levels were centered at approximately 15, 45, 75, and 106 m above the ground, but the heights of such centers changed continuously in a small range since the vertical coordinate system used was the sigma-pressure coordinate. Each time step, though, all wind speeds were interpolated vertically between two layer centers to exactly 100 m, the hub height of the wind turbine assumed for the calculations here.

The model solves the momentum equation with the potential- enstrophy-, vorticity-, energy-, and mass-conserving scheme of Arakawa and Lamb\textsuperscript{20}. Two-dimensional ocean mixed-layer dynamics conserves the same four properties while predicting mixed-layer velocities, heights, and energy transport\textsuperscript{21}. The model solves 3-D ocean energy and chemistry diffusion, 3-D ocean equilibrium chemistry, and ocean-atmosphere exchange. The model also treats subgrid soil classes, each with a 10-layer soil model, and surface energy and moisture fluxes separately over each subgrid class\textsuperscript{16}.

In order to calculate wind power from the model, we first selected a turbine, the REPW 5M wind turbine. With a diameter of 126 m and a hub height of 100 m, it reaches the rated power 5 MW at the rated speed of \(V_{\text{rated}}=12.5\) m/s. Manufacturer power output data as a function of wind speed were provided as a graphic curve in one-unit intervals. A third-order polynomial fit was used to obtain wind power output \(P\) as a continuous function of 100-m wind speed \(v\):

\[
P = av^3 + bv^2 + cv + d, \tag{1}
\]

where the coefficients \(a, b, c,\) and \(d\) are shown in Fig. 1. No power can be produced at wind speeds lower than 3.5 m/s (cut-in speed) or higher than 25 m/s (cut-off speed). Because of the change in the curve concavity, different coefficients were derived for low versus high wind speeds.

![Fig. 1 Power curve of the REPW 5M wind turbine, with coefficients valid below 10 m/s (lower polynomial, black line) and above or equal to 10 m/s (upper polynomial, grey line) used to interpolate the manufacturer’s data.](image-url)
each column in the model was applied to Equation 1 to determine the instantaneous wind power at 100 m for a single wind turbine. Wind power at 100 m was stored so that monthly, seasonal, and annual statistics could be obtained.

### 2.2 Numerical simulations

Three simulations were run, each with a different horizontal resolution and start date (Table 1). Initial conditions for each simulation were obtained with 1°x1° reanalysis fields. To eliminate the effect of the initial state, the model results for the first several months of each simulation were discarded and only results since March 2007 were retained.

<table>
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<th>End date</th>
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<td>1 Jan 2006</td>
<td>31 Dec 2009</td>
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<tr>
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<td>30</td>
<td>19 Feb 2006</td>
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### 2.3 Assumptions for global wind power calculations

After each simulation, a maximum number of turbines in each grid cell was determined by dividing the grid cell surface area by the spacing area of a single turbine, estimated as $A=\pi D^2$, where $A$ is the turbine diameter (126 m in this case) [Masters, p. 352]. The power output from the model per turbine for either a month, season, or year was then multiplied by the number of turbines in the grid cell to obtain the power available in the cell before the system efficiency was accounted for. This power is referred to as “turbine power” and is used in this paper only for calculations of the capacity factor (in Section 3.1). Power output accounting for system efficiency was then tabulated. This power is referred to as “end-use power”. Except for capacity factor, all power results reported in this paper are end-use power, thus accounting for system efficiency.

The system efficiency of a wind farm $\eta$ is the ratio of energy delivered to raw energy produced by the turbines. It accounts for array, transmission, and distribution losses (but not for maintenance or availability losses).

Array losses are energy losses resulting from reductions in wind speed that occur in a large wind farm when upstream turbines extract energy from the wind, reducing the wind speed for downstream turbines. Upstream turbines also create vortices or ripples (turbulence) in their wakes that can interfere with downwind turbines. The greater the spacing between wind turbines, the lower the array losses due to loss of energy in the wind, vortices, and wakes. Array losses are generally 5-20 percent.

Transmission and distribution losses are losses that occur between the power source and end users of electricity. Transmission losses are losses of energy that occur along a transmission line due to resistance. Distribution losses occur due to step-up transformers, which increase voltage from an energy source to a high-voltage transmission line and decrease voltage from the high-voltage transmission line to the local distribution line. The average transmission plus distribution losses in the U.S. in 2007 were 6.5 percent.

The overall system efficiency of a wind farm, accounting for array, transmission, and distribution losses typically ranges from 0.85 to 0.9; here we assumed an average $\eta=0.875$, corresponding to a system loss of 12.5 percent.

### 3. Results

#### 3.1 Mapping the global wind resource at various resolutions

Fig. 2 provides global wind speeds from the three simulations during the northern hemisphere (NH) winter. Additional maps for the entire simulation period are available at http://suntans.stanford.edu/~lozej/mark_model. The strongest winds are in the NH, especially over the waters in the northern Pacific and Atlantic oceans, where the Aleutian and the Icelandic low-pressure systems cause storms and strong winds near the surface. Whereas all runs are consistent with each other in the NH, some differences are found in the SH. For example, the annular structure of strong winds over the Southern Ocean appears continuous at 2x2.5 degrees, but somewhat discontinuous at 1.5x1.5 degrees. Also, a secondary wind speed maximum appears to the west of northern Australia in the 1.5x1.5 run only. Overall, however, the runs are in agreement with each other during DJF, although the 2x2.5 run shows generally higher wind speeds in the SH than does the 1.5x1.5 run.

Fig. 3 shows the 100-m wind speed distribution during the NH summer (JJA). The runs are in good qualitative agreement, with the 2x2.5 again producing slightly higher and more continuous winds over the Southern Ocean. The localized wind speed maximum offshore of California is a persistent feature in the northern Pacific during the NH summer and it represents possibly the greatest summertime offshore wind resource in North America during the season with the highest electric load. Although there is a second maximum offshore of Japan in JJA, the summer wind speed maximum offshore of California is predicted correctly by this model at all resolutions, with the least accuracy at 4x5 degree resolution.
Fig. 2  Average wind speed at 100 m during December-January-February from model runs: 4x5 (a); 2x2.5 (b); and 1.5x1.5 (c).
Fig. 3  Average wind speed at 100 m during June-July-August from model runs: 4x5 (a); 2x2.5 (b); and 1.5x1.5 (c).
The capacity factor (CF) of a turbine is the ratio of the actual power generated by the turbine to its rated power. The capacity factor in this definition does not account for the system efficiency, only the turbine efficiency and the variability of the wind, thus is a gross CF. Modern wind turbines installed in areas with average 100-m wind speeds greater than 7 m/s can achieve a gross CF>40%. By contrast, wind turbines exposed to average wind speeds lower than 7 m/s are less likely to be economically feasible, although recent progress in the development of low wind speed turbines may reduce this threshold from 7 to 6.5 m/s in the near future. The rest of this analysis focuses on “windy” areas, defined as those with yearly-average wind speeds at 100 m ≥7 m/s.

Fig. 4 shows the average gross capacity factor in January 2008 obtained with the REPower 5M wind turbine for all grid points over windy land and windy shallow (<200 m) waters only, without considering land or water use restrictions. The figure was obtained by masking out wind speeds lower than 7 m/s and then overlapping the resulting map with wind power divided by the rated power of the benchmark turbine (5000 kW). Areas with high CF (>0.3) in Fig. 4 are the most economical for wind power development over land. Aside from the mid-latitude areas in both NH continents, noticeable is the vast area in the Sahara and Sahel deserts with a CF~0.5.

As mentioned in the introduction, the horizontal resolution of these simulations is not fine enough to properly resolve some meso- and fine-scale features, such as steep topography or sudden surface roughness or landuse horizontal variations, which can cause localized high winds. This somewhat coarse resolution, however, is likely to result in an under-estimate, rather than an over-estimate, of wind speeds and wind power. For example, Fig. 4 shows little potential in Spain and Portugal, whereas both countries have installed over 30 GW of wind capacity in 2010 alone [need ref].

### 3.2 The global wind power potential: top-down methods

The global wind power potential can be estimated in at least three ways: from theoretical calculations, from observations, and from numerical modeling. The first is a top-down approach, the others are bottom-up.

Theoretical calculations rely on the basic equations of motion in the atmosphere, but require the use of simplifying assumptions (e.g., hydrostatic equilibrium, quasi-geostrophic balance, horizontal homogeneity) and spatially- and temporally-averaged values of physical variables (e.g., albedo, latent heat release, solar radiation, surface roughness) to solve them. Because of these limitations, the order of magnitude of these estimates, not their exact values, should be considered valid at most.

A distinction must first be made between the kinetic energy of the atmosphere (KE), measured either in units of joules (J, for the entire Earth) or J/m² (joules per square meter of Earth’s surface), and the so-called KE dissipation rate $\mathcal{D}$ expressed either in units of power (W) or power per unit area (W/m²), which represents the rate at which kinetic energy naturally drains out of the atmospheric motion field due to molecular viscous (or frictional) processes, occurring both in the mean flow (~9.5%) and in the unresolved scales from turbulent stresses (~90.5%)²⁷.
An expression for \( D \) is obtained by taking the scalar product of the momentum equation with the velocity vector \( \vec{v} \), then integrating over the entire volume of the atmosphere \( V \) with density \( \rho \):

\[
D = \int_V \rho F \cdot \vec{v} \, dV
\]  

(2)

where \( F \) is friction per unit mass in m/s² [Holt²⁸, p. 340], which is expressed as \( \nu \nabla^2 \vec{v} \) (or \( \frac{\partial^2 \vec{u}}{\partial x_i^2} \) with the Einstein notation) for incompressible flows, and \( \nu \) is the air kinematic viscosity in m²/s. Note that the volume integral in Eq. (2) can be calculated over smaller volumes than the entire atmosphere, such as over a region or in the wake of a turbine. When mechanical or thermal...
turbulence is considered, then \( D \) is the sum of a mean (\( \overline{D} \)) and a perturbation (\( D' \)) component as follows:

\[
\overline{D} = \int \rho \nu \overline{\partial u_i \overline{\partial x_j}} \, dV
\]  
(3)

\[
D' = \int \rho \nu \left( \frac{\partial u_i}{\partial x_j} \right) \, dV
\]  
(4)

where \( \overline{u_i} \) indicates a mean and \( u'_i \) a turbulent component of the velocity vector and the bar indicates a time or an ensemble average [Holm23, p. 340; Peixoto and Oort27, p. 376-377; AMS25]. Dividing Eqs. 2-4 by the Earth’s surface area gives \( D \) in units of W/m². Note that the term “dissipation rate” often refers to the expressions inside the integral in Eq. 4 (without the air density) as follows:

\[
\varepsilon = \nu \left( \frac{\partial u'_i}{\partial x_j} \right)^2
\]  
(5)

which has units of m²/s³ [AMS, 2000] and is always parameterized in models.

Regardless of the formulation used, the KE dissipation rate \( D \) is not a good proxy for wind speed or wind power because it is either the product of wind speed and friction (Eq. 2 or 3) or the square of turbulent stresses (Eq. 4). As such, knowing \( D \) alone is not sufficient to reconstruct wind speed.

Whereas the atmosphere has a large reservoir of KE (~11.8 x 10²⁷ J/m²; Peixoto and Oort27, p. 385), the dissipative term \( D \) is often negligible, except near the Earth’s surface, in regions of strong wind shear (e.g., the jet streams and in convective clouds) and of breaking gravity waves; it is also responsible for ocean surface currents. Because the friction vector always points opposite from the velocity vector, \( D \) is always negative (from Eq. 2) and therefore represents a sink, never a source, of KE. Dissipation \( D \) ultimately converts KE to internal energy (IE) via heating [Lorenz30, p.14]. Part of internal energy itself converts back to potential energy (PE) through, for example, buoyant convection, and gradients of PE reproduce KE. Treating energy exchange in the atmosphere involves treating not only PE, KE, and IE, but also solar and infrared radiation, latent heat, conduction, and geothermal heat.

The ratio of natural KE dissipation \( D \) to the globally- and annually-averaged downward solar radiation at the top of the atmosphere (~350 W/m²) is the atmospheric efficiency\(^{\text{39}} \eta. This efficiency represents the fraction of the incoming energy that is fed into the atmosphere to maintain the global circulation against dissipation. Lorenz30 estimated that \( \eta \) is at most 2% and thus \( D \) is ~7 W/m² or 3600 TW for the whole Earth (assuming a surface area of 5.12 x 10¹⁴ m²). King Hubbert11 later estimated a value of \( D \) that was 10x lower: ~370 TW (~0.72 W/m²) or \( \eta \approx -0.2\% \). Subsequent studies indicated that this value was too low. Peixoto and Oort27,32,33 estimated \( D \approx 1.88-2 \) W/m², corresponding to ~962-1024 TW; Li et al.34 calculated \( D \approx 2.06-2.55 \) W/m² from global reanalyses (~1054-1306 TW); and Stacey and Davis35 used the length of day variations to estimate an average for \( D \) of 434 TW (~0.85 W/m²). Sorensen36[p. 86] states that the few available direct estimates of dissipation are 4-10 W/m² (2000-5100 TW), much higher than previous estimates, which are derived indirectly to ensure consistency with estimates of sources of energy, suggesting the dissipation is tuned, not calculated from first principles. In summary, the literature indicates that even the order of magnitude of dissipation is unclear, with possible values in the 450-3800 TW range.

Regardless of its exact value, the KE dissipation rate \( D \) is relevant to wind energy because wind turbines locally increase atmospheric KE dissipation \( D \) by increasing surface friction, turbulent kinetic energy (TKE) dissipation, and direct conversion to heat. First, just like any mountain, tree, building, or obstacle in the path of wind, wind turbines increase surface roughness and therefore increase \( \overline{D} \) via increased surface friction. Second, some KE is converted to turbulent KE (TKE) in the wake (thus increasing the TKE production term \( u'_i u'_j \frac{\partial U}{\partial x_j} \)) and then some of this TKE is converted to heat via molecular viscous effects (thus increasing \( D' \)). Third, wind turbines also have another unique dissipative effect: they force the atmosphere to perform work (rotating the blades) to generate electricity and thus directly remove KE from the wind flow (decreasing the wind speed).

Since electricity cannot be stored and is almost immediately converted to heat added back to the atmosphere by end users dispersed widely, wind turbines result in heat addition back to the atmosphere over a larger area than a building or tree. The relative magnitudes of these three effects are currently not known precisely, but some initial parameterizations have been proposed37.

The third effect, KE conversion to electricity, is at most equal to 16/27 of the impinging KE (at the Betz limit). The remaining KE (at least 11/27) is in part converted to TKE (as described above) and in part remains in the mean flow since the mean wind speed past a wind turbine is reduced but not zero. The exact distribution of the remaining KE between mean flow and turbulent wake past the turbine is not known, nor is the fraction of TKE in the wake that is actually dissipated to heat via molecular viscous processes. In summary, wind turbines can be considered as converters of atmospheric KE to IE, some of which is converted back to PE.

Whereas it is accepted that wind turbines increase KE dissipation locally, the effect of wind turbines on the overall KE dissipation of the atmosphere is yet to be understood. Several studies suggest that the atmosphere will maintain its current dissipation rate regardless of the number of obstacles, whether buildings or wind turbines, that are added at the surface\(^{38,39,40,41} \). The theoretical justification for this view is that the efficiency of the atmosphere as a heat engine is already nearly maximized and therefore no additional work can be performed by the atmosphere given its IE (or thermal) inputs and outputs. This implies that, if KE dissipation is increased at one location by adding a wind turbine, KE dissipation must decrease equally somewhere else to keep total dissipation constant. The only way to decrease KE dissipation away from the turbine is to decrease wind speeds, which was argued to occur not only in the wake but also at other locations with simplified numerical simulations\(^{40,41} \). With this approach, the natural KE dissipation rate \( D \) would represent the
maximum theoretical limit to wind power extraction.

There are several inconsistencies with this view. First, if KE dissipation and the thermal inputs and outputs of the atmosphere remain constant, KE should also stay constant, whereas the addition of wind turbines decreases KE and local wind speeds. Second, KE cannot decrease without IE increasing (and vice versa), but this conversion is not possible without increasing KE-to-IE conversion (or decreasing IE-to-KE conversions), which cannot happen if \( D \) is constant. Third, if 100% of the KE dissipation were “extracted” via wind turbines, then the near-surface wind speeds would be zero everywhere except where the turbines are. Instead, Young et al.\(^{42}\) found that observed near-surface wind speeds have been increasing, not decreasing, over the oceans during the past 20 years despite the addition of dozens of gigawatts of installed wind power worldwide. These inconsistencies suggest that another explanation is needed.

Other studies cite potential climate effects of extracting wind energy. For example, Miller et al.\(^{41}\) claim that the climate effects of extracting 18-68 TW of wind power are equivalent to doubling carbon dioxide. However, their study first ignores the fact that wind power results in no net additional heat to the air since it replaces thermal power plants (coal, nuclear, natural gas), all of which directly add the same or more heat to the air than wind power directly through combustion or nuclear reaction. These other sources, including nuclear, also add carbon dioxide during the processing or use of their fuel, which wind energy does not do. Second, even if wind turbines did not replace thermal power plants, the actual heat resulting from converting 18-68 TW of wind power to electricity, which then gets converted to heat, is 0.035-0.13 W/m\(^2\). The radiative heating due to doubling of CO\(_2\) is 3.7 W/m\(^2\), a factor of 28-106 higher. As such, even if 18-68 TW of wind power were extracted, it would affect temperatures by 28-106 times less than doubling carbon dioxide, not by the same amount. However, since wind displaces thermal power plants, its net heat added to the atmosphere is effectively zero.

We propose here that KE dissipation is not constant for the Earth. Any increase in the number of obstacles increases dissipation, and any increase in KE dissipation causes an equal increase in IE generation rate (via heat) and therefore a change in the energy balance, but an overall conservation of energy. This is consistent with KE dissipation being a transfer of energy from the KE to the IE reservoir\(^{45}\). To compensate for this additional IE generation, the atmosphere must therefore increase the transfer of a portion of energy from the IE back to the KE reservoir, via an increase in the Potential Energy (PE) generation first and then an increase in the PE-to-KE conversion via adiabatic processes. At equilibrium, this KE generation must offset KE dissipation\(^{43}\). KE decreases initially when turbines are installed and the KE dissipation rate is increased (output > input), consistent with findings by Santa Maria and Jacobson\(^{44}\). At equilibrium, however, this lower KE is maintained (output = input), and so is the higher IE. As such, altering KE dissipation can feed back to the Earth’s climate, albeit by an uncertain quantity. However, we do know that the building of all cities and infrastructure for human civilization to date have had little effect on global climate change; energy from the KE dissipation rate relative to changes in evapotranspiration, albedo, and specific heat (e.g., the urban heat island effect) and changes in precipitation due to urban areas.

If this proposed theory is correct, then is there an upper limit to the significant impacts on the global circulation would not occur? This value would be the limit to wind power extraction. Archer and Caldeira\(^{14}\) showed with a modified climate model (inclusive of KE dissipation to heat by idealized airborne wind turbines scattered uniformly in the entire atmosphere) that, for KE extraction of the same order of magnitude as human energy consumption in 2005 (~18 TW, ~1% of natural \( D \)), climatic effects are negligible; however, for KE extractions of 840 and 2010 TW (50 times and 100 times the current human energy consumption, respectively, or 50% and 100% of natural \( D \)), larger, non-linear changes to the climate can occur, such as cooler surface temperatures and increased polar sea ice extent. Thus, their findings support indirectly that an upper limit to additional dissipation from wind turbines lies between 1% and 50% of the current \( D \).

Regardless of the actual maximum value of KE dissipation, even if all human demand for energy were met with wind power, the current KE dissipation would only be increased by ~1%, with negligible climatic effects\(^{4}\). Also, because wind generation would replace other larger sources of heat such as coal, natural gas, or nuclear power plants, which were not accounted for by Archer and Caldeira\(^{14}\), the net heat input is expected to be even smaller and thus the climatic impact reduced\(^{41}\).

As discussed, the order of magnitude of the natural dissipation rate of kinetic energy by winds is still under debate, with estimates ranging from 450 to 3800 TW. Using 1200 TW as an intermediate (~2.2 W/m\(^2\)) and 10% as an intermediate between 1% and 50% for the maximum additional KE dissipation by wind turbines, an estimate of the theoretical maximum wind power extractable with little climate impact is 0.10 x 1200 TW = 120 TW.

World end-use power demand in 2008 for all purposes was approximately 12.5 TW and is expected to grow to 16.9 TW by 2030. Electrification and conversion to electrolytic hydrogen of the transportation, energy, and industrial sectors would reduce 2030 end-use power demand to 11.5 TW\(^{43}\). Jacobson and DeLucchi\(^2\) suggested a feasible target of 50 percent (5.75 TW) of this power supplied by wind. Thus, if half the world’s power for all purposes were to be supplied by wind, and assuming previous literature estimates of world wind resources, only 0.1-1% of the world’s all-wind-speed wind power at 100 m wind speed would be needed, with negligible climatic impacts. In other words, the world wind resource is 100-1000 times what the world needs in terms of wind power.

3.3 The global wind power potential: bottom-up methods

Whereas theoretical calculations represent a top-down approach to the evaluation of the global wind power potential, observation- and model-based estimates are bottom-up approaches in which the total potential is determined from the combined output of individual wind turbines scattered over the Earth.

All bottom-up methods share one common implicit assumption: each additional wind turbine alters the atmospheric circulation only within the wake volume downwind of the turbine. Within this volume, wind speeds first decrease then increase, eventually converging to the background wind speed.
As wind speeds first decrease within a wake, the vertical gradient in wind speed increases, increasing the downward turbulent flux of faster winds from aloft to hub height and decreasing the downward turbulent flux of winds at hub height to the surface, ultimately replenishing winds some distance downwind of each turbine. Similarly, the horizontal pressure gradient force continuously acts on the winds at a given height and contributes to regenerating winds. Whether full regeneration in the wake occurs depends on the distance between turbines in the direction of the wind and on the pressure gradient force and the rate of turbulent diffusion. In wind turbine arrays, additional interactions between wakes can occur.

Fig. 5 shows evidence of wind regeneration in an array. The data, from Frandsen, indicate that, despite wind speed reductions and incomplete regeneration past turbine rows 1 and 2, wind speeds in subsequent turbine rows stayed constant or increased compared with row 3. This could occur only with the regeneration mechanisms discussed. The overall reduction in wind speed between rows 1 and 7 is only ~8% with diameter spacing of 6D between rows. This represents an array efficiency of 92%. Similarly, Barthelmie et al. found that, after an initial decrease in wind power output between the first and the second row at two large offshore wind farms in Denmark, wind power output in subsequent rows either stayed constant or slightly increased. Greater spacing results in greater array efficiency [e.g., Masters].

Fig. 5 Measured ratio of wind speed at the given turbine row to that at the first turbine row from Norrekoer Enge II wind farm for four cases of initial upstream wind speed U (m/s). Wind speeds were derived from power output from an average of six 300-kW turbines in each of seven rows spaced 7D to 8D within rows and 6D between rows. The solid line is the result of a wake model. Reproduced with permission from Frandsen.

Wind observations can also be derived from satellite products. For example, wind speeds derived from space-based scatterometer on QuikSCAT (at 12.5 km horizontal resolution) were used by Li et al. to evaluate the wind power distribution over the ocean. However, no global wind power output at near-shore locations were provided. Capps and Zender utilized 7 years of QuikSCAT 10-m wind speed data over the oceans (at 0.25°x0.25° horizontal resolution) and extrapolated them to 100 m using Monin-Obukhov similarity theory. With high-resolution bathymetry data (one arc-minute), they calculated that up to 39 TW of wind power are available at shallow (≤ 200 m) offshore locations worldwide, without including water-use restrictions.

Lu et al. used a new reanalysis dataset, the Goddard Earth Observing System Data Assimilation System version 5 (GEOS-5), at a horizontal resolution of 2/3° longitude by 1/2° latitude and a time resolution of 6 hr, with 2.5 MW wind turbines over land (excluding forested, urban, permanently ice covered, and inland water regions) and 3.6 MW turbines deployed offshore (excluding depths >200 m and distances from shore >93 km), both with 100-m hub heights, to estimate the global technical wind power potential as ~840 PWh, or 96 TW, over land and near-shore areas with capacity factor greater than 20% and accounting for exclusions over forested land and some other types of land use. Without limiting the capacity factor, their practical global potential (on- and off-shore) was 1300 PWh, or 148 TW. Because the GEOS-5 reanalyses include both model
3.4 Seasonality and geographic distribution of the global wind power potential

Globally-integrated wind power is calculated here with a bottom-up approach by summing the area-weighted hourly wind power in all grid cells over land (excluding regions poleward of 66.56 degrees North and 60 South) that exhibited a yearly-average wind speed at 100 m above ground greater than 7 m/s. The turbine density is \(10^6 \text{ m}^2/(7Dx4D)^{2.336}=2.25 \text{ turbines/km}^2\), where \(D\) is the diameter of the REPower 5M turbine (126 m). This corresponds to an installed capacity density of 11.25 MW/km². Wind turbines are assumed to affect circulation in their wake volumes only, thus interactions among wakes are neglected. The monthly totals for the three runs 4x5, 2x2.5, and 1.5x1.5 for the later years of the simulations are shown in Fig. 6.

![Wind power over windy land (no polar regions)](image)

**Fig. 6** Globally-integrated monthly wind power at 100 m above ground over land (excluding polar regions and including system losses) in locations where the mean wind speed exceeds 7 m/s for the three simulations: 4x5, 2x2.5, and 1.5x1.5.

The results are quite remarkable. First, the three runs give very similar results, generally varying within ±14.5% from one another. As expected, the coarse-resolution run (4x4.5) gives slightly lower wind power than both the intermediate (2x2.5) and the fine (1.5x1.5) resolution runs (~6% and -5% respectively), which are very similar to one another (~6% difference on average). Because of this similarity, the fine-resolution run was stopped in December 2008, due to its high computer time and storage requirements. As such, the intermediate-resolution run (2x2.5) will be used as the benchmark for further analyses in the rest of this paper.

Second, wind energy at the global scale is neither constant throughout the seasons, as one might expect from the complementarity of the seasons in the two hemispheres, nor bi-modal, as the generally-stronger winter winds in both hemispheres might suggest. The monthly pattern of wind power over land is dominated by the seasons in the Northern Hemisphere (NH), with maxima in DJF and minima in September. Global wind power over land during the NH winter (DJF) is ~2x greater than that during the NH summer (JJA), consistent with the higher intensity of the NH energy cycle in January than in July observed by Oort and Peixoto\(^{25}\) [p. 2715].

Furthermore, Fig. 7 shows that wind power over land in the NH (114 TW on average, dark green shade) is about 2x greater than that in the SH (60 TW on average, light green shade) on average, and up to 7x during the NH winter, even when Antarctica is included in the SH land. This can be explained by the difference in the land areas of the two hemispheres, because the land area in the NH is ~2x greater than that in the SH (30,632,880 km² vs. 6,704,187 km²) if the polar regions are excluded.

![Wind power over land and ocean areas with annual-average wind speed >7 m/s in each hemisphere (2x2.5)](image)

**Fig. 7** Stacked-area plot of total wind power from areas with yearly-average wind speed >7 m/s over land and over ocean in the Northern and Southern hemispheres (NH and SH respectively), including the polar regions and including system losses. Total wind power from all areas with monthly-average wind speed >0 m/s is shown with a black solid line. The total wind power over ocean is purely hypothetical and is only shown for comparison purposes.

Further insights into the wind power resources over land in the two hemispheres can be provided by area-averaged wind speeds. Fig. 8 shows that area-averaged monthly 100-m wind speeds over land (excluding regions poleward of 60 degrees North and South) are higher in the NH (6.25 m/s) than in the SH (5.40 m/s). The opposite is true over the oceans (at all latitudes), where winds speeds are higher in the SH (8.79 m/s) than in the NH (6.53 m/s).

This suggests that the two hemispheres have different wind resources. The SH is generally more energetic (average wind speed is 7.91 m/s in the SH and 6.53 m/s in the NH) and its seasonal cycles are driven by the oceans. The latter is due to the large fraction of SH covered by oceans (78%), and the former is due to a combination of two factors: first, the lower surface roughness of the ocean compared to that of land, and, second, the absence of any land barrier to the westerly winds around Antarctica causes the highest wind speeds on the planet to be observed in the Southern Ocean. On the other hand, 60% of the NH is covered by land, thus it is generally less energetic than the SH, but its wind speed over land is higher than in the SH.
Fig. 8 Area-averaged 100-m wind speed from run 2x2.5 over land (excluding polar regions) and over oceans in each hemisphere and globally.

In order to put the wind power estimates over land in context, Fig. 7 also shows the wind power over the oceans in both hemispheres from run 2x2.5, calculated with the same wind power curve used over land (Fig. 1) at grid cells with monthly-average wind speeds \( \geq 7 \) m/s. These ocean totals are hypothetical and do not represent a feasible near-term potential due to the great distance from shore of most locations and the current difficulty of installing turbines in deep water or on floating platforms.

The wind power resource at wind speeds \( \geq 7 \) m/s over the oceans is \( \approx 6 \times \) larger than that over land on average (1010 TW vs. 174 TW). Whereas wind power over land is higher in the NH than in the SH (114 vs 60 TW), the opposite is true for wind power over the oceans: 751 TW in the SH and 255 TW in the NH on average (\( \approx 3 \times \)), and up to 7x at most.

Because Fig. 7 is a stacked-area plot, the global wind power potential, defined as the wind power from land and ocean areas in both hemispheres with monthly-average 100-m wind speed \( \geq 7 \) m/s, is given by the total shaded area, including all colors. On average, it is \( \approx 1180 \) TW. This global wind power at high speeds is not constant throughout a year, but it is the result of the wind power cycles over land (dominated by the NH) and over oceans (dominated by the SH). Because the SH oceans represent the largest fraction, the global wind power is generally higher during the NH summer. At the end of the NH summer, winds over the SH decrease faster than the increase in NH winds, and therefore it is during the NH fall that the global wind power resource is at its lowest.

If wind power were harnessed hypothetically at all grid points, including the remote oceans, the coastal areas, the polar regions, and at all wind speeds, then another \( \approx 370 \) TW would be added to the previous total, to give an average of \( \approx 1550 \) TW (black line in Fig. 7). This number represents an estimate of the global wind power at all wind speeds over land and ocean, accounting for transmission, distribution, and array losses from typical wind farms. In reality, most of the ocean power is not readily accessible. The wind power over land and ocean at all wind speeds are 320 TW and 1220 TW, respectively. Thus, the wind power at wind speeds \( \geq 7 \) m/s is approximately 53%, 82%, and 76% of the wind power at all speeds over land, ocean, and globally, respectively.

3.5 On- and off-shore wind power resources by regions

Bathymetry data\(^{48}\) at 0.0167 degree resolution and MODIS-derived land use data at 0.01 degree resolution were used to calculate on- and off-shore wind power potentials (without land- and water-use restrictions) for each of the 19 IPCC regions shown in Fig. 9, in which grid cells with bathymetry \( < 200 \) m are shaded in gray.

Fig. 9 Map of the 19 regions used in this study and location of offshore grid points (shaded in grey) with bathymetry \( < 200 \) m and soil fraction \( \geq 1\% \) from run 1.5x1.5 (excluding both Polar regions). Only a subset of these offshore locations have yearly-average 100-m wind speeds \( > 7 \) m/s.

The DJF, JJA, and annual on- and off-shore averages from run 1.5x1.5 during 2007-2008, from areas with annual 100-m wind speeds greater than 7 m/s and including system losses, are summarized in Table 2. Minor inconsistencies between the values in Table 2 and those in the rest of the paper are due to the remapping of the region definition data to the model grid. To our
knowledge, this is the first comprehensive table of such wind potentials obtained with the same model for on- and off-shore resources. Since not even the finest run 1.5x1.5 can resolve well the sharp thermal contrast between ocean and land along coastlines, our maps may be missing some narrow windy offshore locations, such as along the California coast\textsuperscript{13,12,11}. Because of this lack of resolution, the actual wind resources may be higher than in Table 2.

Our results are consistent with those by Greenblatt\textsuperscript{49}, with the Americas and Europe offering the largest offshore potentials and Africa/Middle East the lowest. Our findings show a greater resource than that found by Greenblatt\textsuperscript{49} in North America (1.39 vs 1.26 TW), Africa/Middle East (0.54 vs 0.21 TW), and Oceania (0.82 vs 0.58 TW), but lower resources in Europe (1.02 vs. 1.36 TW) and Asia (0.63 vs 0.94 TW). Because of differences in region definitions, the abundant resource in Regions 11 and 18, missing in Greenblatt\textsuperscript{49}, and other differences in the calculations of the capacity factors, the global offshore potential in this study, excluding polar regions, is 9.2 TW, about a factor of 2 greater than that in Greenblatt\textsuperscript{49}, 5.63 TW.

NREL\textsuperscript{47} calculated an annual-average wind power over land in the US with gross CF>30% of 7.39 TW if conflicting landuses are not excluded (5.35 TW if excluded). Since NREL assumed an installed nameplate capacity of 5 MW/km\textsuperscript{2}, a factor of 2.25 lower than that in this study (11.25 MW/km\textsuperscript{2}), which is based on a 5-MW turbine with a D=126-m rotor and spacing of 4Dx7D, our estimated 14.17 TW is consistent with NREL’s estimate when their assumption of low turbine spacing is accounted for. In practice, wind farms with both coarse and fine spacing exist worldwide.

For offshore wind in the US, our estimate of 0.83 TW (Table 2) is very close to the high-resolution model studies for the west coast (up to 0.1 TW before exclusions)\textsuperscript{12} and east coast (up to 0.25 TW before exclusions) by Dvorak et al.\textsuperscript{51}, which were both evaluated heavily against data. Those studies assumed spacing of 10D x 10D. Converting that spacing to the spacing assumed here (7D x 4D) gives their total potential as ~1.25 TW.

<table>
<thead>
<tr>
<th>Region n.</th>
<th>Region name</th>
<th>Windy land</th>
<th>DJF Offshore</th>
<th>Total</th>
<th>Windy land</th>
<th>JJA Offshore</th>
<th>Total</th>
<th>Windy land</th>
<th>Year Offshore</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Canada</td>
<td>13.08</td>
<td>0.85</td>
<td>13.94</td>
<td>2.13</td>
<td>0.25</td>
<td>2.36</td>
<td>7.67</td>
<td>0.56</td>
<td>8.23</td>
</tr>
<tr>
<td>2</td>
<td>USA</td>
<td>20.93</td>
<td>1.24</td>
<td>22.17</td>
<td>7.21</td>
<td>0.35</td>
<td>7.55</td>
<td>14.17</td>
<td>0.83</td>
<td>15.00</td>
</tr>
<tr>
<td>3</td>
<td>Central America</td>
<td>0.67</td>
<td>0.17</td>
<td>0.84</td>
<td>0.29</td>
<td>0.07</td>
<td>0.36</td>
<td>0.46</td>
<td>0.12</td>
<td>0.58</td>
</tr>
<tr>
<td>4</td>
<td>South America</td>
<td>3.98</td>
<td>0.89</td>
<td>4.88</td>
<td>7.46</td>
<td>1.60</td>
<td>9.05</td>
<td>5.47</td>
<td>1.16</td>
<td>6.64</td>
</tr>
<tr>
<td>5</td>
<td>Northern Africa</td>
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<td>0.40</td>
<td>16.06</td>
<td>12.00</td>
<td>0.35</td>
<td>12.36</td>
<td>13.81</td>
<td>0.36</td>
<td>14.17</td>
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<tr>
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<td>14.91</td>
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<td>14.97</td>
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<td>10.23</td>
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<td>8.99</td>
<td>0.03</td>
<td>9.01</td>
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<td>Southern Africa</td>
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<td>1.27</td>
<td>2.35</td>
<td>&lt;0.01</td>
<td>2.35</td>
<td>1.67</td>
<td>&lt;0.01</td>
<td>1.67</td>
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<tr>
<td>9</td>
<td>OECD Europe</td>
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<td>1.73</td>
<td>8.31</td>
<td>1.30</td>
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<td>1.63</td>
<td>3.69</td>
<td>1.02</td>
<td>4.71</td>
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<tr>
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<td>2.72</td>
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<td>0.00</td>
<td>0.68</td>
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</tr>
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<td>11.56</td>
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<td>12.69</td>
<td>22.14</td>
<td>2.22</td>
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<td>3.11</td>
<td>3.12</td>
<td>0.15</td>
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<td>2.77</td>
<td>0.11</td>
<td>2.88</td>
</tr>
<tr>
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<td>East Asia</td>
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<td>0.72</td>
<td>29.59</td>
<td>10.91</td>
<td>0.25</td>
<td>11.16</td>
<td>18.71</td>
<td>0.51</td>
<td>19.22</td>
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<tr>
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<td>0.02</td>
<td>1.43</td>
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<td>0.85</td>
<td>0.01</td>
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<td>17.16</td>
<td>16.91</td>
<td>0.88</td>
<td>17.79</td>
<td>16.39</td>
<td>0.82</td>
<td>17.22</td>
</tr>
<tr>
<td>17</td>
<td>Japan</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
</tr>
<tr>
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<td>Greenland</td>
<td>5.95</td>
<td>0.14</td>
<td>6.08</td>
<td>1.71</td>
<td>0.05</td>
<td>1.76</td>
<td>3.79</td>
<td>0.09</td>
<td>3.88</td>
</tr>
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<td>34.37</td>
<td>60.06</td>
<td>1.94</td>
<td>62.01</td>
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<td>World</td>
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<td>238.0</td>
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<td>8.70</td>
<td>173.4</td>
<td>187.9</td>
<td>11.30</td>
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<tr>
<td>World (no polar regions)</td>
<td>183.9</td>
<td>11.7</td>
<td>195.5</td>
<td>102.5</td>
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<td>108.9</td>
<td>137.5</td>
<td>9.02</td>
<td>146.5</td>
<td></td>
</tr>
</tbody>
</table>

Table 2 Wind power potential over windy land (mean annual wind speed at 100 m ≥ 7 m/s) and offshore by region and season (in TW) from run 1.5x1.5 in 2007-2008, including system losses.

4. Validation

Fig. 10 compares the modeled 2006 15-m wind speed at 2x2.5 degree resolution with 10-m Quikscat data at 1.5x1.5 degree resolution over the ocean for the same year. Despite the coarser resolution of the model and the slightly different height (15 vs. 10 m above ground), the comparison indicates general qualitative agreement, especially in the regions of the strongest winds. The model matched the magnitude and location of the “roaring 40s” in the Southern Hemisphere (SH) and locations of the Northern-Hemisphere (NH) midlatitude westerlies. The magnitudes of the westerlies were slightly underpredicted, suggesting that wind power estimates over the ocean there could be slightly underpredicted. The model also generally underestimated wind speeds along the tropics, in the middle latitudes in both hemispheres, and along some coastal regions (north-eastern South America, western Africa, southeast Asia, off the coast of Somalia). It is therefore unlikely that the modeled wind speed magnitudes here are overpredicted relative to the data. As such, our wind power estimates may be conservative.
Modeled wind speeds at the lowest vertical level (15 m) were also compared with observations at the lowest available vertical level (10 m) at all sounding stations worldwide (Table 3), a total of about 600 stations. Because the lowest model level (~15 m) was above the level of the observations, the bias was generally positive, for both the medium- and the high-resolution runs. Bias and Normalized Gross Error (NGE) were both lower in the high-resolution run for all months in 2008, the most recent complete year of high-resolution model results. This confirms that more accurate results can be obtained by running the model at finer resolutions. The months with the lowest NGEs were MAM, and those with the highest NGEs were DJF. The average bias for the 2x2.5 (1.5x1.5) run was 0.32 (0.14) m/s and the average NGE was 61% (59%).

Table 3  Statistical evaluation of modeled 15-m wind speed (runs 2x2.5 and 1.5x1.5) versus 10-m observed wind speed at all sounding locations worldwide (with at least 10 valid readings per month) in 2008.

<table>
<thead>
<tr>
<th>N. of sites</th>
<th>Average (m/s)</th>
<th>Standard deviation (m/s)</th>
<th>Bias (m/s)</th>
<th>RMSE (m/s)</th>
<th>NGE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Obs (10 m)</td>
<td>2x2.5 (15 m)</td>
<td>1.5x1.5 (15 m)</td>
<td>Obs (10 m)</td>
<td>2x2.5 (15 m)</td>
</tr>
<tr>
<td>January</td>
<td>653</td>
<td>3.58</td>
<td>4.06</td>
<td>3.93</td>
<td>1.99</td>
</tr>
<tr>
<td>February</td>
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The geographic distribution of model versus observed wind speeds at the lowest available levels (15 m and 10 m respectively) is shown in Fig. 11 for the month with the lowest (a, May) and the highest (b, November) bias for run 1.5x1.5. The model slightly underpredicted wind speeds at most places, but exhibited a larger bias at a few specific locations, such as India and eastern China, thus causing the overall bias to be slightly positive. Overall, the model results are satisfactory both qualitatively (from Quickscat) and quantitatively (from sounding data).
5. Implications and conclusions

The wind resource analysis here suggests that world power in fast-wind locations (≥ 7 m/s in the annual average at 100 m above the topographical surface) over land and near shore, outside of polar areas, could theoretically supply all energy worldwide in 2030 (11.5 TW), converted to electricity and electrolytic hydrogen, 6-10 times over, or 50% of energy 12-28 times over.

Providing half the world’s energy needs in 2030 from wind would consume <0.5% of the world’s wind power at 100 m, hardly affecting total power in the atmosphere. Practical barriers exist to realize this potential, including transmission, zoning, and political issues. Nevertheless, resource analysis is an important step in determining the optimal locations for wind farms, as it provides information for planning the efficient placement of wind farms and necessary transmission infrastructure.

In addition to the above, important findings of this paper are as follows:

- The global technical wind power potential, defined as the fraction of the theoretical wind power potential deliverable from 100-m winds over windy land and windy near-shore areas outside of the polar areas, including system losses but not including land and water use restrictions, is about 110-120 TW.

- The global technical wind power potential is not constant but varies significantly with season and hemisphere. During DJF (JJA), the global wind resource is ~160 (80) TW. The NH wind potential is over five times higher than that in the SH on average (107 vs. 17 TW); in December, the NH wind power over land is up to 10 times greater than that in the SH.

- The near offshore (< 200 m water depth) technical wind power potential is ~9 TW at 100 m, varying between 6 and 12 TW from JJA to DJF. Offshore potential would increase significantly with the large-scale development of floating wind turbines that would allow access to wind in deeper water.

- The theoretical wind power over all land and ocean worldwide at all wind speeds, considering transmission, distribution, and array losses for typical wind farms, is ~1500 TW.

- High-wind locations, defined as over-land and near-shore areas outside of polar regions with yearly-average wind speeds at 100 m ≥ 7 m/s, are ubiquitous, covering ~30% of all land and near-shore areas outside of polar regions.

Finally, we propose here that the addition of wind turbines (or other obstacles) increases kinetic energy (KE) dissipation in the atmosphere, rather than competing with natural processes to maintain KE dissipation constant, as has previously been assumed. Conservation of energy requires that the lost KE convert to internal energy (IE). An increase in IE creates buoyancy, causing air to rise and some IE to transfer to potential energy (PE). An increase in PE increases the PE-to-KE conversion rate via adiabatic processes. In equilibrium the total KE of the atmosphere is lower with wind turbines than without, whereas IE, PE, and KE dissipation (=generation) rates are higher than prior to the addition of wind turbines. An energy-conserving climate model, inclusive of a parameterization of the conversion of KE to IE via heat due to wind turbines and of the consequent IE-to-PE-to-KE conversions, is needed to understand fully the complex interactions between winds and the Earth climate and energy systems.

6. Acknowledgements

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7. References


26. Holt


