



A 32-year Perspective on the Origin of Wind Energy in a warming Climate

Citation

Huang, Junling, and Michael B McElroy. 2015. A 32-year perspective on the origin of wind energy in a warming climate, *Renewable Energy* 77, no. May: 482-492.

Published Version

<http://www.sciencedirect.com/science/article/pii/S0960148114008726>

Permanent link

<http://nrs.harvard.edu/urn-3:HUL.InstRepos:13919173>

Terms of Use

This article was downloaded from Harvard University's DASH repository, and is made available under the terms and conditions applicable to Other Posted Material, as set forth at <http://nrs.harvard.edu/urn-3:HUL.InstRepos:dash.current.terms-of-use#LAA>

Share Your Story

The Harvard community has made this article openly available. Please share how this access benefits you. [Submit a story](#).

[Accessibility](#)

1 **A 32-year Perspective on the Origin of Wind Energy in a warming Climate**

2 **Junling Huang^{a, b*}, Michael B. McElroy^a**

3 ^a School of Engineering and Applied Sciences, Harvard University, Cambridge, MA 02138, USA

4 ^b John F. Kennedy School of Government, Harvard University, Cambridge, MA 02138, USA

5 *Corresponding author

6 Tel.: 617-955-6282

7 Email: junling_huang@post.harvard.edu

8

9

10

11

12

13

14

15

16

17

18

19

20 **Abstract**

21 Based on assimilated meteorological data for the period January 1979 to December 2010, the
22 origin of wind energy is investigated from both mechanical and thermodynamic perspectives,
23 with special focus on the spatial distribution of sources, historical long term variations and the
24 efficiency for kinetic energy production. The dry air component of the atmosphere acts as a
25 thermal engine, absorbing heat at higher temperatures, approximately 256 K, releasing heat at
26 lower temperatures, approximately 252 K. The process is responsible for production of wind
27 kinetic energy at a rate of $2.46 W/m^2$ sustaining thus the circulation of the atmosphere against
28 frictional dissipation. The results indicate an upward trend in kinetic energy production over the
29 past 32 years, indicating that wind energy resources may be varying in the current warming
30 climate. This analysis provides an analytical framework that can be adopted for future studies
31 addressing the ultimate wind energy potential and the possible perturbations to the atmospheric
32 circulation that could arise as a result of significant exploitation of wind energy.

33

34 **Keywords:** origin of wind energy; warming climate; thermal engine; interannual variability

35

36

37

38

39

40

41

42

43 **1. Introduction**

44 Global installed wind capacity reached an unprecedented level of more than 318 *GW* at the end
45 of 2013, of which approximately 35 *GW* were added in 2013, the highest level recorded to date.
46 Wind power contributes close to 4 % to current total global electricity demand. In total, 103
47 countries are using wind power on a commercial basis. Based on current growth rates, the World
48 Wind Energy Association estimates that global wind capacity could increase to as much as
49 700 *GW* by 2020 [1].

50 A number of studies have sought to assess the ultimate potential for wind-generated electricity
51 assuming that the deployment of turbines should not influence the potential source [2-8]. Using
52 data from surface meteorological stations, Archer and Jacobson [4] concluded that 20 % of the
53 global total wind power potential could account annually for as much as 123 *PWh* of electricity,
54 equivalent to 7 times total current global consumption. They restricted their attention to power
55 that could be generated using a network of 1.5 *MW* turbines tapping wind resources from
56 regions with annually averaged wind speeds in excess of 6.9 *m/s* at an elevation of 80 m. Using
57 assimilated meteorological data, Lu et al. [5] argued that a network of land-based 2.5 *MW*
58 turbines restricted to non-forested, ice-free, non-urban areas operating at as little as 20 % of their
59 rated capacity could supply more than 40 times current worldwide demand for electricity, more
60 than 5 times total global use of energy in all forms.

61 Numerous groups have argued that large scale deployment of wind farms could potentially
62 influence the circulation of the atmosphere, altering consequently the global wind energy
63 resources [9-16]. For example, Adams and Keith [16] tried to quantify the limitation of wind
64 energy extraction using a mesoscale model and compared their results with other studies using

65 global atmospheric models. The energetics of the entire atmosphere is different from the
66 energetics of the mesoscale region considered by Adams and Keith [16]. It is essential to
67 understand how kinetic energy of wind is created in the entire atmosphere.

68 Wind energy is essentially the kinetic energy held by the center-of-mass movement of a volume
69 element of air. The movement of the air is driven primarily by the spatial gradient in heat input.
70 Diabatic heating occurs mainly in the warm tropics, with diabatic cooling dominating at
71 relatively cold mid and high latitudes. In this sense, following Carnot, the dry air component of
72 the atmosphere acts as a thermal engine, converting heat to kinetic energy to sustain the general
73 circulation against the force of friction. The standard approach to investigate the energetics of the
74 atmosphere was introduced by Lorenz in 1955 [17]. A number of groups have analyzed the
75 energetics of the atmosphere based on the Lorenz Energy Cycle [18-22]. However, the
76 geographic distribution of kinetic energy production and the temporal variability have not as yet
77 been quantified.

78 This study investigates the origin of wind energy, with a specific focus on the spatial distribution
79 of sources, historical long term variations and the efficiency for kinetic energy production. From
80 a mechanical perspective, kinetic energy can be produced or destroyed only by real forces [23].
81 In the case of an air parcel in the atmosphere, the real forces are: gravity, the pressure gradient
82 force, and friction. From a thermodynamic perspective, the creation of wind energy in the
83 atmosphere involves absorption of heat at high temperature and release at low temperature,
84 following the operational principle of a thermal engine. The paper also analyzes the
85 thermodynamic processes within the atmosphere, quantifying the key thermodynamic variables
86 including the net rate of heat absorption and the efficiency for kinetic energy production. The
87 analysis provides a historical perspective on the production of kinetic energy in the atmosphere

88 and an analytical framework for future studies exploring the ultimate potential for wind energy
89 and potential for significant change in the circulation of the atmosphere as a consequence of
90 future large scale turbine deployment.

91 **2. MATERIALS**

92 The study is based on meteorological data from the MERRA compilation covering the period
93 January 1979 to December 2010. Kinetic energy of wind, wind speeds, air temperatures,
94 geopotential heights and surface roughness were obtained on the basis of retrospective analysis
95 of global meteorological data using Version 5.2.0 of the GEOS-5 DAS. We use the standard 3-
96 hourly outputs of the free atmosphere conditions and the standard hourly outputs of the boundary
97 layer conditions [24]. The multivariate ENSO index is from the National Oceanic and
98 Atmospheric Administration (available at: <http://www.esrl.noaa.gov/psd/enso/mei/>).

99 **3. Atmospheric kinetic energy**

100 The kinetic energy corresponding to unit mass of the atmosphere is given by $|\vec{v}|^2/2$ where \vec{v} is
101 the wind speed. The total and hemispheric atmospheric kinetic energy stocks may be obtained by
102 integrating over the appropriate spatial domains. Composite results for monthly mean values and
103 for the long-term variation of global kinetic energy are shown in Fig. 1. The inter-annual
104 variation of the total kinetic energy stock is associated with the changing phases of the El Niño -
105 Southern Oscillation (ENSO) cycle (Fig. 1a and Fig. 2). During the warm El Nino phase (notably
106 years 1983, 1987, 1997 and 2010), elevated sea surface temperatures (SSTs) result in an increase
107 in the kinetic energy stock; during the cold phase La Nina phase (notably years 1985, 1989, 1999
108 and 2008), colder SSTs contribute to a decrease. The global kinetic energy stock averaged
109 approximately $1.50 \text{ MJ}/\text{m}^2$ over the past 32 years, $1.31 \text{ MJ}/\text{m}^2$ in the Northern Hemisphere
110 with $1.70 \text{ MJ}/\text{m}^2$ in the Southern Hemisphere.

111 The spatial distributions of the annual mean, June - August, and December - February kinetic energy
112 budgets are shown in Fig. 3. Clearly evident is the influence of the dominant storm tracks at mid-
113 latitude, and the steady components of the subtropical and polar jet streams. There are two
114 distinct peaks in the Northern Hemispheric kinetic energy stock east of Japan and east of the
115 North American continent, with a more continuous belt of high kinetic energy located between
116 30 °S and 60 °S in the Southern Hemisphere. As discussed by Huang et al. [25], the boundary
117 layer wind, for example the wind at 100 m, is controlled by conditions in the free atmosphere,
118 perturbed by fast varying turbulence in the boundary layer. Strong winds in the free atmosphere
119 generally lead to strong winds near the surface, and consequently to high instantaneous values of
120 the capacity factors for wind turbines. The spatial distributions in Fig. 3 reflect the geographic
121 distribution and seasonality of wind resources as reported in the earlier studies [5, 26, 27].

122 **4. Production of kinetic energy**

123 For an air parcel of unit mass, production of kinetic energy may be written as:

$$124 \quad \frac{dK}{dt} = -gw - \frac{1}{\rho} \vec{v} \cdot \nabla p + \vec{v} \cdot \vec{F} \quad (1)$$

125 where K is the kinetic energy corresponding to unit mass, g is the gravitational acceleration, w is
126 the vertical velocity, \vec{v} is the velocity, ρ is the air density, p is the pressure and \vec{F} is the frictional
127 force.

128 In calculating the kinetic energy production rate, it is convenient to consider the rate for
129 production of kinetic energy in a fixed unit of volume. Re-organizing equation (1), we have:

$$130 \quad \frac{\partial \rho K}{\partial t} = -\nabla \cdot (K\rho\vec{v}) - \vec{v} \cdot \nabla p + \rho\vec{v} \cdot \vec{F} - g\rho w \quad (2)$$

131 The left hand side of this equation denotes the rate per unit volume for production of kinetic

132 energy. The right hand side defines contributions to the production rate associated with the
 133 convergence of the kinetic energy flux ($-\nabla \cdot (K\rho\vec{v})$), and the work carried out or consumed by
 134 the pressure gradient force ($-\vec{v} \cdot \nabla p$), friction ($\rho\vec{v} \cdot \vec{F}$) and gravity ($-g\rho w$).

135 The atmosphere is in quasi-hydrostatic balance: gravity is balanced approximately by the vertical
 136 pressure gradient force. In this case, equation (2) may be recast in the simpler form:

$$137 \quad \frac{\partial \rho K}{\partial t} = -\nabla \cdot (K\rho\vec{v}) - \vec{v}_h \cdot \nabla_h p + \rho\vec{v} \cdot \vec{F} \quad (3)$$

138 where \vec{v}_h is the horizontal component of \vec{v} , and $\nabla_h p$ is the horizontal gradient of the pressure
 139 force. Production of kinetic energy in the atmosphere, C , can be estimated as $C = -v_h \cdot \nabla_h p$ [17-
 140 22].

141 Fig. 4 illustrates the distribution of kinetic energy production, C , averaged over the past 32 years
 142 in units of $10^{-3} W/kg$. The tropical and subtropical region from $30^\circ S$ to $30^\circ N$, dominated by
 143 the thermally direct Hadley circulation, is responsible for a net source of kinetic energy as
 144 indicated in Fig. 4a. The most prominent sources are located in the mid-latitude oceanic regions
 145 below the $800 hPa$ pressure level, notably in the Southern Hemisphere, as depicted in Fig. 4c.
 146 Production of kinetic energy in these regions is associated with the intense development of
 147 eddies that stir the atmosphere over the ocean, carrying cold air equatorward and warm air
 148 poleward, resulting consequently in cross-isobaric flow. The topographic forcing of the Tibetan
 149 plateau has a noticeable impact on the production of kinetic energy in the upper region of the
 150 atmosphere, from $0 hPa \sim 600 hPa$, as indicated in Fig. 4b.

151 The global and hemispheric rates for production of kinetic energy are obtained by integrating the
 152 production term, C , over the entire atmosphere or over each hemisphere separately. The global
 153 kinetic energy production rate averaged over the past 3 decades is estimated at $2.46 W/m^2$, with

154 a upward trend since the late 1990s (Fig. 5a). The average rate for production in the Northern
155 Hemisphere is $2.44 W/m^2$, $2.49 W/m^2$ for the Southern Hemisphere. Hemispheric production
156 rates indicate strong seasonality (Fig. 5c), reaching maximum power output during local winter,
157 with minima in local summer.

158 **5. Dissipation**

159 Motions of the atmosphere against friction convert kinetic to internal energy. This process is
160 thermally irreversible, resulting in an increase in entropy. Approximately half of the frictional
161 dissipation takes place within the lowest kilometer of the atmosphere, a result of turbulent
162 motions generated mechanically by the flow over the underlying surface. The other half takes
163 place higher in the atmosphere where small-scale disturbances are generated as a result of
164 convection or shear instability of the vertical wind [28]. In the long run, the total kinetic energy
165 in the atmosphere, KE , is determined by a balance between production, C , and dissipation by
166 friction, D . The dissipation term may be quantified according to:

$$167 \quad D = C - \frac{dKE}{dt} \quad (4)$$

168 The long-term variation and seasonal cycle of D are plotted in Fig. 6. Maximum dissipation
169 occurs in February, corresponding to the peak in Northern Hemisphere kinetic energy reflecting
170 the importance of surface roughness associated with Northern Hemisphere continental areas in
171 dissipating kinetic energy. The entropy generation associated with dissipation can be
172 approximated as $\frac{C}{T_{surface}}$, where $T_{surface}$ is the global average surface atmosphere (about 280 K).

173 The fate of kinetic energy in the atmosphere from a mechanical perspective is summarized in Fig.
174 7. The residence time of kinetic energy, τ , calculated as KE/D , is 6.9 days.

175 **6. The thermodynamics of atmospheric motions**

176 According to the first law of thermodynamics:

$$177 \quad C_p \left[\frac{\partial}{\partial t} T + \vec{v} \cdot \nabla T + \omega \left(\frac{\partial T}{\partial p} - \kappa \frac{T}{p} \right) \right] = Q \quad (5)$$

178 where Q defines the rate per unit mass of dry air for diabatic heating, C_p is the specific heat
179 of the air, T is temperature, ω is the vertical component of wind velocity in an isobaric
180 system and $\kappa = 0.286$ [29].

181 The annual mean spatial distribution of diabatic heating Q based on equation (5) is displayed in
182 Fig. 8. The results presented here are consistent with earlier studies [30, 31]. An important
183 fraction of the incoming sunlight reaches the surface which is heated accordingly. This heat finds
184 its way back into the atmosphere as a result of turbulent transport through the atmospheric
185 boundary layer. Most of the solar energy absorbed by the ocean is used to evaporate water. Water
186 vapor in the atmosphere acts as a reservoir for storage of heat that can be released later. As the air
187 ascends, it cools. When it becomes saturated, water vapor condenses with consequent release of
188 latent heat. Heating is dominated in the tropical atmosphere by release of latent heat. Separate
189 bands of relatively deep heating are observed at mid-latitudes where active weather systems
190 result in enhanced precipitation and release of latent heat.

191 The atmospheric system consists of dry air and water. Its total entropy S^{total} and total static
192 energy E^{total} , according to thermodynamics, can be expressed as: $S^{total} = S^{dry} + S^{H_2O}$ and
193 $E^{total} = E^{dry} + E^{H_2O}$, where S^{dry} and E^{dry} represent the associated entropy and static energy of
194 the dry air component and S^{H_2O} and E^{H_2O} represent the associated entropy and static energy of
195 the water component. The focus in this study is on how atmospheric motion of the dry air is
196 maintained by diabatic heating. Condensation and evaporation of water are treated accordingly
197 as external to the dry air component [32], namely as an exchange of entropy and energy with the

198 dry air.

199 Regions of diabatic cooling, dominated by long wave radiation to space, occupy much of the
200 middle and upper troposphere. The rate of change of entropy, s , per unit mass is given by
201 $\frac{ds}{dt} = Q/T$. The spatial distribution of entropy generation is similar to the spatial pattern of Q , as
202 illustrated in Fig. 9.

203 Diabatic heating includes contributions from radiative heating and cooling, release of latent
204 heat associated with phase transitions, heating by conduction of sensible heat, and heating
205 by frictional dissipation:

$$206 \quad Q = -\frac{1}{\rho} \{ \nabla \cdot F_{rad} + \rho L(e - c) + \nabla \cdot J_H + \tau : \nabla \vec{v} \} \quad (6)$$

207 where ρ is the density of air, L is the latent heat of condensation, c and e are the rates of
208 condensation and evaporation per unit mass, F_{rad} is the net radiative flux, J_H is the sensible
209 heat flux due to conduction, τ is the wind stress tensor, and \vec{v} is the wind velocity.

210 The diabatic heating term Q can be written as $Q = Q_h + Q_f$, where Q_h accounts for
211 radiative heating (solar and infrared), latent heating and heating due to conduction:

$$212 \quad Q_h = -\frac{1}{\rho} \{ \nabla \cdot F_{rad} + \rho L(e - c) + \nabla \cdot J_H \} \quad (7)$$

213 The second component, Q_f , is associated with frictional dissipation:

$$214 \quad Q_f = -\frac{1}{\rho} \cdot \tau : \nabla \vec{v} \quad (8)$$

215 By separating Q_h from Q , we may consider Q_h as the external heating responsible, from a
216 thermodynamic perspective, for the motion of the dry air. In the long run, the globally
217 integrated values for Q_f must be balanced by global production of kinetic energy, equal
218 therefore to $2.46 \text{ W}/m^2$. Consequently, we may rewrite the generation of entropy as:

219
$$\frac{ds}{dt} = \frac{ds_h}{dt} + \frac{ds_f}{dt} \quad (9)$$

220 where $\frac{ds_h}{dt} = Q_h/T$, $\frac{ds_f}{dt} = Q_f/T$ and T is the temperature of the environment in the region

221 where heat is either absorbed or released [33, 34].

222 In the long run, the entropy S of the entire atmosphere must remain constant. Thus, with

223 the long term mean indicated by " $\bar{\quad}$ ":

224
$$\int_{global} \bar{\rho} \frac{ds_h}{dt} dV + \int_{global} \bar{\rho} \frac{ds_f}{dt} dV = 0 \quad (10)$$

225 or

226
$$\int_{global} \bar{\rho} \frac{Q_h}{T} dV + \int_{global} \bar{\rho} \frac{Q_f}{T} dV = 0 \quad (11)$$

227 Since Q_f and T are always positive, the second term $\int_{global} \bar{\rho} \frac{Q_f}{T} dV$ representing the entropy

228 generation associated with dissipation is greater than zero, which implies that

229 $\int_{global} \bar{\rho} \left(\frac{Q_h}{T}\right) dV < 0$. It follows that the Q_h and T fields must be positively correlated. In

230 other words, the general circulation can be maintained against the disordering impact of

231 friction only if the heating occurs in warmer regions of the atmosphere with cooling in

232 colder regions. Fig. 10 summarizes the creation and dissipation of kinetic energy in the

233 atmosphere from a thermodynamic perspective.

234 The global heat source Q_{in} in Fig. 10 represents the heat that the atmosphere absorbs at the

235 higher temperature, T_{hot} , environment in order to do mechanical work. It is defined as

236 $\int_{Q_h>0} \rho Q_h dV$. The global heat sink Q_{out} in Fig. 10 represents the heat that the atmosphere

237 releases into the lower temperature, T_{cold} , environment and is defined by $Q_{out} =$

238 $\int_{Q_h<0} \rho Q_h dV$.

239 The mechanical work produced by the atmosphere is dissipated by friction and converted to heat
 240 that is released back into the atmosphere. This process is thermally equivalent to using the
 241 mechanical work to turn on a heater and return the exhausted heat back to the atmosphere, as
 242 depicted in Fig. 10. However, it is difficult to distinguish between Q_h and Q_f , and the absolute
 243 value of the global integral of Q_f is negligible compared to the global integral for Q_{in} and Q_{out} .
 244 Thus, the global heat source Q_{in} can be approximated as: $Q_{in} \approx \int_{Q>0} \rho Q dV$ with Q_{out}
 245 approximated as: $Q_{out} \approx \int_{Q<0} \rho Q dV$.

246 The value for the global heat source $\int_{Q>0} \rho Q dV$ averaged over the past three decades is estimated
 247 at $244 W/m^2$. The average kinetic energy production rate over the same period is calculated as
 248 $2.46 W/m^2$. It follows that the average efficiency for kinetic energy production is equal to
 249 approximately 1%.

250 The effective temperature $\langle T_{hot} \rangle$ at which heat is absorbed can be calculated as:

$$251 \quad \langle T_{hot} \rangle = \frac{1}{\Delta S} \int_{t_1}^{t_2} \int_{Q_h>0} T \frac{dS}{dt} dV dt \quad (12)$$

252 or approximated as:

$$253 \quad \langle T_{hot} \rangle \approx \frac{1}{\Delta S} \int_{t_1}^{t_2} \int_{Q>0} T \frac{dS}{dt} dV dt \quad (13)$$

254 where $\Delta S = \int_{t_1}^{t_2} \int_{Q_h>0} \frac{dS}{dt} dV dt$, with t_1 and t_2 representing the starting and ending times for the
 255 integration. In the long run, the entropy S of the entire atmosphere is required to remain
 256 constant. Equation (10) can be recast as:

$$257 \quad \frac{Q_{in}}{\langle T_{hot} \rangle} - \frac{Q_{out}}{\langle T_{cold} \rangle} + \frac{C}{T_{surface}} = 0 \quad (14)$$

258 where $\frac{C}{T_{surface}}$ represents the entropy generation due to dissipation [34]. The effective

259 temperature $\langle T_{cold} \rangle$ at which heat is released can be estimated accordingly.

260 The schematic illustration of the dry air component of the atmosphere as a thermal engine is
261 summarized in Fig. 11, with values included here representing averages for the past 32 years.

262 The dry air component of the atmosphere acts as a thermal engine, absorbing heat at a
263 temperature of approximately $256K$, releasing heat at a temperature of approximately $252K$.

264 The process produces kinetic energy at a rate of $2.46 W/m^2$ sustaining thus the circulation of the
265 atmosphere against friction.

266 **7. Discussion and summary**

267 The study started with a quantification of the total kinetic energy stock of the atmosphere and
268 subsequently investigated how kinetic energy is generated and dissipated from mechanical and
269 thermodynamic perspectives.

270 The total kinetic energy stock of the atmosphere displays significant inter-annual variability, as
271 indicated in Fig. 1 and Fig. 2, with the changing phases of the ENSO cycle playing an important
272 role. This inter-annual variation reflects the fact that the wind energy potential for a particular
273 location can fluctuate on a long-term basis, under the influences of long-term atmospheric
274 oscillations which can alter the circulation of the atmosphere including the distribution of kinetic
275 energy.

276 To illustrate the inter-annual variation of wind energy potentials, we select two locations, one in
277 Texas ($34.5^\circ N$, $101.3^\circ W$) and the other in North Dakota ($47^\circ N$, $101.3^\circ W$), as indicated in Fig
278 12a. In calculating the potential electricity generated from wind, we chose to use power curves
279 and technical parameters for the GE 2.5 MW turbines (rated wind speed 12.0 m/s, cut-in wind
280 speed 3.5 m/s, and cut-out speed 25.0 m/s). The power curve of the wind turbine defines the

281 variation of power output as a function of wind speed. The hourly wind speeds at 100 m are
 282 extrapolated from winds at 50 m according to the relation: $V_{100} = V_{50} \cdot \frac{\ln(Z_{100}/Z_0)}{\ln(Z_{50}/Z_0)}$, where V_{100}
 283 and V_{50} indicate hourly values for the wind speed at 100 m and 50 m respectively, Z_{100} and Z_{50}
 284 define the elevation of the turbine hub (100 m) and the reference 50 m altitude, and Z_0 defines
 285 the surface roughness length.

286 The capacity factor (CF) values in Fig. 12b, at a particular time t_0 , are calculated as:

$$287 \quad CF(t_0) = \left(\int_{t_0-0.5\text{year}}^{t_0+0.5\text{year}} P_{real}(t) \cdot dt \right) / (P_{rated} \cdot 1\text{year}) \quad (15)$$

288 where P_{real} denotes the power actually realized, and P_{rated} refers to the power that could have
 289 been realized had conditions permitted the turbine to operate at its name plate capacity. The
 290 seasonality of wind energy potentials, represent by CF values, have been removed due to the
 291 averaging period defined in equation (15): averaging P_{real} from $t_0 - 0.5\text{year}$ to $t_0 + 0.5\text{year}$.

292 CF values of the wind farms in Texas and North Dakota display significant interannual variation.
 293 The ups and downs of CF values in Fig 12b are the embodiments of the long-term atmospheric
 294 oscillations. Modern wind turbines are designed to work with an anticipated lifespan of 20 years.
 295 Wind energy potentials, as exemplified by the Texas and North Dakota cases, can vary on a year-
 296 to-year basis with a large amplitude over a 20 years period. Predictions of wind power for the
 297 next 20 years, or at least limits on its possible variation, will pose an important challenge for
 298 prospective investors in wind power.

299 The kinetic energy of wind in the atmosphere is constantly dissipated by friction. The residence
 300 time of kinetic energy, τ , is estimated at 6.9 days. The dry air component of the atmosphere
 301 generates kinetic energy as a thermal engine to sustain the general circulation of the atmosphere

302 against frictional dissipation. Key thermodynamic properties were quantified, including the
303 kinetic energy production rate, C , the heat absorption rate, Q_{in} , the effective temperature at
304 which heat is absorbed, $\langle T_{hot} \rangle$, and the effective temperature at which heat is released, $\langle T_{cold} \rangle$.

305 The calculations of these key properties are based on the assimilated meteorological data from
306 the MERRA compilation. Data assimilation is the process of incorporating historical
307 observations of the atmosphere into a numerical physical model, and produces the most reliable
308 estimate of the past meteorological conditions. However, some uncertainties with the final
309 outputs, such as wind speed data, cannot be completely eliminated.

310 The kinetic energy production rate, C , is calculated from a mechanical perspective using wind
311 speed data and pressure gradient data. Wind speed data and pressure data are accurately obtained
312 in the assimilation process [24]. Thus, the kinetic energy production quantified here is reliable,
313 and the results obtained are consistent with other studies [18-22]. The quantification of other
314 variables, notably diabatic heating and effective temperatures, involves parameters such as the
315 vertical velocity of the air with relatively large uncertainties [24]. Absolute values of these
316 thermodynamic properties are subject to relatively large uncertainty, depending as they do on the
317 accuracy of the input data, the MERRA analysis in the case. It is not possible to place error bars
318 on the values derived here for these parameters.

319 The globally averaged combined land and ocean surface temperature data indicate a warming of
320 0.85 K, over the period 1880 to 2012 [35]. A number of studies argued that the warming climate
321 over the past decades has influenced the wind resource potential [36-44]. The upward trend in
322 kinetic energy production rate obtained here confirms the fact that the thermodynamic conditions
323 of the atmosphere have undergone a significant change over the past 32 years. A key question is

324 whether the conclusions reached in the study may be conditioned by the use of a specific data
325 base. Other datasets including NCEP-1, NCEP-2, ERA-40 and JRA-25 should be employed in
326 future to compare with results from the present study. Regarding the future warming climate,
327 according to the IPCC 2014 report [35], the change in global surface temperature by the end of
328 the 21st century is likely to exceed 1.5°C relative to the average from year 1850 to 1900 under
329 most future greenhouse emission scenarios. It is essential to investigate how the atmosphere, as a
330 thermal engine, will adjust under the different scenarios, altering thus the distributions and values
331 of wind energy resources.

332 A number of studies have suggested that large scale deployment of wind farms could potentially
333 influence the circulation of the atmosphere [9, 11-16, 45-49]. With a simple parameterization of
334 turbine operations, Miller et al. [46] performed numerical experiments and found that a
335 maximum of $34\ TW$ of electricity could be generated. Marvel et al. [47] extended Miller's work
336 by parameterizing the turbines as sinks for momentum and concluded that wind turbines placed
337 at the Earth's surface could extract kinetic energy at a rate of at least $400\ TW$, whereas high-
338 altitude wind turbines could extract more than $1,800\ TW$. With a different global model and
339 parameterization approach, Jacobson and Archer [48] argued that as the number of wind turbines
340 increases over large geographic regions, power extraction would first increase linearly, then
341 converge to a saturation limit, with a saturation potential in excess of $250\ TW$ at 100 m globally,
342 $380\ TW$ at 10 km. There is a notable discrepancy between these various estimates. Adams and
343 Keith [16] addressed the question using a mesoscale model. They concluded that wind power
344 production would be limited to about $1\ \text{W}/\text{m}^2$ at wind farm scales larger than about $100\ \text{km}^2$ and
345 that the mesoscale model results are quantitatively consistent with results from global models
346 that simulated the climate response to much larger wind power capacities. However, as noted

347 earlier, the energetics of the entire atmosphere is different from the energetics of the mesoscale
348 region.

349 The quantity of wind energy that can be extracted from the atmosphere to generate electricity
350 depends ultimately on the rate at which kinetic energy is produced, not on the quantity of kinetic
351 energy stored in the atmosphere [50]. Answering the question of the ultimate limit of the
352 atmosphere as a source of wind-generated electric power requires a detailed study of the
353 underlying thermodynamics of the global atmosphere. While not trying to quantify the ultimate
354 wind potential, this study provides an analytical framework that can be adapted for future studies
355 addressing the ultimate wind energy potential and the potential perturbations to the atmospheric
356 circulation that could arise as a result of significant exploitation of this potential. It will be
357 critical to understand how the key thermodynamic variables, such as the effective temperature
358 (T_{hot} and T_{cold}) and diabatic heating (Q_{in} and Q_{out}), evolve as increasing numbers of large scale
359 wind farms are deployed.

360

361 **Acknowledgements**

362 The work described here was supported by the National Science Foundation, NSF-AGS-1019134.
363 Junling Huang was also supported by the Harvard Graduate Consortium on Energy and
364 Environment. We acknowledge helpful and constructive comments from Michael J. Aziz, and Xi
365 Lu.

366

367

368

369 **Reference:**

- 370 [1] The World Wind Energy Association 2013 report. April 2014, Bonn, Germany.
- 371 [2] Landberg L, Myllerup L, Rathmann O, Petersen EL, Jørgensen BH, Badger J, and Mortensen
372 NG. Wind resource estimation—an overview. *Wind Energy* 2003; 6:3-261.
- 373 [3] Hoogwijk M, de Vries B, and Turkenburg W. Assessment of the global and regional
374 geographical, technical and economic potential of onshore wind energy. *Energy Economics* 2004;
375 26:5-889.
- 376 [4] Archer CL, and Jacobson MZ. Evaluation of global wind power. *Journal of Geophysical*
377 *Research: Atmospheres* (1984–2012) 2005; 110:D12.
- 378 [5] Lu X, McElroy MB, and Kiviluoma J. Global potential for wind-generated electricity.
379 *Proceedings of the National Academy of Sciences* 2009; 106:27-10933.
- 380 [6] Tapiador FJ. Assessment of renewable energy potential through satellite data and numerical
381 models. *Energy & Environmental Science* 2009; 2:11-1142.
- 382 [7] de Castro C, Mediavilla M, Miguel LJ, and Frechoso F. Global wind power potential:
383 Physical and technological limits. *Energy Policy* 2011; 39:10-6677.
- 384 [8] Zhou Y, Luckow P, Smith SJ, and Clarke L. Evaluation of global onshore wind energy
385 potential and generation costs. *Environmental science & technology* 2012; 46:14-7857.
- 386 [9] Keith DW, DeCarolis JF, Denkenberger DC, Lenschow DH, Malyshev SL, Pacala S, and
387 Rasch PJ. The influence of large-scale wind power on global climate. *Proceedings of the national*
388 *academy of sciences of the United States of America* 2004; 101:46-16115.

- 389 [10] Wang C, Prinn RG. Potential climatic impacts and reliability of very large-scale wind farms.
390 Atmospheric Chemistry and Physics 2010; 10:4-2053.
- 391 [11] Wang C, Prinn RG. Potential climatic impacts and reliability of large-scale offshore wind
392 farms. Environmental Research Letters 2011; 6:2-025101.
- 393 [12] Walsh-Thomas JM, Cervone G, Agouris P, Manca G. Further evidence of impacts of large-
394 scale wind farms on land surface temperature. Renewable and Sustainable Energy Reviews, 2012;
395 16:8-6432.
- 396 [13] Fitch AC, Olson JB, Lundquist JK, Dudhia J, Gupta AK, Michalakes J, Barstad I. Local and
397 mesoscale impacts of wind farms as parameterized in a mesoscale NWP model. Monthly
398 Weather Review, 2012; 140:9-3017.
- 399 [14] Fitch AC, Lundquist JK, Olson JB. Mesoscale influences of wind farms throughout a
400 diurnal cycle. Monthly Weather Review 2013; 141:7-2173.
- 401 [15] Fitch AC, Olson JB, Lundquist JK. Parameterization of wind farms in climate models.
402 Journal of Climate 2013; 26:17-6439.
- 403 [16] Adams AS, Keith DW. Are global wind power resource estimates overstated?
404 Environmental Research Letters 2013; 8:1-015021.
- 405 [17] Lorenz EN. Available potential energy and the maintenance of the general circulation.
406 Tellus 1955; 7:2-157.
- 407 [18] Oort AH. On estimates of the atmospheric energy cycle. Monthly Weather Review 1964;
408 92:11-483.

- 409 [19] Oort AH, Yienger JJ. Observed interannual variability in the Hadley circulation and its
410 connection to ENSO. *Journal of Climate* 1996; 9:11-2751.
- 411 [20] Li L, Ingersoll AP, Jiang X, Feldman D, Yung YL. Lorenz energy cycle of the global
412 atmosphere based on reanalysis datasets. *Geophysical Research Letters* 2007; 34:16.
- 413 [21] Marques CAF, Rocha A, Corte-Real J. Comparative energetics of ERA-40, JRA-25 and
414 NCEP-R2 reanalysis, in the wave number domain. *Dynamics of Atmospheres and Oceans* 2010;
415 50:3-375.
- 416 [22] Kim YH, Kim MK. Examination of the global Lorenz energy cycle using MERRA and
417 NCEP-reanalysis 2. *Climate Dynamics* 2013; 40:5-6.
- 418 [23] Lorenz EN. *The nature and theory of the general circulation of the atmosphere* (Vol. 218).
419 Geneva: World Meteorological Organization; 1967.
- 420 [24] Rienecker M, et al. The GEOS-5 data assimilation system—Documentation of versions
421 5.0.1 and 5.1.0. NASA GSFC, Tech. Rep. Series on Global Modeling and Data Assimilation
422 2007; NASA/TM-2007-104606, Vol. 27.
- 423 [25] Huang J, Lu X, McElroy MB. Meteorologically defined limits to reduction in the variability
424 of outputs from a coupled wind farm system in the Central US. *Renewable Energy* 2014; 62:
425 331-340.
- 426 [26] Heide D, Von Bremen L, Greiner M., Hoffmann C, Speckmann M, Bofinger S. Seasonal
427 optimal mix of wind and solar power in a future, highly renewable Europe. *Renewable Energy*
428 2010; 35:11-2483.

- 429 [27] Archer CL, and Jacobson MZ. Geographical and seasonal variability of the global “practical”
430 wind resources. *Applied Geography* 2013; 45: 119.
- 431 [28] Kung EC. Large-scale balance of kinetic energy in the atmosphere. *Mon. Wea. Rev* 1966;
432 94:11-627.
- 433 [29] Holton JR, and Hakim GJ. *An introduction to dynamic meteorology*. Academic press; 2013.
- 434 [30] Hagos S, et al. Estimates of tropical diabatic heating profiles: Commonalities and
435 uncertainties. *Journal of Climate* 2010; 23:3-542.
- 436 [31] Ling J, Zhang C. Diabatic heating profiles in recent global reanalyses. *Journal of Climate*
437 2013; 26:10-3307.
- 438 [32] Johnson DR. “General Coldness of Climate Models” and the Second Law: Implications for
439 Modeling the Earth System. *Journal of climate* 1997; 10:11-2826.
- 440 [33] Peixoto JP, Oort AH, De Almeida M, Tomé A. Entropy budget of the atmosphere. *Journal*
441 *of Geophysical Research: Atmospheres* (1984–2012) 1991; 96:D6-10981.
- 442 [34] Peixoto JP, Oort AH. *Physics of climate*. American institute of physics; 1992.
- 443 [35] Stocker TF, et al. *Climate Change 2013. The Physical Science Basis*. Working Group I
444 *Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change-*
445 *Abstract for decision-makers*. Groupe d'experts intergouvernemental sur l'evolution du
446 climat/Intergovernmental Panel on Climate Change-IPCC, C/O World Meteorological
447 Organization, 7bis Avenue de la Paix, CP 2300 CH-1211 Geneva 2 (Switzerland), 2013.
- 448 [36] Breslow PB, Sailor DJ. Vulnerability of wind power resources to climate change in the

449 continental United States. *Renewable Energy* 2002; 27:4-585.

450 [37] Pryor SC, Schoof JT, Barthelmie RJ. Climate change impacts on wind speeds and wind
451 energy density in northern Europe: empirical downscaling of multiple AOGCMs. *Climate Res.*
452 2005; 29:183.

453 [38] Sailor DJ, Smith M, Hart M. Climate change implications for wind power resources in the
454 Northwest United States. *Renewable Energy* 2008; 33:11-2393.

455 [39] Bloom A, Kotroni V, Lagouvardos K. Climate change impact of wind energy availability in
456 the Eastern Mediterranean using the regional climate model PRECIS. *Natural Hazards and Earth*
457 *System Science* 2008; 8:6-1249.

458 [40] Pryor SC, Barthelmie RJ. Climate change impacts on wind energy: A review. *Renewable*
459 *and sustainable energy reviews* 2010; 14:1-430.

460 [41] Mideksa TK, Kallbekken S. The impact of climate change on the electricity market: A
461 review. *Energy Policy* 2010; 38:7-3579.

462 [42] Pereira de Lucena, AF, Szklo AS, Schaeffer R., Dutra RM. The vulnerability of wind power
463 to climate change in Brazil. *Renewable Energy* 2010; 35:5-904.

464 [43] Wan H, Wang XL, and Swail VR. Homogenization and trend analysis of Canadian near-
465 surface wind speeds. *Journal of Climate* 2010; 23:5-1209.

466 [44] Jiang Y, Luo Y, Zhao Z, Tao S. Changes in wind speed over China during 1956–2004.
467 *Theoretical and Applied Climatology* 2010; 99:3-4.

468 [45] Lu H, Porté-Agel F. Large-eddy simulation of a very large wind farm in a stable
469 atmospheric boundary layer. *Physics of Fluids (1994-present)* 2011; 23:6-065101.

470 [46] Miller LM, Gans F, Kleidon A. Estimating maximum global land surface wind power
471 extractability and associated climatic consequences. *Earth Syst. Dynam* 2011; 2:1-1.

472 [47] Marvel K, Kravitz B, Caldeira K. Geophysical limits to global wind power. *Nature Climate*
473 *Change* 2013; 3:2-118.

474 [48] Jacobson MZ, Archer CL. Saturation wind power potential and its implications for wind
475 energy. *Proceedings of the National Academy of Sciences* 2012; 109:39-15679.

476 [49] Roy SB, Traiteur JJ. Impacts of wind farms on surface air temperatures. *Proceedings of the*
477 *National Academy of Sciences* 2010; 107:42-17899.

478 [50] Gustavson MR. Limits to wind power utilization. *Science* 1979; 204:4388-13.

479

480

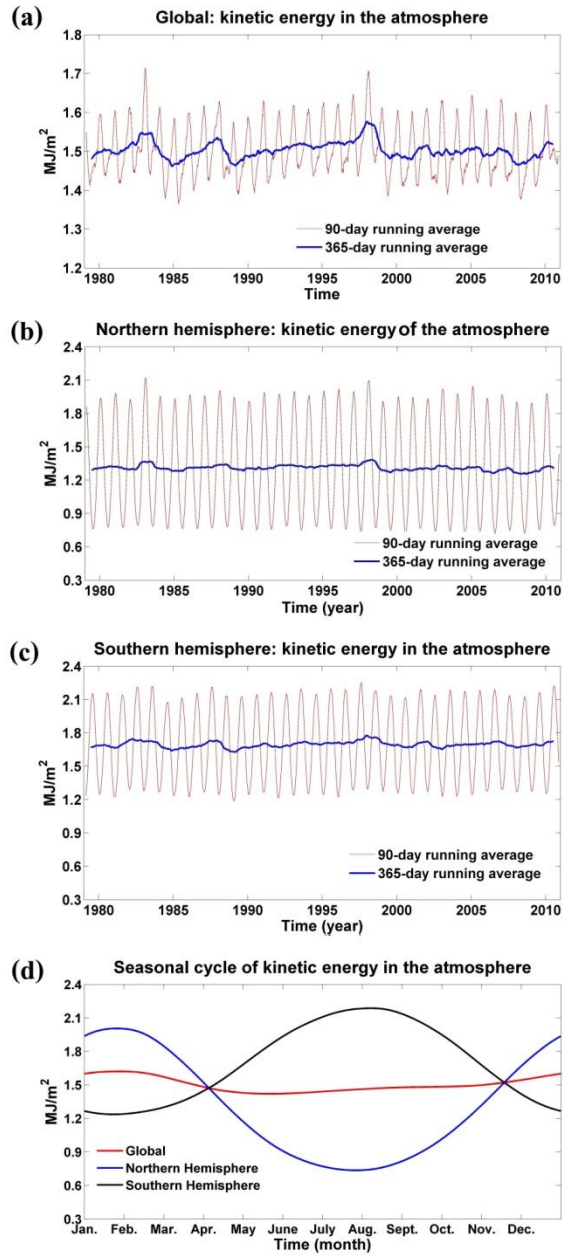
481

482

483

484

485

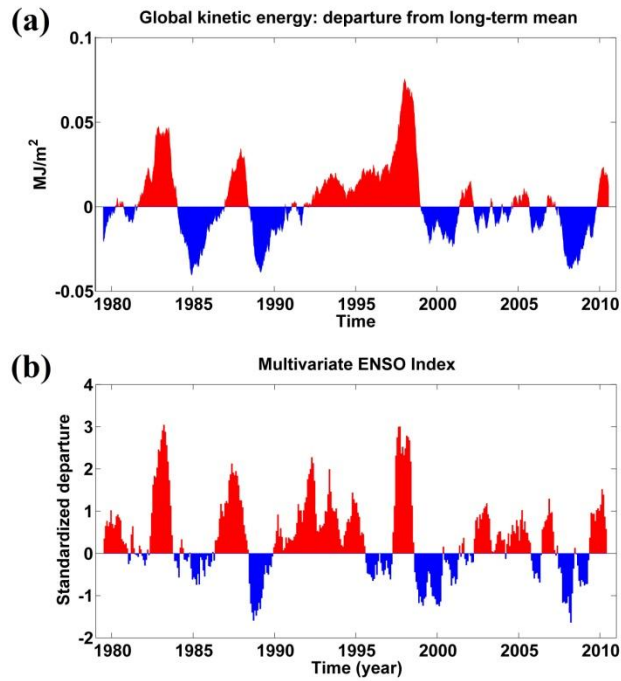


487

488 **Fig. 1.** (a) Variation of the global kinetic energy from January 1979 to December 2010. (b)
 489 Variation of the Northern Hemisphere kinetic energy from January 1979 to December 2010. (c)
 490 Variation of the Southern Hemisphere kinetic energy from January 1979 to December 2010. (d)
 491 The composite seasonal cycle of the kinetic energy of the atmosphere averaged over the past 32
 492 years.

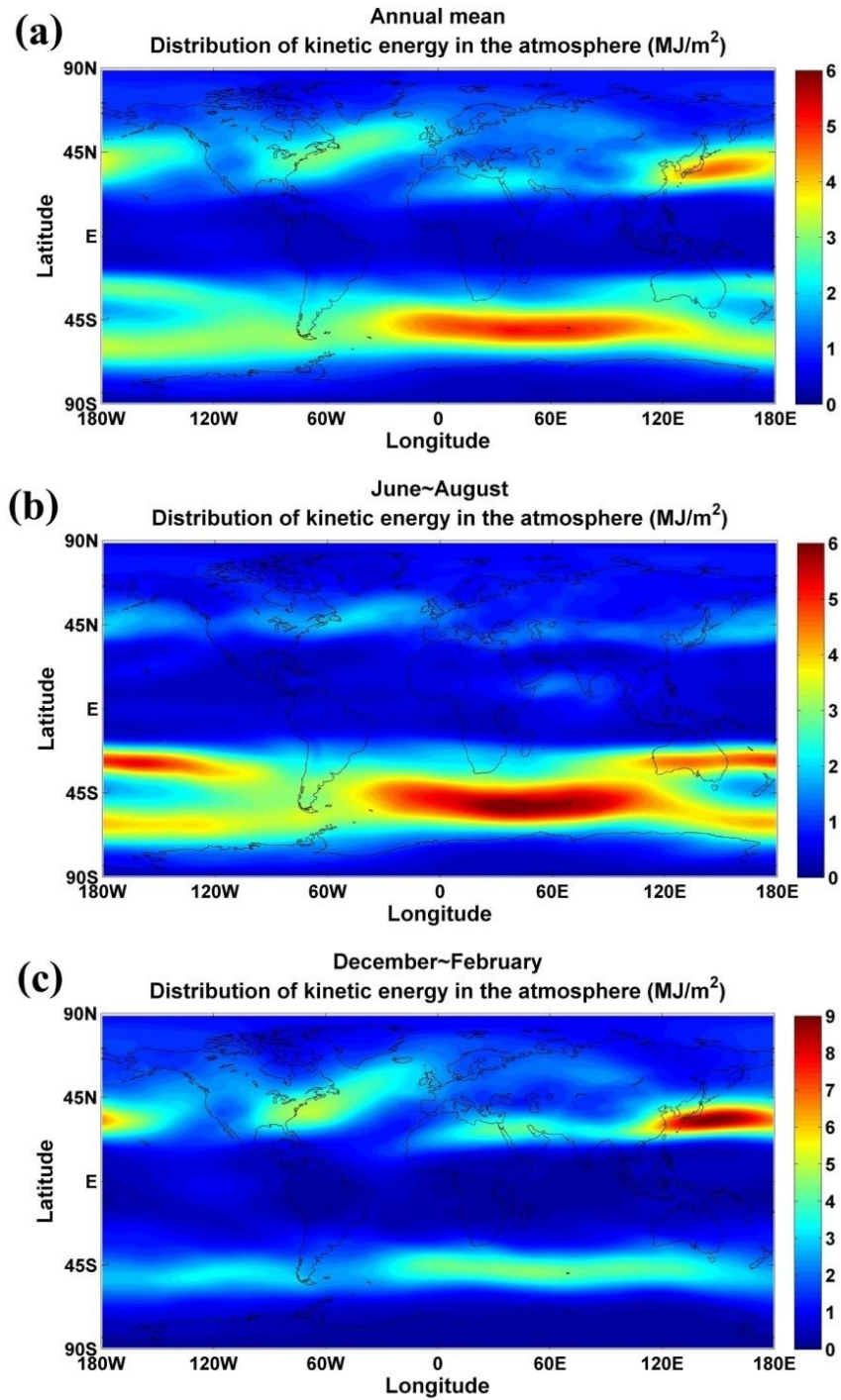
493

494
495



496
497
498
499
500
501
502
503
504

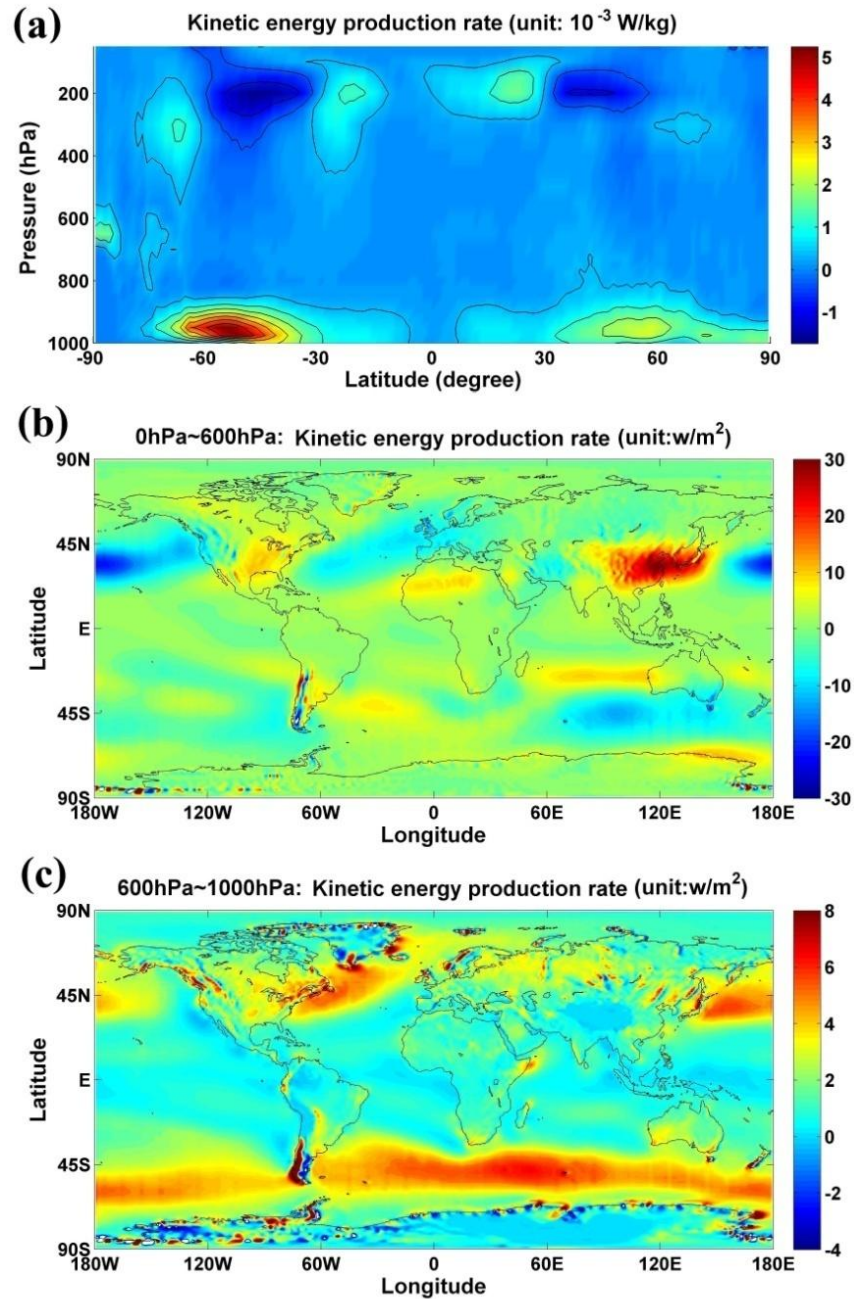
Fig. 2. (a) The departure of global kinetic energy from its 32 years' mean value $1.50 \text{ MJ}/\text{m}^2$. The seasonality of the departure is removed via 365-day running average. (b) The time series of the multivariate ENSO index from January 1979 to December 2010. Positive values correspond to the warm events of the ENSO phenomena, while the negative ones correspond to the cold events.



505

506 **Fig. 3.** (a) Spatial distribution of the annual mean kinetic energy of the atmosphere in MJ/m^2 ,
 507 calculated based the past 32 years' data. (b) June ~ August, calculated based the past 32 years'
 508 data. (c) December ~ February, based on the past 32 years' data.

509

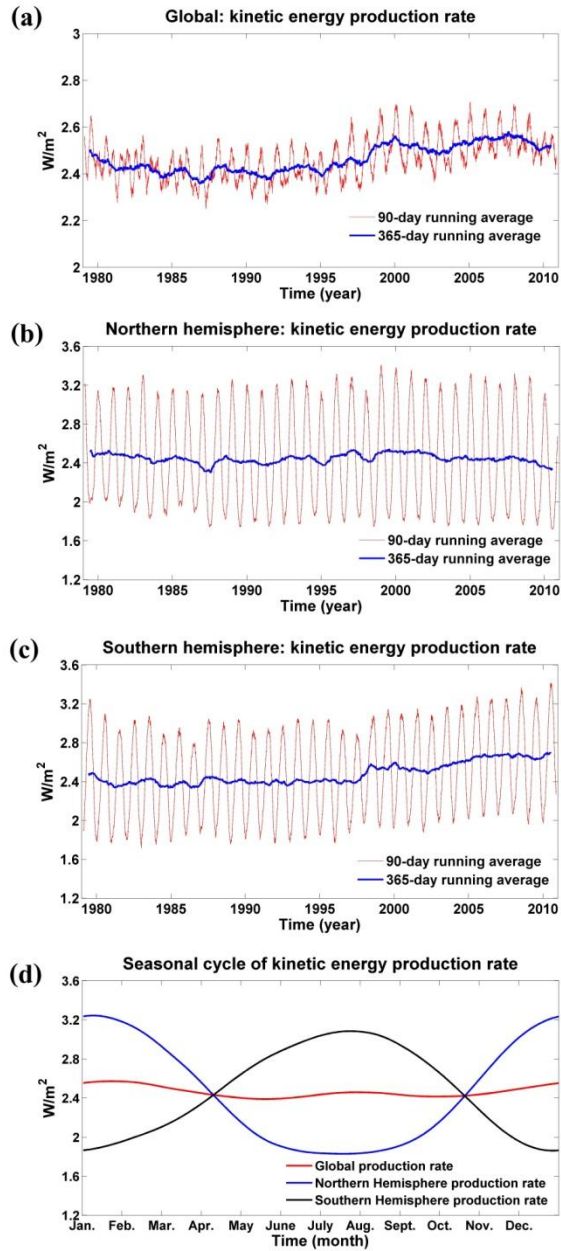


510

511 **Fig. 4.** (a) The vertical profile of kinetic energy production rate, C . (b) Kinetic energy production
 512 rate, C , in the layer between 0 hPa ~ 600 hPa. (c) Kinetic energy production rate, C , in the
 513 layer between 600 hPa ~ 1000 hPa.

514

515

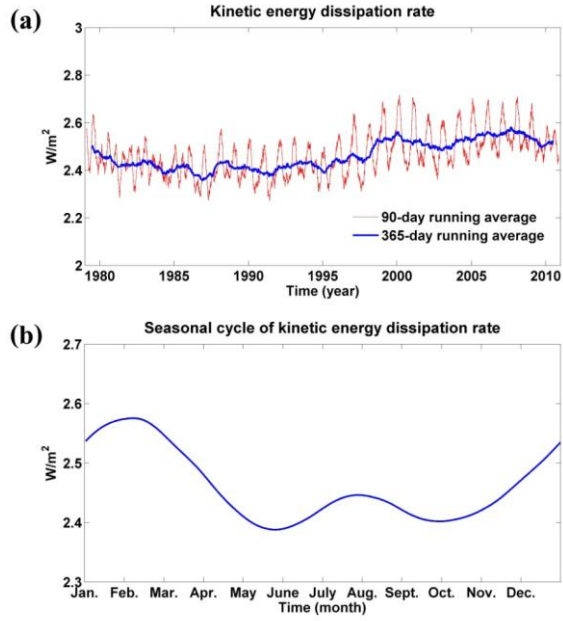


516

517 **Fig. 5.** (a) Variation of the global kinetic energy production rate, C , from January 1979 to
 518 December 2010. (b) Variation of the Northern Hemisphere kinetic energy production trend, C ,
 519 from January 1979 to December 2010. (c) Variation of the Southern Hemisphere kinetic energy
 520 production trend, C , from January 1979 to December 2010. (d) The composite seasonal cycle of
 521 the kinetic energy production rate, C , based on the past 32 years' data.

522

523



524

525 **Fig. 6.** (a) Variation of kinetic energy dissipation rate, D , from January 1979 to December 2010;

526 (b) The composite seasonal cycle based on the past 32 years.

527

528

529

530

531

532

533

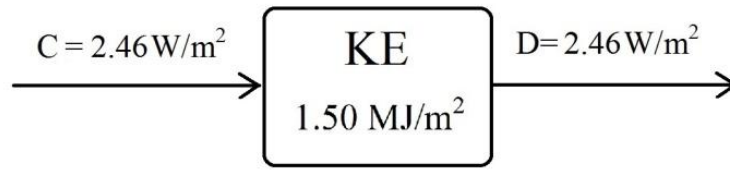
534

535

536

537

538



539

540 **Fig. 7.** Mechanical perspective on the budget of atmospheric kinetic energy.

541

542

543

544

545

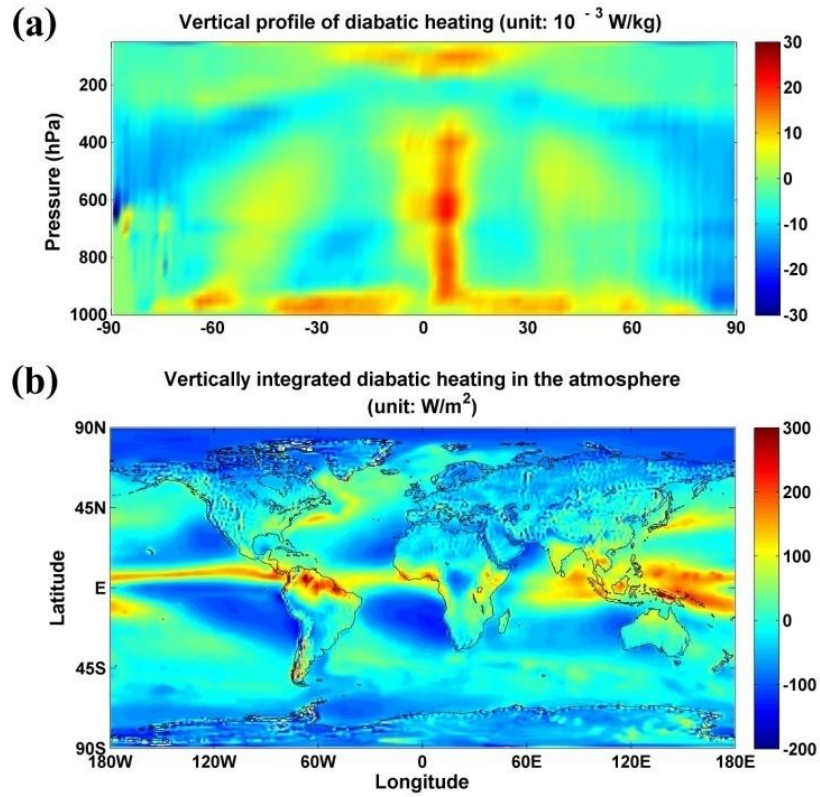
546

547

548

549

550



551

552 **Fig. 8.** (a) Vertical profile of diabatic heating. (b) Vertically integrated results.

553

554

555

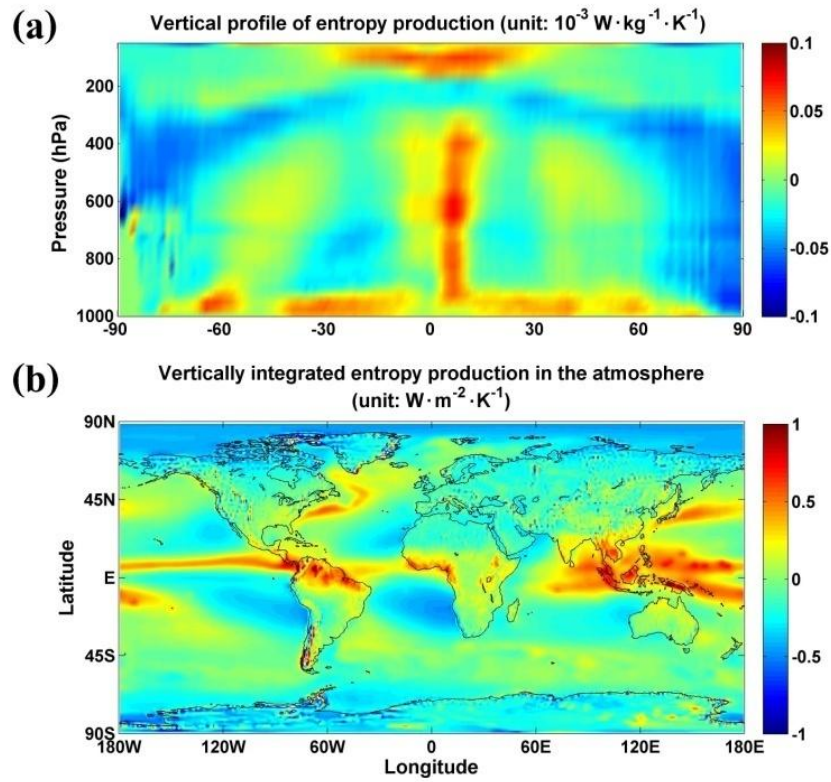
556

557

558

559

560



561

562 **Fig. 9.** (a) Vertical profile of entropy production. (b) Vertically integrated results.

563

564

565

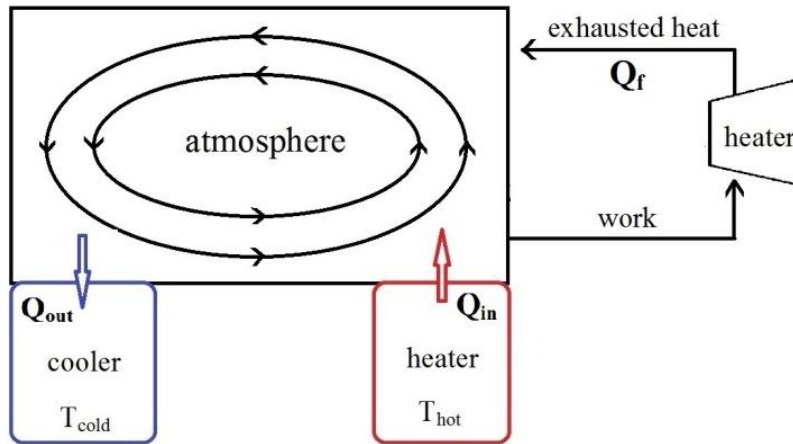
566

567

568

569

570



571

572 **Fig. 10.** Schematic depiction of the atmosphere as a thermal engine.

573

574

575

576

577

578

579

580

581

582

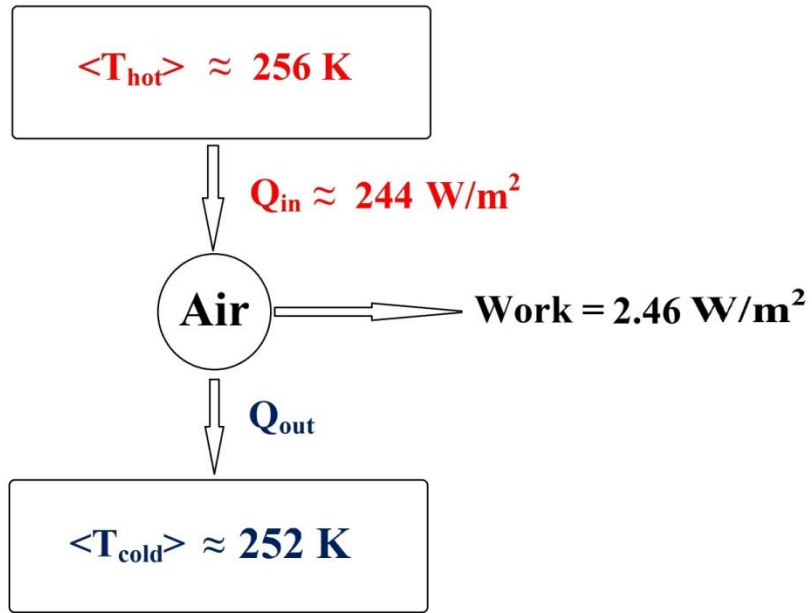
583

584

585

586

587



588

589 **Fig. 11.** Illustration of the atmosphere as a Carnot engine. Work, C , is dissipated ultimately by
 590 friction.

591

592

593

594

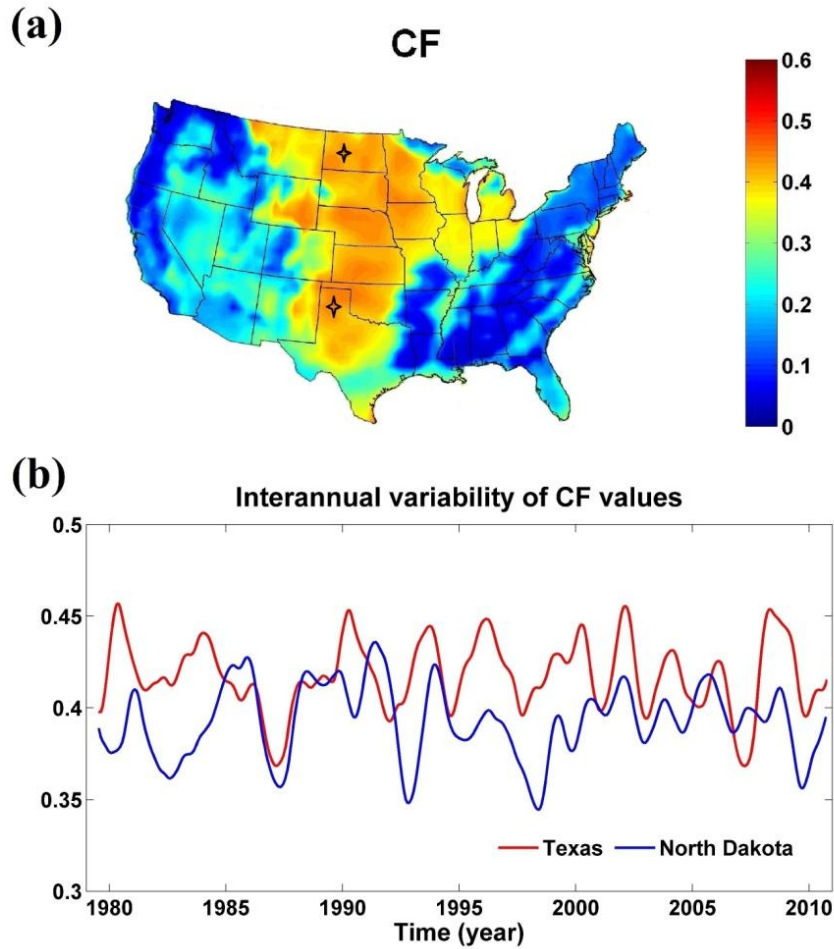
595

596

597

598

599



600

601 **Fig. 12.** (a) Color coded values for CF as a function of position averaged over the 32 year period
 602 Jan 1st 1979 to Dec 30th 2013. Positions of two wind farms considered in this paper are
 603 indicated by the stars. (b) CF values for two wind farms in Texas and North Dakota with
 604 seasonal cycle removed.