Could wind turbines be contributing to recent arctic warming and unusual extreme weather?

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Abstract.

Wind energy could be responsible for recent: rapid global warming, arctic amplification and unusual mid latitude extreme weather. The deployment of wind turbines over the last 15 year has been a major change to the earth system and could be having a significant effect on climate. Wind turbines could contribute to global warming by reducing prevailing westerly wind thereby reducing equatorward Coriolis force and facilitating poleward air flow. Increased poleward flow in the upper troposphere increases subsidence in higher latitude and the associated subsidence warming. Reducing Coriolis force diminishes a force resisting poleward air flow. Facilitating poleward flow is a more immediate global warming concern than greenhouse gasses because the heat stored in the warm seas is more than sufficient to melt all polar ice; there is no need to wait for radiative unbalance to warm the oceans. The article describes a mechanism whereby wind turbines could affect weather and climate. The point where wind energy production is starting to have significant effect on climate may have been passed. The article suggests that global warming could be slowed down by shutting down wind turbines. The global warming effect of wind energy has not been fully appreciated and needs attention.

1. Introduction

Wind turbines could be contributing to recent rapid global warming by reducing westerly wind thereby reducing equatorward Coriolis force and facilitating poleward air flow. Wind turbines reduce westerly winds more than winds from other directions because westerly winds are the prevailing ones. Poleward air flow in the upper troposphere results in subsidence warming in high latitudes. Global warming increased from 0.01 °C per year between 1980 and 2000 to 0.1 °C per year since 2013. The 10 fold post 2013 warming increase could be just noise but could also indicate that something in the earth system has changed. Installed wind turbine capacity is increasing exponentially by approximately 25 % per year; it was 60 and 430 GW at the end of 2005 and 2015 respectively and is increasing by 60 GW per year; see Fig. 1, (GWEC, 2016). Wind turbines have an average capacity factor of 20 % of their maximum rated output. Installed wind turbines produce an average of 85 GW and a maximum of 300 GW of electrical energy. Their average production of 85 GW is 4 % of the average worldwide electricity production of 2,300 GW and 0.5 % of the worldwide primary energy production of 18,000 GW. There were over 300,000 installed large wind turbines at the end 2015. Taken together wind turbines are the largest human made structures; they reduce the kinetic energy of the wind and could be having a significant effect on climate.

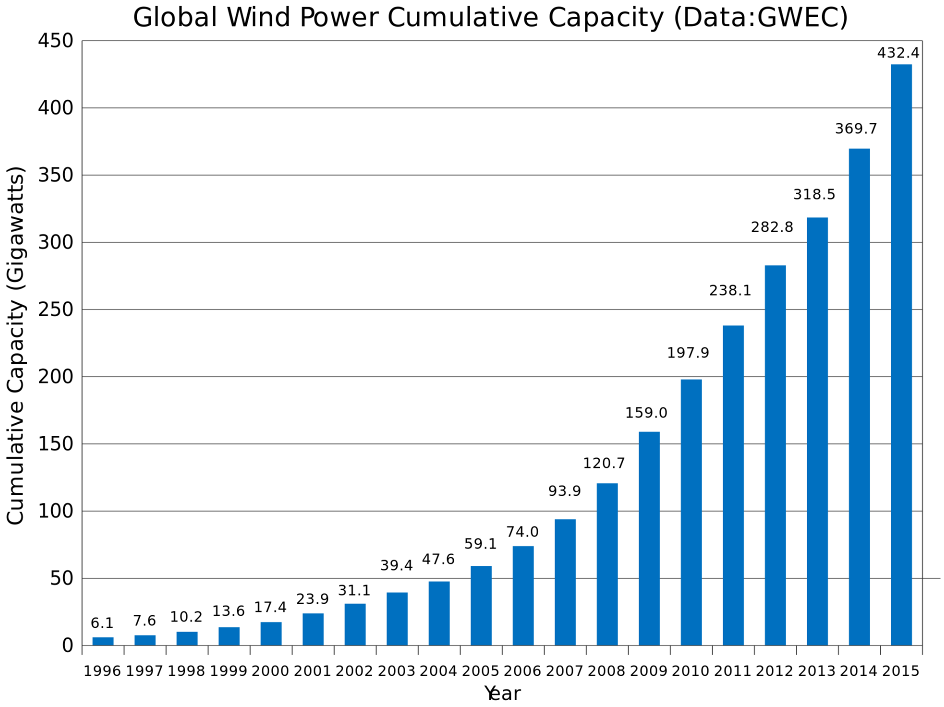

Fig.1. Global installed wind turbine capacity, from Global Wind Energy Council.

Atmospheric carbon dioxide is increasing arithmetically by approximately 3 ppm per year (0.7 %/a) and cannot explain the recent ten fold increase in global warming. Radiation forcing due to human greenhouse gas emissions can only slowly increase the earth's temperature. The current radiation forcing of 0.9 W m^{-2}, Trenberth et al. (2009), can increase ocean temperature by a maximum of 0.1 K per decade. Raising the earth's temperature is a slow process; warming the oceans takes decades, Cheng et al. (2017). Figure 2, Hansen (2010), shows that the recent period of rapid global warming coincides with the rapid growth in wind energy of Fig. 1. Climate Science Special Report, (CSSR 2017), states in Key Finding #3 that human activities, especially carbon dioxide emissions, are primary responsible for climate change and that there are no alternative explanations. Wind turbines are an alternative explanation grounded in well understood physical mechanisms and that is appropriate in scale and consistent in timing. The warming effect of wind turbines is faster than that of greenhouse gasses because the heat is already stored in warm sea water; there is no need to wait for radiative forcing to warm the oceans. Global warming could be aggravated by a well intentioned human response aimed at reducing carbon emission. Ironically, there is a possibility that reducing carbon emissions by replacing fossil fuel with wind energy could be increasing rather than reducing global warming.

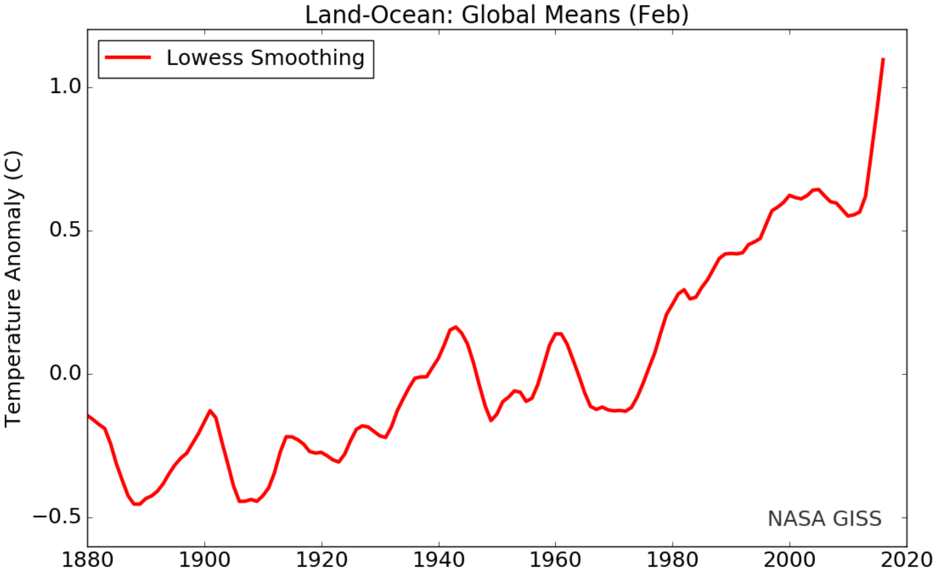

Fig. 2. Global mean February surface temperature anomaly, from NASA-GISS (Lowess 4).

Section 2 reviews how subsidence warming compensates for radiative cooling. Section 3 examines the role of Coriolis force in restraining poleward upper tropospheric wind. Section 4 looks at how wind turbines decrease zonal flow. Section 5 discusses the limits to wind energy production. Section 6 justifies the use of the neglected thermodynamic method rather than fluid dynamics models. Section 7 points out the urgent need to investigate the effect of wind turbines on climate.

2. Subsidence warming

Infrared radiation to space cools the troposphere but over the long run the temperature of the troposphere remains constant. Keeping the temperature of the upper troposphere constant requires that the energy loss by radiation be replaced. Fasullo and Trenberth (2008) established the oceanic and atmospheric meridional energy flow required to balance top of the atmosphere net radiative energy flux. In *oceanic* meridional energy transfer, energy is transferred by exchanging the positions of water masses of different temperatures. *Atmospheric* meridional energy transfer is a thermodynamic process wherein energy is transferred mainly by work of compression; the subsiding air is warmed by compression. Work of compression can transfer energy both upward and poleward, from wherever it is received to wherever it is radiated to space. The majority of the energy transported poleward by the atmosphere is received at low elevation in low latitudes and given up at higher elevation in higher latitudes. Atmospheric meridional energy transport is usually attributed to transient eddies and stationary waves, see: Peixoto and Oort (1992) Fig. 13.14. Fasullo and Trenberth (2008) wisely used the generic term energy transfer rather than heat transfer and thus avoided getting into the details of the energy transfer process.

Updrafts do not increase the temperature of the environment at their level of detrainment; they increase the temperature of the compressed underlying subsiding air. Irrespective of entrainment and detrainment updrafts rise to their level of neutral buoyancy where their temperature is essentially the same as the temperature of the environment. Latent heat of condensation contributes to keeping the updrafts buoyant, but does not increase the temperature at the level of detrainment. Compensating for radiative cooling requires that the troposphere subside at a definite rate:

$$w = \frac{Q}{(a_d - a)} \qquad (1)$$

where w is the *required* subsidence velocity in m/d, where Q is the daily radiative cooling rate in K/d, where a_d is the dry-adiabatic lapse rate (9.75 K/km) and where a is the environmental lapse rate, both in K/m in eq. (1). In the mid latitudes troposphere, for a radiative heat loss of 1.5 K d^{-1} and a lapse rate of 6.5 K km^{-1}, the required subsidence velocity, w, is 460 m d^{-1} (0.0053 m s^{-1}). This subsidence velocity corresponds to mass flows of 1.9 and 6.5 g (m^2·s)$^{-1}$ at the top and bottom of the troposphere respectively corresponding to subsidence of 1.6 and 5.5 kPa d^{-1}. The subsidence mass flow is smaller at higher elevation because a given change in pressure has more effect on temperature at lower pressure. Updrafts rising to a range of elevations can produce a mass flow decreasing with height capable of balancing radiative heat loss at any elevation. In order to prevent the temperature of the descending air from getting warmer than that of the ambient air, the air must descend slowly to allow time for heat loss by radiation. The subsidence velocity (w) required to keep troposphere temperature constant is usually between 100 and 1000 m/d. In high latitudes, where cooling rate (Q) the lapse rate (a) are small, w can be as low as 100 m/d.

Fig. 3 illustrates the type of circulation required to produce a quasi uniform subsidence velocity. The required subsidence is achieved by a circulation consisting of a combination of fast rising updrafts of small area and slowly subsiding layers over the whole earth surface. Michaud (2000) used simple closed thermodynamic systems to calculate the mechanical energy that can be produced by atmospheric upward heat flux. The effect of subsidence warming is easier to see in simple models than in complex ones. Simpler models readily explain how a combination of fast updrafts and slowly subsiding layers transfers energy upward and poleward. Michaud (2004) unpublished manuscript: "Subsidence required to replace heat loss by radiation with work of compression" derived eq. (1), extended the Michaud (2000) concept to include subsidence, and described the type of circulation required to balance top of the atmosphere heat flux. Michaud (2004) did not consider the Coriolis force. Fig. 3 of this article is Fig. 7 of Michaud (2004) with the addition of Coriolis force.

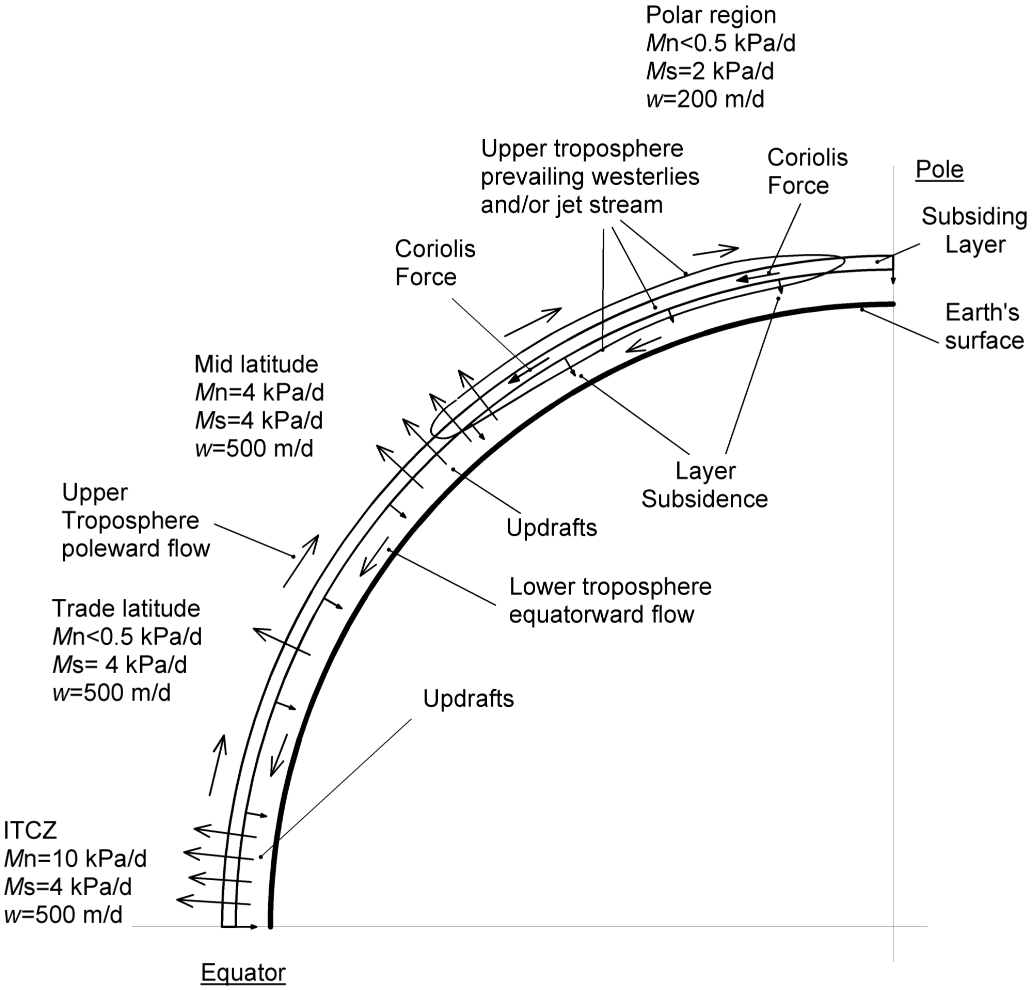

Fig. 3. The heating of the earth's surface by solar radiation results in fast updrafts and slow subsidence. The process transfers energy from where it is received to where it is radiated to space. Subsidence occurs preferentially where the air is cold thereby controlling tropospheric vertical temperature profile. Coriolis force resists poleward flow in the upper troposphere. For clarity, the figure shows one subsidence layer divided into 4 zones; there can be more than one subsiding layer. M_n net zone upflow, M_s zone subsidence, w subsidence velocity.

Adding air at the top of a column of air with a sub-adiabatic lapse rate while removing an equal quantity of air from its bottom adds energy to the column because the air entering the column has more potential energy than the air leaving the column. The energy transferred to a column of subsiding pure air is equal to the static energy of the air entering the top of the column minus the static energy of the air leaving the bottom of the column. Raymond (1995) independently showed that the required subsidence velocity is equal to the radiative cooling rate divided by the lapse rate of potential temperature; his eq. (9) is equivalent to eq. (1). Emanuel et al. (1994) showed how convection controls the vertical temperature profile of the atmosphere.

The subsidence velocity does not need to be constant; a short duration descent of 1000 m every two days has the same final warming effect as a uniform descent of 500 m d^{-1}. The requirement to keep tropospheric temperatures at their long term average puts limits on the subsidence velocity; the upper and lower limits could be a sustained subsidence of 2000 m/d for a few days and no subsidence for a week. Without subsidence, the temperature at any given pressure level would decrease by 1.5 K d^{-1}. Without radiative cooling, the temperature of the subsiding air after descending 460 m would be 1.5 K warmer than that of the original ambient air temperature at the lower level. The temperature at a given level tends to increase when the actual subsidence rate is more than *w,* and to decrease when air subsides at less than *w*. The time required for a layer to subside from the top to the bottom of the tropical troposphere is typically 30 days. Rapid descent would bring the final temperature of the descending air to its initial potential temperature which can be 40 K higher than surface temperature.

Subsidence heating is the dominant temperature control process in the troposphere. The updrafts responsible for the subsidence can be local or remote and can be cumulus, thunderstorms or cyclonic storms. The heat source responsible for the buoyancy of the updrafts can be sensible or latent heat. Updrafts spread out at their level on neutral buoyancy and tend to settle preferentially where the underlying air is cool and needs warming. Updrafts can rise to a range of elevations and can enter subsiding air mass at any level. Subsidence is self regulating and tends to occur where the air is coolest and easiest to compress and thus tends to prevent temperature from deviating too far from long term average. If the temperature of an air mass decreases for any reason, subsidence eventually increases in the area thereby countering the temperature decrease. The updrafts do not have to descend in the area of subsidence to produce the warming; displacing the air previously at its level of neutral buoyancy towards the low temperature area is sufficient. Thus updrafts in the tropic can result in almost immediate subsidence and warming in high latitudes.

The area of the updrafts is smaller than the subsidence area because a high subsidence velocity would result in excessive warming. Raymond (1995) pointed out that the area of the updrafts must be much smaller than the subsidence area. Heavy rain areas typically cover less than 5 % of the earth's surface. Strong updrafts typically cover 10 to 20 % of the earth's area while subsidence occurs everywhere. The typical upward velocity of updrafts of 0.5 to 5 m s^{-1}, (LeMone and Zipser, 1980) is 100 to 1000 times the required subsidence velocity of approximately 0.005 m s^{-1}. Subsidence velocity is difficult to measure because it is much smaller than the vertical velocity of updrafts or downdrafts. The role of subsidence heating has been recognized by: Raymond (1995), Satoh and Hayashi (1992), Satoh (1994), and by Iwasa et al. (2002) but is not universally appreciated. Subsidence warming is more effective at moving energy poleward and upward than either eddies or stationary waves. Adding a kilogram of air at the top and removing a kilogram from the bottom of a column of mid-latitude air can add 40,000 J of energy to the column. Inserting a kilogram of air and withdrawing a kilogram of air 2 °C colder at the same level in an air column only adds 2000 J to the energy of the column and does not transport energy upward.

A horizontal poleward velocity of 1 to 5 m s^{-1} in a various layers in the troposphere would be sufficient to provide the subsidence required to compensate for high latitude radiative cooling.

Deflecting high level westerlies slightly poleward would be sufficient to produce a significant increase in high latitude subsidence. Poleward energy transfer via eddies and stationary waves requires much more air movement than subsidence. Transferring a large quantity of energy poleward with eddies would requires well organized currents of warm air moving poleward and cold air moving equatorward. The process would require large meridional velocities and large longitudinal temperature differences. The meandering jet stream does not necessarily transport large quantities of energy poleward; the same air can move poleward and back equatorward.

3. Coriolis Force

At a given level in the upper troposphere, the pressure is higher in low than in high latitudes, see: Miller et al. (2011b) Fig. 1; Peixoto and Oort (1992) Fig. 7.10a; and Walsh (2014) Fig. 2. The meridional pressure differential tends to push upper troposphere air poleward. The Coriolis force due to the prevailing westerly upper troposphere winds is directed equatorward and opposes poleward flow. Coriolis force is the effect of centrifugal force in a rotating frame of reference. The pressure differential due to Coriolis force is proportional to wind velocity, to the sine of latitude and to the mass of the moving air. Upper troposphere meridional flow is the net result of meridional differential pressure trying to increase poleward flow and of Coriolis force trying to resist this flow. At any given time the forces are in equilibrium, therefore reducing Coriolis force in the upper troposphere increases poleward flow. Tropospheric temperatures are lower in high than in low latitudes mainly because more Coriolis force has to be overcome to get to the high latitudes.

Without Coriolis force the equator to pole surface temperature difference would be much smaller. Satoh (1994) Fig. 7 showed that for the same solar heat flux stopping the earth's rotation would reduce the surface equator to pole temperature gradient from 50 to 10 °C; polar temperatures would increase by 30 °C and equatorial temperatures would decrease by 10 °C. Satoh (1994) Fig. 6 shows that, for the no earth rotation case, infrared radiation to space would increase by 110 W/m^2 in polar regions and decrease by 70 W/m^2 in equatorial regions. Polar surface temperature is higher in the non rotating earth case than in the rotating earth case because there is no need to overcome Coriolis force to produce subsidence warming in high latitudes. Satoh`s (1994) investigation of the effect of the earth's speed of rotation show how looking at implausible scenarios can lead to valuable research results.

Decreasing Coriolis force by reducing westerly wind with turbines could have an effect on equator to pole temperature gradient similar to the effect of reducing the earth's speed of rotation. Reducing Coriolis force with wind turbines could be driving polar surface temperature towards Satoh`s no earth rotation case. In low latitudes, the pressure at a given level in the upper troposphere is essentially constant because geopotential heights are essentially constant. Geopotential heights are higher in low latitudes than in high latitudes. In high latitudes, geopotential heights are lower in winter than in summer, see Walsh (2014). The meridional pressure differential between points at the same elevation is therefore higher in winter than in summer.

Subsidence warming is a complex process and depends on the balance between the density of the descending air, the meridional-horizontal pressure gradient, Coriolis force and other dynamic forces. Cold lower troposphere air may not subside despite high density at low elevation due to low density at higher elevation. Eventually subsidence or lack thereof prevent surface temperatures from getting too low or too high and limit the range of surface temperatures. The horizontal pole to equator pressure differential due to Coriolis force could be 1 to 4 kPa; wind turbines could occasionally reduce this pressure differential by 0.2 to 1 kPa resulting in a surge in poleward upper troposphere flow and in sudden arctic warming.

4. Effect of Wind Turbines on zonal wind

Wind turbines extract kinetic energy from low level wind. Each wind turbine reduces the kinetic energy of the air flowing through its rotor by approximately 50 %. The reduced kinetic energy air mixes with the surrounding air resulting in a combined wind velocity of say 98 % of the undisturbed wind velocity (U1). In a large wind farm, the same air can go through several turbines reducing the wind to say 90 % of U1. The air can go through several wind farms reducing the average wind velocity to say 80 % of U1. The overall effect is cumulative and can result in a significant reduction in wind. Wind turbines in Eurasia and America can both contribute to reducing global westerly wind. Wind turbines in Eurasia can contribute to global warming in America and vice versa. The effect of wind farms on local climate is small compared to their effect on global climate. Westerly winds are reduced more than winds from other directions because they are the prevailing ones.

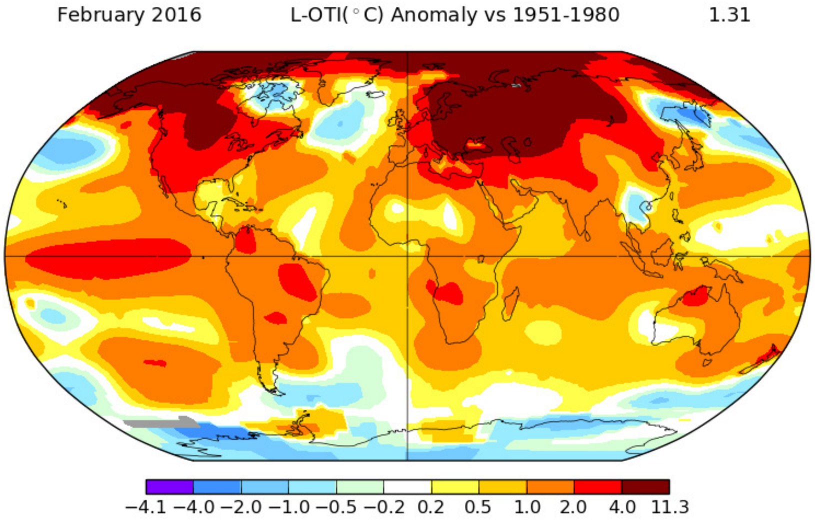

Fig. 4 Average surface temperature anomaly for February 2016 - from NASA-GISS.

Figures 4 and 5, Hansen (2010), shows surface temperature monthly anomalies versus the 1951-1980 average for February and July 2016. The number at the upper right of the figures is the worldwide average anomaly for each month. The February 2016 anomaly was the highest monthly anomaly ever measured; the February anomaly was: 0.54 °C in 2014, 0.87 °C in 2015, 1.31 °C in 2016 and 1.11 °C in 2017. The February temperature anomaly went up by 0.6 °C in 3 years, (0.2 °C/a). Climate change increases temperature anomalies at all latitudes but more so in high latitudes, a phenomenon called arctic amplification (AA). Arctic temperature anomalies are 2 to 3 times higher than low latitude anomalies, Francis and Varvus (2012). Figure 4 shows that February surface temperature anomalies have been over 4 °C for large swaths of boreal areas. Arctic temperature anomalies are higher than mid-latitudes ones because there are more opportunities for reducing Coriolis force in high latitudes. Arctic winter temperature anomalies are higher than arctic summer anomalies because Coriolis force is higher in winter than in summer and there are therefore more opportunities for wind turbines to reduce Coriolis force. There is no indication that warming is slowing down; October and November 2016 temperature anomalies indicate that AA is accelerating. The November 2016 average arctic anomaly was 8 °C, Hansen (2010), corresponding to an arctic amplification factor of 8.

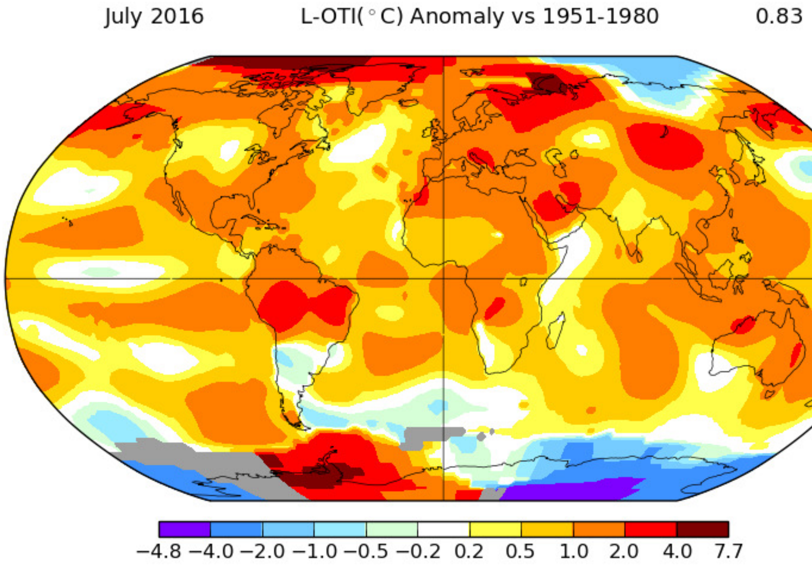

Fig. 5 Average surface temperature anomaly for July 2016 – from NASA-GISS.

Figure 5 shows that there is no similar high latitude winter temperature anomaly in the southern hemisphere. The lack of antarctic warming may be due to the fact that 95 % of wind turbines are located in the northern hemisphere. Wind turbines in the northern hemisphere may be favoring northward over southward heat flow thereby resulting in major warming in the arctic and only minor warming in the antarctic. The reason for temperatures being lower in the antarctic than in the arctic, at least in pre-industrial times, may have been that there was less elevated terrain in the southern hemisphere. In the winter both poles were surrounded with ice, therefore the poleward energy transfer must have been almost entirely *atmospheric* at both poles. Figures 4 and 5 were selected to show the contrast between seasons and the two hemispheres; the pattern of amplified winter arctic warming has been going on for several years.

According to Vautard (2010) and Zhao (2011) annual mean wind speed had diminished 5 to 15% between 1979 and 2008. Coumou et al. (2015) reported a significant weakening of summer zonal-mean wind at the 50 kPa level between latitudes 35°N and 70°N. Coumou et al. (2015) reported a decline of 8 to 15 % in the summer eddy kinetic energy (EKE) of the zonal wind between 1979 and 2013 and noted that periods of high temperature anomalies coincide with periods of low EKE. The equator to pole temperature gradient could be proportional to zonal wind speed; both have decreased by 10 to 15% over the last thirty years. Coumou et al. (2010) pointed out that rapid warming of the arctic could influence mid-latitude circulation by reducing the poleward temperature gradient. Distinguishing between cause and effect can be difficult; in this case reduced zonal circulation must be the cause and arctic warming is the effect and not vice versa. Fausto et al. (2016) noted that non radiative heat transfer is the dominant factor in Greenland ice melting; non radiative heat transfer would include air warmed by subsidence.

Westerly winds prevail at the 50 kPa level in the mid latitude troposphere because most of the updrafts are produced in low latitude where the tangential velocity of the earth's surface is highest. The westerly velocity of the poleward moving air relative to the earth's surface increases as it move poleward to conserve angular momentum. Wind turbines located in mid latitude can affect upper troposphere wind because weak surface winds increase drag and because mid latitude thermals carry air with reduced westerly velocity upwards where it mixes with the air from more equatorial areas. The weakening in boundary layer westerly wind due to wind turbines eventually propagates upward and reduces upper troposphere westerly wind. Wind turbines located at ground level could reduce jet stream velocity and have an impact on climate similar to that of the wind turbines located in the jet stream described in Miller et al. (2011b). Wind turbines are small compared to mountain ranges and to large cities and were therefore not initially expected to have a significant effect on climate. Wind turbines may be more effective at removing kinetic energy from the wind than stationary structures of similar size. Cities and other man made structures, which are predominantly located in the northern hemisphere, could be responsible for a small part of the northern hemisphere warming.

There have been many highly unusual high temperature related weather events during the 2015-2016 winter including record high temperatures in the vicinity of the North Pole, in Alaska and in Northern Canada plus a January hurricane in the North Atlantic, see: (NOAA, 2016), and Coumou and Rahmstrof (2012). Francis and Varvus (2012) attempted to link arctic amplification to weakened zonal winds and to extreme weather in mid-latitudes. Cohen et al. (2014) Fig. 2 and 3 show that AA and mid-latitude extreme weather events both started around 2000. Figure 1 shows that significant deployment of wind turbines started at the same time. Reduce Coriolis force due to wind turbine could be the cause of both the AA and of the mid-latitude weather extreme documented by Cohen (2014). Wind turbines could explain: AA, loss of arctic sea ice, recent rapid global warming and recent unusual extreme mid-latitude weather. A reduction in Coriolis force could explain many recent unusual weather phenomena and could have other unanticipated weather and climate effects. Wind turbines in central United States could be contributing to the high temperature anomalies in central Canada of Fig. 4.

During the arctic winter subsidence warming is the only process capable of compensating for infrared radiation to space because there is no incoming short wave radiation; because there is little upward heat flow from the frozen surface; and because energy transport by horizontal air eddies or air currents must be small. Winter arctic inversions must be due to subsidence warming; otherwise the arctic troposphere would cool from infrared radiation to space. The energy responsible for melting arctic ice could be the result of tropical heat being transferred poleward via subsidence warming.

There have been reports of reduced wind and reduced energy production from wind farms. According to Rife (2016), during the first half of 2015, large swaths of the United States experienced anomalously low winds, whose geographic extent and longevity eclipses any similar event in recent history. Winds 6 to 20 % below their long term average persisted for extended periods. According to the New York Times in Germany in 2016, a 11 % increase in wind capacity produced a 1 % increase in wind power, Porter (2017). New wind turbines may already be reducing the output of previously installed ones. Reduction in wind turbines power output could be an indicator of the reduction in zonal wind and in Coriolis force. The power output of wind turbines is proportional to the cube of wind speed. The 15% reduction in mean wind speed reported by Vautard (2010) and Zhoa (2017) could result in a 50% reduction in wind turbine power output. Zhoa (2017) pointed out the possible role of wind turbines in reducing wind speed in China. Zou et al. (2017) investigated the link between extreme winter haze in the East China plains and reduced wind velocity.

Satellite images showed persistent unusual northward moving rain bands about 400 km east of the eye of hurricane Matthew, (Wikipedia 2016). Hurricane rain bands were formerly evenly distributed around the eye. In 2016 rain bands have been more prevalent on the eastside of the eye and often absent on the three other sides. Reduction in Coriolis force may be favoring northward moving rain bands on the east side of the eye and inhibiting south flowing rain bands on the west side of the eye. Coriolis force in low latitude is small but reducing Coriolis force anywhere along the poleward travel path increases poleward flow in both low and high latitudes. Increasing subsidence in high latitudes would be associated with increased poleward flow in low latitudes.

5. Wind energy production limits

The earth receives 174,000 TW of energy from the sun of which 50,000 TW is carried upward by convection, Trenberth et al. (2009). There is a possibility of converting a maximum of 12 % of the heat carried upward by convection to mechanical energy because the heat is received and given up at average temperatures of +15 °C and -20 °C, Renno (2008), Michaud (2000). Kleidon (2012) estimated the maximum energy production of the atmosphere at 6000 TW. The total wind energy actually produced in the atmospheres must be much less than this 6000 TW reversible limit because the process is irreversible and because the mechanical energy readily degrades becoming unavailable to produce sustained wind, Michaud (2000). Emanuel et al. (2016) workshop on the effect of wind turbines agreed to an upper bound on wind energy production of 1000 TW. Part of the mechanical energy produced in the atmosphere is used to raise water and is also unavailable to produce wind. The mechanical energy required to drive prevailing winds could be as low as 5 to 100 TW. Vertical heating gradients may only be capable of producing sustained wind when associated with horizontal heating gradients.

The above top down thermodynamics approach establishes an upper limit on how much wind energy can be produced. The energy required to sustain horizontal wind can be estimated by using the bottom up techniques similar to that used to calculate the energy required to sustain flow in conduits. The power required to sustain a laminar flow with a velocity of 50 m/s in a horizontal tube 5 km in diameter and 40,000 km long is approximately 0.1 TW. Frictional losses for air can be very low because air has a low viscosity. Density stratification in the atmosphere, particularly in the upper troposphere, tends to suppress turbulence and to keep the flow laminar thereby reducing friction losses.

The 0.1 to 0.3 TW of wind energy extracted by presently installed turbines could already be having an unacceptable effect on climate. Confirmation that current level of wind energy extraction of 0.1 TW is affecting climate could indicate that the energy available to sustain prevailing winds is low and possibly in the order of 10 TW. The maximum mechanical energy that could be extracted with wind turbines could be as low as 1 TW. The wind energy that can be extracted without adverse climate effect could be even lower. The year 2000 start of arctic amplification, Cohen et al. (2015) Fig. 2, coincided with the start of significant wind turbine deployment of Fig. 1; installed wind turbine capacity in 2000 was only 0.02 TW. Wind turbines could have had a detectable effect on arctic climate at a deployment level of 0.02 TW. The current installed capacity of 0.5 TW could be causing significant climate changes. Fig. 4 could be an indication that amplified temperature anomalies are spreading to mid-latitudes.

Extracting kinetic energy from the wind does not necessarily increase wind energy production. In a horizontally uniform non-rotating atmosphere, there is no mechanism whereby the mechanical energy can be stored for later use such as for driving sustained horizontal wind. In a non-uniform rotating atmosphere, the elevation of a given pressure in the upper troposphere is higher in low than in high latitude. The potential energy of low latitude upper troposphere air can be a form of stored energy analogous to elevated water. This stored potential energy can later be used to overcome friction and to sustain prevailing wind. Coriolis force is the dam that prevents the work from degrading to heat right away. The high potential energy air cannot flow poleward and produce high latitude subsidence warming until Coriolis force has been reduced either in overcoming resistance to prevailing westerly wind or in powering wind turbines. Lowering 20 kPa air at constant pressure from 12 km in low latitude to 11.2 km in middle latitude would produce 8000 J/kg of air, see: Peixoto and Oort (1992) Fig. 7.10.

There is a wide spread in estimates of how much wind energy is produced and of the maximum quantity that could be extracted. Marvel et al. (2012) estimated that wind turbines at the earth's surface could extract kinetic energy at a rate of at least 400 TW, whereas high-altitude wind power could extract more than 1,800 TW. They concluded that, at the present level of primary power demand of 18 TW, wind turbines are unlikely to substantially affect the Earth's climate. Keith et al. (2004) estimated an upper limit of wind power at 800 TW. They simulated the effect of wind turbines on climate by increasing the drag coefficient in the lower troposphere in numerical models. Increasing drag coefficient is not equivalent to extracting kinetic energy with wind turbines. The effect of increasing drag coefficient may be similar to effect of high terrain or of stationary structures; wind velocity increases to get around obstacle and then returns to its original value. Energy extracted by wind turbines can not be recovered. Surface drag reduces the wind velocity in the bottom 10 to 50 m of the atmosphere; wind turbines could be reducing velocity in the bottom kilometer of the atmosphere.

Estimates of how much wind energy is actually produced or could be extracted by wind turbines vary widely. Miller et al. (2011a) estimated the upper limit on the mechanical wind energy that can be extracted from the atmosphere at 18 to 68 TW. Their lower limit is based on the fact that each additional wind turbines reduces wind; see also Gans et al. (2010). They warned that wind energy production has an upper limit and that wind energy extraction could affect climate. Miller et al. (2011b) pointed out that the mechanical energy required to sustain wind is low compared to the kinetic energy of the wind. The only energy that can be extracted with wind turbines is the energy that can be replaced which corresponds to the energy required to sustain the flow and not to the kinetic energy of the flow. Most studies of the effect of wind turbines on climate have focused on the local effect of wind turbines or on how much power they could produce. Keith et al. (2004) concluded that wind farm would have negligible effect on local temperature and that their effect on global climate is much smaller that the effect of producing the same power with fossil fuel.

6. Method

Thermodynamic case studies are widely used in engineering to study the effect of a wide range of process parameters on both energy and mass transfer. Michaud (2000) used rigorously defined thermodynamic systems to calculate the work produced during atmospheric rearrangement processes and showed how starting with a simple process and adding entities one at a time can help understand atmospheric energy production and dissipation. Michaud (2000) progressed systematically from pure air with a dry adiabatic lapse rate, to air with sub-adiabatic lapse rate, to non uniform lapse rate; from pure air to moist air; from closed discontinuous process to closed continuous process, from reversible to irreversible process; and from close to open systems. The thermodynamic method shows that the ideal work when heat is carried upward by convection is always roughly equal to the heat received multiplied the Carnot efficiency based on the average temperature at which heat is received and given up. The reversible process is the only one for which energy production can readily be calculated, Van Ness (1969). The mechanical energy produced in irreversible processes cannot be calculated because there are numerous ways in which ideal work can degrade.

This article extends the thermodynamic approach to the subsiding air process. An insulated closed system consisting of piston covered air column system can be used to show that the energy transferred to a column of subsiding pure air is equal to the difference between the static energy of the air entering the top of the column minus the static energy of the air leaving the bottom of the column. Fig. 4 of Michaud (2000) illustrates how work of compression can transfer energy upward and poleward.

Energy transformations are difficult to analyze with fluid mechanics models because ideal work can result in a wide variety of motions and because work readily degrades to heat. The thermodynamic method is powerful; conclusions can be based on analyzing hypothetical initial and final conditions - there is little need for actual measurements. The thermodynamic method can show that entrainment and detrainment do not change the basic subsidence warming process. The method of calculation is documented with examples in Michaud (2000 and 2004). Thermodynamic systems have rarely been used for atmospheric processes system because they have difficulty coping with: moist air; varying lapse rates; and open systems. Michaud (2012) showed how the thermodynamic approach can be used to calculate both hurricane intensity and hurricane sea to air heat transfer.

7. Discussion

No one seems to have anticipated that wind power could have significant climate effect at its current low production level. There could be a maximum wind energy production limit resulting from wind turbines reducing zonal wind and Coriolis force thereby facilitating upper troposphere poleward air flow and increasing subsidence warming particularly in high and middle latitudes. The global effect of wind farms could be much more serious than their local effect. A small reduction in westerly wind could be having a large effect on boreal temperatures.

The effect of wind turbines on climate needs to be studied by every available means. Greenhouse gasses produce global warming by increasing radiative forcing; wind turbines produce warming by removing an obstacle to the flow of heat from low to high latitudes. The heat stored in tropical oceans is sufficient to melt all polar ice making facilitating poleward heat flow more hazardous than carbon emissions. The response time of climate to wind turbines is much shorter than its response time to radiative forcing because radiative forcing takes decades to warm the oceans. The extra heat already stored in the oceans, Cheng et al. (2017), due to greenhouse gases aggravates the danger inherent in reducing Coriolis force with wind turbines. Anthropogenic greenhouse gasses have already increased ocean surface temperatures by 0.5 to 1 °C. Arctic warming is one of the most hazardous aspects of global warming because it could cause the melting of glaciers particularly of those in Greenland. The melting of glaciers would result in quick, irreversible and disastrous sea level rise.

Shutting down wind turbines could be an opportunity to carry out controlled experiments by manipulating a disturbance large enough to have significant effect on weather. Shutting down all wind turbines could have a noticeable reduction in global warming within a few months. The experiment is on going whether turbine deployment continues or whether wind turbines are shutdown.

Installed wind turbine capacity is currently increasing by 25 % per year and is doubling every three years. Doubling wind turbine capacity could double arctic temperature anomalies. New wind turbines are already reducing the output of existing ones. If wind turbines are the cause of the recent rapid global warming, the warming pace of the last few years is bound to continue because its cause is increasing exponentially. There would continue to be 0.1 to 0.2 °C/a increase in global mean surface temperature and the 2 °C limit of the Paris climate accord could be reached within 5 years. The wind turbine climate change hypothesis needs to be either *proved* or *refuted*. Should the hypothesis be correct replacing fossil fuel with wind turbines is not the remedy for global warming.

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