PROPERTIES AND STATISTICAL ANALYSIS OF THE WIND

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INTRODUCTION

Wind, along with renewable and non-renewable energy forms on Earth, has as its origin in the nuclear fusion reactions occurring in the sun which are converting its large hydrogen supply into helium. Tidal, fission and geothermal sources are exceptions.

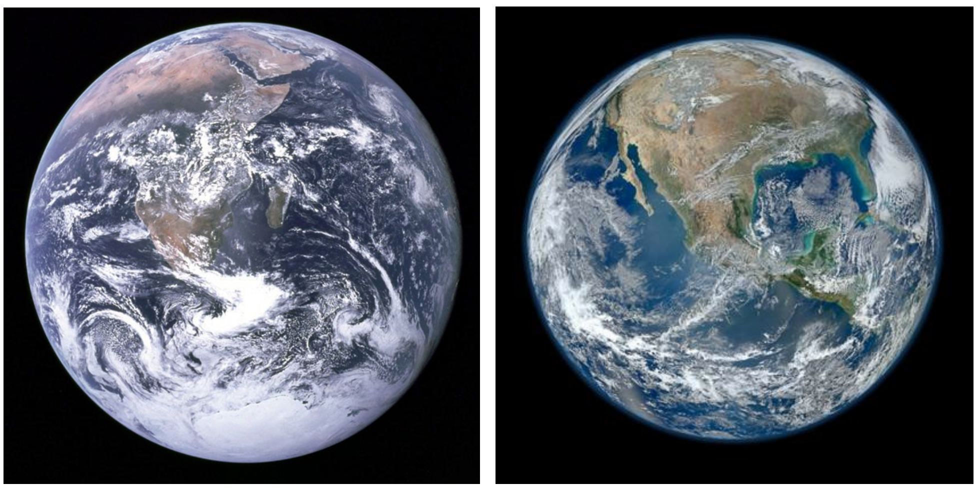


Figure 1. Earth weather systems and wind directions as viewed from space. Source: NOAA, NASA.

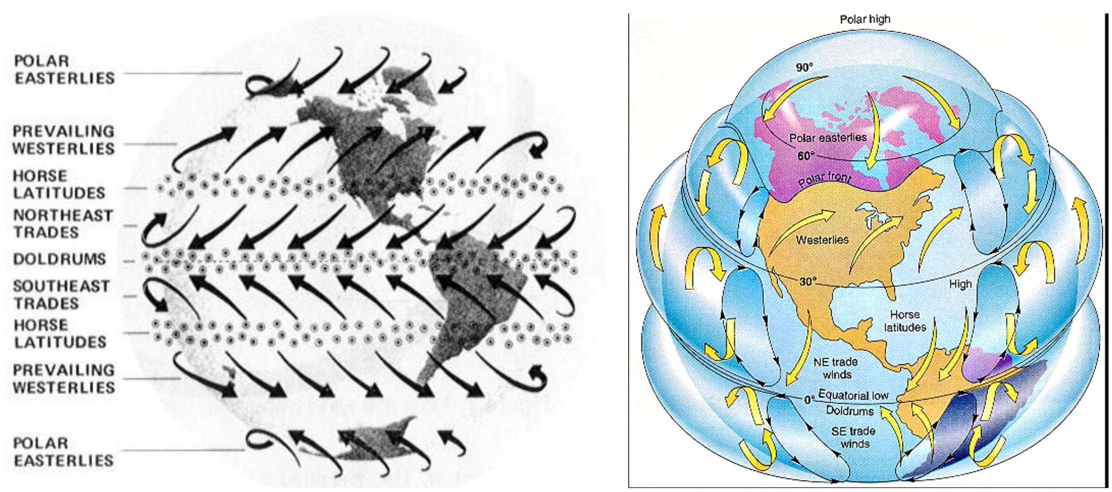


Figure 2. Earth wind directions created by uneven heating in the land and sea masses, geographical features and the Coriolis force.

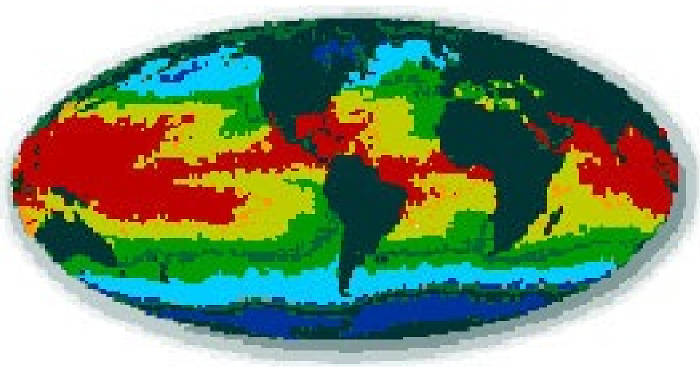


Figure 3. Temperature differences on the Earth's surface.

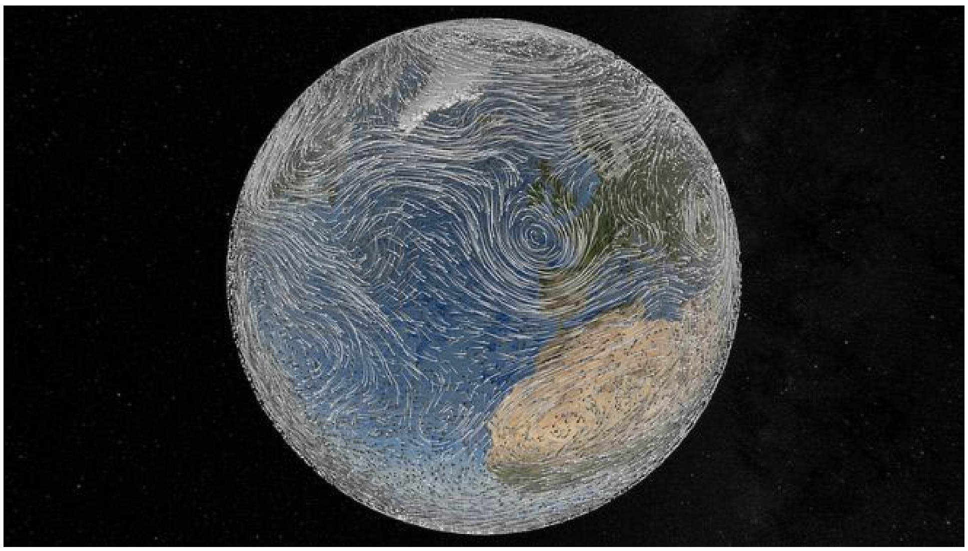


Figure 4. The Earth winds even-out the temperature distribution. Source: NASA/Goddard.

The air in the atmosphere cannot remain still and is continuously circulating on Earth because of the temperature and pressure variations on it. The resulting air current is what is designated as wind. The wind is characterized by its velocity which is a vector quantity that is described by its magnitude as speed and its direction.

The wind drives the waves in the oceans, and the rotation of the Earth cycles the atmosphere through its daily exposure to the radiant energy of the sun. The steady rotation of the Earth induces the swirling, in opposite directions in each Earth hemisphere, of the weather patterns leading to the Coriolis acceleration.

The rotating Earth's angular momentum is slowly degraded by the surface drag effects of these induced winds in addition the drag of the circulating ocean currents, and the tides that are primarily driven by it. As the Earth's rotational energy is expended, it rotates slightly slower by one leap second, and the mass of the moon is accelerated and it moves a few centimeters away from the Earth every year. The wind, tide and waves are expected to last for 500 million years, if the present theories of planetary and star formation are accurate.

The Earth's weather is much more energetic as a result of the rotating Earth compared with Venus, which although exposed to higher levels of solar radiation, has a daily rotation that is 166 times slower. It is though less energetic than on Mars which possesses high surface winds.

TERRESTIAL STILLING AND INCREASING WIND SPEED

A major reversal occurred in a trend of decreasing wind speeds over the last three decades, known as global terrestrial stilling, which threatened to halve the world's wind power potential by the end of the century. Previous studies have found that increased "roughness" on the Earth's surface, from new buildings and urbanization, has acted as a buffer by slowing wind speeds by up to 2.3 percent every decade since the late 1970s.

The latest research shows that large-scale ocean and atmospheric circulation patterns could be making wind speeds faster again. The main drivers of the world's quickening wind speeds were the Pacific decadal oscillation, the North Atlantic oscillation and the Tropical North Atlantic index.

Global climatic variation could lead to more renewable electricity being generated by spurring faster wind speeds for the world's growing number of windfarms. The world's shifting ocean circulation patterns may trigger an increase in wind speeds. A research team analyzed data from 9,000 international weather stations since the late 1970s and found that wind speeds had unexpectedly increased after a three-decade slowdown. Zhenzhong Zeng, a professor at Princeton University and the lead author of the report, said the research team was surprised by the findings after setting out to study the slowdown in global wind speeds.

The faster than expected wind speeds could help increase the amount of renewable electricity generated by windfarms by more than a third to 3.3m kilowatt hours (kWh) by 2024. Zeng said the unexpected acceleration is likely to have played a bigger role in improving the efficiency of windfarms in the USA than technological innovations. Adrian Chappell, a professor at Cardiff University said that the rapid increase in global wind speed bodes well for the expansion of renewable energy which will be central to keeping global heating to below 2 ºC.

The effect of global heating on the world's wind speeds remains largely uncertain because rising temperatures would have a diverse range of impacts that are not fully understood. The study of wind as a climate variable can shed light on the dynamic mechanisms of climate variation

EARTH'S WIND POWER

The sun radiates to the Earth energy in the electromagnetic spectrum including visible and infrared radiation at a power of 1.74×10^{17} Watts (W). This can be estimated as follows. The power flux or insolation from the sun on the spherical surface of the Earth at its average trajectory is:

$$p = 1.37 \frac{kW}{m^2}$$

This power flux impinges on a disc with an insolation area of:

$$A = 1.27 \times 10^{14} m^2$$

Multiplying the power flux p by the insolation area A yields the solar power available on Earth as:

$$\begin{aligned} P_{Solar} &= p.A \\ &= 1.37 \frac{kW}{m^2} \times 1.27 \times 10^{14} m^2 \times 10^3 \frac{W}{kW} \\ &= 1.7399 \times 10^{17} W \end{aligned} \tag{1}$$

This is a prodigious 1.74 x 10^{11} MegaWatts (MW) or 1.74 x 10^{8} GigaWatts (GW) of power.

Only a fraction of about 1 percent of this power is converted on Earth into wind power. Thus:

$$\begin{aligned} P_{Wind} &= 0.01 P_{Solar} \\ &= 10^{-2} \times 1.74 \times 10^{17} W \\ &= 1.74 \times 10^{15} W \end{aligned} \tag{2}$$

The floral or plant global Net Primary Production (NPP) in all the links of the food and energy chain is:

$$NPP = 4.95 \times 10^6 \frac{calories}{m^2.year}$$

The Earth's surface area is:

$$A_{Earth} = 5.09 \times 10^{14} m^2$$

The net power stored in floral or plant life becomes:

$$\begin{aligned} P_{Floral} &= NPP.A_{Earth} \\ &= 4.95 \times 10^6 \frac{calories}{m^2.year} 5.09 \times 10^{14} m^2 \times 4.186 \frac{Joule}{calorie} \frac{1}{3.1536x10^7} \frac{year}{\sec} \frac{Watt.\sec}{Joule} \\ &= 3.34 \times 10^{14} \ W \end{aligned} \tag{3}$$

where we used the conversion factor:

$$1 calorie = 4.186 Joules$$

The fraction of the solar energy impinging on Earth that is converted into stored floral energy is a very small value:

$$\begin{aligned} f &= \frac{P_{Floral}}{P_{Solar}} \\ &= \frac{3.34\times10^{14}}{1.74\times10^{17}} = 1.92\times10^{-3} = 0.00192 \\ &= 0.192\ percent. \end{aligned} \tag{4}$$

The ratio of wind power to floral power is:

$$\frac{P_{Wind}}{P_{Floral}} = \frac{1.74\times10^{15}}{3.34\times10^{14}} = 5.21 \tag{5}$$

Thus it can be concluded that wind power is about 5 times the energy converted into biomass through photosynthesis by all floral plants on Earth. This suggests that wind power conversion comes ahead of any biomass based processes.

WIND CIRCULATION

The temperature differences on the Earth's surface from the equator to the Polar Regions and from land to water masses, generates part of the wind circulation around it.

The equatorial regions receive more heat from the sun than the rest of the globe. The lower density of warm air causes it to rise in the troposphere, the part of the Earth's atmosphere where the weather phenomena are created. The warm air rises to about 10 kms or 6 miles in altitude and spreads from the equatorial region to the Northern and Southern latitudes.

Cold surface winds blow from the poles to the equator to replace the warm rising air.

The troposphere is just 11 km or 36,000 ft in altitude. The globe diameter is 12,000 km and its radius is 6,000 km, which makes the thickness of the atmosphere a small fraction of:

$$\delta_{atmosphere} = \frac{11}{6,000} = \frac{1}{545.45} = 1.83\times10^{-3}$$

or no more than 1/545 of the globe's radius.

To create an analogy, the atmosphere would be a thin 1 mm thick layer surrounding a ball of:

2 x 545.45 = 1,090.9 mm = 1.09 m,

or about 1 meter in diameter.

If the Earth did not rotate, the warm air would cool down at the Polar Regions then sink down and return back toward the equatorial latitudes. However, the Earth's rotation creates a unique pattern of air flow.

Figure 5. Earth's atmosphere thickness as seen from the International Space Station. Source: NASA.

THE CORIOLIS FORCE

As a result of the Earth's rotation, inertia leads to the deflection of the cold air near the surface to the west, while the warm air in the upper atmosphere is deflected to the east. This generates large counter clockwise circulation around the low pressure areas in the northern atmosphere and a clockwise circulation in the southern atmosphere.

Facing the North Pole, the Earth rotates from west to east. Thus any movement in the northern hemisphere is diverted from the west to the east and appears to be moving from left to right if observed from a fixed position on the Earth's surface. In the southern hemisphere, the opposite occurs. This apparent bending force is named after French mathematician Gustave Gaspard Coriolis (1792-1843) who first described it.

Rivers that flow in a north to south direction like the Nile in Africa and the Mississippi in North America are affected by the Coriolis Force causing them to drift from east to west leaving a flood plain on their east banks until they hit high cliffs or bluffs on their west banks. Railroad tracks for trains moving north to south are subject to more wear on one side than the other. The rotation of vortices in tornadoes, hurricanes and even water discharges in kitchen sinks and bathtubs are affected by the Coriolis force rotating in opposite directions in the upper and the lower Earth's hemispheres.

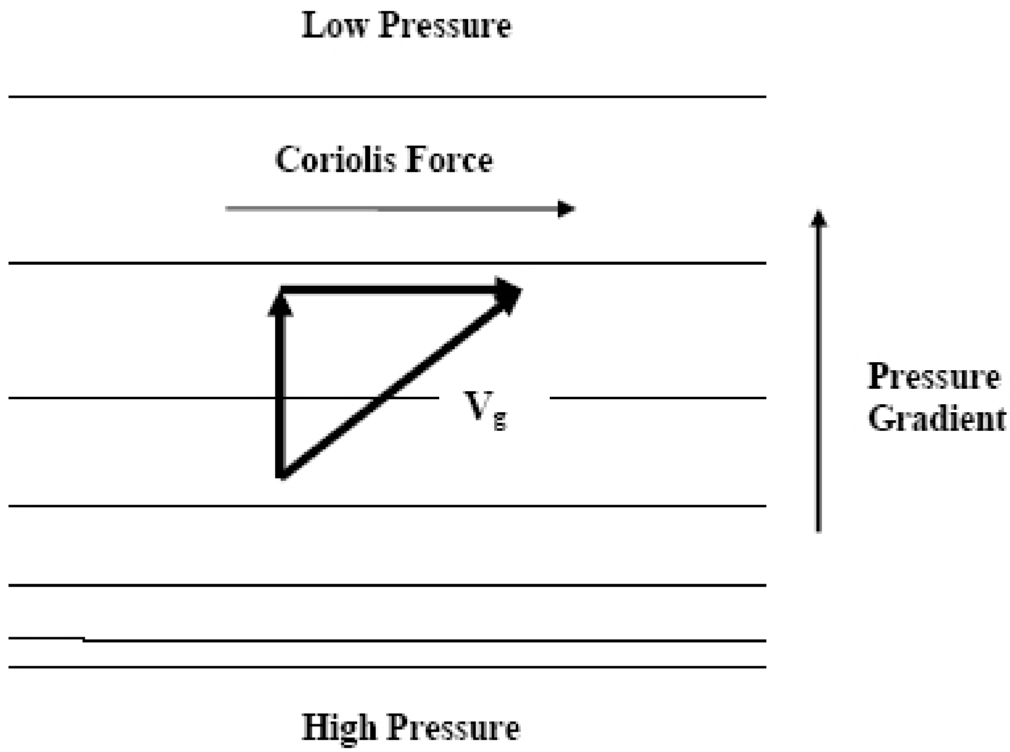


Figure 6. Formation of the Geostrophic wind.

GEOSTROPHIC WINDS

The global or Geostrophic winds are primarily driven by temperature differences, and consequently pressure differences. These winds are not much influenced by the surface of the Earth and they occur at altitudes above 1,000 meters or 3,300 ft above ground level. The Geostrophic wind speeds are measured with instruments usually carried on board weather balloons.

In each hemisphere one can discern 3 or more cells: a tropical cell, a temperate cell, and a polar cell. These cells rotate one against the other like the cogs in a gear box. The north and south tropical cells are separated from each other by the equatorial "doldrums," which is a low pressure area, and from the temperate cells by the subtropical high pressure belts at the "horse latitudes." These names were given to these areas by the ancient mariners who first observed them and used for navigation and trade.

In the Northern hemisphere the wind tends to rotate counterclockwise as seen from above as it approaches a low pressure area. In the Southern hemisphere the wind rotates clockwise around a low pressure area. This also occurs in hurricanes and cyclones.

Even more complicated, the uneven heating of the land masses and the oceans, surface features, and seasonal variations divide and deform the high and low pressure regions.

There exist also disturbances created by masses of cold air which move from time to time from the poles to the equator. The state of the Earth's atmosphere is continually evolving.

The wind circulation follows the general pattern:

1. At the poles cooling of the air generates a high pressure and the wind sinks down from the troposphere to the earth surface.
2. The warm low density wind rises from the equator and flows north and south in the troposphere.
3. At around 30 degrees in latitude in both atmospheres the Coriolis force prevents the air from proceeding farther. A high pressure area at this latitude causes the wind to sink to the Earth's surface.
4. As the wind rises from the equator a low pressure area causes the wind to flow close to the ground from the north and south.

The temperature differences and the Coriolis rotational force combine to create patterns of wind flow that were given different names by the ancient mariners such as the trade winds, the easterlies and the westerlies.

These wind patterns affect differently locations on Earth and must be accounted for in siting wind turbine generators. Local geography and existing obstacles will also affect the siting.

Wind is generally stronger over the oceans than on land, caused by the disparity in vegetation and relief that could impede the wind stream. This favors offshore locations and coastal areas for wind power production.

Table 1. Prevailing wind directions at different latitudes.

Prevailing wind direction	Latitude range, degrees
NE	90-60 N
SW	60-30 N
NE	30-00 N
SE	00-30 S
NW	30-60 S
SE	60-90 S

SURFACE WINDS

Winds are affected by the Earth's boundary layer at the ground surface to an altitude of about 100 meters. The Earth's surface roughness and obstacles will affect the wind speed and direction. Wind directions near the surface could be different from the direction of the Geostrophic wind because of the Earth's rotation and the Coriolis force.

When considering wind energy, we are really dealing with the surface winds and their usable energy content.

The horizontal component of surface wind direction and speed are continuously varying. Within a short period of time or the order of one second, the wind velocity may double, and the direction may be considerably modified, particularly during wind gusts, posing a significant challenge in the design of the drive trains and gearboxes or transmissions of wind machines.

Following the passage of a fast cold front the wind velocity was observed to have changed from 23 to 37 m/s, by a factor of 37/23 = 1.6, within ¼ of a second.

The vertical wind variations are only 1/10 – 1/5 of the variations in the horizontal directions. Thus the horizontal variations merit a special consideration.

WIND GUSTS

The rapid speed and direction variation suggests that the horizontal component of the surface wind is in fact a superposition of a uniform stream component and a rotating whirlwind or vortex component.

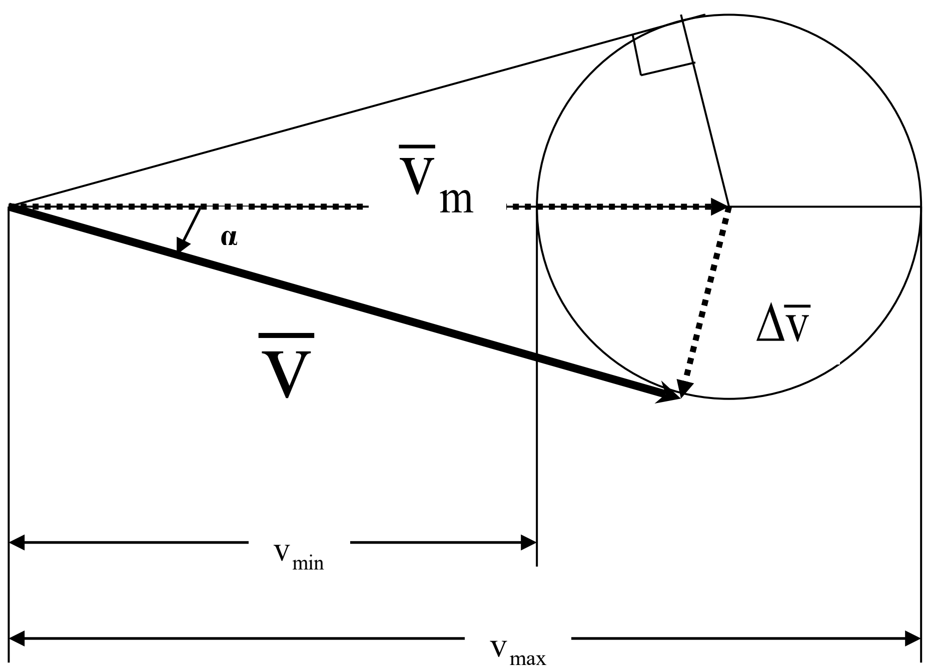


Figure 7. The resultant of uniform wind stream and a whirlwind vary between a minimum speed v_{min} and a maximum speed v_{max}.

If we consider a uniform stream with a speed $\bar{v}_m$ that carries a whirlwind whose tangential speed is $\Delta\bar{v}$, it results in an oscillatory velocity given by:

$$\bar{v} = \bar{v}_m + \Delta\bar{v} \qquad (6)$$

When the directions of the uniform stream and the whirlwind are the same, the resultant speed is at a maximum and is given by:

$$v_{max} = v_m + \Delta v \qquad (7)$$

When the direction of the whirlwind is opposite that of the uniform stream, the resultant velocity is at a minimum and is given by:

$$v_{min} = v_m - \Delta v \qquad (8)$$

Summing then subtracting the last two equations we get:

$$v_m = \frac{(v_{max} + v_{min})}{2}$$
$$\Delta v = \frac{(v_{max} - v_{min})}{2} \qquad (9)$$

The magnitude of the direction of oscillation is expressed in terms of the sine of the angle α between the stream velocity and the instantaneous wind speed:

$$\sin\alpha = \frac{\Delta v}{v_m} \qquad (10)$$

and:

$$\alpha = \sin^{-1}\left(\frac{\Delta v}{v_m}\right) \qquad (11)$$

During wind gusts, the wind turbines would be subjected within a short period of time of 6 - 32 seconds to significant changes in the wind direction as well as significantly different maximum and minimum wind speeds, and must be designed and operated accordingly.

Table 2. Changes in direction resulting from gust wind maximum and minimum speeds.

Observed v_{max} [m/s]	Observed v_{min} [m/s]	v_m [m/s]	Δv [m/s]	sin α	α [degrees]
53.0	39.0	46.00	7.00	0.152174	± 8.75
36.5	16.7	26.60	9.90	0.372180	± 21.85
20.5	11.0	15.75	4.75	0.301587	± 17.55

LOCAL WINDS

Even though the global winds are taken into consideration in assessing the prevailing wind direction in a given location, the local climatic conditions yield a significant influence on the local wind directions useful for wind power generation.

The global and local wind effects add up to a vector sum of both. If the global winds are weak, the local wind patterns predominate and become the main influence on the siting of wind generation systems. We here consider some of the local winds patterns.

SEA AND LAND BREEZES

Land masses adjacent to large bodies of water such as lakes or seas are heated unevenly by the sun's radiation. Land masses are heated more rapidly during day time.

The specific heat of the water is larger than that of soil, causing the air temperature to rise more rapidly during the day over the continents than on the lakes and oceans. The hotter air expands, its density decreases, and it rises as the cooler air from the sea blows in to replace it. The corresponding flow is designated as the "sea breeze."

At sunset, a temporary period of calm occurs when the temperature of the land mass and the water body are equalized.

As night falls, the land mass loses its temperature faster than the water which has a higher heat capacity and keeps the thermal energy longer. As a result the wind reverses direction and blows from the land to the water body as a "land breeze."

Land and sea breezes can extend up to 50 km from the shore lines in the medium latitudes. It can expand to 250 km inland in the tropics.

This affects the operation of wind turbines in that they have to reverse direction and use a yaw mechanism to rotate and face the prevailing sea or land breeze from day to night.

The land breeze has a lower magnitude than the sea breeze because the temperature difference between land and water is smaller at night than during the day.

The famous Monsoon winds in South East Asia are in fact a large-scale form of the sea and land breezes. Instead of a variation between day and night, the variation is between seasons caused by the faster heating and cooling of land masses compared with the ocean. The word Monsoon originates from the Arabic word "mawsem," meaning season. It refers to the season when the winds shift and cause thunderstorms.

MOUNTAIN WINDS

Winds patterns arising in the mountainous regions are interesting in nature. In the morning, the summit heats up ahead of the valley. The valley wind rises on a south facing mountain slope in the northern hemisphere. The slope and the surrounding air absorb solar energy with a temperature increase and a decrease in density. The low density air rises to the top of the mountain following the slope. At night the direction reverses and turns into a down-slope wind.

If a valley exists between two mountain slopes a canyon wind results, which may move up or down the valley.

Wind flowing down the leeward of mountains can be quite powerful. Examples of these winds are known as:

1. The Chinook winds in the Rocky Mountains in North America.
2. The Foehn wind in the Alps in Europe.
3. The Zonda wind in the Andes Mountains in South America,
4. The Santa Ana winds in Southern California.
5. The Diablo winds in Northern California.

Other known local wind systems are:

1. The Scirocco a southerly wind flowing from the Sahara desert into the Mediterranean Sea.
2. The Khammassin (In Arabic: The Fifties) wind blowing into Egypt and the Middle East during the spring over a period of fifty day, hence its name. It conveys hot desert air and dust storms obscuring the sky and causing breathing lung difficulties.
3. The Mistral wind blowing down the Rhône valley in France to the Mediterranean Sea.
4. The Etesian winds, famous since antiquity in the Mediterranean area.



Figure 8. Seasonal Khammassin (fifties) wind carrying dust from the Sahara Desert obscures the sky over the Nile River, Cairo, Egypt, January 2019 (top), November 2021 (bottom).

GREEK MYTHOLOGY WINDS

In Greek mythology the Titans Astraeus (Starry) and the Eos (Dawn) were the parents of the four wind gods collectively called Anemoi, but each was ascribed a compass direction from which their respective winds come. Aeolus: was the keeper of the winds on the island of Aeolia, where Odysseus met him:

Boreas: is the cold north wind and the bringer of winter. He has a violent temper.
Zephyrus: is the west wind and the gentlest of them all.
Notus: is the south wind, bringer of storms and destroyer of crops.
Eurus: is the east wind, bringing gentle rain.

SANTA ANA WINDS

The Santa Ana Winds are often mentioned in works of fiction, and are described as being responsible for a tense, uneasy wrathful mood among Angelenos (residents of Los Angeles, California, USA). According to Raymond Chandler in “Red Wind”:

> “There was a desert wind blowing that night. It was one of those hot dry Santa Anas that come down through the mountain passes and curl your hair and make your nerves jump and your skin itches.”

The Santa Ana winds are very dry downslope winds that originate inland over the dry desert areas of Southern California. These north-easterly winds encounter the Transverse Ranges that separate coastal Southern California from the deserts. As the dry air is funneled through the mountain passes and the canyons, its speed increases through the wind tunnel effect making them ideal for wind power generation. As the air descends, its pressure increases causing it to be heated, making the air even drier. This causes strong and very dry winds infamously famous for causing regional wild fires.

The phenomenon typically peaks in October but can occur anytime from late to early spring. The wind speed can be magnified as air tries to squeeze over mountain passes and rush downhill through the canyons that are aligned in a northeast to southwest direction. As the air descends in elevation, it becomes compressed and heats up and dries out even more.

Moderate Santa Ana winds can often break tree limbs, send unsecured debris flying into windows, raise clouds of dust and cause wildfires to ignite and spread rapidly. In addition to a heightened risk of wildfires, whole trees and high-profile vehicles can be knocked over, and sporadic power outages are likely in more extreme cases.

When winds aloft become aligned from the same direction as that of the winds near the surface, the strongest gusts occur. Sometimes wind gusts can reach the force of a hurricane at 74 mph or greater. Gusts during this particular setup can lead to extensive property damage and widespread power outages. Most Santa Ana events peak for a 12- to 24-hour period, then the winds ease. On rare occasions, strong winds can persist for a few days. While a wildfire can break out in absence of a Santa Ana wind, it is during these long-lasting events, that multiple and extensive wildfires can result.

DIABLO WIND

Just as Southern California has its notorious Santa Ana winds that fan wildfire flames, Northern California's winds are known as Diablo winds. Diablo winds appear around the San Francisco Bay region and are produced by the same mechanism that produces a Santa Ana wind. These winds are magnified by terrain effects similar to Santa Ana winds. These flow from east to west up and over the Diablo Range over the East Bay region of the San Francisco Bay area.

They fan catastrophic Northern California wild fires and are most common during the winter, spring and fall but can occur during the late summer as well. Surface pressure in the Great Basin builds much higher than the surface pressure in the San Francisco Bay area. This pressure difference causes the strong easterly down-sloping winds into the Sacramento Valley and up and over the Diablo range. Diablo, a Spanish word which translates to "devil" in English, is also the name of a mountain in Contra Costa County, which is where these winds originate. Mount Diablo is an actual mountain peak with an elevation of 3,848 feet. This mountain is notorious for strong winds. Typically, when the winds are flowing from east to west out of the Sierra Nevada Mountains to the east, they sink as they move into the lower elevation areas of the Sacramento Valley then move up and over the Diablo range. The winds, which are capable of reaching hurricane force, almost always bring a great surge in temperature and plenty of dry air. The winds increase as the air is forced up over the Diablo Range and can reach winds gusts over 80 mph. While this wind pattern occurs in both the spring and fall, it is most dangerous in the fall, when vegetation is at its driest. During these Diablo wind events, there can be wind damage leading to power outages. When the vegetation is very dry, this leads to an increased fire danger.

FOEHN WIND

People in the Alps Mountains in Europe have attributed health issues, headaches in particular, to the mountain wind known as the Foehn. They might be more sensitive to variability in barometric pressure when they are under stress [5].

It is a very strong wind that can blow at speeds of 150 km / hour, and is also a very warm wind. In the middle of winter temperatures of 20 °C can be recorded in the Foehn valleys. That warm dry wind roaring down from the mountain glaciers occurs when moist air builds up on the southern side of the Alps. As soon as it reaches the Alpine divide the air descends, and while descending, the air warms, it gets drier and speeds up generating a down-slope wind storm, or a lee warm-air flow.

When the dry warm Foehn wind blows, it sucks all the moisture out of the air, meaning the visibility is clear. On a Foehn day the Eiger Mountain peak at 60 km from Berne, the Swiss capital, looks close to the viewer [5].

THE KHAMMASSIN, FIFTIES WINDS

The Khammassin, Fifties is a seasonal oppressive, hot, dry and dusty south or south-east wind occurring in North Africa, around the Eastern Mediterranean and the Arabian Peninsula. It blows intermittently in late winter and early summer, but most frequently between April and June. As a counterpart of the Scirocco wind, it is a southerly wind over Egypt blowing from the Sahara Desert and an easterly over the Negev Desert and parts of Saudi Arabia. The name is also applied to very strong southerly or south-westerly winds over the Red Sea.

Saladin or the Sultan Salah Al Din Al Ayoubi (The Jacobian), well-cognizant of the local climatological conditions, took advantage of a Khammassin wind episode to defeat a heavily battle-armored crusaders army at the Batlle of Hittin by defending the water wells with infantry and light cavalry, and setting the plains grasses on fire.

Like the Scirocco wind, the Khammassin wind usually blows ahead of depressions which move eastward or north-eastward in the Mediterranean Sea or across North Africa, with high pressure to the east.

In other parts of North Africa and the Mediterranean similar winds are variously named as Kibly, Scirocco and Leveche.

THE MEDITERRANEAN ETESIAN WINDS

The Etesian winds, known since antiquity, generate constant strong winds all summer in the Mediterranean region. They are seasonal winds of the Monsoon type associated with the western sector of a summer depression centered around Iraq, South Asia and West India, and a high pressure region over the Balkans and Central Europe. The Azores anticyclone then extends tongues of high pressure over Soutern Europe up to the Balkan Peninsula.

The Etesian winds primarily blow during the July and August months, and are less frequent in May, June, September and October. Even in the winter months, low pressures over Cyprus and the Middle East associated with high pressures over the Balkans cause wind spells almost identical to the summer Etesians [2].

During the Mediterranean summer, a large pressure gradient occurs in the South Aegean, the Dodecanese and East Crete. The inland area of mainland Greece and the Ionian coastal area are poorer in wind resources. The Etesian winds blow from the North-East in the North Aegean, backing to Northerly and North-Easterly as the flow continues to South Greece, the East Mediterranean and the coasts of Egypt at constant and significant speed.

The Etesian winds contributed to the rise of civilization in Ancient Egypt and the Middle East. Travel down-river was facilitated by the Nile's current. The Etesian winds blew from the north and carried sailboats up the river. Egyptian traders with goods of their own and goods from the African region of Cush, further south in The Sudan, Ethiopia and Somalia, could travel out into the Mediterranean, down the Red Sea, and along overland routes up the Fertile Crescent.

The gradient is not sometimes strong enough, leading to long spells without the Etesians. However, local sea breezes can maintain the operation of wind turbines built over coastal hills in locations where the sea breeze and the pressure gradient coincide in direction.

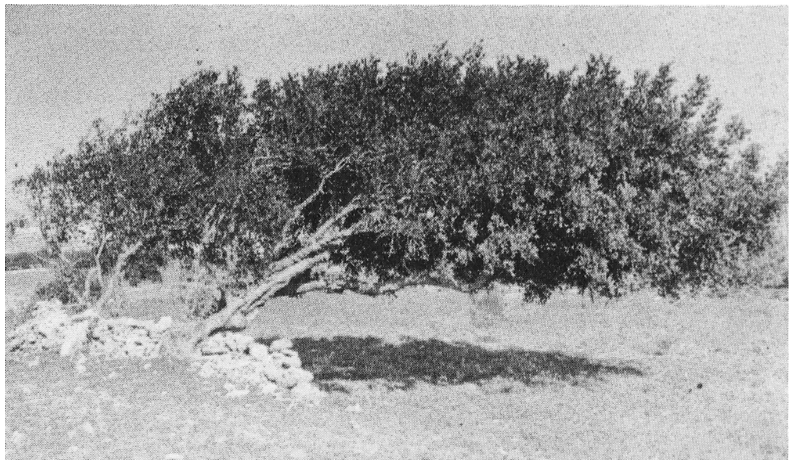


Figure 9. Effect of prevailing local Etesian North westerly winds on the Ceratonia Siliqua tree at the north coastal area of the island of Crete, Mediterranean Sea [3].

Figure 10. Effect of local wind on trees at the Hawaiian islands.

The Etesian winds do not blow continually, but in periods of 3-5 days with an intensity of 6-8 maximum and 2-4 minimum on the Beaufort wind scale, sometimes interrupted by a complete calm. They blow during the years with variable frequency. In a period of a few years there are situations in which during the whole summer the Etesian winds blow very little or disappear. In the year 1955, for instance, the Etesian wind practically disappeared.

Ancient Greek philosophers noted the remarkable variability of the Etesians from year to year. Theophrastus reported that: "Etesians sometimes blow strong and continuous and sometimes weak and intermittent."

An important observation is that in the years of maximum solar sunspots activity, the numbers of days of Etesians are always higher, and in the years of minimum, they are lower than their average. The positive correlation coefficient between the sunspots number and total days of Etesians recorded in a year is 0.71 [4].

HYPOTHESIZED EXPLANATION OF CORRELATION BETWEEN SUNSPOTS AND WIND ACTIVITIES

The observed positive 0.71 correlation between solar sunspots activity and wind activity on Earth is interesting in that sunspots are associated with a stronger solar magnetic activity.

We here suggest an explanation that needs detailed investigation. A stronger solar magnetic field associated with sunspots activity would shield the whole solar system, including the Earth, from incoming galactic cosmic rays. A lower flux of galactic cosmic rays in the Earth's atmosphere means lower nucleation sites for cloud formation. A lower incidence of cloud formation reduces the reflection of solar radiation and hence leads to a higher level of warming of the Earth's atmosphere, hence stronger wind flows.

The opposite would also be true: a lower level of sunspots activity, implies a weaker solar magnetic field, a higher flux of galactic cosmic rays impinging on the Earth, more cloud formation and rainfall and snowfall events leading to flooding, more solar energy reflection by the clouds, climate cooling, and lower winds activity.

Figure 11. Highest recorded wind speed in the USA at Mount Washington Observatory in the state of New Hampshire.

BEAUFORT WIND SPEED SCALE

Admiral Sir Francis Beaufort introduced an international scale that divides the wind speeds into 18 strength categories from 0-17.

The Beaufort scale gives land and sea conditions as they correspond to different wind speeds. It is useful for estimating instantaneous, and not average wind speeds.

The average wind pressure in Newtons per square meter on a flat plate perpendicular to the wind at a speed v [m/s] can be calculated from the relationship:

$$p = 0.13\text{v}^2[\frac{N}{m^2}] \qquad (6)$$

In tropical hurricanes, wind speeds of up to 220 km/hr are not exceptional, as well as around 45 degrees of latitude south, known as the roaring forties. The highest recorded wind speed occurred on April 12th, 1934 at Mount Washington at New Hampshire, USA, and reached an average speed of 338 km/hr over a 5 minutes period.

Table 3. Beaufort wind speed scale.

Beaufort scale number	Wind speed			Description	Wave height [m]	Pressure on a flat plate [daN/m^2]
	[m/s]	[km/hr]	knots			
0	0.0-0.4	< 1	1.0	Calm	-	-
1	0.5-1.5	1-6	1-3	Light air	-	0.13 (1.0 m/s)
2	2.0-3.0	7-11	4-5	Light breeze	0.15-0.30	0.8 (2.5 m/s)
3	3.5-5.0	12-19	7-10	Gentle breeze	0.6-1.0	3.2 (5 m/s)
4	5.5-8.0	20-28	11-16	Moderate breeze	1.0-1.5	6.4 (7 m/s)
5	8.1-10.9	29-38	17-21	Fresh Breeze	1.8-2.5	13 (10 m/s)
6	11.4-13.9	39-49	22-27	Strong breeze	3.0-4.0	22 (13 m/s)
7	14.1-16.9	50-61	28-33	Near gale	4.0-6.0	33 (16 m/s)
8	17.4-20.4	62-74	34-40	Gale	5.5-7.5	52 (20 m/s)
9	20.5-23.9	75-88	41-47	Strong gale	7.0-9.75	69 (23 m/s)
10	24.4-28.0	89-102	48-55	Storm	9.0-12.5	95 (27 m/s)
11	28.4-32.5	103-117	56-63	Violent storm	11.3-16.0	117 (30 m/s)
12	32.6-35.9	118-133	64-71	Hurricane	13.70	160 (35 m/s)
13	36.9-40.4	134-149	72-80	-	-	208 (40 m/s)
14	40.1-45.4	150-166	81-89	-	-	265 (45 m/s)
15	45.1-50	167-183	90-99	-	-	325 (50 m/s)
16	50.1-54	184-201	100-108	-	-	365 (54 m/s)
17	54.1-60	202-220	109-118	-	-	470 (60 m/s)

For different Beaufort numbers, a correlation exists between sea and land observations.

Table 4. Beaufort scale phenomena at land and sea, and effects on wind turbines.

Beaufort Scale Number	Land observations	Sea observations	Wind Turbine Effects
0	Smoke rises vertically	Sea exhibits a mirrored surface.	-
1	Wind inclines smoke. Weather vane does not rotate.	Ripples with the appearance of scales. No crests formation.	-
2	Tree leaves quiver. Wind can be felt blowing on face.	Small wavelets; short but pronounced. Crests have glassy appearance and do not break.	-
3	Leaves and little branches move gently	Large wavelets. Crests begin to break. Foam has glassy appearance. Possibly scattered with white horses.	Small size turbines start.
4	Wind blows dust and leaves on roads. Branches move.	Small waves becoming larger. Frequent white horses.	Start up of electrical generation.
5	Little trees sway in the wind.	Moderate waves taking a pronounced long form. Many white horses formed. Possible spray.	Useful power generation at 1/3 of capacity.
6	Big branches move. Electrical wires vibrate. Using an umbrella becomes difficult.	Large waves forming. White foam crests are more extensive. Probable spray.	Rated power range.
7	Trees sway. Walking against the wind unpleasant.	Sea leaps up. White foam from breaking waves blown in streaks along the wind direction.	Full capacity.
8	Little branches break. Walking outside becomes difficult.	Moderate high waves of greater length. Edges of crests break into spindrift. Foam is blown in well-marked streaks along wind direction.	Shut down initiated.
9	Tree branches break.	High waves.	All wind machines shut

		Dense streaks of foam along wind direction. Crests of waves topple, tumble and roll over. Spray may affect visibility.	down.
10	Trees uprooted. Roofs damaged.	Very high waves with long overhanging crests. Resulting foam in large patches blown in den se white streaks along wind direction. Surface of sea takes a white appearance. Tumbling of sea becomes heavy and shocklike. Visibility affected.	Design criterion against damage
11	Extensive destruction. Roofs torn off. Houses destroyed.	Exceptionally large waves. Small and medium ships temporarily lost from view behind the waves. Sea is completely covered long white patches of foam along wind direction. Edges of wave crests are blown into froth everywhere. Decreased visibility.	-
12	-	Air is filled with foam and spray. Sea is completely white with driving spray. Visibility seriously reduced.	Serious damage.

GRIGGS-PUTMAN WIND INDEX

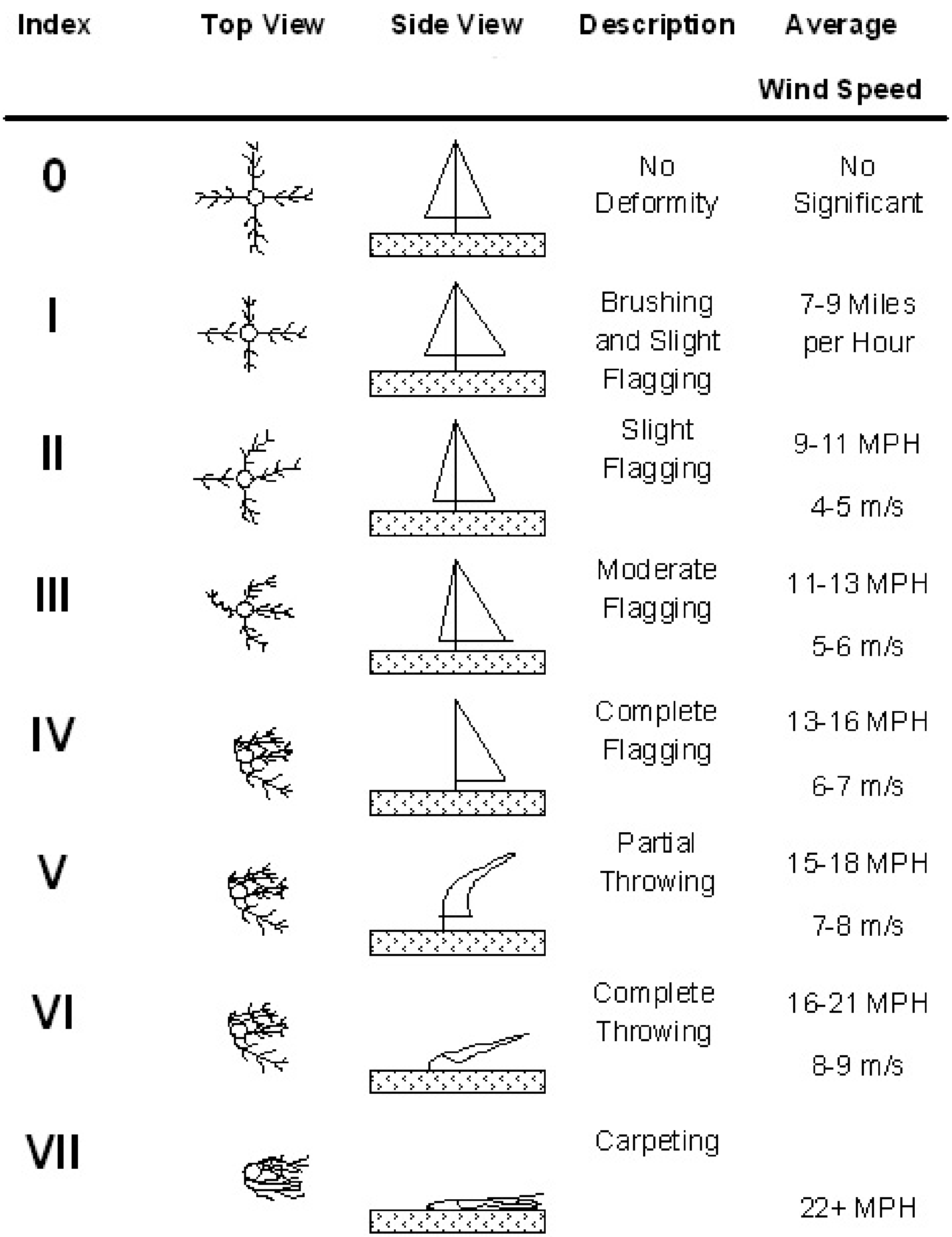
The Griggs-Putman wind index is based on the permanent tree deformation caused by wind, and is useful for estimating the average wind speed in an area.

It is scaled for use with true fir trees or Abies in the Northeastern USA, but it is also relatively accurate for Douglas Fir and Ponderosa Pine.

It will not work for any conifer, since some trees are inherently stiffer than others. To use the scale, one should survey a set of at least 5 trees in open terrain.

The scale does not work for trees in a forest or protected by other geography or structures. We should look at the degree of flagging or deformation that is visible over at least 50 percent of the tree's height. The chart is used to find the approximate average wind speed, based on tree deformation.

Table 5. Griggs-Putman Wind Index of Trees Deformity.



WIND SPEED VARIATION: THE WEIBULL PROBABILITY DENSITY FUNCTION

In optimizing the design of wind generators and minimizing the generating cost, it is important to assess the distribution of wind speeds. The economic analysis also needs such information to estimate the income stream from alternative investments.

If wind speeds are measured over a year period at a given location, it can be observed that in most cases strong gale force winds occur with a small probability. Moderate wind speeds occur with a higher probability. The variation in wind speed at a given site is usually described in terms of the Weibull probability density function. In the distribution shown Fig. 11, the most probable wind speed occurs at the peak of the curve and is 7 m/s.

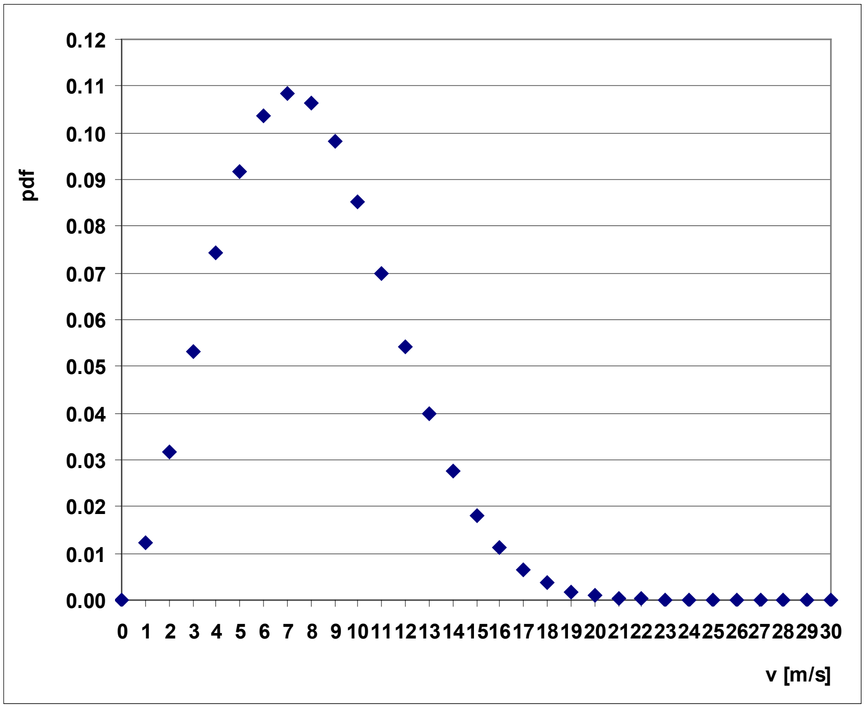


Figure 12. Discrete probability density function (pdf) representation of the Weibull distribution of wind speeds with 1 m/s speed bins. Most probable speed is at 7 m/s.

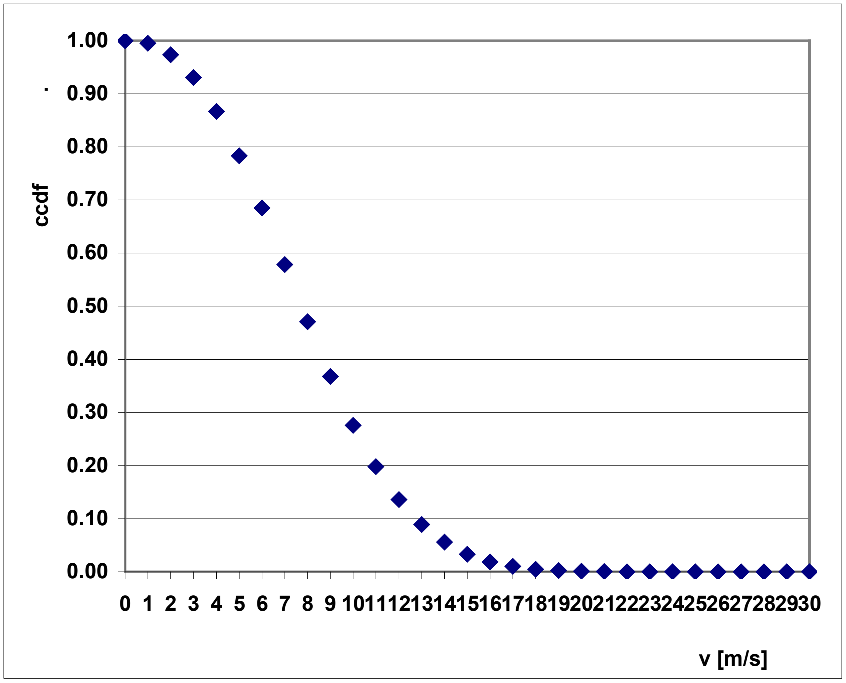


Figure 13. Weibull discrete complementary cumulative distribution function (ccdf). Expresses the probability that the wind speed exceeds or is equal to a given value on the x axis.

The probability density function (pdf) of the two parameter Weibull distribution is:

$$W(v) = \frac{k}{C}\left(\frac{v}{C}\right)^{k-1} e^{-\left(\frac{v}{C}\right)^{k}}$$

$$\begin{aligned} where: \ & k = shape\ parameter\ or\ slope \\ & C = scale\ parameter\ or\ charactreristic\ wind\ speed \end{aligned} \tag{6}$$

The area under the curve is normalized to unity, since the probability that the wind will be blowing at some wind speed including zero must be unity or 100 percent.

The value at the 50 percent probability is 8 m/s and is called the median of the distribution. This means that half the time the wind will be blowing at less than 8 m/s, the other half it will be blowing faster than 8 m/s.

Table 6. Probability density function (pdf), cumulative distribution function (cdf), complementary cumulative distribution function (ccdf) of wind speeds and data used in the estimation of the Weibull parameters k and C.

Wind Speed v [m/s]	pdf	cdf	ccdf	-ln(ccdf)	ln(-ln(ccdf))	ln(v)

0.000	0.000	0.000	1.000			
1.000	0.012	0.005	0.995	0.000	-0.005	-5.273
2.000	0.032	0.027	0.973	0.693	-0.027	-3.610
3.000	0.053	0.069	0.931	1.099	-0.072	-2.637
4.000	0.074	0.133	0.867	1.386	-0.143	-1.946
5.000	0.092	0.216	0.784	1.609	-0.244	-1.411
6.000	0.104	0.315	0.685	1.792	-0.378	-0.973
7.000	0.109	0.421	0.579	1.946	-0.547	-0.603
8.000	0.106	0.529	0.471	2.079	-0.754	-0.283
9.000	0.098	0.632	0.368	2.197	-1.000	0.000
10.000	0.085	0.724	0.276	2.303	-1.288	0.253
11.000	0.070	0.802	0.198	2.398	-1.619	0.482
12.000	0.054	0.864	0.136	2.485	-1.995	0.690
13.000	0.040	0.911	0.089	2.565	-2.417	0.883
14.000	0.028	0.944	0.056	2.639	-2.888	1.060
15.000	0.018	0.967	0.033	2.708	-3.408	1.226
16.000	0.011	0.981	0.019	2.773	-3.978	1.381
17.000	0.007	0.990	0.010	2.833	-4.601	1.526
18.000	0.004	0.995	0.005	2.890	-5.278	1.664
19.000	0.002	0.998	0.002	2.944	-6.009	1.793
20.000	0.001	0.999	0.001	2.996	-6.797	1.916
21.000	0.000	1.000	0.000	3.045	-7.641	2.034
22.000	0.000	1.000	0.000	3.091	-8.543	2.145
23.000	0.000	1.000	0.000	3.135	-9.505	2.252
24.000	0.000	1.000	0.000	3.178	-10.527	2.354
25.000	0.000	1.000	0.000	3.219	-11.611	2.452
26.000	0.000	1.000	0.000	3.258	-12.757	2.546
27.000	0.000	1.000	0.000	3.296	-13.967	2.637
28.000	0.000	1.000	0.000	3.332	-15.240	2.724
29.000	0.000	1.000	0.000	3.367	-16.580	2.808
30.000	0.000	1.000	0.000	3.401	-17.985	2.890

The mean wind speed is different from the median wind speed. It is actually the average of the wind speed observations at a given site. The mean wind speed can be estimated from the Weibull pdf as:

$$\begin{aligned}\overline{v} &= \int_0^\infty v.W(v)dv, \forall v \neq 0 \\ &= \frac{k}{C}\int_0^\infty v\left(\frac{v}{C}\right)^{k-1} e^{-\left(\frac{v}{C}\right)^k} dv \qquad (7) \\ &= k\int_0^\infty \left(\frac{v}{C}\right)^k e^{-\left(\frac{v}{C}\right)^k} dv\end{aligned}$$

The distribution of wind speeds is skewed and is not symmetrical. Sometimes very high wind speeds will be observed, but their occurrence is very rare.

Wind speeds of 7 m/s occur at the peak of the distribution as the most probable value. The most probable speed is also called the "modal value" of the distribution.

The statistical distribution of wind speeds varies from place to place around the globe, depending upon local climate conditions, the landscape, and the surface characteristics. The Weibull distribution may thus vary both in its shape and in its mean speed value.

The cumulative Weibull distribution function gives the probability of the wind speed not exceeding, that is being less or equal to the value x, is:

$$\begin{aligned} cdf &= \int_0^v W(v)dv \\ &= \int_o^v \frac{k}{C}\left(\frac{v}{C}\right)^{k-1} e^{-\left(\frac{v}{C}\right)^k} dv \\ &= 1 - e^{-\left(\frac{v}{C}\right)^k} \end{aligned} \tag{8}$$

The complementary cumulative distribution function gives the probability of the wind speed exceeding or being equal to the value x; and is:

$$\begin{aligned} ccdf &= 1 - cdf \\ &= 1 - \int_0^v W(v)dv \\ &= 1 - \int_o^v \frac{k}{v}\left(\frac{v}{C}\right)^{k-1} e^{-\left(\frac{v}{C}\right)^k} dv \\ &= e^{-\left(\frac{v}{C}\right)^k} \end{aligned} \tag{9}$$

The probability of the occurrence of a wind speed between v_1 and v_2 is then given by:

$$P(v_1 < v < v_2) = e^{-\left(\frac{v_2}{C}\right)^k} - e^{-\left(\frac{v_1}{C}\right)^k} \tag{10}$$

DETERMINATION OF THE WEIBULL PARAMETERS

To determine the parameters C and k, we take the natural logarithm of the ccdf as:

$$\ln ccdf = \ln e^{-\left(\frac{v}{C}\right)^k}$$
$$= -\left(\frac{v}{C}\right)^k$$

We take again the natural logarithm of the negative of the natural logarithm of the ccdf as:

$$\begin{aligned} \ln(-\ln ccdf) &= \ln\left(\frac{v}{C}\right)^k \\ &= k\ln\left(\frac{v}{C}\right) \\ &= k\ln v - k\ln C \end{aligned} \tag{11}$$

This has the form of a straight line:

$$y = mx + a$$

If we plot the left hand side of Eq. 11 as the y axis against ln v as the x axis, we obtain a straight line of slope m = k. The intersection of the line with the x axis occurs at y = 0, giving the value of C as:

$$\begin{aligned} &k\ln v = k\ln C \\ &\ln C = \ln v, \forall k \neq 0 \\ &C = e^{\ln C} = e^{\ln v} = v \end{aligned} \tag{12}$$

Thus by plotting ln(-ln ccdf) as the y axis against ln v as the x axis, we obtain points that can be fitted to a line of slope k, and C can determined from Eqn. 12 from the intersection of the line with the x axis.

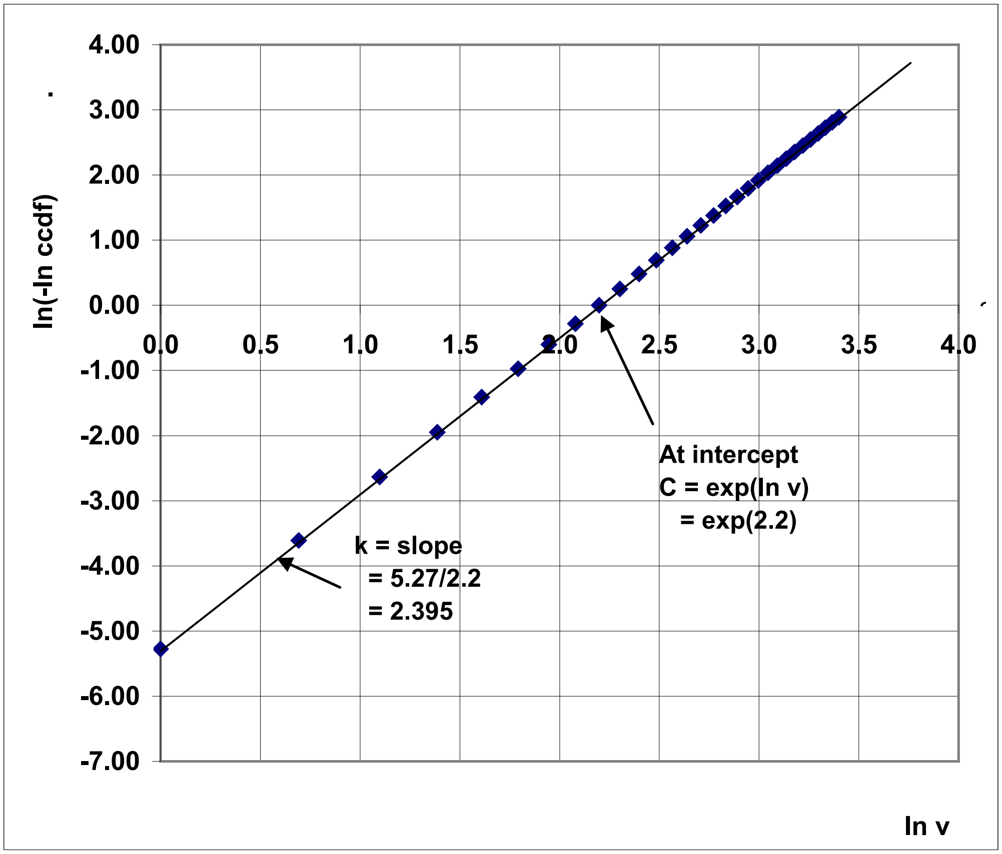


Figure 14. Fitting empirical data to the Weibull distribution to determine the values of the shape parameter k and the scale parameter or characteristic wind speed, C.

FITTED CONTINUOUS DISTRIBUTION

Using Eqn. 6 and the graphically determined values of the shape parameter k = 2.395 and the scale parameter or characteristic wind speed:

$$C = \exp(2.2) = 2.17828^{2.2} = 9.03$$

one can now fit the observation data to a Weibull probability density function:

$$\begin{aligned} W(v) &= \frac{k}{C}\left(\frac{v}{C}\right)^{k-1} e^{-\left(\frac{v}{C}\right)^{k}} \\ &= \frac{2.395}{9.03}\left(\frac{v}{9.03}\right)^{1.395} e^{-\left(\frac{v}{9.03}\right)^{2.395}} \end{aligned} \qquad (6)'$$

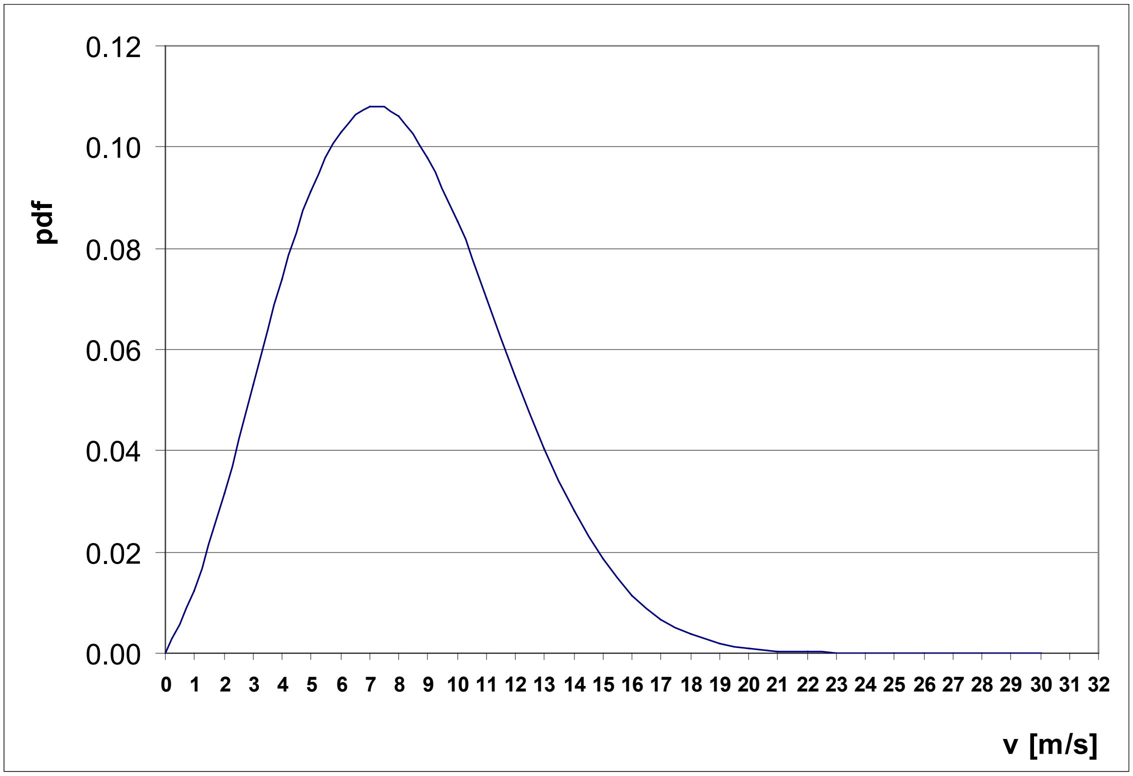


Figure 15. Fitted empirical data to Weibull distribution with scale parameter C = 9.03 and shape parameter k = 2.395.

A Fortran procedure can display the continuous Weibull distribution:

```
!      Weibull distribution
!      Program written in ANSI Fortran-90
!      Digital Visual Fortran Compiler
!      Procedure saves output to file:output1
!      This output file can be exported to a plotting routine
!      Dr. M. Ragheb
       program Weibull
!      xk is weibull shape parameter
!      C is scale parameter or characteristic wind speed
!      v is speed in m/s
!      real :: xk = 2.4
!      real :: C = 9
       real :: xk = 2.395
       real :: C = 9.03
       integer :: steps=30
       real dum,speed(31),pdf(31),cdf(31),ccdf(31)
       real lnspeed(31),lnccdf(31),ln_lnccdf(31)
       write(*,*) xk, C
!      Open output file
       open(10,file='output1')
!      Calculate Weibull probability density function
       steps = steps +1
       do i =  1, steps
```

```
                speed(i) = i-1
                dum =(speed(i)/C)
                pdf(i) = (xk/C)*(dum**(xk-1.0))*exp(-dum**xk)
                cdf(i) = 1.0 - exp(-dum**xk)
                ccdf(i) = exp(-dum**xk)
                        if(i.eq.1) goto 1
                lnspeed(i)=log(speed(i))
                lnccdf(i)=log(ccdf(i))
                ln_lnccdf(i)=log(-lnccdf(i))
                        goto 2
1               lnspeed(i)=0.0
                lnccdf(i)=0.0
                ln_lnccdf(i)=0.0
!       Write results on output file
2               write(10,11)speed(i),pdf(i),cdf(i),ccdf(i),lnspeed(i),lnccdf(i),ln_lnccdf(i)
11              format(7(e14.8,1x))
!       Display results on screen
                write(*,*) speed(i),pdf(i),cdf(i),ccdf(i),lnspeed(i),lnccdf(i),ln_lnccdf(i)
        end do
        end
```

RAYLEIGH DISTRIBUTION

A value of the shape parameter k = 2 gives a distribution designated as the cumulative Rayleigh distribution, from Eqn. 9:

$$ccdf = e^{-\left(\frac{v}{C}\right)^2} \qquad (13)$$

Wind turbine manufacturers often report the standard performance figures for their machines using the Rayleigh distribution.

In Northern Europe this value of k = 2 is used.

EXPONENTIAL DISTRIBUTION

When the dimensionless shape parameter in the Weibull distribution is taken as k = 1, the exponential distribution results. Its complementary cumulative distribution function becomes from Eqn. 9:

$$ccdf = e^{-\left(\frac{v}{C}\right)} \qquad (13)'$$

FREQUENCY DISTRIBUTION

The annual empirical wind speed frequency distribution is based on actual rather than theoretical wind speeds. The frequency distribution at Lee Ranch, New Mexico is shown corrected for 40 meters height speed data.

Those measurements are conducted at specially erected wind towers equipped with anemometers for the measurement of wind speeds at potential wind park sites.

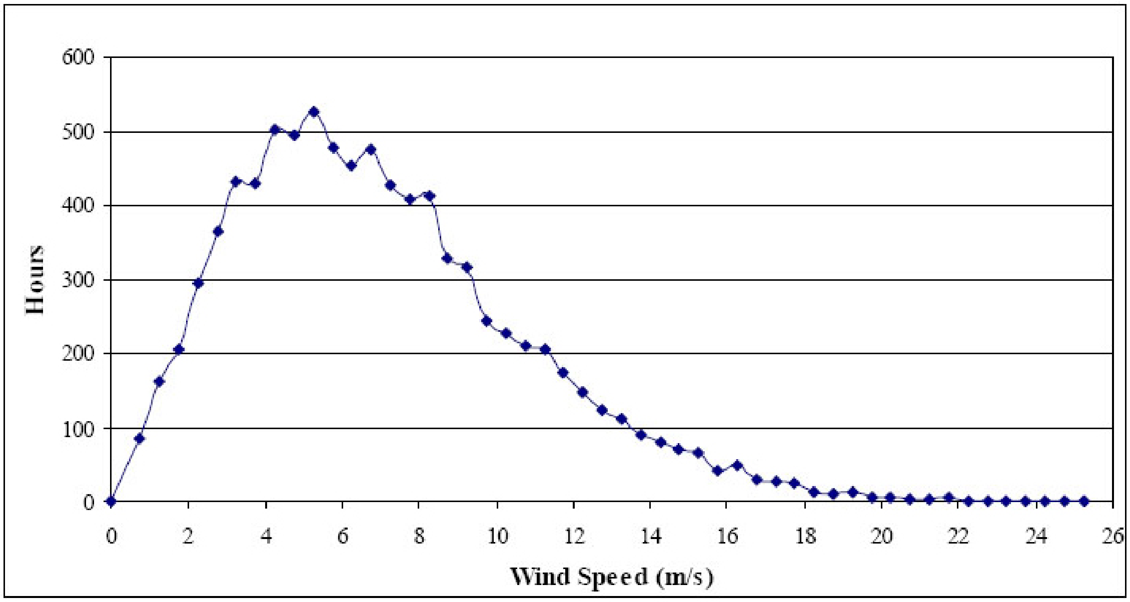


Figure 16. Annual wind speed frequency distribution for Lee Ranch, New Mexico, 2002.

Figure 17. Radio towers with two anemometers for wind measurements at highest point in Champaign County, Illinois, USA. Photo: Paul Lenz.

WIND ROSES

Annual wind roses show the percent time and percent energy in each direction sector for data collected from January through December of a given year. Wind roses can be constructed of two bars in each of 16 wind direction sectors, representing the percent of total time and the percent of total wind energy. Monthly wind roses show the prevailing wind directions and the turbulence intensity by wind direction sector.

In Fig. 17, the predominant wind direction is from the west-northwest for Lee Ranch in New Mexico, USA. In Fig. 18, the wind rose at Schiphol Airport in The Netherlands is shown.

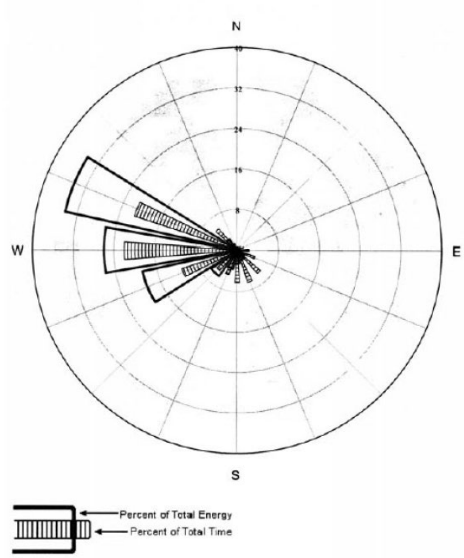


Figure 18. Annual wind rose for the Lee Ranch, New Mexico.

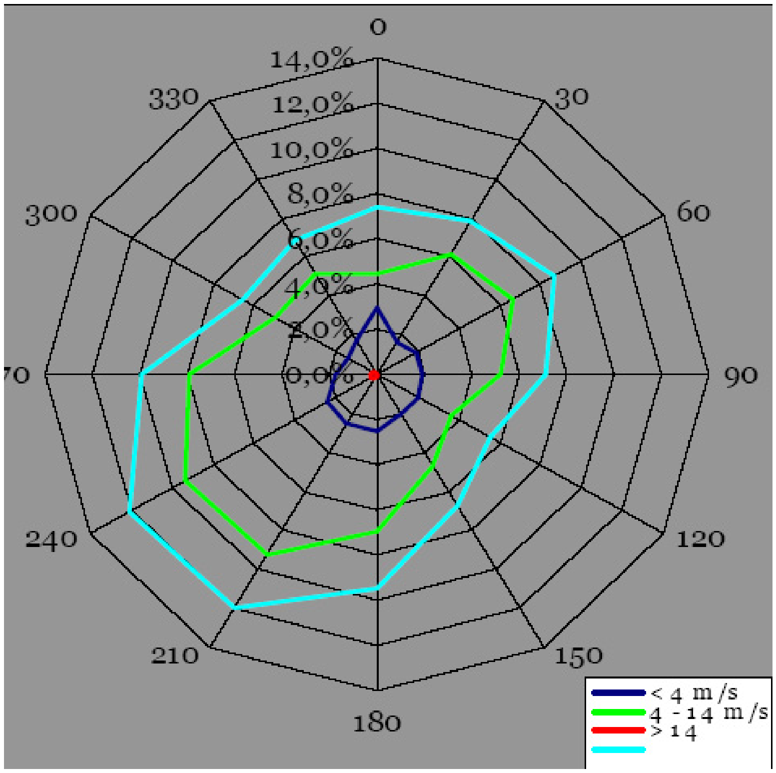


Figure 19. Wind rose at Schiphol Airport, The Netherlands.

WIND SPEED DATA

SEASONAL VARIATIONS

Wind speeds are measured for a given site on a monthly basis. Figure 20 shows that the wind speeds are highest during the January-March period and lowest during the July-October period.

It can be observed that the wind speed is higher in winter than in the summer; a favorable factor, since energy needs are higher in the winter than in the summer.

If we take the ratio of recorded speeds in January to July as:

$$r_{January/July} = \frac{v_{January}}{v_{July}} = \frac{8.5}{4.75} = 1.79$$

Since the energy production is proportional to the cube of the wind speed:

$$\frac{E_{January}}{E_{July}} = r^3_{January/July} = (1.79)^3 = 5.73$$

This suggests that a wind turbine could produce about 6 times more energy in the winter than in the summer.

Since solar energy would provide more energy during the summer than in the winter because of the decreased cloud cover, wind and solar energy production appear complementary to each other.

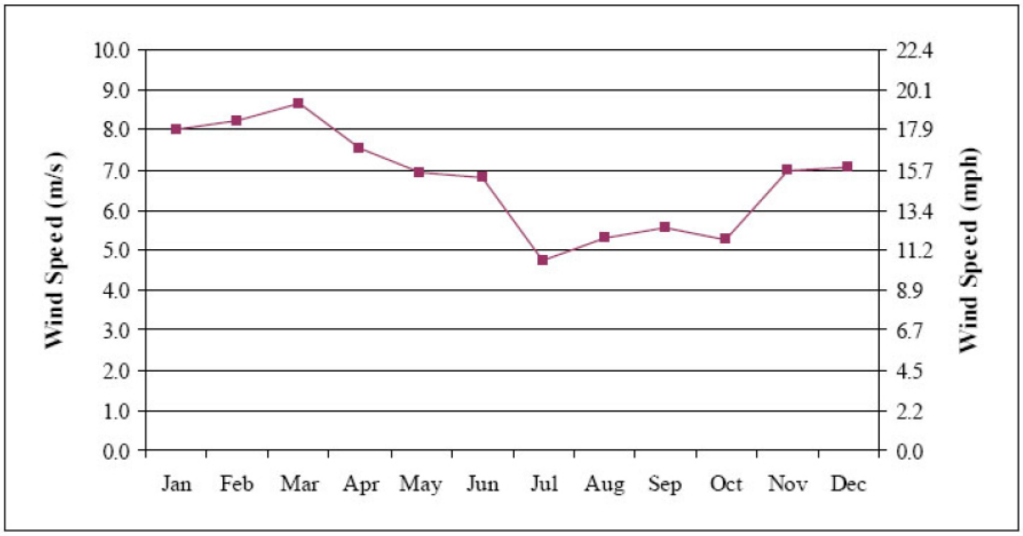


Figure 20. Monthly wind speed at 40 meters height, Lee Ranch, New Mexico.

DIURNAL VARIATIONS

Diurnal wind speeds are also measured on a 24 hours basis. Annually, the wind speeds are highest midday over the period noon-5:00 pm. The diurnal wind speeds also vary depending on the season of the year.

The diurnal variations are caused by air convection effects.

Defining a ratio of diurnal variation as:

$$r_{Afternoon/Morning} = \frac{v_{Afternoon}}{v_{Morning}} = \frac{7.5}{6.0} = 1.25$$

Since the energy production is proportional to the cube of the wind speed:

$$\frac{E_{Afternoon}}{E_{Morning}} = r^3_{Afetrnoon/Morning} = (1.25)^3 = 1.95$$

This suggests that a wind turbine could produce about 2 times more energy in the afternoon than in the morning.

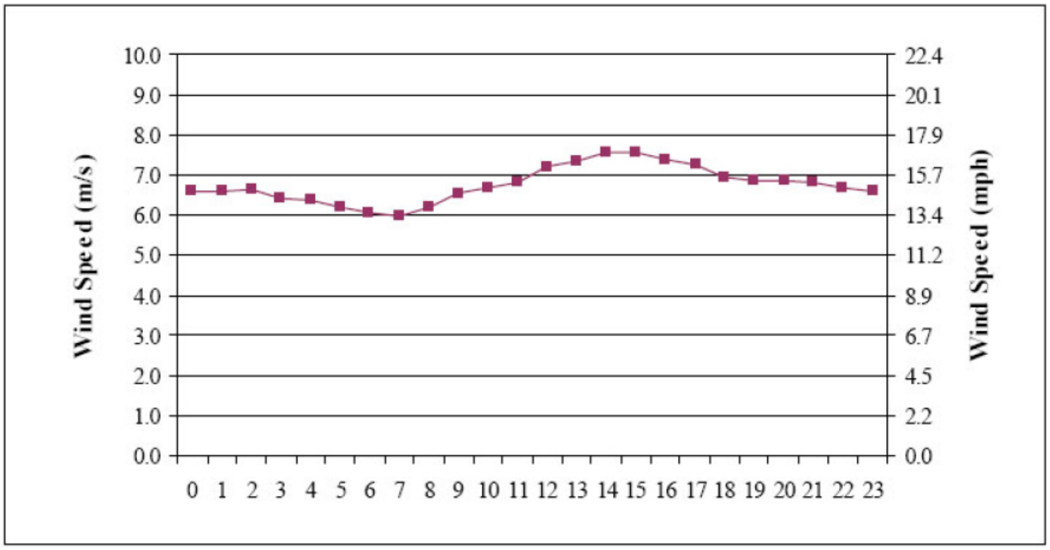


Figure 21. Annual diurnal wind speed at 40 meters height, Lee ranch, New Mexico.

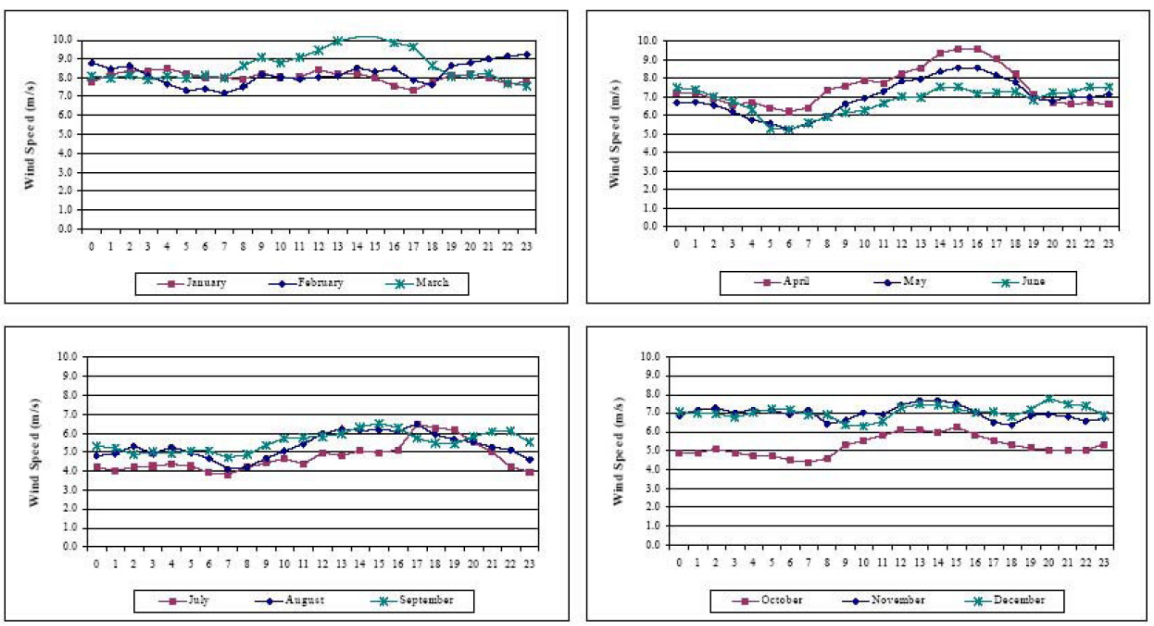


Figure 22. Monthly diurnal wind speeds at 40 meters height, Lee Ranch, New Mexico.

WIND SHEAR AND EFFECT OF ALTITUDE

The increase of the wind speed as a function of altitude is a known effect. Near the ground, the wind speed is reduced due to friction caused by obstacles. The relative increase of wind speed differs from one location to another.

The mean velocity profile or wind shear values are estimated over an average height of between 10 meters for meteorological applications and 40-50 meters for wind power production applications. They are expressed in terms of a wind shear exponent. To develop maximum power, a wind generator must be mounted as high as possible.

A power law that is accurate within the boundary layer is used. A logarithmic law gives a good fit within the 30 – 50 m height.

POWER LAW

Several authors have suggested the following statistical simple law of variation of wind speed with height:

$$\frac{V}{V_0} = \left(\frac{H}{H_0}\right)^n \tag{14}$$

where V_0 is the observed speed at H_0 meters above ground, and V is the wind speed at altitude H.

The value of H_0 is usually given at 10 m height, and the coefficient n takes values over the range 0.1 – 0.4. This law depends on a large number of observations and not necessarily in individual situations.

LOGARITHMIC LAW

Another logarithmic law takes into account the surface roughness of the surrounding terrain:

$$\frac{V}{V_0} = \frac{\ln\left(\frac{H}{z_0}\right)}{\ln\left(\frac{H_0}{z_0}\right)} \tag{15}$$

Both the power law exponent n and the characteristic height z_0 depend on the surface roughness.

Table 7. Relationship of surface roughness to power law exponent n and to the characteristic height z_0.

Terrain roughness	Power exponent n	Characteristic height z_0 [m]
Smooth: sea, sand, snow	0.10 – 0.13	0.001 – 0.020
Moderate rough: short grass, grass crops, rural	0.13 – 0.20	0.02 – 0.30

areas		
Rough terrain: woods, suburbs	0.20 – 0.27	0.30 – 2.00
Very rough: tall buildings, urban areas	0.27 – 0.40	2.0 – 10.0

In applying these laws the heights H and H_0 are strictly not heights above the ground surface, but rather heights above the surface of zero wind. This would be the average corn or wheat height in a dense corn or wheat field, or the height in a forest at which the branches of adjacent trees touch each other.

A transitional height exists beyond which the local terrain roughness does not affect the velocity profile:

$$\begin{aligned} &H_{transition} \approx 0.08\,\Delta x \\ &\Delta x = \text{the distance of the location considered} \\ &\qquad \text{to the change in the ground roughness} \end{aligned} \tag{16}$$

For Δx > 5 km, the transition zone is insignificant. At Δx < 5 km and below the transition height, the characteristics of the wind profile become related to the roughness of the downwind ground surface. Over the transition height they are related to the upwind terrain roughness.

EXTRACTABLE ENERGY

The extractable power and hence energy over a period of time in the wind is proportional to the cube of the wind speed. Using Eqn. 14, the ratio of extractable energy E/E_0 at a height of H meters above a level ground can thus be expressed as:

$$\frac{E}{E_0} = \left(\frac{V}{V_0}\right)^3 = \left(\frac{H}{H_0}\right)^{3n} \tag{17}$$

with $0.30 < 3n < 1.20$.

To extract maximal power from wind turbines, they must be mounted as high as possible on top of towers

WIND TURBULENCE

The wind turbulence intensity is measured normally from the dominant wind direction. To be suitable for wind energy production, a given location must experience low turbulence intensities. Wind turbines must be located at least 8 – 10 meters above the surrounding vegetation or obstacles to avoid turbulence.

Turbulent locations resulting from obstructions such as trees or buildings will severely limit the lifetime of wind turbines and maximize the chance of their catastrophic failure. They must be carefully avoided in the process of siting wind turbines at different locations.

APPENDIX

FRAMES OF REFERENCE

Question: Why is it daylight at, say, 12:00 noon when the Earth is on one side of the sun and not dark when it travels to the other side of the sun? If the Earth spins around its axis every 24 hours making a full rotation and further orbits around the sun in 365 days completing a full ellipse, 12:00 noon should, during that time, change in its exposure to the sun throughout the year; and when the Earth is on the other side of the sun, 12:00 noon should be totally dark. Should it not?

Answer: The Earth rotates once in about 24 hours with respect to the sun and once every 23 hours, 56 minutes and 4 seconds with respect to the stars. Take the 4 minute 4 second difference or 244 seconds, multiply by half a year's worth of days (365/2) and divide by 3,600 seconds to get hours and we find the slippage is 12.36 hours or about half a day. When we factor in leap seconds, leap years, and the rotation of our solar system as part of our spiral Milky Way galaxy, it all works out to keep the sun roughly overhead at noon time.

We must have a fixed reference to calculate time. Nuclear clocks are set to this 24 hour rotation, which requires a fixed reference, that reference, and the point of rotational return must be absolute, else we would account for a full day's slippage in every calendar year. The reason the Polaris North Star never moves is because it is so far away; and in that time is, essentially, a measure of degrees, and we do not change our disposition in relation to some stars and 360 degrees to others.

Question: When looking into the sky, especially in summer, one sees a partial moon, meaning that the Earth should be casting a shadow on the moon, in a direct line to the sun, by what is it shaded? The Earth is obviously not in between the sun and moon, why is it in partial phase? How is it possible for there to be a partial moon and full sun in a direct line in the sky if Earth’s blocking of the sun's light shades the moon causing its phases?

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EXERCISES

1. The following measurements were reported for wind gusts at a meteorological station:

Observed v_{max} [m/s]	Observed v_{min} [m/s]	Measured variations
53.0	39.0	$\pm 8^o$
36.5	16.7	$\pm 22^o$
20.5	11.0	$\pm 17^o$

a) Calculate the variations according to the whirlwind model.
b) Estimate the relative percentage discrepancy between the experimental results and the theoretical model.
2. The wind speed at 20 meters height at the Eiffel Tower is about 2 m/s, and it is about 7-8 m/s at 300 meters above ground.
What range of values of the coefficient n best fits the Eiffel Tower situation?
Hint: Solve for n by taking the natural logarithm of both sides of the power wind shear equation.
3. Plot the energy ratio for the situation of the Eiffel Tower using the values of n that was derived in the last problem.
4. Consider the exponential probability density function (pdf):

$$p(v)dv = \frac{1}{C} e^{-\frac{v}{C}} dv$$

a) Apply the normalization condition to prove that it is indeed a probability density function.
b) Derive the expression for its cumulative distribution function (cdf).
c) Derive the expression for its complementary cumulative distribution function (ccdf).
Use a plotting routine to plot the pdf, cdf, and ccdf for a value of C = 5.