Makarieva A.M., Gorshkov V.G. (2013) Energetics of locomotion in animate and inanimate nature. Energy: Economics, Technology, Ecology, 6(2013), 46-52. Authors' translation of the original Russian text.

ENERGETICS OF LOCOMOTION IN ANIMATE AND INANIMATE NATURE

Makarieva A.M., Gorshkov V.G.

(Petersburg Nuclear Physics Institute, Gatchina, Leningrad district, Russia)

Except for tsunami and earthquakes, all types of motion on the Earth's surface owe themselves to various transformations of solar energy. The Earth reflects back to space one third of the incoming solar radiation. The atmosphere absorbs another third. In the result, with an account of the diurnal and seasonal changes, the mean flux of solar radiation per unit area of the Earth's surface amounts to about 150 W/m^2. Efficiency at which solar energy is transformed to any type of motion at the Earth's surface does not exceed several percents. Global atmospheric circulation with its mean winds of about 5 m/s is characterized by a global mean power not exceeding 4 W/m^2. The power of the biosphere – the rate of plant growth expressed in energy units– reaches the same order of magnitude (about 2 W/m^2) only in the most productive equatorial rainforests.

On the other hand, human sportsmen like weightlifters or sprinters are able to develop power in excess of 10 kW. Taken per unit area of the ground surface their bodies occupy, this corresponds to a power output of several tens of kilowatts per square meter. Hurricanes and tornadoes that occasionally form in the atmosphere develop wind velocities up to 100 m/s. Their power per unit area of the Earth's surface exceeds by many times not only the flux of solar radiation reaching the Earth's surface, but also the flux of solar radiation outside the atmosphere – the so-called solar constant equal to 1.4 kW/m^2. In this paper we consider how such motions with their power significantly exceeding the power of solar radiation are maintained in animate and inanimate worlds. What is the link between forest functioning on land and the formation of the most powerful atmospheric vortices like hurricane Sandy or typhoon Bopha?

Locomotion and immobility in life

One of the striking, eye-catching features of life on land is the division of all organisms into two kinds: immobile plants and fungi that are attached to the ground surface versus freely moving animals. Immobile plants–for example, trees in a forest–form a continuous cover where crowns of different plants border with each other. A continuous cover is formed by the mycelium of fungi; their fruit bodies (like edible mushrooms) are attached to the ground similar to plants. In contrast, locomotive animals rarely get in sight. This means that animals have large feeding territories that by far exceed the size of the animal body. It is over these feeding territories (home ranges) that the animals move.

The reason for this drastic dichotomy of life with respect to motion lies in the physical laws that govern energy consumption by living organisms. The universal biochemical nature of life prescribes that all organisms are on average characterized by a universal power q (W/m^3) of energy consumption/spending per unit volume of any biochemically active part of the organism. Indeed, it was found that organisms from very different taxonomic groups and of very different sizes, from the smallest bacteria and algae to insects and the largest animals–mammals, all consume about one Watt per kilogram of live mass (or about 1 kW per cubic meter) [1,2], Fig. 1.

The volume-specific energy consumption rate being universal, total energy consumption of living organisms grows proportionally to body volume. Energy and food can only enter the organism via some part of its body surface (e.g. via the mouth of animals). As body density of most living organisms is close to liquid water density, $\rho = 10^3$ kg/m^3, it is natural to define the linear body size l as $l = (m/\rho)^{1/3}$, where m is body mass. Body volume is naturally proportional to l^3, while the body surface area is proportional to l^2. Energy imported into the organism via a surface of area proportional to l^2 should be distributed over the entire body volume proportional to l^3. Total energy consumption power characterizing the organism as a whole is $q\, l^3$, where $q \approx 1$ kW/m^3 (= 1 kW/t) is a life-universal magnitude. This total power $q\, l^3$ should be equal to sl^2, where s is the actual rate at which the organism consumes energy from the environment per unit area of its body surface (in particular, per unit area of the mouth surface of an animal). The energy conservation relationship $sl^2 = ql^3$ means that $s = ql$: **the surface-specific rate of energy consumption by the organism must increase proportionally to the linear body size *l*.**

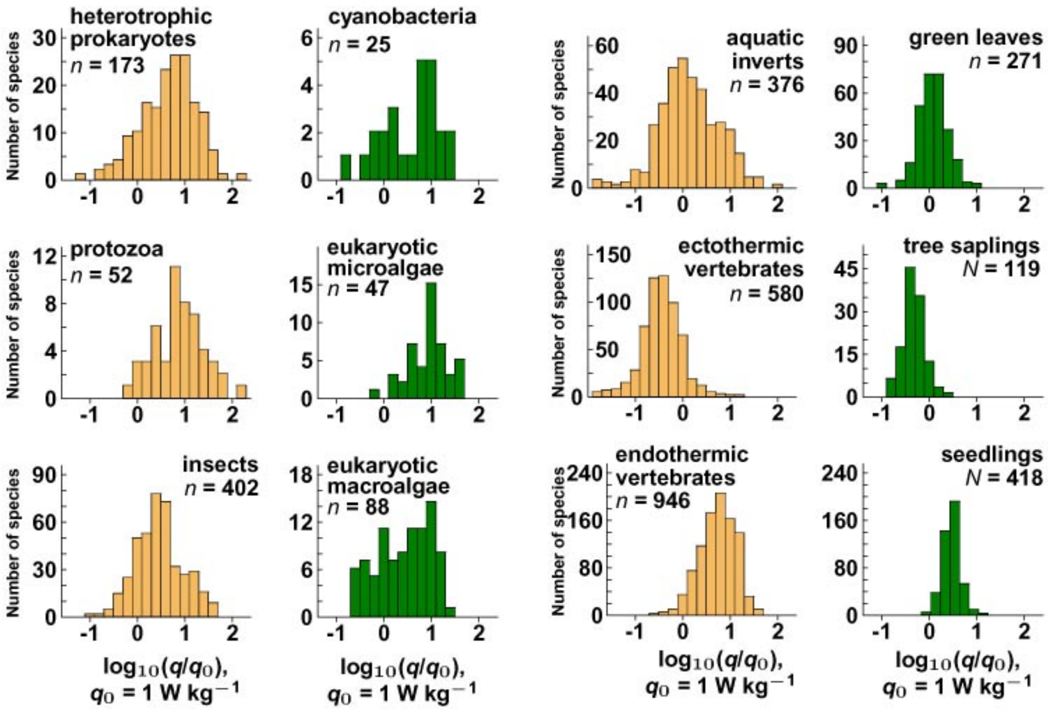

Fig. 1. Frequency distribution of energy consumption rates per unit live mass in various ecological and taxonomic groups of organisms [2]. Light and dark histograms represent autotrophs and heterotrophs, respectively; *n* and *N* are the total numbers of investigated species or individuals, respectively, in each group.

The ultimate energetic basis for all life on Earth is the consumption of solar energy by plants. Leaves play the role of plant "mouths". Plants increase their biomass by synthesizing energy-rich organic compounds. This energy is used by plants themselves as well as by the rest of life – bacteria, fungi, and animals. The flux of solar energy per unit area of the Earth's surface $I \approx 150$ W/m^2 is limited from the above by the flux of solar energy reaching the Earth's extremities. Efficiency $\varepsilon \sim 1\%$ of solar power transformation into the power of photosynthesis is approximately universal across all plants. Hence, per unit area of plant surface, i.e., per unit area of the continuous plant cover, the rate of energy consumption $s = \varepsilon I \approx$ 1 W/m^2 is approximately constant: it is determined by the flux of solar radiation. Knowing the rate of energy consumption per unit body volume q, the flux of solar radiation I and efficiency ε at which solar power is transformed to plant photosynthetic power, we can unambiguously determine the maximum possible vertical size of the biochemically active live plant biomass $l = s/q = \varepsilon I/q \sim$ (1 W/m^2)/(10^3 W/m^3) ~ 1 mm. This means that the vertical size of plants in our temperate zone is of the order of one millimeter.

This result originally comes as surprising and controversial. Indeed, the apparently huge trees are rendered dwarfs even compared to a tiny mouse, let alone large animals like man or the elephant. However, as soon as we recall what we know about trees, the controversy is resolved. Indeed, many trees are very big, but their roots, branches and stems actually claim a very small part of the total space occupied by the tree. The major part of this space is empty and filled with air or soil. The supporting construction of the tree – its stem – largely consists of dead (metabolically inactive) wood. Wood is covered by a thin living layer (cambium) which transports various substances in two directions, from roots to leaves and back, in order to ensure biomass synthesis by leaves as well as biomass consumption by all the parts of the tree including its branches and roots. If the metabolically active tree biomass is uniformly spread over the area of the tree's projection on the ground surface, the vertical size a "pancake" thus formed will not exceed 1 mm.

Thus, to satisfy the major condition of life maintenance and to achieve energy consumption rate per unit live volume of the order of q ~1 kW/m^3 it is necessary to ensure that the mean thickness of life biomass, if the latter uniformly spread over the Earth's surface, does not exceed 1 mm. It is only in this case that the flux of solar energy is sufficient for the maintenance of living organisms. This condition is fulfilled for all plants, fungi and bacteria. Their life occurs at a constant mean store of biomass of these organisms in the ecosystem.

But how then do animals exist with their body sizes significantly exceeding this critical size? It is not possible to "spread" the animal body as a 1-mm layer over the Earth's surface!

All substances having mass are able to accumulate. (Solar photons do not have mass.) Live mass (biomass) is peculiar in that it contains a lot of energy. This energy is released when the biomass is decomposed into inorganic compounds; it determines the caloric content of food. As the biomass locally accumulates, so does the energy it contains. After the biomass and energy have been accumulated, the energy can be consumed at any rate independent of the rate at which it was accumulating. Large animals including man, with their body sizes hundred of times larger than the thickness of the metabolically active plant biomass, have to consume biomass a hundred of times faster than it is being synthesized by plants to meet the energy demands of their bodies. Once biomass is locally consumed, there is no longer edible food locally available. The animal must move to another place where the edible biomass is still present. The animal can return to the original place only after the edible biomass has re-grown. This condition determines the size of the feeding territory of the animal. The animal will only survive if there are no other animals on its feeding territory that would claim the same food resources. This conditions strictly limits population density in all animal species.

Consuming plant biomass at a rate hundreds of times higher than the rate of local biomass re-growth, all animals must have an individual feeding territory with a linear size significantly exceeding the size of the animal itself. Only plants, fungi and bacteria with their layer of metabolically active biomass not exceeding 1 mm can survive without active locomotion forming a continuous cover on the Earth's surface. Unlike large animals, these organisms do not destroy the local store of biomass. They consume (eat) it at a rate equal to the rate of biomass increment, such that the store of biomass can remain constant. Animals are unable to survive in such a regime. They inevitably destroy the local store of biomass, which disappears in the presence of animals and re-grows only after their long-term absence. If the animal comes back before the biomass has recovered, local life disintegrates. This is a very strict condition imposed on the organization of life in the presence of large animals. The major condition of life persistence in the presence of large animals is the active defense by the animal of its exclusive feeding territory to prevent animal population densities from growing.

Plants feed on a unique substance–sunlight, which consists of photons. Photons are particles that carry energy but they have no mass and thus cannot be accumulated at the Earth's surface. As plants feed on massless photons, their locomotion would not lead to an increase of energy consumption by plants. Even if capable of locomotion (which also involves additional energy expenditures) plants would be unable to increase the vertical size of their metabolically active biomass above 1 mm. From the viewpoint of their energy budget, it makes no sense for plants to move. Thus, we can see that plants do not move and can form a continuous close cover.

Concentration of energy in hurricanes and tornadoes

All major processes in the inanimate nature that occur on the Earth's surface are also supported by solar energy. The power of those physical processes that use solar power directly is limited by the flux of solar energy and the efficiency of solar power transformation into the local power of the physical process in question. Such direct physical processes are analogous to plant photosynthesis. For example, the global mean power at which the kinetic energy of winds is generated in the atmosphere of Earth is about 4 W/m^2 with the mean wind velocity approximately 5 m/s [3].

In the living world the high rate of energy consumption per unit area of the ground surface is related to the large animal body size and the universality of the volume-specific energy consumption rate q. In the inanimate world wind power can be concentrated up to several thousand watts per square meter in compact atmospheric vortices like hurricanes and tornadoes where wind velocity may achieve 100 m/s. Such a concentration occurs as a consequence of a radial compression of air rotation. The effect is determined by the rotation of the Earth and the law of conservation of angular momentum a, $a \equiv \omega r^2 = \text{const}$, where ω is angular velocity and r is radius. The law of conservation of angular momentum prescribes that when the rotation radius shrinks, the angular velocity grows and the rotation accelerates. Sportsmen (figure skaters, divers) as well as ballet dancers make use of this effect in their motions. Elsewhere in the living world this effect is practically absent in macroscopic living organisms presumably because of the physical danger associated with a high concentration of energy and high angular velocity.

Hurricane with a typical radius R ~400 km is not spatially uniform. It has a circular windwall where the vertical velocity of ascending air is maximal and the horizontal rotating wind may reach over a hundred meters per second. Bounded by the windwall from the outside is the so-called hurricane eye, where the air descends and warms. For this reason there is no condensation in the eye, it has a fair weather with sunshine and no clouds. The eye rotates as a solid body with an angular velocity coinciding with the angular velocity of the windwall. In the eye center wind speed is zero. The eye and windwall radius r_0 is of the order of 40 km, i.e. it is ten times smaller than hurricane radius R. The windwall moves at the same velocity as the hurricane as a whole and in each location that it visits brings about a catastrophic devastation in as little as two-three hours.

At the hurricane outskirts the rotation features a larger radius R and a small angular velocity $\omega_E = \Omega_E \sin \upsilon$. Angular velocity ω_E at latitude υ is equal to the projection of the angular velocity of the Earth's rotation $\Omega_E = 2\pi/(24 \text{ hours})$ on the normal vector to the Earth's surface. As the air approaches the windwall conserving its angular momentum $a \equiv \omega_E R^2 = \omega r^2$, rotation with a large radius R and a small angular velocity ω_E is transformed into rotaion with a small radius r_0 and a large angular velocity ω of the windwall and the eye. The velocity of the rotating wind is $v = \omega r = a/r$. Energy of wind rotation per unit air volume is equal to $\rho v^2/2$, where ρ is air density. As the rotation shrinks, rotation radius decreases and the angular velocity grows, so the kinetic energy is being concentrated per unit air volume proportionally to $v^2 = (\omega r)^2 = a^2/r^2$. In other words, energy concentration per unit volume grows inversely proportionally to the squared radius of the windwall. Thus, in the hurricane the energy of all water vapor accumulated in the entire condensation area of radius R ~ 400 km is concentrated in a small region of the windwall with radius r_0~ 40 km. Wind speed thus increases by (R / r) ~ 10 times and wind energy increases by $(R / r_0)^2$ ~ 100 times.

At small values of angular momentum a the radius of the eye and the windwall r_0 proves to approximately linearly depend on a [4]. Thus, the smaller the value of a, the narrower the eye and the greater the concentration of wind energy in the windwall. At a fixed value of angular momentum a windwall shrinking and energy concentration cannot occur infinitely because the energy accumulated in the hurricane area is finite. The kinetic energy of rotation near the windwall represents the maximum possible kinetic energy that is equal to the potential energy of all water vapor in the condensation area.

Hurricanes do not arise at the equator where $\upsilon = 0$ because the opposite rotation at a distance of the order of hurricane radius R on both sides from the equator cancel each other. As the hurricane moves poleward, υ grows, the windwall on average expands, and the maximum winds weaken. Energy ceases to be concentrated in the windwall. The hurricane transforms into an ordinary cyclone where the windwall radius is of the order of the radius of the entire condensation area. All available energy is then spent on "eye" rotation. Since this energy is finite, this sets a limit on the maximum radial size of the cyclone of the order of a thousand kilometers. The water vapor potential energy is insufficient to rotate an "eye" of a bigger radius.

Motion of hurricanes and tornadoes

The powerful vortices of hurricanes and tornadoes can only survive in the same regime as do the locomotive animals: i.e., they must consume ("eat") the locally accumulated energy at a rate hundreds of times exceeding the rate at which this energy has been accumulated in the gradual process of solar energy consumption at the surface. Such vortices must continually move across their "feeding territory" which must contain energy in a form "edible" for the hurricane or tornado, Fig. 2. What is hurricane's food then?

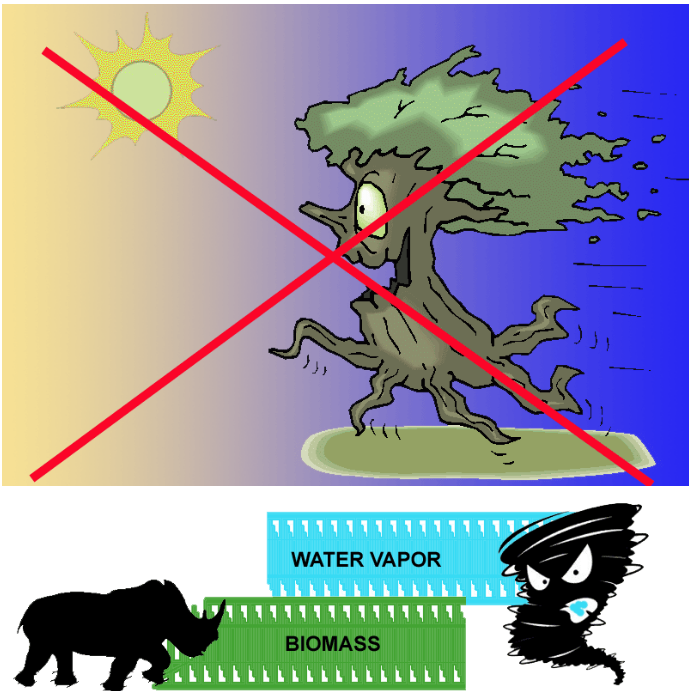

Fig. 2. Peculiarities of motion in animate and inanimate worlds. Plants "feeding" on massless solar photons do not move, as photons do not accumulate. Energy consumption by plants does not exceed 1 W/m^2. Large animals and atmospheric vortices that consume over 10^3 W/m^2 must move and consume energy contained in biomass and atmospheric water vapor, respectively.

Atmospheric air is characterized by pressure. Pressure p has the dimension of force f acting on a unit surface of area l^2, i.e. $p = f/l^2$. Considering a cube with an edge of unit length l we can express pressure as $p = fl/l^3$, $l = 1$ m. But the product of force and length fl is work, or the energy associated with the action of force f over a unit of length l. Thus pressure has the meaning of energy comprised in a unit atmospheric volume. Which part of this energy is "edible" for the hurricane? Hurricane's edible energy is water vapor – a gaseous atmospheric constituent, which slowly accumulates in the process of evaporation of the oceanic water as the ocean absorbs solar radiation [4]. When moist air cools, the water vapor condenses producing fog and clouds: this process reduces air pressure. The maximum possible (saturated) amount of water vapor per unit volume the air can contain depends on temperature. This saturated amount decreases by approximately two times per each ten degrees of temperature decline. When the air rises, the mean velocity of its molecules decreases together with air temperature to match the corresponding increase of the gravitational potential energy. (It is similar to a bouncing ball losing its kinetic energy as it ascends and acquires potential energy.) The drop of air temperature causes water vapor to condense – it quits the gaseous phase forming condensate particles. This results in a drop of air pressure. Thus condensation makes the "food" (water vapor) "edible" for the hurricanes: it can be consumed or it can be wasted if dissipated over the entire atmosphere.

The higher the vertical velocity of the ascending air, the higher the rate of condensation and the larger the drop of air pressure. The air is however acted upon by the gravitational field of the Earth, which does not allow the air to ascend too high. In the result, it is the horizontal winds that increase – those blowing towards the condensation area in the lower atmosphere and those blowing outside the condensation in the upper atmosphere. Moist air containing water vapor starts to arrive from the neighboring areas to the area where the vertical velocity of ascent is maximal. This enhances condensation within the area of most rapid ascent. The air pressure continues to fall until all hurricane's "food" – the water vapor accumulated in the area affected by condensation – has been used up. If the hurricane did not move as a whole, all the water vapor would have been "eaten" in a very short period of time after which the hurricane would be "starved to death" and ceased to exist. In order to survive, the hurricane, very much alike a big animal, must move to a new area with abundant water vapor, consume the water vapor in the new area and move along. The velocity of hurricane movement is on average about 5 m/s ~ 20 km/hour ~ 500 km/day. Radius R of hurricanes is about 400 km. It takes the hurricane approximately one day to leave the area it currently occupies.

The only way to destroy a hurricane is to deprive it of its "food" (the water vapor) along the way of its movement. However, only an undisturbed large-scale forest cover can perform this difficult task. The forest transforms the destructive energy of would-be hurricanes into the calm winds of moderate cyclones that feed with water all life on land.

Link between hurricanes' destructive power and the forest moisture pump

Owing to the high cumulative area of the green leaves of their canopies (the so-called leaf area index) natural forests are able to evaporate moisture at a much higher rate per unit ground surface area than does the open water surface of the ocean. The atmosphere can be therefore enriched with moisture more rapidly above the forest than above the ocean. This increases the mean condensation rate over the forests and leads to the formation of a low-pressure zone that brings about winds blowing from the ocean towards land. The incoming moisture flux feeds precipitation on land such that the forest can compensate the inevitable loss of liquid water as runoff to the ocean. In other words, the forest pulls moist air laden with water vapor from over the ocean to land and thus deprives the hurricanes of their food.

The forest spends the oceanic water vapor very sparingly, ensures its gradual penetration over many thousand kilometers towards the continental interior. The forest regulates the intensity of water vapor condensation by attenuating evapotranspiration from leaves and by controlling the emission of biogenic condensation nuclei. Precipitation over the forest keeps the soil sufficiently but not exceedingly moistened such that neither dangerous floods nor droughts normally develop. Moreover, the large height of trees in an undisturbed forest canopy creates the necessary roughness in the condensation area preventing the formation of hurricanes and tornadoes alike. Forest roughness is unprecedented in the inanimate world. E.g., roughness of oceanic waves is associated with much smaller friction, which allows for the development of the destructive hurricane winds – where the forests do not do their job of "stealing" moisture from ocean to land.

The on-going deforestation disrupts the biotic pumping of water vapor from the ocean to land producing droughts and river lows. One of the strongest droughts affected a large area in the United States in 2011-2012 unambiguously indicating lack of the ocean-to-land moisture transport. Moisture evaporated from the oceanic surface remained in the atmosphere above the ocean raising the probability of hurricane formation and their passage near the coastal zone. Hurricane Sandy in 2012 with its enormous size of the condensation area can be viewed as a result of the continental-scale drought in the US. Hurricanes and typhoons that form closest to the equator – like typhoon Bopha that struck the Philippines in 2012 – have the smallest possible angular momentum and windwall radius. What is more, such systems have access to the largest amounts of water vapor in the warm near-equatorial air column. As a result, such a typhoon should be characterized by maximum possible concentration of wind energy at the windwall and have maximum destructive power. These extreme weather events are related to the diminishing area of tropical forests in Indonesia and Indochina as well as to the complete elimination of forests on the Philippines. These forests no longer move vapor away from the adjacent areas of the Pacific Ocean in amounts sufficient for the prevention of the violent super-typhoons.

Literature

[1] Gorshkov V.G. (1981) The distribution of energy flow among the organisms of different dimensions. Journal of General Biology, 42(3), 417-429.

[2] Makarieva A.M., Gorshkov V.G., Li B.-L., Chown S.L., Reich P.B., Gavrilov V.M. (2008) Mean mass-specific metabolic rates are strikingly similar across life's major domains: Evidence for life's metabolic optimum. Proceedings of the National Academy of Sciences U.S.A., 105, 16994-16999.

[3] Makarieva A.M., Gorshkov V.G., Sheil D., Nobre A.D., Li B.-L. (2013) Where do winds come from? A new theory on how water vapor condensation influences atmospheric pressure and dynamics. Atmospheric Chemistry and Physics, 13, 1039-1056.

[4] Makarieva A.M., Gorshkov V.G. (2011) Radial profiles of velocity and pressure for condensation-induced hurricanes. Physics Letters A, 375, 1053-1058.