EARTH – A SOMEWHAT BIGGER LABORATORY FOR SCHOOL PHYSICS

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Rationale

Indications for teaching Science in XXIth century abstract from specific disciplines, like Physics or Geography and come back to treating so-called natural sciences as a unique entity. Newton's mechanics and Maxwell's laws disappear from school curricula and become substituted by "Light and energy" [Jordan, 2009] or "Energy sources and use" [Millar, 2011].

In Poland, the recent reform of school programmes, so-called "Programme basis" removed teaching Biology, Chemistry, Geography and Physics from upper secondary school, substituting them by a general Science (MEN, 2008). Science will be taught to all students that choose Humanities as their specialization. The present detailed programme of Science seems a puzzle crosswords: in vertical the four specific subjects and in horizontal 25 themes, starting from science methodology but including "Laughing and crying", "Biggest and smallest" and so on. The new programmes were decided in 2007 but no textbooks were prepared in advance and no university proposed any specific training for teachers. In 2012, in view of prompt entering the new CVs to schools, the Ministry allowed any teacher of the four specific subjects to hold the whole course of Science. For all these reasons, searching for interdisciplinary paths in-between, say, Physics and Chemistry [Gagoś & Karwasz, 2012], Physics and Geography [Karwasz & Chojnacka, 2012] but also Geography and History [Karwasz, 2014] becomes urgent.

Didactics of Physics Division at Nicolaus Copernicus University Toruń is recognized as a pioneering center for interactive didactics. Simple objects, commonly called "toys" are used by us to substitute traditional (and frequently annoying) school experiments. This way of extra-scholar teaching Physics, first introduced in Poland some 15 years ago [Karwasz, 1998] obtained a really unexpected diffusion and step-by-step growth up to national science centers.

Earth is one of the larger laboratories, that one can imagine, and only the Universe is larger. Phenomena of Geophysics include optics (rainbow, hallo, blue sky, mirages etc.), thermodynamics (weather patterns, ocean currents, volcanoes etc.), mechanics (Earth's orbit, Earth's interaction with Moon, a flattened globe, mountain formations), radioactivity (age determining, radioactive energy balance) and others.

In present work we outline some experiments which can be used in interdisciplinary teaching Geography: how some of complex phenomena like climate patterns can be illustrated by simple physical laws. Experiments presented can be repeated by teachers, seen in science centers or even done by pupils at home. Experiments described here will receive an internet virtual mirror at Didactics of Physics Division .

Laws of Physics

Phenomena on a great, Earth-like scale obey the same physical laws as the laboratory experiments. Just few physical laws determine the main behavior of atmosphere, lithosphere, hydrosphere. Moreover, due to the approximately closed nature of the system Earth+Sun +Moon, these phenomena are governed by quasi-static equations. The equation can be, additionally, simplified by separating the vertical and horizontal coordinates [Peixoto & Oort, 1984]. To the first approximation, the mathematics behind Earth's phenomena is not complex We will use these theoretical indications while illustrating Geophysics by our simple experiments.

I. Shape of Earth

The shape of Earth is usually referred to as "geoide" what is a tautology: Earth's shape is "earth - like". To the first approximation the shape of Earth is an ellipsoid – a sphere flattened by the quick rotation of the globe, like a bulk of clay flattens on the potter's rotating plate, see our experiment with a rotating spring in fig. 01.

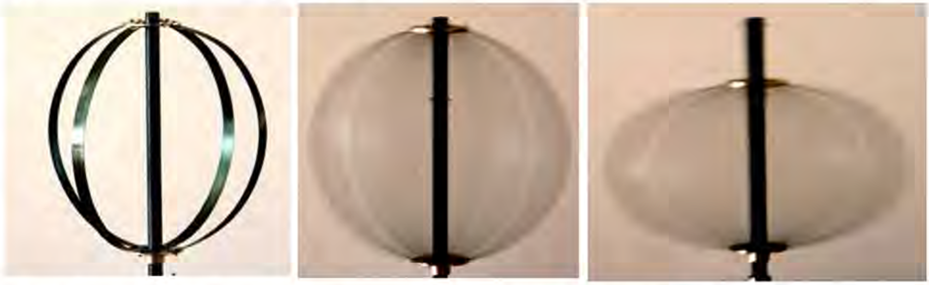

Fig. 01. Rotating spring flattens with increasing velocity of rotation – the same as planets.

A more exact determination of the ellipsoid is not trivial. The question was posed already by Copernicus on first pages of his "De revolutionibus". He asked why water does not flow down from a spherical Earth. Copernicus used Aristotle's way of reasoning – "because water is heavy so it fills up hollows in the soil". Now, after Newton, we know that a correct answer is because of centrally acting gravitational force. But the question on the shape still remains.

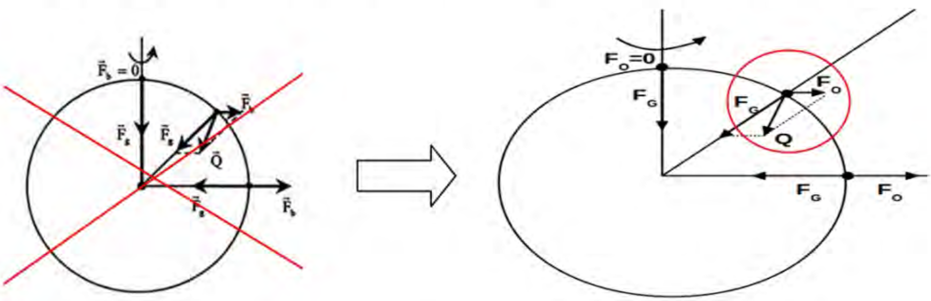

Fig. 02. The gravity force FG, acting towards the center of Earth sums up with the centrifugal force F0 acting horizontally on this picture, giving the effective gravity force Q. The effective gravity is stronger on the poles than on the equator. If Earth were a sphere (fig.02a), the effective gravity vector would show a component along the surface of Earth. This would cause the water flowing towards equator. The shape of Earth is ellipsoid (fig. 02b) in a way that the effective gravity is in every point perpendicular to Earth's surface. The latter phrase is the definition of the geoide.

To illustrate a flatted Earth's ball, a picture like in fig. 02a is usually shown. But it is wrong! If Earth were like that on fig. 1a, the effective gravity (i.e. the centrally acting gravity force and horizontally in fig. 02a acting centrifugal force) would have a component along the Earth's surface. This would mean that waves of kilometric heights would wash up the surface of Earth in a continuous way: the effective gravity force can not have a surface-along component! The effective gravity force must be perpendicular to the surface of Earth, or rather opposite: the surface of Earth is such that the gravity force is perpendicular to it in every point. A flattened sphere, i.e. an ellipsoid, as in fig. 02b. satisfies this condition.

Defining Earth's shape by the point-to-point vertical vector of gravity is somewhat clumsy. Geographers use another definition: they show the height over the sea level, like in fig. 03a. The lines shown in fig. 03a, called in Polish "poziomica", i.e. "level-lines" are the lines of a constant height. In Physics we call them lines of a constant potential energy, i.e. "equi-potential" lines. They apply to electrostatics [see for ex. Sadowska & Karwasz, 2011], to gravity [see for. ex. Karwasz & Chojnacka, 2012] and to other physical fields as well. Now, we have an exact definition: geoide is a shape defined by an equipotential surface of the gravity. In other words, it is the shape of Earth if totally covered by water, like in the question postulated by Copernicus. "Also marine waters are arranged to form a spherical shape [...] as land and water lay on a gravity center of the Earth, which is also the centre of its volume".

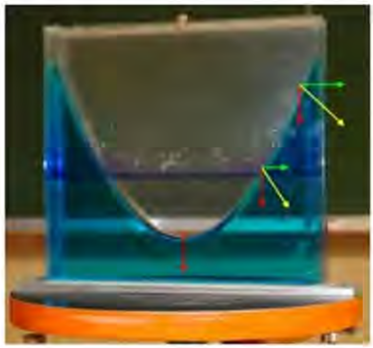

Fig. 03. The sea level is the reference level to determine the height on Earth's surface (fig. 03a). Rivers flow along the maximum difference of the level, what correspond to the maximum vicinity of the equi-potential lines (fig. 03a). The vector of force is always perpendicular to the surface of water, like in the rotating aquarium (fig. 03b). Both pictures illustrate that the effective gravity force acts perpendicular to the effective gravity equi-potential lines.

We are not able to show centrally acting gravity force vector, perpendicular to Earth's surface like in fig. 02b, but we can illustrate this concept by a rotating flat aquarium, see fig. 03b. Both the surface of Earth and the surface of water rotating in aquarium are perpendicular to the force vector. In the case of aquarium the gravity is vertical and the centrifugal force, rising with the distance from the rotation axis, is horizontal. As a result the surface of water is a paraboloid, see fig. 03b. On Earth the surface of water would by an ellipsoid, if no other effects were present. In every case, the gravity measured with a plumb-line is always perpendicular to the sea line, see fig. 04a.

Effective gravity depends on many factors, like the distribution of mass inside Earth, oceans and continents continents, land and see tides, and presence of mineral reservoirs. A dedicated satellite GOCE sent by European Space Agency in 2010, flying on a low (150 km) orbit has measured the equipotential surface over the Earth with a centimeter precision. Measurements done confirm earlier results that the geoid surface differs from the ellipsoid by up to 100 meters in some regions. The geoid is higher than ellipsoid in the region of Indonesia and Iceland but lower than the ellipsoid in the region of Himalaya, see a map on fig. 04b. We are not able to explain it without the mathematical expression for the gravitational potential V.

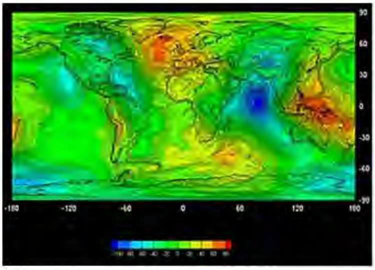

Fig. 04a. The geoid surface is defined by sea level; it is always perpendicular to the gravity force, as measured by plumb-line (beach of Sopot on the photo).

Fig. 04b. The difference between the geoide and ellipsoid surface – dark gray are negative differences, mid-tone gray are positive differences. The geoid is about 100 m below ellipsoid in the region of Indian Ocean (and less in Himalaya) and 100 m above the ellipsoid over Iceland and Indonesia. The Indian Ocean basis is formed of light, calcite rocks, Iceland is the region of the outflow of heavy, magmatic rocks from Earth's depths.

The gravitation potential created by a mass M at a distance r in expressed by a simple relation $V = G\frac{M}{r}$, where G is the gravitational constant. In the case of geoide, if the mass beneath is smaller (rocks are light), in order to keep a constant potential, the surface of the geoide must be below the ellipsoid surface. In fact, both Himalaya and the seabed of the Indian Ocean are made of a thick layer of light (limestone) rocks, so the geoide surface there is below the ellipsoid; opposite in Iceland, with relative heavy basalts flowing continuously out from the volcanic ridge in the middle of Atlantic Ocean – the geoide is above the ellipsoid, see fig. 04b.

II Age of Earth, Universe and Moon

The age of Earth is sure more than the biblic 6000 years, but even prominent scientists like Lord Kelvin hundred years ago calculated it as about 100 million years. There is an easy way to estimated the age of Earth using one of the subjects listed in "Science for XXI century" [Millar, 2011], i.e. the radioactivity. The subject is important as a part of social consciousness in energetic questions, cancer treatments, health security and so on. Usually, the radioactivity is associated with uranium or plutonium, but these are not the only cases: the radioactivity was discovered in uranium and plutonium is one of the first chemical elements created artificially, but radioactivity is present everywhere, so can be shown easily (and with a high didactical profit) in school laboratories.

The experiment we propose is the radioactive decay of potassium, ^{40}K. A portable radiation counter used for security monitoring in scientific laboratories is simple and relatively cheap, see fig. 05a. A small amount of any substance containing potassium (we use KCl) gives a measureable signal on the counter – several counts per second. Potassium ^{40}K decays into stable ^{40}Ar in β-reactions $^{40}K \rightarrow {}^{40}Ar + e^- + \underline{\nu}$, i.e. emitting an electron and antineutrino. The well known half-life time of ^{40}K is 1.2 billion years, but we can check it experimentally.

In order to estimate the age of the sample containing potassium we need to know only the percentage of the radioactive ^{40}K isotope (which is $1.2 \cdot 10^{-4}$). The amount N' of potassium ^{40}K nuclei decaying in a second is proportional to the number of these nuclei N_0 in the sample and the decay rate λ, according to equation $N' = \lambda N_0$. The decay rate is related to half-life time $T_{1/2}$ through the relation $T_{1/2} = \ln 2/\lambda$.

In the proposed experiment, some 1.5 g of KCl (i.e. about 0.02 mol, the amount chosen to make calculations simple) is placed in a thin layer (to avoid the absorption of the emitted electrons in the sample), just below the counter. Measuring about 8 counts/sec (with the background level of about 1 count/sec) but knowing that half of the electrons is emitted down and detector's efficiency is about 50%, we estimate the number of decays as some N'=28/sec. With Avogadro's number of $6\cdot10^{23}$ atoms/mole one gets totally 12×10^{21} potassium nuclei, out of them $N_0=14\cdot10^{17}$ being ^{40}K. These numbers give $\lambda=N'/N_0 \approx 28/14\cdot10^{17}/s \approx 2\cdot10^{-17}/s$ and finally $T_{1/2}= 3.5\cdot10^{16}$ s, i.e. $1.1\cdot10^{9}$ yrs, in good agreement with the precise value.

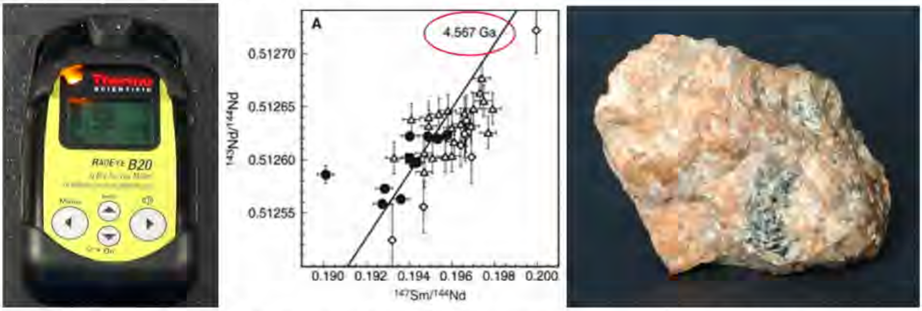

Fig. 05. The age of Earth. **a**. Radioactive decay of potassium ^{40}K isotope; even if the contents of the ^{40}K isotope is relatively small, a simple radioactivity tester shows about 8 decays/second from a thin layer of potassium salt below its head. **b**. Scientific determining Earth's age from radioactive decays; measurements in zirconia crystals for ^{147}Sm and ^{144}Nd ratio indicate the age of Earth as 4.567 billion yrs [Boyet & Carlson, 2005]. **c** Big crystals in granite sample from Helsinki indicate slow cooling; the age of this sample is about 3.5 billion years (collection GK).

The age of the potassium sample must be, therefore, at least several billion years: the initial amount of ^{40}K decays very slowly, but thanks to a great numbers of atoms in a small sample, the signal is measureable. The same idea stays behind the determination of the age of Earth. Different nuclei decay with various times – the most abundant out of uranium isotopes ^{238}U decays with $T_{1/2}$=4.4 billion yrs but radon ^{222}Rn with $T_{1/2}$=3.8 d. The ^{238}U radioactive decay starts a series, as following: $^{238}U\ \alpha\rightarrow\ ^{234}Th\ \beta\rightarrow\ ^{234}Pa\ \beta\rightarrow\ ^{234}U\ \alpha\rightarrow\ ^{230}Th\ \alpha\rightarrow\ ^{226}Ra\ \alpha\rightarrow\ ^{222}Rn\ \alpha\rightarrow\ ^{218}Po\ \alpha\rightarrow\ ^{214}Pb\ \beta\rightarrow\ ^{214}Bi\ \beta\rightarrow\ ^{214}Po\ \alpha\rightarrow\ ^{210}Pb\ \beta\rightarrow\ ^{210}Bi\ \beta\rightarrow\ ^{210}Po\ \alpha\rightarrow\ ^{206}Pb$ (stable), with specific lifetimes for every nuclei. The contents of slowly decaying isotopes forms a fingerprint for the age of the rock. Modern radiation detectors allow to trace very rare isotopes. Choosing rocks and mineral geologically almost stable, like micro-crystal of zirconia, it is possible to determine their age. One of such recent determinations gave the age of Earth (and therefore of the whole Solar System) as 4.567 billion years [Boyet et al., 2005]. Hectic searches are under way to find the oldest possible rocks solidified on Earth, see for ex. [O'Neil, 2008]: there are several possible candidates, like Acasta gneisses. We note, that all those solidified rocks coming from Hadean Eon are now found in drifted-out continental plates, like Greenland, South Africa, Australia. A sample of granite with extremely big crystals, testifying slow cooling (i.e. hot Earth) comes from Helsinki airport area and is some 3.7 billion years old, see fig. 5c. Many pieces of old granites were dragged from Scandinavia to Poland by glaciers and each pupil can make an own collection.

Tracing specific (especially heavier than Fe) chemical elements gives the information on the supernova explosion than formed the Solar System: due to the physical reasons [the nuclei binding energy, see for ex. Karwasz & Więcek, 2012] elements heavier than Fe must be formed inside neutron-like stars. To go earlier in time, towards the Big Bang, one finds another fingerprint, left just some 300,000 after the beginning of the Universe. It is so-called cosmic background radiation: it comes from the moment that "darkness separated from the light", see a mosaic from St. Marco's Cathedral in Venice from XII century in fig. 06a. Physically, the initial Universe was so dense, that any emitted light was immediately absorbed by other atoms. We observe such auto-absorption in yellow (sodium) road lamps [Karwasz et al. 1999]. When the Universe became less dense, the trapped light was freed. Due to the expansion of the whole Space, the light that belonged to the visible range now has a longer wavelength and is observed as microwaves – by ground-based radiotelescopes like that in Piwnice near Toruń, see fig. 06b or by space missions like Planck. The latter gave the most accurate number for the age of the Universe – 13.82 billion years. But the background cosmic radiation can be seen on the old TV – some 1/3 of the "noise" on the screen comes from the beginning of the Universe, fig. 06c.

Fig. 06. Determining the age of Universe. **a**. Biblical separation of light from darkness in the Book of Genesis, according to the imagination of the artist of the XIIth century is shown on the mosaic at Venice cathedral. **b**. the microwave cosmic background radiation can be measured ground-based radiotelescopes (at UMK observatory in Piwnice), a more precise map was obtained by Planck space mission. **c**. The primordial microwave signal can be seen also on an old TV screen.

Moon is an inseparable companion of Earth. Apollo missions brought pieces of rocks, resembling much those present in Earth's external part, i.e. in the mantle. This indicates that these rocks once were part of Earth. Some 100 million years after formation, the Earth was hit by an object of the size of Mars. The encounter tore a powerful piece of matter and debris, which, it is believed, in 24 hours formed the Moon. It was the most violent day in the history of Earth. At the beginning of its history, the Moon orbit the Earth closer than today. Now, each year, moving away from her by about 4 cm per year. Moon is the main reasons for ocean tides, and these are tides which favored the life's climbing from waters to the land.

By a strange coincidence angular sizes Moon as seen from Earth are almost the same as the angular size of the Sun seen from Earth, compare with a photo from Apollo mission in fig. 07a. The period of rotation of Moon around its own axis is the same as its orbiting time around Earth; in other words only half of Moon is visible from Earth. Such a celestial mechanics correlation not unique in Solar System; for example a 2:3 resonance governs the movement of Mercury. However, to slow down a period of rotation some non-conservative forces must be present in the system. For the Moon+Earth system these are oceanic tides which can absorb the energy and lead to the adjusting of the rotation and circulation periods.

Fig. 07. **a**. As seen from the Moon it is difficult to say whether Moon accompanies Earth or Earth follows the Moon (photo NASA Apollo 11); **b**. the system Earth - Moon can be compared to canoes from Polynesia: the natives are sailing on a larger boat, but the smaller one is needed for balance. **c**. A funny bicycle rider remains in balance thanks to a small ball on the other side of the lever.

The crucial role of Moon for Earth are not only tides. Numerical simulations showed that without Moon the Earth's axis Moon would enter big oscillations just in 10 million years time. In other words, a much smaller and 81 times lighter Moon, posed at relatively small distance (about 10 Earth's circumferences) exercises a stabilizing function on our planet. This is like Polinesia navigation on a boat stabilized by a smaller one, see fig. 07b. Numerous objects, like that on fig. 07c illustrate the same concept.

III Earth' internal structure

Earth's internal structure can be studied with a great detail (i.e. down to the depth of the iron-nickel core and with a few kilometer resolution) detecting seismic waves. The two physical types of waves – longitudinal and perpendicular propagate with different velocities, get attenuated and reflected in different manners. A slinky spring [Karwasz et al. 2005] kept with a adjustable tension can be used to show these properties of both types of waves.

Earth's interior is called core, see fig. 08a, but its dimensions are unusual for what we typically name as a core – the radius of Earth's core is half of the planet radius. The core is composed of iron and nickel, remnants of the end of nuclear reactions in pre-Sun [see more on nuclear reactions in Karwasz & Więcek, 2012]. The velocity of longitudinal wave indicate that it probably contains also some lighter elements, maybe silicon. But nobody reproduced in lab the iron-nickel-silicon alloy under such great pressures, so do not know a proper crystallographic structure. Cognitivistically, we compare Earth's structure to an avocado fruit – a big hard core, a soft mantle and a thin, harder skin ("crust"), see fig. 08b.

Fig. 08. The internal structure of Earth. **a**. A double naming of the layers in Earth – a Greek one (lithosphere, mesosphere) and Mohorovičić-like (crust, mantle). **b**. Illustrative section of avaocado-like Earth. **c**. Lava lamp, with two liquids of different thermal dilatation, similar to different mineralogical phases (olivine, magnesium silicates and so on) shows a mechanism of the vertical convective transport in the Earth's mantle.

A soft, semi-liquid mantle is unique among the planets of the Solar System. A right balance between the heat coming from the interior (some 20 TW) and created from radioactive decays (next 20 TW) of uranium, thorium and potassium contained in a form of light compounds (oxides, silicates) in the mantle assures this energy flow. Thanks to it the surface plates are still, after 4.5 billion years, in constant motion. The negative outcome are earthquakes but the silicate-carbonate rock transitions in liquid magma assured a supply of CO_2 to atmosphere, and therefore the pleasant, 33 K greenhouse effect [see for ex. Karwasz & Służewski, 2013].

We show a vertical convective motion inside the mantle using a so-called lava lamp, see fig. 08b. Two liquids with different thermal expansion coefficients, heated from below, mix up-and-down, like lava rising in volcano channels. In fig. 09a we show an aquarium heated from below, where the liquefied wax floating on water surface once cooled forms plates-like pattern, with some hills, mountains and trenches. Continental plates will move for next hundreds of million years, as follows from recent computer modeling, in 50 mln yrs America and Eurasia will collide at the North Pole. Oceanic plates are thinner, but heavier, and continental one are light, like the ice plates covered by snow on the Baltic sea, see photo 09c.

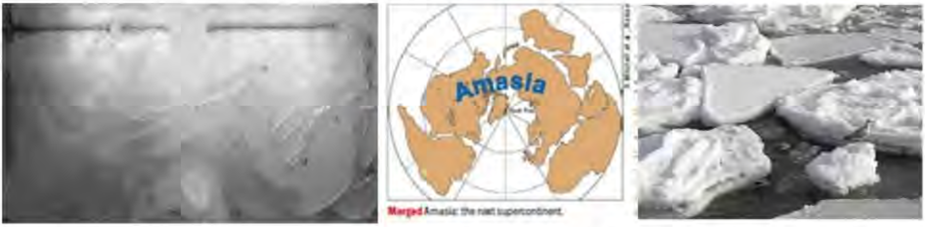

Fig. 09. **a**. Paraffin wax on the surface of the water shows the distribution of the tectonic plates (photo A. Karbowski). **b**. America and Eurasia will collide in some 50mln years at the North Pole [source: Physic World, March 2013]. **c**. Continental and oceanic plates resemble pieces of sea-water ice: some of them thicker, covered with snow, some of the barely floating on the sea surface, like on this photo taken from Sopot molo (M. Karwasz).

IV Atmosphere and oceans

A dominant feature in understanding atmosphere mechanics and thermodynamics is the diversified in vertical layers and geographical latitudes, infrared-radiation budget, see for ex. [Karwasz & Służewski, 2013]. The warm, wet (and therefore light) air rises above the equator, dries-up at the edge of the troposphere (giving tropical rains) and is convected, like in lava lamp, towards tropics. There, dry, cold (and heavy) sinks down to the ground at Sahara, Gobi and Kalahari regions. This is so called Hadley cell, coupled with a weaker cell above our latitudes. But for the horizontal transport, this is so-called Coriolis force that governs the weather, see fig 10a.

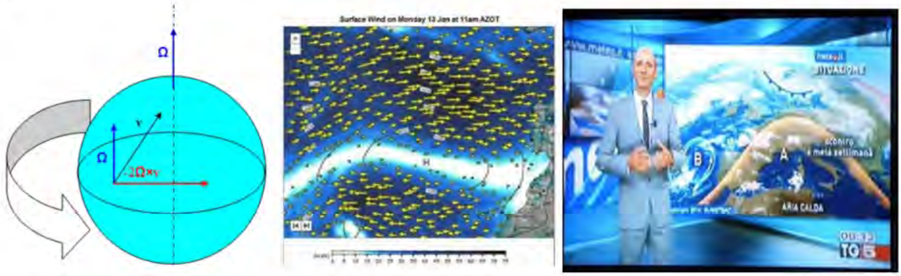

Fig. 10. Coriolis force is due to rotation of Earth: objects moving from equator towards the poles find the Earth's surface too slow. **a**. The mathematical formulation with vector products is rather difficult but the rule is simple: on the Northern hemisphere the air moving North is deviated to the right. **b**. Coriolis force makes the air flowing out from the region of high pressure (like above Azores on Jan 6th 2014) circulate in clockwise direction. **c**. The air flowing-in towards the pole of low pressure circulates (on Northern hemisphere) anti-clockwise.

Coriolis force is related to the fact, that Earth rotates; physically in a rotating reference frame apparent (i.e. not predicted by the II Newton's law) are present. We already mentioned the centrifugal force. Coriolis force appears if an object tries to move in a rotating frame – it is like a mysterious force "cutting legs" when we walk on a rotating plate. Its mathematical formulation is not so easy, see fig. 10a. Coriolis force is the cause that winds flowing out-of center (i.e. at high-pressure poles, see fig. 10b) tend to rotate clockwise on the Northern hemispehere (and anti-clockwise on the South hemisphere). Low-pressure poles behave to the contrary – rotate anti-clockwise on Notherrn Hemisphere, see the weather forecast in fig. 10c.

Coupled with the Hadley cell, Coriolis force is also the reason for so-called trade winds, used by Columbus when he travelled west in October and came back East in March, see fig. 11a. The route of Columbus is a nice example of closing loops in atmosphere and hydrosphere circulation: oceanic currents flow in one direction on the surface and close the loop in depths. This is also the case of Gulf Stream – waters heated in Sargassic Sea flow towards Europe, cool down in the region of Iceland and come back in depth, like we illustrate it in the experiment in fig. 11b.

Fig. 11. **a**. Columbus used the seasonal variation of trade winds to complete his travel (Source: Wikipedia). **b**. Similar closed in depth loops characterize oceanic currents; we show it in experiment with hot coloured water rising up in aquarium and cooled by the ice on the right corner.

Didactical hints

As an attentive reader surely noted, the presented topics follow always a similar line:

1) formulation of the cognitive problem concept ("what is the shape of Earth?"), 2) simplified illustration (flattening ball made of spring ribbon), 3) a more rigorous explanation (ellipsoid), 4) modern, scientific follow-up (GOCE experiment). This is clearly a constructivistic-like path [see Karwasz, 2013], needed for the modern, interdisciplinary school, not only in Poland.

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