Being wrong – but for good reasons

French 18th century attempts to understand the Trade winds through fluid dynamic experiments 200 years ahead of their times

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Thanks to our hindsight wisdom we tend to underestimate scientists from previous centuries or millennia. So for example in the 1600's one needn't be "conservative", "stupid" or "dogmatic" to question the Copernican heliocentric system. It is so obviously true for us today that we forget that before Newton there were no good answers to the question: why we didn't fall off the Earth? It is after all spinning around its axis with 200-400 m/s and orbiting around the sun with 30 km/sec!

This is a story about scientists of the 18th and early 19th century who held on to a theory about the mechanism of the Trade winds, which turned out not to be quite correct. They have been belittled by modern scholars, but they based their views on good scientific reasoning and in some respects showed more scientific judgement than later generations.

The interest in the Trade winds

In the 1500s, with the increased shipping and the exploration of the marine routes to Asia and the New World, the need to map and understand the general circulation of the atmosphere and oceans became an important issue. By 1600 it was known that irregular winds from a westerly direction dominated only higher latitudes; around latitude 30º there was a torrid zone with weak winds; and to the south of this latitude there were regular north-easterly winds, what came to be called the Trade Winds. This pattern appeared to mirror itself south of the equator with a steadily south-east Trade Wind (figure 1).

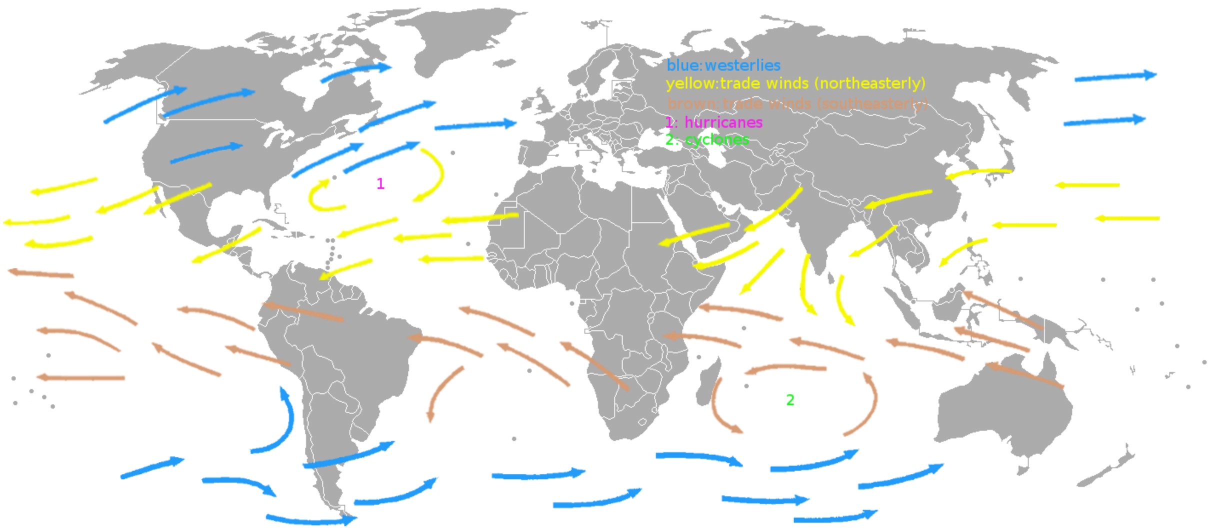


***Figure 1*: Prevailing winds at the Earth's surface during winter.** *Winds from the west, in blue, north of the Tropics of Cancer and south of the Tropics of Capricorn. Winds from east (Trade winds) between the tropics: from north in the northern hemisphere and from south in the southern hemisphere (image WikiCommons, author KPDV).*

From early on the scientific discussions centred on these Trade Winds, which thanks to their steadiness were assumed to be the easiest to explain. Although they were thought to be a consequence of the Earths' rotation, exactly how the rotation affected them was not clear. During 150 years, from 1686 to 1837, at least three intuitively appealing explanations would emerge.

The 1st explanation: Galileo's and Kepler

Galileo and Kepler suggested that the atmosphere moved with a uniform velocity representative of the eastward speed of latitude 30°, since this latitude divided the hemispheres into two equal parts.[1] The westward (easterly) wind patterns equatorward of 30° were consequences of the failure of the Earths' gaseous envelop to "keep up" with the speed of the earth's more rapid rotation, while the eastward (westerly) winds poleward of 30° were a consequence of the gaseous envelop "running ahead" because of the earth's slower rotation (fig. 1). To Galileo and Kepler the rotation of the Earth not only explained the Trade Winds, the Trade Winds themselves were a proof of the Earth's rotation.

1. The lateral surface of the portion of sphere above the 30° parallel is πR^2, which is the half of the surface of the hemisphere.

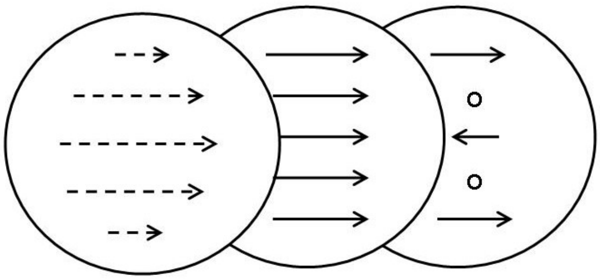


***Fig. 2:* Galileo's and Kepler's explanation of the general circulation and in particular the easterly Trade Winds.** *While the velocity of the Earth's surface decreased from the Equator (dashed arrows to the left), the eastward absolute motion of air or water was supposed to be independent of latitude (full arrows, centre). As a consequence (right) the flow "moved ahead" at higher latitudes with westerly winds, lagged behind around the Equator with easterly winds. In the latitudes in between the winds would be weak.*

This explanation was further elaborated by other scientists and came to dominate the thinking for most of the 1600's. One of those scientists was Edme Mariotte (1620-1684), whose posthumous *Traité du movement des eaux et des autres corps fluides* was presented to the Royal Society, 28th April, 1686. This was the same meeting when the first manuscript of Isaac Newton's *Philosophiae Naturalis principia mathematica* was presented. Both treatises were introduced by the Society's leading scientist, the astronomer Edmond Halley.

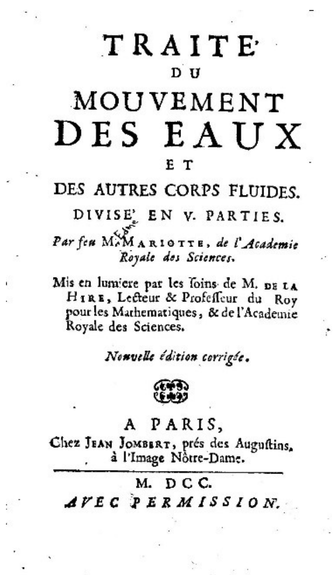

TRAITE
DU
MOUVEMENT
DES EAUX
ET
DES AUTRES CORPS FLUIDES.
DIVISE' EN V. PARTIES.
Par feu M. MARIOTTE, de l'Academie Royale des Sciences.
Mis en lumiere par les soins de M. DE LA HIRE, Lecteur & Professeur du Roy pour les Mathematiques, & de l'Academie Royale des Sciences.
Nouvelle édition corrigée.
A PARIS,
Chez JEAN JOMBERT, prés des Augustins, à l'Image Notre-Dame.
M. DCC.
AVEC PERMISSION.

***Figure 3 :* Mariotte, Traité du mouvement des eaux et des autres corps fluides (1686).** *The 1700 reissue can be found online, archive.org.*

In contrast to Newton's manuscript, later famous under its shortened title *Principia*, Mariotte's paper is much less known although at its time it was considered to be a major scientific work in the understanding of the atmosphere and oceans. Mariotte's treaty suggested three causes of winds, the first being:

"The motion of the Earth from West to East, or, if that hypothesis is not allowed, that of the sky from East to West" ("Le mouvement de la terre de l'Occident à l'Orient, ou, si l'on n'admet point cette hypothèse, celui du ciel de l'Orient à l'Occident"). The second invoked the heating of the Sun and condensation processes, the third influences by the moon.

THE 2ND EXPLANATION: EDMOND HALLEY

Edmond Halley (1656-1742) studied Mariotte in great detail but didn't quite accept his elaboration on Galileo's and Kepler's explanations. As a good friend to Isaac Newton he could follow his work from "inside" and understood that the air would not lag behind, but would be kept on the rotating Earth by the Earth's gravity.

Halley instead published his own version, *"An Historical Account of the Trade Winds, and Monsoons, observable in the Seas between and near the Tropicks, with an attempt to assign the Phisical cause of the said Winds".* The paper was based on his experienced from an excursion to the mid-Atlantic island St-Helena some 10-15 years earlier, when he had studied the tropical wind regimes. Back in England he had systematically interviewed English navigators; and by 1686 he had acquired a remarkable good overview of the wind patterns in the tropics (fig.4).

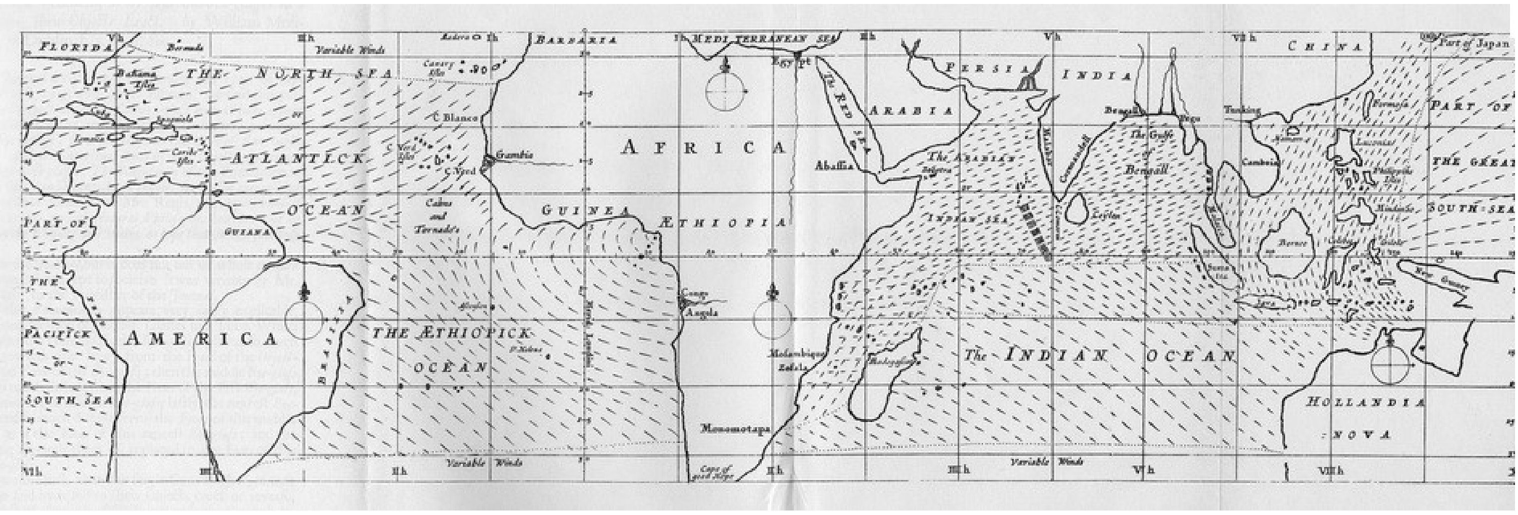


***Figure 4:* Halley's marine wind chart from 1686.** *Although the prevailing NE-ly and SE-ly trade winds are visible (the wind arrows are difficult to discern, but the thick end marks the head of the arrow, the thin end points to the origin of the wind). However, many ocean areas show other wind directions.*

According to Halley, irrespective if the Earth was circulating around the Sun or the Sun around the Earth, there would be a diurnal displacement from east to west of the sun's maximum heating. This would, Halley thought, lead to an influx of air "from behind", from the east and thus explain the Trade winds (fig.5).

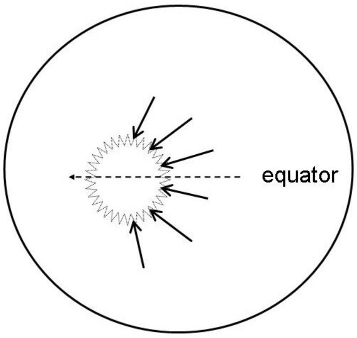
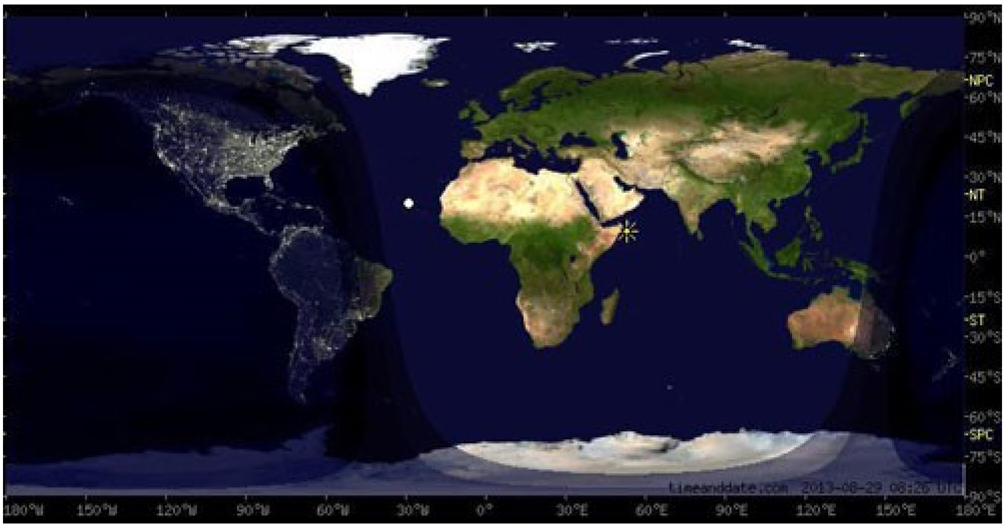


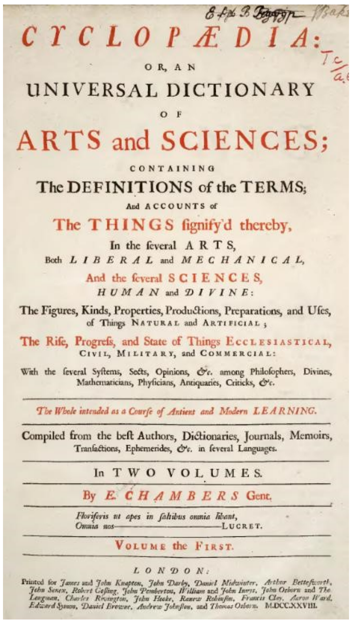
Fig. 5 *(above):* ***Halley's explanation of the easterly Trade-winds.*** *As the maximum heating of the Sun at the Earth's surface during the day moves westward, air will be sucked in from behind and replace the air that has been heated and risen.*

Fig. 5bis *(below): Visualisation of the subsolar point on a day-night map. It can be seen on the north-eastern coast of Africa (map is drawn in August ⇒ subsolar point is North of Equator) (9h30 a.m. GMT ⇒ the subsolar point, or zenital point, is East of Greenwich, UK) (image site TimeandDate)*



Halley also inferred the atmospheric westerly flow at upper levels, as a way to transport away the air that had converged in the heated area. Halley's explanation soon found its way into the prestigious "Chamber's Cyclopaedia" where the section "Physical Cause of Winds" is copied straight from the last five pages of Halley's text (figure 6). This part of Chamber's book was later translated into French and incorporated into Diderot and d'Alembert's *Encyclopédie* of 1765 (in 1781 incorporated into Brisson's *Dictionnaire Raisonné de Physique)*.

In 1747 d'Alembert produced an explanation of his own *"Reflexions sur la cause générale des Vents"* which did not consider the rotation of the Earth at all and rather explored the effects of the gravitational attractions from the Moon and the Sun, similar to the tidal effects.


CYCLOPÆDIA:
OR, AN
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ARTS and SCIENCES;
CONTAINING
The DEFINITIONS of the TERMS;
And ACCOUNTS of
The THINGS fignify'd thereby,
In the feveral ARTS,
Both LIBERAL and MECHANICAL,
And the feveral SCIENCES,
HUMAN and DIVINE:
The Figures, Kinds, Properties, Productions, Preparations, and Ufes, of Things NATURAL and ARTIFICIAL;
The Rife, Progrefs, and State of Things ECCLESIASTICAL, CIVIL, MILITARY, and COMMERCIAL:
With the feveral Syftems, Sects, Opinions, &c. among Philofophers, Divines, Mathematicians, Phyficians, Antiquaries, Criticks, &c.

The Whole intended as a Courfe of Antient and Modern LEARNING.

Compiled from the beft Authors, Dictionaries, Journals, Memoirs, Tranfactions, Ephemerides, &c. in feveral Languages.

In TWO VOLUMES.

By E. CHAMBERS Gent.

Floriferis ut apes in faltibus omnia libant,
Omnia nos——LUCRET.

VOLUME the FIRST.

LONDON:
Printed for James and John Knapton, John Darby, Daniel Midwinter, Arthur Bettefworth, John Senex, Robert Gofling, John Pemberton, William and John Innys, John Osborn and Tho. Longman, Charles Rivington, John Hooke, Ranew Robinfon, Francis Clay, Aaron Ward, Edward Symon, Daniel Browne, Andrew Johnfton, and Thomas Osborn. MDCCXXVIII.


KONGL. VETENSKAPS-
ACADEMIENS
HANDLINGAR,
FÖR MÅNADERNE
JULIUS, AUGUSTUS, SEPTEMBER,
År 1762.
PRÆSES
Herr CARL LEHNBERG,
Directeur.

Kårta Anmårkningar,
Om
Blås-Vådren.

Jorden är til några mils högd omgifven af en fin flytande materia, fom kallas Luft, hvilken har många märkvärdiga egenfkaper. Vid det-
L ta

<u>Figure 6:</u> *(left)* ***the Cyclopedia, by Ephraïm Chambers (1680-1740), first edition 1728;*** *(right)* ***the internationally renowned Swedish astronomer Pehr Wargentin stated in a paper 1762 "Short Notes On Windy Weather" that Halley, and possible also d'Alembert, were the only ones who had provided trusted explanations of the Trade winds.***

Halley's explanation of the Trade Winds would remain the most widely known and accepted for 150 years; it was abandoned only in the 1830's when the third explanation, which also involved the rotation of the Earth, was presented by a set of German and English scientists.

THE 3RD EXPLANATION: DOVE AND HADLEY

Since the 1830's are the years when Gaspard-Gustave Coriolis (1792-1843) published his famous paper on relative motion in rotating systems[2] and Siméon-Denis Poisson (1781-1840) showed how this "Coriolis Effect" explained the deflection of artillery grenades, it would be natural to assume that the third explanation of the Trade winds drew its inspiration from the works of these prestigious scientists. Instead, it was an explanation that had been presented 100 years before by a fairly unknown English meteorologist and lawyer.

2. See A. Moatti, analysis of Coriolis' 1831 & 1835 articles, BibNum, October 2011.

In his 1735 paper "*Concerning the cause of the general trade-winds*"[3] published in the 34th volume of *Philosophical Transactions of the Royal Society* George Hadley (1685-1768) had suggested a rather "common sense" explanation of the Trade winds: air moving from say Tropics of Cancer at 23° N equatorward would enter latitudes with faster speeds and, while retaining its absolute speed, appear to "lag behind" and thus create winds from north east or east (figure 5).

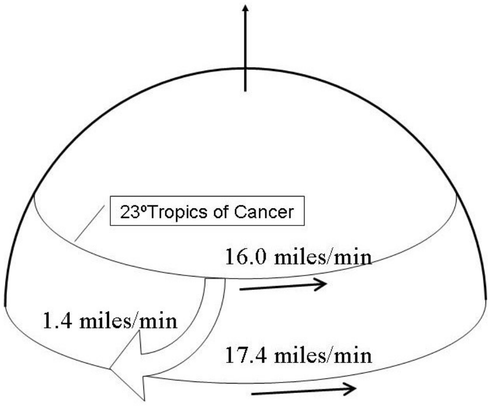


***Fig. 7:* Hadley's "common sense" explanation of the Trade-winds (with his own units):** *air moving from higher latitudes to lower and conserving its absolute velocity will, when entering latitudes with higher velocities, appear to lag behind, and thus creating easterly wind components.*

Air moving poleward would for the opposite reason appear to "run ahead" of the more slowly moving latitudes and create south-westerly or westerly winds. In both cases, the air parcels would follow *clockwise* trajectories.

For many scientists in the 1830's, Hadley's explanation, or "Hadley's Principle" as it became known, provided "a rational and satisfactory explanation", as one of them, the influential English chemist and natural philosopher John Dalton (1766-1844), expressed it. It was supported also by the influential British astronomer John Herschel (1792-1871), son to the even more famous astronomer William Herschel, the discoverer of Uranus. It was endorsed at the highest level by James Thomson (1822-1892), elder brother of Lord Kelvin (William Thomson) in his 1892 Royal Society "Bakerian Lecture" on the general circulation of the atmosphere:

> *Hadley's theory in its main features* [...] *must be substantially true, and must form the basis of any tenable theory* [of the general circulation of the atmosphere] *that could be devised.*

3. See O. Talagrand, analysis of Hadley's article, BibNum, September 2013.

However, by Thomson's 1892 speech the "Hadley-Dove Principle" was wrested out of German hands and was made solidly "British". Thomson emphatically hailed Hadley and mentioned his name almost 40 times.

Today George Hadley is reckoned among the great English scientists. There is a "Hadley Crater" on the moon, the convective atmospheric overturning in the tropics is called "The Hadley Cell" and the climatological centre of the UK Meteorological Office "The Hadley Centre", is named after him.

Figure 8 ***: Logo de l'Office britannique de recherches climatiques.*** *Cet organisme de recherches, créé en 1990, a été nommé en hommage à Hadley.*

WHY DID IT TAKE SO LONG?

Scholars of the history of meteorology have, however, grappled with the question why it took so long to replace Edmond Halley's model with George Hadley's – or somebody else's of a similar type. During the 1700's the same "common sense" explanation as Hadley's was suggested by other scientists, Colin Maclaurin (1698-1746) in 1740, Immanuel Kant in the 1750's, Pierre-Simon de Laplace at the end of the century, among others. Maclaurin was even awarded a prize by the French Academy of Science; Kant was well known and read in all of Europe and so was Laplace. Still Edmond Halley's 1686 explanation prevailed for 150 years.

Should it be taken as yet another example of the "inertia in science", the tendency for quoting older inadequate theories, while continuing to ignore the more recent and more acceptable ones? This might be true in many cases, but perhaps not in this case, because George Hadley's explanation is *physically impossible*, whereas Edmond Halley's is not.

The metaphysical "Hadley's Principle"

The success of "Hadley's Principle" lies in explaining the *direction* of the winds in an intuitively appealing way, *easy to understand, remember and teach*. But there is no similar success in explaining the very unrealistic *velocities* of the winds. As Hadley himself noted in his paper, air arriving at the Equator would in his model have acquired a westward severe hurricane gale velocity of 37 m/s (figure 7).

Hadley explained the absence of such extreme winds by the effects of friction. This was not quite convincing since the wind increase was stronger at higher latitudes, even over rather smooth surfaces. Air moving poleward the short distance from Santander in northernmost Spain over the Bay of Biscay, then over Brest to Plymouth, would increase its velocity into the same severe hurricane winds of 30-35 m/s, but now from west.[4]

Later during the 1800's it was theoretically shown that material bodies moving (without friction) over the Earth's surface will just not behave as predicted by "Hadley's Principle". More can be said about this, but let us here remain at the level of understanding of the 1700's. At that time it was easy to see that Hadley's 1735 model was unrealistic due to its excessive winds, but Halley's 1686 model was not – it *yielded quite realistic predictions, rather close to reality.*

Edmond Halley's model confirmed

In his Bakerian Lecture 1892, James Thomson had suggested an experiment to be carried out to check Halley's 1686 theory:

> *a spirit lamp or other heater* [should be] *kept revolving slowly round in a circular path under a circular tray filled with water, the path being of a little smaller radius than the tray. The question being would or would not the water be set into revolutional motion, and if so, would it revolve in the same direction as the lamp or other source of heat does?"*

To test Halley's 1686 hypothesis as suggested by Thomson, such an experiment was indeed carried out at the meteorological department at University of Chicago in the 1950's by Professor Dave Fultz (1921-2002) and his

4. A simple calculation can be made: Earth's velocity at equator is 464 m/s; at Santander (latitude 43,5°), it is 464 * cos (43,5°) = 336 m/s; at Plymouth (latitude 48,5°) = 307 m/s. So there is a 30 m/s difference in velocity between Santander and Plymouth.

colleagues. Their research centred on the dynamics of water in *rotating* dishpans, warmed at the rim (the "equator") by a Bunsen burner and cooled at the centre (the "North Pole") by ice. Such a fluid dynamical model provided important clues to the understanding of atmospheric and ocean dynamics (figure 9).

***Figure 9:* A rotating dishpan experiment of the type normally conducted by Dave Fultz and his colleagues in the 1950's** *(and now common all over the world). The thermal difference between the heated edges and the cooled center of the dishpan creates motions, which by the rotation develop wave motions very similar to the atmospheric flow at jet stream height 9-12 km.*

When Fultz and his collaborators held the dishpan *stationary*, while the Bunsen flame was rotated underneath the outer rim, a flow pattern, quite similar to the real atmosphere's, formed in front of their eyes (figure 10).

At the bottom near the rim (= the equator), an easterly flow developed and near the centre (= the polar region and mid-latitudes) a westerly flow. But most surprising was that at the upper water surface (= the free atmosphere) this motion was from west to east, i.e in a direction opposite to the heat source rotation and in agreement with upper air observations.

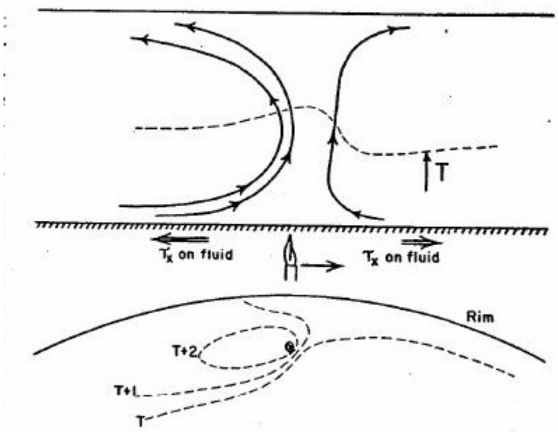


***Figure 10:* Dave Fultz's sketch of a suggested mechanism in the vicinity of the moving flame.** *The top half is a vertical cross section along the direction of the flame,*

moving to the right, corresponding to the "west". The dashed line is a schematic isotherm. There is a weak circulation ahead, to the "west" (right, above), a stronger behind, to the "east" (left, above), implying winds from the east at low levels, just as observed in the atmosphere, and winds from the west at higher levels, as mostly is the case in the atmosphere. The bottom half is the corresponding plan sketch of the isotherms.

Fultz and his colleagues commented in their report that "it is at least a curious irony that, when Halley's idea was at long last finally checked, the results were in the sense he would have expected both for the tropical surface easterlies and the upper westerlies further to the north."[5]

So there seemed to have been good reasons for scientists in the 1700's to hold on the Halley's idea. It was not only physically realistic; it even created motions similar to the real atmosphere's. *But how could they possibly know about Fultz's experiments 200 years later?*

They could! A French scientist, Nicolas Sarrabat, had in 1730 conducted the same type of experiments - *and reached almost the same results!*

Nicolas Sarrabat (1698-1739)

The main source of information about Nicolas Sarrabat is a 1845 article in *Revue du Lyonnais*, by Léonard Boitel: *"Mathematiciens et savants Lyonnais"*.

Nicolas Sarrabat was born 7 February 1698 in Lyon to a prosperous protestant bourgeois family of clock- and watchmakers. His father, Daniel Sarrabat (1666-1748), who was a talented painter, had converted to Catholicism. « Beauty, vivacity and genius of Nicolas brightened from his childhood on. » (« La beauté, la vivacité et le génie de Nicolas éclatèrent dès son enfance. »)

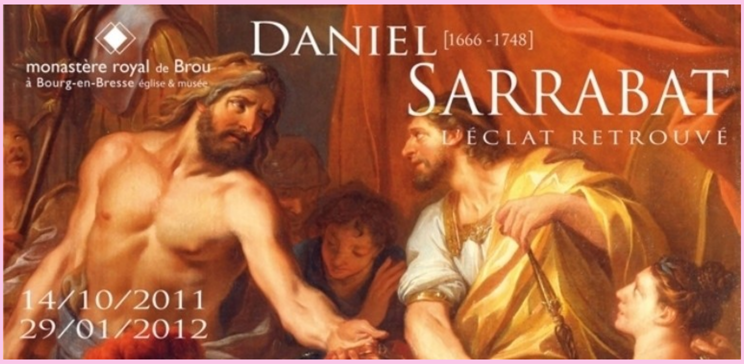


***Figure 11:* An exhibition of Daniel Sarrabat's work in Royal monastery in Brou (Bourg-en Bresse), in 2011-2012.**

5. Fultz D, Long R, Owens G, Boehm W, Kaylor R and Weil J, 1959, "Studies of thermal convection in a rotating cylinder with some implications for large-scale atmospheric motion". *Meteor. Monographs. Amer. Meteor. Soc* 104 pp.

He received his early education almost unbeknownst to his parents. He defended his general thesis of philosophy at Trinity College. When he had finished school, his taste led him into science and the Jesuit Order, the scientific elite at the time.
As a dedicated and obviously very gifted physicist, Nicolas took part and won many prizes offered by the *Académie des sciences, des belles-lettres et des arts* in Bordeaux. In 1727 he won a prize on a new hypothesis on the magnetic needle, in 1728 on the salinity of sea water and in 1730 on the causes of the variations of the winds. He treated several other issues such as plant physiology, almost always with success. In 1729 on the 31st July in Nîmes, he became famous for discovering a comet[6].

SARRABAT'S 1730 TREATISE

What interests us here is his 1730 treatise "*Dissertation sur les causes et les variations des vents"* (figure 12).

This text, although written almost 300 years ago, comes today over as a very direct, almost literary piece of text. Already in the first lines he sets a tune which sounds like a manifesto for the whole Enlightenment:

> *Les variations des Vents et leurs singularités sont une partie considérable et intéressante de l'Histoire naturelle, et la recherche de leurs causes occupe les Philosophes, depuis qu'il y en a d'assez curieux pour vouloir sonder les secrets de la nature. Mais il en est de ce point particulier de Physique comme de plusieurs autres : on cherche, on raisonne, on observe, on fait même des découvertes; et à mesure qu'on avance, on trouve toujours plus à découvrir: ne nous lassons pas pourtant, multiplions les recherches, faisons toujours de nouvelles Observations, ramassons autant de connaissances que nous pourrons ; nous n'atteindrons peut-être pas à une vérité exacte ; n'importe, la vraisemblance a son mérite en Physique, et quelques lumières de plus y sont précieuses plus que partout ailleurs.*
>
> [The variation of the Winds and their peculiarities is an interesting and considerable part of Natural history. The search for their causes keeps Philosophers busy, since they are quite curious and want to probe the secrets of nature. But it is with this particular point in Physics as with several other: we search, we reason, we observe, we even make discoveries; and as a measure that we advance we always find more to discover: Let us not get tired yet, multiply the research, always make new observations, pick up as much knowledge as we can. We may not attain

6. The "C/1729 P1 (Sarrabat)" comet (Wikipedia).

an exact truth; that doesn't matter, the likelihood has its merit in Physics, and some more knowledge is more valuable than everything else.]


DISSERTATION
SUR LES CAUSES
ET LES VARIATIONS
DES VENTS.
QUI a remporté le Prix à l'Academie Royale des Belles Lettres, Sciences & Arts, pour l'année 1730.
Par le Reverend Pere SARRABAT, de la Compagnie de JESUS.
A BORDEAUX,
Chez PIERRE BRUN, Imprimeur de l'Academie Royale, ruë Saint James.
M. DCC. XXX.
AVEC PERMISSION.

***Figure 12:* The cover of Sarrabat's thesis "Dissertation sur les causes et les variations des vents" (1730).**

After the introductory pages, he goes directly to the point that the Sun is "a body of fire" and the most important factor for annual and seasonal climate variability. He ridiculed those who denied this or believed that the Moon produced the winds:

Mr. Mariotte prétend avoir observé que les Vents du Nord et de Nord-Est règnent ordinairement aux nouvelles et pleines Lunes; les Mariniers & les gens de campagnes ont sur cela leurs proverbes, des Philosophes l'ont assuré sans autre preuve; pour moi, après deux ans et demi d'observations, je puis dire que je n'ai rien trouvé de réglé à cet égard.

[Mr. Mariotte claims to have observed that the Winds from North and Northeast usually dominate at new and full moons. Seafarers and the folks on the countryside have their proverbs about this. Philosophers have been certain without further proof. For me, after two years and a half of observations, I can say that I have found no rule in this respect.] (p. 26)

It is now, to prove the point about the Sun as the driving force, Sarrabat staged an experiment which was similar to the one conducted by Fultz and the Chicago group.

SARRABAT'S EXPERIMENT

Just like the Chicago group in the 1950s, Sarrabat wanted to create flow patterns which could be observed and compared with the atmosphere (p. 7-14). Just like them he let a water filled basin, 32 cm in diameter and 16 cm deep, represent the atmosphere and a heated nut-shaped red-hot piece of iron, which measured around 3 x 4.5 cm, represent the Sun.

What inspired Sarrabat?

Sarabat had got the idea from a respected "savant" of the time, the German Jesuit Athanasius Kircher (1602-1684), probably from his most successful book *Mundus subterraneus* (1665). After a two-year visit to Sicily, where Kircher had witnessed volcanic eruptions, he had come to the conclusions that volcanoes act as occasionally emerging safety valves for continually circulating channels of fire and water in the Earth's interior. These, in conjunction with the wind, were responsible for all weather and geological events. Sarrabat did not agree with this, but it gave him the idea for his experiment.

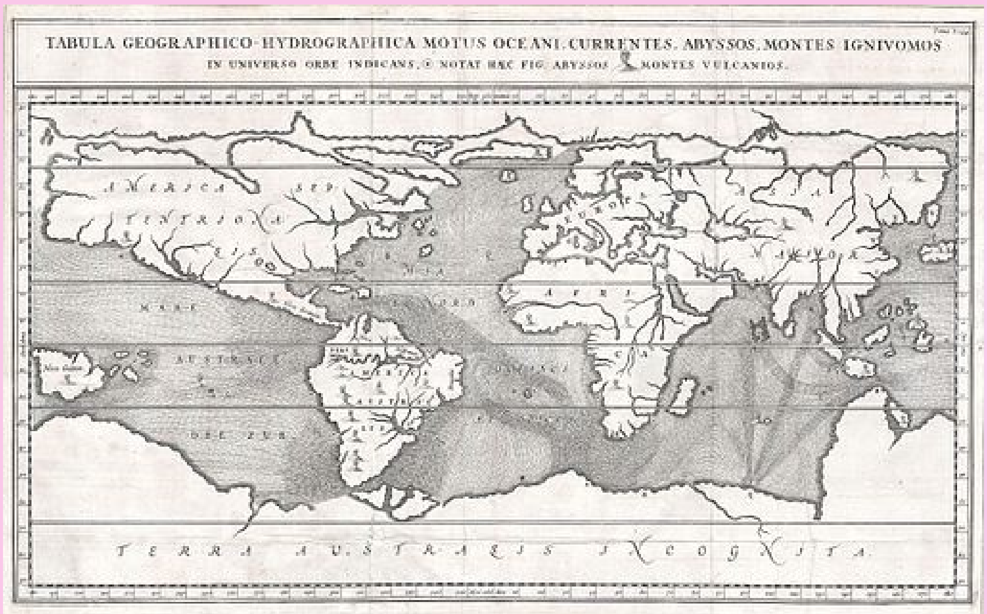


***Figure 13 :* From Mundus Subterraneus (1665), this is most likely the first world map to depict the oceans currents** *(brought to Wikimedia Commons by Geographicus Rare Antique Maps).*

To be able to observe the movements of the water he put small pieces of straw or grains on its surface as tracers. As soon as the heat from the iron started to affect the water, he could see how the tracers moved away from the centre and after a quarter of an hour clustered along the edge of the basin. He drew from this experiment the conclusion that there is in the Sun, as with the heated iron, “a force of pulsation” which tends to separate the fluids from the main point where its rays dominate.

> *Je conclus donc de ses expériences, qu’il y a dans le Soleil comme dans ce fer en feu, une force de pulsion, laquelle tend à écarter les fluides du point principal où ses rayons dominent* [p. 9]

He then conducted the crucial experiment by moving the iron over the water, just like the sun over the earth’s atmosphere in Halley’s explanation of the Trade winds. He could now see how the hot iron, when approaching the straws, made them double their speed away from the iron. At the same time straws were coming up from behind. This did not happen when he kept the iron at rest.

> *Quelquefois je faisais couler le fer le long de la verge, quelquefois je l'y laissais immobile; lorsque je remuais le fer, les fétus contre lesquels il avançait , doublaient de vitesse, et s'écartaient en formant des espèces de courbes, qui revenant en arrière, poussaient les fétus qui s'y trouvaient, et les forçaient à suivre, quoique lentement le mouvement du fer rouge; mais lorsque je le laissais immobile , ils s'écartaient tous du centre , en décrivant des spirales plus évasées que celles qu'ils décrivaient dans le petit bassin* [p. 7-8]

> [Sometimes I made the iron move along the stick, sometimes I kept it still; when I moved the iron, the straws against which it advanced, doubled their speed and separated in forming a sort of curves, which coming back from behind, pushed the straws which were there and forced them to follow although slowly the motion of the red iron. But when I let it be motionless, they separated all from the centre while describing spirals in the small basin.]

Sarrabat had from the start made the wise decision to make the experiments in more than one way not to become victim of random effects. But when he repeated the experiment over and over again, it always gave the same result, also when he tried different sized basins. This confirmed without doubt that the predictions made in Halley’s model were correct; the way the water reacted affected by the hot iron, as could be seen from the motions of the straws, was also how the atmosphere was expected to behave affected by the sun.

Did Sarrabat see the Coriolis effect?

The “circulation” or “spirals” he saw were attributed to “reflexions of the edges” (*réflexions des côtés*). Were they thermally driven amplifications of a small already existing circulation? Or was he, without knowing it, seeing the effects of the Earth’s rotation? That would in such a case have shown up as a deflection to the right, but he never mentions the orientation of the "spirals". With the sizes of the basins and the speed of the tracers, the Coriolis deflection from the centre to the edges would have been less than a centimetre, not enough to be identified by an unaware observer not prepared to look out for Coriolis effects.

By accidentally dropping the iron into the water and observing the bubbling water, he made comparisons with boiling vegetables, and then drew the conclusion:

> *Il en doit être de même de l'atmosphère échauffée par le Soleil dans l'endroit où il agit plus perpendiculairement: l'air doit s'élever, et de la par une pente naturelle, il doit se répandre sur celui dont la surface se trouve à un niveau inférieur; tandis que par en bas il se fait un reflux opposé, qui par une circulation nécessaire vient remplacer l'air que le Soleil continue d'élever.*
>
> [It should be the same with atmosphere heated by the Sun in the place where the rays strike most perpendicularly: the air must rise by a natural slope, it must spread upon those which are at a lower surface level; while from below there is an opposite inflow, which requires a circulation that replaces the air as the sun continues to raise.] (p.10-11)

With this Sarrabat leaved the laboratory experiment and turned to the atmosphere:

> *Ce ne sont là que des principes; Il est temps d'en venir à l'application.*
>
> [These are just the principles. It is time to go to the applications] (page 11)

When we try to understand how Sarrabat applied the experimental results to the atmosphere, we are hampered by our modern knowledge of the dynamics and thermodynamics of the atmosphere. In Sarrabat's understanding the Sun's rays do not only make the air expand; the rays also act like some mechanical forcing, "pushing the air". Today we know that the Sun's radiation, being composed of rather short wavelengths, cannot heat the air to any significant degree. Instead the Sun's radiation heats the ground, which then, by its outgoing longwave radiation, heats the atmosphere (which is also heated by convective and condensation processes). Further, the time scales of the heating from the oceans are different (longer) than from the land masses.

SARRABAT'S INTERPRETATION OF THE EXPERIMENTS

Although Sarrabat was not able to give a proper theoretical interpretation of his experiments, they nevertheless helped him empirically to get most of his reasoning about the atmosphere fairly correct. There are, according to Sarrabat (page 11) three motions in the atmosphere produced by the sun:

– Winds at upper levels come about because of air raised and diverted away from the point of maximal heating;
– The air having moved away from the most heated region to less heated, starts to sink down and spreads over this cooler air;
– This air is attracted by the Sun to return back towards those parts which are most heated at low level in a circular motion.

In order to apply these "three motions" to explain the Trade winds, Sarrabat positioned himself above the North Pole and looked "down" on the Northern Hemisphere (figure 11). He first considered, A-E-H-C, the part of the western Hemisphere where the Sun is approaching and rising (p.11). Here he attributes the Sun's "pulsating power" (*la force de pulsion*) for pushing the air in front of itself westward.

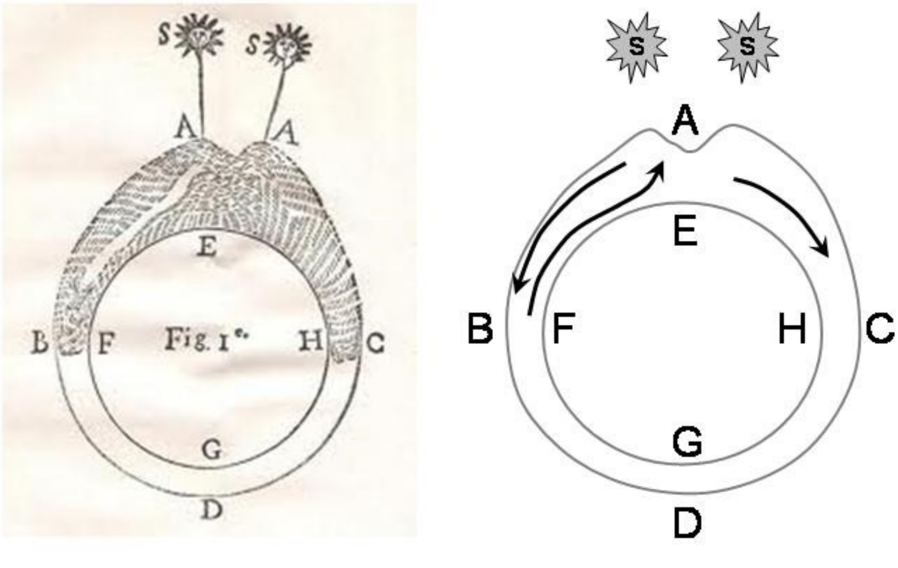


Figure 14: ***The Sun, and the Earth and its atmosphere seen from the North pole;*** *with the equator (EFGH), the upper parts of the tropical atmosphere (ABDC) and the sun (S) as depicted in Sarrabat's figure 1 in his Treaties. The reader can imagine that E is Central Africa, F Indonesia and H Central America, with the Atlantic between E and H, the Indian Ocean between E and F.*

He then turns to the other direction, the part A-B-F-E where the Sun is leaving and descending (p.12-13). Here the movement of the atmosphere is "much more composed". Air at A is by the Sun expanded more than anywhere else and therefore rises above the rest of the atmosphere. Hence this air tends to flow down on either side of A. But as the sun always advance westwards, ahead of the parts of the air that has been raised by the heating, this upper air is blocked from flowing down westward and can only descend eastwards, towards B. Moving over the air already being there will push this air westwards at lower levels to replace the air that the Sun continues to rise.

Like Fultz and his team, Sarrabat interpreted his experimental results to the effect

> that [where] the sun is setting, it reigns two contrary Winds, one in the upper Region from west to east, the other in the lower regions from East to West (page 13)
>
> *De là il suit que dans la partie ABFE, pour laquelle le Soleil est au couchant, il règne deux vents contraires, l'un dans la région supérieure d'Occident en Orient, l'autre dans les régions inferieures d'Orient en Occident.*

We may discuss to what degree Sarrabat actually deduced the circulation of the tropics. However, any contemporary reader of his 1730 Treaties would be left in no doubts that he had provided an experimental confirmation of Edmond Halley's 1686 trade wind model.

AN ENCYCLOPAEDIA OF GLOBAL WINDS

On the following pages Sarrabat discusses the winds beyond the Tropics, what we today call the subtropics and mid-latitudes. Here he is not successful since on these latitudes one must take into account the rotation of the Earth, not just the displacement of the Sun's maximal heating.

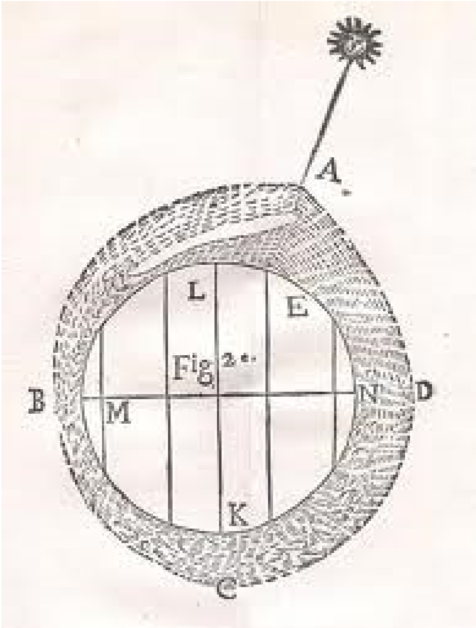


***Figure 15:* Sarrabat's image when discussing the winds beyond the Tropics.**

In Part II (p. 31-59) Sarrabat goes into more detail about the observed regular winds, mainly the Mediterranean and the oceans at the more northern and southern latitudes. A special section is devoted to the wind regimes over the Indian Ocean for which he also presented a rather detailed wind chart (fig 16): he describes (on pages 57-58) how the south-easterly wind over the South Indian Ocean, what we call the South-east Monsoon, when it encounters Madagascar, is split up into two branches, one going north of the island, crossing the equator and heading towards India, the other one turning south of the island and joining the north to north-easterly flow along the African coast (figure 16):

> *Depuis le 15 Avril environ jusqu'au mois de Juin il vente de Nord dans le Canal de Mozambique et jusqu'au Cap de bonne Esperance, tandis qu'en même temps c'est du Sud-Est qu'il vente à l'Orient et au Nord de Madagascar jusques à l'Équateur, et du Sud-Ouest de l'autre côté de l'Équateur depuis la Côte d'Ajan [Somalie] jusque vers Goa.*
>
> [After 15 April, until approximately June it blows from North in the Mozambique Channel and to the Cape of Good Hope, while at the same time it blows from Southeast on the East and North of Madagascar to the Equator, and from South-West on the other side of the Equator from Cote d'Ajan [Somalia] to Goa and thereabout.]

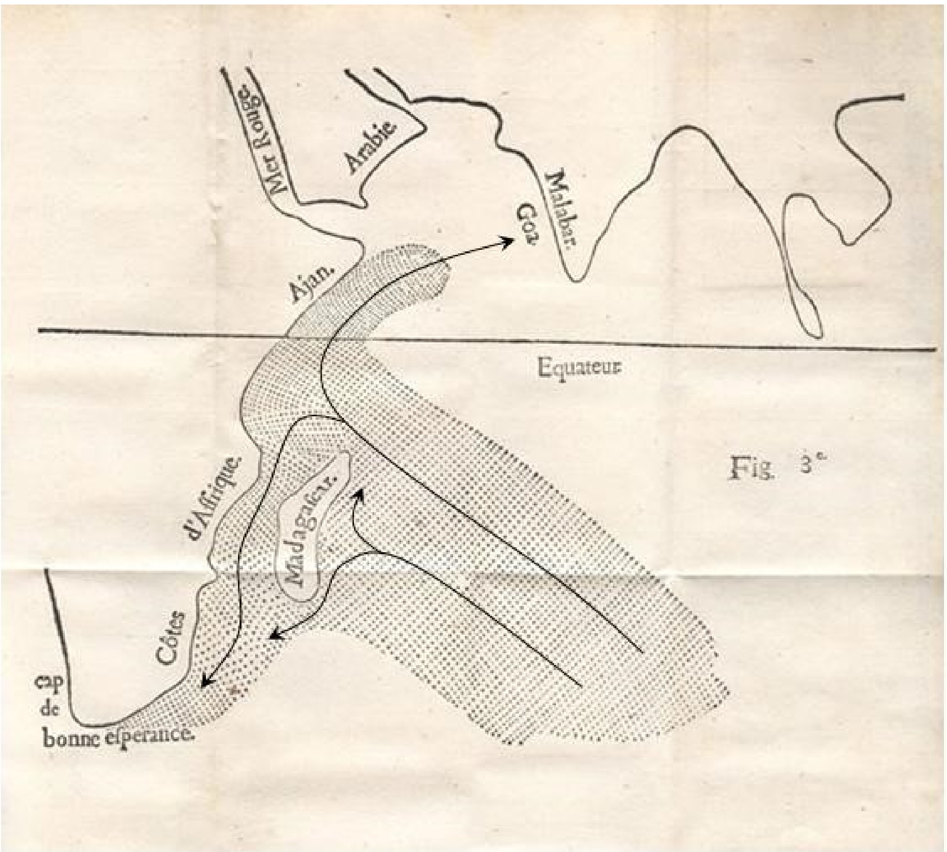


***Figure 16:* Sarrabat's figure 3 depicting the wind regimes over the Indian Ocean from mid-April until late June, the season when the Indian monsoon develops.**
The map lacks indications of the wind direction, which have been added here (black lines and arrows).

Finally, in the last part (Part III) Sarrabat discusses "free and irregular winds", i.e. the winds at what we call the mid-latitudes, poleward of 35°. As we now know, they are determined by the travelling low pressure systems (extra-tropical cyclones).

SARRABAT'S LATER CAREER

At the end of his Treaties Sarrabat invited anybody with different views to come forward if they had contrary information:

Je n'ai rapporté dans cette seconde partie que des faits sûrs et vérifiés, ou par le consentement des voyageurs, ou par le rapport uniforme des personnes entendues que j'ai consultées ou fait consulter dans les ports de mer. Je prie ceux qui auront quelque objection à faire contre mes explications, de ne se servir pour les attaquer que des faits pareils, et de ne pas se fier à tous ceux qui diront : j'ai observé. Tout le monde a ses observations sur les vents: et combien peu en ont fait? J'ai remarqué, me disait l'autre jour quelqu'un, homme d'esprit. D'ailleurs, qu'il vente toujours de bise le jour de l'Équinoxe ; et très sûrement il n'avait fait *d'autre observation, sinon que ce jour-là était celui de l'Équinoxe, et que la Bise soufflait alors. Toutes les remarques qu'on dit avoir fait sur les Vents, ne sont pas encore si exactes.*

[I have reported in this second part only the certain and verified facts, either by the consent of travellers, or the consistent reporting of people I interviewed myself or through somebody else in the harbours. I ask those who have any objection to make against my explanations to only use the same type of facts to denounce mine, and not to trust those who will say, "I have observed". Everyone have observations of the wind, but how many of them have made observations? An educated man I met the other day said: 'By the way, it always blows from north on the day of the equinox.' And surely he had not made other observations except that this day was the day of the Equinox, when then blew the northerly wind. All the remarks we make about the Winds, are not yet so accurate.] (page 59)

It can be assumed that nobody felt competent enough to step forward!

Sarrabat had then become so successful that the Academy did not allow him to take part in any more competitions. He told his confidents he didn't want his proper name on the list for the next competition, not to discourage others to submit contributions. So when in 1737 he published a dissertation on the circulation of the sap flow in plants, he sent it to the Academy of Bordeaux under the borrowed name of *La Baisse (The Worst),* the Academy recognized the real author in his disguise, withdrew the prize and changed the subject.

Nicolas Sarrabat became professor in mathematics in Marseilles but on a mission to Paris, he died on April 27, 1739, aged 41.

SARRABAT'S RECEPTION BY 18TH CENTURY SCIENTISTS

Sarrabat's 1730 Treaties seems to have been widely accepted by scientists in the 1700's and early 1800's. In Louis Cotte's *"Mémoires sur la* météorologie" from 1774 there is an extensive review of Sarrabat's work. He also got an honourable mentioning in 1806 by Bernard von Lindenau in the German scientific journal *Zach's Monthly Correspondence,* and in 1831 by Ludwig Friedrich Kämtz in his textbook in meteorology.

The fact that Sarrabat was still referenced 100 years after his publication is a sign that his work had influence on the scientific thinking and contributed to the acceptance of Halley's theory. It is true that it did not explain the trade winds, but it explained at least one *possible* physical system, Nicolaus Sarrabat's and Dave Fultz stationary dishpans.

On the other hand, George Hadley's model did not apply *to any known physical system at all*.

So why Hadley?

The reader might now ask: - If "Hadley's Principle" is erroneous, how come it was ever accepted – and is still today? Why is it used as a basis for explanation of the Trade winds and even the atmosphere's general circulation, not only in many popular books' on the subject but also in not so few academic?[7]

One reason is, perhaps, that the "Hadley Principle" is easy to understand, remember and teach. But since it is completely wrong, it leads the students and scientists into a dead alley. From "Hadley's Principle" nothing else can be understood. That is why, to understand the Coriolis effect in the atmosphere, it is also necessary to understand why "Hadley's Priciple" is wrong.

Some insight might come from a brief look into how the "Hadley Principle" once became accepted through a mixture of charlatanism, political pressure and national pride.

The "Hadley Principle" was a... German invention

All sciences have their "despots", scientists who dominate not only through their achievements, but also unduly through their strong personality and/or political connections. If there ever was a "meteorological despot", it would be Heinrich Wilhelm Dove (1803-1879). For around half a century he dominated European and in particular German meteorology in an authoritarian and unhealthy way.

Dove made his name in 1826 with his "Wind Law". During his stay in at the University of Königsberg (now Kaliningrad), he had noted that the wind typically changed, "veered", by going from S to W to N. He found support for this correct observation in the works of other scientists.

His finding was made before regular mapping of daily weather charts had become a routine. They would have shown that this regularity was a simple

7. There is at least one case when an American publisher of textbooks in meteorology forced an author, a renowned expert in dynamic meteorology, against his will, to include the erroneous "Hadley Principle".

consequence of low pressure systems, with their counter-clockwise circulating winds, moving north of most places in Central and Southern Europe (figure 17).

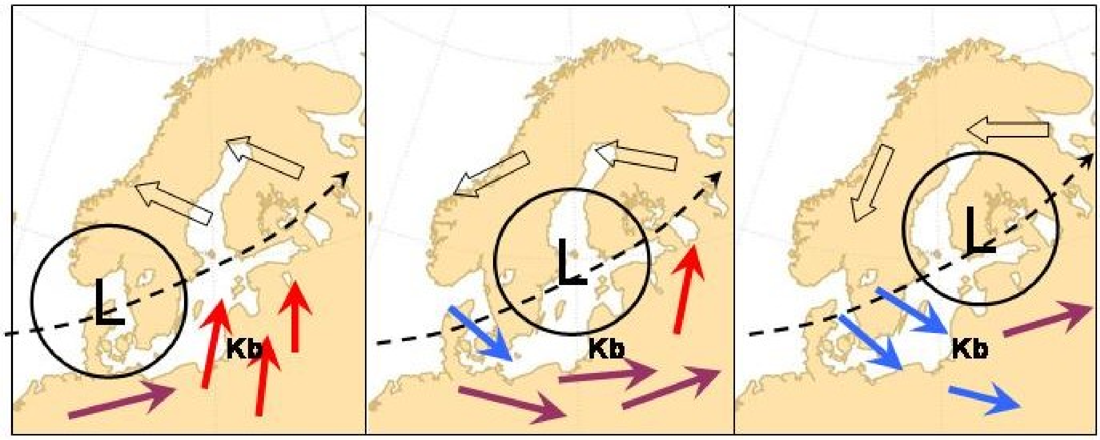


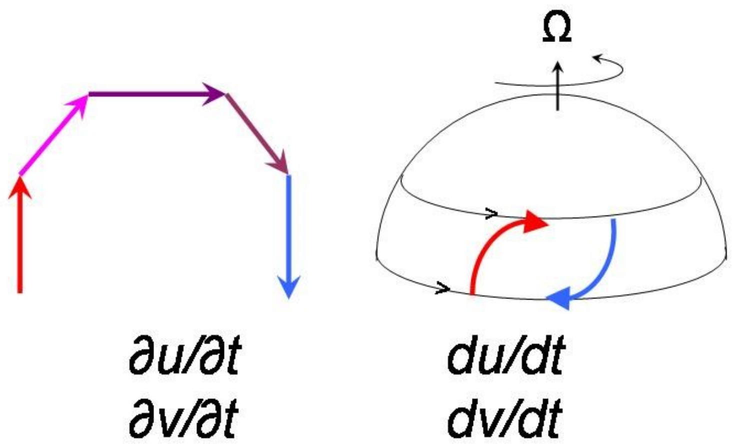
***Figure 17:* The reality behind the "Wind Law" Dove thought he had detected while in Königsberg (Kb).** *Since most moving low pressure systems with their counter clockwise wind circulation typically move in a path to North of where most of Europeans and their scientist live, this majority can easily get an impression there exists a "wind law", according to which the wind frequently turns from a southerly direction, over a westerly to a northerly. The minority of Europeans who normally live in the low pressure path or to the north of it, Scots and Scandinavians would of course experience quite a different "wind law" - if any "law" at all.*

In the Scandinavian countries, located as they are in the middle or north of the storm track, Dove's "Wind Law" did not apply. When a Danish professor Joakim F. Schouw (1798-1852), in a 1826 book on the climate of Denmark, expressed doubts about the general validity of the "wind law", Dove reacted furiously, and Schouw was subjected to publicly complain in a 1833 letter to the prestigious journal *Annalen der Physik* about Dove's "guerrilla war".

DOVE'S "WIND LAW" BECOMES THE "HADLEY-DOVE PRINCIPLE"

Dove was keen to find theoretical motivations for his "Wind Law". He thought he had found that by applying the same "common sense" reasoning as before him Hadley, McLaurin, Kant and many others applied: that air moving in the north-south direction, would be deflected to the east or west. Since this deflection was, as we have seen above, *clockwise* and thus in the same direction as in Dove's own "Wind Law", it became a strong argument that he had found a sound theoretical motivation.

He didn't, however, realise that the clockwise veering in the "Wind Law" was mathematically *Eulerian* (local time derivative, ∂/∂t), whereas in Hadley's model it was *Lagrangian* (individual time derivatives, d/dt) …



<u>Figure 18:</u> *(left)* ***A hodograph of Dove's wind observation, i.e. the successive wind observations placed one after the other, together forming a clockwise motion;*** *(right)* ***The trajectories in Hadley's Trade wind model also form a clockwise rotation.*** *However, the one to the left relates to local observations of changing winds, the second the motion of individual air parcels. The changes in the first are described by local (Eulerian) derivatives, the second by individual (Lagrangian) derivatives.*

This garbled reasoning now became the basis for Dove's 1835 major article "Über den Einfluss der Drehung der Erde auf die Strömungen ihrer Atmosphäre" in *Annalen der Physik*. In autumn 1837, it was translated into English in *Philosophical Magazine and Journal of Science* as "The Influence of the Rotation of the Earth on the Currents of its Atmosphere; being Outlines of a general Theory of the Winds".

A lucky coincidence now came to his rescue and ensured Dove's success and fame. The article was read by John Dalton who in letters to the editor-in-chiefs of *Philosophical Magazine* and *Annalen der Physik* pointed out that George Hadley had already in 1735 come up with this explanation.

Dove was most likely not aware of Hadley's 1735 paper. But now, thanks to Dalton's intervention, Dove had been given, almost from heaven, the theoretical basis he so urgently needed: a scientific paper published in the prestigious *Philosophical Transactions of the Royal Society*. From now on, Dove never failed to mention Hadley's name and would during the coming decades champion Hadley so persistently that "Dove's Wind Law" gradually became known as the "Hadley-Dove Principle".

The promotion of the "Hadley-Dove Principle" was mainly done by non-meteorologists such as Dalton, Herschel and Thompson. Meteorologists on both the practical and theoretical side objected strongly. Theoreticians such as William Ferrel (1857) in the USA, Charles Delaunay (1859) in France and Adolph Sprung (1885) in Germany provided conclusive evidence that the "Hadley-Dove Principle" was wrong. Experts in maritime meteorology such as Jean Lartigue (1840) from France, Matthew F. Maury (1855) from the USA and John K. Laughton (1870) from Britain were equally critical. Laughton took the attitude *that if "Hadley's Principle" was true then the rotation of the Earth had no effect on the motions of the atmosphere!*

DOVE AND "BUYS BALLOT'S LAW"

At this time, national meteorological centres were created with the main purpose to investigate local climate and keep an eye on the daily weather. For this purpose, daily weather maps were routinely drawn. But this was not allowed in the Prussian weather service since Dove's locally based "Wind Law" was supposed enough.

This attitude caused tension with a Dutch meteorologist C.H.D. Buys Ballot (1817-1890). Originally a devoted follower of Dove and his concepts, he had to break with him in order to advance the science of weather forecasting. In 1857 Buys Ballot published his now classical paper on the coupling between the horizontal pressure distribution and the wind direction, with the famous "Buys Ballot's Rule": *"if a person stands with his back to the wind in the Northern Hemisphere, the low pressure area will be on his left"*.

This cost him the favour of his beneficiary Dove because with "Buys Ballot's Rule", everyone could see that the wind blew about parallel to the isobars, independently of the direction. This did not agree with Dove's idea that only north-south winds were affected by the Earth's rotation.

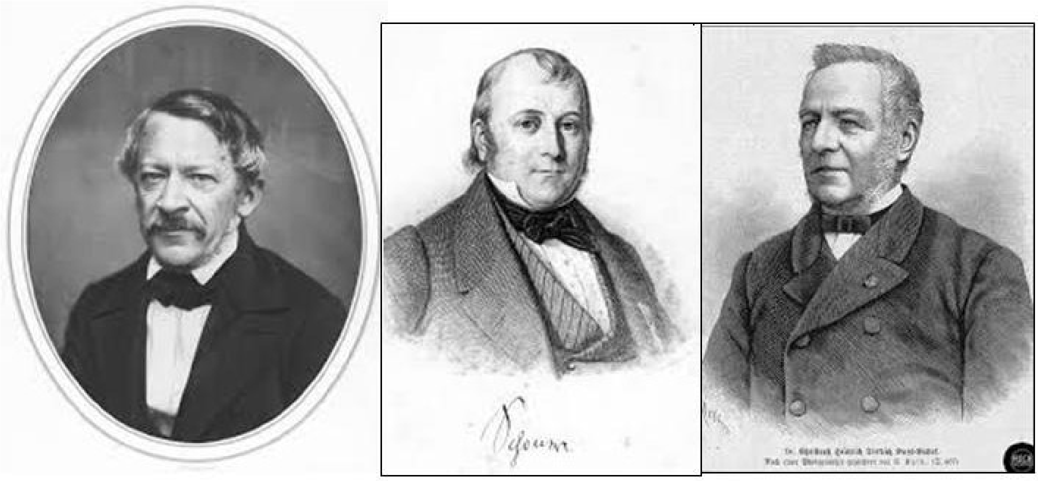


***Figure 19:* Heinrich W. Dove (left) and two of his scientific opponents, Joakim F. Scouw (center) and Christoph Buys Ballot (right).**

Still, Dove's 1841 book *Über das Gesetz der Stürme* (On the Law of the Storms, 1857 – La Loi des tempêtes, 1864) finally established him as the world's leading authority on the dynamics of the atmosphere. He was hailed as the "greatest meteorologist of our time" and "the Father of present day Meteorology". When he died in 1879, he was Professor at the university in Berlin, lecturer at several civilian and military schools, a member of the Prussian Academy of Science and Director of the Prussian Meteorological Institute.

HADLEY AND SARRABAT – GREAT SCIENTISTS AFTER ALL?

You do not have to be "right" to qualify as a good scientist. Neither Hadley nor Sarrabat were "right", but both drew their conclusions with scientific rigour: Sarrabat by relying on carefully designed experiments, Hadley by clearly pointing out the main weakness in his theory. This gives them higher scientific status than colleagues from later years who swept their uncertainties under the carpet and endorsed uncritically physically completely unrealistic explanations. Just because we credit Hadley and Sarrabat for being good scientists *in their times* there is no reason why we *today* should uncritically accept their explanations.

■

(December 2014)