Hadley's Principle:

Part 1 – A brainchild with many fathers

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> *'I think the causes of the General Trade Winds have not been fully explained by any of those who have written on that subject …' George Hadley (1735)*[1]

In May 1735 in a paper, *On the Cause of the General Trade Winds,* a fairly unknown English scientist, George Hadley (1685–1768), suggested a new mechanism for the formation of the Trade Winds, *the rotation of the Earth*. But it took 100 years for his theory to become accepted by the scientific community and even longer to have himself properly acknowledged. But today there is a 'Hadley Crater' on the moon, the convective overturning in the tropics is called 'The Hadley Cell' and the climate change research centre of the UK Met Office, 'The Hadley Centre', is named after him. This is the story of Hadley's Principle as it would subsequently be known (Sprung, 1879).

The understanding of the global atmospheric circulation 400 years ago

In the sixteenth century, 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 around 30° latitude the climate was rather dry with weak winds. South of this 'torrid zone' in the Northern Hemisphere were regular north-easterly winds, the Trade Winds. This pattern appeared to mirror itself south of the equator with steady Trade Winds from the South-East. When scientists tried to understand the general circulation of the atmosphere, their interest centred early on these Trade Winds, which, thanks to their steadiness, were assumed to be the easiest to explain.

Galileo Galilee (1564–1642) saw the Trade Winds as a consequence of the failure of the Earth's gaseous envelope to 'keep up' with the speed of the Earth's rotation (Figure 1). A similar argument was used by Johannes Kepler (1571–1630) to explain the westward motion of the tropical oceans (Burstyn, 1966). To both Galileo and Kepler the rotation of the Earth not only explained the Trade Winds, the winds themselves were a proof that the Earth rotated.

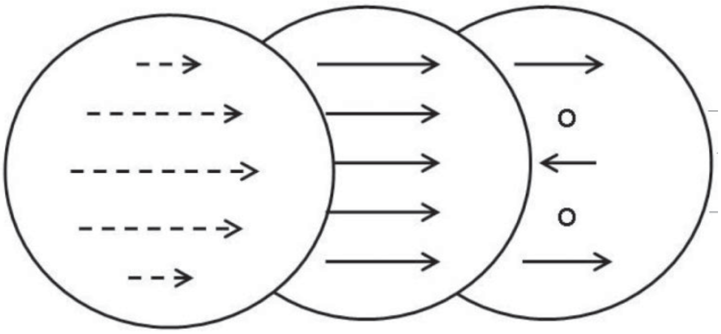

Figure 1. Galileo and Kepler's explanation of the general circulation and, in particular, the easterly Trade Winds. While the velocity of the Earth's surface decreased from the equator (left), the eastward absolute motion of air or water was supposed to be independent of latitude (centre), which would make the flow 'go ahead' at higher latitudes and lag behind around the equator with weak winds in between (right).

Edmond Halley's explanation 1686

In 1685, the Royal Society in England organized a debate about the general circulation of the atmosphere. The prominent astronomer Edmond Halley (1656–1742) suggested as the main mechanism of the Trade Winds the diurnal displacement from east to west of the sun's heating in the tropical belt (Figure 2). (Halley, 1686; Burstyn, 1966).

Halley's explanation eventually found its way into *Chamber's Cyclopaedia* where the section 'Physical Cause of Winds' is copied straight from the last five pages of Halley's text (Chambers, 1728). This part of Chamber´s book was in turn later incorporated into the French *Le Grande Encyclopedie* which made Halley's explanation of the Trade Winds the most widely-known until the beginning of the nineteenth century.

Few people who read these encyclopaedias knew that Halley had almost immediately begun to question his own hypothesis after facing critical remarks from his friends. They thought that his model would rather suggest a diurnal change of wind between west in the morning and east in the evening, with calm conditions at midday and midnight. To one of the sceptics, the mathematician John Wallis (1616–1703), Halley admitted that he should be glad to see 'some other notion' to explain the phenomena (Burstyn, 1966).

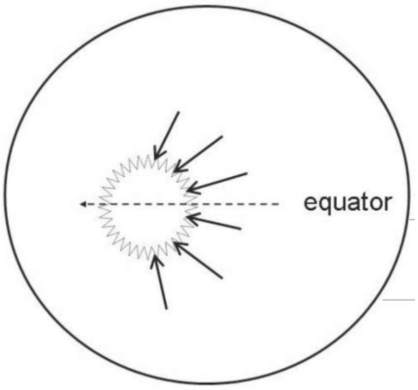

Figure 2. Halley's explanation of the easterly Trade Winds: as the maximum heating of the sun at the Earth's surface during the day moves westward, air will be sucked in from behind and replace the air that has been heated and risen.

At this time, April 1686, Halley had become occupied with other matters like reviewing a fresh manuscript about the laws of dynamics which had just been delivered by Isaac Newton.[2] 'Some other notion' did not

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[1] References for the original text of Hadley's paper, apart from Hadley (1735), also include Abbe (1910), Shaw (1979), Hellmann (1896) and Burstyn (1966).

[2] These were also the tumultuous years preceding the Glorious Revolution of 1688 with the last successful invasion of the British Isles (by the Dutch) and the establishment of a United Kingdom in 1707.

come forward for almost half a century until George Hadley's paper appeared in 1735.

George Hadley and his 'Principle' 1735

Born in London, by profession a lawyer, Hadley had, at the age of 50, just become a member of the Royal Society in charge of the Society's meteorological work. It consisted of providing instruments to foreign correspondents and of supervising, collecting and scrutinizing the continental network of meteorological observations (Shaw, 1920, 1931; Hellmann, 1896; Burstyn, 1966). The work made him think about the variations of the surface pressure and its relation to the winds, which he found 'of so uncertain and variable nature'. Their motion would not be along a great circle, but 'in some other Line' as he wrote in a paper published in 1737, but probably written before 1735:

> *In general, all Winds, as they come nearer the Equator will become more easterly, and as they recede from it, more and more westerly, unless some other Cause intervene. (Hadley, 1737)*

The novelty of the explanation in George Hadley's celebrated 1735 paper was to take into consideration the direct effect of the Earth's rotation around its axis, rather than as in Halley's explanation, the sun's apparent motion due to this rotation:

> *For let us suppose the Air in every Part to keep an equal Pace with the Earth in its diurnal Motion; in which case there will be no relative Motion of the Surface of the Earth and Air, and consequently no Wind; then by the Action of the Sun on the parts about the Equator, and the Rarefaction of the Air proceeding there from, let the Air be drawn thither from the N. and S. parts.*

The circumference of latitude circles at the Tropics of Cancer have, Hadley reasoned, an absolute difference of 2083 English miles compared to the equatorial circle, to which they relate as 917 to 1000, which indicated the difference in absolute velocity:

> *From which it follows, that the Air, as it moves from the Tropics towards the Equator, having a less Velocity than the Parts of the Earth it arrived at, will have a relative Motion contrary to that of the diurnal Motion of the Earth in those Parts, which being combined with the Motion towards the Equator, a N.E. wind be produced on this Side of the Equator, and S.E. on the other …*

Hadley pointed out that his model also applied to the higher latitudes. The heated equatorial air would rise and spread poleward while being deflected to the east. Since the air would gradually cool, it would become heavier and sink down and thereby constitute the mid-latitude westerlies. He realized that these westerly winds at higher latitudes must be compensated by equally strong easterly winds in the tropics; else the rotation of the Earth would change.

The only problem he saw with his model was that it predicted equatorial east winds of 37 m/s, the difference of rotational velocity between 23° latitude (426 m/s) and the equator (463 m/s). He explained that frictional losses against the surfaces of the ground and the sea substantially weakened the wind (Figure 3).

For two reasons Hadley's name was slow to be connected to his 'Principle'. One was that he was confused, in particular outside Britain, with Edmond Halley and his widely publicized theory. In his own country, George Hadley was also confused with his elder brother, John Hadley (1682–1744), who was famous in his own right for astronomical contributions, among them the 'Hadley sextant'. The other reason was that during the ensuing 100 years or so, Hadley's principle would also, as we will see, be discovered or rediscovered by other scientists. The first time this happened was just a few years after Hadley's paper was published.

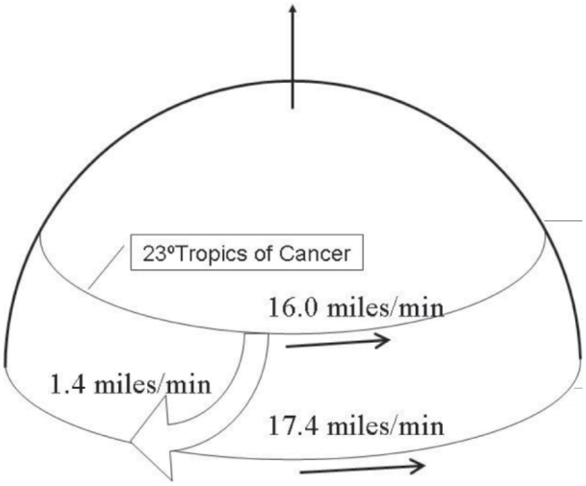


Figure 3. Hadley's explanation of the Trade Winds (with his own units): air moving from higher latitudes to lower to replace air that has been heated and risen will conserve its absolute velocity (16.0 miles/minute) and, when entering latitudes with higher velocities (17.4 miles/minute), appear to lag behind.

Colin Maclaurin 1740

Since Colin Maclaurin (1698–1746) was Scottish, it is difficult to imagine, in spite of the tense political situation between Scotland and England at the time, that he was not familiar with Hadley's paper in the publications of the Royal Society. In his work *De Causa physica fluxus et refluxus maris* (*On the cause of tides*) Maclaurin argued, without referring to Hadley and without mathematics (but in Latin), that the sea currents were affected by 'the uneven velocity of a body carried by the earth in its daily motion around its axis':

> *If water be carried from the south toward the north, either by the general motion of the tide or by any other cause whatever, the course of the water will thereby be deflected little by little toward the east, because the water at a prior time was carried by the diurnal motion toward this sea with a greater velocity than pertains to the more northerly place. Conversely, if the water be carried from the north toward the south, the course of the water, on account of a similar cause, will be deflected toward the west. From this source I suspect various phenomena of the motion of the sea to arise.*

Maclaurin was aware that this explanation could be extended to other motions in the atmosphere and the sea. 'But it is not possible to go into this in any detail' (Maclaurin, 1741; Burstyn, 1966).

Jean Rond de d'Alembert 1746

Maclaurin's paper was one of the prize-winning contributions in a competition launched by the French Royal Academy of Science 1740. This might have been the inspirational source which made the Berlin Academy of Sciences a few years later announce a prize for anybody who could determine 'the nature and the law' which the wind ought to obey in case the Earth was covered by an ocean. The solution had to be presented in a form that allowed predictions. The winning contribution, by Jean le Rond d'Alembert (1717–1783), was published under the title *Reflexions sur la cause generale des vents* (d'Alembert, 1747).

D'Alembert made two *a priori* assumptions which for a modern reader, seem completely off the mark: he disregarded the effects of the Earth's rotation and, more astonishingly, the solar heating. The winds were supposed to be solely the result of the attractive forces of the sun and the moon. Assuming that these forces were perpendicular to the Earth's axis of rotation, d'Alembert developed equations expressing the resulting oscillations. In a final part, he considered the effect of landmasses, in particular mountains (d'Alembert, 1747).

D'Alembert's approach must be understood from the background of the success of the Newtonian concepts, which, among other virtues, had been able to explain the dynamics of tides without invoking effects of thermal heating. Although d'Alembert stated correctly that the rotation of the Earth has no effect on the *speed* of the wind, he never seemed to have realized its modifying effect on the *direction* of air parcels already in motion.

D'Alembert's was, however, the first attempt to express the motions of the atmosphere in mathematical terms, a new fruitful approach which would see its major 'milestones' in William Ferrel's equations of motion in 1860, Lewis F. Richardson's numerical hand-calculations in 1922, and Norman A. Phillips's computer-based general circulation experiment in 1956.

Together with Denis Diderot (1713–1784), d'Alembert was instrumental in the creation of the legendary *Grande Encyclopedie*. Originally only a project to translate *Chamber's Cyclopaedia* into French, it soon took off in its own direction. The section about 'Winds' was, as mentioned above, a straight translation of Halley's explanation in the Chamber's version, complemented with an insertion outlining d'Alembert's own explanation.

D'Alembert's theory did not find many followers, except in France, where as late as 1859 it provided the basis for a paper on the wind regimes over the North Atlantic (Keller, 1859; Kämtz, 1859). Instead Hadley's Principle slowly started to become appreciated, although independently of Hadley. It first happened at the other end of Central Europe, in Königsberg (today's Kaliningrad) and by its most renowned son, the philosopher Immanuel Kant.

Immanuel Kant 1756

It is easy to overlook that Immanuel Kant (1724–1804) during most of his professional life worked as a scientist or academic in physics, mathematics and earth sciences (Körber, 1977). His philosophical works, in particular *Critique of Pure Reason*, on which his fame rests, came about quite late in his life, when he was in his 50s. In the period 1747–1756, when Kant was between 24 and 32, he published several works on kinetic energy, the possible changes of the Earth's rotation, the age of the earth and the mechanisms of earthquakes. In 1755 he outlined a theory of the formation of the universe, in particular the solar system, later to be further developed by Laplace into the 'Kant-Laplace nebular hypothesis'.

Kant's texts on meteorological problems, in particular on winds, are found mainly in three sources: the first, *Neue Anmerkungen zur Erläuterung der Theorie der Winde* (New Comments to clarify the Theory of Winds), consists of about 15–20 pages and was published in Königsberg in April 1756. Kant reached the conclusion that there existed an upper current directed towards the pole. Weather is caused when this upper wind comes into conflict with the surface wind. He noted, as others before him (and after him would do), that the wind locally tended to veer from east to south to west (Kant, 1756, 1910).

The second source, *Physikalische Geographie* (Physical Geography) comprises 158 pages out of which 17 deal with the atmosphere's general circulation (Kant, 1802, 1923). It was published at the end of Kant's life, but was probably written 20 years earlier. Finally, Kant's handwritten lecture notes from 1756 to 1796 contain about ten pages of meteorology (Kant, 1925).

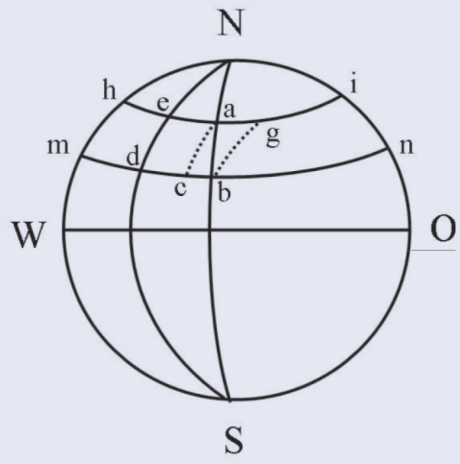
Like John Wallis and others, Kant found Halley's. Trade Wind explanation 'badly chosen'. In his handwritten notes we can follow how he was contemplating an explanation of his own:

> *'I am right here busy to renew, the old theory, though with one added condition only to make it mechanical possible … This rule, which as far as I know, not anyone has considered, may be seen as a key to a general theory of the winds' (Kant, 1925)*

From his handwritten notes we are able to reconstruct, also graphically, how he, on the blackboard at the university in Königsberg, outlined a deflective effect of the Earth's rotation, his 'key to the general theory of the winds', in a similar way as George Hadley had done 20 years earlier (see Box 1).

Box 1: From Kant's lecture notes at the University of Königsberg

'**N** and **S** denote the two Poles, **W** to **O** the equatorial circle. Two latitude circles are marked as **mn** and **hi**, and the remaining are meridians. If there is no wind in **a** so it has no other motion than the one which is appropriate for the earth's surface in this point **a**, that is in 12 hours, it covers a distance from west to east equal to half of the latitude circle **hi**.



Immanuel Kant's explanation of the Trade Winds: air moving from ***a*** *to* ***b*** *is deflected to the path* ***ac,*** *while air moving from* ***b*** *to* ***a*** *is deflect along* ***bg***.

From now on let us assume that the air in **a** moves to **b** along a meridian, and let us imagine that this increasing north wind in the same time could follow the curve **ea** from west to east due to the rotation of the earth. Then follows, if we disregard all obstacles that could meet the air during its course, is on a moving earth would not be at **b**, but at **c** at the end of this time, so that **dc** = **ea** and **cb** the difference of similar latitude circles, because the air with its intrinsic westerly velocity of the place, from whence it came, can cover in the same time the curve **dc** = **ea** from west to east, since the earth meanwhile at this latitude has described the curve **db**. Since it does not matter if the air moves with respect to the earth, or the earth moves with respect to the air, a combined movement will follow along a certain diagonal curve **ac**, of which the sides **ab** and **bc** represent those northerly wind velocities, and the difference of the motion at both latitude circles, respectively.'

Kant then proceeded to apply the same reasoning for winds moving poleward along **ba**, but due to the Earth's rotation deflected to the path **bg**. The more the air moved away from the equator, the more it was deflected until it became straight from west.

Throughout the nineteenth century, there are occasional references to Kant in the meteorological literature, mostly related to the publication of his 1802 book on physical geography. It is a task for the vital field of Kantian research to find out how much impact Kant's ideas on the general circulation of the atmosphere had on contemporary science.

Pierre Simon de Laplace 1775, 1796 and 1799

In 1775 Pierre Simon de Laplace (1749–1827) set out to develop what would become known as 'Laplace Tidal Equations', a rigorous mathematical description of the motions of the atmosphere and ocean, taking the rotation of the Earth into account. The latter was not least important because Laplace had reached the conclusion, in contrast to d'Alembert, that the rotation of the Earth had an importance of its own, not only for changing the diurnal position of the sun and moon.

Immanuel Kant and Simon de Laplace never met or exchanged letters. Nor are there any indications that Laplace ever read Kant's works, in particular those dealing with meteorological problems. Laplace mentioned in his preface that he was inspired by Newton, Euler and Bernoulli, but most by d'Alembert and Maclaurin (Laplace, 1775). It is probably from Maclaurin's oceanographic work that Laplace had borrowed this qualitative reasoning:

> *'Considering that the planet has a rotation like a liquid, the velocity of a molecule is supposed to be the same in the direction of a latitude, its angular velocity increasing or decreasing if it moves away or approaches the equator, so that it changes the meridian of this motion when it changes latitude.'* (Laplace, 1775, 1893)

The extension to the atmosphere came in 1796 in Laplace's semi-popular presentation on celestial mechanics. Laplace envisaged two opposite currents of air, one in the lower part of the atmosphere and the other one in the upper part of the atmosphere:

> *'However, the real velocity of the air, due to the rotation of the earth, becomes lower when it is much closer to the pole. Thus it should when advancing towards the equator, rotate more slowly than the corresponding parts of the earth, and the bodies placed on the earth's surface should hit it with the excess of their velocity and feel as a reaction, a resistance counter to their motion of rotation. Thus, for an observer who believes himself to be immobile, the air appears to blow in the opposite direction to the one of the rotation of the earth, that is to say from east to west, this is indeed the direction of the Trade-Winds.'* (Laplace, 1796, 1884)

In his *Traité de Mécanique celeste* Laplace (1799) would repeat, with renewed emphasis, and in indirect polemic with d'Alembert, that the Trade Winds are not caused by the gravitational attraction from the sun and the moon.

It is about this time, at the end of the eighteenth century, that George Hadley's name at last starts to be referenced in the scientific literature.

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