

Some Historical Remarks on the General Circulation

“Science is done by humans.” (starting sentence in Werner Heisenberg’s autobiography).

“... at any given time, the most active scientists and technicians – in the rush of new discoveries and inventions, or their sturdy adherence to old methods or their own convictions – will never be sufficiently aware of their one-sidedness. The only possible, but by no means reliable, remedy would be to try to learn from history.” (Bergeron, 1959).

- Galilee, Kepler (around 1600)
- Halley (1686)
- Hadley (1735)
- Kant (1756)
- Laplace (1775, 1796)
- Dalton (1793, 1837)
- Dove (1830’s)
- Ferrel (1856, 1858)
- Thomson (1857, 1892)

- Defant (1921)
- Jeffreys (1926)

- Modern Era: Rossby, Palmen, Charney, Eady, Phillips, Lorenz, Green (not naming anybody still alive)

3

Lorenz (1983):

The prevailing ideas have evolved in a manner that appears to be far from random. Indeed, to a present-day dynamic meteorologist, an account of the development of these ideas is suggestive of a giant stepwise numerical integration, with time steps of half a century or longer. At the beginning of each step, certain ideas appear more or less as established facts in the standard texts, but are questioned by the avant-garde. Within each step there occurs a formulation of new theoretical ideas, an interval in which these ideas are rejected or simply ignored, an interval of fairly general acceptance, a more or less concurrent discovery of observational facts that contradict the new theory, an interval in which these observations are ignored or questioned, and a final acceptance of the new observations and a rejection of the theory by the new avant-garde. To many readers, our time steps will be more suggestive of innings.

Galilei & Kepler (around 1600): absolute eastward motion of the fluid (atmosphere or ocean) independent of latitude → westward (easterly) relative motion near the Equator, eastward (westerly) relative motion in higher latitudes; to both Galilei and Kepler the trade winds were a proof that the Earth rotated

from Persson (2008)

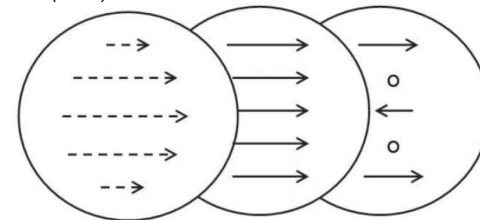


Figure 1. Galileo and Kepler’s explanation of the general circulation and, in particular, the easterly Trade Winds. While the velocity of the Earth’s surface decreased from the equator (left), the eastward absolute motion of air or water was supposed to be independent of latitude (centre), which would make the flow ‘go ahead’ at higher latitudes and lag behind around the equator with weak winds in between (right).⁴

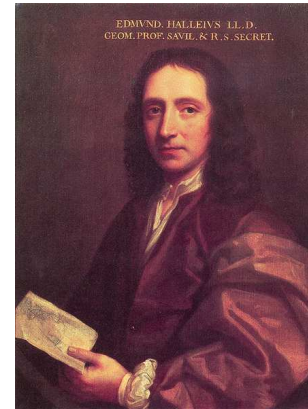
Certain Observations of the Midland Salt-Springs of Worcester-shire, Stafford-shire and Cheshire. Of the Crude Salt, which grows from the Stone-powder dejected by the said Brines in Boiling. Of the specific difference betwixt Sea Salt and Common Salt. A way (which seems to be the true method of Nature) of Distilling Sweet and Fresh Water from Sea Water, by the Breath of Sea Plants growing in it. That this Breath probably is the Material Cause of the Trade or Tropick Winds. In a Letter to the Publisher from the learned Martin Lister Dr. of Physick of the University of Oxon.

Among the known *Sea Plants* the *Sargosse* or *Lenticula Marina*, is not to be forgot; this grows in vast quantities from 36 to 18 Degrees Northern Latitude, and elsewhere upon the deepest Seas. And I think (to say something by the by of that great Phenomenn of the Winds) from the daily and constant breath of that *Plant*, the *Trade* or *Tropic Winds* do in great part arise: because the matter of that *Wind*, coming (as we suppose) from the breath of only one *Plant*, it must needs make it constant and uniform: Whereas the great variety of *Plants* and *Trees* at Land must needs furnish a confused matter of *Winds*: Again the *Levant Breezes* are brisker about *Noon*, the *Sun* quickning the *Plant* most then, causing it to *breath* faster, and more vigorously; and that *Plants* mostly languish in the *night* is evident from many of them, which contract themselves and close at that time; also from the effects of our *Winters* upon them, which cause them to cast both fruit and leaves too; whereas they are said (the same *Plants* for kind) universally to flourish all the year alike within the *Tropicks*.

As for the direction of this Breeze from East to West, it may be owing to the General current of the Sea, for a gentle Air will still be led with the stream of our Rivers, for example. Again every *Plant* is in some measure an *Heliotrop*, and bends it self, and moves after the *Sun*, and consequently emits its vapours thitherward, and so its direction is in that respect also owing in some measure to the Course of the *Sun*.

5

An Historical Account of the Trade Winds, and Monsoons, observable in the Seas between and near the Tropicks, with an attempt to assign the Physical cause of the said Winds, by E. Halley.



Edmund Halley
(1656–1742), picture around 1687
An Historical Account of the Trade Winds, and Monsoons, observable in the Seas between and near the Tropicks, with an attempt to assign the Physical cause of the said Winds. Philos. Trans. (1686)

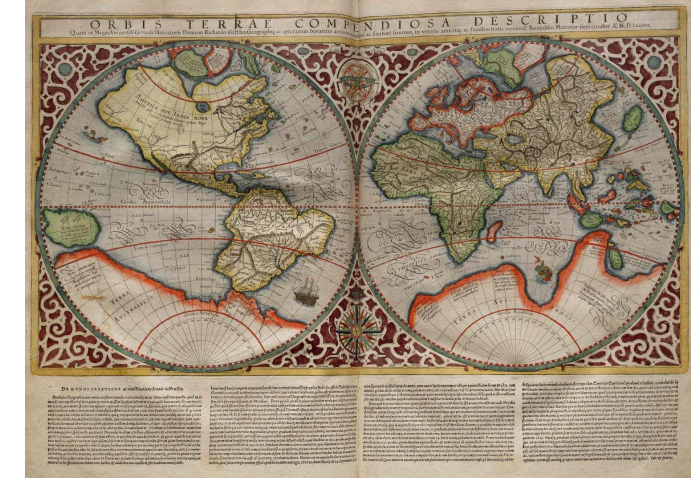
Historical side note: Halley was in contact with Newton and convinced him to publish his Principia, which appeared just one year after his trade wind paper, in 1687!

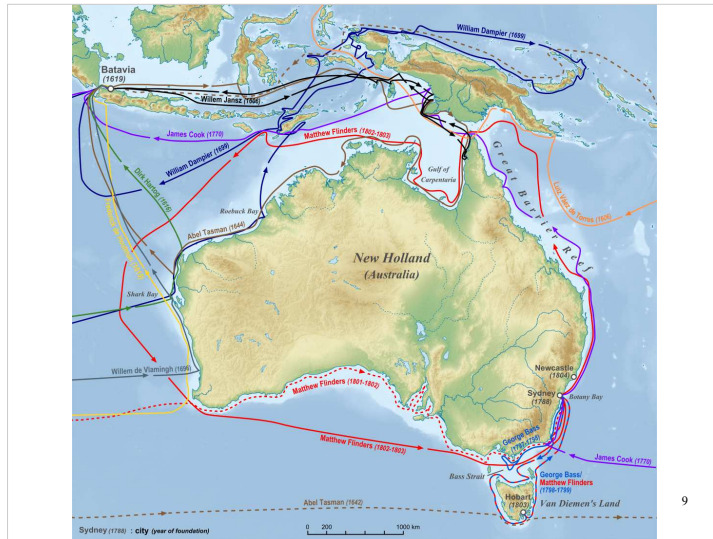
Map from Halley's 1686 paper

"New Holland"

7

Mercator, 1587, Terra Australis Incognita - "unknown land of the South"





Halley (1686): solar heating as the driving force behind the trade winds

- causes air to rise near the Equator
- this air has to be replaced from the subtropics
- flow is “pulled” westward by diurnal movement of sun

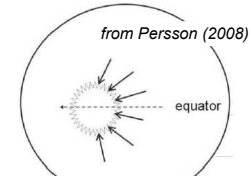
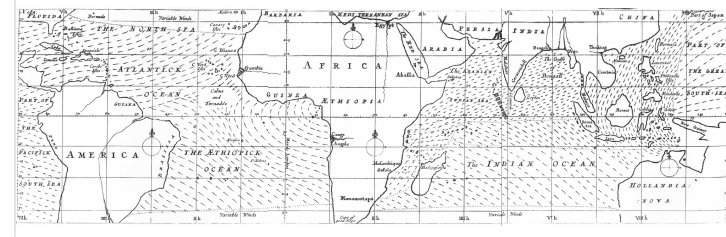


Figure 2. Halley’s explanation of the easterly Trade Winds: as the maximum heating of the sun at the Earth’s surface during the day moves westward, air will be sucked in from behind and replace the air that has been heated and risen.



George Hadley
(1685–1768)
Concerning the Cause of the General Trade-Winds. Philos. Trans. London (1735).

VI. Concerning the Cause of the General Trade-Winds : By Geo. Hadley, Esq; F. R. S.

I Think the Causes of the General Trade-Winds have not been fully explained by any of those who have wrote on that Subject, for want of more particularly and distinctly considering the Share the diurnal Motion of the Earth has in the Production of them : For although this has been

Crucial role of Earth’s rotation

Global angular momentum conservation

... and greater Length than I propose. From what has been said it follows :
First, That without the Assistance of the diurnal Motion of the Earth, Navigation, especially Easterly and Westerly, would be very tedious, and to make the whole Circuit of the Earth perhaps impracticable.
Secondly, That the N. E. and S. E. Winds within the Tropicks must be compensated by as much N. W. and S. W. in other Parts, and generally all Winds from any one Quarter must be compensated by a contrary Wind some where or other ; otherwise some Change must be produced in the Motion of the Earth round its Axis.

George Hadley
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Concerning the cause of the general trade winds. Philos. Trans. London (1735).

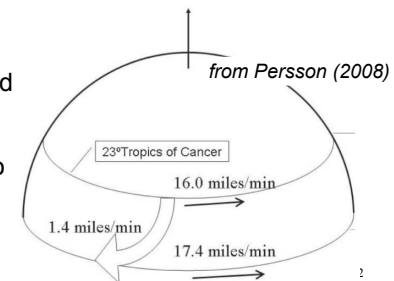
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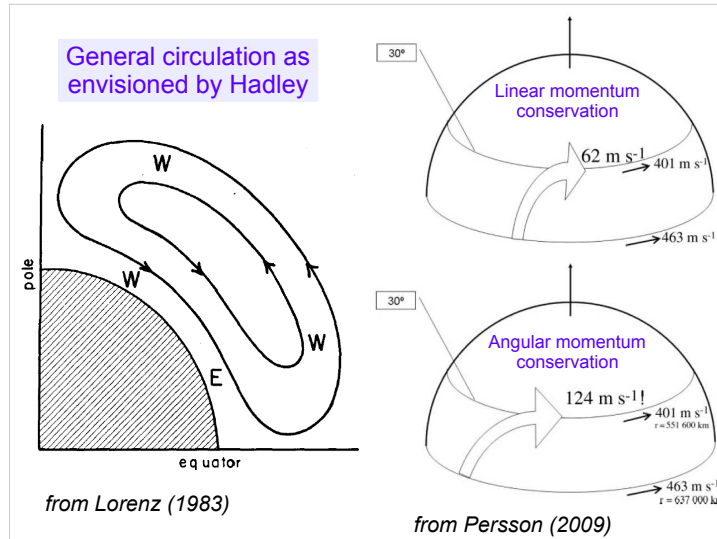
I Think the Causes of the General Trade-Winds have not been fully explained by any of those who have wrote on that Subject, for want of more particularly and distinctly considering the Share the diurnal Motion of the Earth has in the Production of them : For although this has been

conservation of linear momentum → surface wind of ~40 m/s at the equator

friction slows down wind to observed speeds

Conservation of angular momentum → ~70 m/s!!





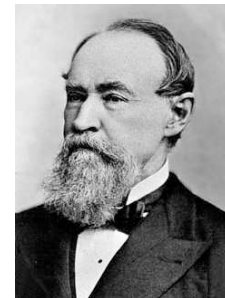
- Hadley's work remained largely unnoticed for decades
- Hadley's explanation of the trade winds was rediscovered several times:
 - Immanuel Kant in 1756
 - Pierre Simon de Laplace in 1775, 1796
 - John Dalton in 1793, who while his book was in print found out about Hadley's work and added a comment
 - Heinrich Dove in the 1830's, but later 'Dove-Hadley Principle'
- eventually Ferrel (1856, 1858), who brought in the full Coriolis effect

Dove, 1837: ...it must seem strange that since 1686, in which year Halley published his theory of the trade-winds, consequently for 150 years, not a step has been made towards a general solution of the question. *from Persson (2009)*

Dalton, 1837: Notice relative to the Theory of Winds
 By John Dalton, D. C. L., F. R. S.
 To Richard Taylor, Esq
 Dear Friend
 Manchester, Sept 5th 1837
 I published a theory of the Trade Winds, &c, as Mr Dove has published. - it was forty-four years ago, as may be seen in my Meteorology, 1793 and 1834. It was first published by G. Hadley, Esq, in 1735, as I afterwards learnt. It is astonishing to find how the true theory should have stood out so long.
 John Dalton

Dove, reply: It is unnecessary in a scientific journal to mention what everybody already knows and no other theory than his can have been alluded to.

William Ferrel
 (1817–1891)
 An essay on the winds and the currents of the ocean.
 Nashville Journal of Medicine and Surgery (1856).



"If a body is moving in any direction, there is a force arising from the Earth's rotation, which always deflects it to the right in the northern hemisphere, and to the left in the southern hemisphere."

Ferrel, 1858: THE ASTRONOMICAL JOURNAL. No. 109.

VOL. V. ALBANY, 1858, JANUARY 30. NO. 11.

THE INFLUENCE OF THE EARTH'S ROTATION UPON THE RELATIVE MOTION OF BODIES NEAR ITS SURFACE.

BY W. FERREL.

In a body upon or near the earth's surface receive a motion relative to the earth, either by means of a single impulse or by a continually acting force, this motion, combined with the rotary motion of the earth, gives rise to a deflecting force relatively to the earth, which causes a different relative motion from that of a body acted upon in a similar manner upon the earth at rest. It is proposed, in this paper, to examine a few of the effects produced by this deflecting force.

Let x, y and z be three rectangular coordinates having their origin at the center of the earth, z corresponding with the axis; and P, Q and R be the forces which act respectively in the directions of these ordinates. We shall then have

$\frac{dx}{dt} = P; \frac{dy}{dt} = Q; \frac{dz}{dt} = R.$ [1]

Let r = the distance of the body from the earth's center
 θ = its polar distance
 ω = its longitude [printed σ in the French]
 ωt = the rotary motion of the earth.

We shall then have

$x = r \cos \theta; y = r \sin \theta \cos(\omega t + \omega); z = r \sin \theta \sin(\omega t + \omega)$ [2]

Substituting the second differential of the value of x in the first of equations [1], we get

$\cos \theta \frac{d^2 x}{dt^2} - 2 \sin \theta \frac{d\theta}{dt} \frac{d^2 y}{dt^2} - r \cos \theta \frac{d^2 \omega}{dt^2} = P$ [3]

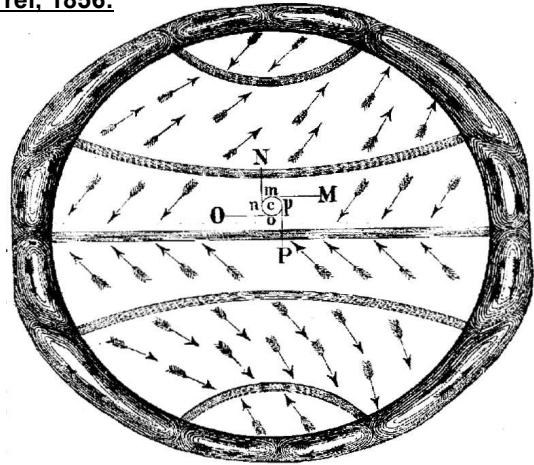
Substituting in like manner the second differentials of y and z in the last two of equations [2], and multiplying the former by $\cos(\omega t + \omega)$ and the latter by $\sin(\omega t + \omega)$, and adding, we get

$\sin \theta \frac{d^2 y}{dt^2} + 2 \cos \theta \frac{d\theta}{dt} \frac{d^2 y}{dt^2} - \sin \theta \frac{d^2 \omega}{dt^2} + r \cos \theta \frac{d^2 \omega}{dt^2} - r \sin \theta \left(\omega + \frac{d\omega}{dt} \right)^2 = \cos(\omega t + \omega) Q + \sin(\omega t + \omega) R$ [4]

Multiplying equation [3] by $\cos \theta$ and equation [4] by $\sin \theta$, and adding, we get the first of equations [5]. Multiplying the former by $\sin \theta$ and the latter by $\cos \theta$, and subtracting the latter from the former, we get the second of equations [5]. Again, after subtracting the last one of the following equations:

$\frac{d^2 z}{dt^2} - r \frac{d^2 \omega}{dt^2} = \sin \theta \left(\omega + \frac{d\omega}{dt} \right)^2 = \cos \theta P + \sin \theta Q + \sin \theta \cos(\omega t + \omega) R$
 $- r \frac{d^2 \omega}{dt^2} - \frac{d^2 \theta}{dt^2} + \sin \theta \cos \theta \left(\omega + \frac{d\omega}{dt} \right)^2 = \sin \theta P - \cos \theta Q + \cos \theta \sin(\omega t + \omega) R$
 $- r \sin \theta \frac{d^2 \omega}{dt^2} - 2 \sin \theta \frac{d\theta}{dt} \frac{d^2 y}{dt^2} - 2 r \cos \theta \left(\omega + \frac{d\omega}{dt} \right)^2 = \sin \theta \cos(\omega t + \omega) Q - \cos(\omega t + \omega) R.$ [5]

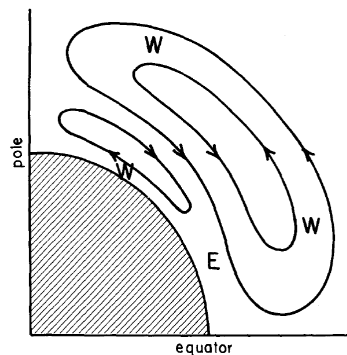
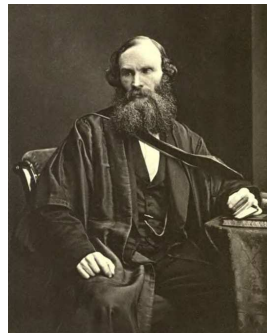
Ferrel, 1856:



From Hann-Süring (Lehrbuch der Meteorologie - "Textbook of Meteorology", 1926): (loosely translated)

"Ferrel's Theory ... was first published at places and in such a form, that hampered its distribution and recognition. The mathematical form, in which it appeared, was not very comprehensible to most readers and likewise appeared uninviting to others, due to its lack of elegance."

James Thomson (1822–1892): Bakerian Lecture. On the grand currents of atmospheric circulation. Phil. Trans. London (1892).

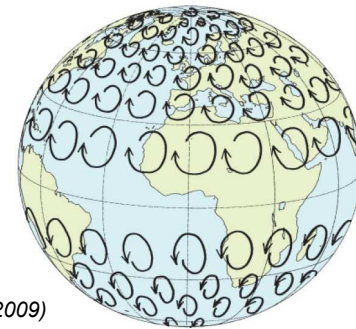


from Lorenz (1983)

"Hadley's theory in its main features ... must be substantially true, and must ... form the basis of any tenable theory that could be devised."

The fundamental Flaw of Hadley's Model

"In practice the motion of a mass of air through a large range of latitude, while retaining its original angular momentum about the axis of the Earth, can never arise." (Brunt, 1934, 1944)



from Persson (2009)

Figure 4. Any particle, moving frictionless and under inertia over the Earth's surface will, while conserving its angular momentum, follow almost circular motions due to the Coriolis Effect. To reach any considerable distance the parcel must have substantial velocity. The 'inertia circles' in the figure correspond to velocities of 50m s⁻¹. Due to the latitudinal variation of Coriolis Effect the trajectories are more curved towards the poles which induces a slight westward drift. The rotation of the Earth therefore has, quite counter-intuitively, not only the effect of constraining the motion of the atmosphere (and oceans), but also of pushing it slightly to the west, against the rotation (the 'Beta Effect').