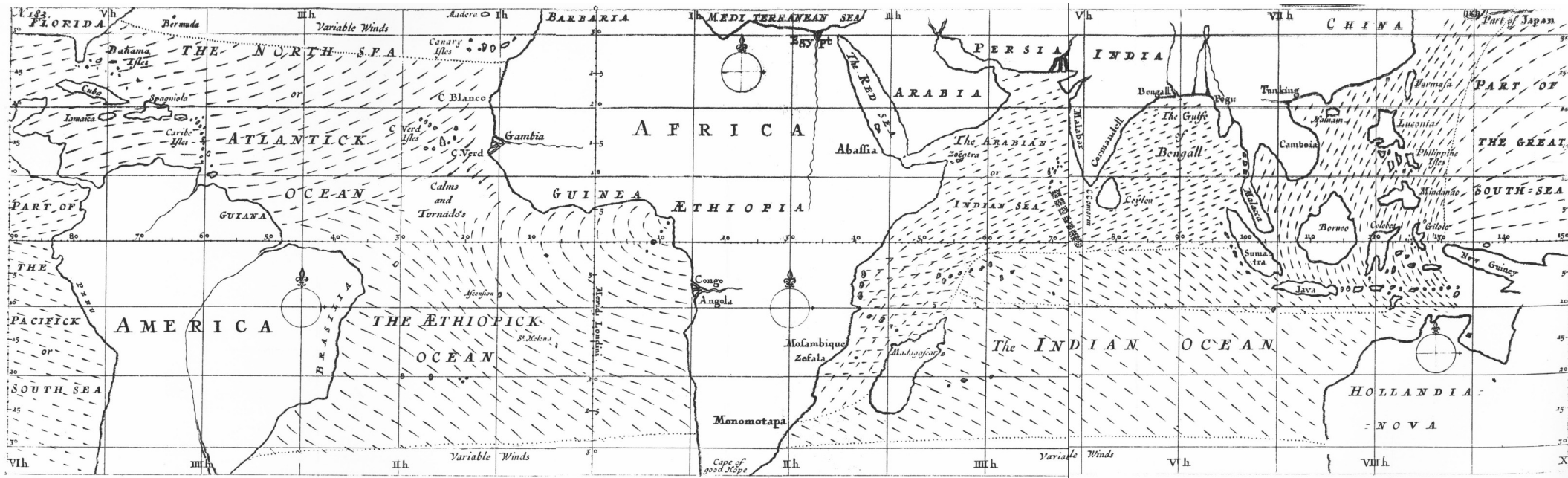
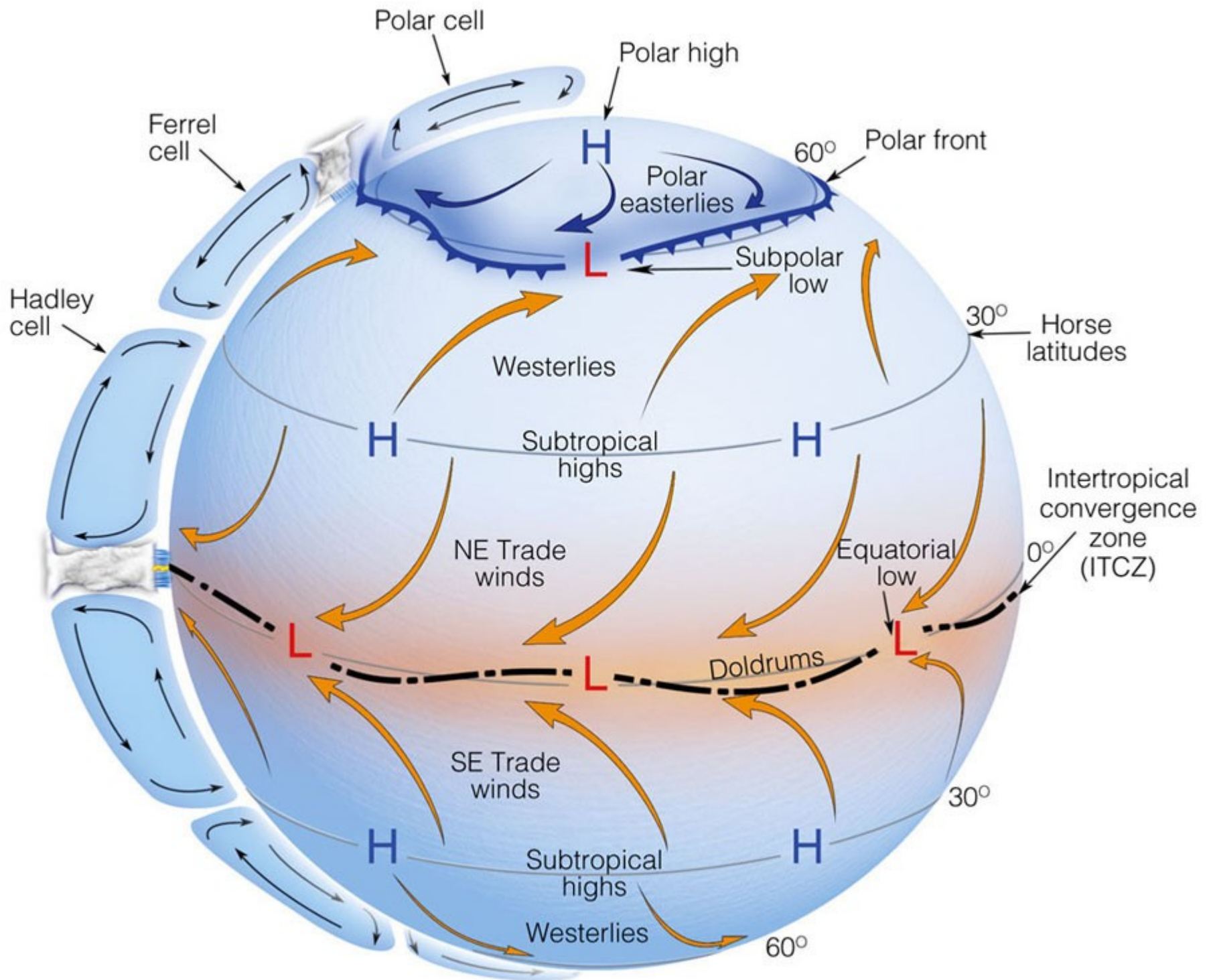


Discovery of Australia & General Circulation History





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)

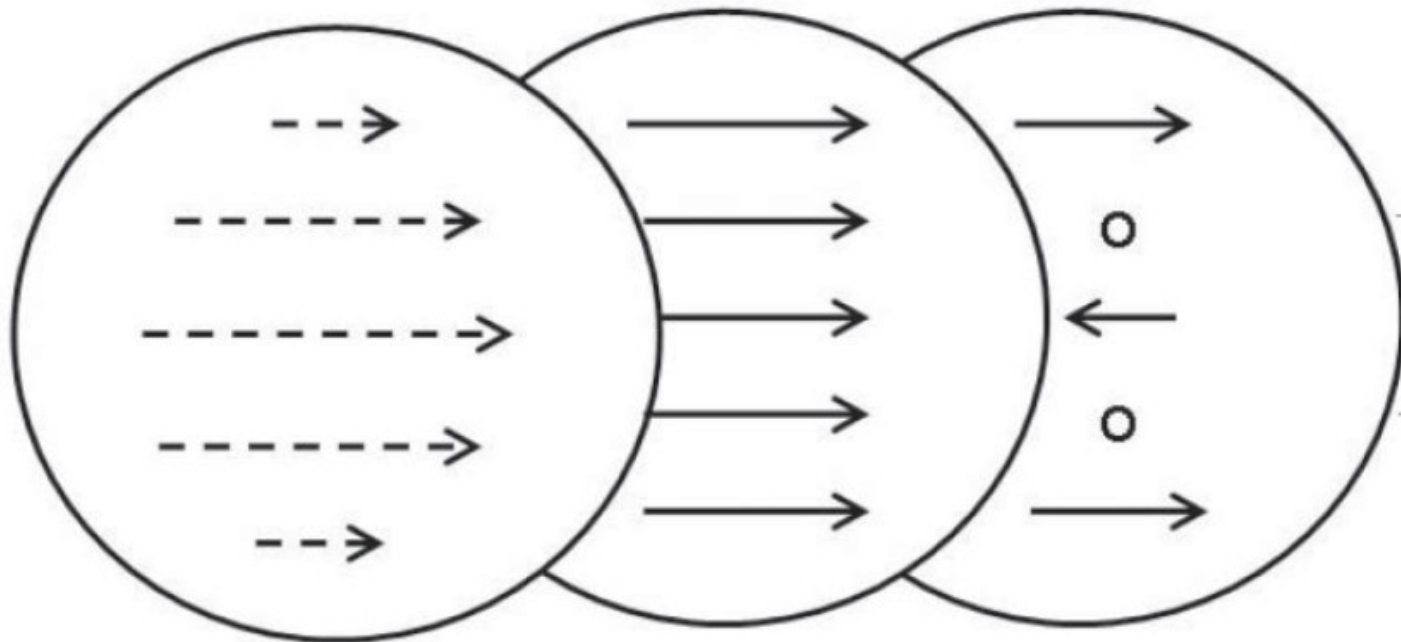
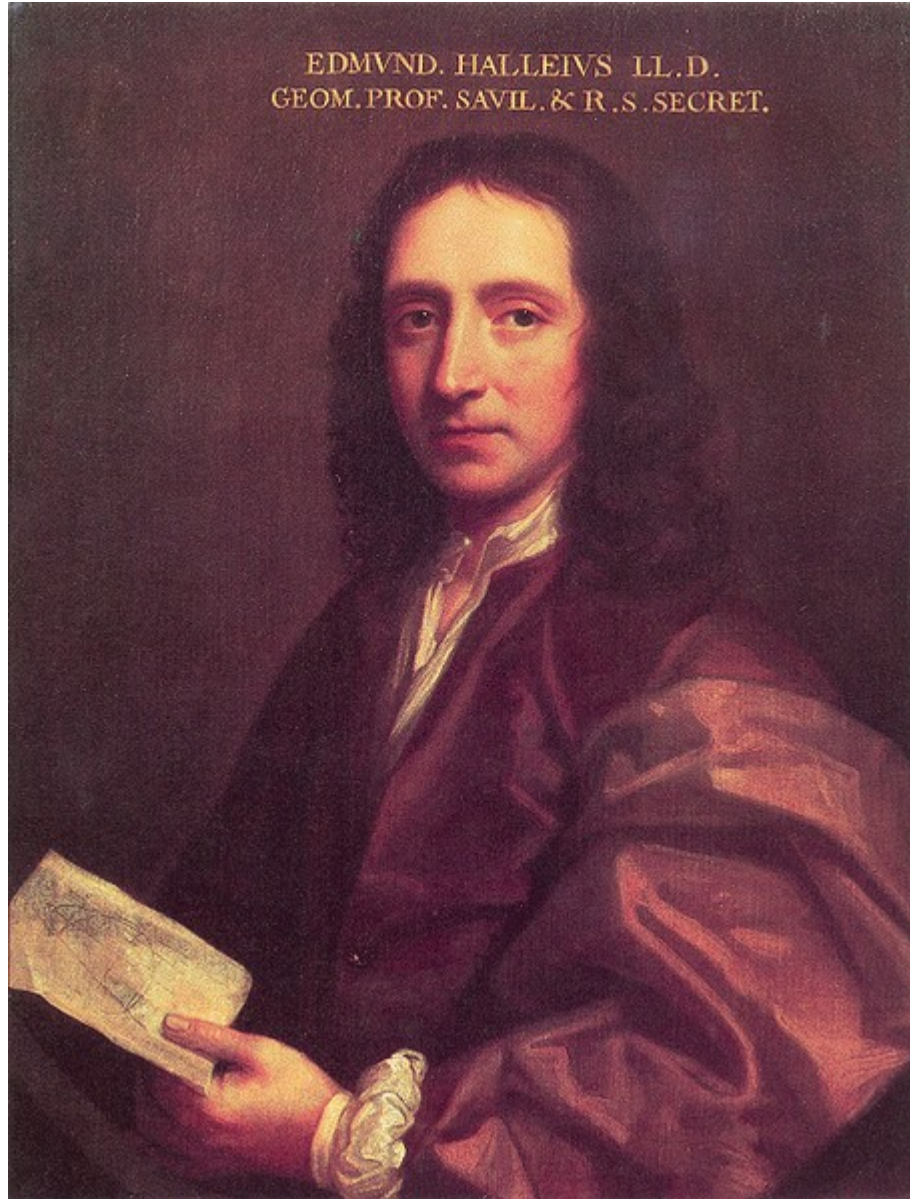


Figure 1. Galileo and Kepler's explanation of the general circulation and, in particular, the easterly Trade Winds. While the velocity of the Earth's surface decreased from the equator (left), the eastward absolute motion of air or water was supposed to be independent of latitude (centre), which would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

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.

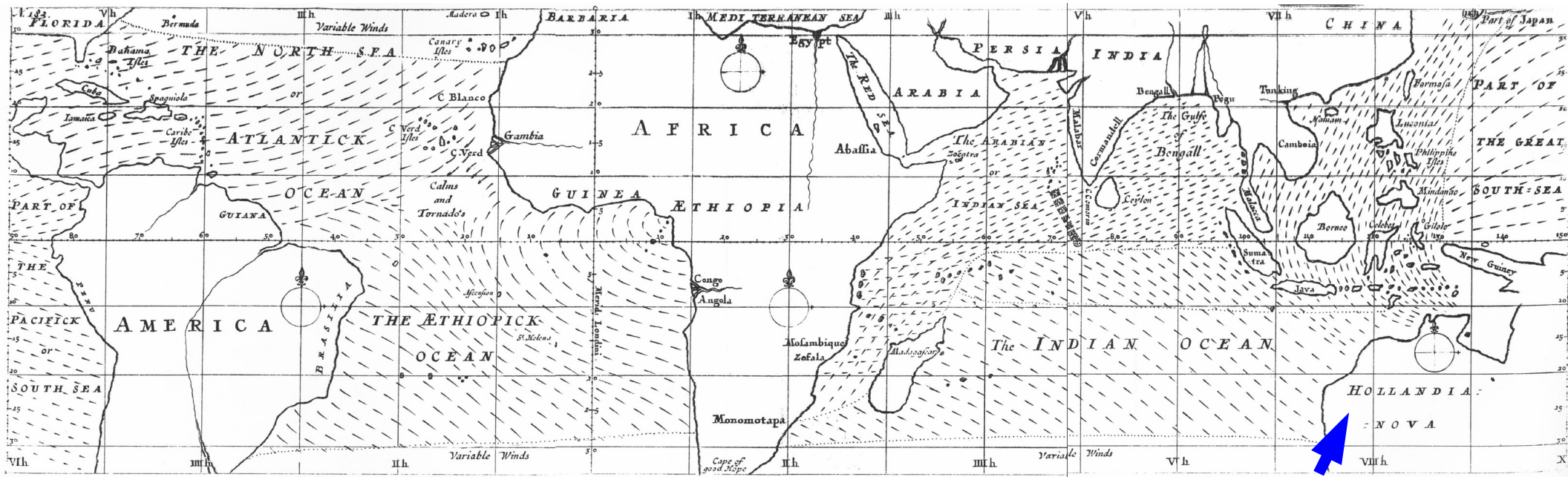


Edmond Halley

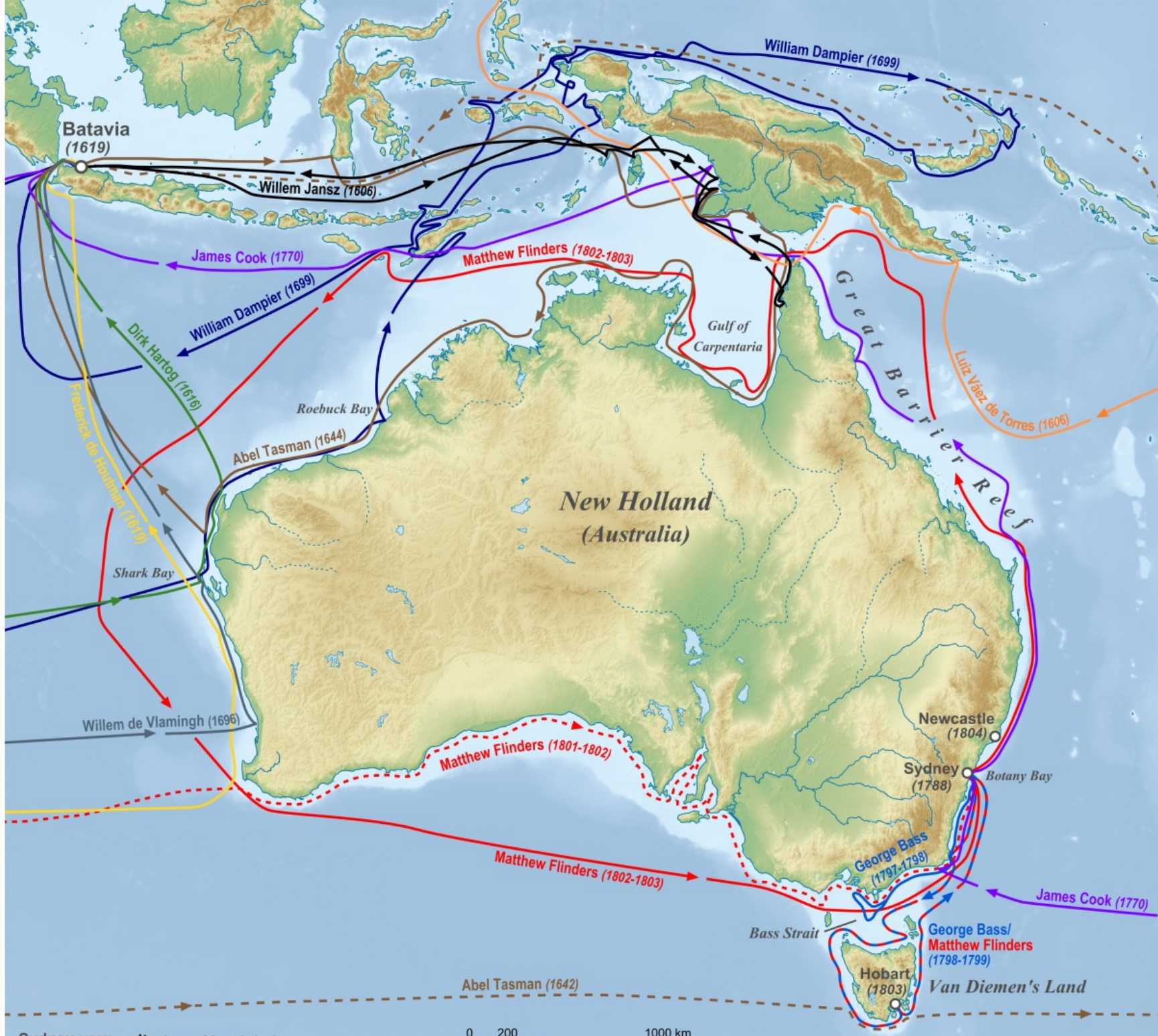
(1656–1742), picture around 1687
An Historical Account of the Trade Winds, and Monsoons, observable in the Seas between and near the Tropicks, with an attempt to assign the Physical cause of the said Winds. Philos. Trans. (1686)

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”



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

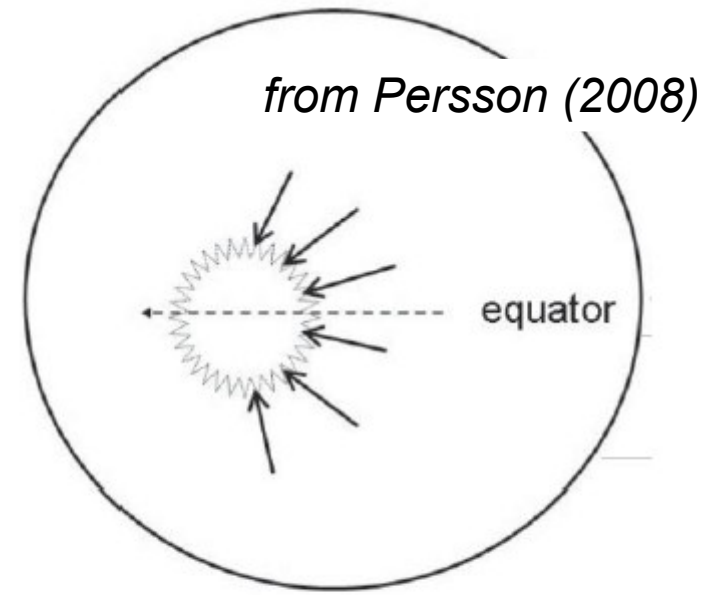
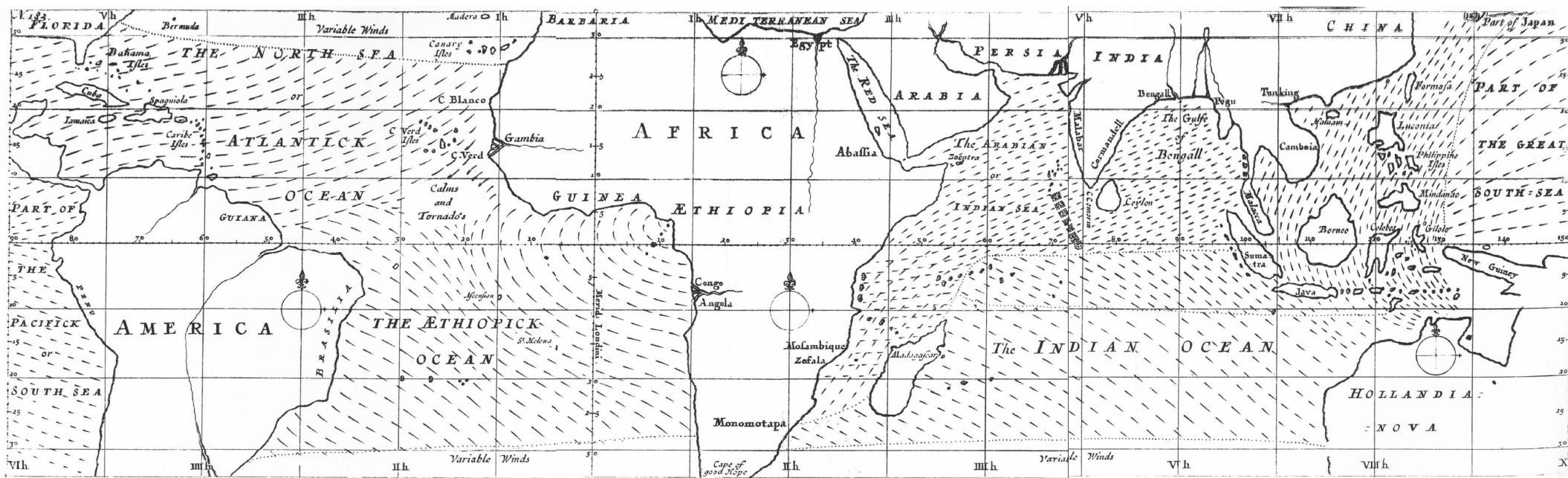


Figure 2. Halley's explanation of the easterly Trade Winds: as the maximum heating of the sun at the Earth's surface during the day moves westward, air will be sucked in from behind and replace the air that has been heated and risen.



George Hadley

(1685–1768)

Concerning the Cause
of the General Trade-
Winds. Philos. Trans.
London (1735).

Crucial role of
Earth's rotation

Global angular
momentum
conservation

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
I 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

... the 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 impracti-
cable.

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

(1685–1768)

Concerning the Cause
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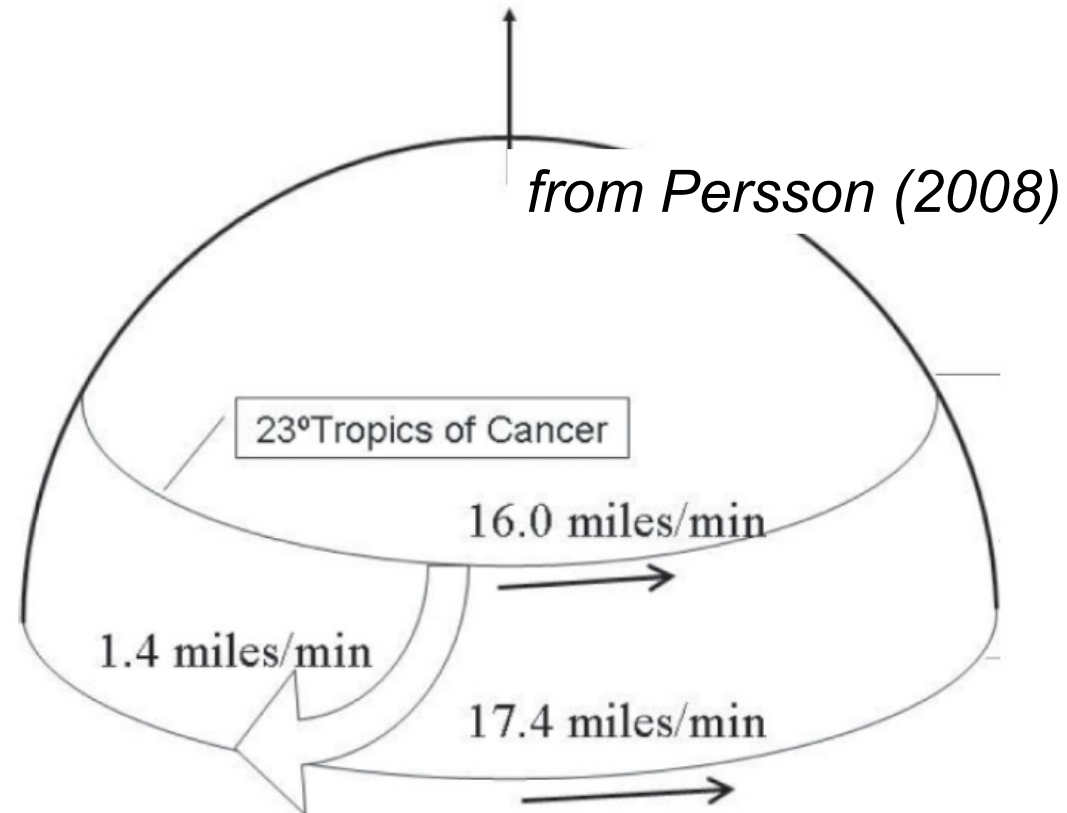
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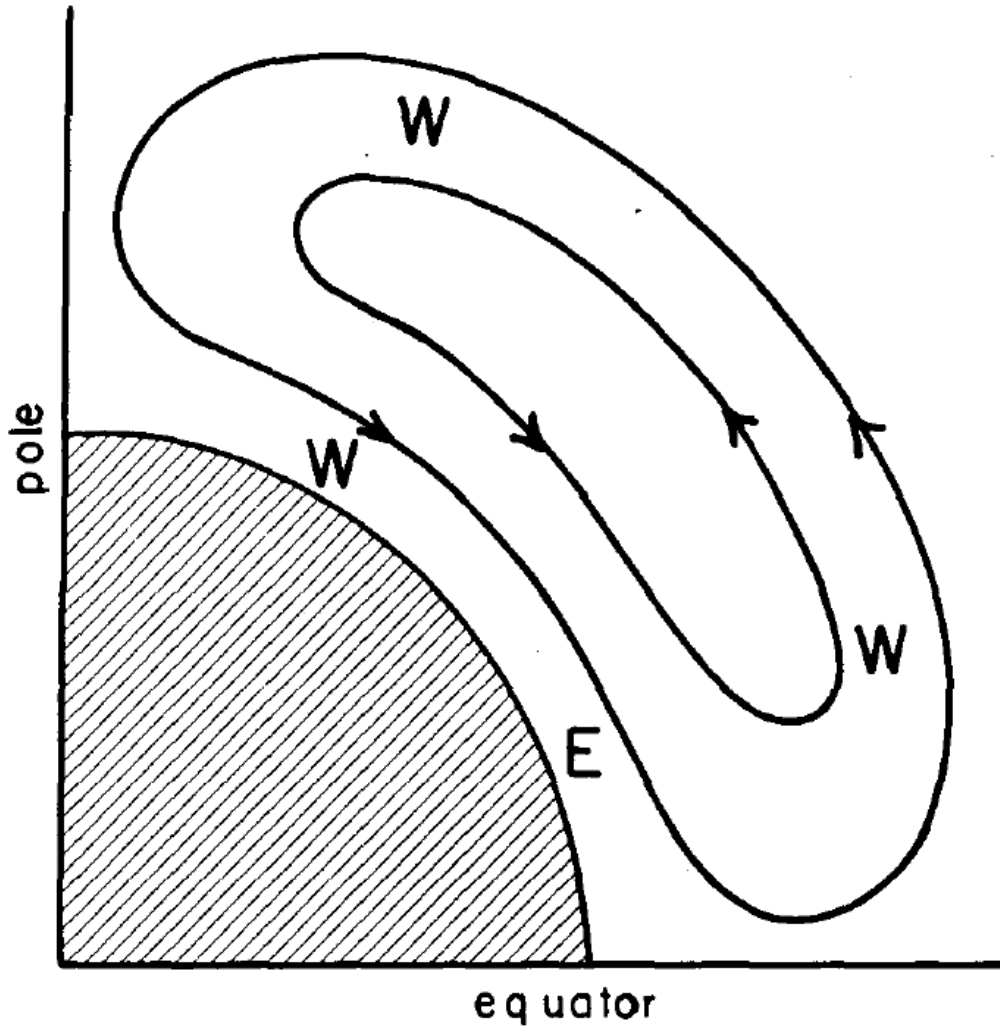
conservation of linear momentum → surface wind of ~40 m/s (~85 mi/h) at the equator

friction slows down wind to observed speeds

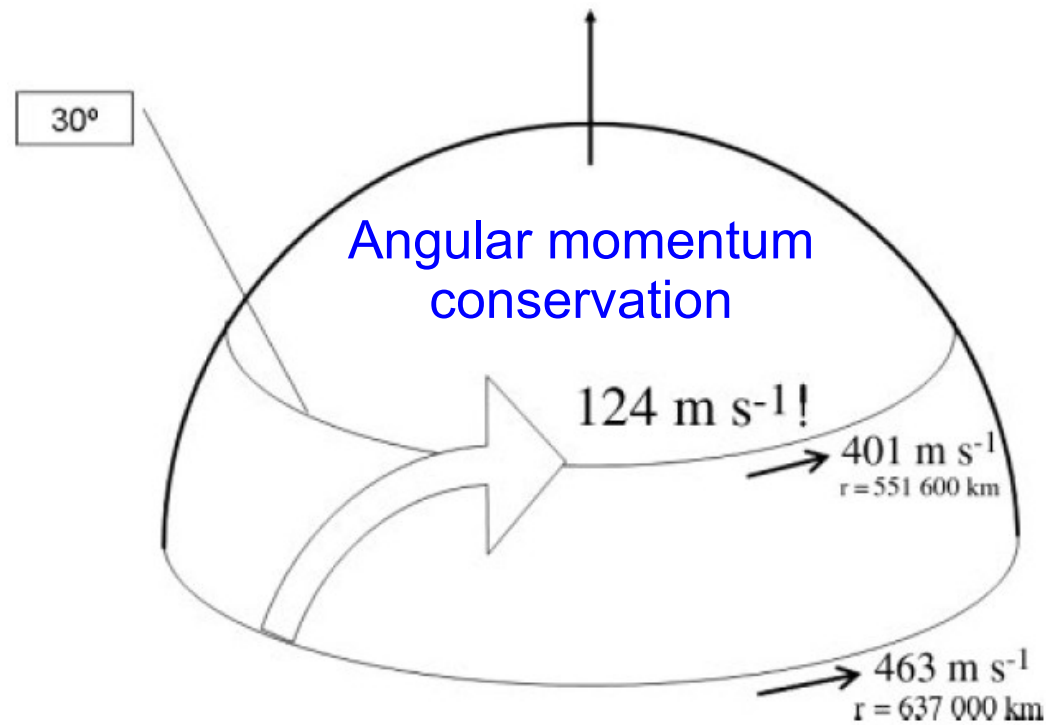
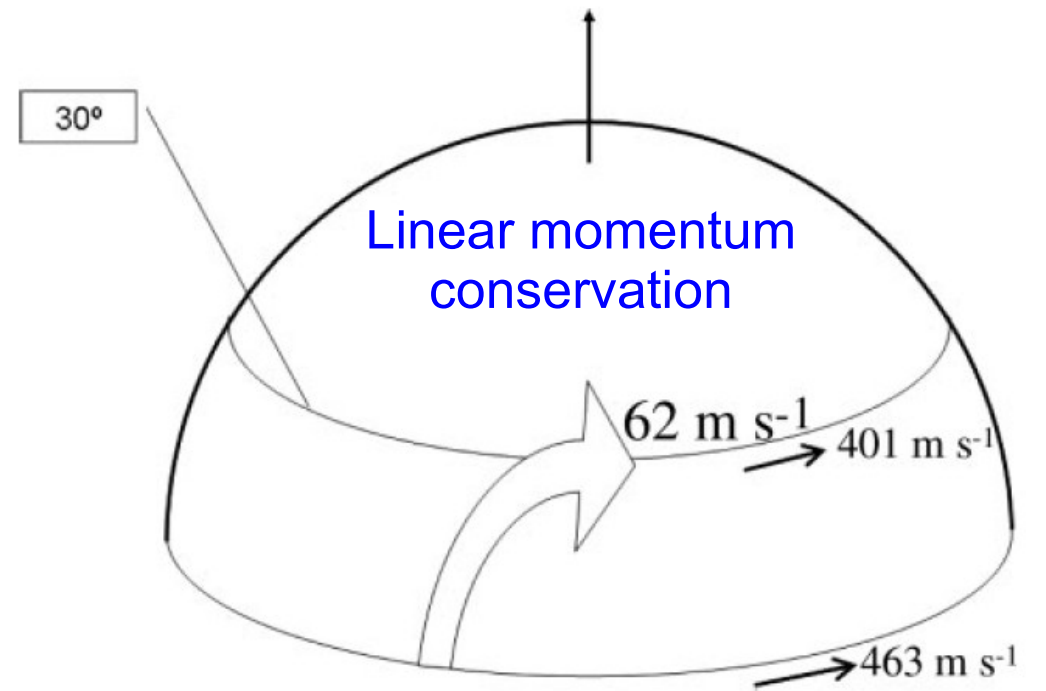
Conservation of angular momentum → ~70 m/s (~160 mi/h)!!



General circulation as envisioned by Hadley



from Lorenz (1983)



from Persson (2009)

- 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).

Ferrel, 1858:

ASTRONOMICAL JOURNAL.

No. 109.

VOL. V.

ALBANY, 1858, JANUARY 20.

NO. 13.

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

BY W. FERREL.

If a body upon or near the earth's surface receive a motion relatively to the earth, either by means of a single impulse or by a continually acting force, this motion, combined with the rotatory 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 coördinates having their origin at the center of the earth, x 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

$$\frac{ddx}{dt^2} = P; \quad \frac{ddy}{dt^2} = Q; \quad \frac{ddz}{dt^2} = R. \quad [1]$$

$$\sin \theta \frac{ddr}{dt^2} + 2 \cos \theta \frac{dr}{dt} \cdot \frac{d\theta}{dt} - r \sin \theta \frac{d\theta^2}{dt^2} + r \cos \theta \frac{dd\theta}{dt^2} - r \sin \theta \left(n + \frac{d\pi}{dt} \right)^2 = \cos (nt + \varpi) Q + \sin (nt + \varpi) R \quad [4]$$

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, we get the second of equations [5]. Again, after sub-

$$\begin{aligned} \frac{ddr}{dt^2} - r \frac{d\theta^2}{dt^2} - r \sin^2 \theta \left(n + \frac{d\pi}{dt} \right)^2 &= \cos \theta P + \sin \theta \cos (nt + \varpi) Q + \sin \theta \sin (nt + \varpi) R; \\ - r \frac{dd\theta}{dt^2} - 2 \frac{dr}{dt} \cdot \frac{d\theta}{dt} + r \sin \theta \cos \theta \left(n + \frac{d\pi}{dt} \right)^2 &= \sin \theta P - \cos \theta \cos (nt + \varpi) Q - \cos \theta \sin (nt + \varpi) R; \\ - r \sin \theta \frac{dd\pi}{dt^2} - 2 \sin \theta \left(n + \frac{d\pi}{dt} \right) \frac{dr}{dt} - 2 r \cos \theta \left(n + \frac{d\pi}{dt} \right) \frac{d\theta}{dt} &= (\sin nt + \varpi) Q - \cos (nt + \varpi) R. \end{aligned} \quad [5]$$

Let r = the distance of the body from the earth's center
 θ = its polar distance
 ϖ = its longitude [printed π in the fractions]
 nt = the rotatory motion of the earth.

We shall then have

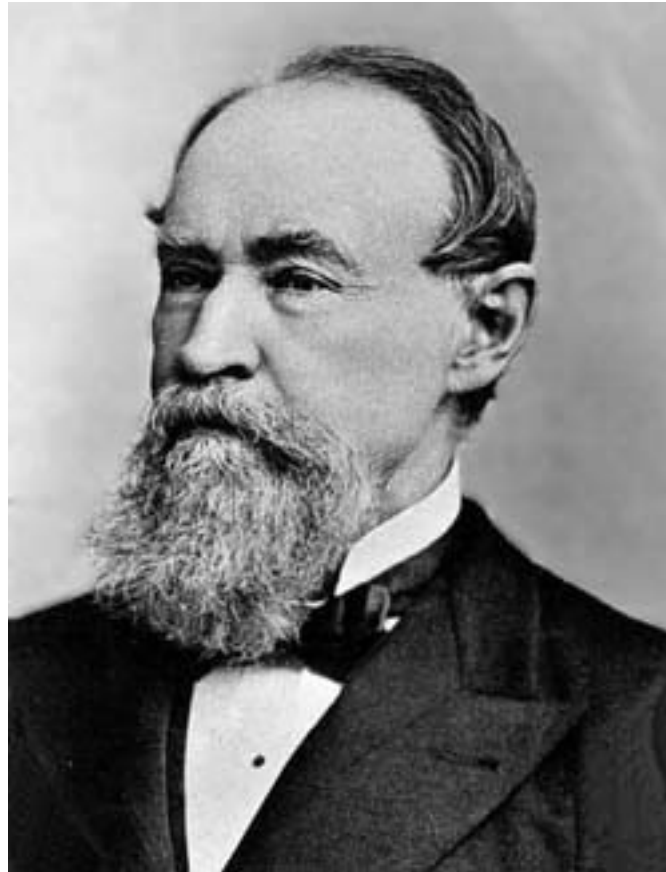
$$x = r \cos \theta; \quad y = r \sin \theta \cos (nt + \varpi); \quad z = r \sin \theta \sin (nt + \varpi) \quad [2]$$

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

$$\cos \theta \frac{ddr}{dt^2} - 2 \sin \theta \frac{dr}{dt} \cdot \frac{d\theta}{dt} - r \cos \theta \frac{d\theta^2}{dt^2} - r \sin \theta \frac{dd\theta}{dt^2} = P \quad [3]$$

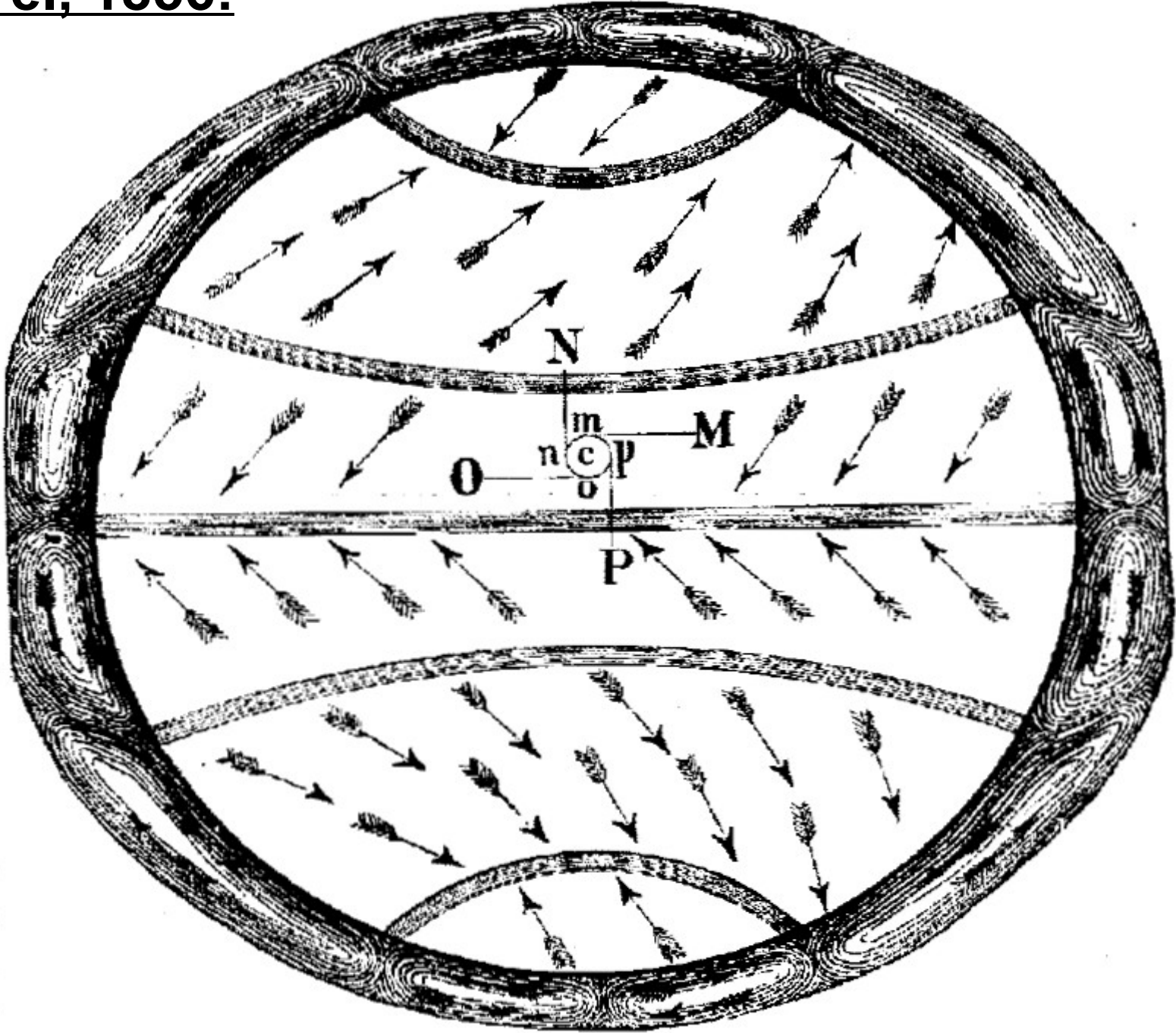
Substituting in like manner the second differentials of y and z in the last two of equations [2], and multiplying the former by $\cos (nt + \varpi)$ and the latter by $\sin (nt + \varpi)$, and adding, we get

stituting the second differentials of y and z , as stated above, in the last two of equations [1], if we multiply the former by $\sin (nt + \varpi)$ and the latter by $\cos (nt + \varpi)$, and subtract, we get the last one of the following equations.



“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.”

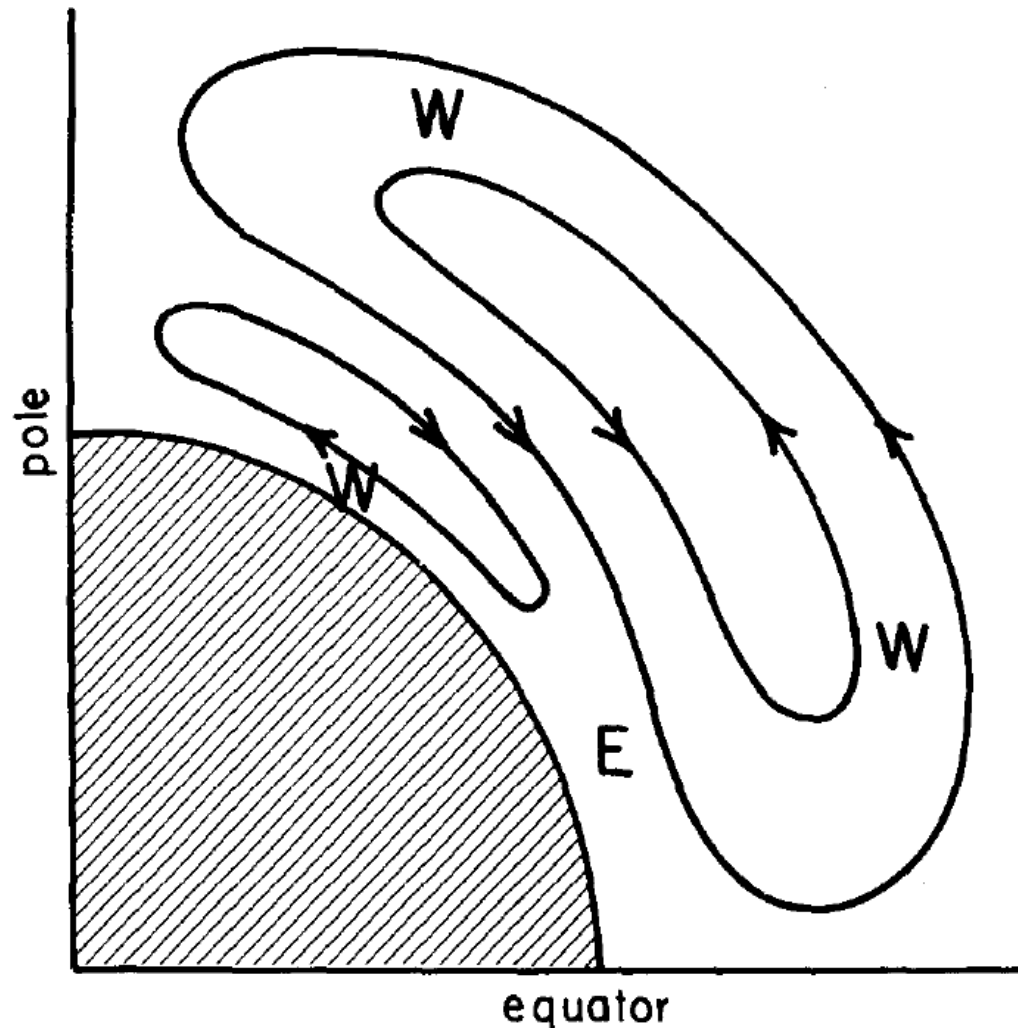
Ferrel, 1856:



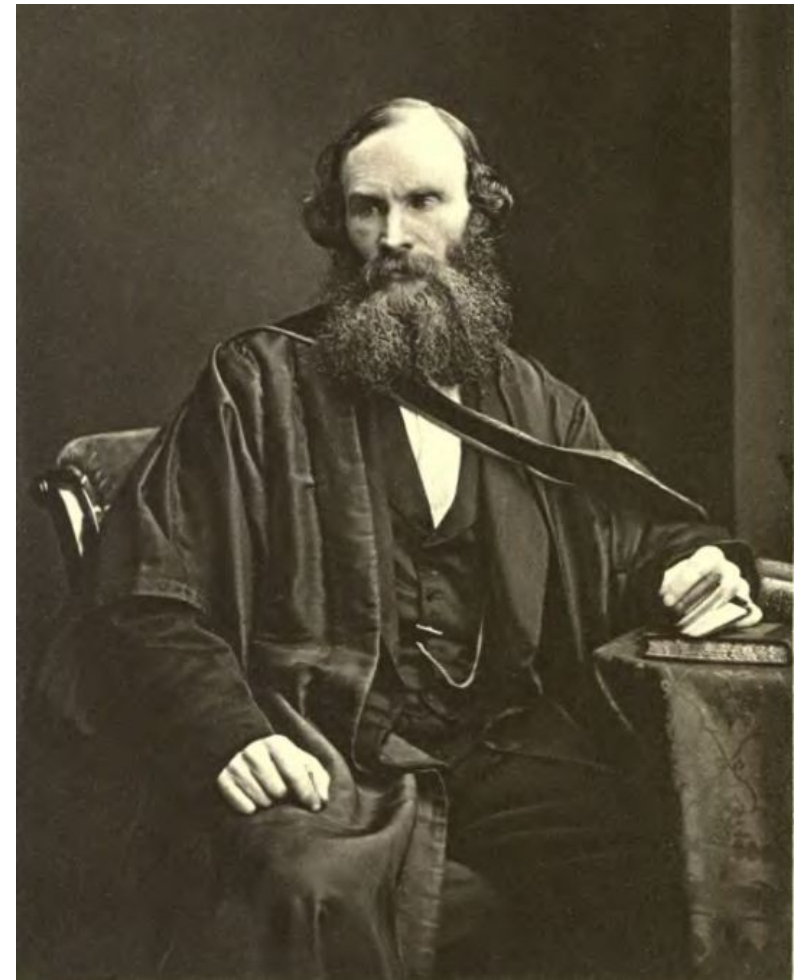
From Hann-Süiring (Lehrbuch der Meteorologie -
“Textbook of Meteorology”, 1926): (loosely translated)

“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).



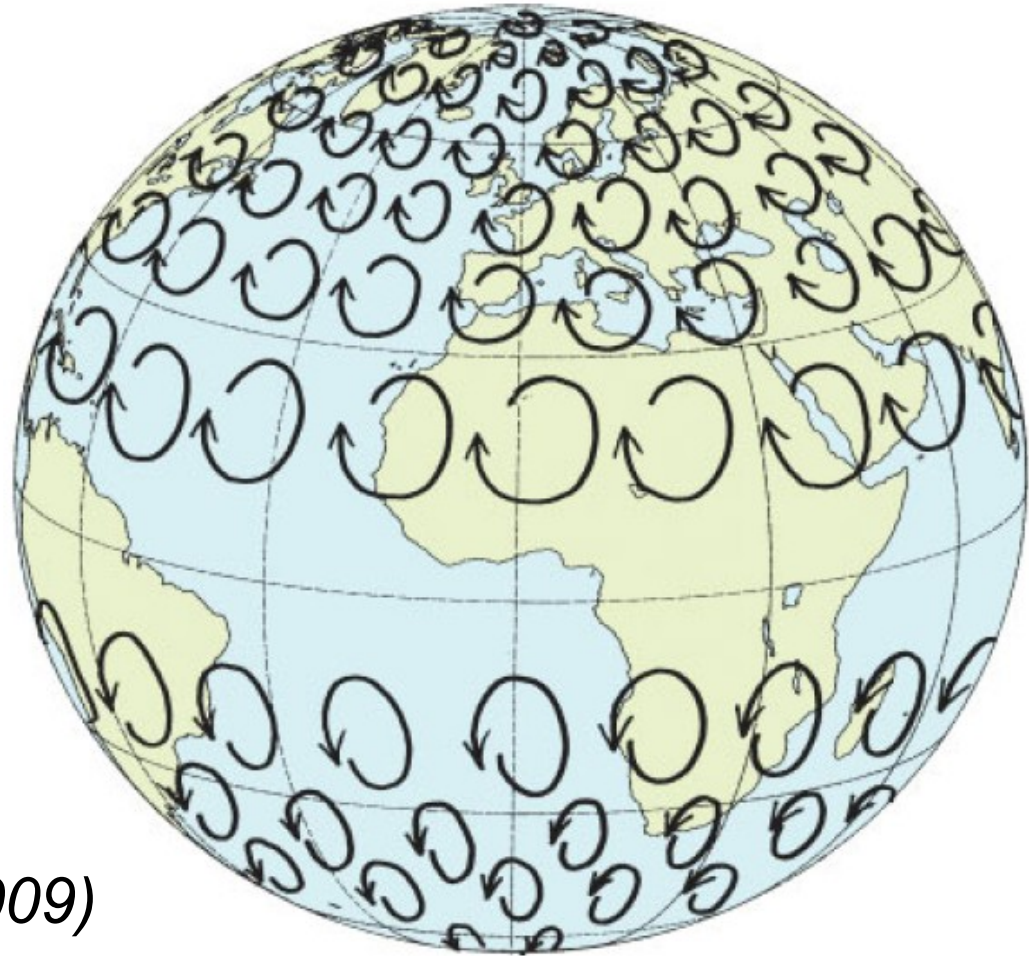
from Lorenz (1983)



“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').