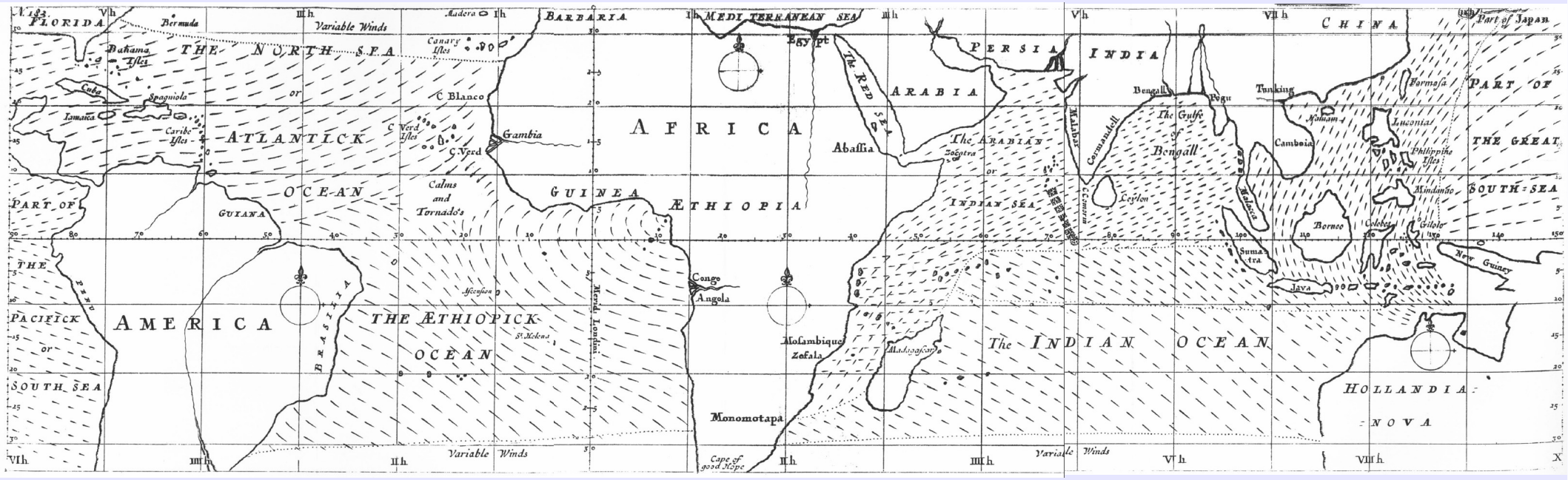
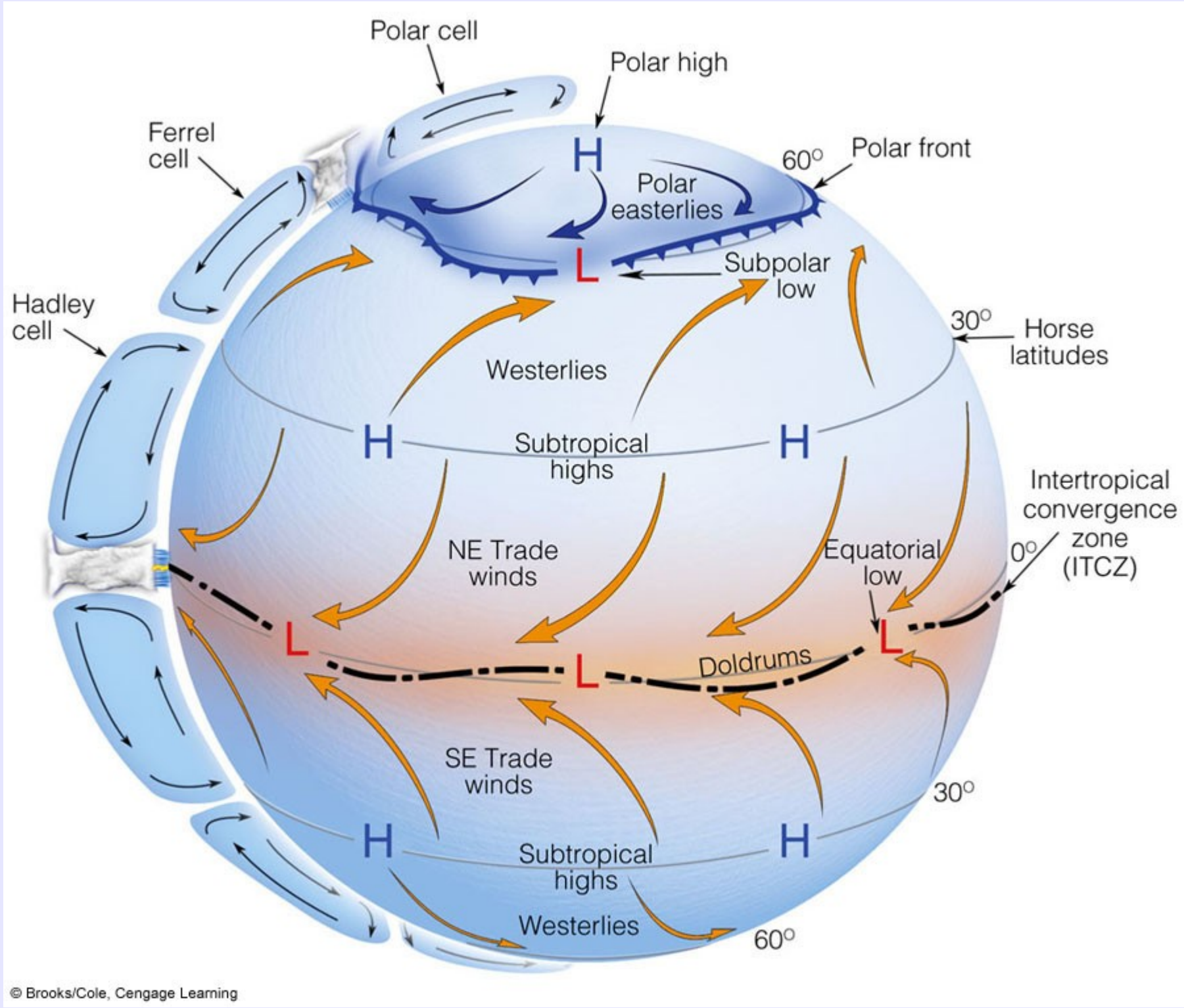
Presentation given at CMMAP Teachers Workshop, 14 July 2011, Thomas Birner

Discovery of Australia & General Circulation History




Polar cell
Polar high
Ferrel cell
H
60°
Polar front
Polar easterlies
L
Subpolar low
Hadley cell
30°
Horse latitudes
Westerlies
H
Subtropical highs
H
Intertropical convergence zone (ITCZ)
NE Trade winds
Equatorial low
0°
L
L
Doldrums
L
SE Trade winds
30°
H
Subtropical highs
H
Westerlies
60°
© Brooks/Cole, Cengage Learning

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)

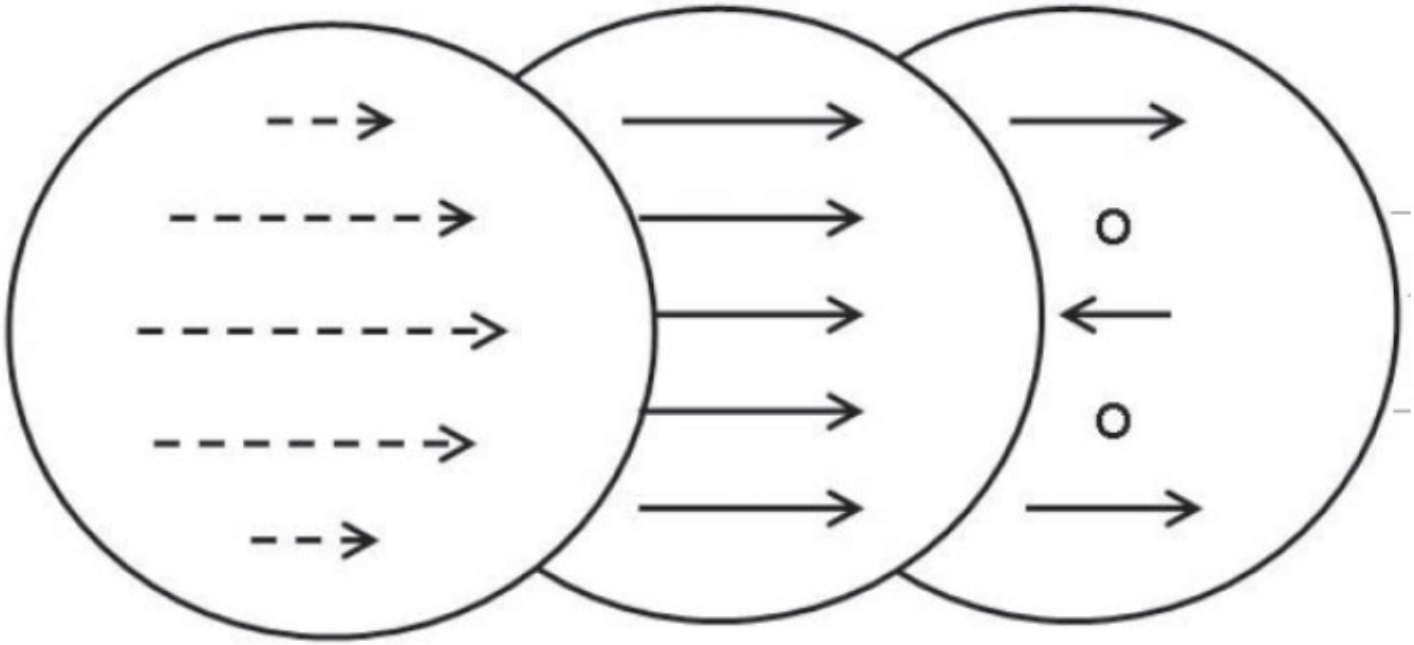
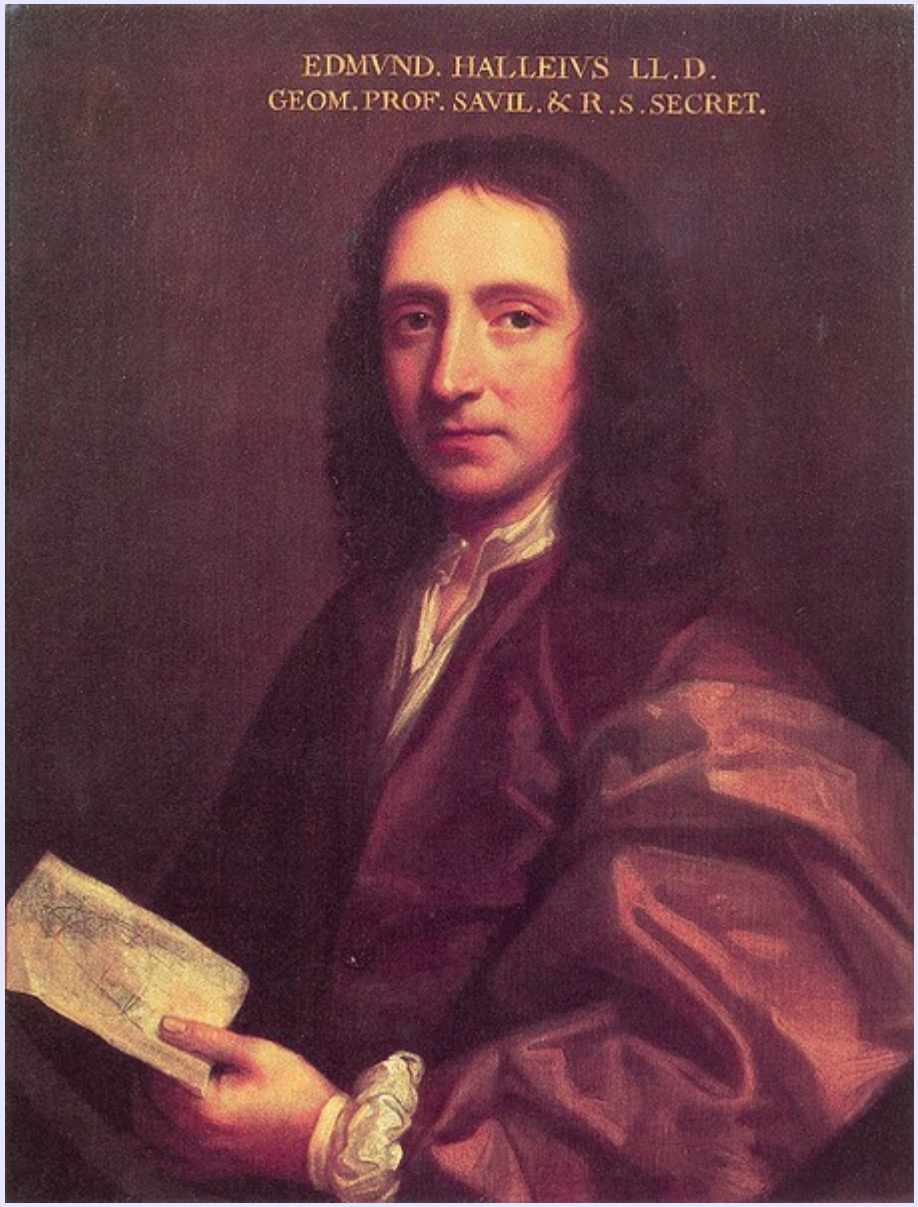


Figure 1. Galileo and Kepler's explanation of the general circulation and, in particular, the easterly Trade Winds. While the velocity of the Earth's surface decreased from the equator (left), the eastward absolute motion of air or water was supposed to be independent of latitude (centre), which would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

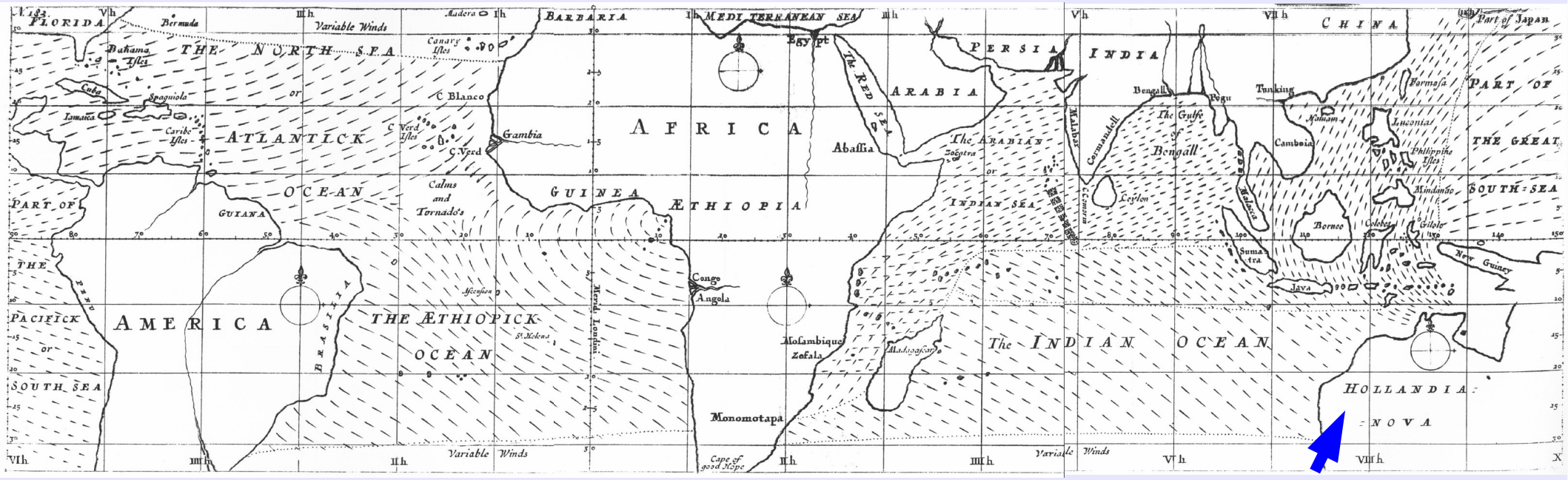
An Historical Account of the Trade Winds, *and* Monsoons, *observable in the Seas between and near the* Tropicks, *with an attempt to assign the Phisical cause of the said Winds, by* E. Halley.



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)

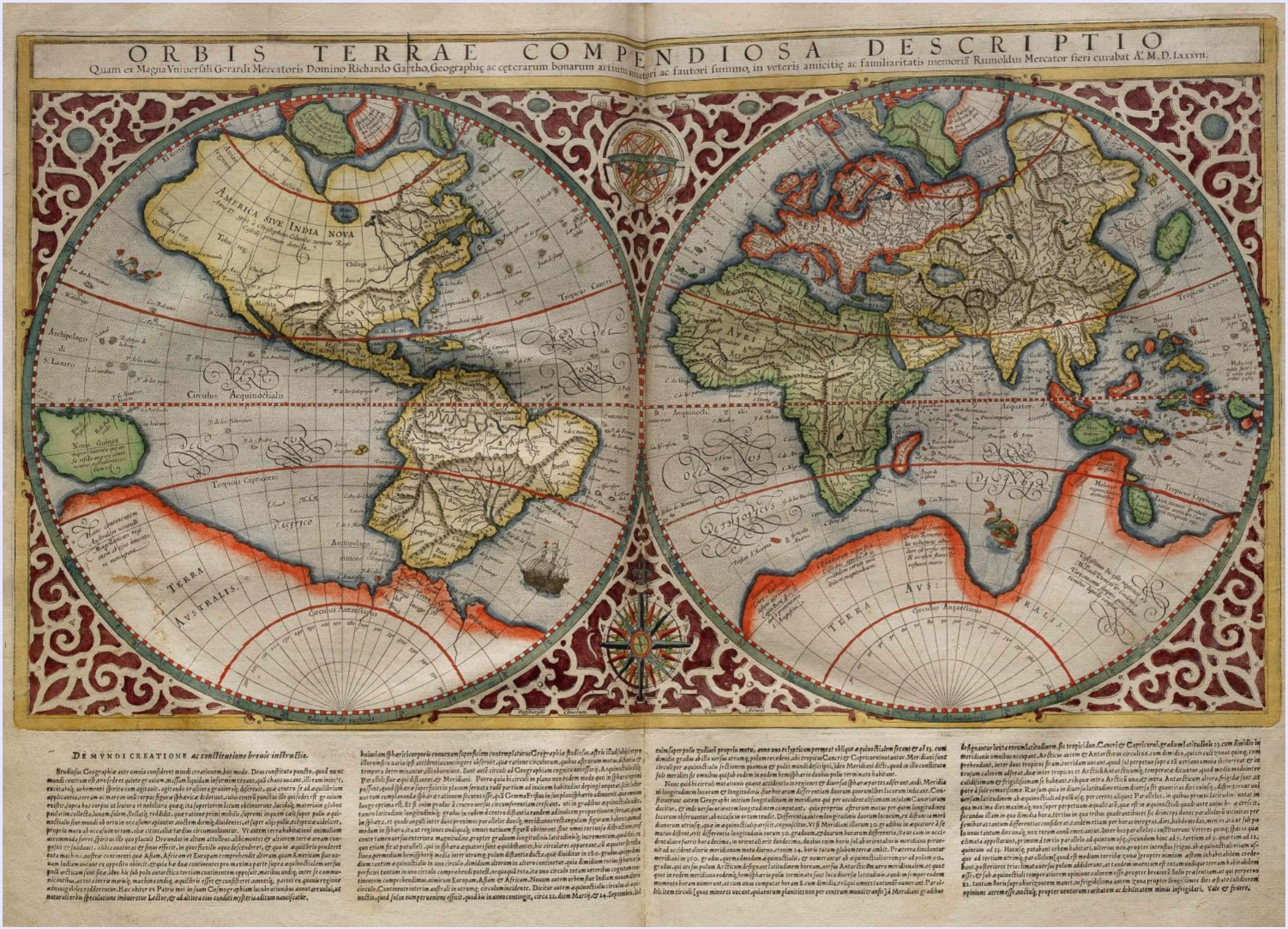
Historical side note: Halley was in contact with Newton and convinced him to publish his Principia, which appeared just one year after his trade wind paper, in 1687!

Map from Halley's 1686 paper



"New Holland"

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

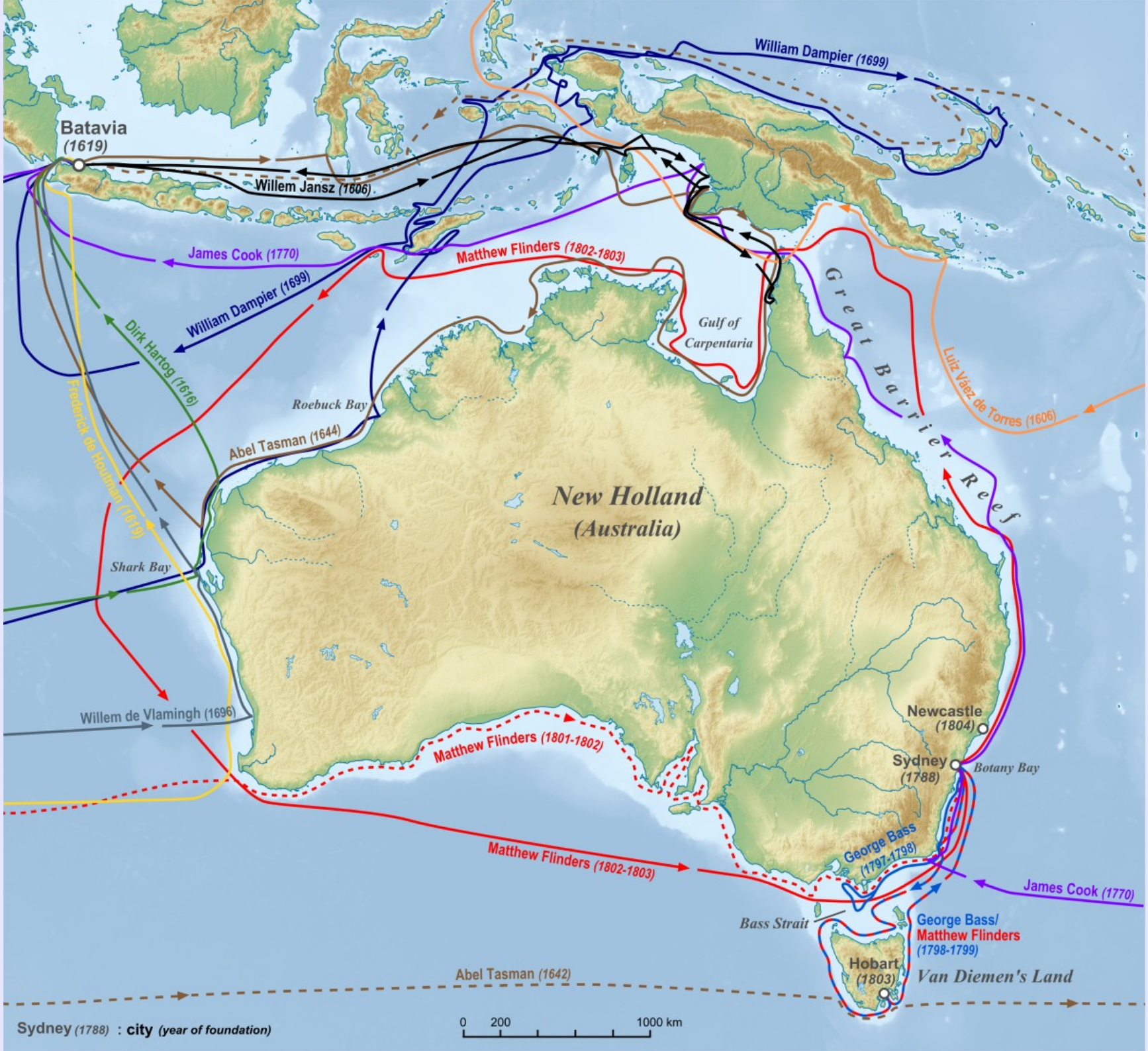


DE MVNDI CREATIONE *ac constitutione breuis instructio.*

Studiosæ Geographiæ ante omnia conſideret mundi creationem, hoc modo. Deus conſtituto puncto, quod nunc mundi centrum eſt, ex eo ſedet et quietè gr auium maſſam liquidam inſarmien tes eas, quã chaos uocant, illi eam inite't, excitato, uehementi ſpiritu eam agitauit, agitando craſſiora grauiora, deſcenſit, que centro ſe ad æquilibrium applicantia, terram ac mare ex unã corpus figuræ ſphæricæ dederunt, cuius centrũ punctus ille qui cedes eſt gr auium exiſtit, ſupra hoc corpus ut leuiora et mobiliora quæq, ita ſuperiorem locum obtinuerunt, lucidaq, materiam globos paulatim collectã, lucam, ſolem, ſtellaſq, reddidit, quæ ratione primi mobilis, ſuprem i in quem cæli ſuper polis æquinoctialis ſiue mundi ab ortu in occaſum epiantur, noſtem diemq, diuidentes, et ſuper alios polis eclipticæ adelicet, propriis motu ab occaſu in ortum, ubi eã itus alibi tardius circumuoluantur. Vt autem terra habitationi animalium accommoda fieret, ſperſit ue illa qua placuit Deo undas in altum attollent, alibi montes & aliu iem terræ eram cinxerunt et ſaldauit, alibi cauatteras & ſinus effecit, in quos fluuiis aquæ deſcenderet, & qua in æquilibrio penderet tota machina, conſtat e continenti qua Aſiam, Africã et Europam comprehendit alteram quam Americam ſiue nouam Indiam uocant ex oppoſito obiecit, ea quia hæ duæ continentes pro maxima parte ſupra æquinoctialem uerſus polũ arcticum ſunt ſitæ, ideo his ſub polo antarctico tertiam continentem oppoſuit, maribus undiq, inter ſe communicantibus, ut tot terræ mariq; machinæ undiq, æquilibrio eſſet & conſiſteret omneq, partes ex quauis regione admodũ habiles reddcretur. Hæc obiter ex Patris mei in ſuam Coſmographiam lucubrationibus annotare uolui, ut naturali ordine ſpeculatione imbiberetur Lector, & ad altiora eius conditi myſteria aditum naneiſcatur.

huiuſmodi ſphæricicorpore ie conuexam ſuperficiem contemplaturus Geographie ſtudioſus, aſtris illud ſubiectis prius ſitu uaria ipſi accidentia contingere obſeruet, quæ ratione circulorum, quibus aſtrorum motus, ſchatie & tempora determinantur, illi obuenient. Sunt autẽ circuli ad Geographiam cognitu neceſſarij. Æquinoctialis, Paralleli ſiue æqui diſtantes & Meridiani. Porro quia hi circuli in plano non eodem modo quo in ſphæra rerum poſſunt, quod ſphæræ ſuperficies in planum ſeruata eadẽ partium ad inuicem habitudine depingi nequeat, ſcitu dignum eſt eam complectendæ ſphæræ rationem ſecutos eſſe, quã Gemma Friſius in ſuo plani ſphærio adiuuenit, quo omnium longe optima eſt. Et ſi enim gradus à centro uerſus circumferentiam crescant, uti in gradibus æquinoctialis uidetur, tamen latitudinis longitudinisq; gradus in eadem à centro diſtantia eandem admodum proportionem ſeruant, quam in ſphæra, et quadranguli inter duos proximos parallelos duosq; meridianos rectilineum ſimilem figuram habent, quod modum in ſphæra eſt ut regiones undiquaq; omnes ratiõnem figuræ obtineant, ſiue omni tortuoſa diſtractum, ſiue contracta tamen uerſus exteriora magnitudine propter gradum longitudinis latitudinisq; incrementum, quod ſit, ex quo etiam fit ut parallelli, qui in ſphæra æquatoriſant æquidiſtantes, hic circulares appareant, ut æquator ſimilitudine germedium hemiſphærij media inter utrumq, polum diſtantia ducta, quæ diuiditur in 180. gradus, quibus dimidium tantum æquinoctialis in uno circulo dimidium alterum in altero continetur, quia dimidium totius ſphæræ ſuperficies tantum in uno circulo comprehendi poteſt, neque quã tota, ita uno circulo totam ueteribus cognitam continentem comprehendimus, nimirum Europam, Aſiam & Africam, Nouum autem orbem ſiue Indiam nouam alteri circulo, Continenti interim auſtr dis in utrumq; circulum incidente. Dicitur autem æquinoctialis circulus æquinoctio, quod ſolin eum per ueniens efficit, quod bis in anno contingit, circa 11. diem Martij, & 14. Septembris. Sol enim ſuper polis zodiaci proprio motu, anno uno eclipticam permeat et obliqua æquinoctialem ſecent & ad 23. cum dimidio gradus abillo uerſus utrumq; polum recedens, ubi tropicus Cancri & Capricorni notantur. Meridiani ſunt circuli per æquinoctialis ſectionem quamlibet & polos mundi deſcripti, ideo Meridiani dicti, quod in illo conſtituto ſole meridies ſe omnibus qui ſub eodem in eadem hemiſphærio dumbus polis terminato habitant.

Nunc quid hi circuli mutationis quoue accidentis in regiones & diuerſas ſphæræ partes adferant, audi. Meridiani longitudinem locorum & longitudinis, ſiue horarum differentiam duorum quorumlibet locorum indicant. Conſtituerunt autem Geographi initium longitudinum in meridiano qui per occidentaliſſimam inſulam Canariarum ducitur, & inde uerſus orientem longitudinem computant, quia proprius aſtrorum motus per quem longitudines locorum obſeruantur, ab occaſu in ortum tendit. Differentia autem longitudinis duorum locorum, ex diſtantia meridianorum utriuſq, quæ in æquinoctiali aperiri dicitur, cognoſcitur. Vt ſi Meridiani illorum 30. gr adibus in æquatore à ſe mutuo diſtent, erit differentia longitudinis eorum 30. graduum, & horarum harum differentia, ita ut cum in occidentaliore fuerit hora decima, in orientali erit duodecima, dicitur enim horis ſol ab orientali ad uerſum meridiano peruenire ad occidentalioris meridianum motu diurno, etenim 24. horis totum globum terræ ambit. Præterea duo iuncturæ meridiani in 360. gradus, quemadmodum æquinoctialis, & numerantur ab æquinoctialis uerſus utrumq; ad polum 90. gradus, qui uerſus polum Arcticum deſignant latitudinem boream, uerſus Antarcticum uero meridionalem, at quot quot in eodem meridiano eodemq; hemiſphærio polis terminato ſunt loca diuerſæ latitudinis, tot modi ſemper eodem momento horam numerant, ac cum unus computat horam 8. cum dimidia, reliqui omnes tantundẽ numerant. Parallelli item circuli [quos minores uocant, quia eorum planities non per centrum mundi tranſit] à Meridiani gradibus deſignantur in ea terram latitudinem ſic tropicidue Cancri & Capricorni, gradum latitudinis 23. cum dimidio in meridie omnibus occupant. Arcticus autem & Antarcticus circuli 66. cum dimidio, quia circuli zonas quinq; communes, inter duos tropicos ſitam, torridam uocant, quod ſol perpetuo ſupra eã uerſans omnia ibi torreat & intenſum calorem adferat, duæ inter tropicos et Arcticũ Antarcticumq; temperatæ dicuntur, quod medio modo inter calidiſſimam & frigidiſſimam ſe habeant, reliquæ intra Arcticũ una, & intra Antarcticum altera, frigidæ ſunt, ut pote à ſole remotiſſimæ. Rurſum quia in diuerſa latitudine etiam diuerſa ſit quantitas diei cuiuſq;, diſtinxerunt uniuerſam latitudinem ab æquinoctiali ad poli uſq, per certos aliquot Parallelos, in quibus primũ latitudinis notat in qua maxima dies maximaq; nox ſuper perpetuam æqualitatẽ, quæ eſt in æquinoctiali quadrante unius horæ crescit, ſecundus illam in qua dimidia hora, tertius in qua tribus quadrantibus et ſic deinceps donec parallelorũ uicinitas per ſemihoras tantum differentias conſideret, eadem etiam per horas integras, dies, hebdomadas, menſes, annos ſub polo unius tantum diei unq, non totum annũ emetientes. Inter hos parallelos conſtituerunt Veteres quinq; ſpatia quæ climata appellarunt, primum à tertio parallelo ad quintum uſq, ſecundum hinc ad 9. tertium ad 9. quartum ad 13. quintum ad 15. Hacuſq; patabant orbem habitari, ulterius non propter interuſtus frigus. ab æquinoctiali etiam uſque ad tertium utrimq; parallelum, quod eſt medium torridæ zonæ [propter nimium æſtum inhabitabilem credebant, poſteriores tria climata uerſus polum addiderunt, at tandem inuentum eſt totam uſquequaque terram habitabilem eſſe, & ſub æquinoctiali temperatiorem opinione calorem eſſe propter breuem è Solis præſentiam, at qui perpetuo 12. tantum horis ſupra horizontem manet, in frigidiſſima autem zona propter longiſſimos dies æſtate calidiorem opinione aerem eſſe noctiuq, propter uentorum aſſiduitatem ac debilitatem minus infrigidari. Vale & fruere.


Batavia
(1619)
Willem Jansz (1606)
William Dampier (1699)
James Cook (1770)
Matthew Flinders (1802-1803)
William Dampier (1699)
Dirk Hartog (1616)
Frederick de Houtman (1619)
Shark Bay
Roebuck Bay
Abel Tasman (1644)
Gulf of
Carpentaria
Great Barrier Reef
Luiz Vaez de Torres (1606)
New Holland
(Australia)
Willem de Vlamingh (1696)
Matthew Flinders (1801-1802)
Matthew Flinders (1802-1803)
Newcastle
(1804)
Sydney
(1788)
Botany Bay
George Bass
(1797-1798)
James Cook (1770)
Bass Strait
George Bass/
Matthew Flinders
(1798-1799)
Hobart
(1803)
Van Diemen's Land
Abel Tasman (1642)
Sydney (1788) : city (year of foundation)
0 200 1000 km

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

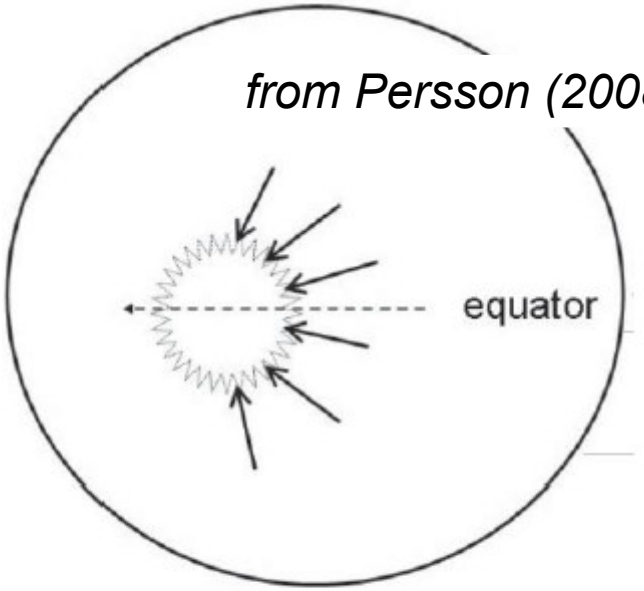
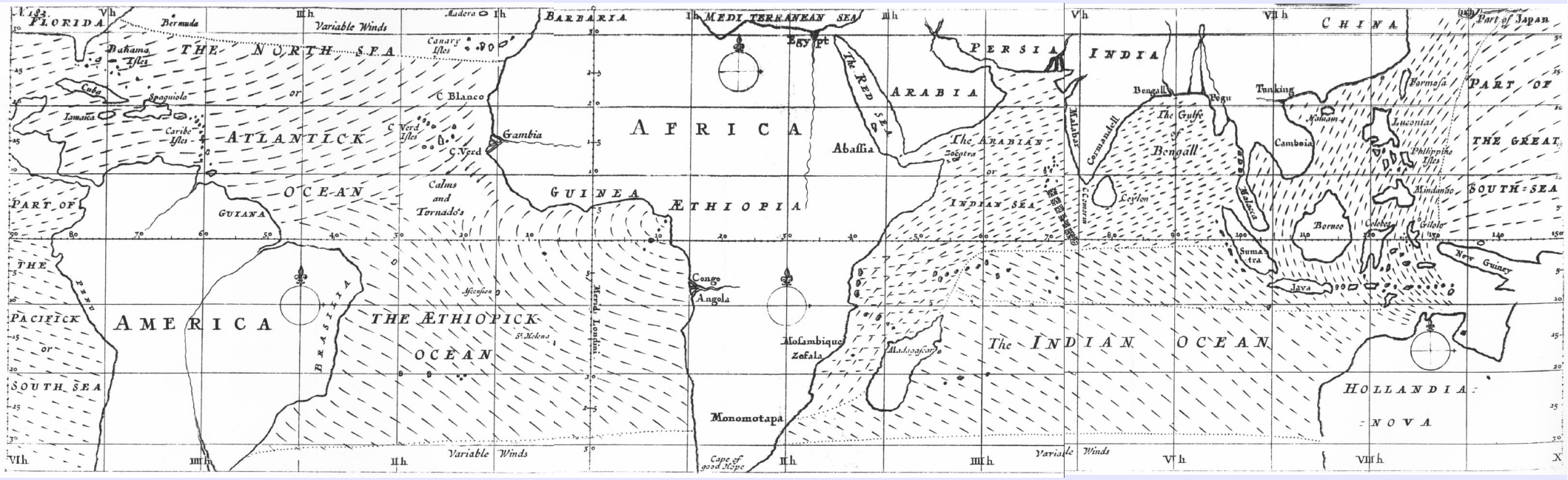


Figure 2. Halley's explanation of the easterly Trade Winds: as the maximum heating of the sun at the Earth's surface during the day moves westward, air will be sucked in from behind and replace the air that has been heated and risen.



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 [illegible]

Crucial role of Earth's rotation

Global angular momentum conservation

[illegible] 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
(1685–1768)
Concerning the Cause of the General Trade Winds. Philos. Trans. London (1735).

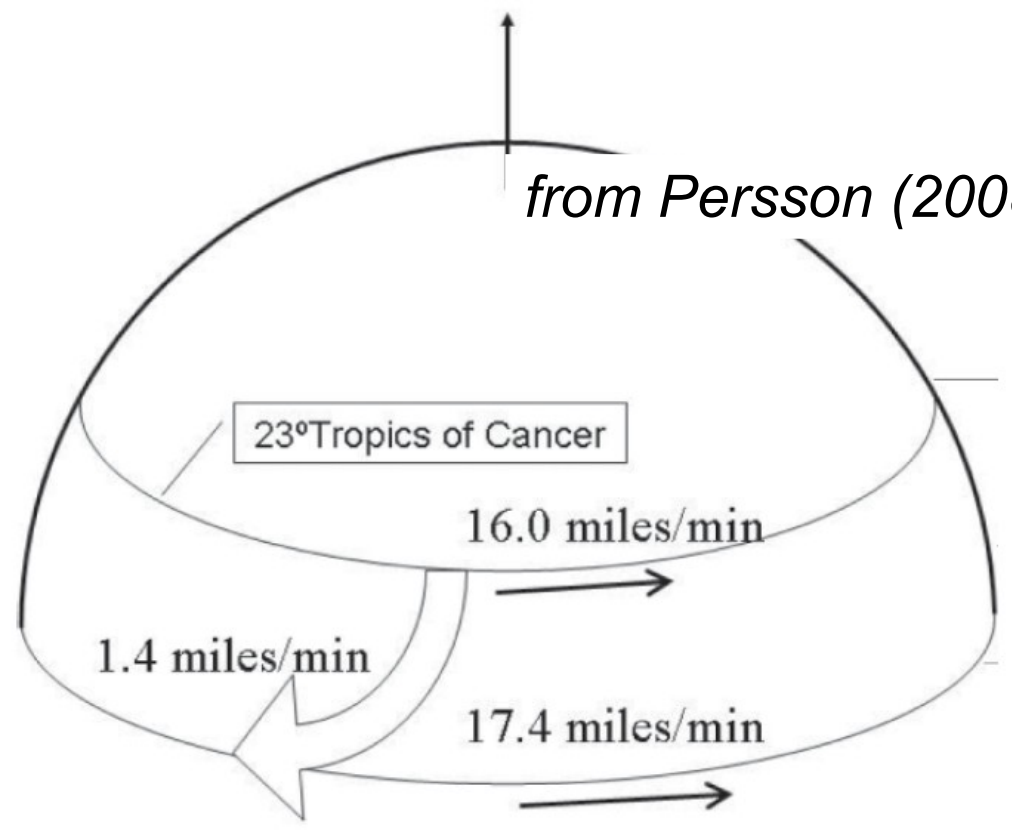
VI. *Concerning* the Cauſe *of the* General Trade-Winds: *By* Geo. Hadley, *Eſq*; *F. R. S.*

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

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

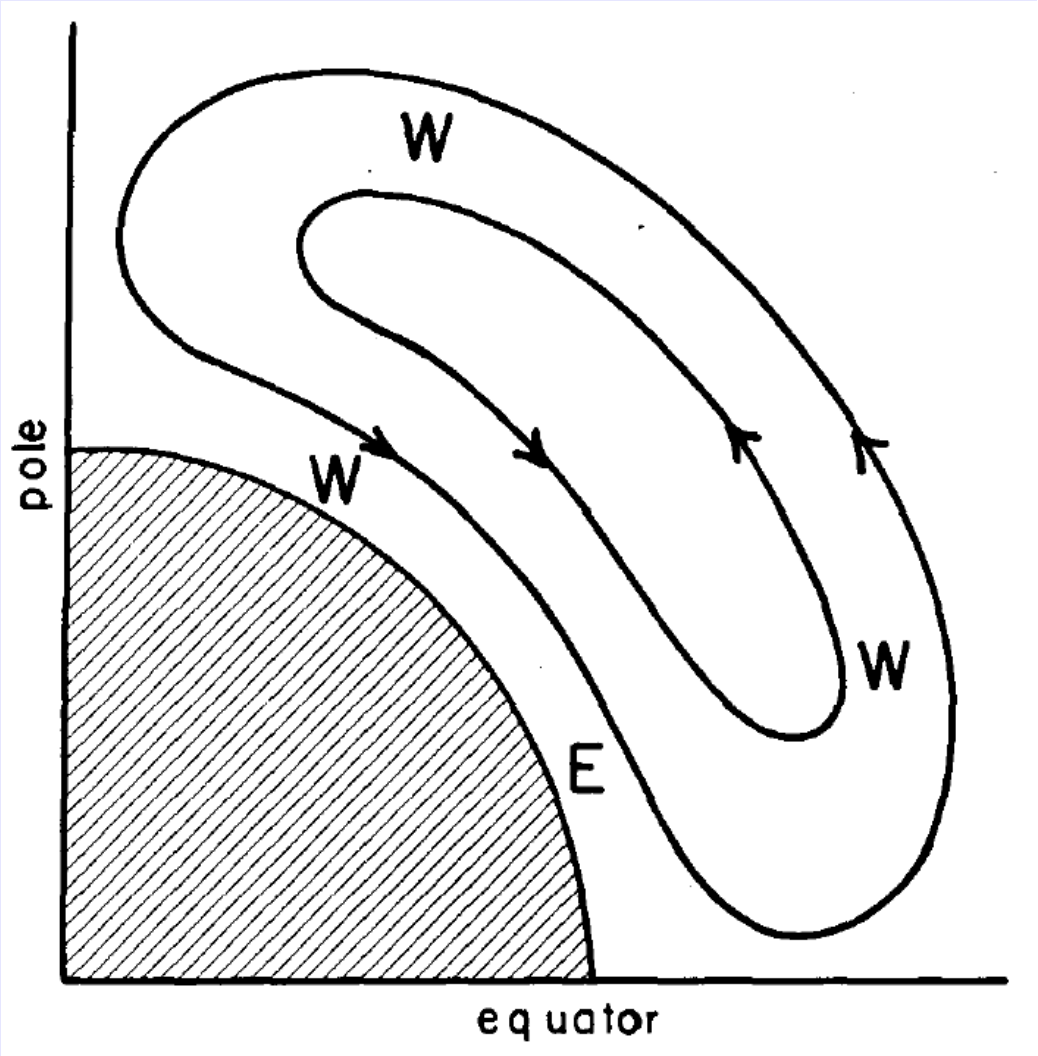
friction slows down wind to observed speeds

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

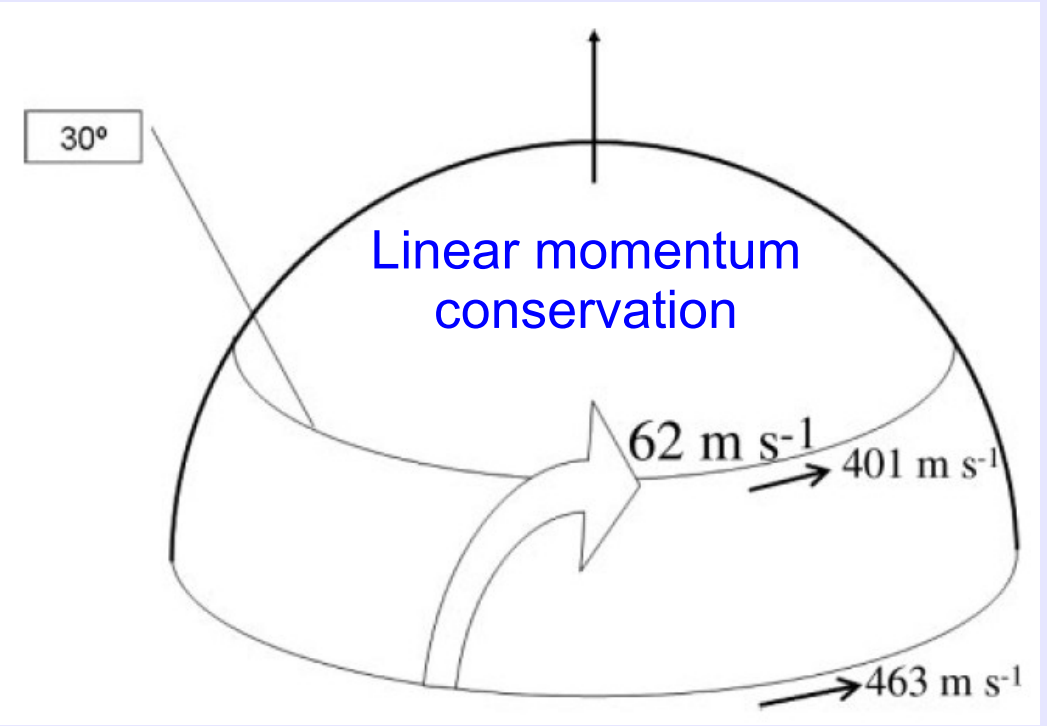


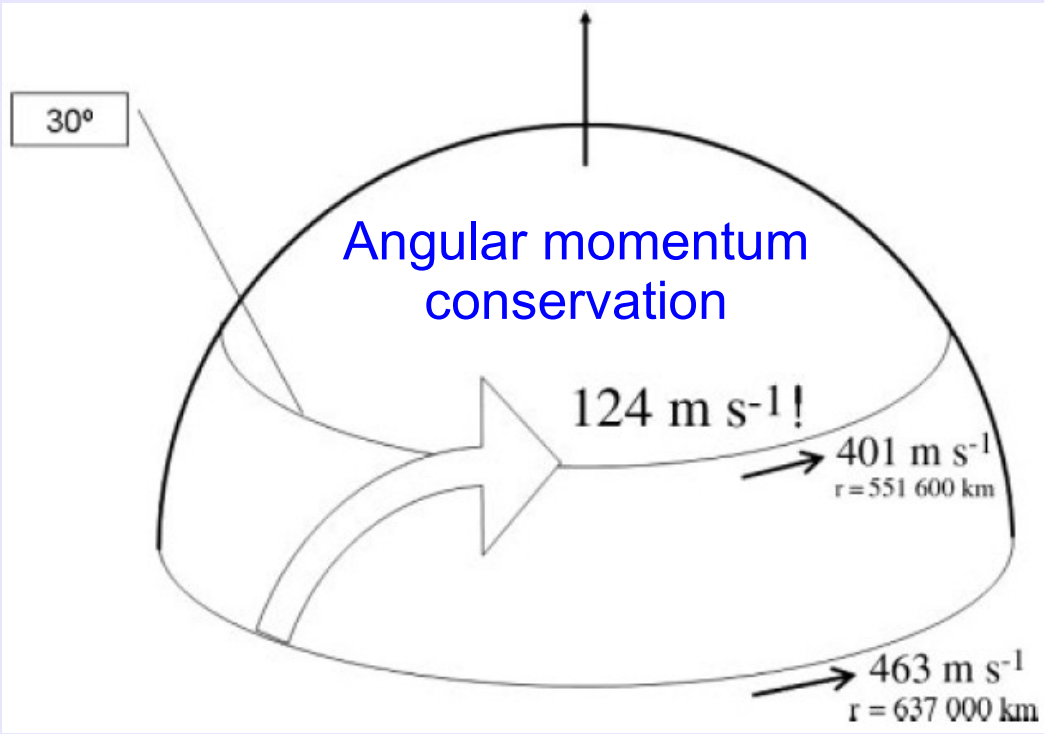
from Persson (2008)

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

from Persson (2009)

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.

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

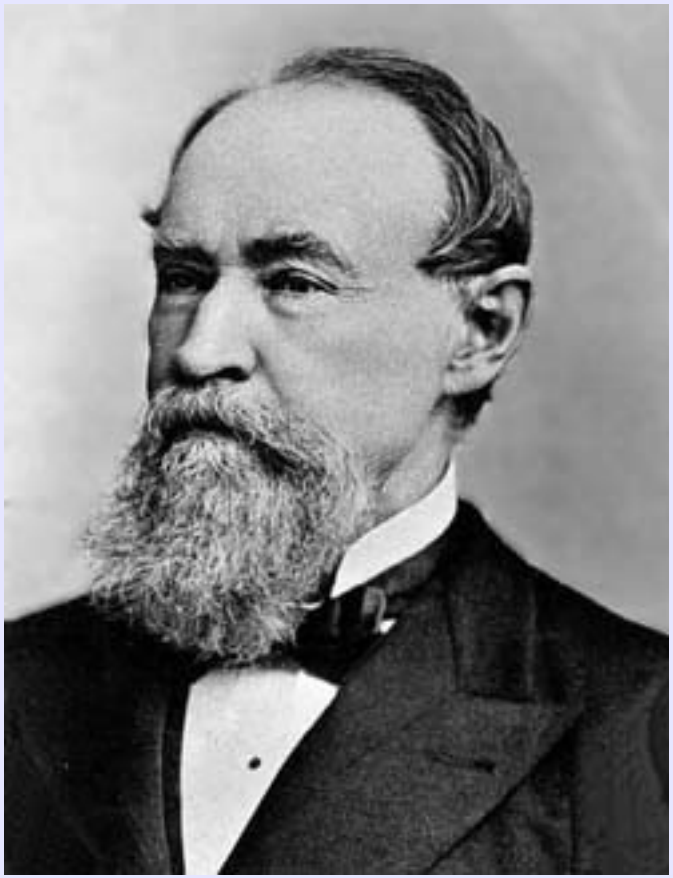
I published a theory of the Trade Winds, &c, as Mr Dove has published, - it was forty-four years ago, as may be seen in my Meteorology, 1793 and 1834. It was first published by G. Hadley, Esq, in 1735, as I afterwards learnt. It is astonishing to find how the true theory should have stood out so long.

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:

THE
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

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

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

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

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

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

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

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

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 substituting 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.

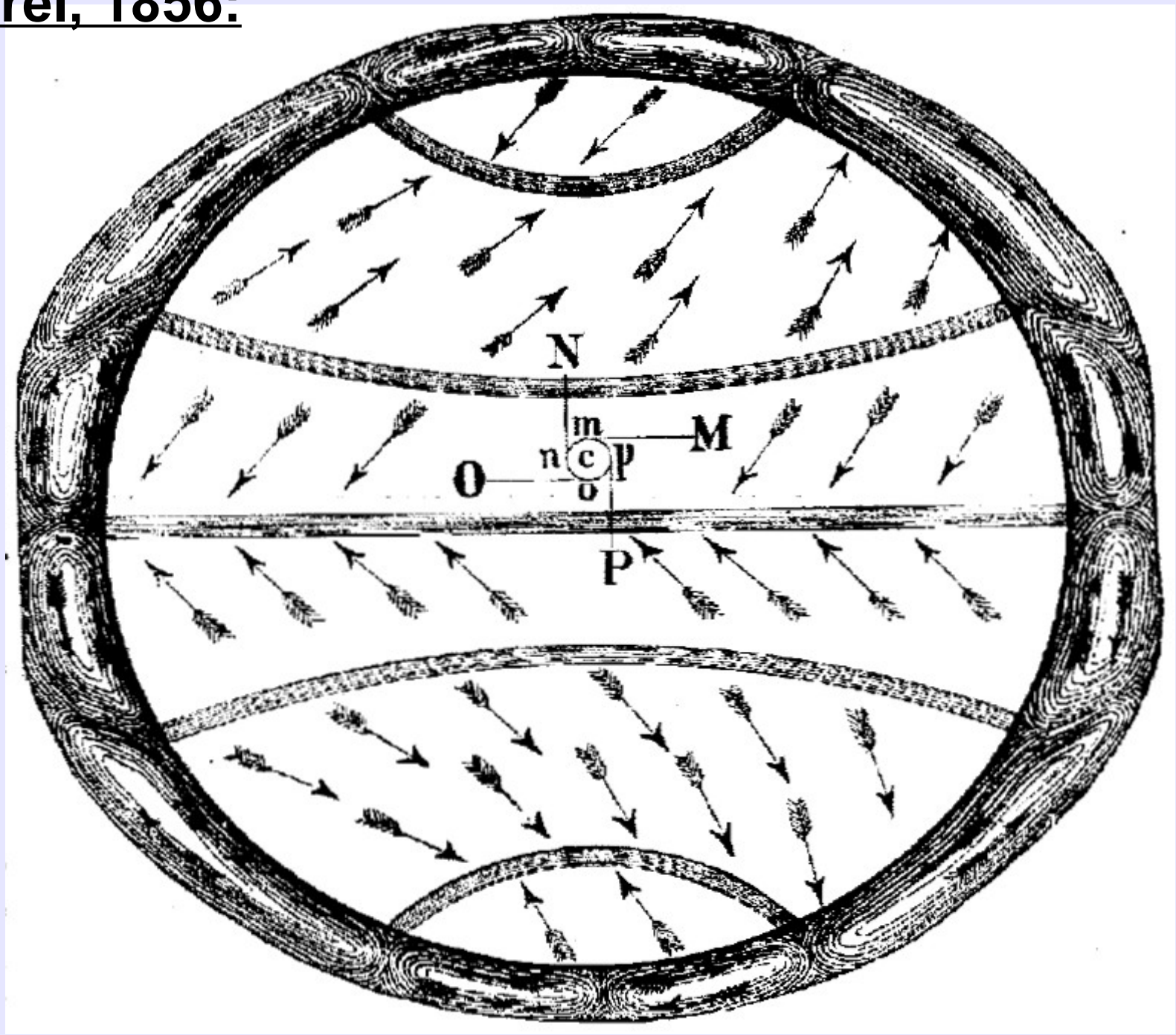
$$\frac{ddr}{dt^2} - r\frac{d\theta^2}{dt^2} - r\sin^2\theta\left(n+\frac{d\pi}{dt}\right)^2 = \cos\theta\,P + \sin\theta\cos(nt+\varpi)\,Q + \sin\theta\sin(nt+\varpi)\,R\,;$$

$$-r\frac{dd\theta}{dt^2} - 2\frac{dr}{dt}\cdot\frac{d\theta}{dt} + r\sin\theta\cos\theta\left(n+\frac{d\pi}{dt}\right)^2 = \sin\theta\,P - \cos\theta\cos(nt+\varpi)\,Q - \cos\theta\sin(nt+\varpi)\,R\,; \qquad [5]$$

$$-r\sin\theta\frac{dd\pi}{dt^2} - 2\sin\theta\left(n+\frac{d\pi}{dt}\right)\frac{dr}{dt} - 2r\cos\theta\left(n+\frac{d\pi}{dt}\right)\frac{d\theta}{dt} = (\sin nt+\varpi)\,Q - \cos(nt+\varpi)\,R.$$

"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."

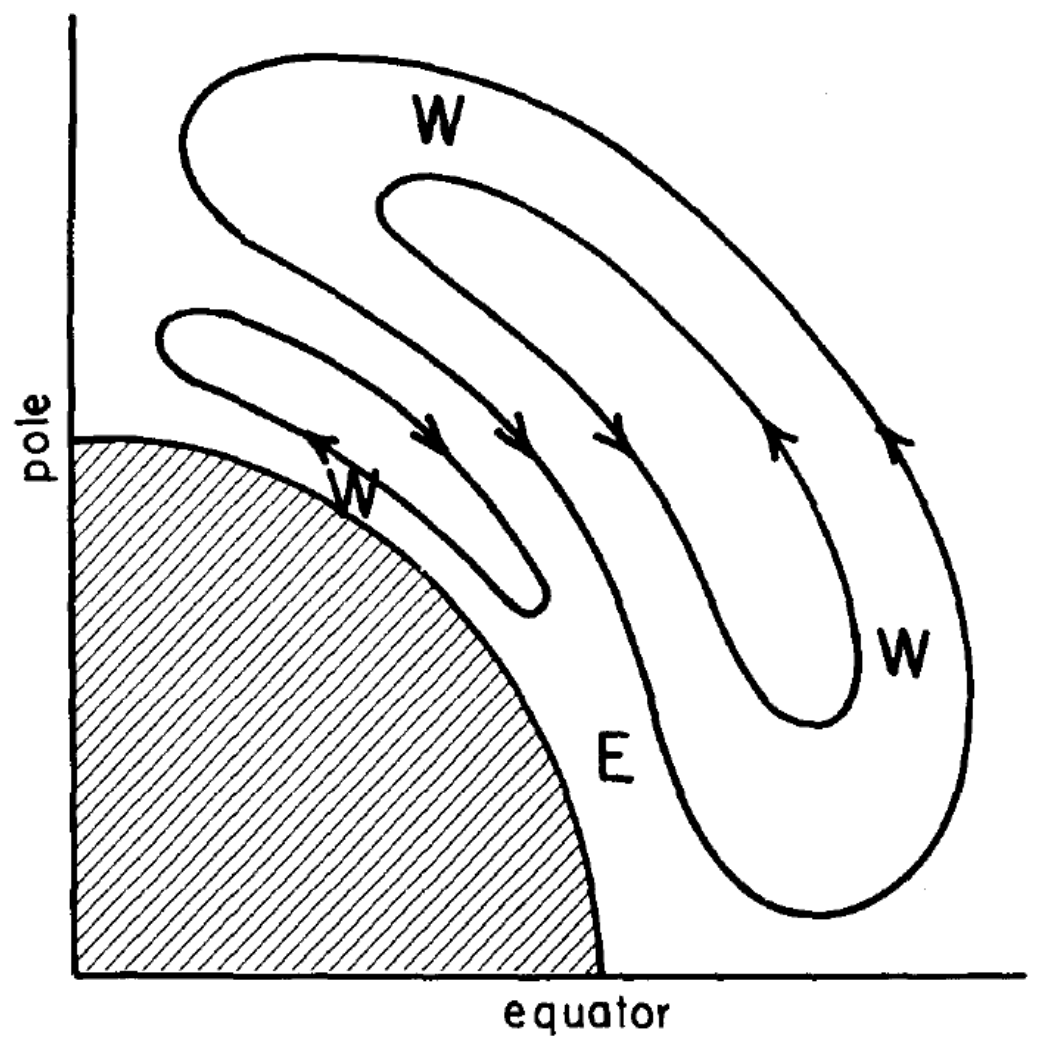
Ferrel, 1856:



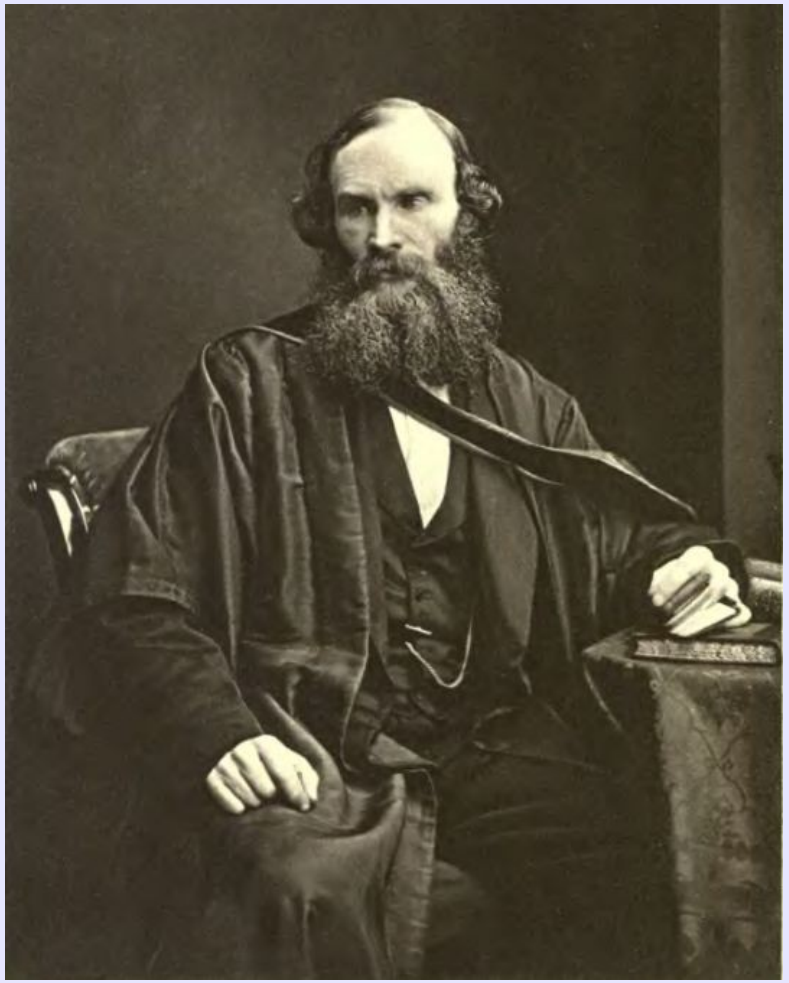
From Hann-Süring (Lehrbuch der Meteorologie - “Textbook of Meteorology”, 1926): (loosely translated)

“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).



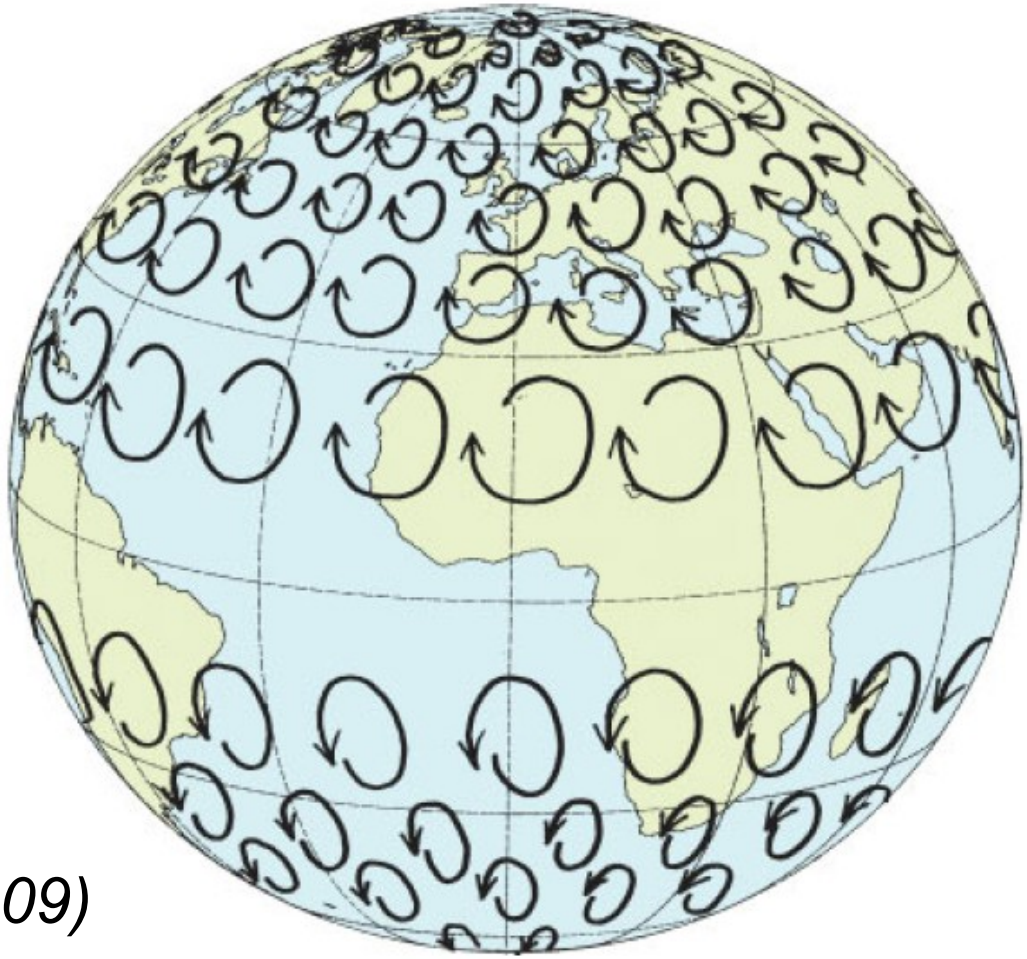
from Lorenz (1983)



"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').