Energy Balance
Atmospheric window

LW up

LW down

Outgoing longwave radiation

Incoming solar radiation

340

Reflected solar radiation

100

TOA

Atmospheric absorption

75

77

Absorbed SW

188

Reflected SW

23

SH

24

LH

88

LW up

398

LW down

345

Cloud effect

165

Clear Sky

40

Atmospheric reflection

(after Stephens et al. 2012)
At the surface...

\[ c_s \rho_s \frac{\partial T_s}{\partial t} = S_0 \downarrow - L_0 \uparrow - F_L - F_S - \text{div} F_O \]

SW Radiation
LW Radiation
Sensible Heat (SH) Flux
Latent Heat (LH) Flux
**Bulk Aerodynamic Formulae**

\[
SH = \rho c_p C_{D,T} \| \mathbf{v}_s \| (T_s - T(z_a))
\]

\[
LH = \rho L C_{D,q} \| \mathbf{v}_s \| (q_s^* - q(z_a)),
\]

where \( T_a := T(z_a), q_a := q(z_a) \) ([\( q \) = kg/kg] denote the respective fields at a reference height \( z_a \), typically 2–10m above the surface.)
Angular Momentum and Surface Winds
Earth’s surface winds

(Source: NCEP/NCAR reanalysis)
Earth’s surface winds

**Source:** NCEP/NCAR reanalysis

- **30°N**
- **30°S**

**Speed:**
- **equatorward & westward**
- **NE Trades**
- **SE Trades**

(Speed: 0, 5, 10 m/s)

(Source: NCEP/NCAR reanalysis)
Earth’s surface winds

(Source: NCEP/NCAR reanalysis)
Earth’s surface winds

Westerlies poleward (!) & eastward

(Source: NCEP/NCAR reanalysis)
Earth’s surface winds

- NE Trades
- SE Trades
- Westerlies

30°N
30°S

Speed:

0
5
10 m/s

(Source: NCEP/NCAR reanalysis)
Earth’s surface winds

Note:

- very turbulent winds, esp. above continents ➔ sailors on oceans
- only in time mean clear evidence of pattern
Mariners used the prevailing winds...

Columbus’ First Voyage (1492)

Westerlies

NE Trades

...but science remained in the Dark Ages.
What is wind?

“It is absurd to suppose that the air which surrounds us becomes wind simply by being in motion. [...] Winds are formed by the gradual collection of small quantities of [dry and moist] exhalation, in the same way that rivers form when the earth is wet. [...] We have thus given an account of the nature and origin of the wind.”

Aristotle, *Meteorologica*, 2, iv (c. 340 BC)
Finally the Royal Society takes on the subject...

“Among the known Sea Plants, the Sargosse, is not to be forgot. [...] From the daily and constant breath of that Plant, the Trade or Tropick 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 make it constant and uniform.”

Martin Lister, *Phil. Trans.*, 15 (1684)
Finally the Royal Society takes on the subject...

“Among the known Sea Plants, the Sargosse, is not to be forgot. [...] From the daily and constant breath of that Plant, the Trade or Tropick 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 make it constant and uniform.”

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Note: Isaac Newton lived 1642-1726
“Wind is most properly defined to be the Stream or Current of the air. [...] It remains to [find] a cause agreeable to the known properties of Air and Water, and the laws of the Motion of fluid Bodies. Such a [cause] is, I conceive, the Action of the Sun Beams upon the Air and Water, as he passes every day over the Oceans.”

Edmond Halley, *Phil. Trans.*, 16 (1686)
Halley’s view of the trade winds
Halley’s view of the trade winds
Halley’s view of the trade winds
Earth’s rotation matters

“The causes of the General Winds have not been fully explained by any of those who have written on that Subject, for want of more particularly and distinctly considering the Share the diurnal Motion of Earth has in the Production of them.”

George Hadley, Phil. Trans., 39 (1735)
Hadley’s view of winds and the general circulation
Hadley’s view of winds and the general circulation

(Source: http://www.youtube.com/watch?v=FyHyni1-zYE)
Hadley’s view of winds and the general circulation
Hadley’s view of winds and the general circulation
“The NE and SE Winds within the Tropics must be compensated by as much NW and SW [Winds] in other Parts; otherwise some Change must be produced in the Motion of the Earth round its Axis.”

„Concerning the Cause of the General Trade-Winds“. G. Hadles (1735)
Theories about the general circulation

How to explain the poleward motion of the mid-latitude westerlies???
Theories about the general circulation

How to explain the poleward motion of the mid-latitude westerlies???

- three cells
- only zonally symmetric circulation
- cyclones and storms were studied but no interaction
What do we know today?
Eastward wind (January)

(Schneider, Ann. Rev. Earth Planet. Sci., 2006)
Eastward wind (January)

![Diagram showing Eastward wind with Hadley cells and Ferrel cells](image)

- **Eastward Wind (January)**
  - **Pressure (mbar)**: 200, 800
  - **Zonal Sfc. Wind (m s⁻¹)**: 0, 8
  - **Latitude**: -50°, 0°, 50°
  - **Easterlies**
  - **Westerlies**

(Figure from Schneider, Ann. Rev. Earth Planet. Sci., 2006)
Jupiter from *Cassini*
Hadley circulation confined to tropics

Extratropical macroturbulence transports angular momentum into regions of wave generation
(1) Solar heating: driving force for air circulation (Halley, 1700)
   ➔ differential heating: poleward flow
   ➔ no east-west component

(2) AM conservation (equiv. to Coriolis force): east-west component (Hadley, 1735)
   ➔ problems: mid-latitude westerlies

(3) Multi-cellular structured circulation (Ferrell, Thomson, 1800-1900)

(4) Storms and Macroturbulence (1900)
   • observations: upper-level mean meridional circulation not sufficient for poleward energy transport
     ➔ finite extent of Hadley cell, not up to poles
     ➔ observations WWII: no upper level winds from tropics to higher latitudes
     ➔ importance of zonal deviations (eddies)
   • turbulence theory for heat transport
   • where do asymmetries come from?
     ➔ (baroclinic) instabilities (Rossby, 1940; Eady, Charney, 1950)
Mean Flows and Eddies

Time mean
\[ \overline{\cdot} = \frac{1}{T} \int_{0}^{T} \cdot \, dt \]

Transient eddy
\[ \cdot' = \cdot - \overline{\cdot} \]

Zonal mean
\[ [\cdot] = \frac{1}{2\pi} \int_{0}^{2\pi} \cdot \, d\lambda \]

Stationary eddy
\[ \overline{\cdot}^* = \overline{\cdot} - [\overline{\cdot}] \]
Eddy angular momentum transport
Macroturbulence in control

Any theory of atmospheric circulations and of climate must be based on a theory of atmospheric macroturbulence.

Because we have no complete theory of macroturbulence, “the causes of the General Winds still have not been fully explained by any of those who have written on that Subject” (Hadley).
Energy Balance & Transport
Mean Flows and Eddies

Time mean
\[ \overline{(\cdot)} = \frac{1}{T} \int_{0}^{T} (\cdot) \, dt \]

Transient eddy
\[ (\cdot)' = (\cdot) - \overline{(\cdot)} \]

Zonal mean
\[ [\cdot] = \frac{1}{2\pi} \int_{0}^{2\pi} (\cdot) \, d\lambda \]

Stationary eddy
\[ \overline{(\cdot)^*} = \overline{(\cdot)} - [\overline{(\cdot)}] \]
Flux Decomposition

Decomposing fluxes, e.g., meridional energy flux $vE$, with $v = \bar{v} + v' = [v][E] + v^*E^*$. So

$$\bar{vE} = \bar{v}\bar{E} + \bar{v'}E'$$ (7.17)

$$[vE] = [v][E] + [v^*E^*]$$ (7.18)

and zonal- and temporal-mean flux

$$[\bar{vE}] = [\bar{v}\bar{E}] + [\bar{v'}E']$$ (7.19)

$$= [\bar{v}] \bar{E} + [\bar{v}^*E^*] + [\bar{v'}E']$$ (7.20)

This is a decomposition into mean circulations, stationary eddies, and transient eddies.
MSE Transport

Transient eddies (KJ m kg\(^{-1}\) s\(^{-1}\))

Stationary eddies (KJ m kg\(^{-1}\) s\(^{-1}\))

Mean meridional circulation (KJ m kg\(^{-1}\) s\(^{-1}\))

MSE Transport
Vertically Integrated MSE Transport

MSE flux (PW)

-9
-3
3
9

Transients eddies
Mean meridional circulations
Stationary eddies
Total

45°S 0 45°N

Vertically Integrated MSE Transport