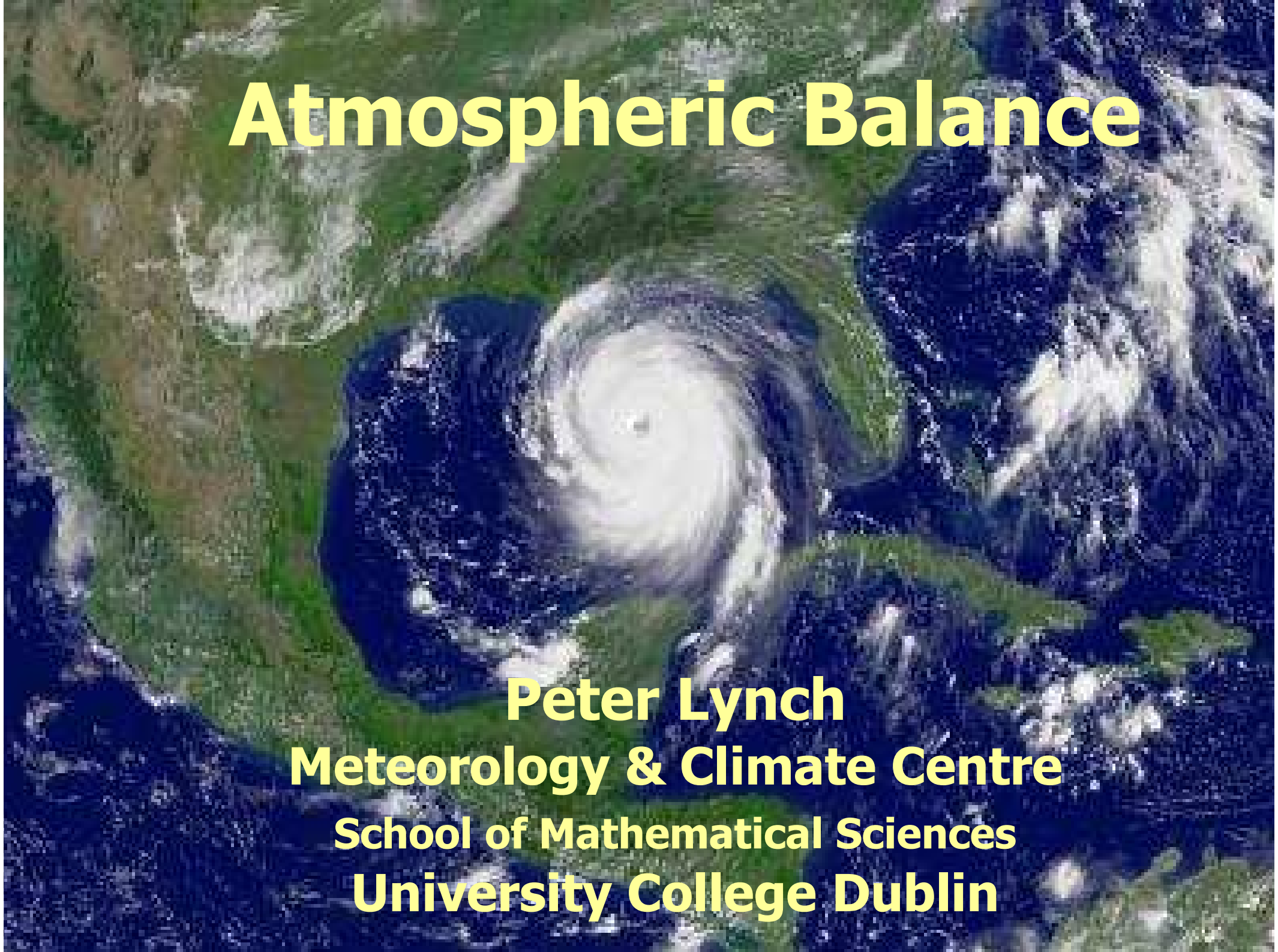


Atmospheric Balance

Peter Lynch
Meteorology & Climate Centre
School of Mathematical Sciences
University College Dublin

Atmospheric Balance

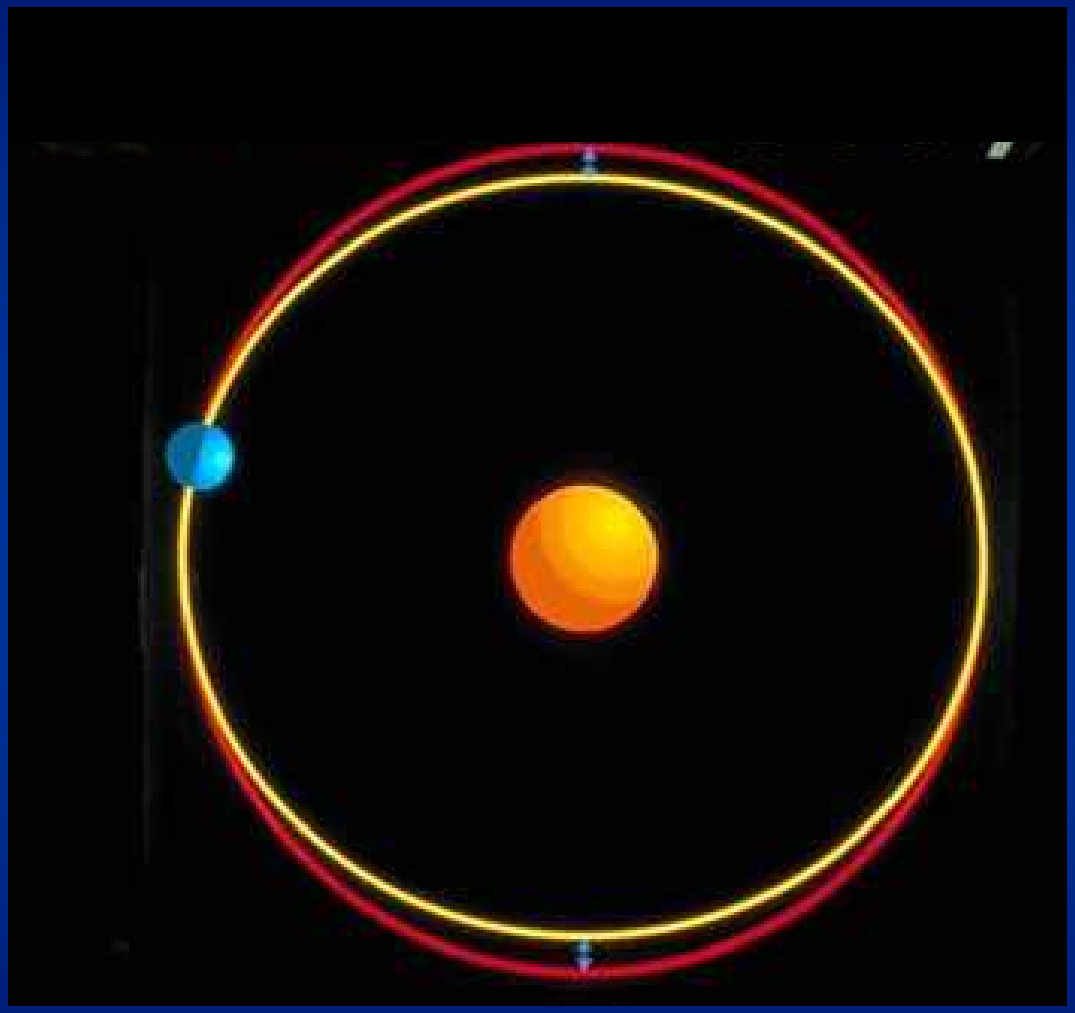
Peter Lynch

Meteorology & Climate Centre

School of Mathematical Sciences

University College Dublin

Earth's Orbit around the Sun

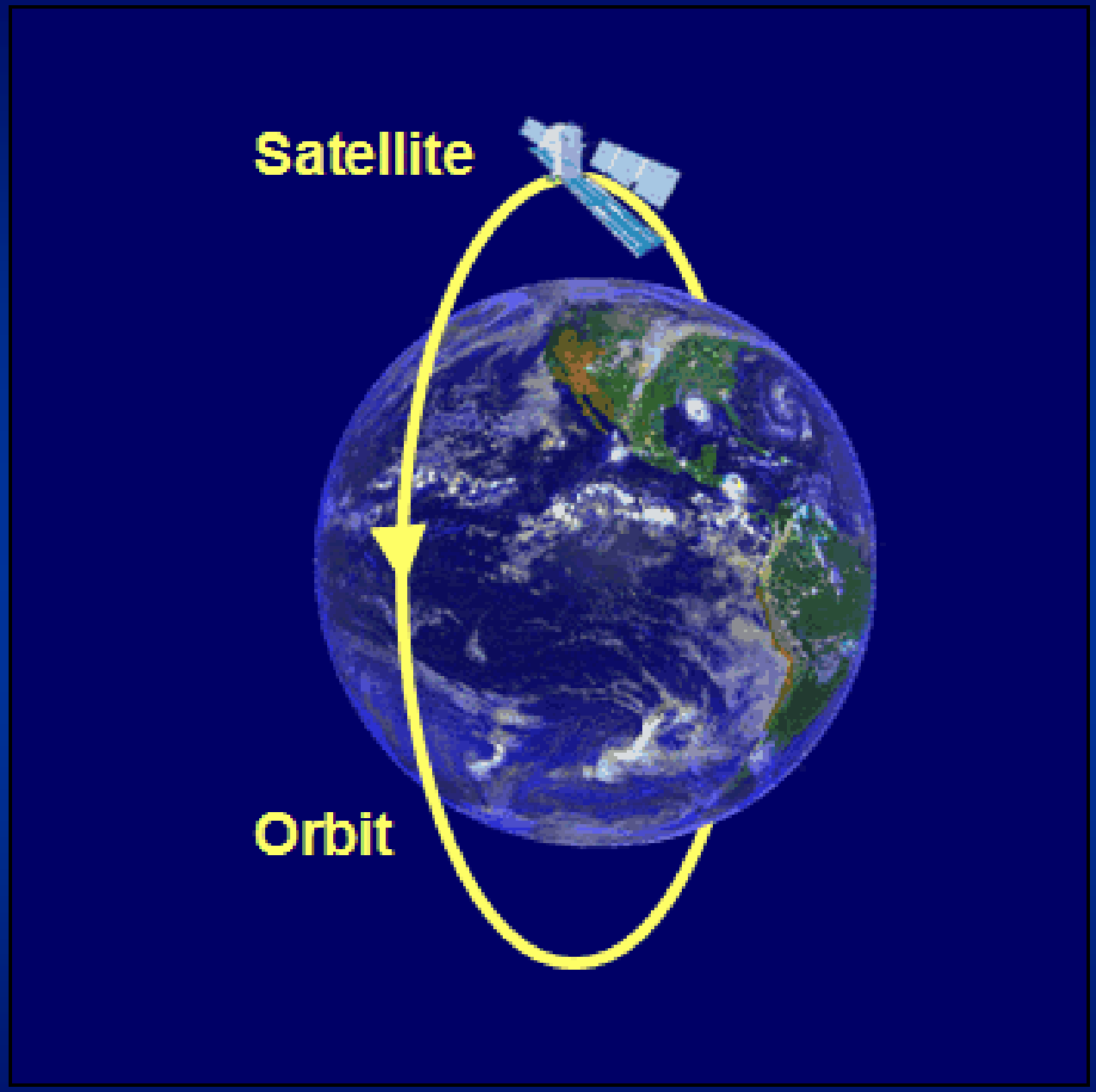


Balance

Gravitational Force

equal and opposite to

Centrifugal Force



Gravitational attraction

balances

Centrifugal force

Atmospheric Balance

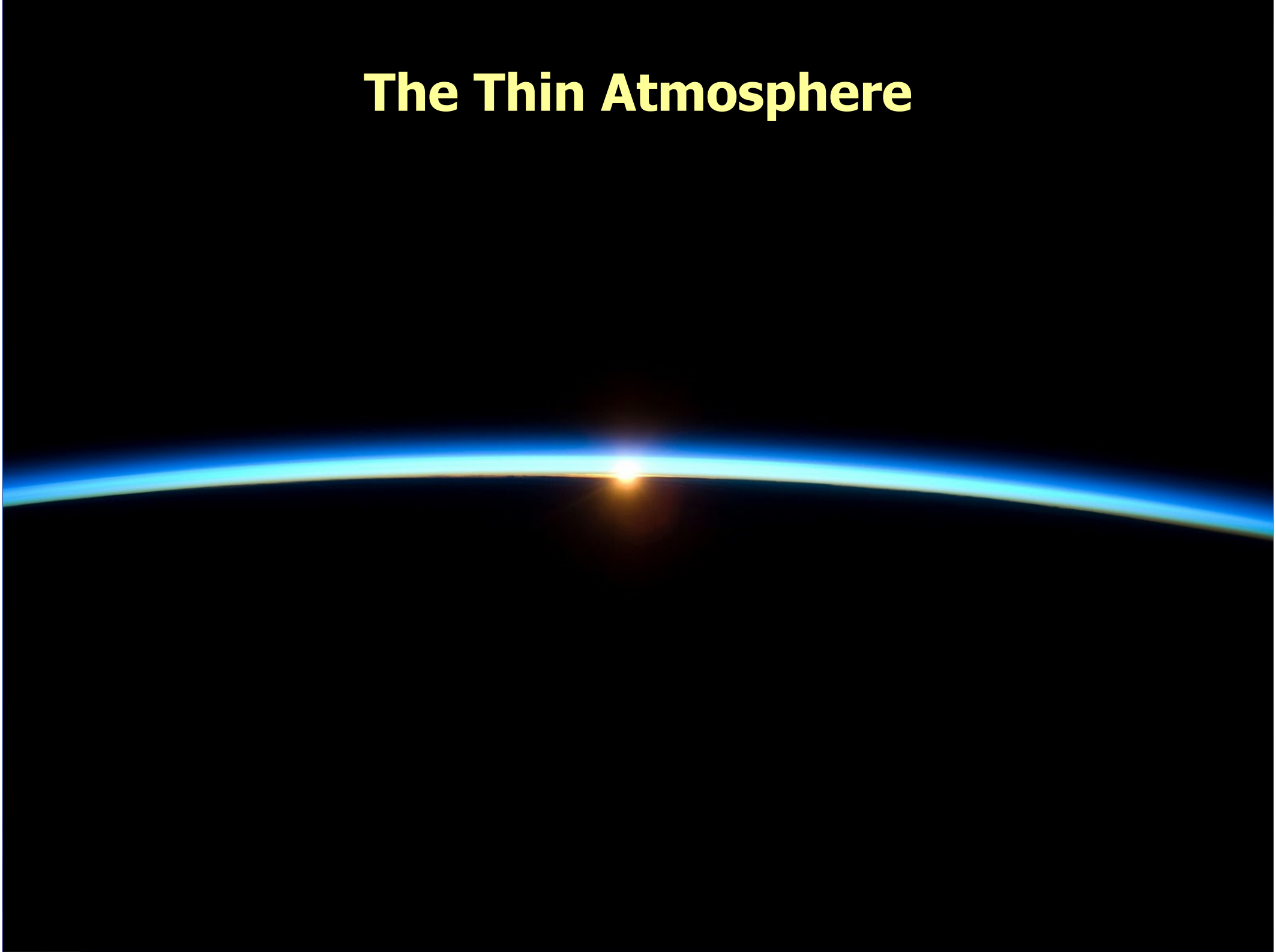
- Hydrostatic balance
- Geostrophic balance
- Quasi-nondivergence
- Quasi-incompressibility
- Ocean atmosphere balance
- Energy balance
- Ice sheet balance
- Etc., etc., etc.

Hydrostatic Balance

or

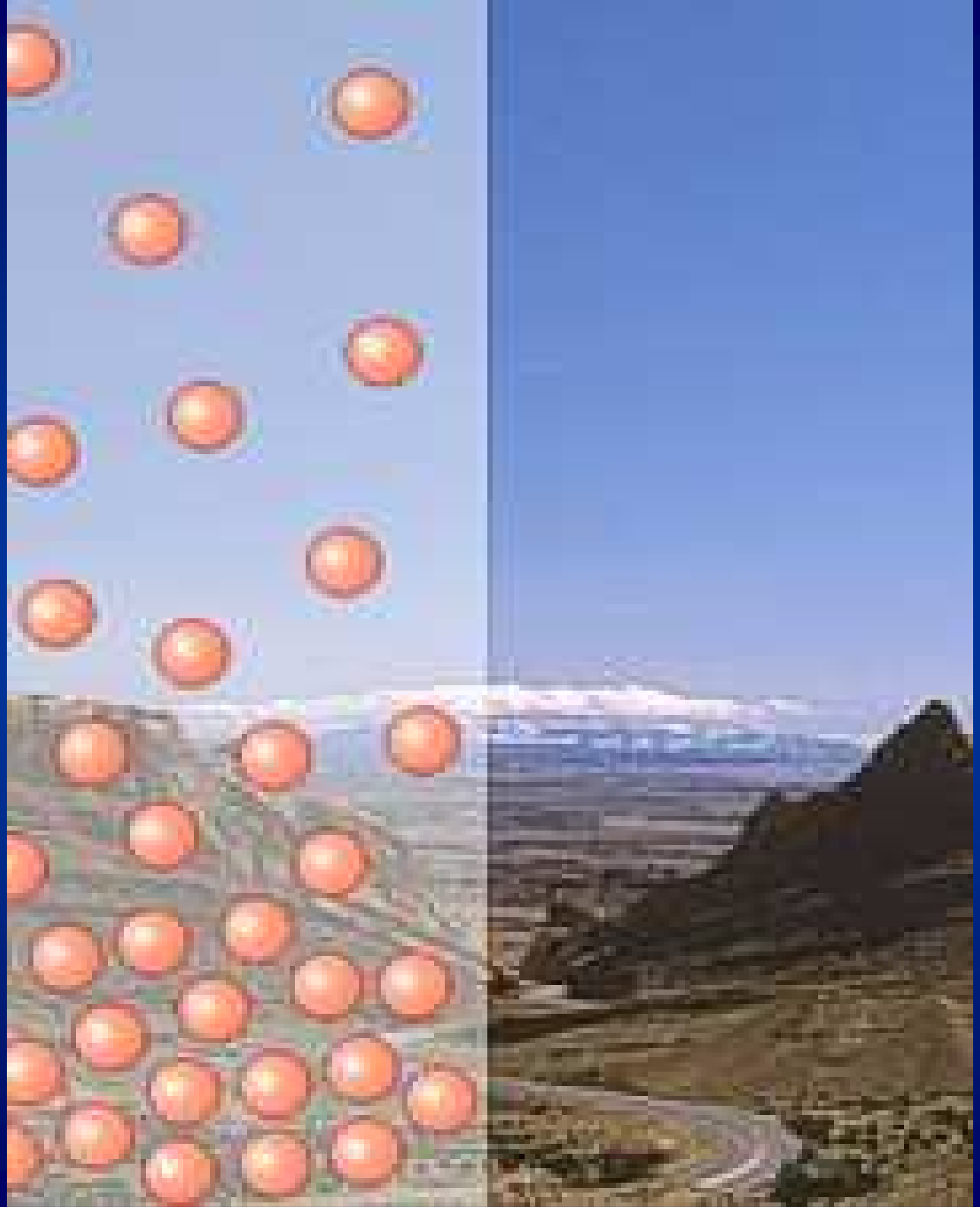
"Why doesn't the air fall down?"

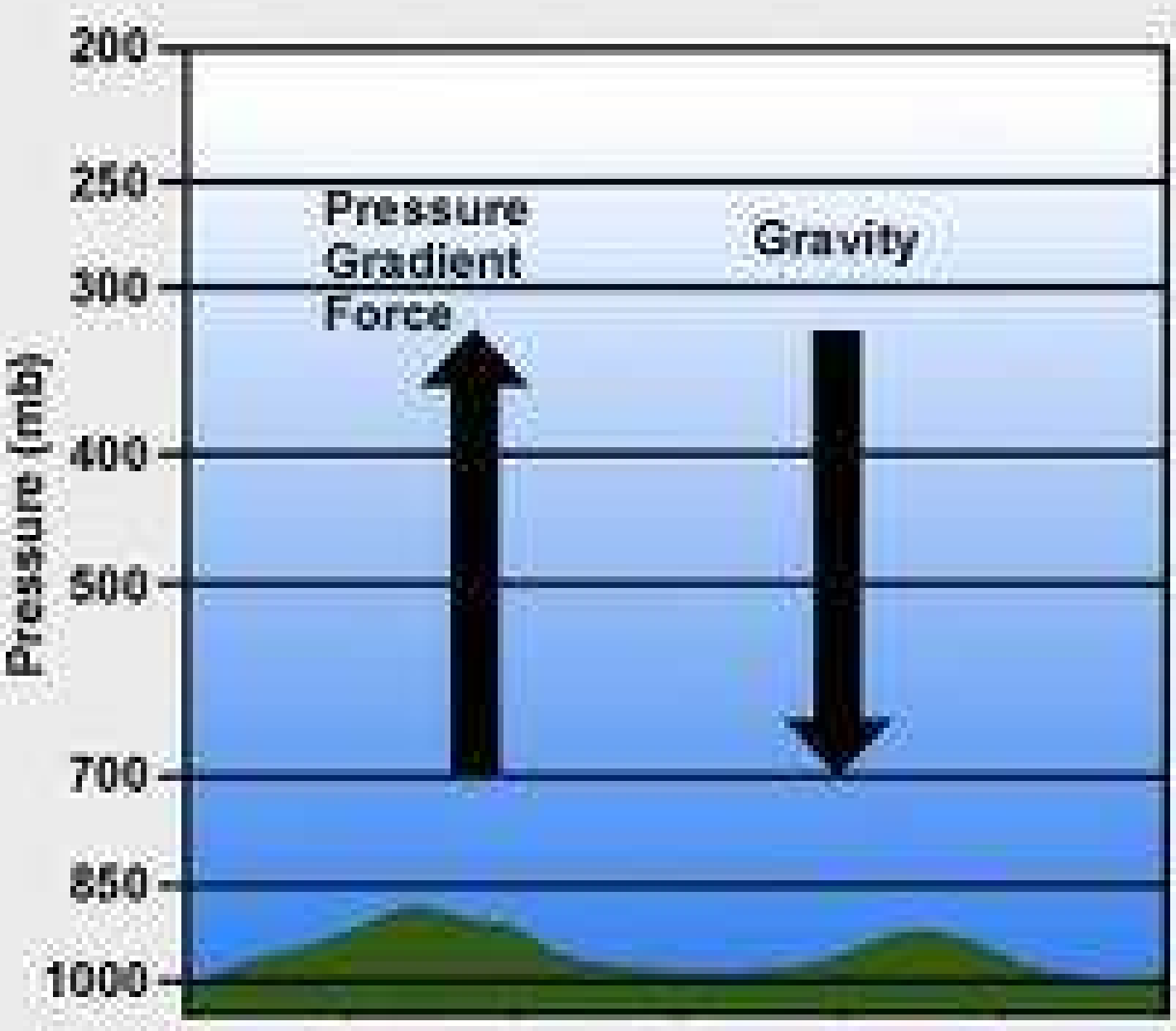
The Thin Atmosphere



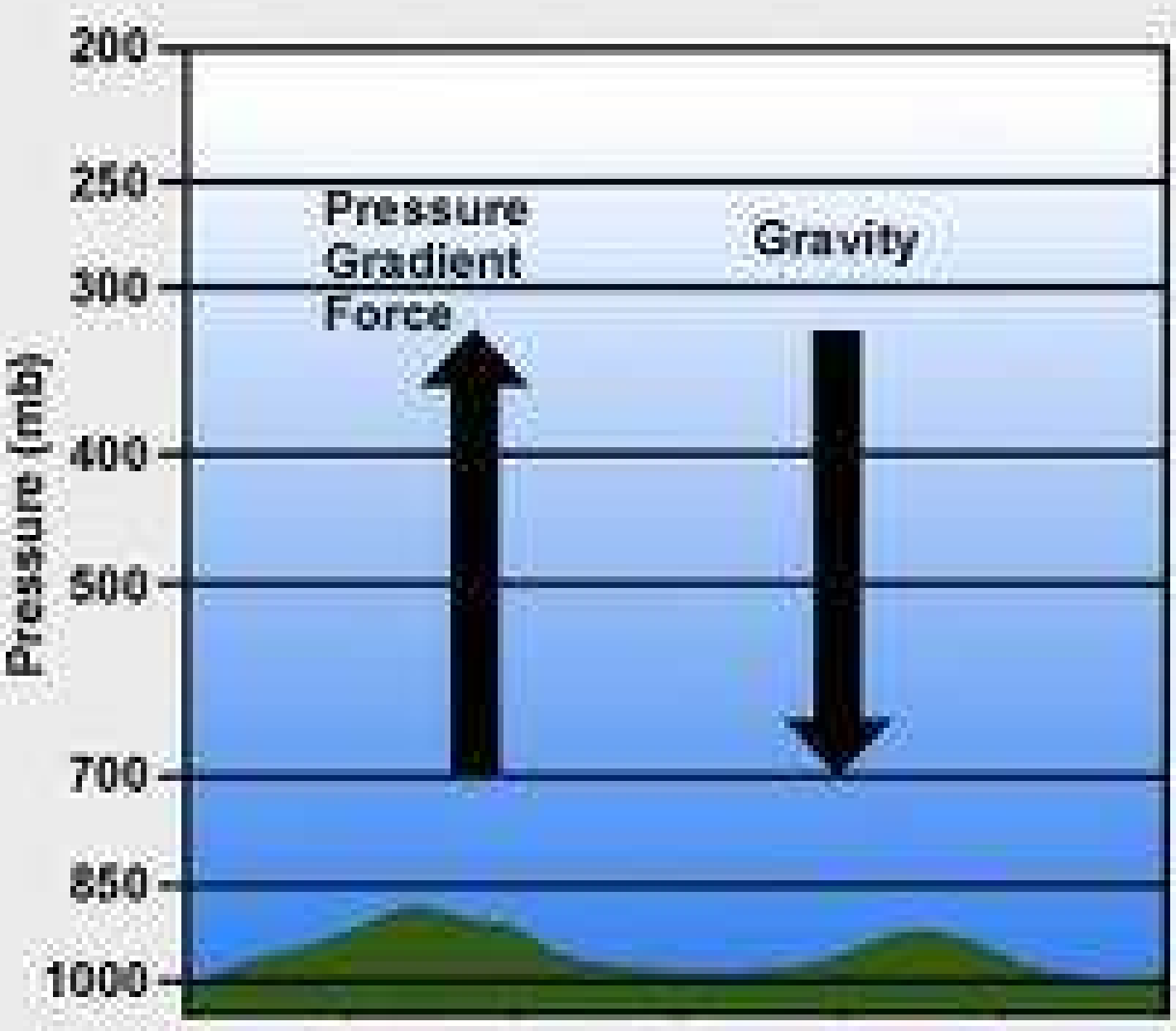
Why doesn't all the air fall down?

- Gravity attracts the air to the Earth.
- Something must be balancing gravity.
- What is it?





Hydrostatic balance in the Atmosphere



$$\frac{\partial p}{\partial z} + \rho g = 0.$$

Hydrostatic balance in the Atmosphere

Hydrostatic Balance

- In the atmosphere, the pressure of the air decreases with increasing altitude.
- This pressure difference causes an upward force , the pressure gradient force.
- The force of gravity balances this, keeping the atmosphere bound to the Earth.

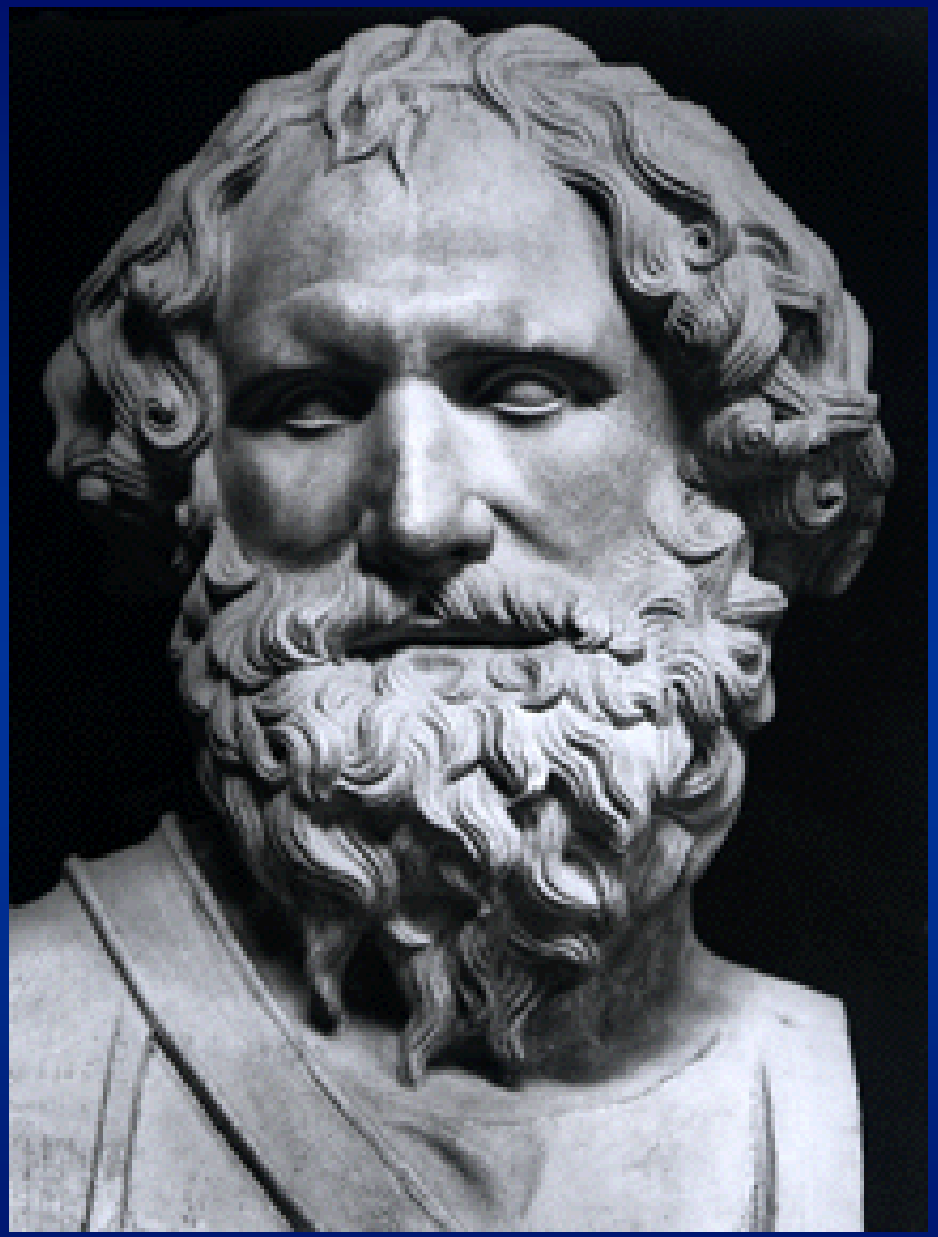
Hydrostatic Balance

Galileo, at the age of 22, wrote a little tract entitled *La Bilancetta*, or "The Little Balance"

What Galileo described was an accurate balance for weighing things in air and water.

This balance can be used to determine the specific gravity of solids by weighing them in air and in water.

Archimedes [287 – 212 BC] established the science of hydrostatics.



Archimedes (287 – 212 BC)

In his treatise *On Floating Bodies,* Mr. A. describes what we now know as Archimedes' Principle

This states that, for a body immersed in a fluid, the buoyancy force is equal to the weight of fluid that the body displaces.

How it Happened
EYPHKA: Version 1

Archimedes was lying in his bath.

He observed that a body immersed in a fluid is buoyed up by a force equal to the weight of fluid displaced.

He jumped up and ran naked through the streets crying *Eureka, Eureka!*

EYPHKA: Version 2

Archimedes was in his bath in Syracuse.

EYPHKA: Version 2

Archimedes was in his bath in Syracuse.

As his wife came in, he cried "*EUREKA*".

EYPHKA: Version 2

Archimedes was in his bath in Syracuse.

As his wife came in, he cried "*EUREKA*".

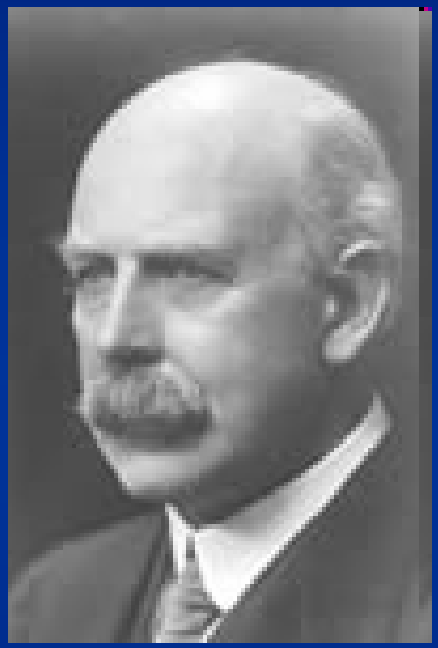
She said "*You no smella so gooda yourself*".

Geostrophic Balance

Γεω στροφη

= Geo strophe

= Turning Earth



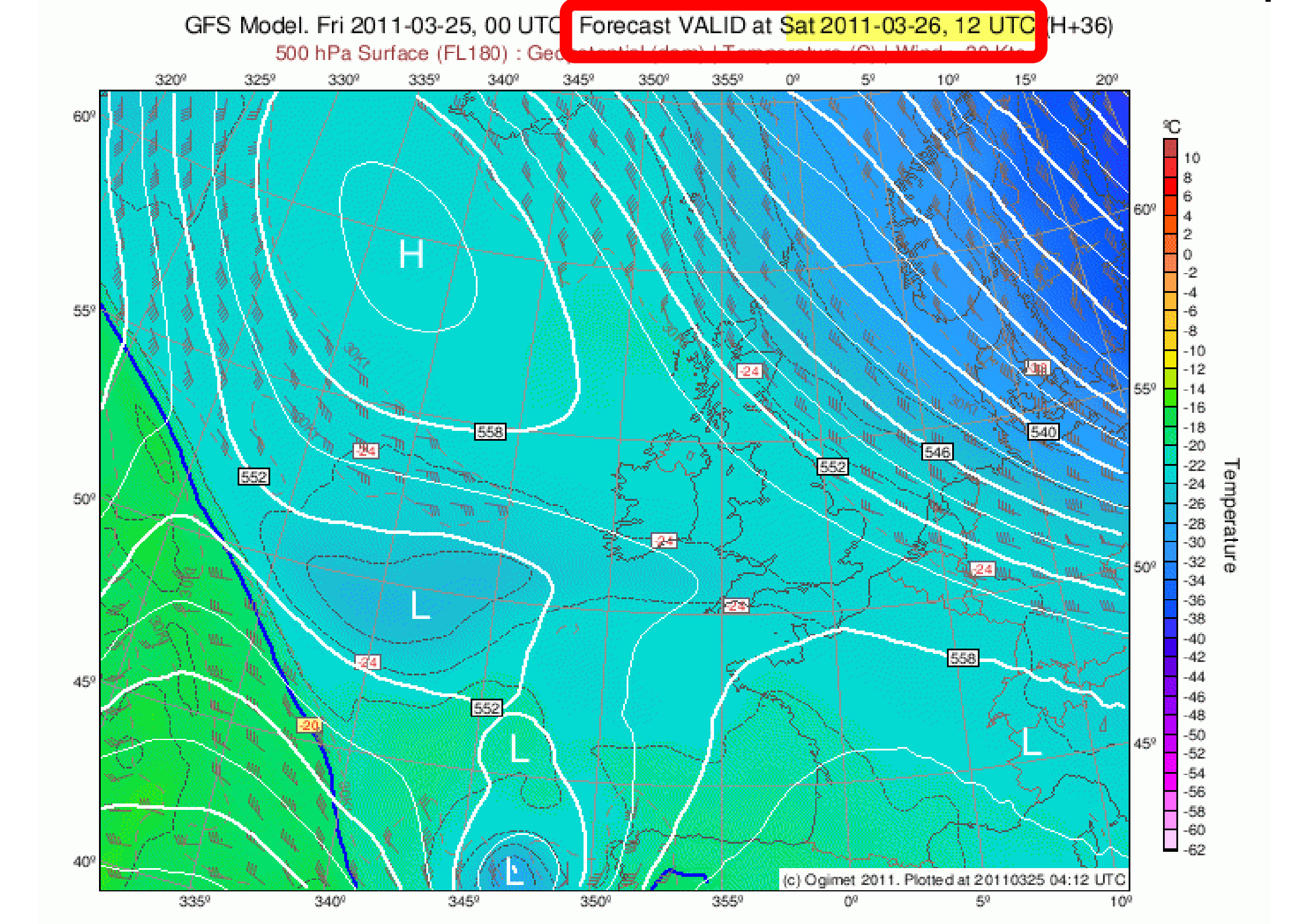
The term was coined by Sir Napier Shaw, Director of the Met Office

Geostrophic Balance

The balance between the Coriolis force

and the

pressure gradient force (PGF)


GFS Model. Fri 2011-03-25, 00 UTC
Forecast VALID at Sat 2011-03-26, 12 UTC (H+36)
500 hPa Surface (FL180) : Geo
320º 325º 330º 335º 340º 345º 350º 355º 0º 5º 10º 15º 20º
60º 55º 50º 45º 40º
H
L
558
552
546
540
-24
-20
30KT
°C
10 8 6 4 2 0 -2 -4 -6 -8 -10 -12 -14 -16 -18 -20 -22 -24 -26 -28 -30 -32 -34 -36 -38 -40 -42 -44 -46 -48 -50 -52 -54 -56 -58 -60 -62
Temperature
(c) Ogimet 2011. Plotted at 20110325 04:12 UTC

Foucault's Pendulum

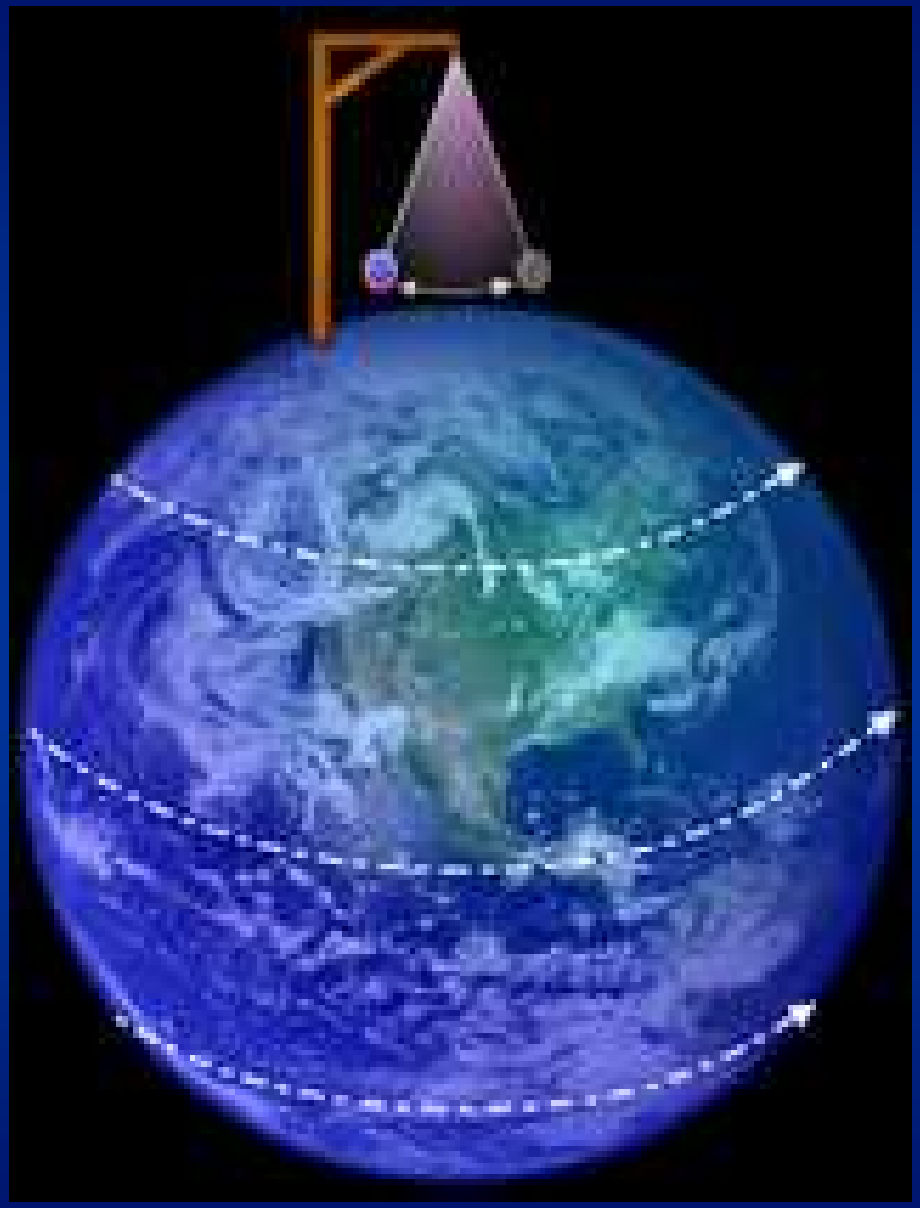
Foucault's pendulum is a simple way to demonstrate the rotation of the Earth.


LA CONVENTION NATIONALE
21
20
19
18
17
16
15
14

Foucault's Pendulum

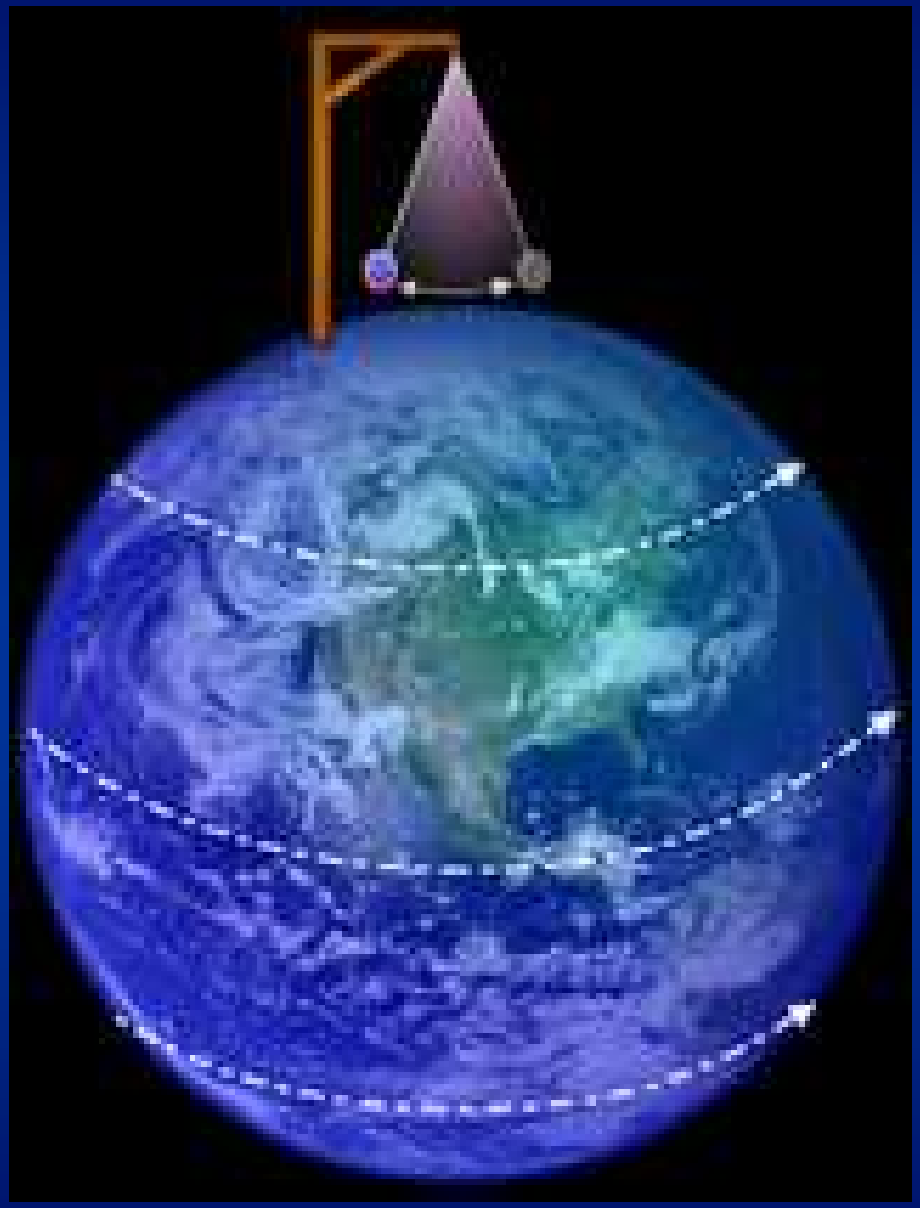
The experiment with the Foucault pendulum in 1851 was the first simple terrestrial demonstration of the Earth's rotation.

These pendulums (or pendula for fuss-pots) are popular in science museums worldwide.



Basic idea:

The pendulum swings in a fixed plane while the Earth spins under it.



Basic idea:

The pendulum swings in a fixed plane while the Earth spins under it.

Things are not quite so simple.

C.H.D. Buys Ballot (1817-1890)

Christophorus Henricus Diedericus Buys Ballot

Buys Ballot's Law

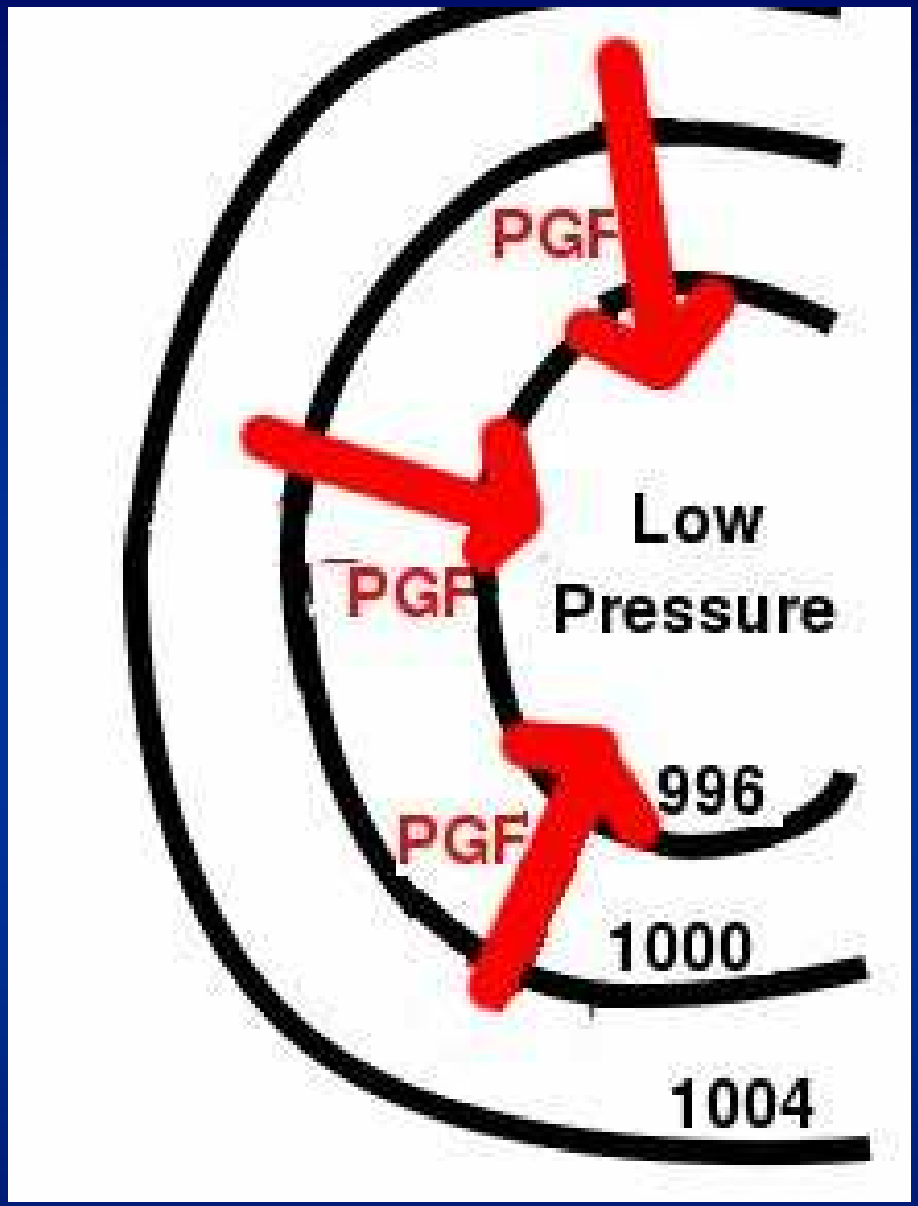
In the Northern Hemisphere,
if you stand with your back to the wind,
the low pressure will be on your left.

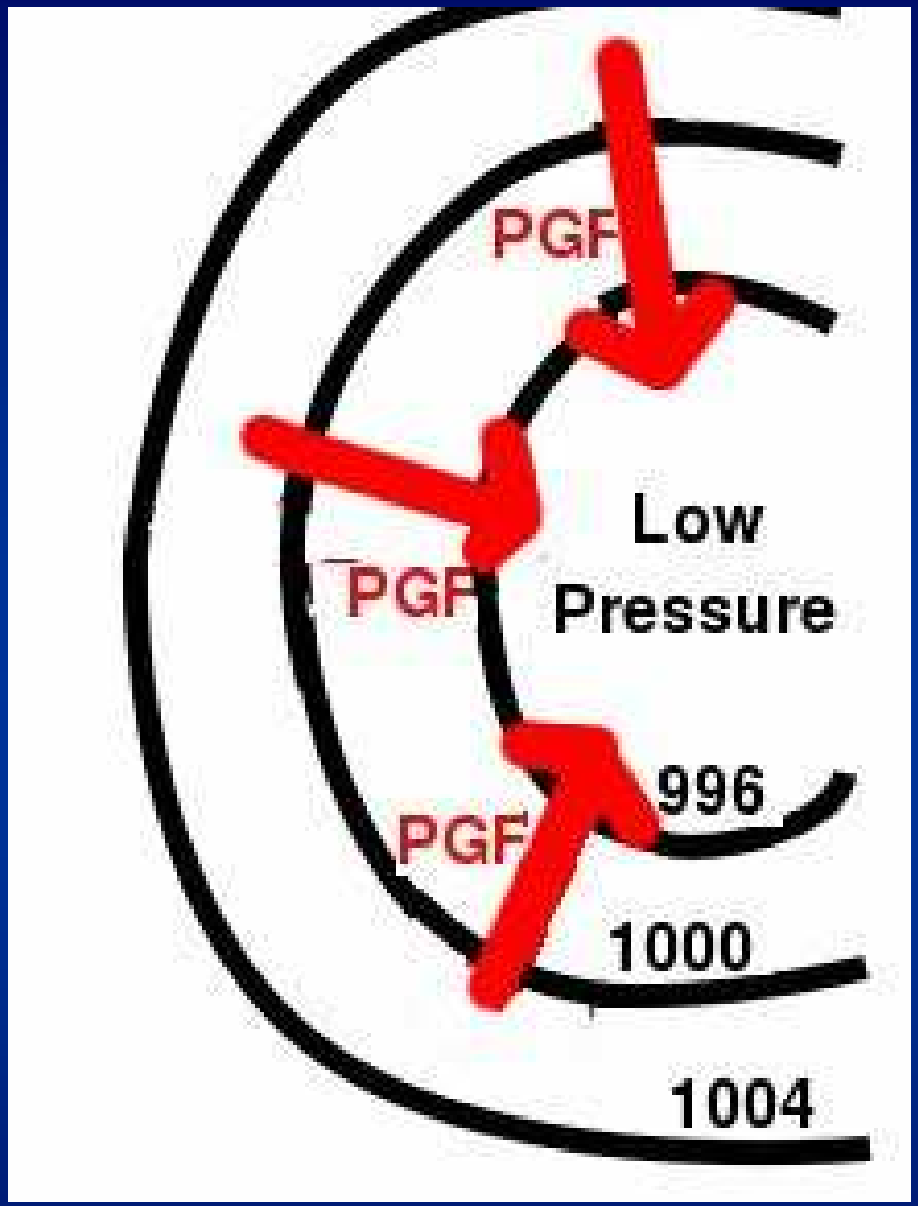
Buys Ballot's Law

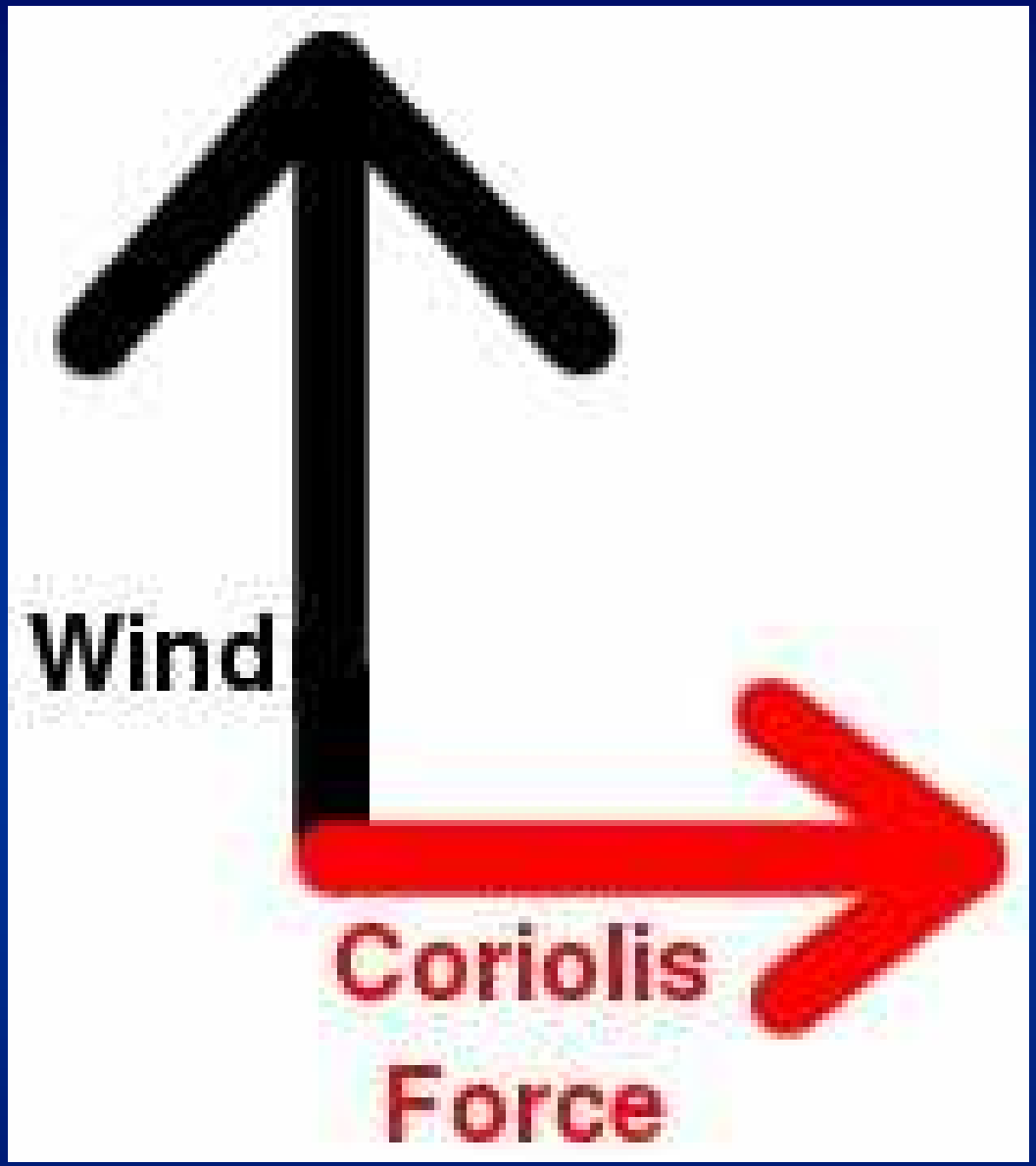
In the Northern Hemisphere,
if you stand with your back to the wind,
the low pressure will be on your left.

or

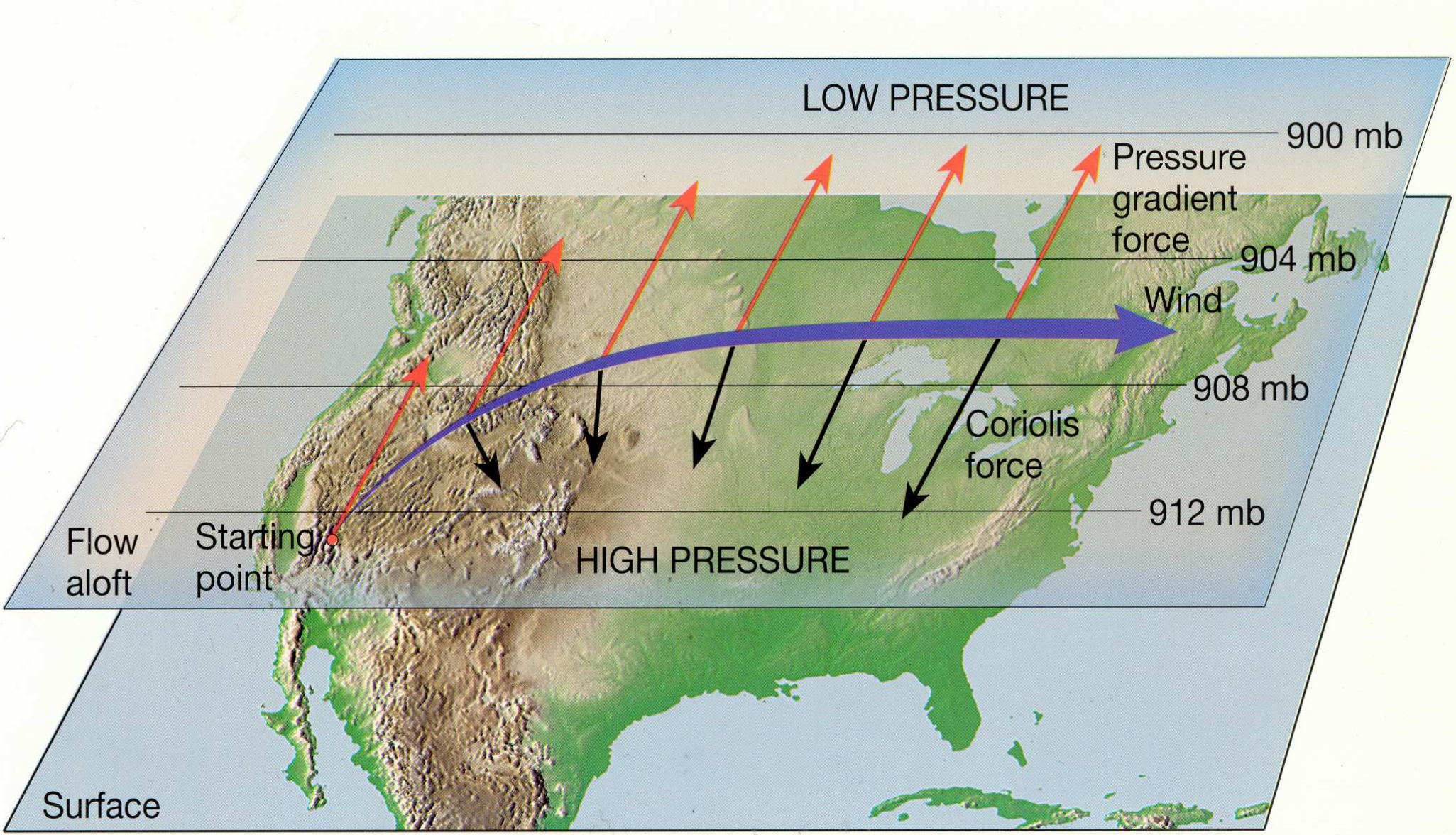
If you stand with your back to the wind,
with the low pressure on your left,
then you are in the Northern Hemisphere.


PGF
PGF
Low
Pressure
PGF
996
1000
1004

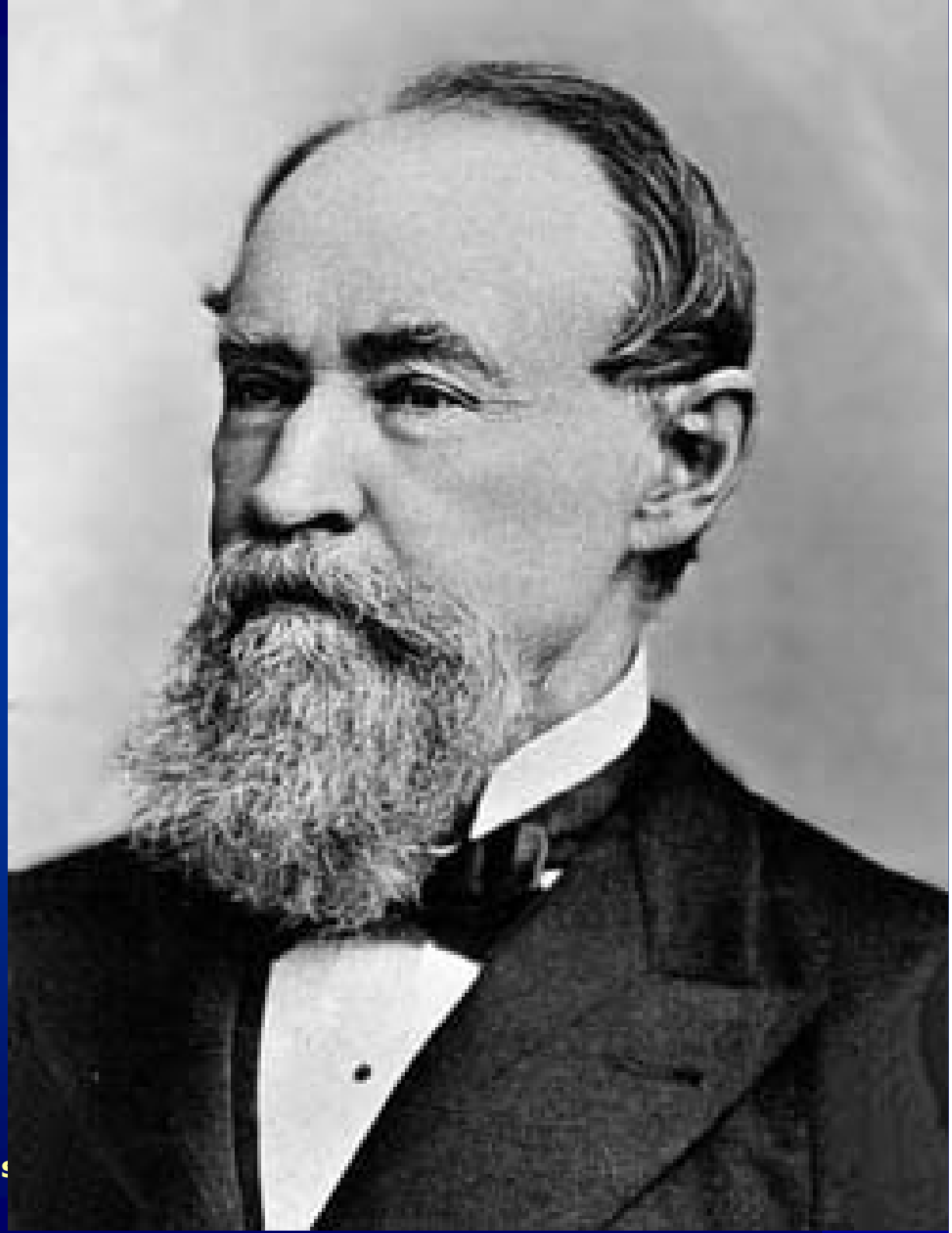

PGF
PGF
PGF
Low
Pressure
996
1000
1004


Wind
Coriolis
Force

The Mechanism of Geostrophic Flow



William Ferrel (1817 – 1891) American meteorologist



Iris

A quote from Ferrel's first paper

An essay on the winds and the currents of the oceans
[Nashville journal of medicine and surgery, 1856]

The fourth and last force arises from the combination of a relative east or west motion of the atmosphere with the rotatory motion of the earth. In consequence of the atmosphere's revolving on a common axis with that of the earth, each particle is impressed with a centrifugal force, which, being resolved into a vertical and a horizontal force, the latter causes it to assume a spheroidal form conforming to the figure of the earth. But, if the rotatory motion of any part of the atmosphere is greater than that of the surface of the earth, or, in other words, if any part of the atmosphere has a relative eastern motion with regard to the earth's surface, this force is increased, and if it has a relative western motion, it is diminished, and this difference gives rise to a disturbing force which prevents the atmosphere being in a state of equilibrium, with a figure conforming to that of the earth's surface, but causes an accumulation of the atmosphere at certain latitudes and a depression at others, and the consequent difference in the pressure of the atmosphere at these latitudes very materially influences its motions.

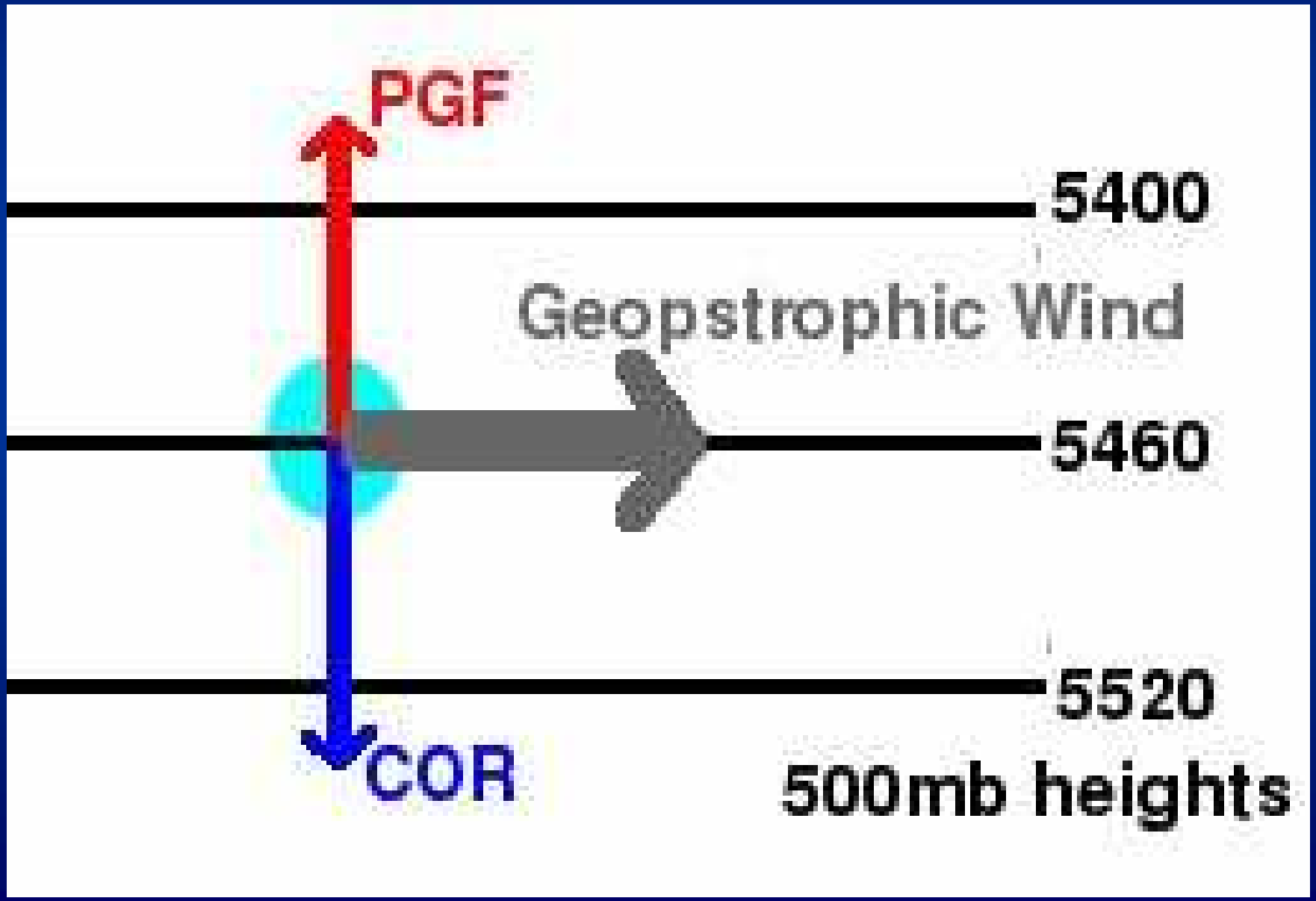
"In consequence of the atmosphere's revolving ... each particle is impressed with a centrifugal force

" But, if the rotatory motion of the atmosphere is greater than that of the earth, this force is increased ...

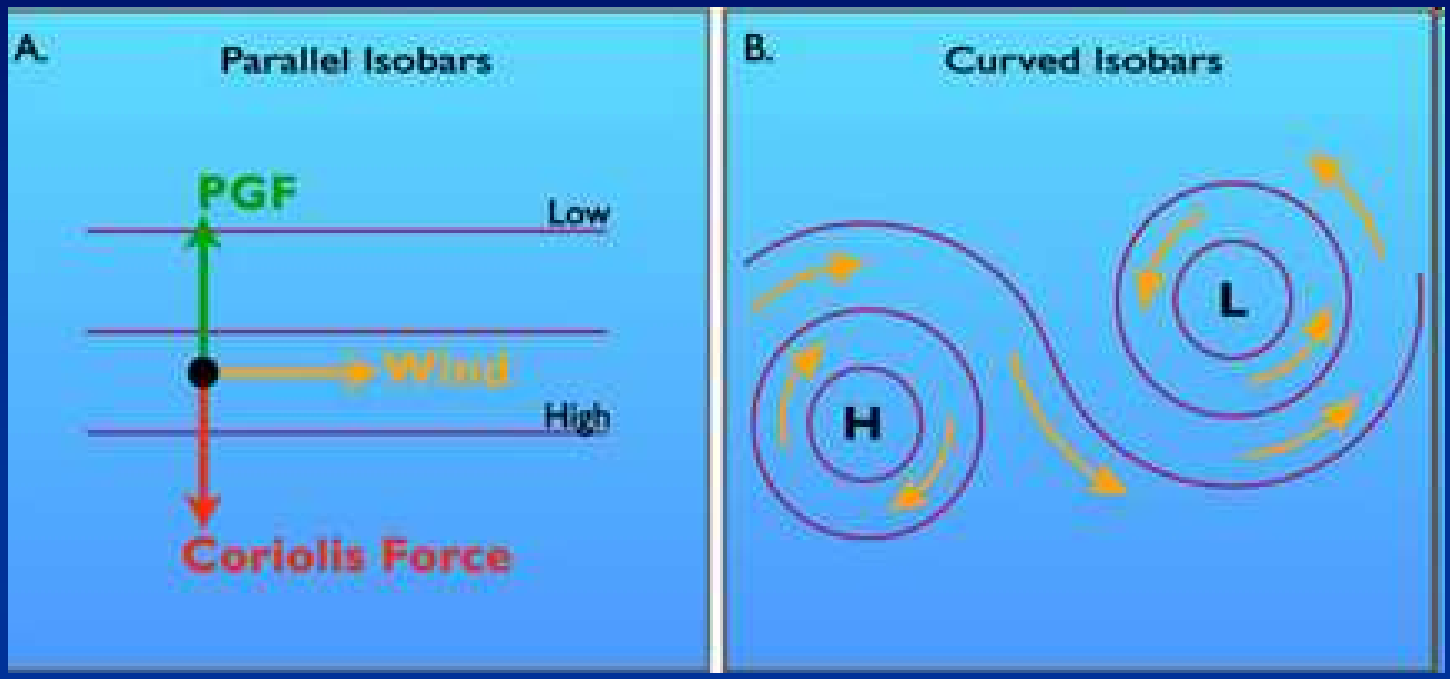
"and if ... [less] ... it is diminished ...

"this difference gives rise to a disturbing force ... which materially influences the motion."

Balance between Coriolis force and pressure gradient force



Gradient Balance



The isobars are normally not straight lines.

We take the curvature into account through the centrifugal force.

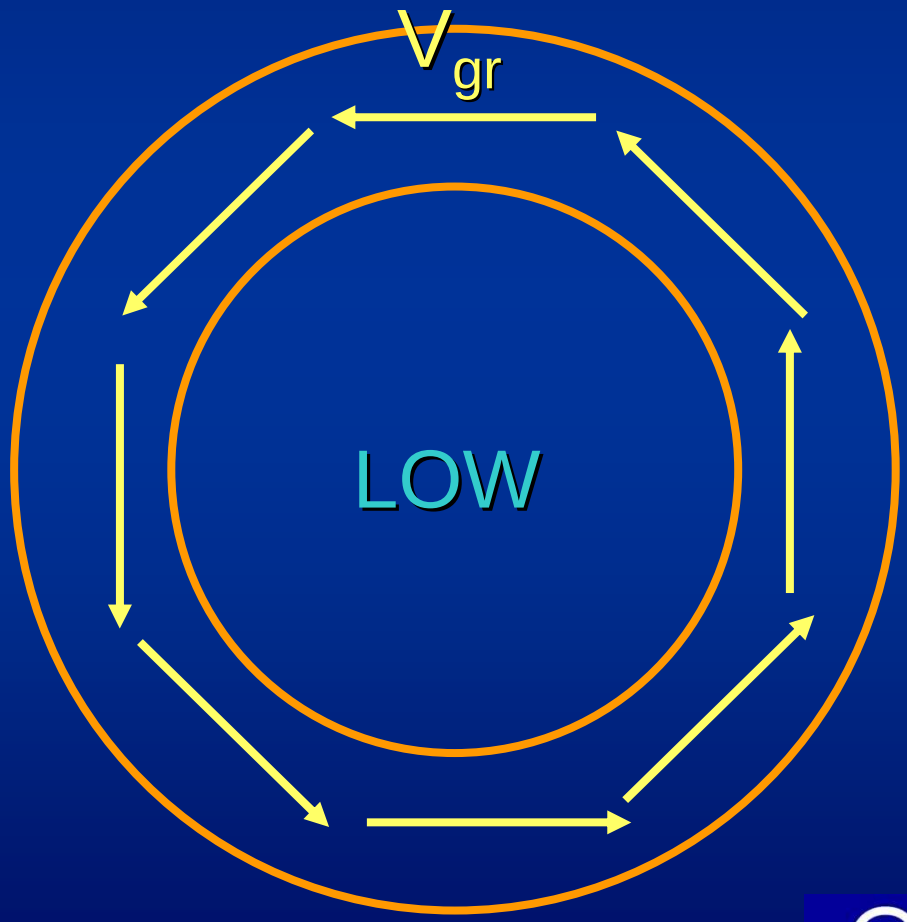
This gives Gradient Balance.

Gradient Balance

Flow around low is the gradient wind.

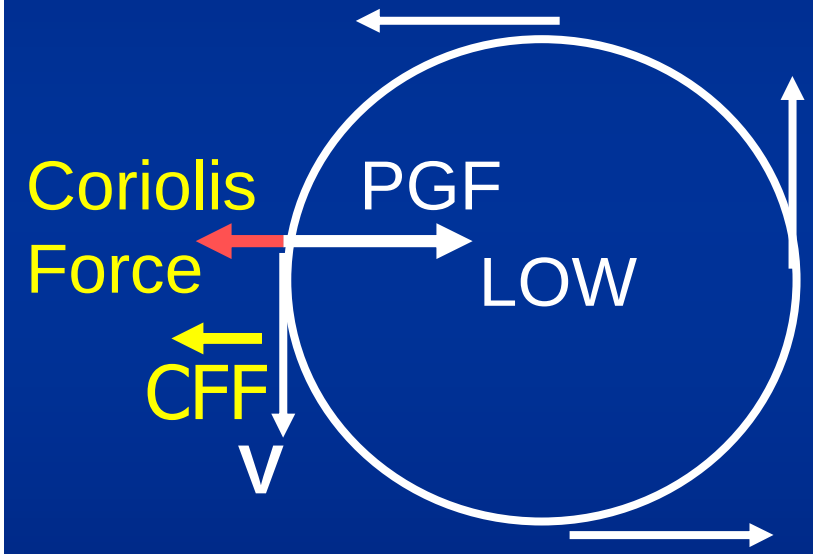
This is a three-way balance between:

- **Pressure gradient force**
- **Coriolis force**
- **Centrifugal force.**

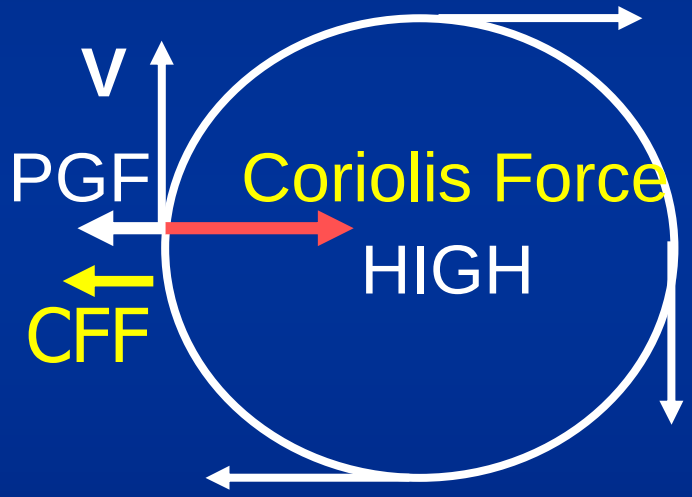


Gradient Balance

Cyclonic flow



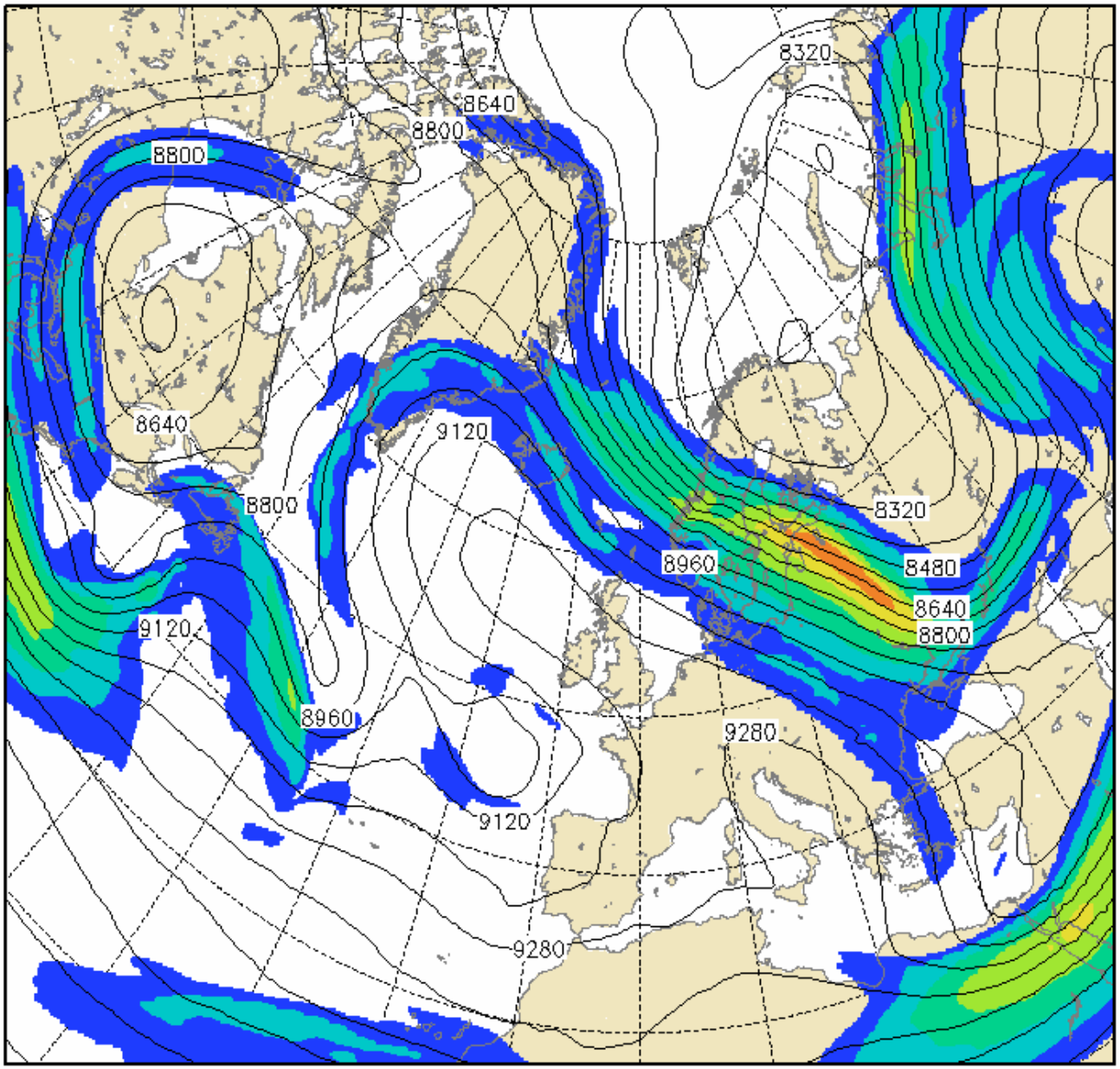
Anticyclonic flow



Sub-geostrophic

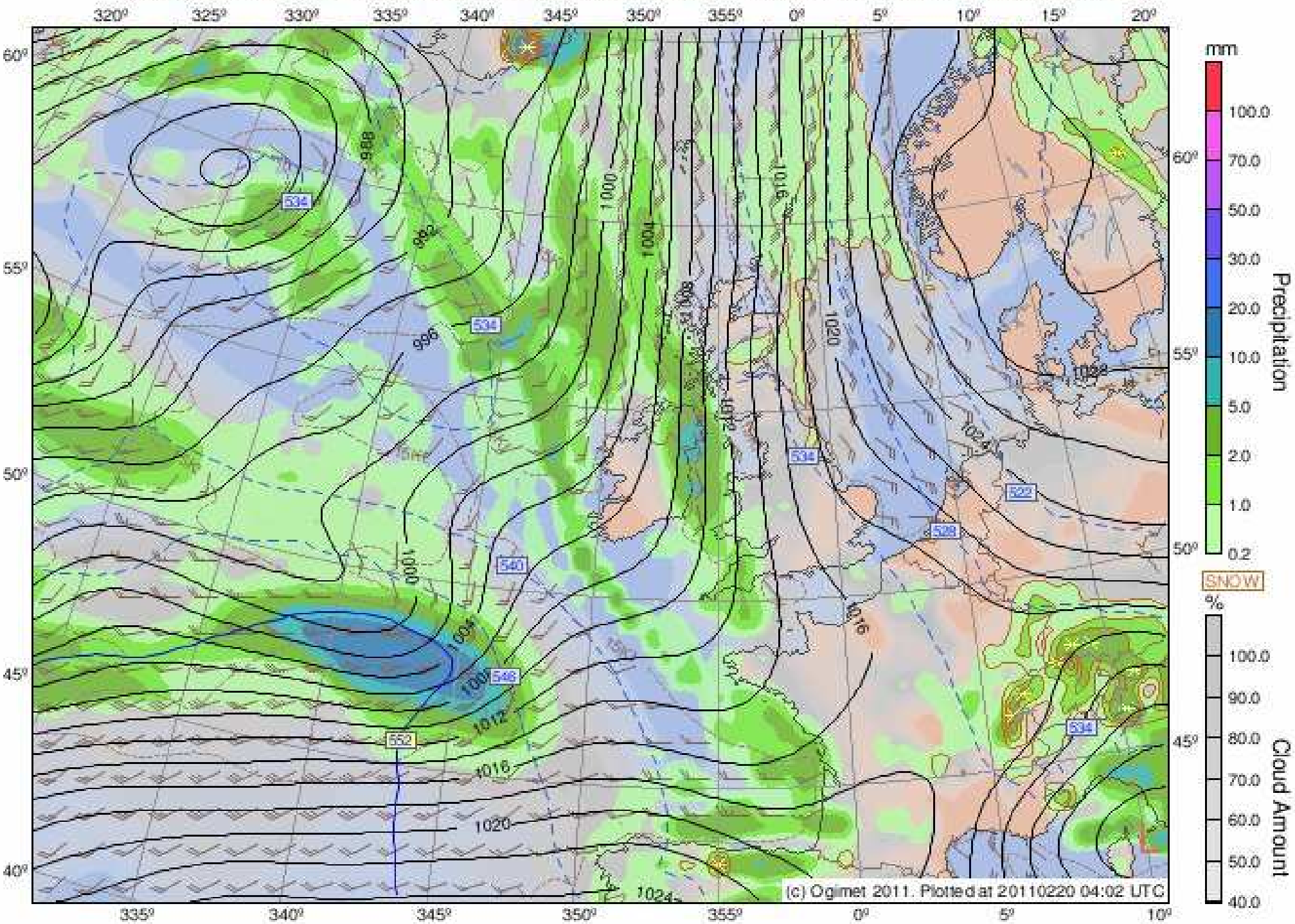
Super-geostrophic

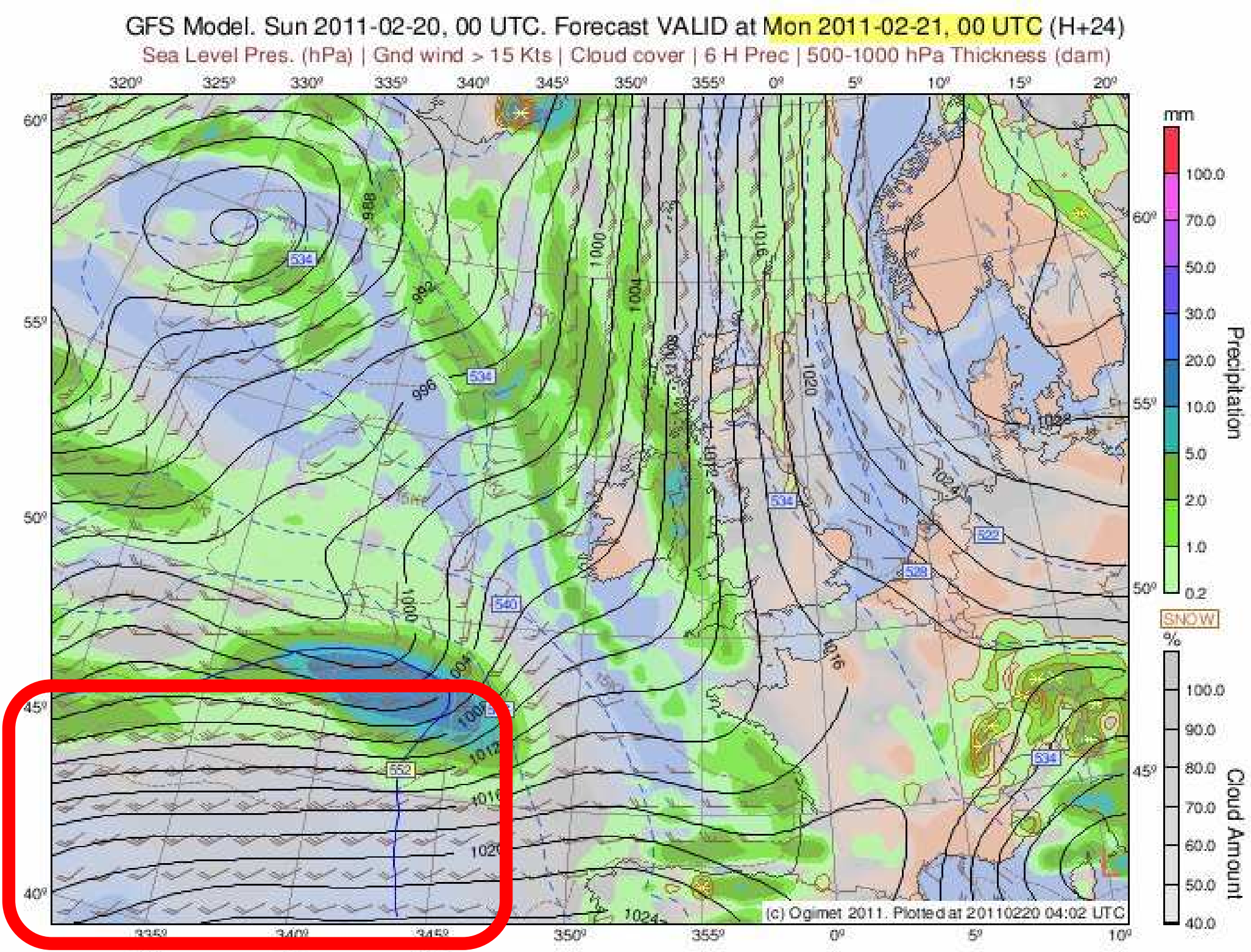
Wind speed (m/s) and geopot. height (m) 300 hPa
initial: 00Z25MAR2011 valid: 01Z25MAR2011



UCD DUBLIN

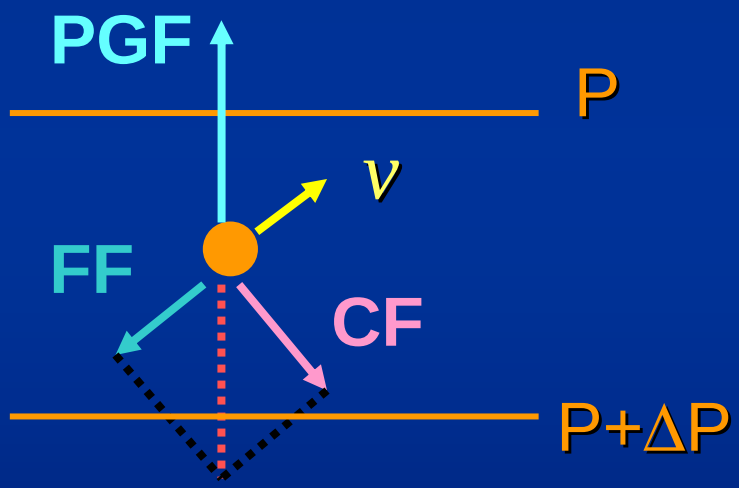
Modified Balance near the Surface due to Friction


GFS Model. Sun 2011-02-20, 00 UTC. Forecast VALID at Mon 2011-02-21, 00 UTC (H+24)
Sea Level Pres. (hPa) | Gnd wind > 15 Kts | Cloud cover | 6 H Prec | 500-1000 hPa Thickness (dam)
320º 325º 330º 335º 340º 345º 350º 355º 0º 5º 10º 15º 20º
60º 55º 50º 45º 40º
534 540 548 552 522 528
988 992 996 1000 1004 1008 1012 1016 1020 1024
mm
100.0 70.0 50.0 30.0 20.0 10.0 5.0 2.0 1.0 0.2
Precipitation
SNOW
%
100.0 90.0 80.0 70.0 60.0 50.0 40.0
Cloud Amount
(c) Ogimet 2011. Plotted at 20110220 04:02 UTC


GFS Model. Sun 2011-02-20, 00 UTC. Forecast VALID at Mon 2011-02-21, 00 UTC (H+24)
Sea Level Pres. (hPa) | Gnd wind > 15 Kts | Cloud cover | 6 H Prec | 500-1000 hPa Thickness (dam)
320º 325º 330º 335º 340º 345º 350º 355º 0º 5º 10º 15º 20º
60º
55º
50º
45º
40º
mm
100.0
70.0
50.0
30.0
20.0
10.0
5.0
2.0
1.0
0.2
Precipitation
SNOW
%
100.0
90.0
80.0
70.0
60.0
50.0
40.0
Cloud Amount
534
540
552
528
522
(c) Ogimet 2011. Plotted at 20110220 04:02 UTC

Frictional Effects

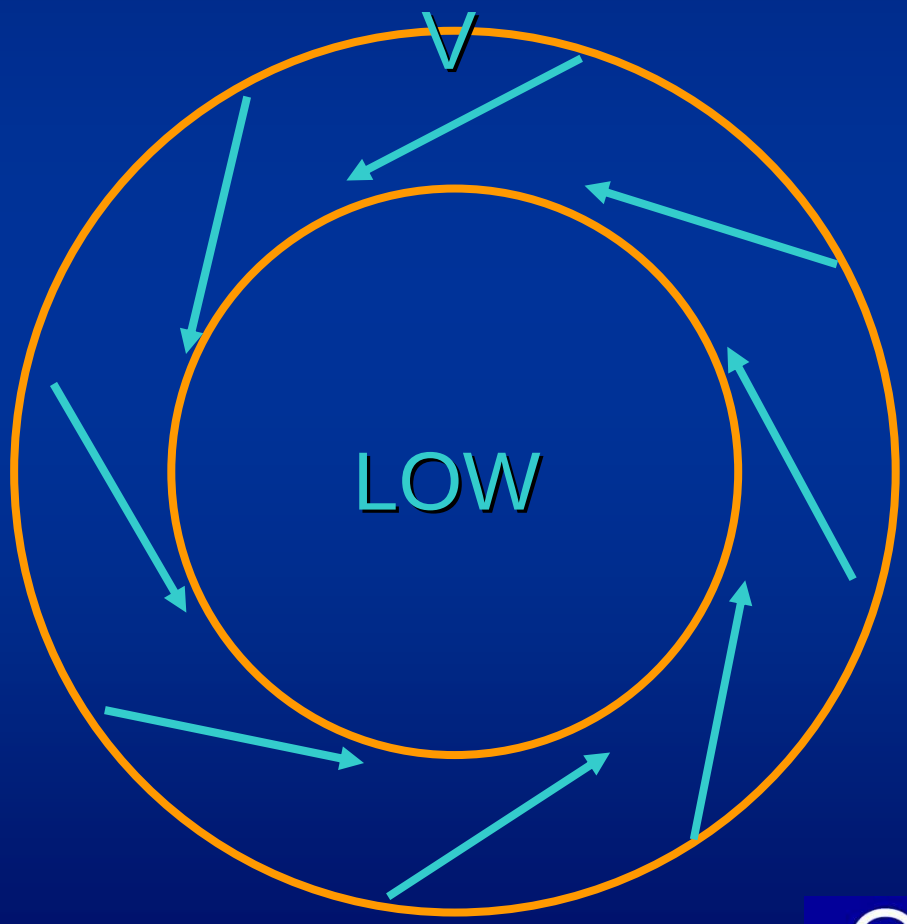
- Friction causes the wind to slow down and back towards lower pressure.



Guldberg-Mohn Balance

Frictional Effects

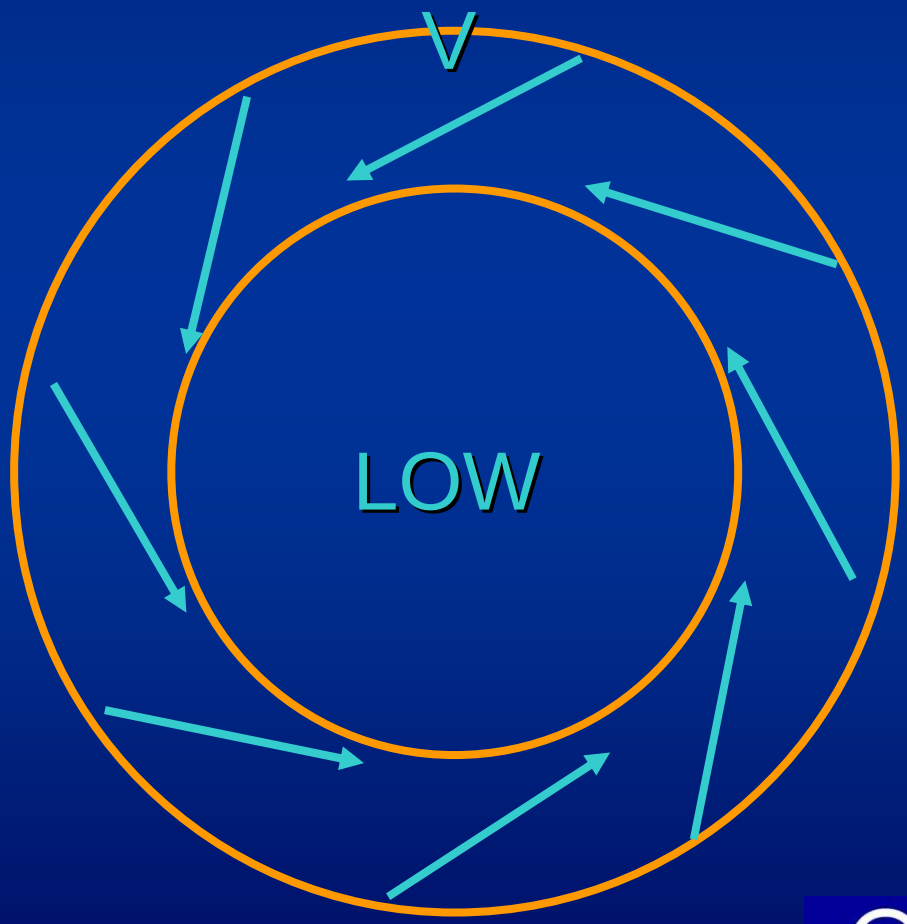
Introducing friction *backs* the wind towards the centre of the low.



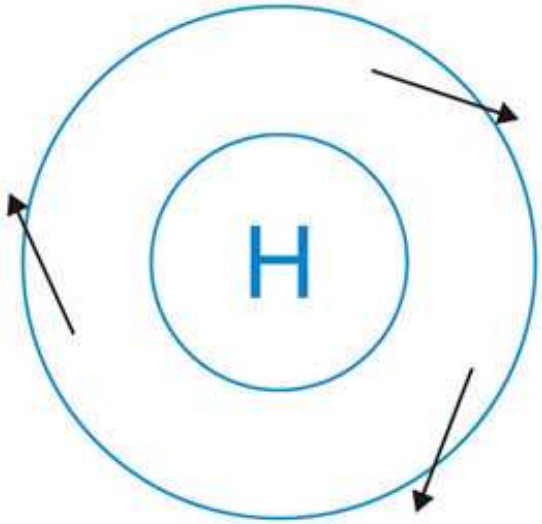
Frictional Effects

Introducing friction *backs* the wind towards the centre of the low.

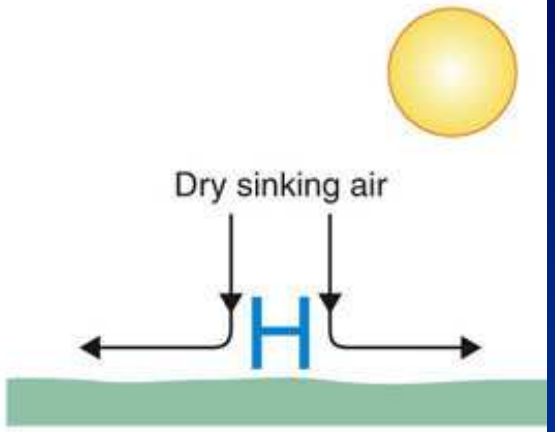
This leads to convergence in the low centre



Surface winds blow clockwise around an anticyclone (high pressure) and diverge.

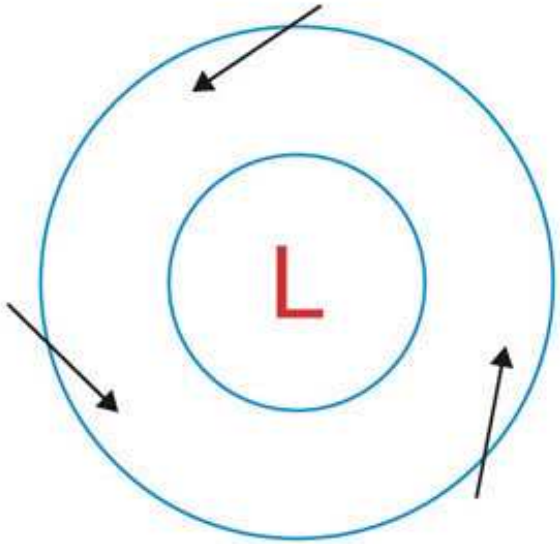


View from above

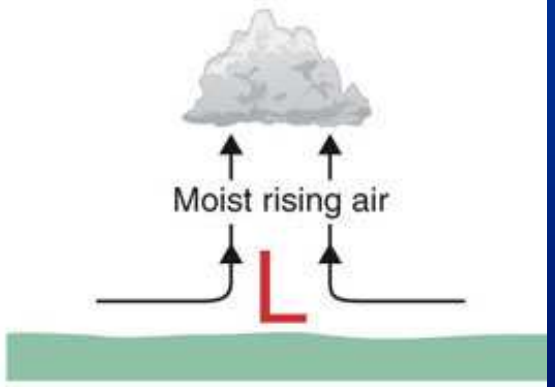


View from side

Surface winds blow counterclockwise around a cyclone (low pressure) and converge.



View from above



View from side

Guldberg-Mohn Balance

At the surface, there is a three-way balance of forces, between the PGF, Coriolis, and friction.

The air parcels move across the isobars towards low pressure.

Over water, the angle of crossing by the wind is 15-30°. Over land it is 25-50°.

Buys Ballot's (revised) Law: With wind at your back, low pressure is at "about 10 o'clock".

Balance at Different Scales

- Extra-tropical depressions
- Hurricanes
- Tornados
- Down the Plug-hole

The Rossby Number

$$Ro = \frac{\text{Centrifugal Force}}{\text{Coriolis Force}}$$

The Rossby Number

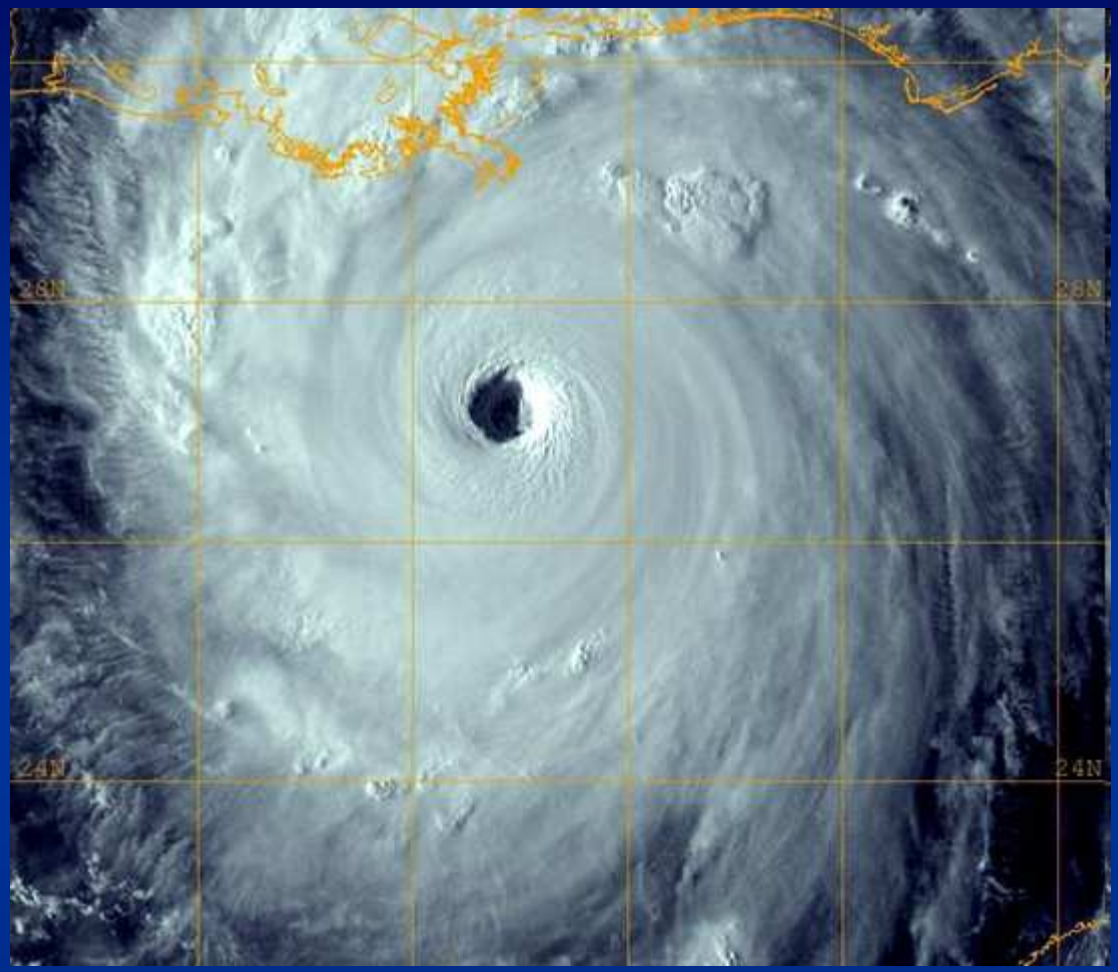
$$Ro = \frac{\text{Centrifugal Force}}{\text{Coriolis Force}}$$

$$Ro = \frac{\text{Spin of the Flow}}{\text{Spin of the Earth}} = \frac{\zeta}{f}$$

Extra-tropical depression

Ro ≈ 1/10

Geostrophic Balance Good
Gradient Balance Better.

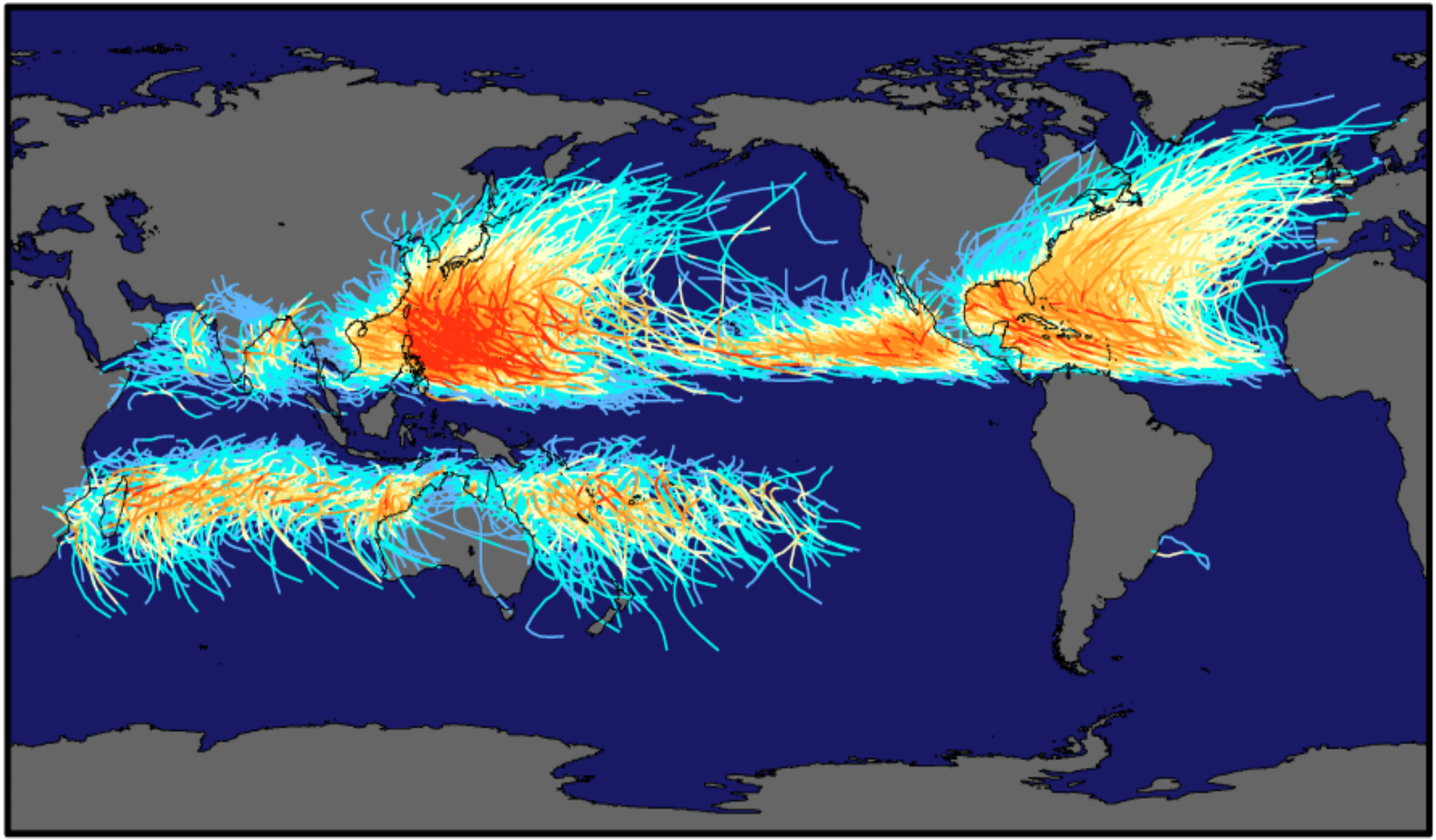


Hurricane

Ro ≈ 10-100

Geostrophic Balance Bad
Gradient Balance Better.

Tracks and Intensity of All Tropical Storms



TD | TS | 1 | 2 | 3 | 4 | 5

Saffir-Simpson Hurricane Intensity Scale

Tornado

Ro ≈ 10,000

Close to Cyclostrophic Balance

Down the Plug-hole

Ro ≈ 100,000

Cyclostrophic Balance.

Review of Dynamic Balances

When all the forces that act on a parcel add up to zero, a balance of forces is achieved.

When there is a balance, there is no acceleration.

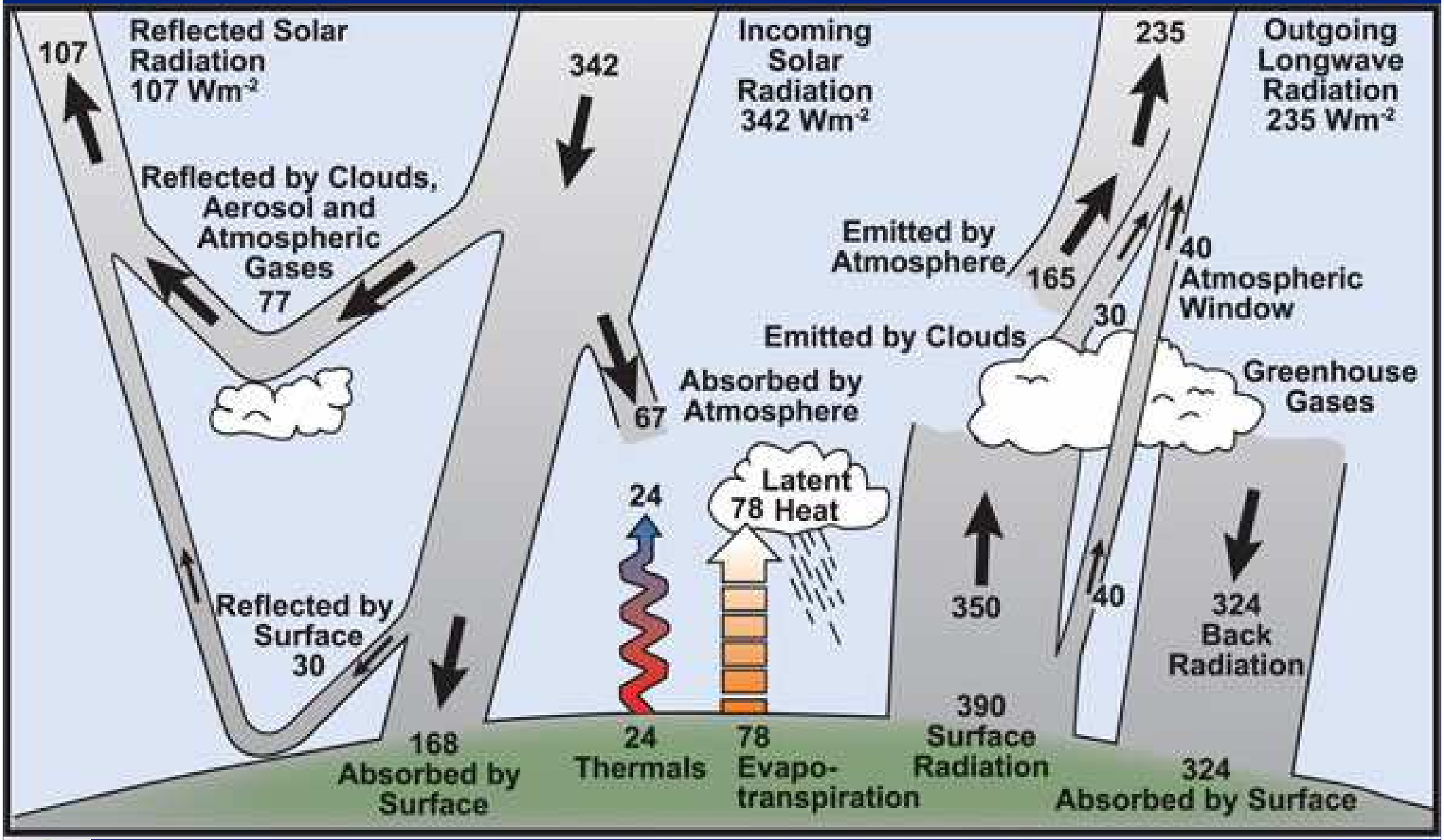
- **Hydrostatic Balance**
- **Geostrophic Balance**
- **Gradient Balance**
- **Guldberg-Mohn Balance**
- **Cyclostrophic Balance**

Energy Balance

and

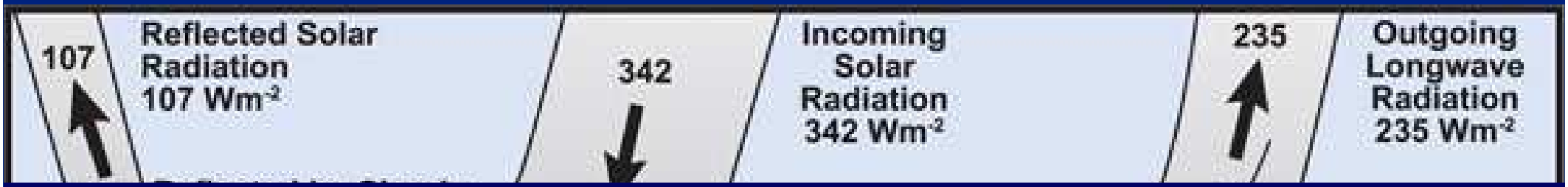
Climate Change

Balance
Energy in = Energy out



Balance

Energy in = Energy out



Energy in = 342 W/m²

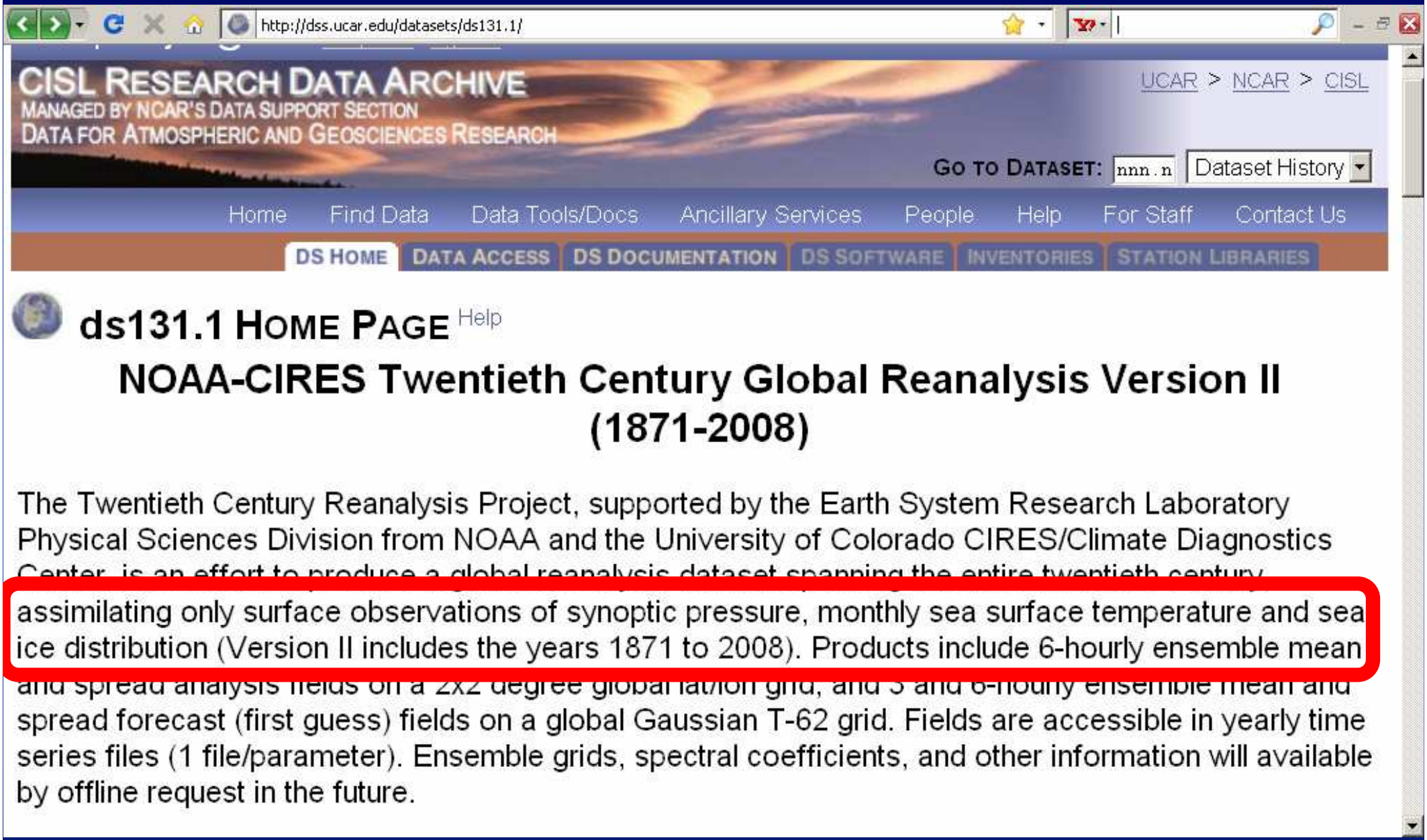
Energy out = 107 + 235 = 342 W/m²

Suppose the Sun warms up

- ➔ More incoming solar radiation
- ➔ Temperature of atmosphere rises (σ T^4)
- ➔ Greater radiation from atmosphere
- ➔ Balance is restored [but at higher T]

20CRv2

NOAA-CIRES Twentieth Century Global Reanalysis, Version II (1871-2008)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CISL RESEARCH DATA ARCHIVE
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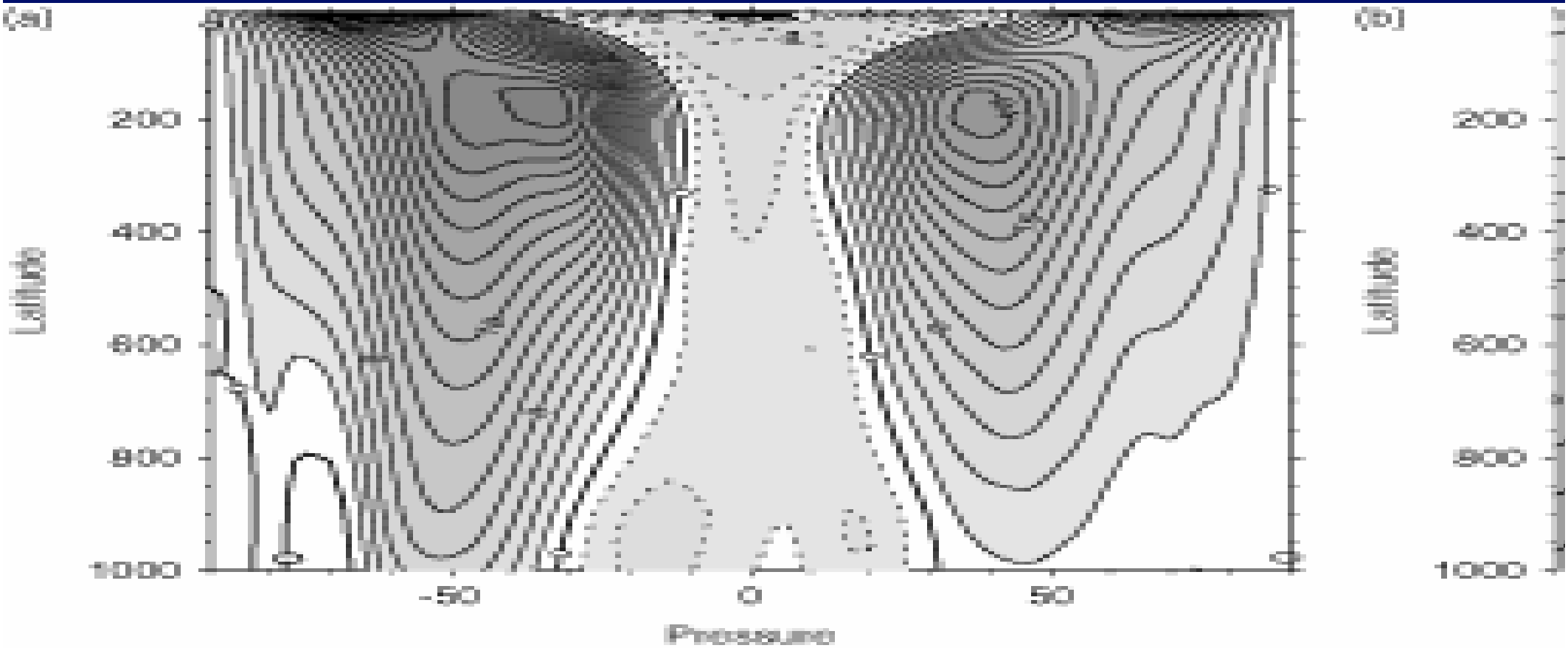
NOAA-CIRES Twentieth Century Global Reanalysis Version II
(1871-2008)
The Twentieth Century Reanalysis Project, supported by the Earth System Research Laboratory Physical Sciences Division from NOAA and the University of Colorado CIRES/Climate Diagnostics
assimilating only surface observations of synoptic pressure, monthly sea surface temperature and sea ice distribution (Version II includes the years 1871 to 2008). Products include 6-hourly ensemble mean
spread forecast (first guess) fields on a global Gaussian T-62 grid. Fields are accessible in yearly time series files (1 file/parameter). Ensemble grids, spectral coefficients, and other information will available by offline request in the future.

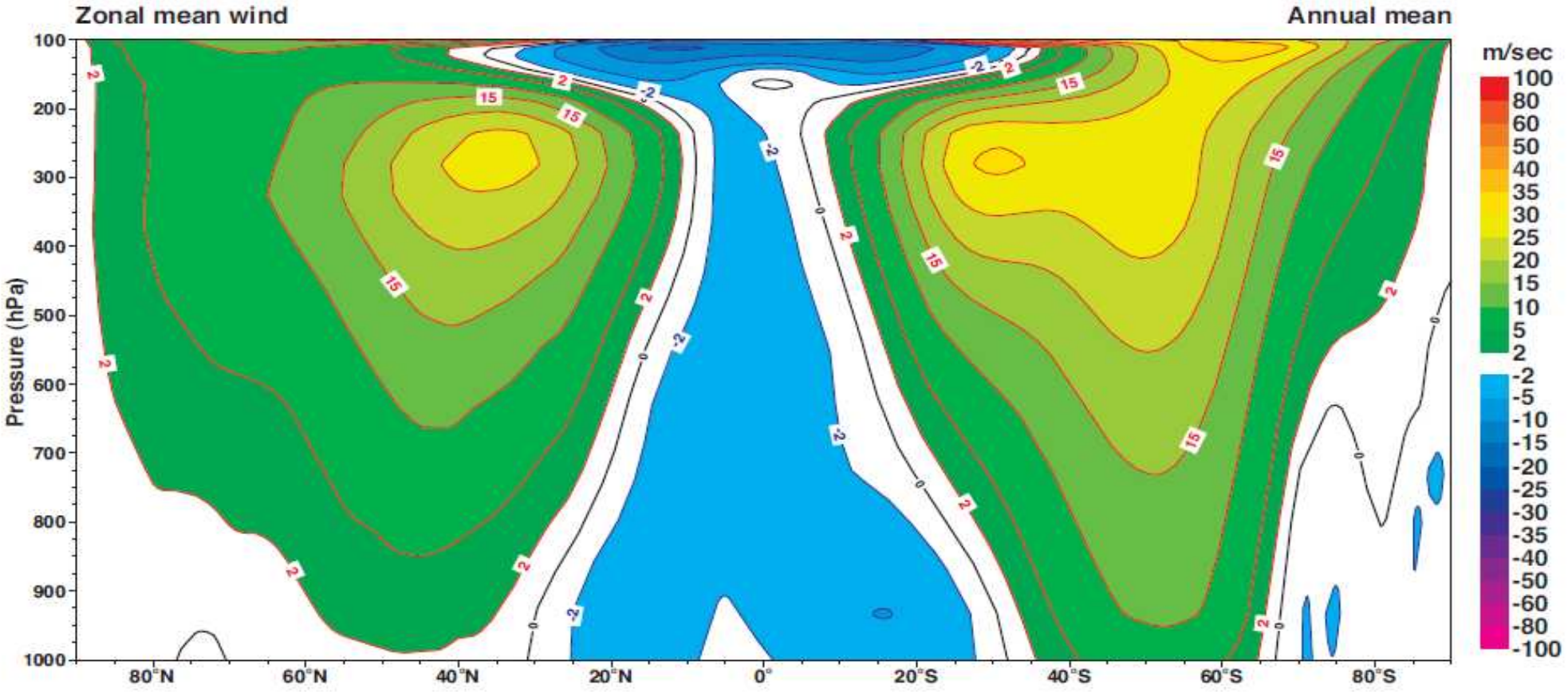
The Twentieth Century Reanalysis Project ...

A global reanalysis dataset spanning the entire twentieth century ...

Assimilating only surface observations of synoptic pressure ...



Zonal mean of zonal wind speed and air temperature from 20CRv2 averaged over the period 1871 to 2008.



ERA-40 Zonal Mean Wind

Conclusion

Reconstruction of the complete three-dimensional structure of the atmosphere is possible ...

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Reconstruction of the complete three-dimensional structure of the atmosphere is possible ...

... because the atmosphere is in a state of balance.

Thank you