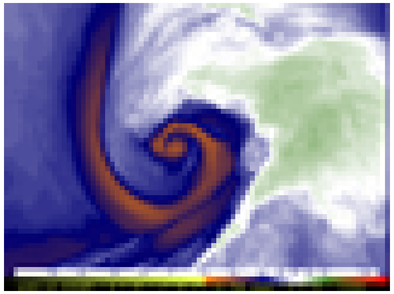
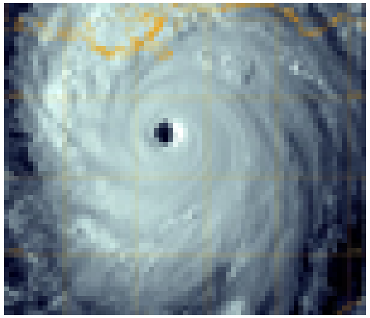
P1: Vortices in the atmosphere

http://weatherclimatelab.mit.edu/projects/weather-and-extremes/observation-data

jet stream



blizzard



hurricane

tornado

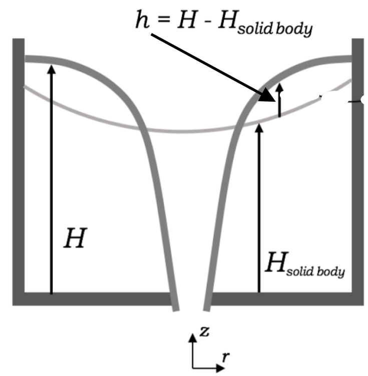
Summary of theory

Inertial Frame

$$V_\theta = v_\theta + \Omega r$$

Rotating Frame

$$\frac{V_\theta^2}{r} = g\frac{\partial H}{\partial r}$$



$$\frac{v_\theta^2}{r} + 2\Omega v_\theta = g\frac{\partial h}{\partial r}$$

$$Ro = \frac{|v_\theta^2/r|}{|2\Omega v_\theta|} = \frac{|v_\theta|}{2\Omega r}$$

$$R_{timescales} = \frac{2\pi/\Omega}{2\pi r/v_\theta} = \frac{v_\theta}{\Omega r} = 2 \times R_o$$

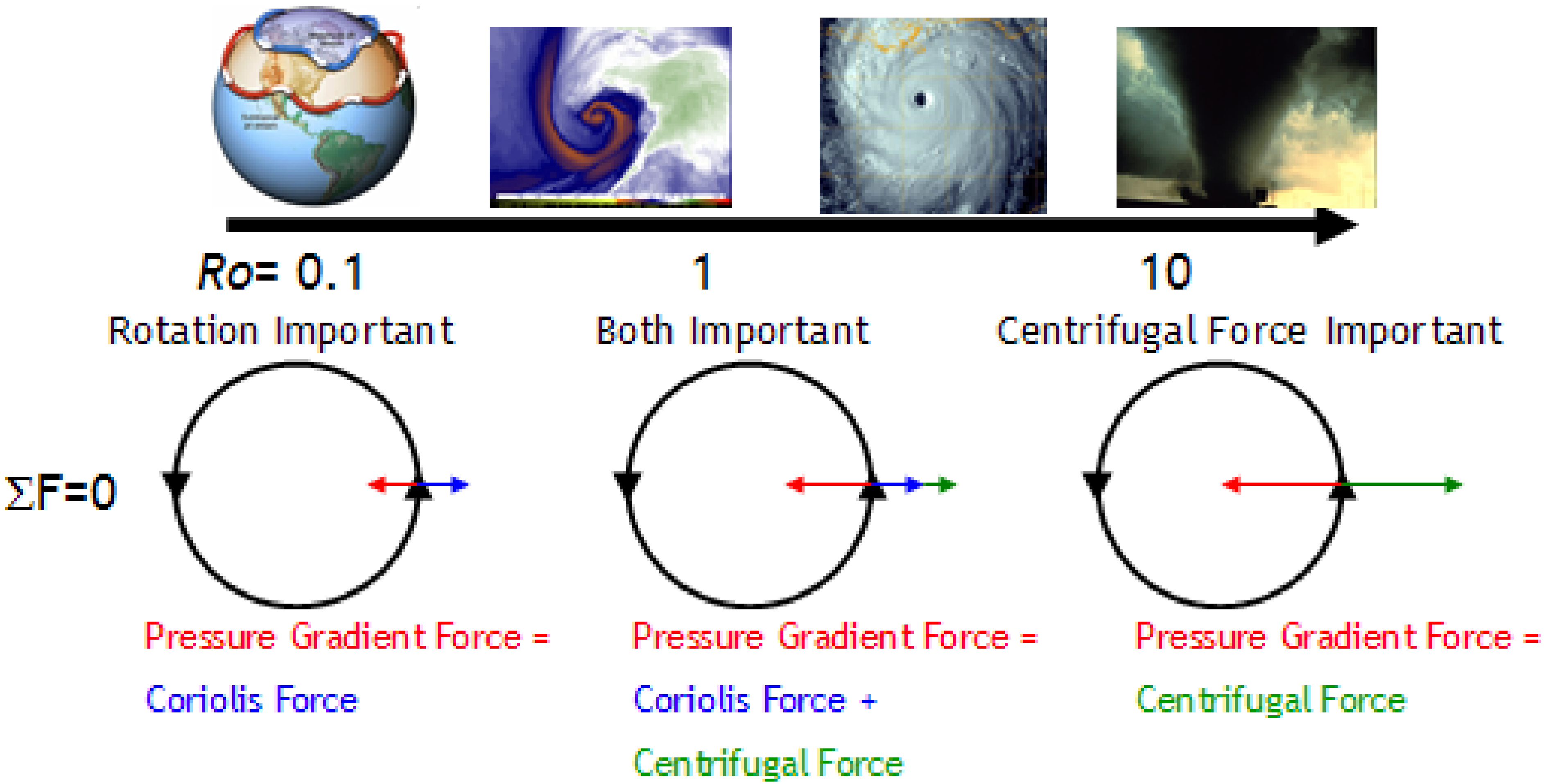
Three limits:

$R_0 \ll 1$: $$2\Omega v_\theta = g\frac{\partial h}{\partial r}$$ Geostrophic balance

$R_0 \sim 1$: $$\frac{v_\theta^2}{r} + 2\Omega v_\theta = g\frac{\partial h}{\partial r}$$ Gradient wind balance

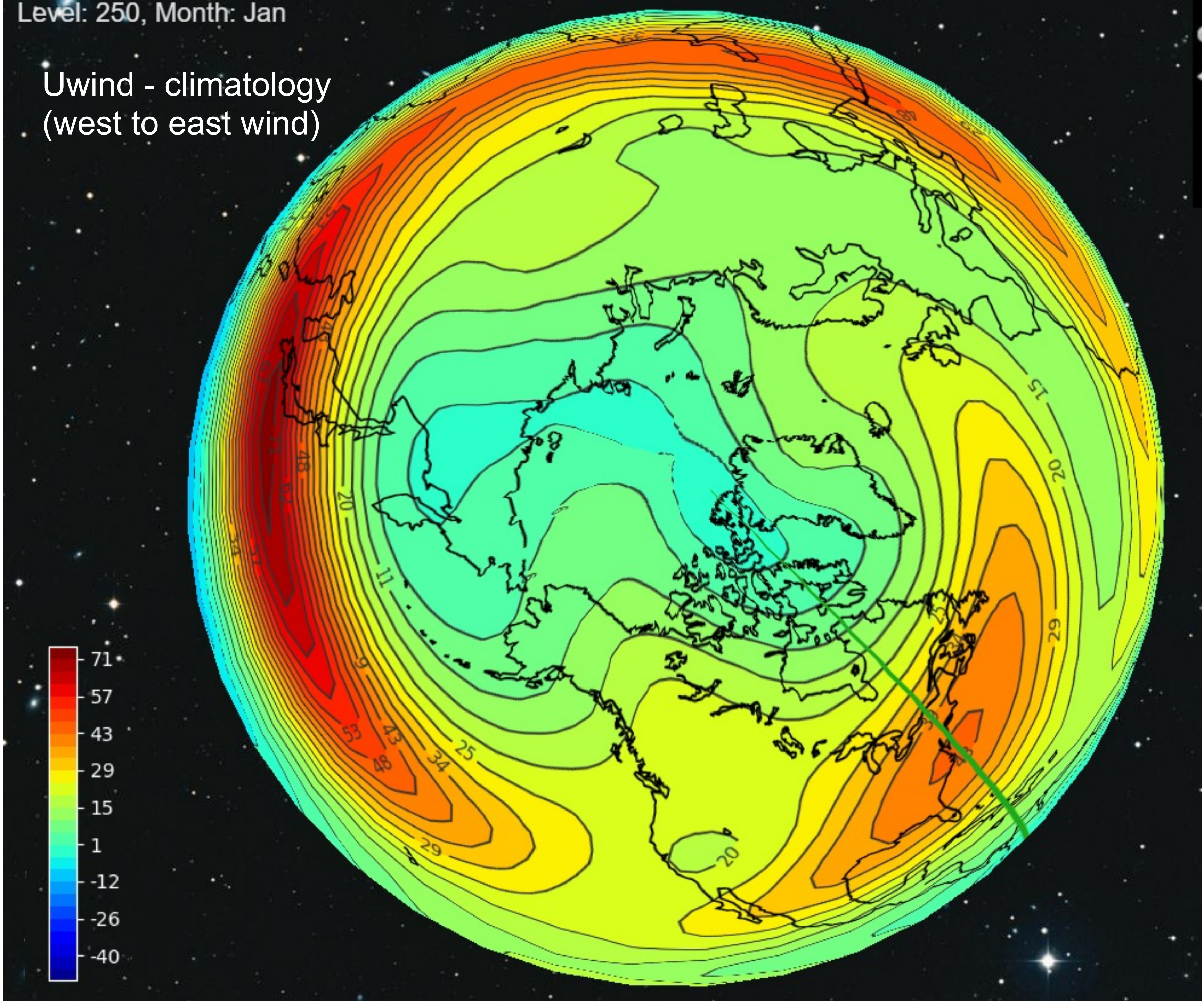
$R_0 \gg 1$: $$\frac{v_\theta^2}{r} = g\frac{\partial h}{\partial r}$$ Cyclostrophic balance

Atmospheric vortices: balance of forces

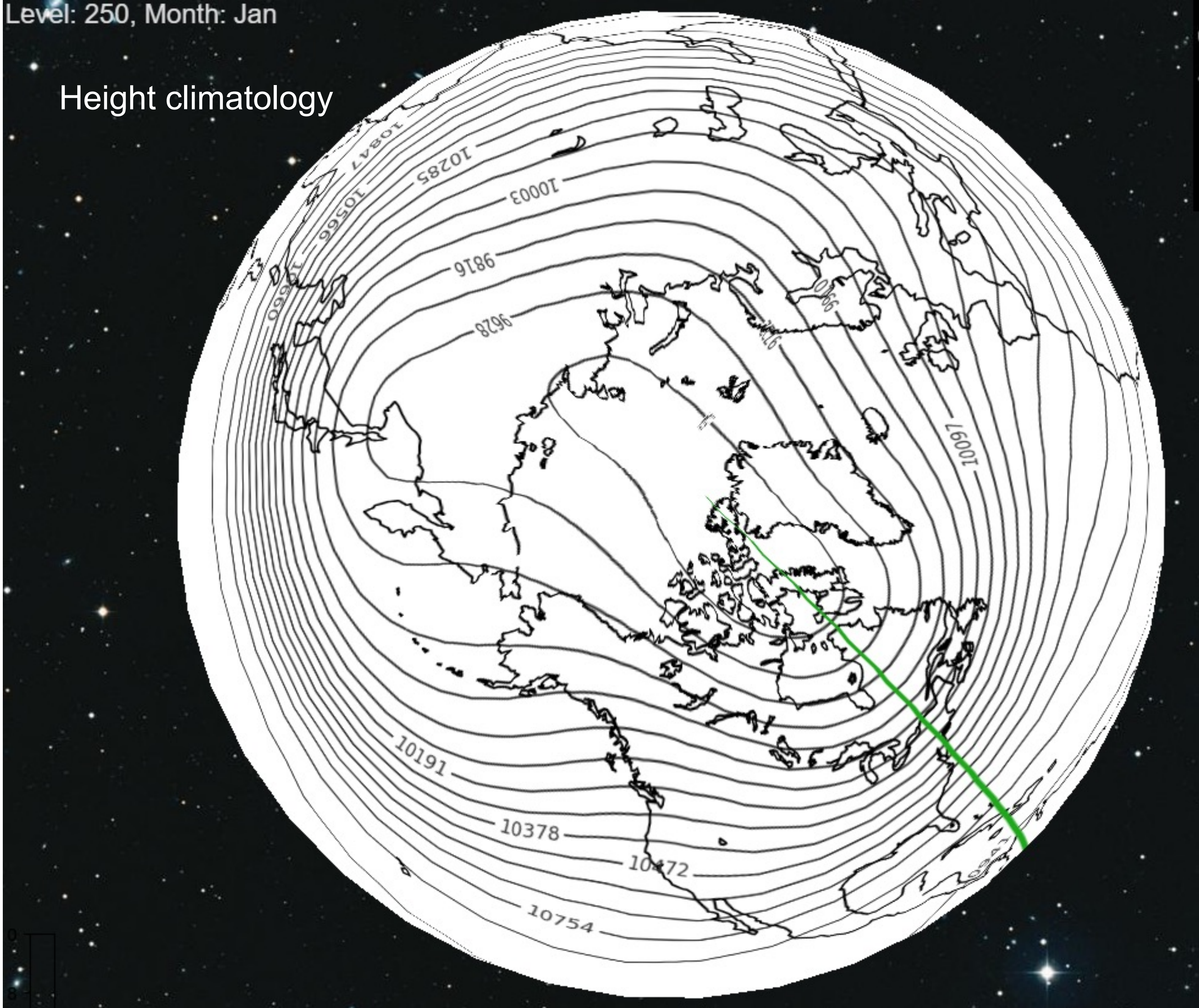


Is the jet stream in geostrophic balance?

Use January climatology to verify it



Level: 250, Month: Jan
Uwind - climatology
(west to east wind)
71
57
43
29
15
1
-12
-26
-40


Level: 250, Month: Jan
Height climatology
10847
10285
10566
10003
9816
9628
10097
10191
10378
10472
10754

Jet stream in geostrophic balance ?

$$2\Omega v_\theta = g\frac{\partial h}{\partial r}$$

Coriolis Force **Pressure Gradient Force**

$$v_\theta = \frac{g}{2\Omega}\frac{\partial h}{\partial r} \simeq \frac{g}{2\Omega}\frac{\Delta h}{\Delta r}$$

Put numbers in…

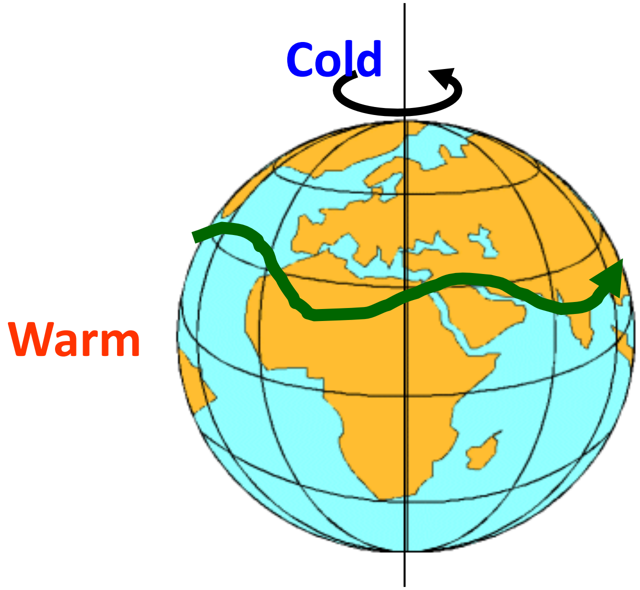
$\Delta h \cong 1.2 \cdot 10^3$ m

$\Delta r \cong 3 \cdot 10^3$ km

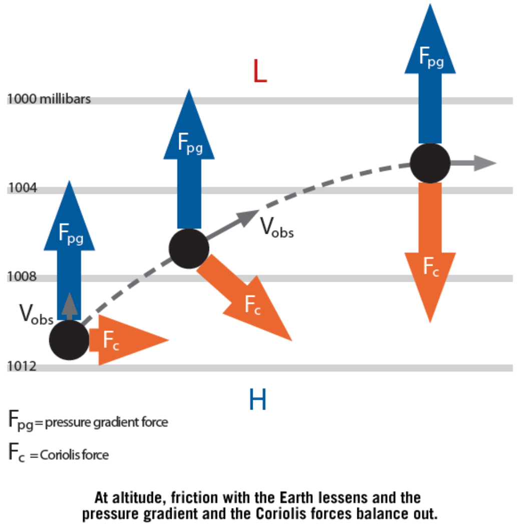
$$\boxed{v_\theta \cong 30\ \frac{m}{sec}}$$

Why is the jet stream generated?

The Equator-to-pole temperature difference induces a meridional (north-south) pressure gradient, with a **Low** pressure over the **Cold** Pole

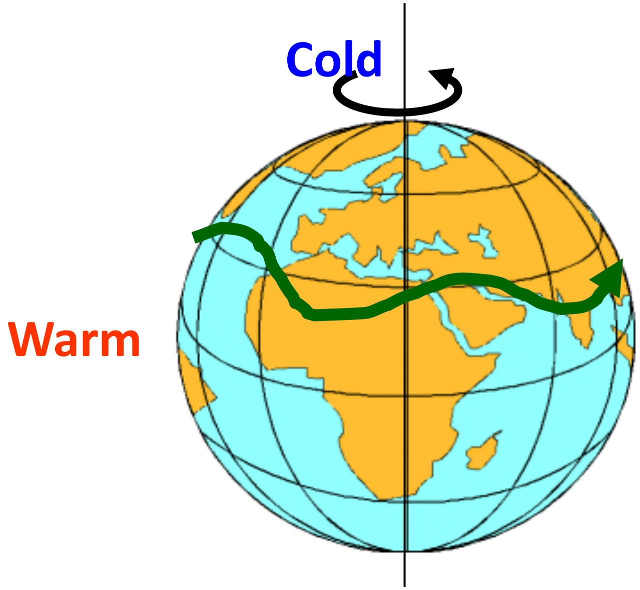


The jet stream is in therefore in *geostrophic balance:* the pressure gradient force is balanced by the Coriolis force



Why is the jet stream strongest at upper levels?

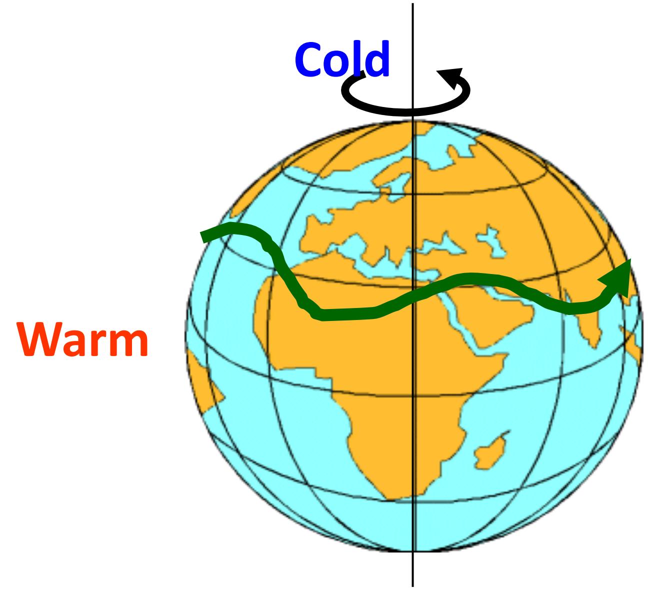
- Because of the N-S temperature difference, pressure gradient force is increasing with height.

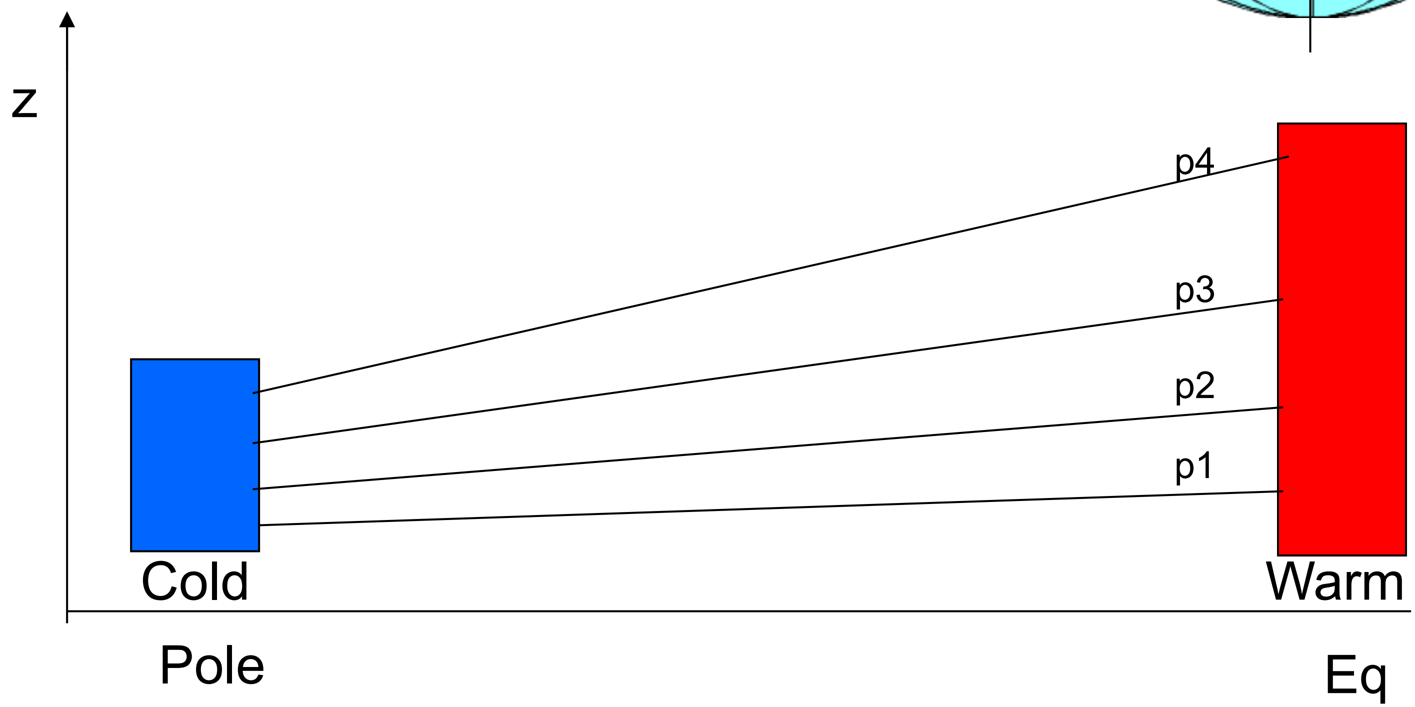


Why is the jet stream strongest at upper levels?

- Because of the N-S temperature difference, pressure gradient force is increasing with height.
- The geostrophic wind is therefore also increasing with height (reaching a maximum at the tropopause)

→ *Thermal wind balance!*





Extratropical weather systems

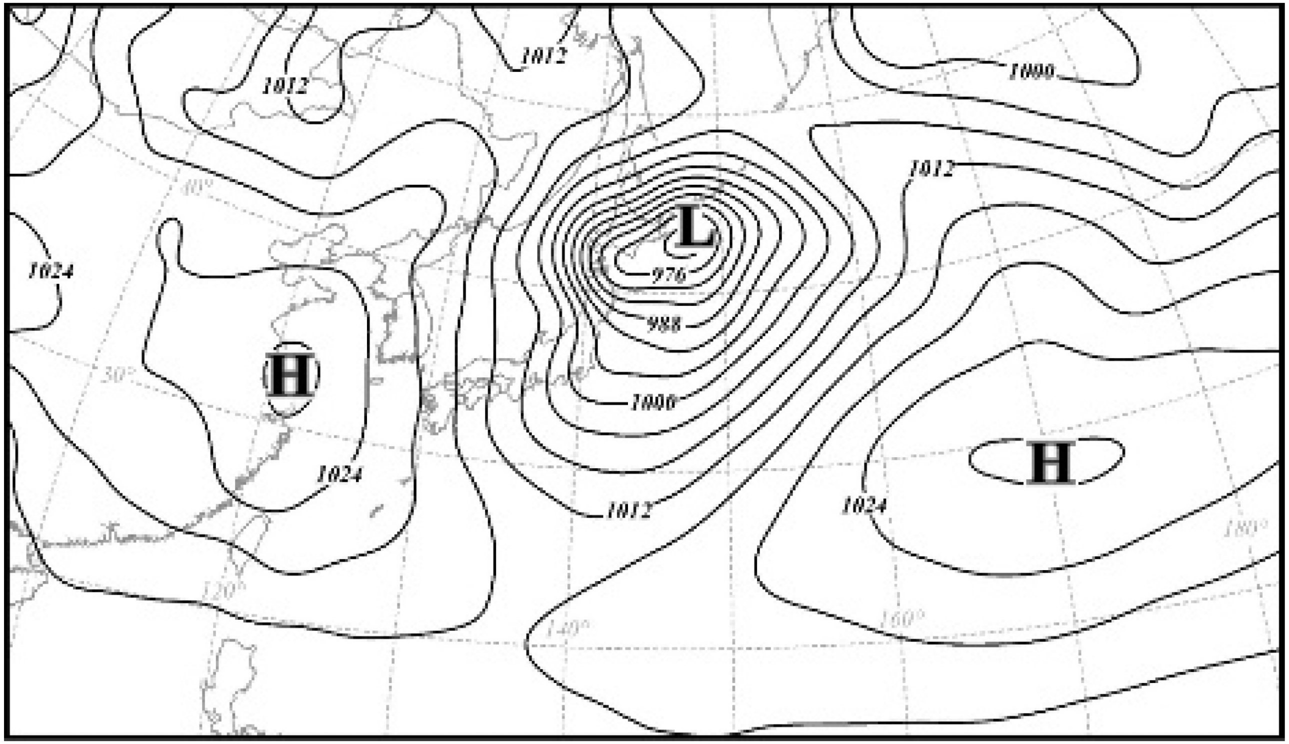


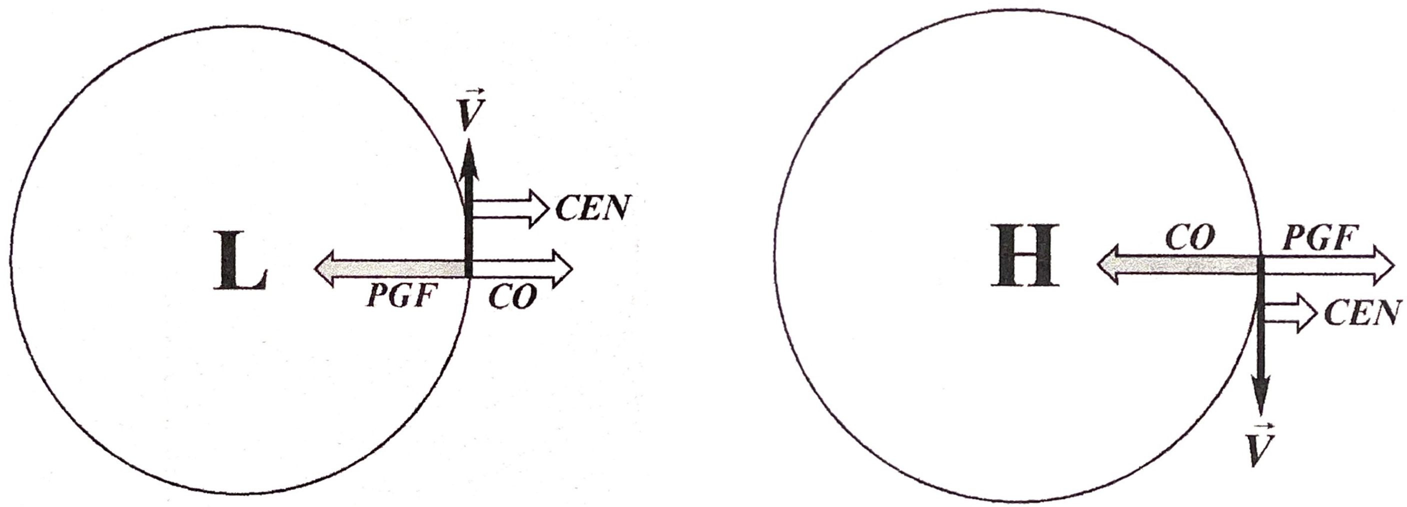
Figure 4.20 Sea-lavel pressure analysis for 0000 UTC 23 February 2004. Solid lines are isobars labeled in hPa and contoured every 4 hPa. Capital L and H represent centers of sea-level low- and high-pressure systems, respectively. Note the tight pressure gradient around the low and the much weaker pressure gradient around the highs

Figure taken from "Mid-Latitude Atmospheric Dynamics: A First Course", book by Jonathan E. Martin

Why are anticyclones (H) weaker and spatially larger than cyclones (L)?

The gradient wind balance-

Balance of forces for cyclones (L) and anticyclones (H)



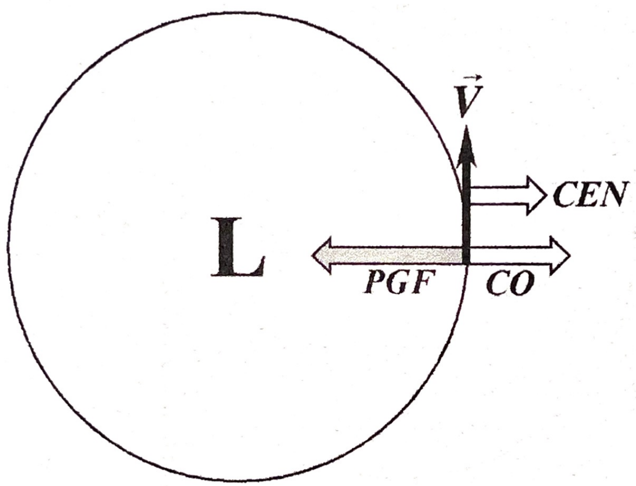
$$\frac{v^2}{r} + fv = g\frac{\partial h}{\partial r}$$

$$\frac{v^2}{r} + fv - g\frac{\partial h}{\partial r} = 0$$

$$\frac{v^2}{r} - f|v| + g|\frac{\partial h}{\partial r}| = 0$$

The gradient wind balance-

Balance of forces for cyclones (L):



$$\frac{v^2}{r} + fv - g\frac{\partial h}{\partial r} = 0$$

Note that $fv_g = g\frac{\partial h}{\partial r}$

$$\Rightarrow \quad f(v_g - v) = \frac{v^2}{r} > 0$$

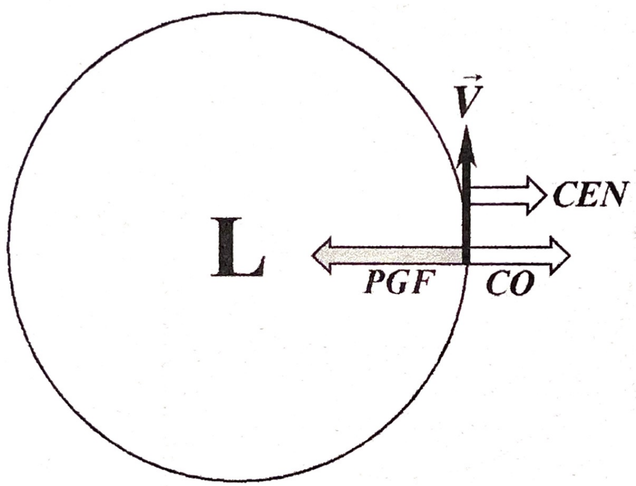
$$\Rightarrow \quad \boxed{v < v_g}$$

Subgeostrophic

The cyclonic wind is always weaker than the geostropic wind!

The gradient wind balance-

Balance of forces for cyclones (L):



$$\frac{v^2}{r} + fv - g\frac{\partial h}{\partial r} = 0$$

$$v = \frac{-fr}{2} \pm \sqrt{\frac{f^2r^2}{4} + rg\frac{\partial h}{\partial r}}$$

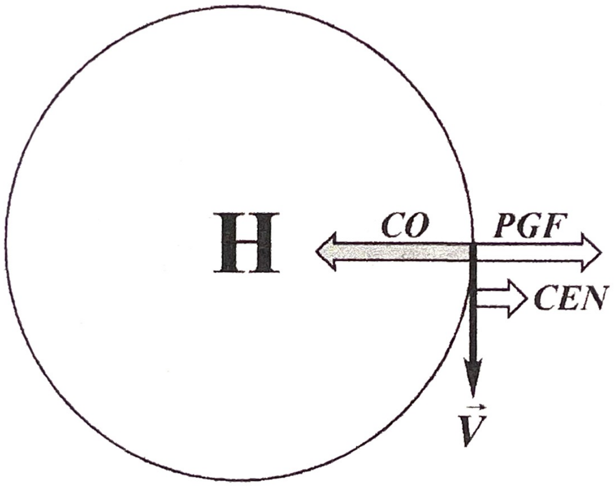
$$v_1 = -\frac{fr}{2} + \sqrt{\frac{f^2r^2}{4} + rg\frac{\partial h}{\partial r}} > 0$$

$$v_2 = -\frac{fr}{2} - \sqrt{\frac{f^2r^2}{4} + rg\frac{\partial h}{\partial r}} < 0$$

$$\boxed{v = -\frac{fr}{2} + \sqrt{\frac{f^2r^2}{4} + rg\frac{\partial h}{\partial r}}}$$

The gradient wind balance-

Balance of forces for anticyclones (H):



$$\frac{v^2}{r} + fv - g\frac{\partial h}{\partial r} = 0$$

Note that $f v_g = g\frac{\partial h}{\partial r}$

$$\boldsymbol{f(|v| - |v_g|) = \frac{v^2}{r} > 0}$$

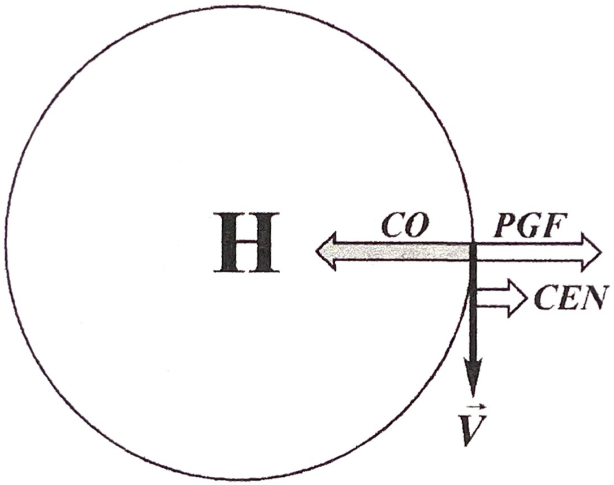
$$\boxed{|v| > |v_g|}$$

Supergeostrophic

The anticyclonic wind is always stronger than the geostropic wind!

The gradient wind balance-

Balance of forces for anticyclones (H):



$$\frac{v^2}{r} + fv - g\frac{\partial h}{\partial r} = 0$$

$$v = -\frac{fr}{2} \pm \sqrt{\frac{f^2r^2}{4} - rg\left|\frac{\partial h}{\partial r}\right|}$$

Solutions only if: $\frac{f^2r^2}{4} - rg\left|\frac{\partial h}{\partial r}\right| > 0$ $\Rightarrow$ $g\left|\frac{\partial h}{\partial r}\right| < \frac{f^2r}{4}$

$$v = \frac{-fr}{2} - \sqrt{\frac{f^2r^2}{4} - rg\left|\frac{\partial h}{\partial r}\right|}$$

The pressure gradient of an anticyclone is bounded!

Also, $\left|\frac{\partial h}{\partial r}\right| \to 0$ when $r \to 0$

Let's check if this simple theory works for real H and L!

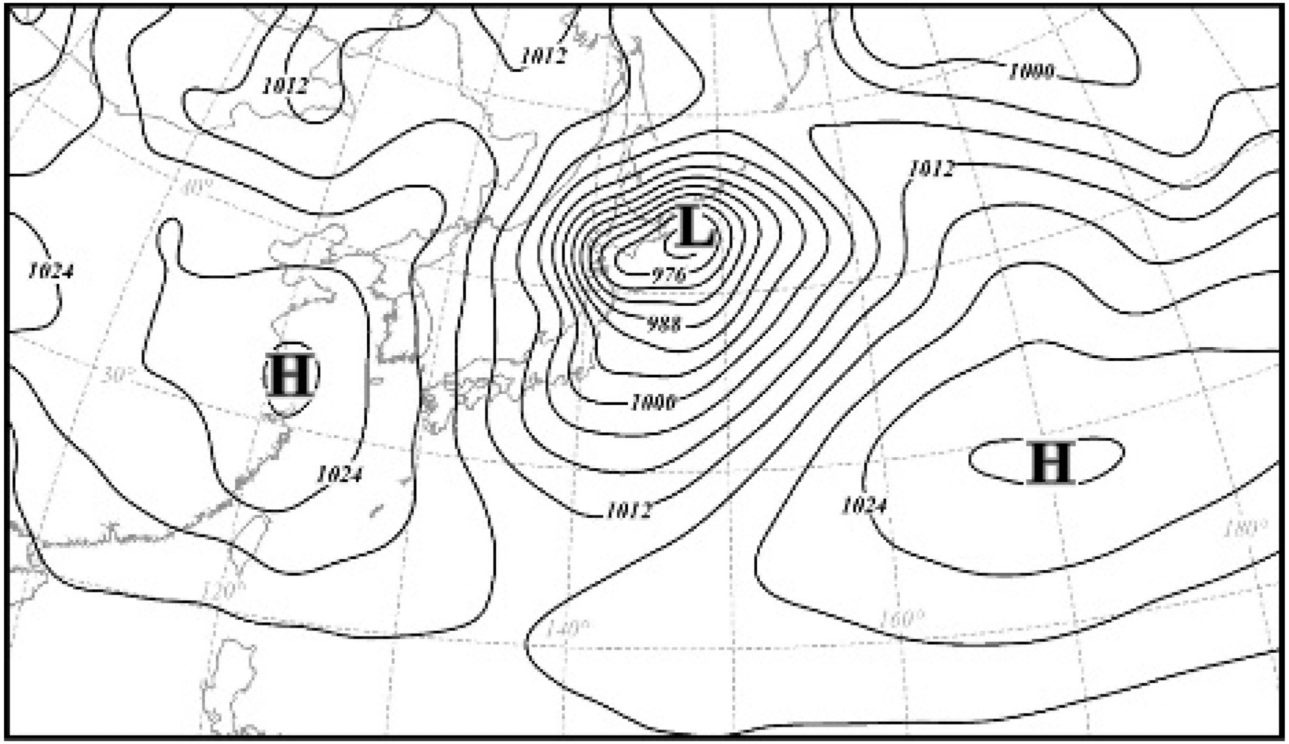


Figure 4.20 Sea-lavel pressure analysis for 0000 UTC 23 February 2004. Solid lines are isobars labeled in hPa and contoured every 4 hPa. Capital L and H represent centers of sea-level low- and high-pressure systems, respectively. Note the tight pressure gradient around the low and the much weaker pressure gradient around the highs

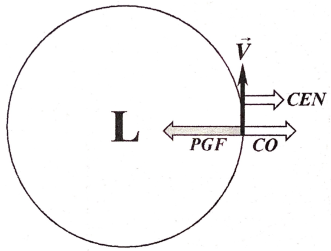
Figure from "Mid-Latitude Atmospheric Dynamics: A First Course", book by Jonathan E. Martin

Note: the fact that $v < v_g$ for cyclones and $|v| > |v_g|$ for anticyclones ***does not*** mean that anticyclones velocities are larger. ***This is true only for the same pressure gradient!***

Note also that-

For cyclones, we had

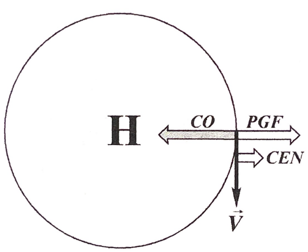
$$\frac{v^2}{r} + fv - fv_g = 0$$



$$\Rightarrow \quad \frac{v^2}{fr} = v_g - v \qquad \Rightarrow \quad \frac{v_g}{v} - 1 = \frac{v}{fr} \equiv R_0$$

For cyclones: $\boxed{\frac{v_g}{v} = R_0 + 1}$ $\Rightarrow$ $\boxed{v < v_g}$

Similarly, for anticyclones we get $\frac{v^2}{r} - f|v| + f|v_g| = 0$



For anticyclones: $\boxed{\frac{|v_g|}{|v|} = 1 - R_0}$ $\Rightarrow$ $\boxed{|v| > |v_g|}$

Let's check if this simple theory works for real H and L!

We will use the Synoptic Laboratory website (Lodo Illari) to plot v, v_g for real atmospheric data.

- Check last week- February 16th, around Washington (WA state) for a nice example.
- Go to *http://synoptic.mit.edu/custom-plots/anyscalarwind/*
- Set:

1. In the "Scaler" field, change "tmpc" to "hght"
2. Set the day to "16" instead of today
3. In the "Wind-skip" option, change to yes (to reduce the number if arrows)
4. In the GAREA option, change "usnps" to "WA--".

→ This will produce a map with wind barbs and the 500mb geopotential height

- Now repeat, but in the "Wind" option change "observed" to "Geostrophic"

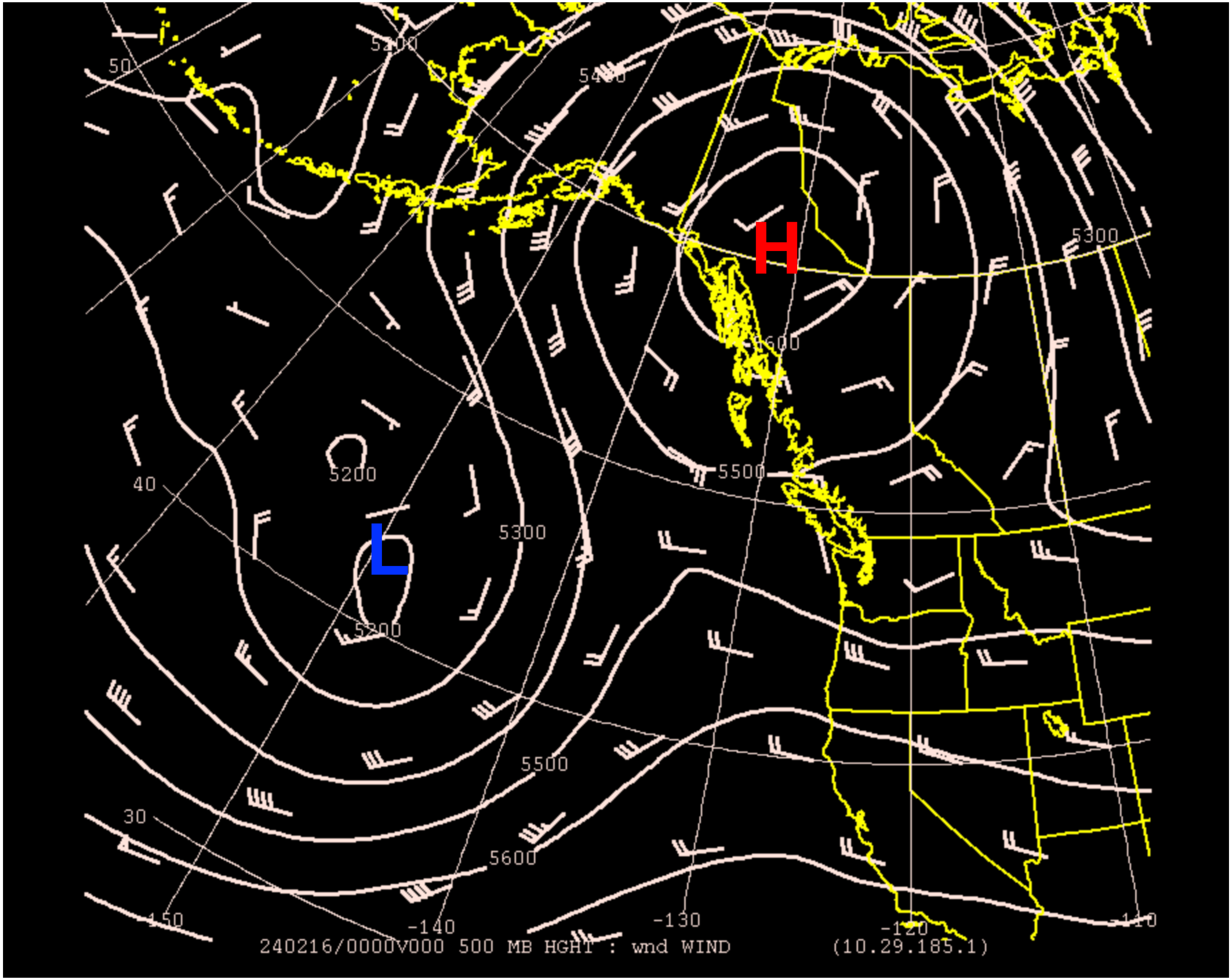
- Is the actual v smaller or larger than the geostrophic velocity in the L/H region?

- Can you estimate the Rossby number?

cyclones $R_0 = \frac{v_g}{v} - 1$

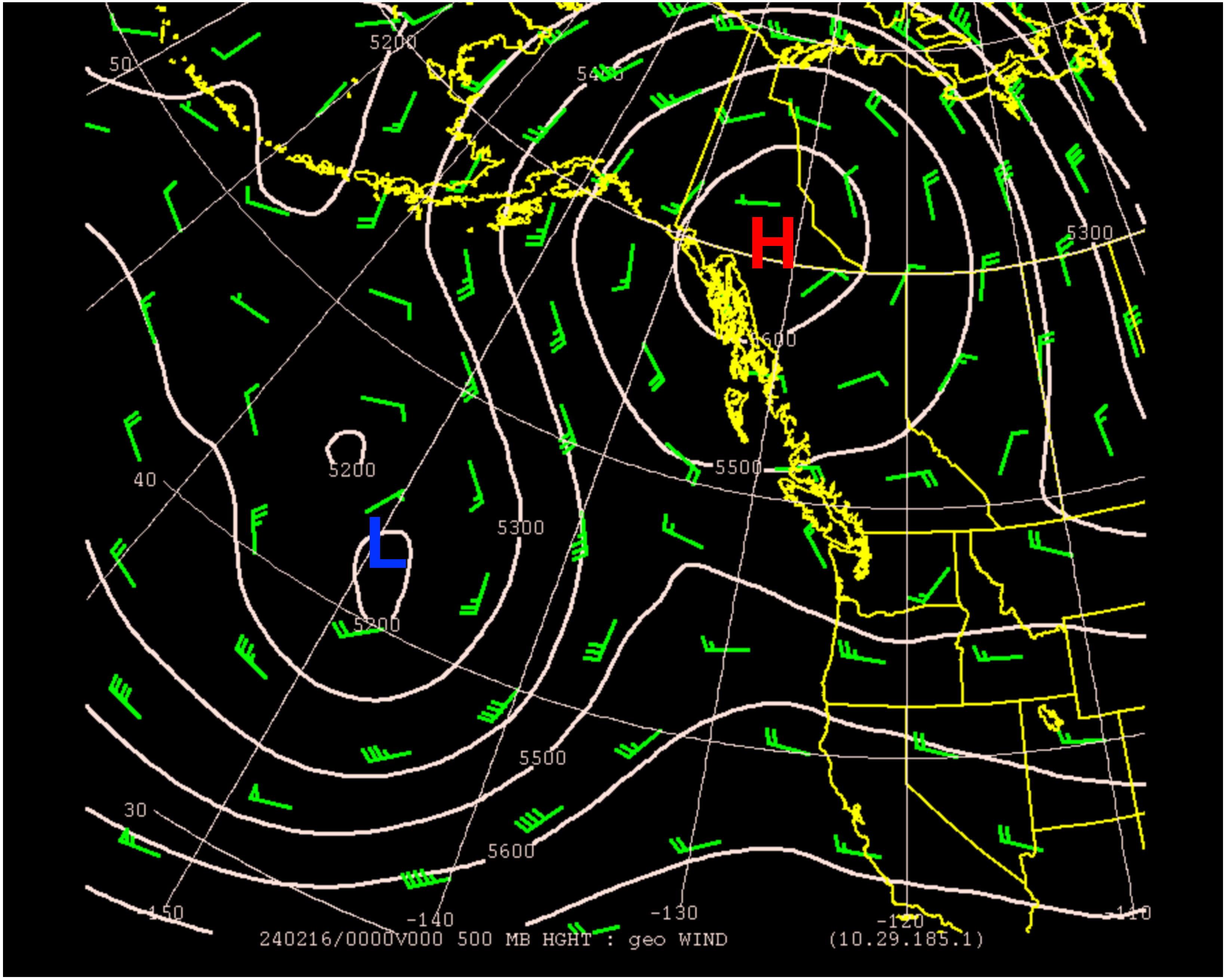
anticyclones $R_0 = 1 - \frac{v_g}{v}$

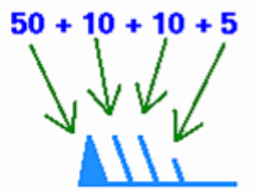
Total wind



5200
5400
5300
5600
5500
5200
5300
5200
5500
5600
50
40
30
-150
-140
-130
-120
-110
H
L
240216/0000V000 500 MB HGHT : wnd WIND (10.29.185.1)

Geostrophic wind





Wind blowing from the west at 75 knots

Wind blowing from the northeast at 25 knots

Wind blowing from the south at 5 knots

Calm winds

Hurricanes-

Next class!

EsGlobe uses a **globa**l dataset:

Winds from the **GFS - Global Forecast Model** (NCEP)

lat, lon grid with a resolution of ¼ of degree = ~ 25km

Not enough resolution to represent well an hurricane, which has a radius of few hundreds km

To study the balance of forces in a hurricane we are using a special dataset: surface wind data from the “**scatterometer**” instrument

See scatterometer_instructions

Hurricane flow and the balanced vortex experiment