ATM 241, Spring 2020
Lecture 6
Near-Surface Flow

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Marshall & Plumb

Ch. 7.4

In this section…

Definitions

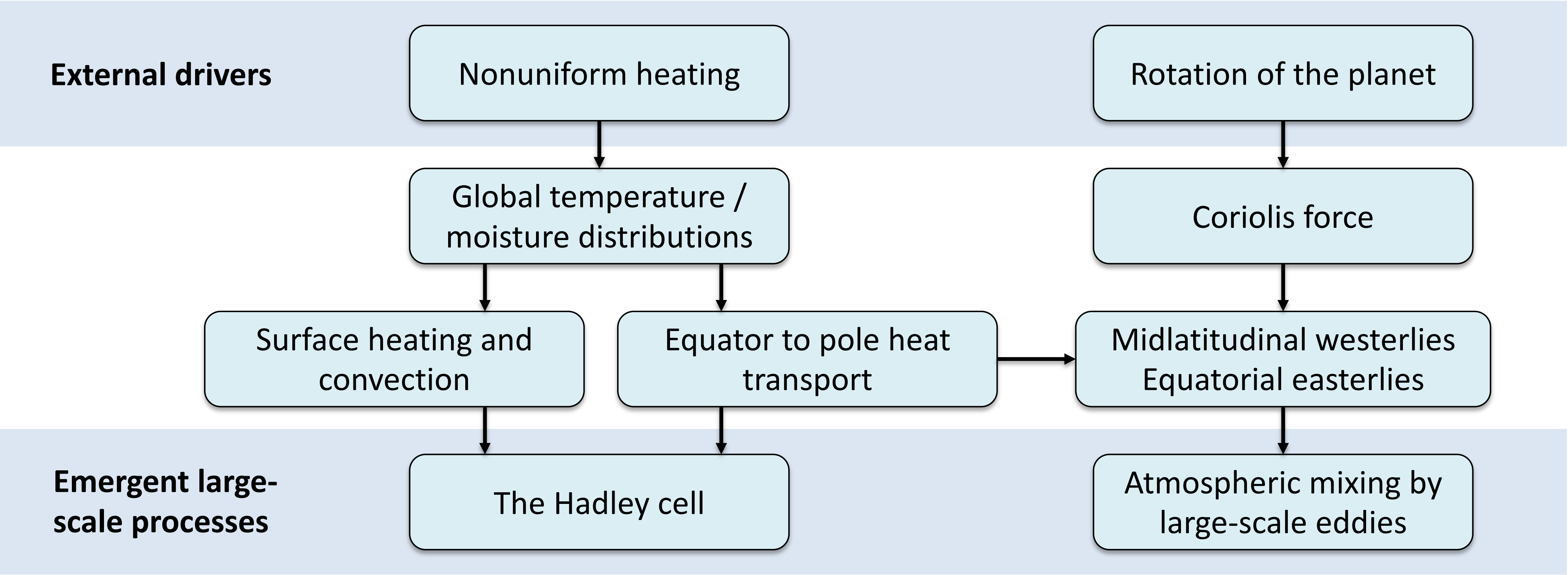
- Ekman layer
- Ekman pumping
- Ekman suction

Questions

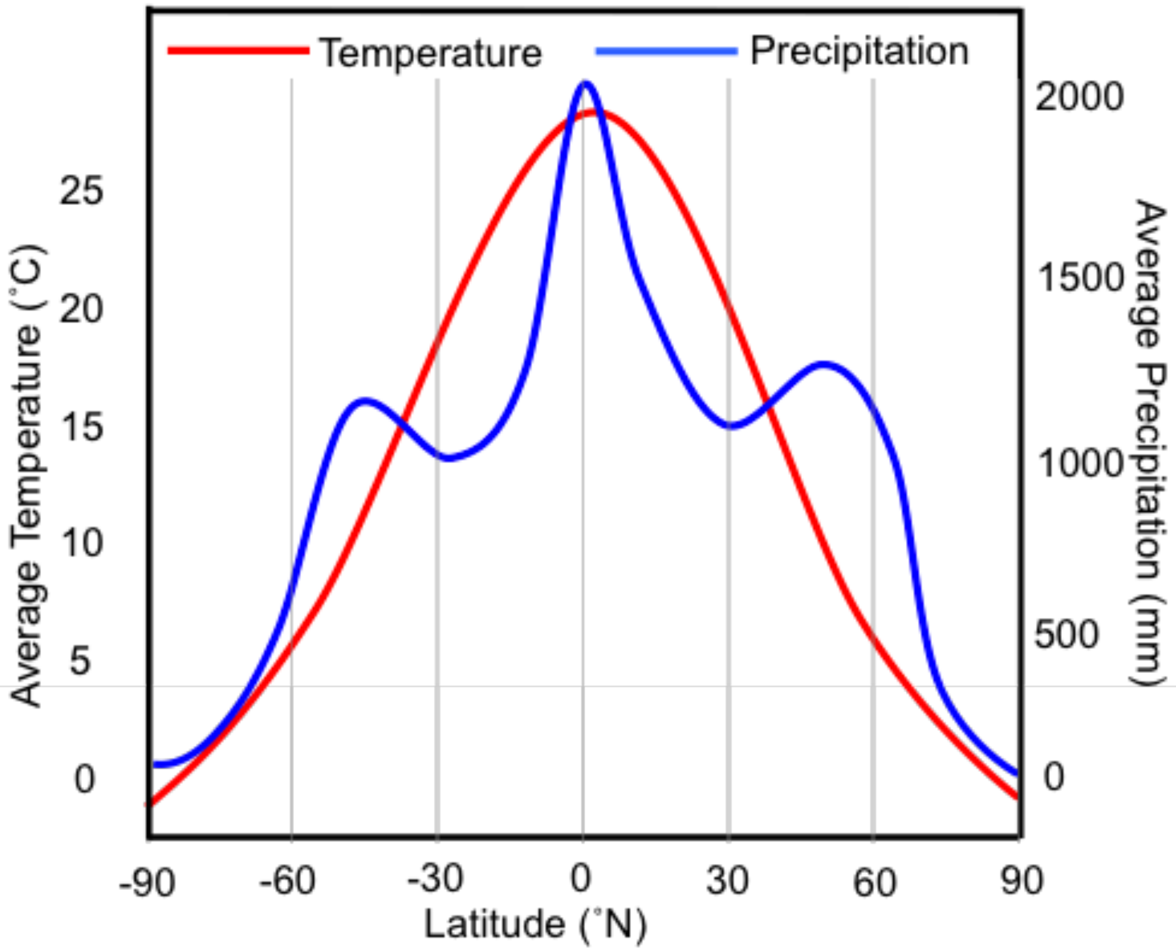
- How does surface heterogeneity affect the climate system?
- How are the dynamics of the near-surface different from the dynamics of the free atmosphere?
- What is the effect of frictional forces on atmospheric fluid parcels?

Climate Dynamics

Figure: A high-level depiction of the features and processes driving the general circulation.



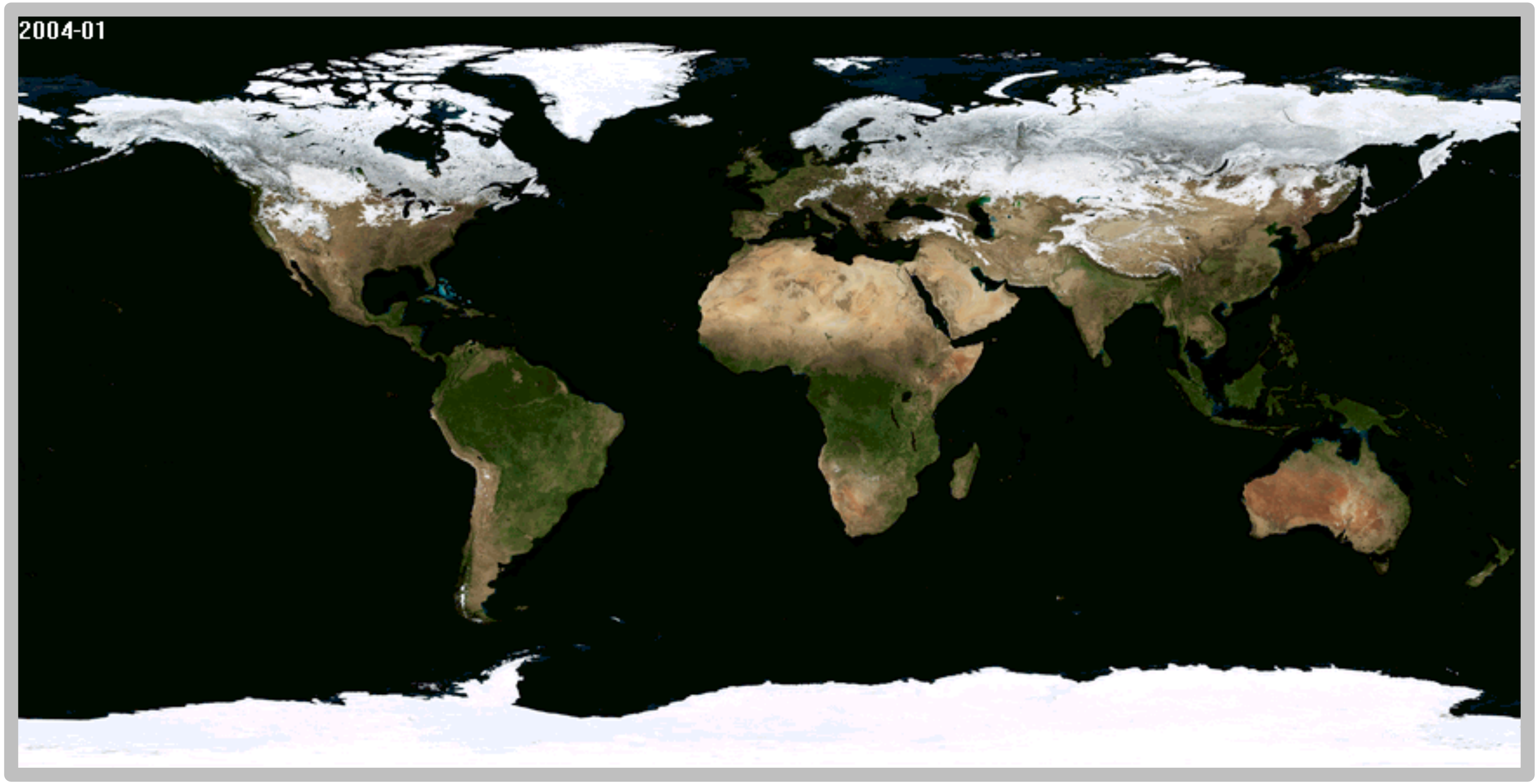
Temperature and Precipitation



https://commons.wikimedia.org/wiki/File:Relationship_between_latitude_vs._temperature_and_precipitation.png

Surface Heterogeneity

Question: How does surface heterogeneity affect the climate system?

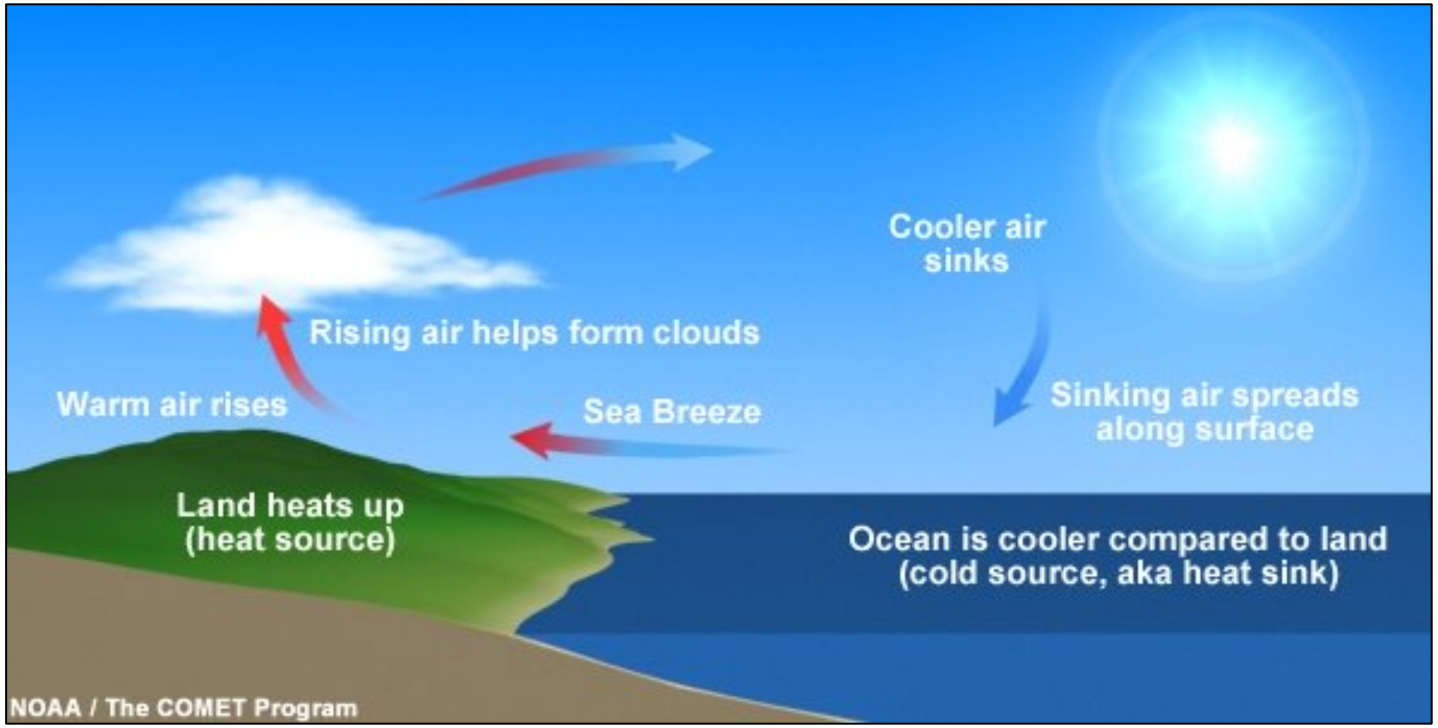


Author: NASA images by Reto Stöckli, 2004

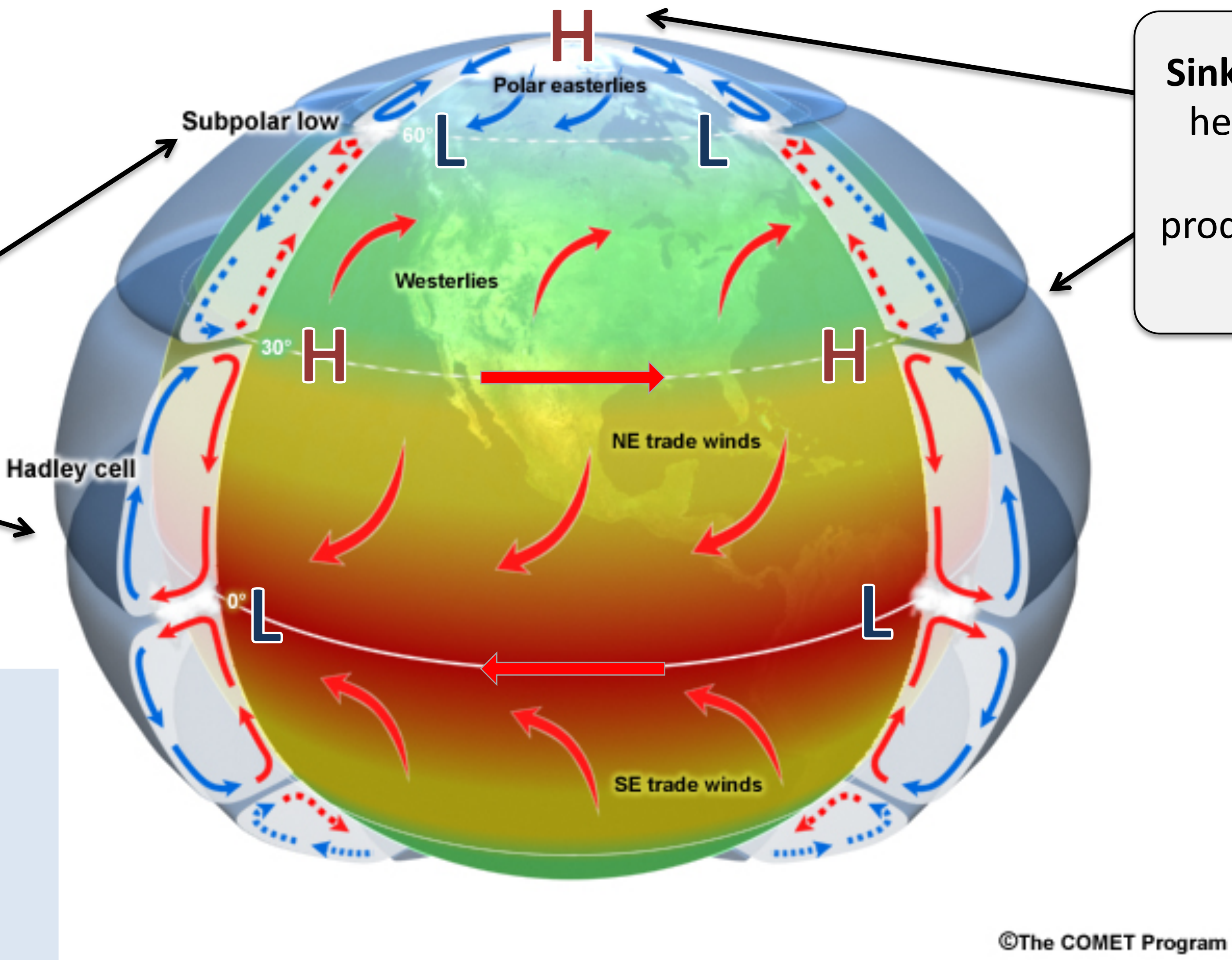
Sea Breeze Circulation

Figure: One of the most prominent features that arise due to surface heterogeneity is the **sea breeze**. At night this circulation is reversed producing a **land breeze**.

Monsoons (including the famous Indian monsoon) are examples of large-scale sea/land breezes.



The Hadley Cell



Rising air here removes air from the near surface, producing **low surface pressure**.

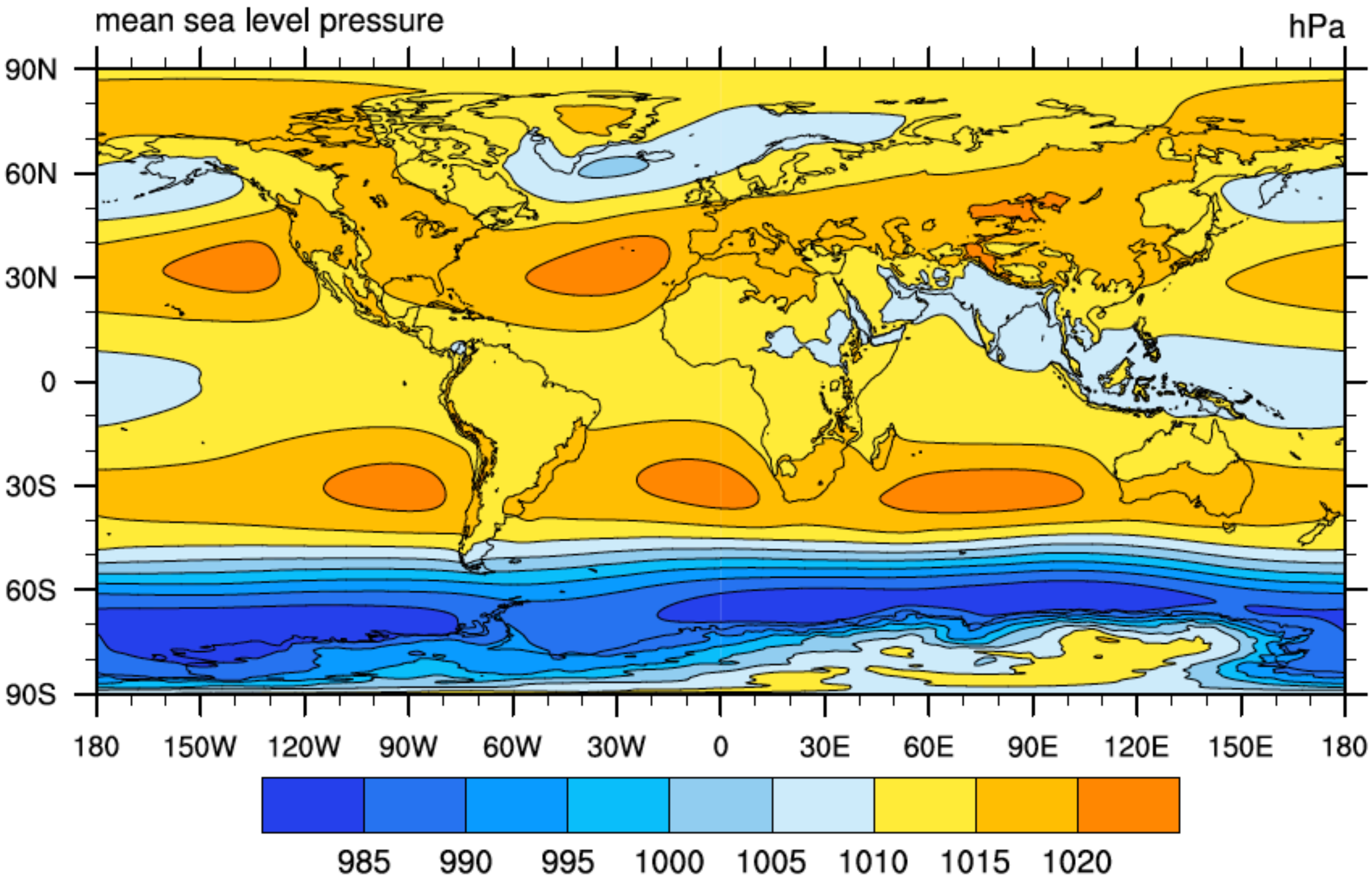
Sinking (subsiding) air here adds air to the near surface, producing **high surface pressure**.

Key point: This image is an idealization that neglects the heterogeneous structure of the land surface.

The Real Global Sea Level Pressure

Figure: The idealized image on the previous slide doesn't account for surface heterogeneity due to the presence of land surfaces.

Features such as the Pacific High or Bermuda High are produced because of this heterogeneity and are important for producing regional weather patterns.



Geostrophic Balance

Assume acceleration is small (and friction is negligible):

$$\frac{du}{dt} = -\left(\frac{\partial \Phi}{\partial y}\right)_p + fv + \nu \nabla^2 u$$

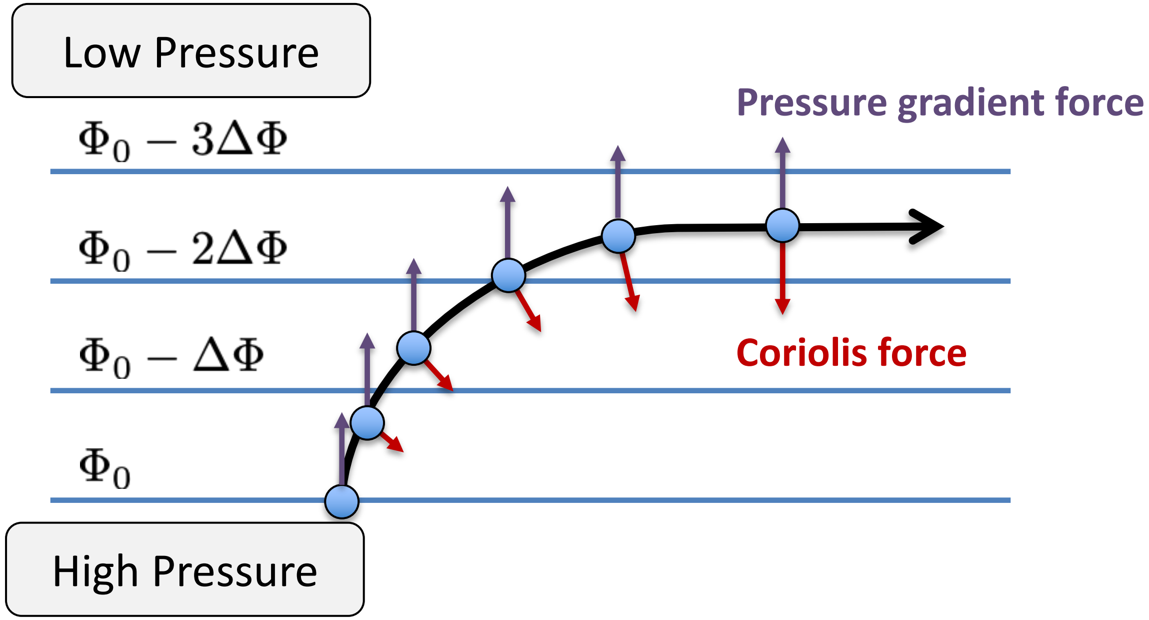
$$\frac{dv}{dt} = -\left(\frac{\partial \Phi}{\partial x}\right)_p - fu + \nu \nabla^2 v$$

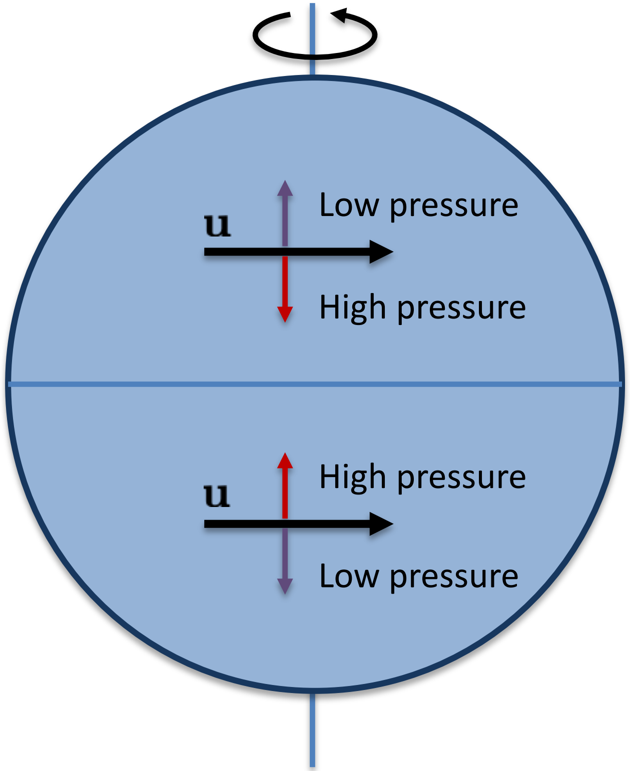
Definition: Geostrophic wind:

$$u_g = -\frac{1}{f}\left(\frac{\partial \Phi}{\partial y}\right)_p \qquad v_g = \frac{1}{f}\left(\frac{\partial \Phi}{\partial x}\right)_p$$

Zonal Mean Winds

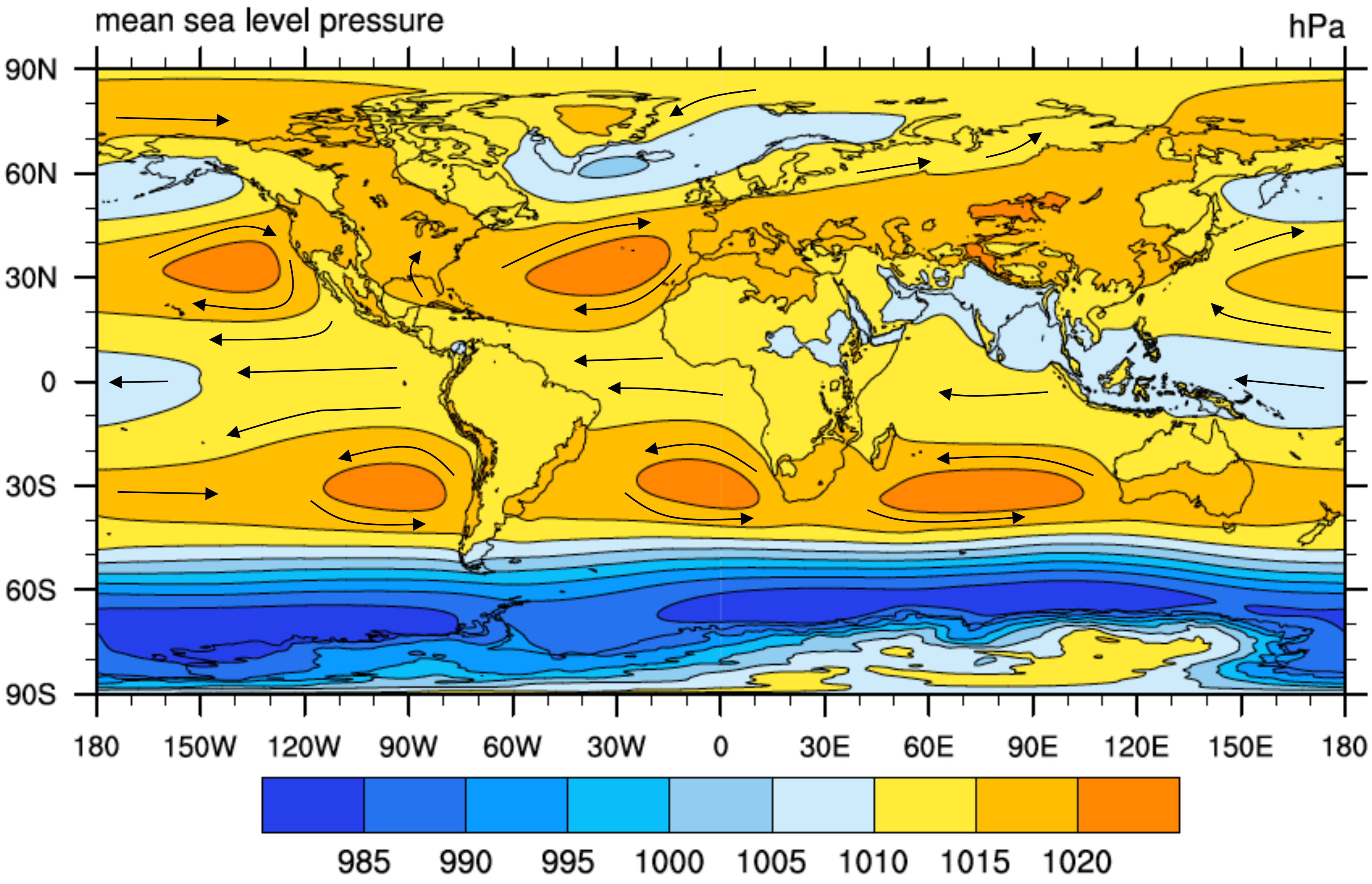
The geostrophic wind is the natural response of **midlatitudinal atmospheric motions** to pressure gradients. It propagates perpendicular to the direction of the pressure gradient force and the Coriolis force (towards the East in the Northern and Southern hemispheres).





Global Sea Level Pressure

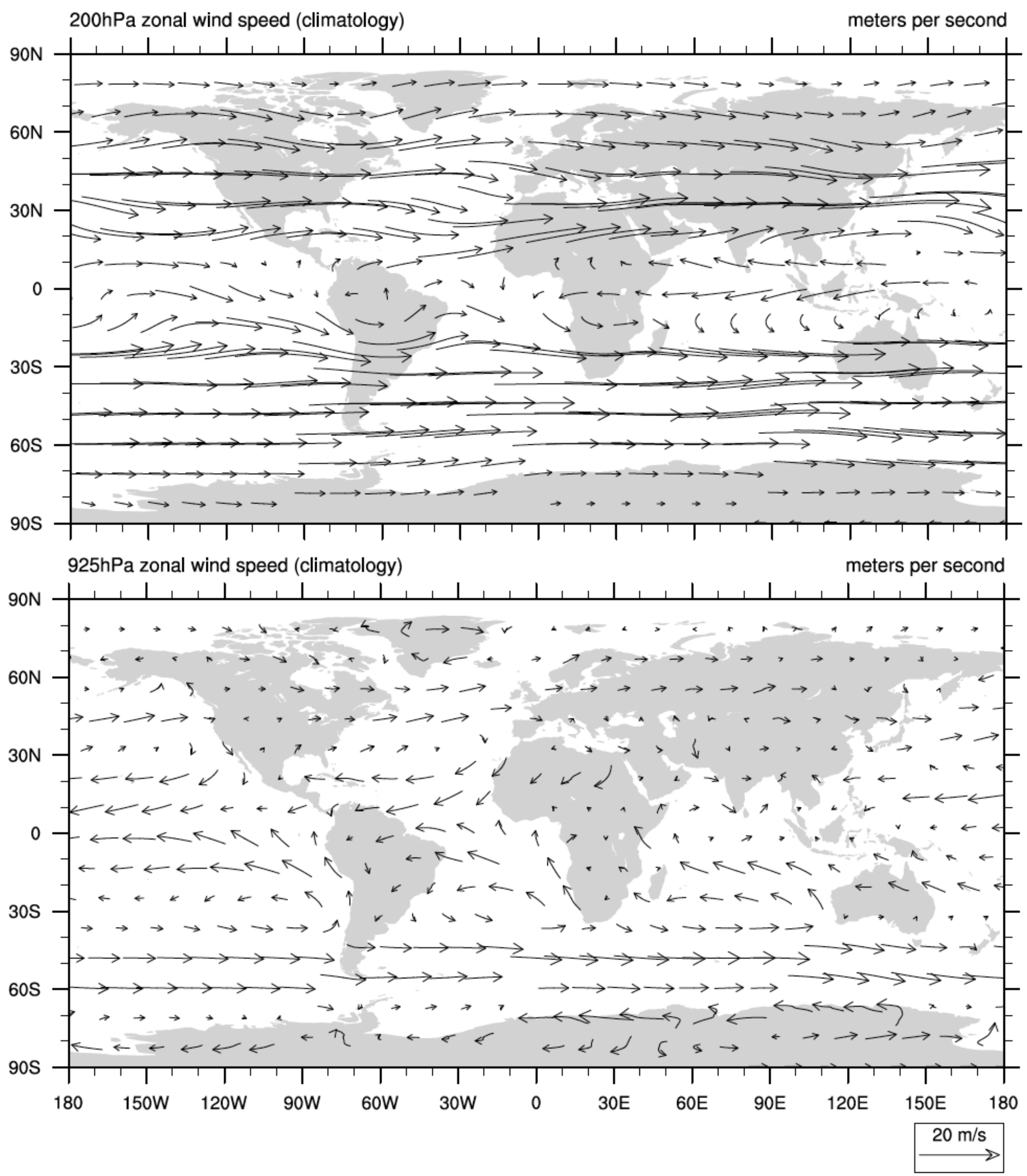
Figure: Near-surface level winds induced by horizontal variations in sea level pressure (under near geostrophic balance).



Zonal Mean Winds

(Upper Figure) Annual Climatology (200 hPa) upper level Winds

(Lower Figure) Annual Climatology (925 hPa) near surface Winds



Geostrophic Balance

Recall the horizontal momentum equation:

$$\frac{\partial \mathbf{u}}{\partial t} = -\frac{1}{\rho}\nabla p - f\mathbf{k} \times \mathbf{u} + \mathcal{F}$$

Acceleration (curvature)
Pressure gradient
Coriolis
Friction

For small Rossby number, curvature is negligible. This is a good approximation nearly everywhere, except near regions of very low pressure (cyclones, tornadoes, etc.):

$$\cancel{\frac{\partial \mathbf{u}}{\partial t}} = -\frac{1}{\rho}\nabla p - f\mathbf{k} \times \mathbf{u} + \mathcal{F}$$

Geostrophic Balance

Away from the surface, frictional forces are negligible, leading to the flow being in geostrophic balance.

$$\frac{1}{\rho}\nabla p = -f\mathbf{k} \times \mathbf{u} + \cancel{\mathcal{F}}$$

Perpendicular to lines of constant pressure

90 degrees to the right of the flow (in the northern hemisphere)

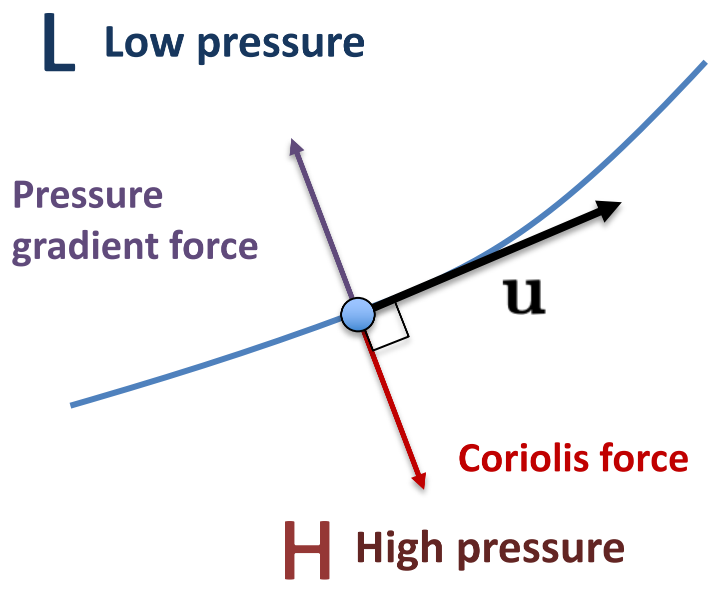
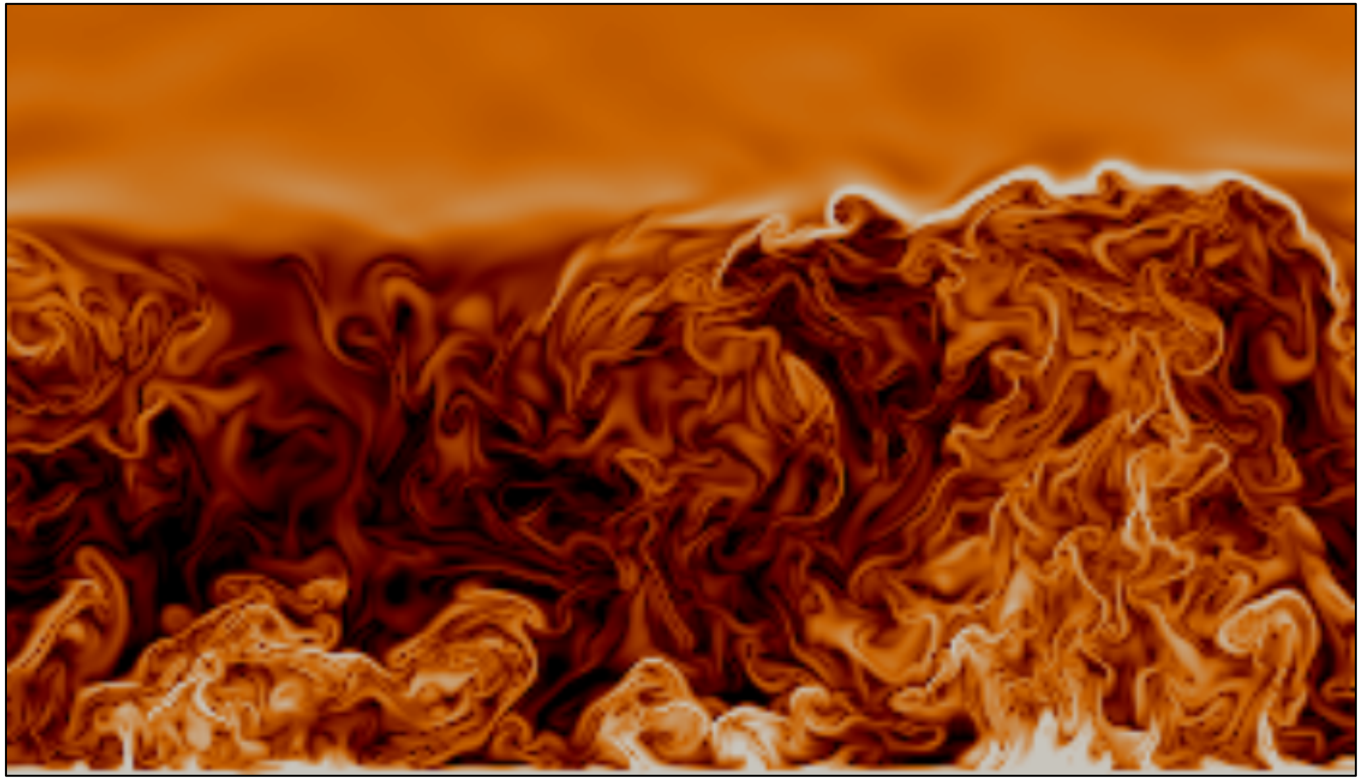


Figure: The balance of forces away from the equator (where Coriolis is relevant) and away from the surface (where friction is negligible). Fluid parcels are directed along lines of constant pressure.

Near-Surface Friction

In the **atmospheric boundary layer** (approximately the lower 1 km of the atmosphere), surface roughness induces turbulence which acts to damp the flow velocity.



Free Atmosphere / Stratified Layer

Inversion

Turbulent Boundary Layer

https://blogs.egu.eu/divisions/as/tag/rayleigh-benard-convection/

Subgeostrophic Flow

Near the surface, frictional effects need to be considered. Friction slows the wind, reducing Coriolis force and leading to wind being directed towards lower pressures.

$$\frac{1}{\rho}\nabla p = -f\mathbf{k}\times\mathbf{u} + \mathcal{F}$$

- $\frac{1}{\rho}\nabla p$: Perpendicular to lines of constant pressure
- $-f\mathbf{k}\times\mathbf{u}$: 90 degrees to the right of the flow (in the northern hemisphere)
- $\mathcal{F}$: In direct opposition to the flow

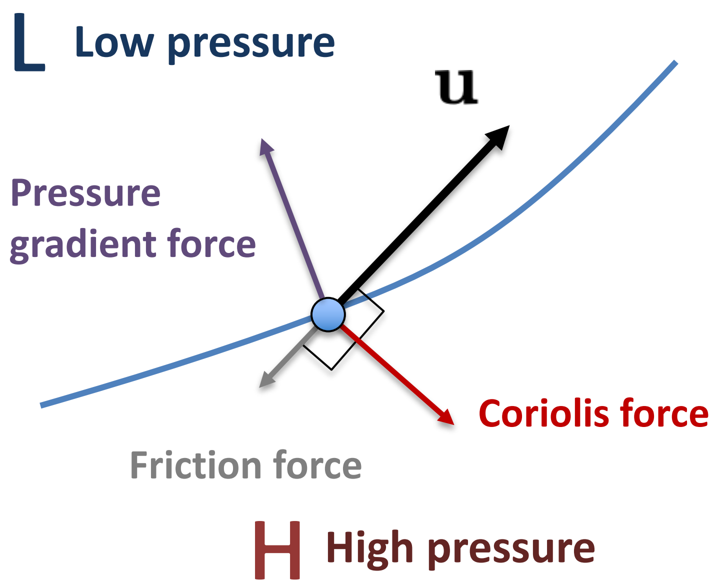


Figure: The balance of forces away from the equator (where Coriolis is relevant) and near the surface (where friction is important).

Subgeostrophic Flow

Definition: The **Ekman layer** is the layer in a fluid where the flow is the result of a balance between pressure gradient, Coriolis and turbulent drag forces.

$$\frac{1}{\rho}\nabla p = -f\mathbf{k}\times\mathbf{u} + \mathcal{F}$$

Perpendicular to lines of constant pressure	90 degrees to the right of the flow (in the northern hemisphere)	In direct opposition to the flow

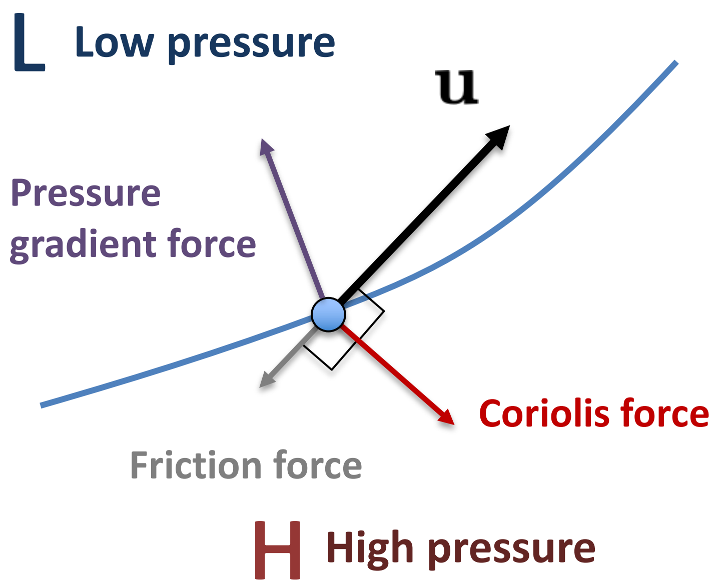


Figure: The balance of forces away from the equator (where Coriolis is relevant) and near the surface (where friction is important).

Subgeostrophic Flow

$$\frac{1}{\rho}\nabla p = -f\mathbf{k}\times\mathbf{u} + \mathcal{F}$$

We can expand the velocity in terms of its **geostrophic** and **ageostrophic** components:

$$\mathbf{u} = \mathbf{u}_g + \mathbf{u}_{ag}$$

Then using the geostrophic wind relationship:

$$f\mathbf{k}\times\mathbf{u}_{ag} = \mathcal{F}$$

The ageostrophic component is always directed "to the right" of the frictional force (in the northern hemisphere).

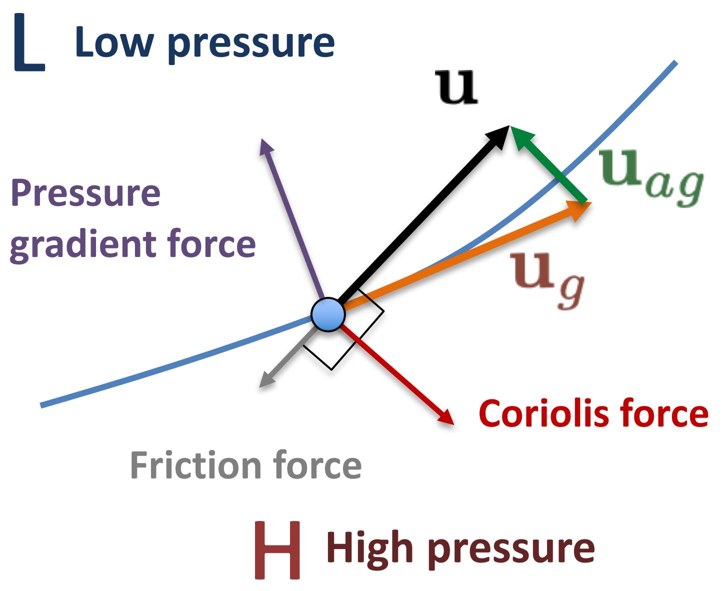
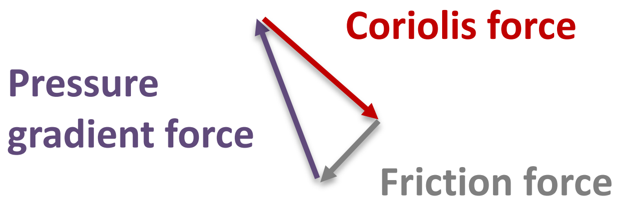


Figure: The balance of forces away from the equator (where Coriolis is relevant) and near the surface (where friction is important).

Subgeostrophic Flow

$$\frac{1}{\rho}\nabla p = -f\mathbf{k}\times\mathbf{u} + \mathcal{F}$$

The sum of the friction force and Coriolis force must balance the pressure gradient force.



This has the effect of directing fluid parcels slightly towards the low pressure system.

At the near-surface winds tend to converge towards low pressure regions.

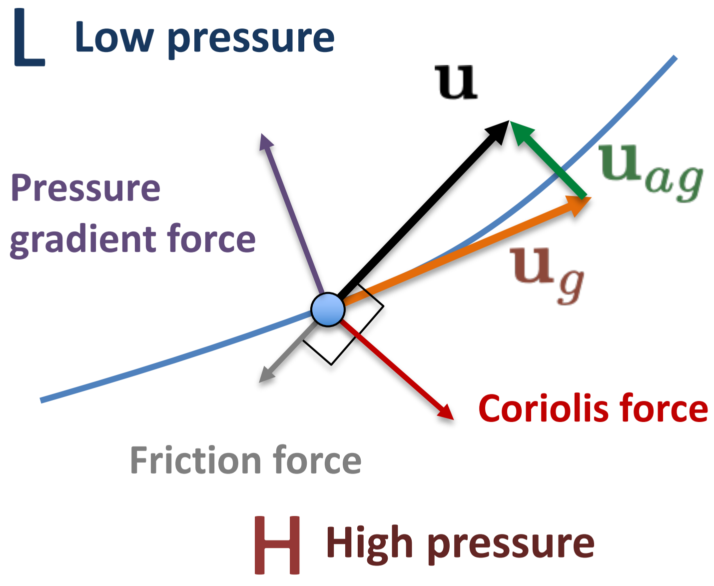


Figure: The balance of forces away from the equator (where Coriolis is relevant) and near the surface (where friction is important).

Subgeostrophic Flow

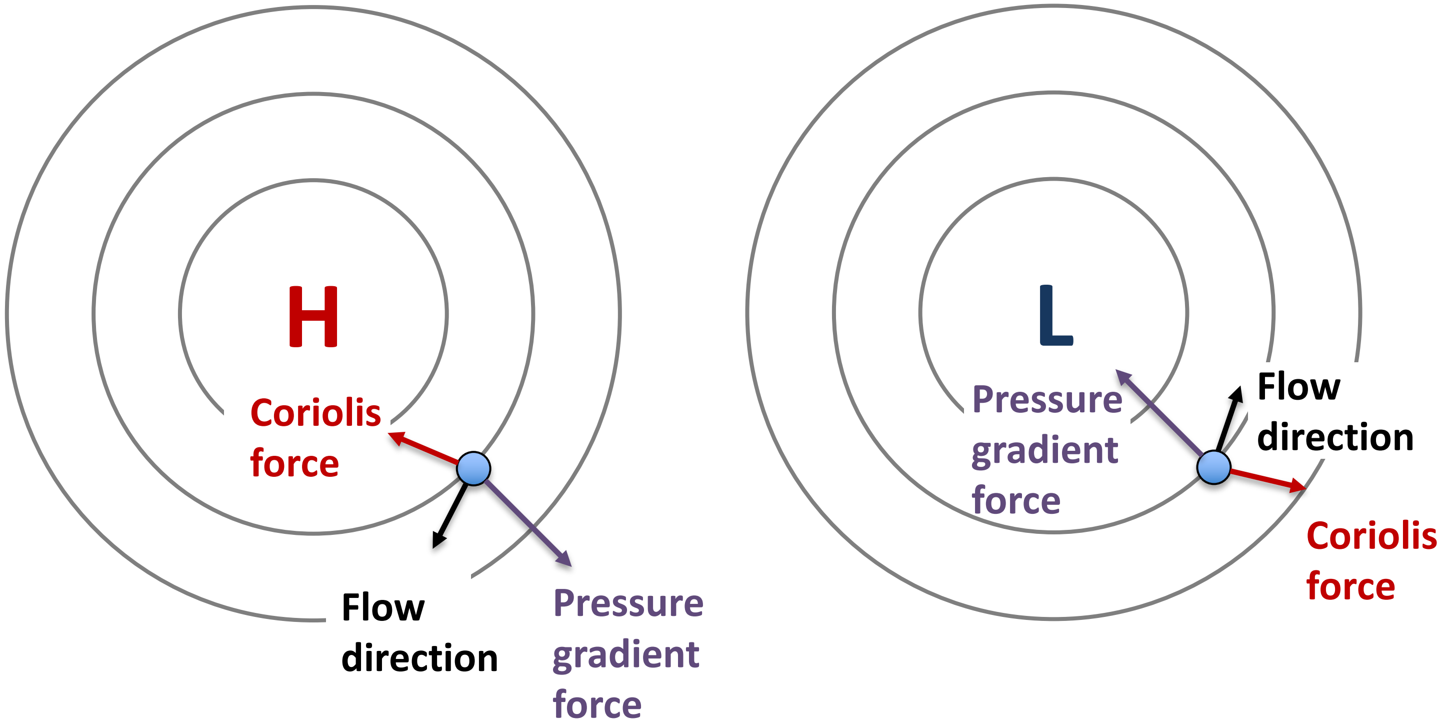


Figure: Ekman flow around (left) a surface high-pressure region and (right) a low-pressure region. Around the high the fluid "falls away from the center", but around the low it "falls toward the center".

Subgeostrophic Flow

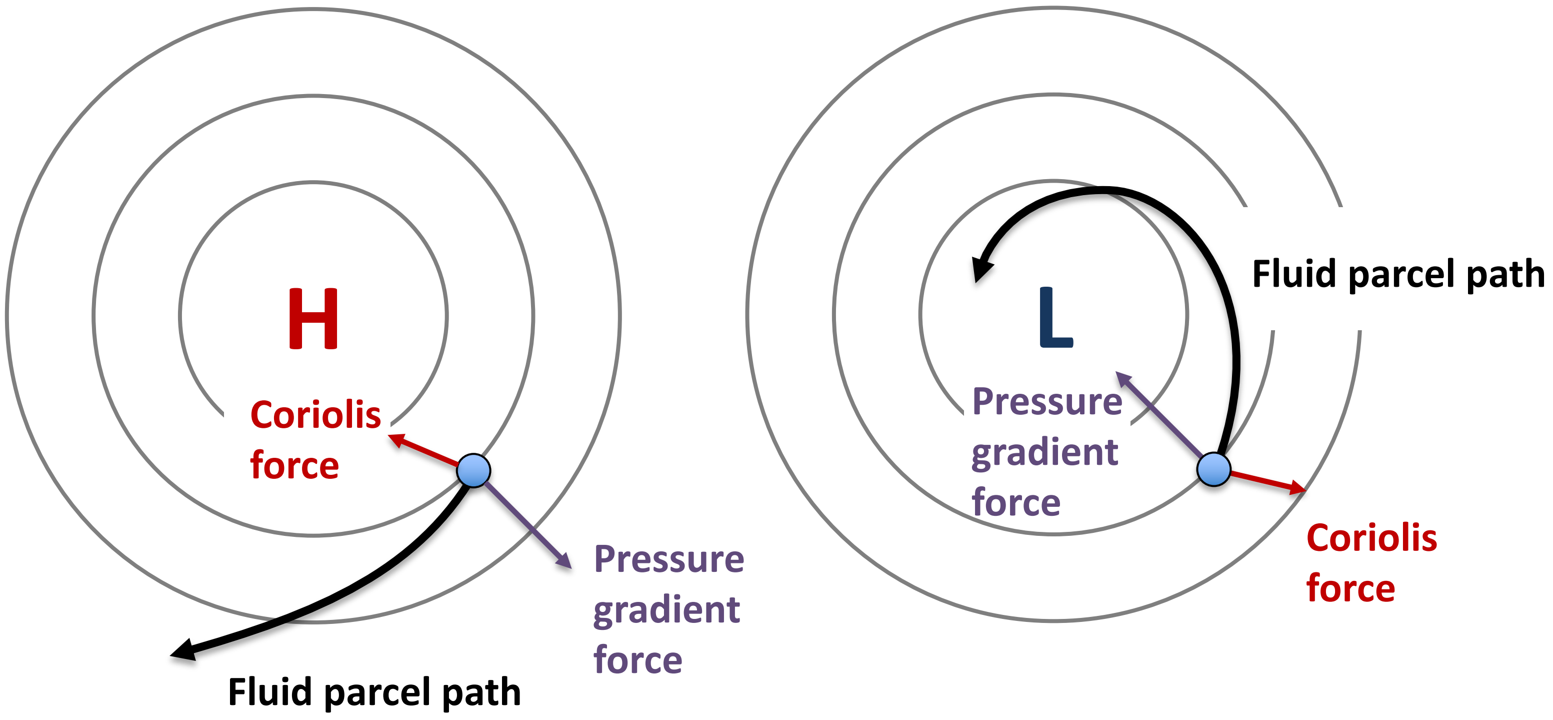
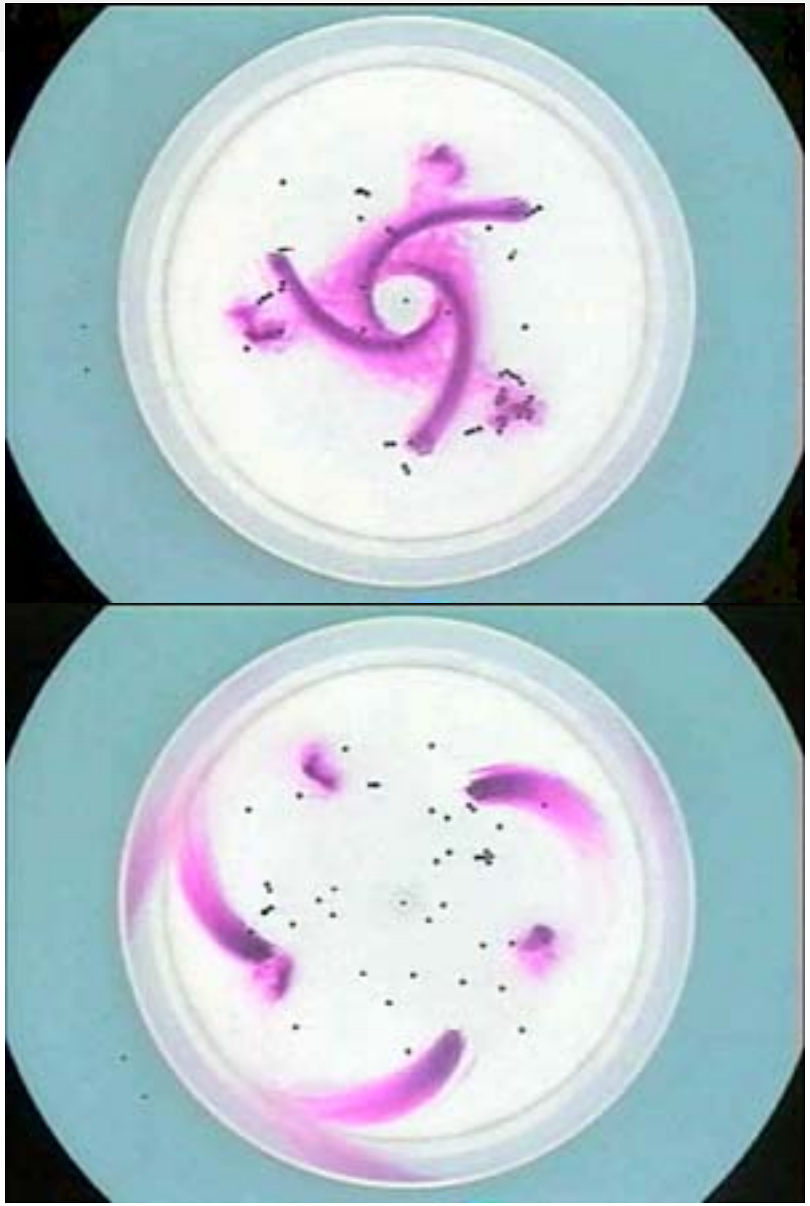


Figure: Ekman flow around (left) a surface high-pressure region and (right) a low-pressure region. Around the high the fluid "falls away from the center", but around the low it "falls toward the center".

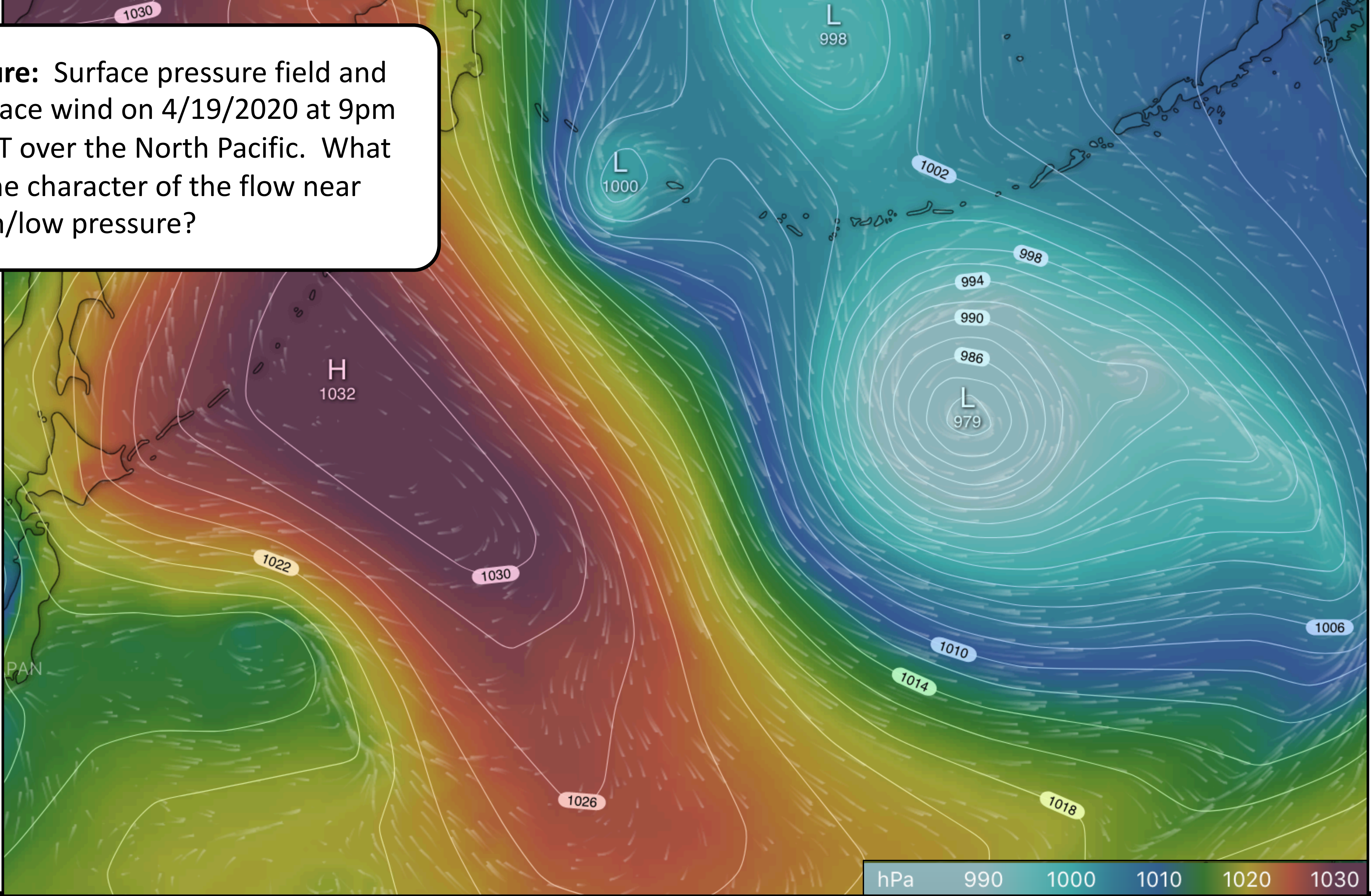
Subgeostrophic Flow

Figure: Ekman transport for a central low-pressure (top) and a central high-pressure (bottom). In the top image the fluid "falls into the center", whereas in the lower image the fluid "falls away from the center."



http://weathertank.mit.edu/links/projects/ekman-layers-introduction/ekman-layers-tank-examples

Figure: Surface pressure field and surface wind on 4/19/2020 at 9pm GMT over the North Pacific. What is the character of the flow near high/low pressure?



source: windy.com

Subgeostrophic Flow

Velocity is expanded in terms of its **geostrophic** and **ageostrophic** components:

$$\mathbf{u} = \mathbf{u}_g + \mathbf{u}_{ag}$$

Under typical atmospheric conditions ageostrophic flow in the boundary layer has about 10% of the magnitude of the geostrophic flow:

$$|\mathbf{u}_{ag}| \approx 0.1 \times |\mathbf{u}_g|$$

Ageostrophic flow is strongest over land (where drag is large) and at low latitudes where flow departs from being in geostrophic balance (f small)

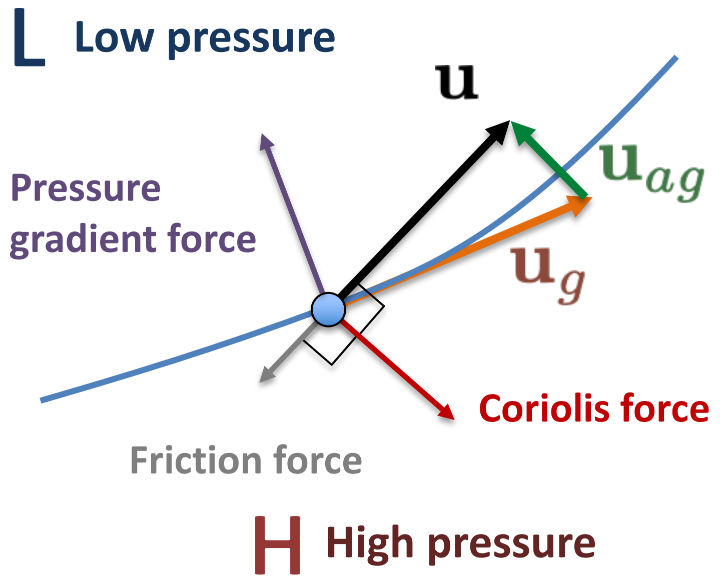


Figure: The balance of forces away from the equator (where Coriolis is relevant) and near the surface (where friction is important).

Ekman Layers: Vertical Motion

Recall that geostrophic flow is non-divergent on pressure surfaces:

$$\nabla_p \cdot \mathbf{u}_g = \frac{\partial}{\partial x}\left[-\frac{1}{f}\left(\frac{\partial \Phi}{\partial y}\right)_p\right] + \frac{\partial}{\partial y}\left[\frac{1}{f}\left(\frac{\partial \Phi}{\partial x}\right)_p\right]$$

$$= -\frac{1}{f}\left(\frac{\partial^2 \Phi}{\partial x \partial y}\right)_p + \frac{1}{f}\left(\frac{\partial^2 \Phi}{\partial y \partial x}\right)_p$$

$$= 0$$

However, ageostrophic flow does lead to horizontal divergence.

Horizontal divergence on pressure surfaces

$$\nabla_p \cdot \mathbf{u}_{ag} \neq 0$$

Using the continuity equation in pressure coordinates:

$$\nabla_p \cdot \mathbf{u} + \frac{\partial \omega}{\partial p} = 0$$

$$\mathbf{u} = \mathbf{u}_g + \mathbf{u}_{ag}$$

$$\nabla_p \cdot \mathbf{u}_g = 0$$

$$\nabla_p \cdot \mathbf{u}_{ag} + \frac{\partial \omega}{\partial p} = 0$$

Ekman Layers: Vertical Motion

$$\frac{\partial \omega}{\partial p} = -\nabla_p \cdot \mathbf{u}_{ag}$$

Hence ageostrophic motion is responsible for inducing vertical velocities.

Question: What are the implications for surface lows?

Question: What are the implications for surface highs?

$$\frac{Dp}{Dt} = \omega > 0, \quad \text{sinking motion,}$$
$$\frac{Dp}{Dt} = \omega < 0, \quad \text{rising motion.}$$

$$\frac{\partial \omega}{\partial p} \sim \frac{\partial w}{\partial z}$$

These two terms have the same sign since

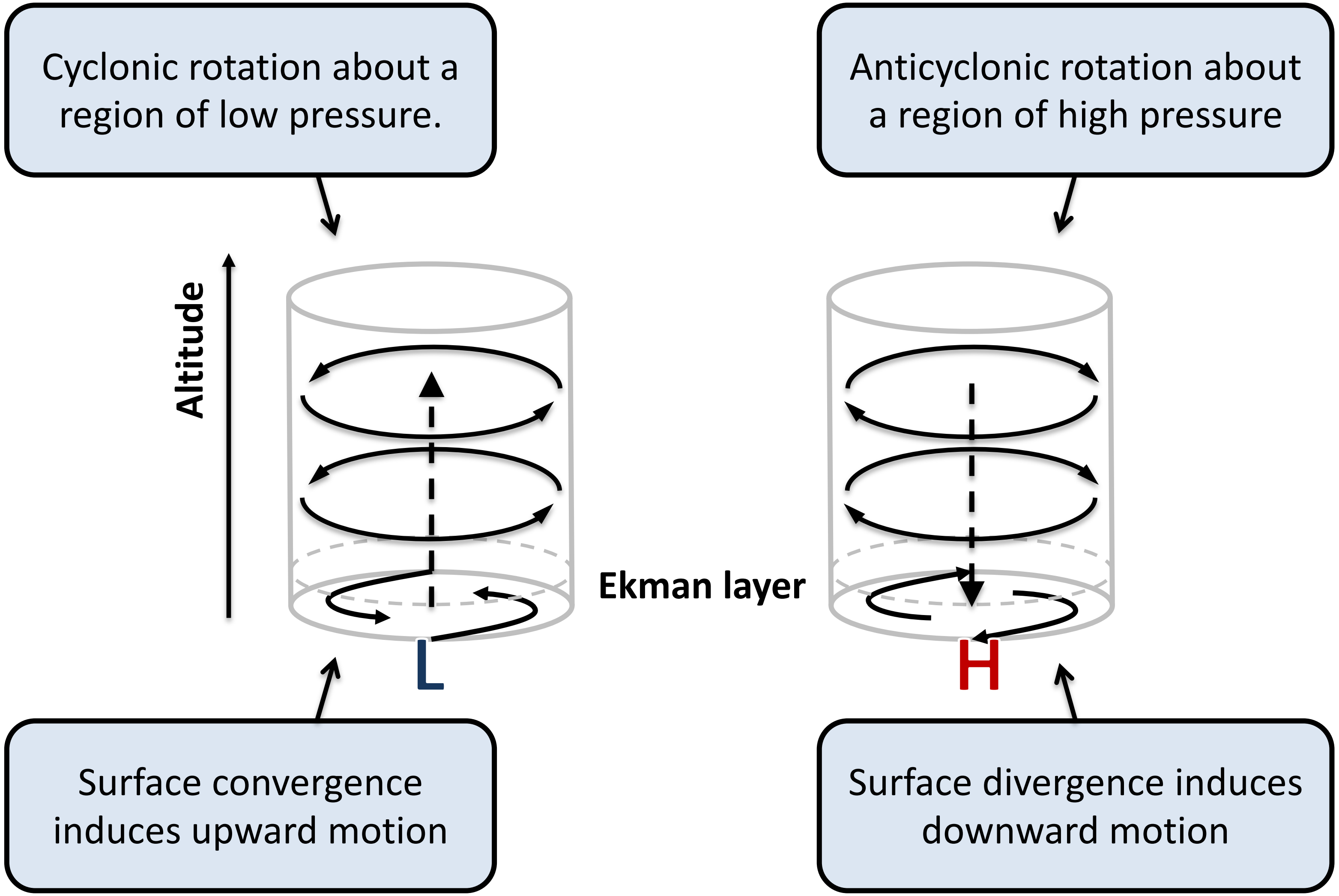
$$p \sim -z$$
$$\omega \sim -w$$

Ekman Layers: Vertical Motion

$$\frac{\partial \omega}{\partial p} = -\nabla_p \cdot \mathbf{u}_{ag}$$

Hence ageostrophic motion is responsible for inducing vertical velocities.

Figure: Schematic diagram showing the direction of frictionally induced ageostrophic flow and induced vertical motion.



Ekman Layers: Vertical Motion

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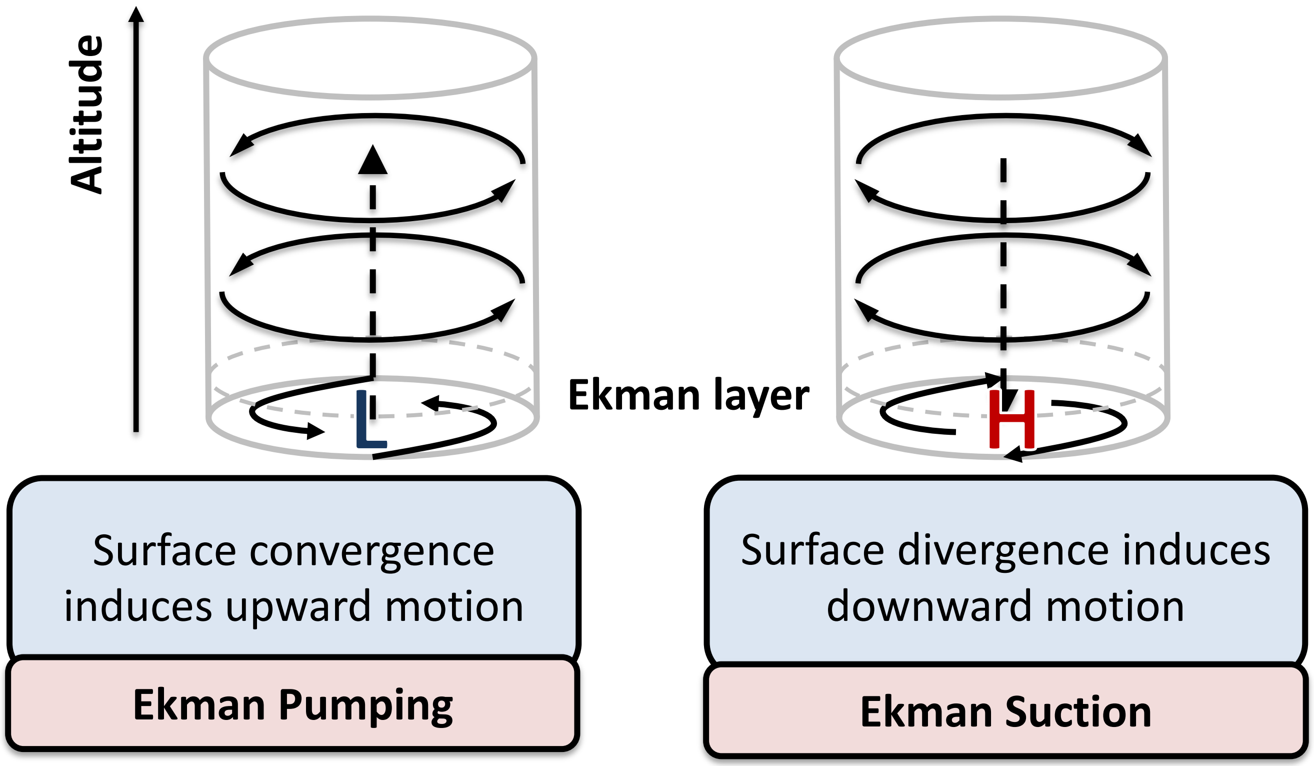
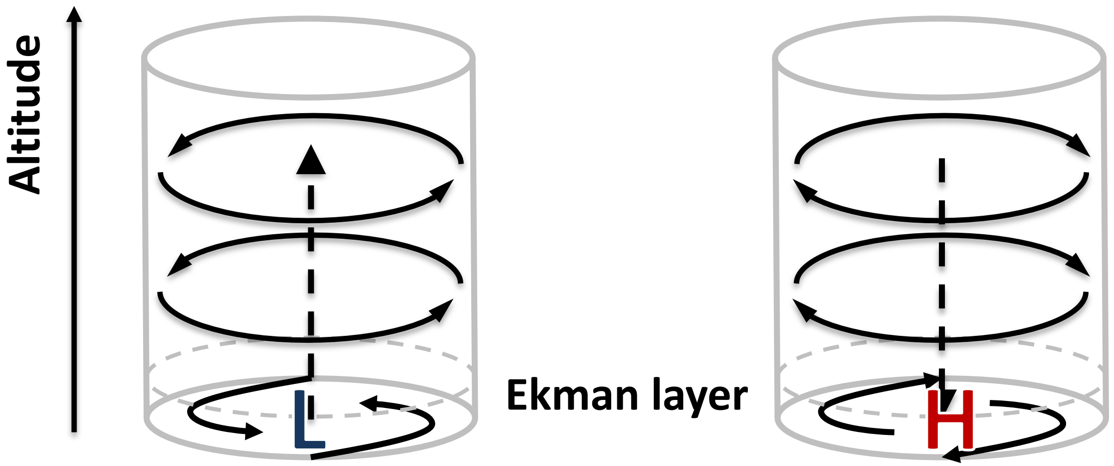


Definition: In the atmosphere, **Ekman pumping**, associated with low surface pressure, is upward motion associated with near-surface convergence. On the other hand, **Ekman suction**, associated with high surface pressure, is downward motion associated with near-surface divergence.

Ekman Layers: Vertical Motion

Figure: Schematic diagram showing the direction of frictionally induced ageostrophic flow and induced vertical motion.



Surface convergence induces upward motion	Surface divergence induces downward motion
Ekman Pumping	**Ekman Suction**

Ekman Pumping
- Cooling of air parcels on ascent and possible condensation
- Cloudy conditions
- Enhanced precipitation

Ekman Suction
- Warming of air parcels in accordance with dry adiabatic lapse rate
- Clear skies
- Suppressed precipitation

Global Mean Sea Level Pressure

Polar highs (subsidence)

Midlatitudinal lows (lifting)

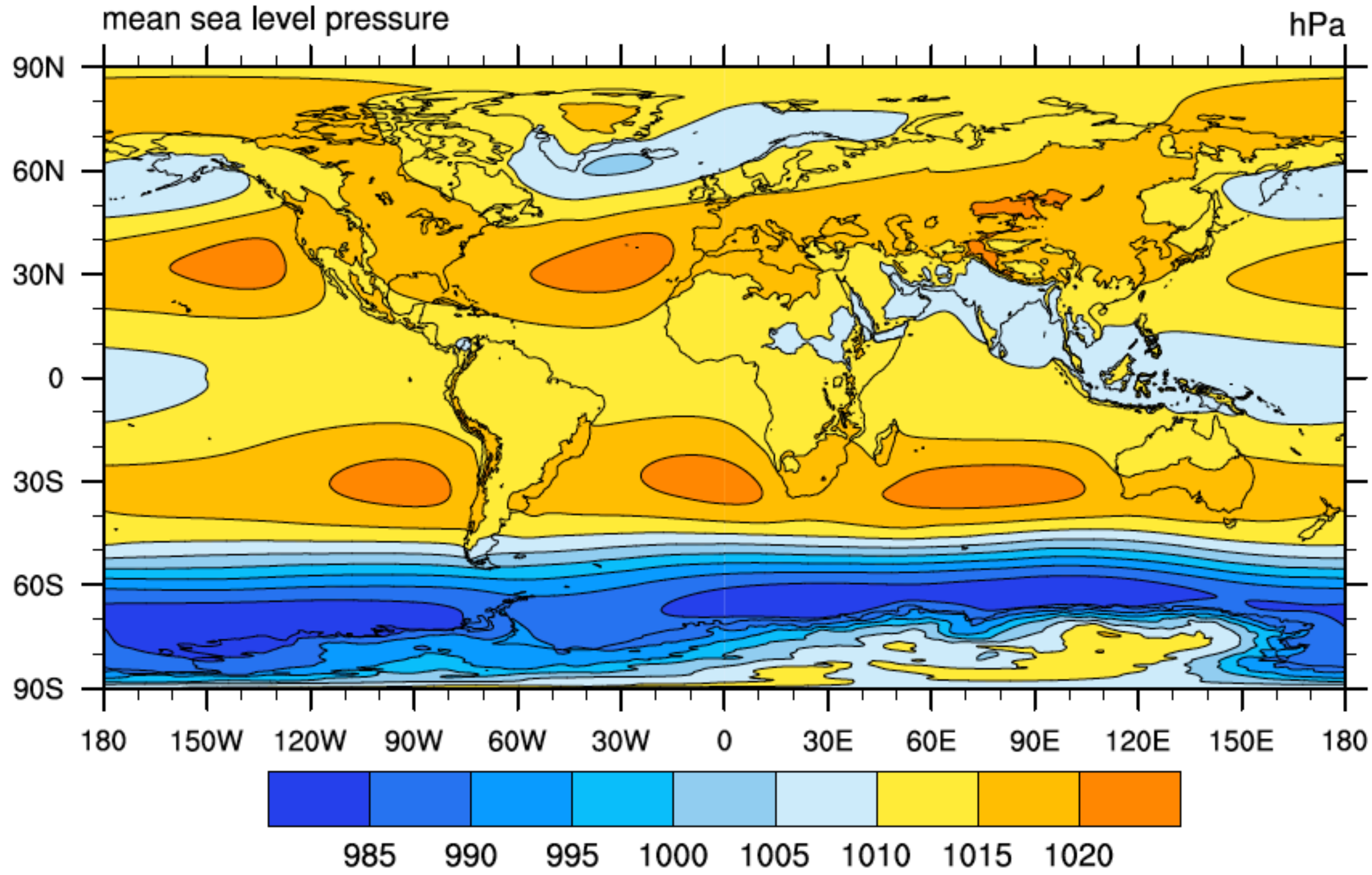
Subtropical highs (subsidence)

Equatorial lows (lifting)

Subtropical highs (subsidence)

Midlatitudinal lows (lifting)

Polar highs (subsidence)



Consequences of Near Surface Flow

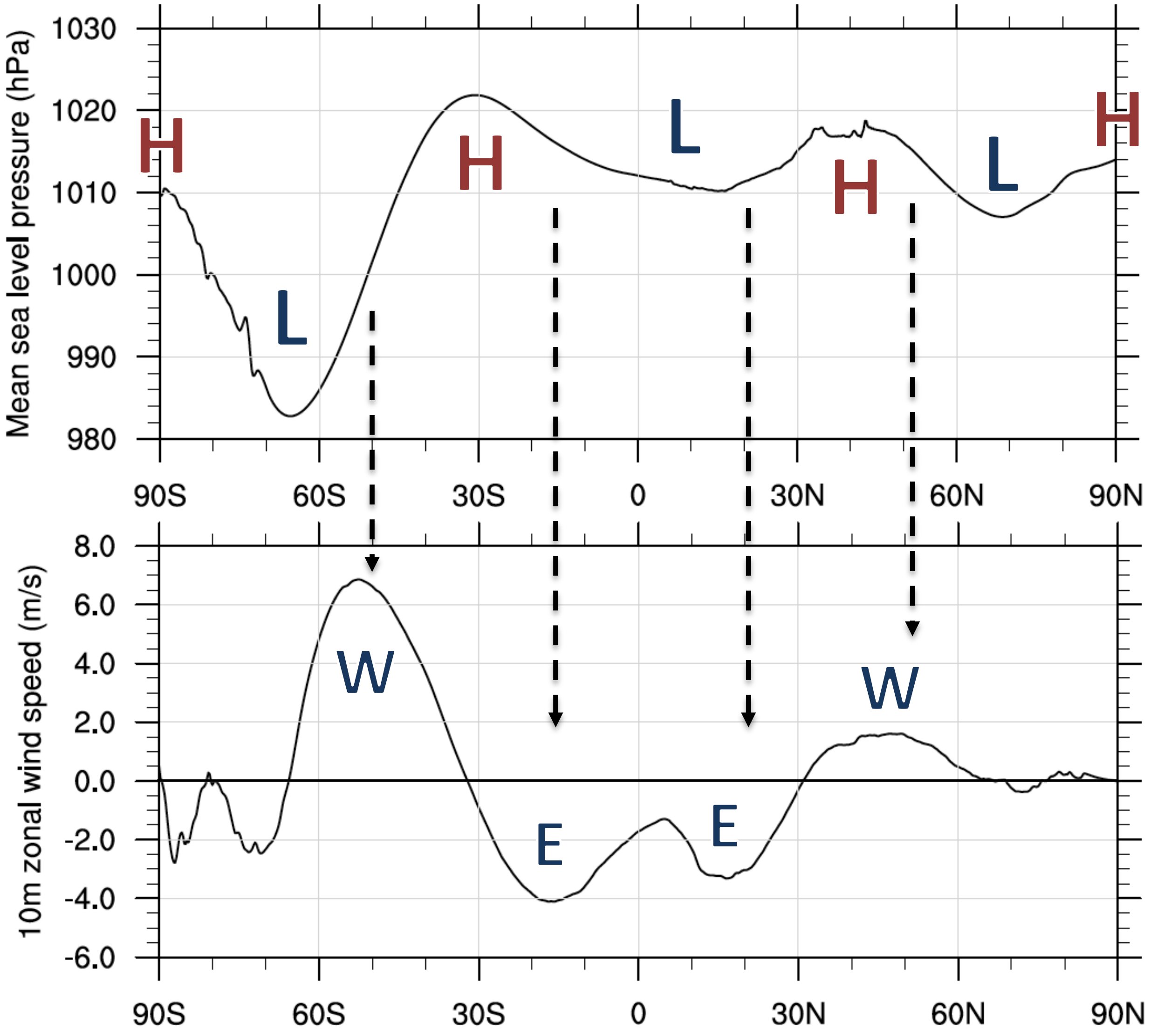


Figure: To a first approximation, surface winds are in geostrophic balance with the pressure field.

$$u_g = -\frac{1}{f\rho}\frac{\partial p}{\partial y}$$

Outside the atmospheric boundary layer, ageostrophic winds are approximately an order of magnitude less than geostrophic winds.

Consequences of Near Surface Flow

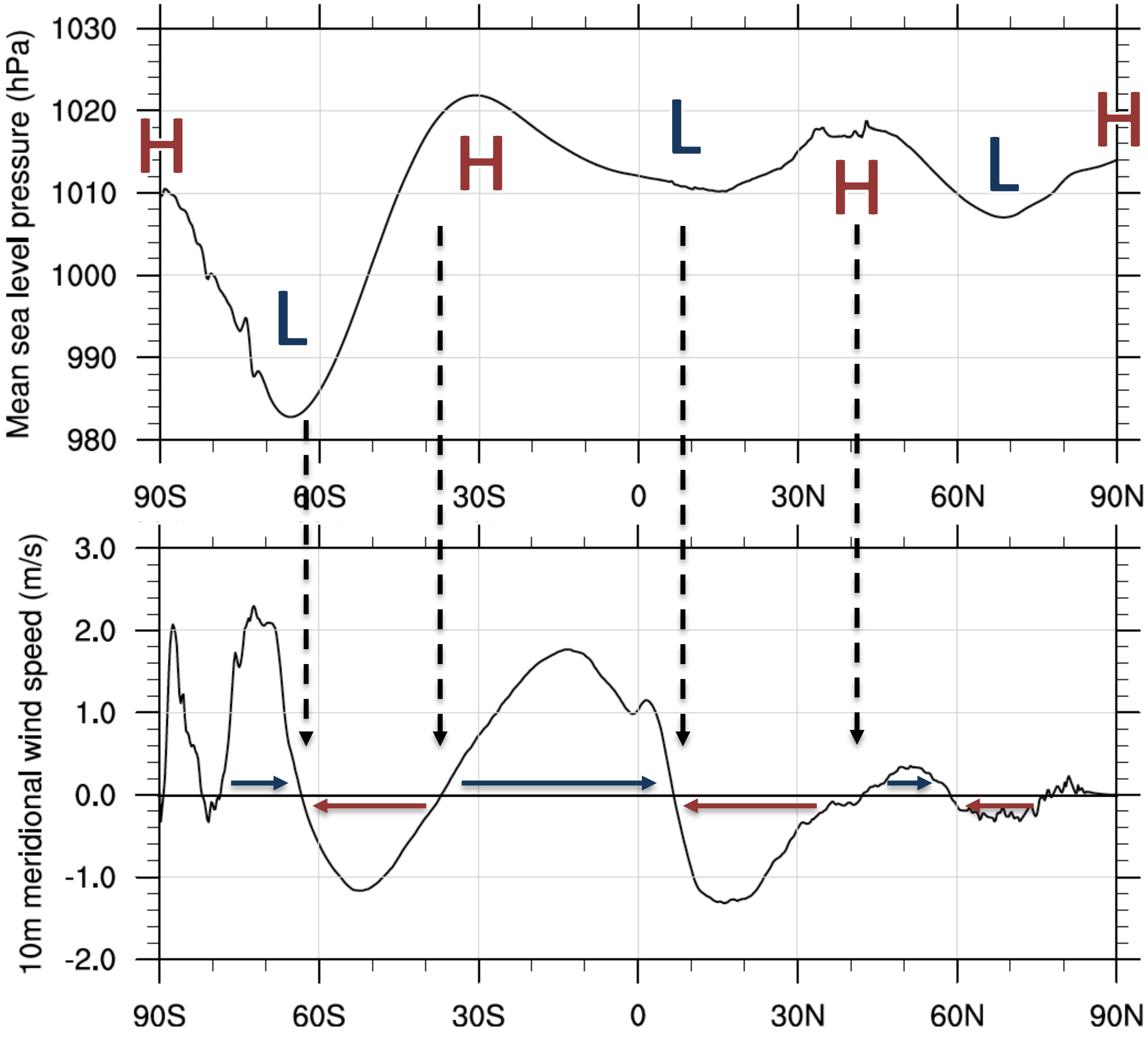


Figure: Near the surface, the pressure gradient leads to an ageostrophic velocity component which is convergent at the equator and divergent at 30N/30S.

ATM 241 Climate Dynamics
Lecture 6
Near-Surface Flow

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Thank You!