# Atmospheric Circulation

Introductory Oceanography

Instructor: Ray Rector

# Atmospheric Circulation

## Key Topics

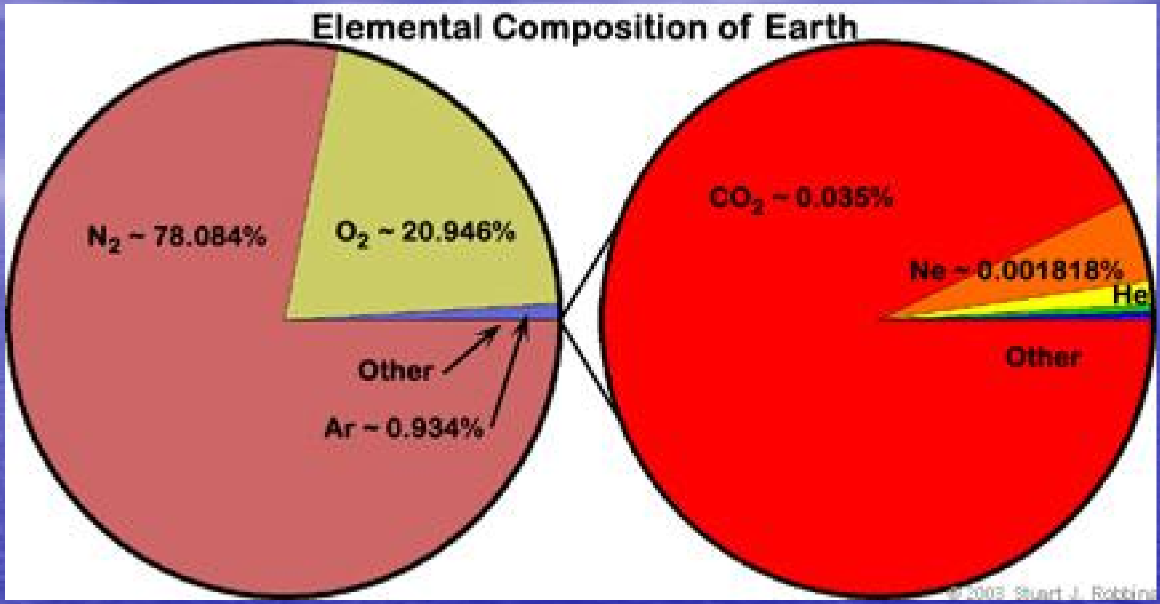
- Composition and Structure
- Solar Heating and Convection
- The Coriolis Effect
- Global Wind Patterns
- Storm Systems
- Climate Patterns
- Effects on Ocean

# Atmospheric Circulation

## Key Concepts

- Earth's atmosphere is stratified and consists mostly of $N_2$ and $O_2$
- Differential heating of Earth's curved surface by incoming solar radiation produces an over-heated equator and under-heated poles
- Heating and cooling creates regions of low and high atmospheric pressure, respectively.  Coupled with gravity, this drives atmospheric convection, i.e. global-scale, circulation system of winds
- The Earth has three major atmospheric circulation cells in each hemisphere – a total of six around the planet
- Earth's rotation causes moving air masses to curve – **left** in the northern hemisphere and **right** in the southern hemisphere; this is called the **Coriolis Effect**
- Atmospheric circulation is responsible for the transfer of **2/3rds** of Earth's surface heat from the equator to the poles
- Spinning storm systems are of two types: Tropical and Extra-tropical
- Circulation of atmosphere and ocean moderates Earth's surface temperatures, and shapes weather and climate
- Surface winds and storms generate ocean currents and wind waves

# Atmosphere Composition




**Proportion of Gases in the Atmosphere**

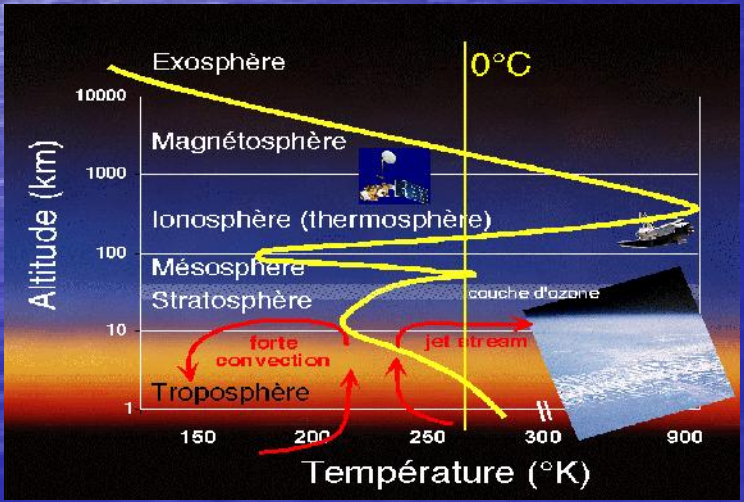
## Key Ideas

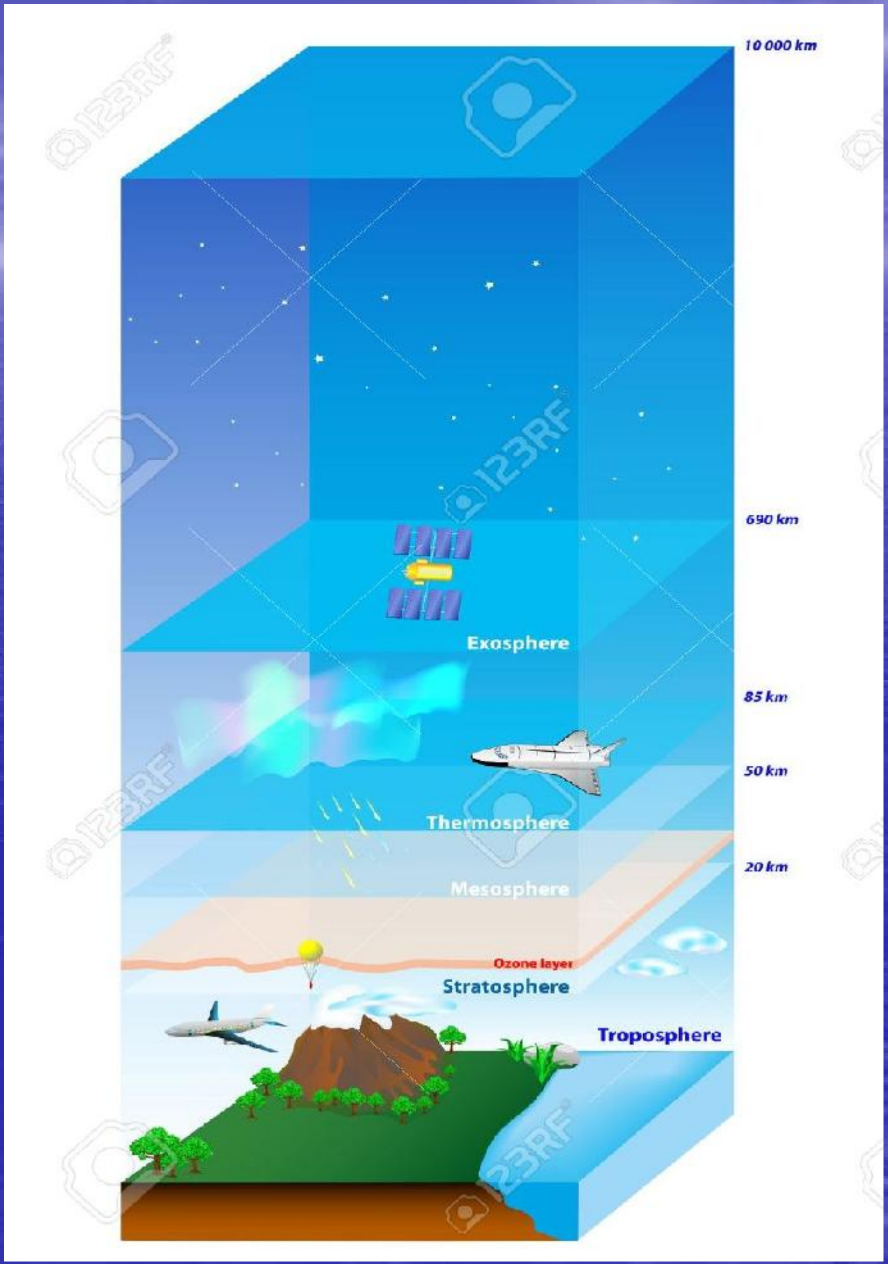
- ✓**Mostly consist of nitrogen (78%), oxygen (21%) and argon (1%)**
- ✓**Water vapor and carbon dioxide important minor components**
- ✓**Water vapor can be as high 4% by volume**
- ✓**Air has mass: 1 sq. foot column of the vertical atmosphere weighs 1 ton**

# Vertical Structure of Atmosphere

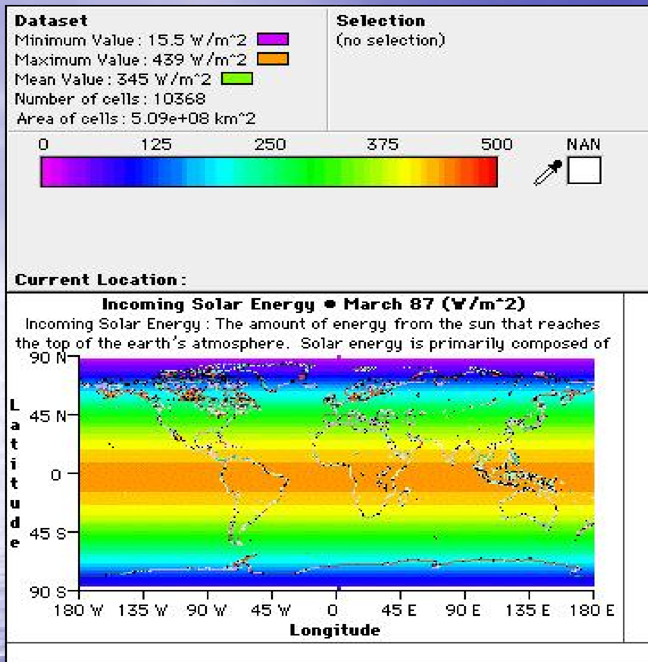
## Key Ideas

- Density-stratified air column
- Most of air found in troposphere
- Weather occurs in troposphere
- Jet stream at top of troposphere
- Ozone found in stratosphere
- Temperature inversions at the layer boundaries

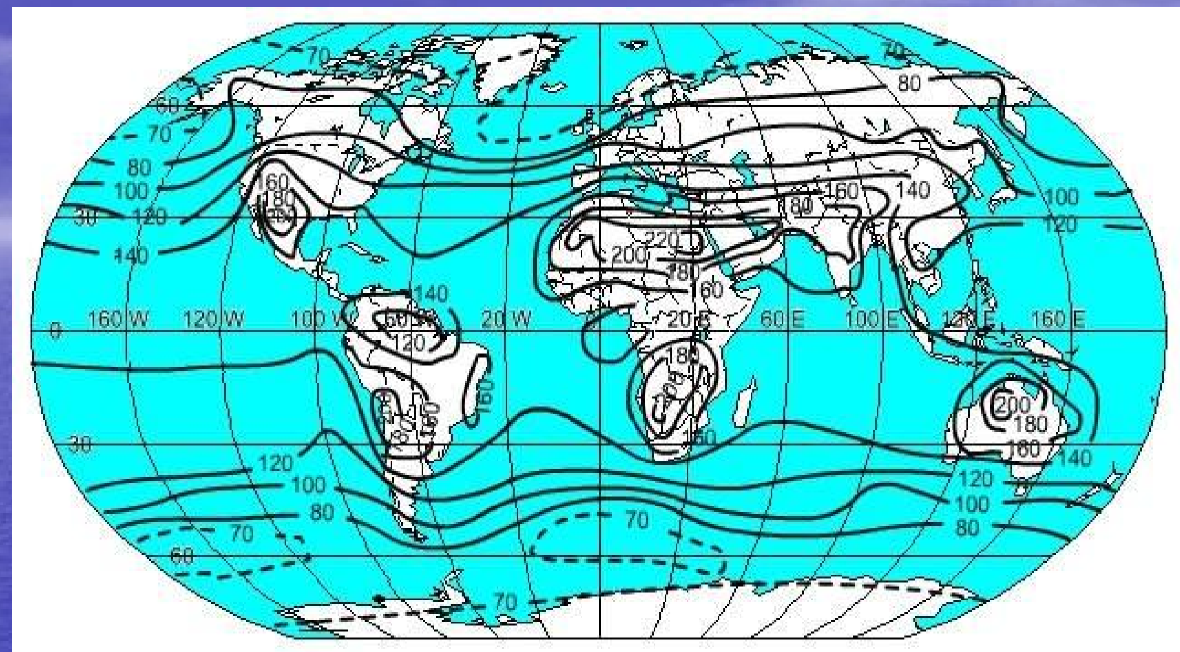


# Annual Solar Energy Striking Earth




Incoming Solar Radiation at Top of Earth's Atmosphere

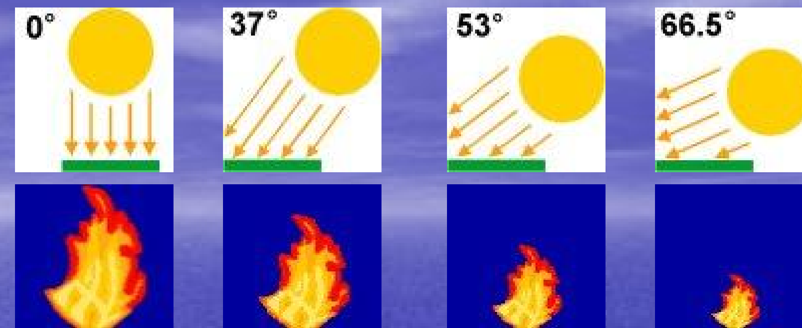


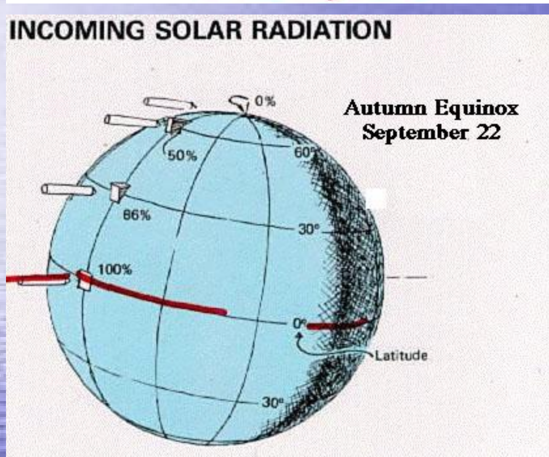

Annual Solar Radiation at Earth's Surface (kcal/cm2/year)

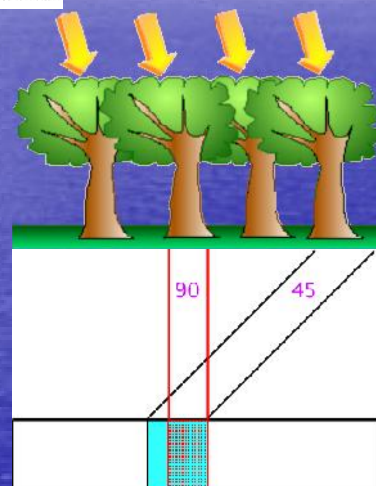
## Key Idea:

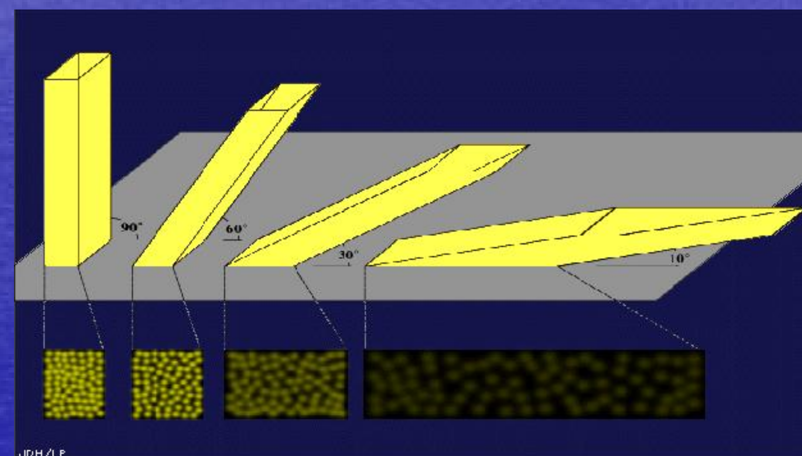
- Global variation in the amount of solar energy striking Earth's surface is controlled by the *latitude*, *season*, *atmospheric conditions*, and *altitude*.

# Differential Heating of Earth's Surface

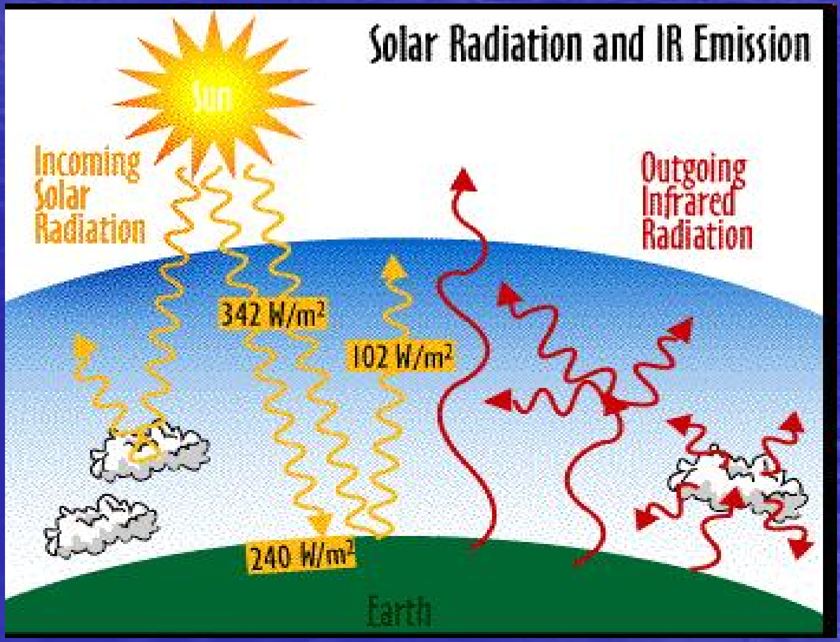

## Key Idea

- **Insolation** is incoming solar radiation. The amount of insolation received at the surface of the earth is primarily controlled by the **sun angle.** Sun angle is a function of latitude and season.

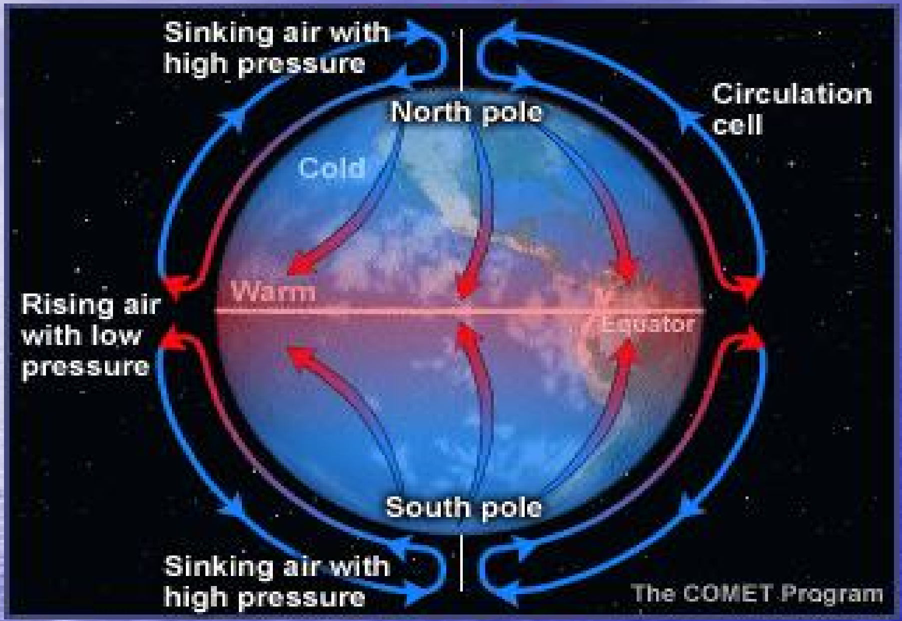
# Atmospheric Conditions Affect Amount of Sunlight Striking Earth's Surface

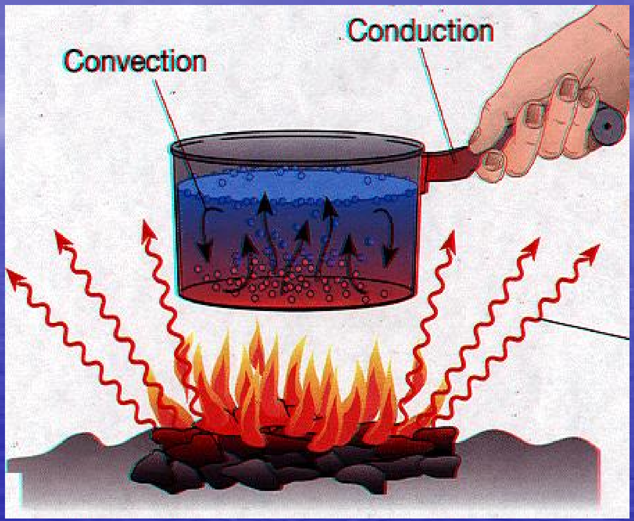
## Key Idea

- The amount of sun energy received at the surface of the earth can also be affected by cloud cover, dust, and other particulates that reflect and/or absorb incoming sunlight
- Sea surfaces are typically much more prone to cloud cover than land surfaces.



# Uneven Solar Heating of Earth's Surface Causes Global-Scale Atmospheric Convection



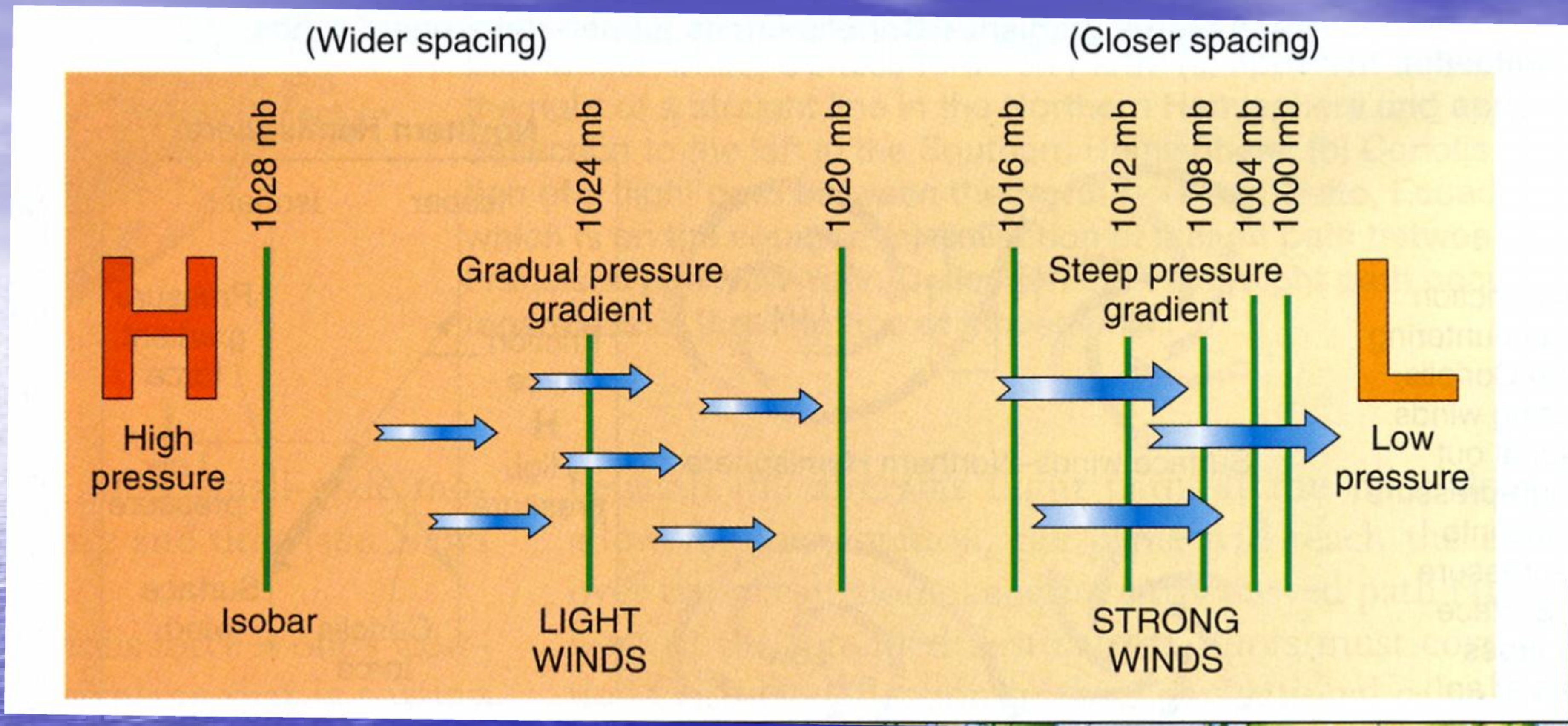




**Human-Scale Convection Process**

## Global-Scale Convection Process

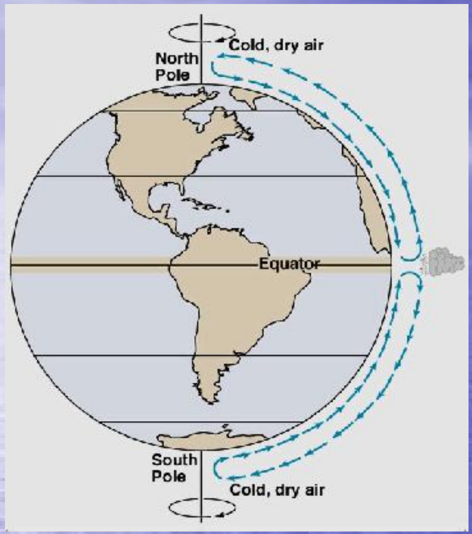
- ✓ Heat difference causes pressure differences in the overlying atmosphere
- ✓ Overheating of equatorial regions forms belt of low pressure
- ✓ Under-heating of polar regions creates centers of high pressure
- ✓ Pressure differences in lower atmosphere cause air masses to moves
- ✓ Air masses move from regions of high pressure to regions of low pressure

# Pressure Gradients Causes Wind to Blow



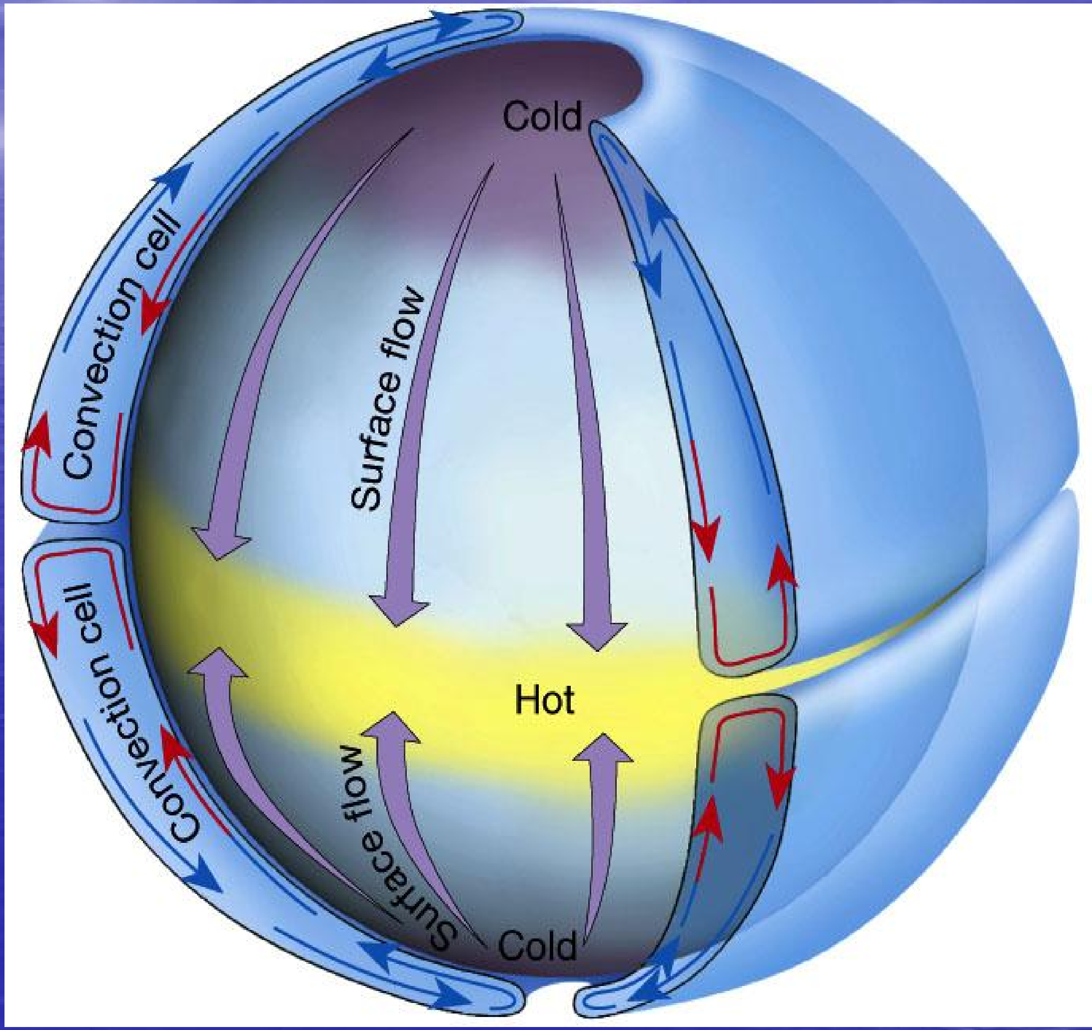

1) Air masses move from regions of high pressure to regions of low pressure
2) Severity of pressure gradient between adjacent regions of high and lows controls how strong of wind will blow between the high and low

# Atmospheric Circulation Model of a *Non-Spinning* Earth



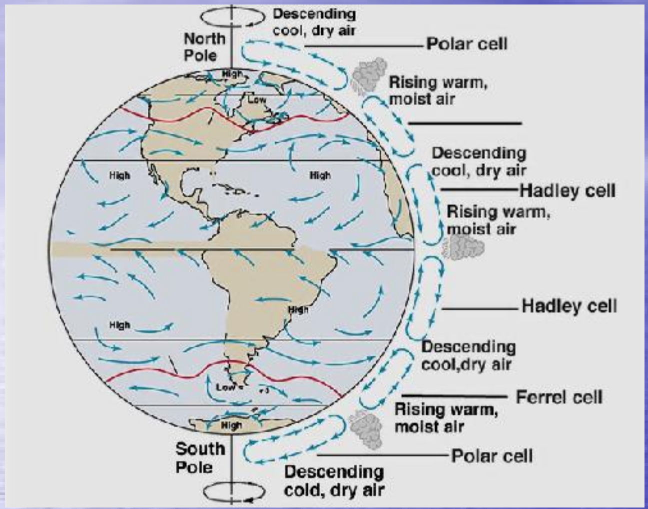

## Key Ideas

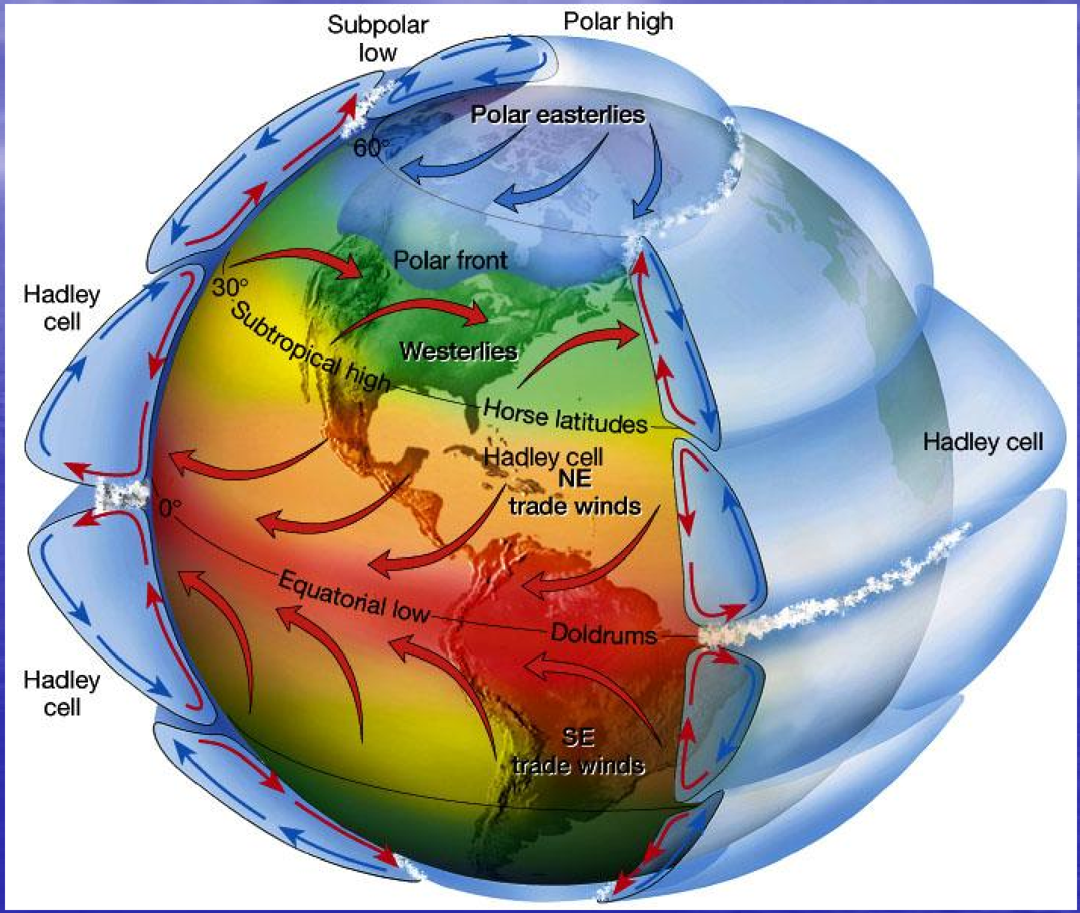
- ✓ One cell per hemisphere
- ✓ Overheated equatorial air rises and moves horizontally aloft toward the poles
- ✓ Overcooled polar air sinks and moves horizontally at surface towards equator




Single-Cell Hemispheric Convection Model

# Atmospheric Circulation Model of a *Spinning* Earth




## Key Ideas

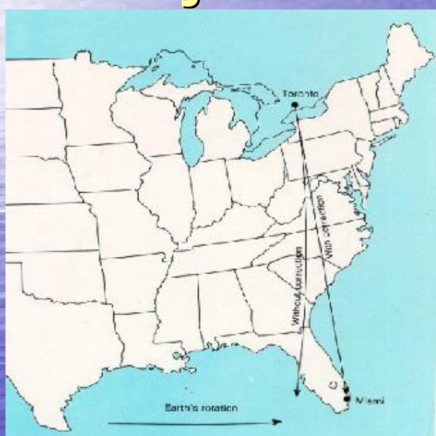
- ✓ Three cells per hemisphere
  - **Hadley, Ferrel, and Polar**
- ✓ Similar convection process
- ✓ Smaller convective cells
- ✓ Two surface convergence zones
- ✓ Two surface divergence zones

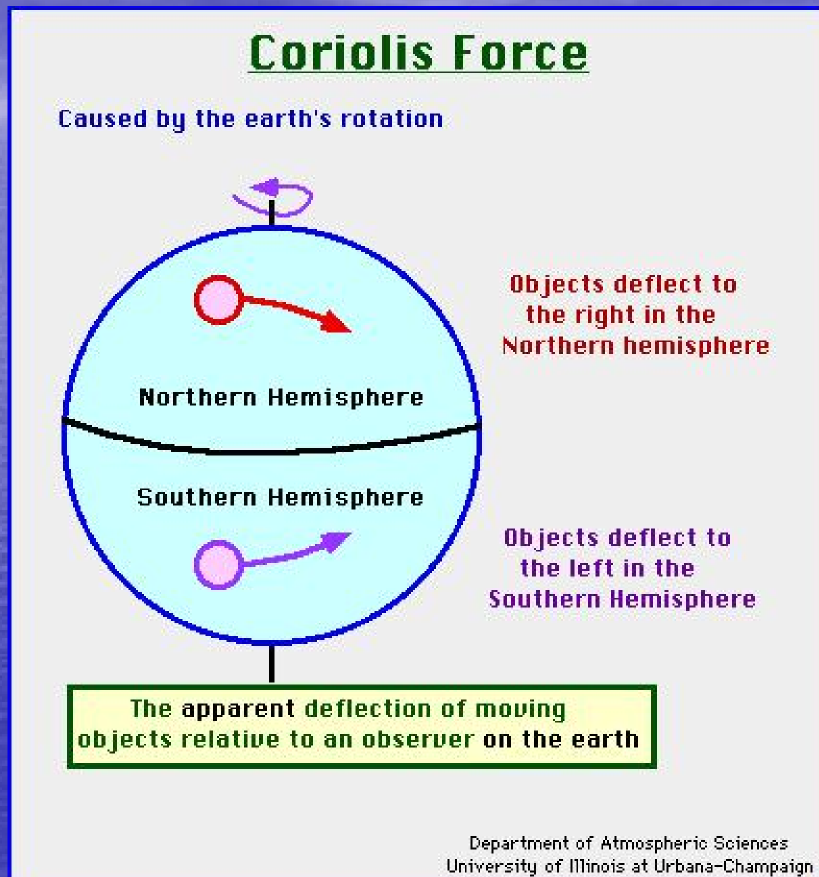
**Triple-Cell Hemispheric Convection Model**

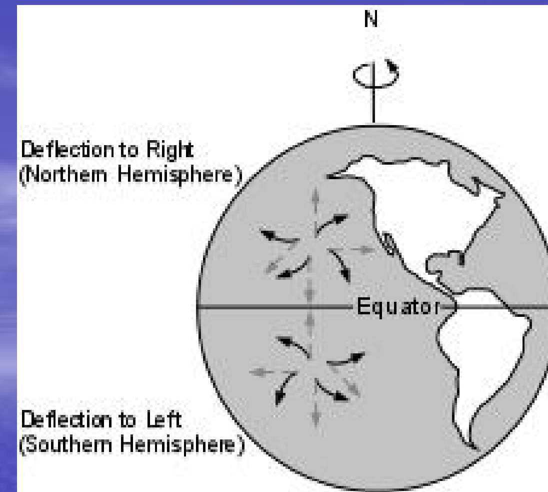
- ✓ Spinning causes the Coriolis effect
- ✓ Coriolis effect deflects air currents

# The Coriolis Effect

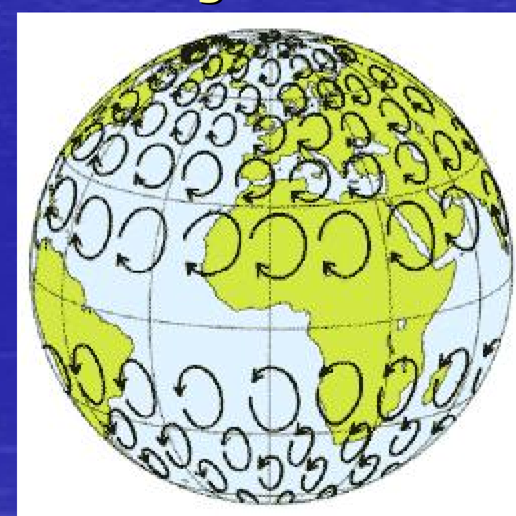

**Deflection of Flying Projectiles**



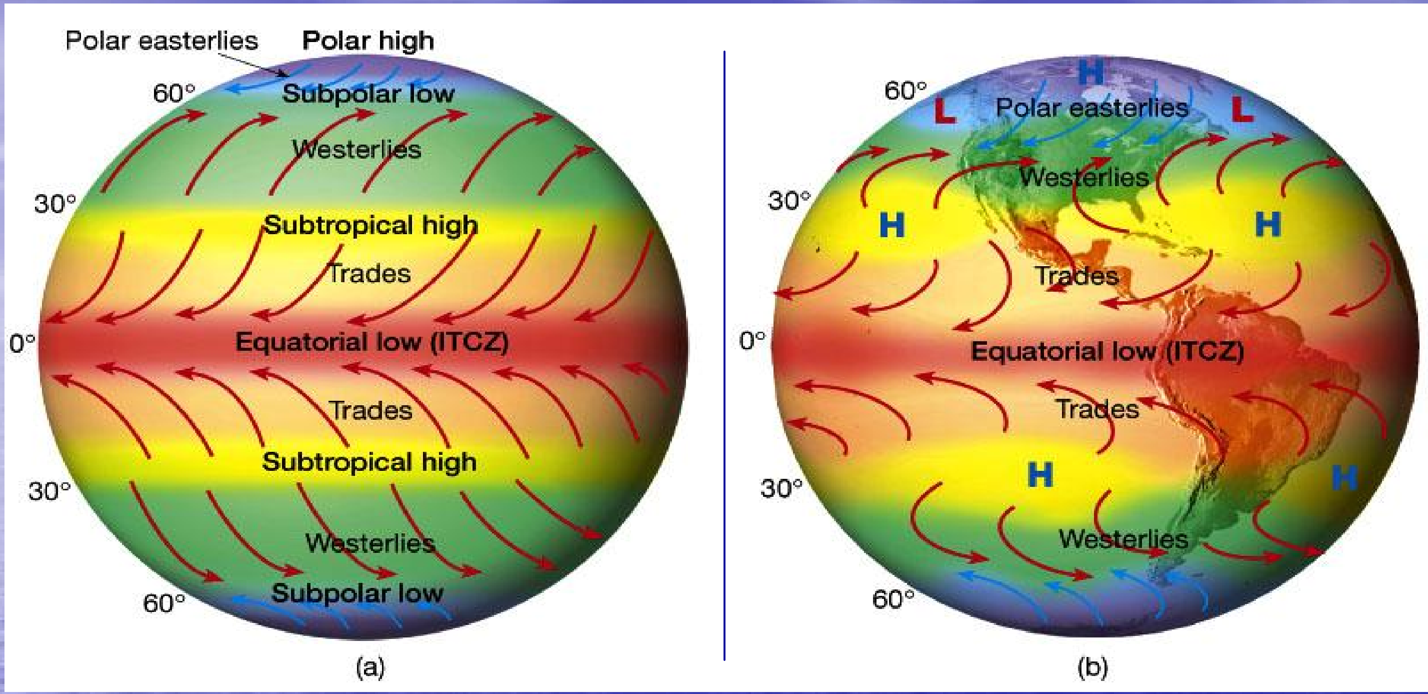

**Deflection of Moving Air Masses**



## Key Ideas

- ✓ Objects deflect to the right in Northern Hemisphere
- ✓ Objects deflect to the left in Southern Hemisphere
- ✓ Moving air masses appear to have curved paths

# Earth’s Surface Winds



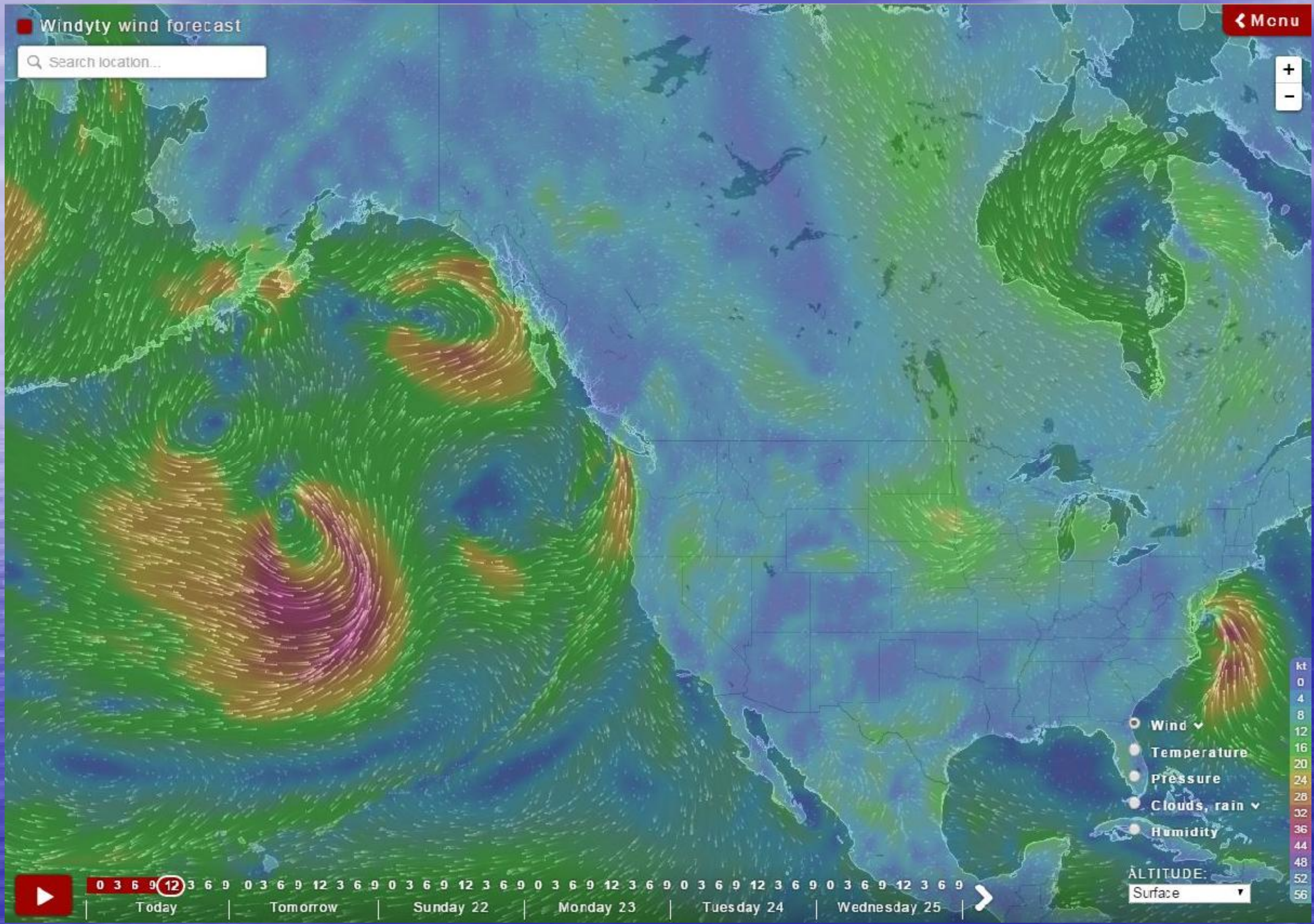

## *Land-free* Circulation Model

1) Polar Easterly belts
2) Mid-latitude Westerly belts
3) Low-latitude Tradewind belts
4) Subpolar low and equatorial low pressure belts
5) Subtropical high pressure belt

## *Landmass* Circulation Model

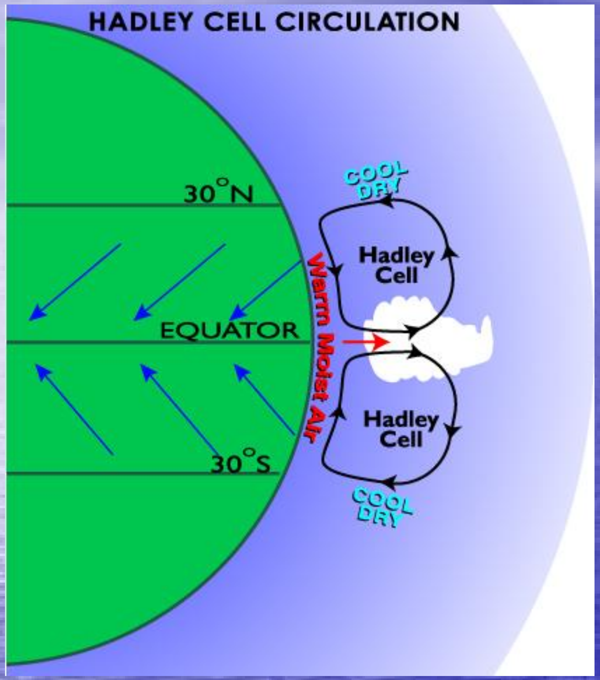
1) Landmasses break up the wind and pressure belts
2) High to mid-latitude pressure centers replace pressure belts
3) Equatorial low pressure belt
4) Seasonal shift of pressure centers

# Real-Time Global Surface Conditions Map

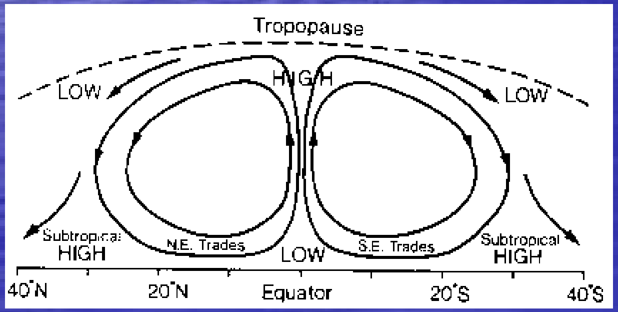


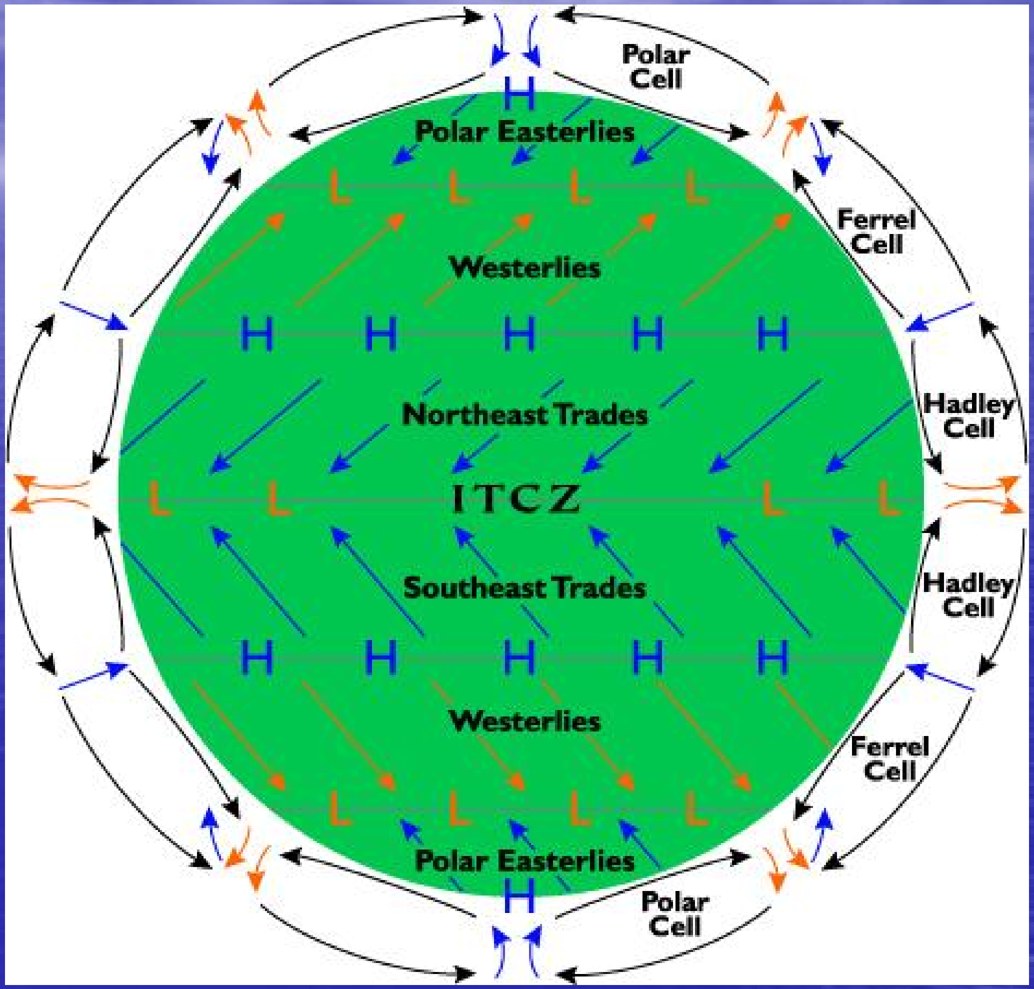

www.windyty.com

# Convergence and Divergence Zones




Equatorial Convergence




**Convergence = Orange L's**

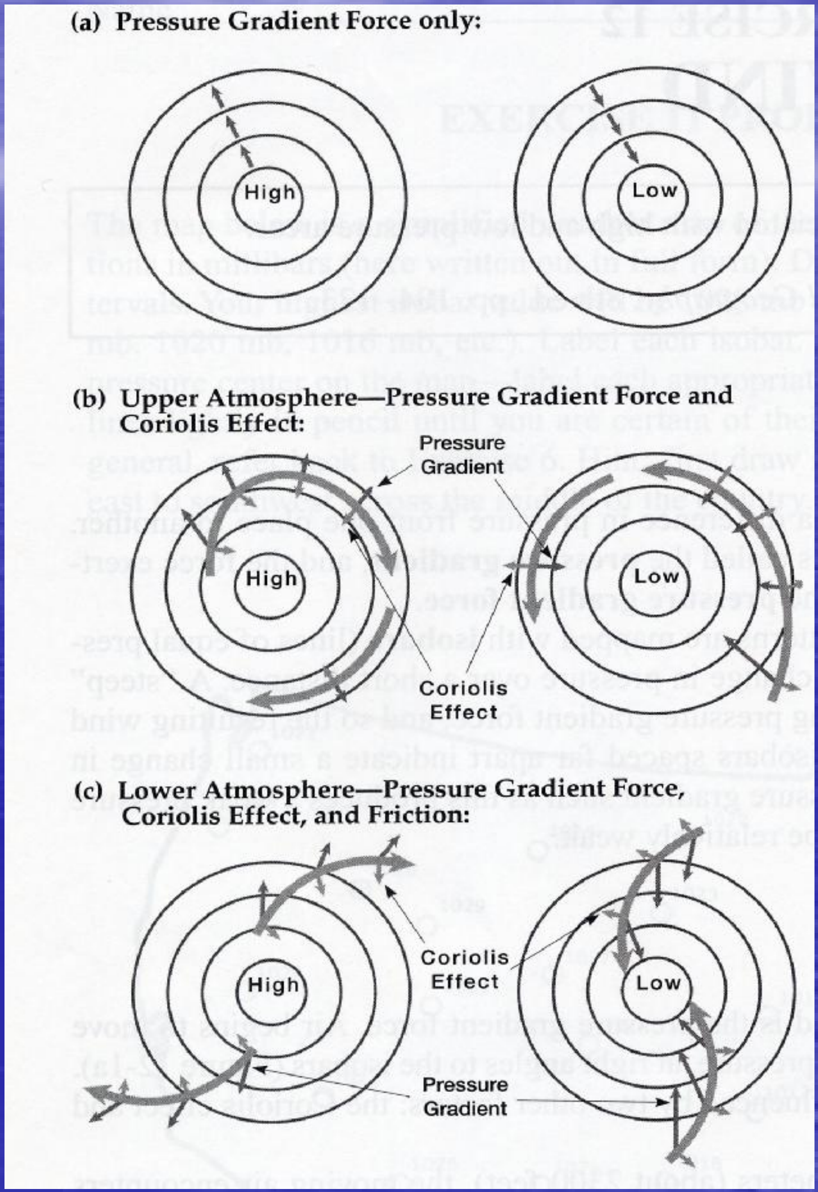
**Divergence = Blue H's**

# High - Low Air Pressure Gradients, Wind, the Coriolis Effect, and Ground Friction

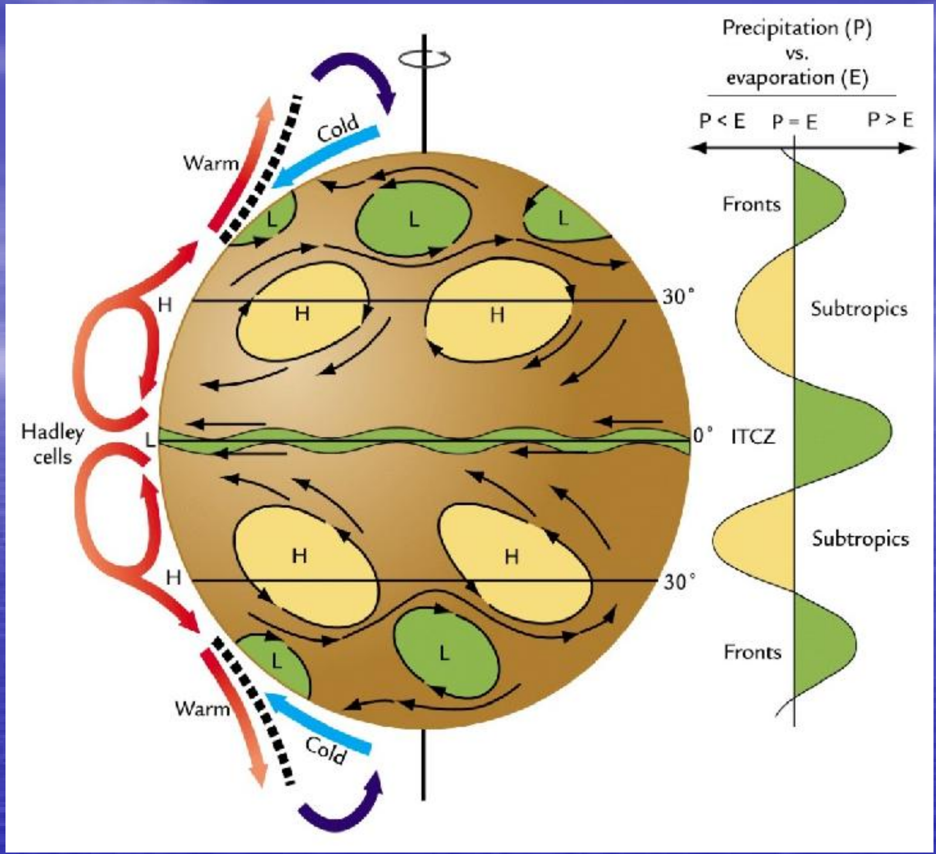
**Pressure Gradient Force only** (without Coriolis effect)

**Pressure Gradient Force** with **Effect of Coriolis** (in the upper atmosphere)

**Pressure Gradient Force** with **Effect of Coriolis and Ground Friction** (in the lower atmosphere at/near ground surface)



# Earth's Climate Zones




Latitudinal Climate Zones:

Regions dominated by low pressure (*Fronts and ITCZ =favors precipitation*)

Regions dominated by high pressure (*Subtropics and poles = favors evaporation*)

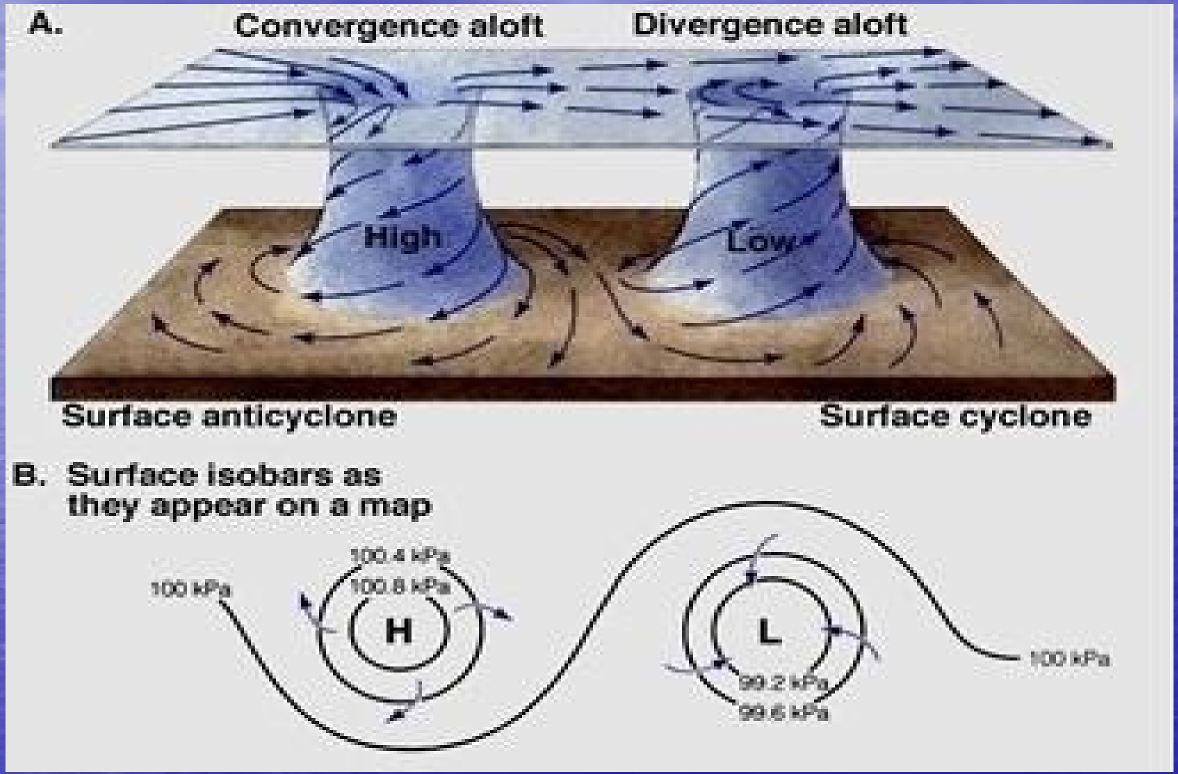
1) Polar high pressure = cold and dry

2) Sub-polar low pressure = polar fronts = cool and wet

3) Sub-tropical high pressure = horse latitudes = warm and dry

4) Equatorial low pressure = ITCZ or doldrums = hot and wet

# Divergence Versus Convergence Air Flow at High and Low Pressure Centers



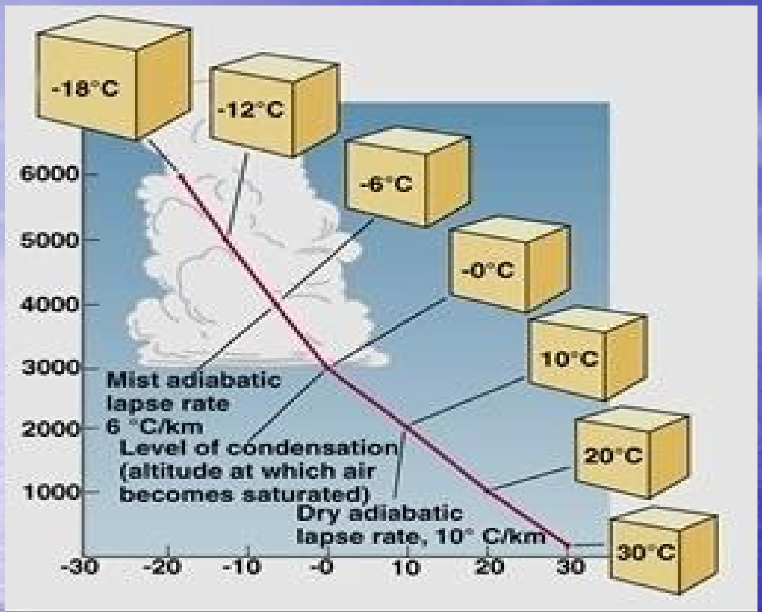

1) Atmosphere pressure differences cause air masses to moves = Wind

2) Air masses move from regions of high pressure to regions of low pressure

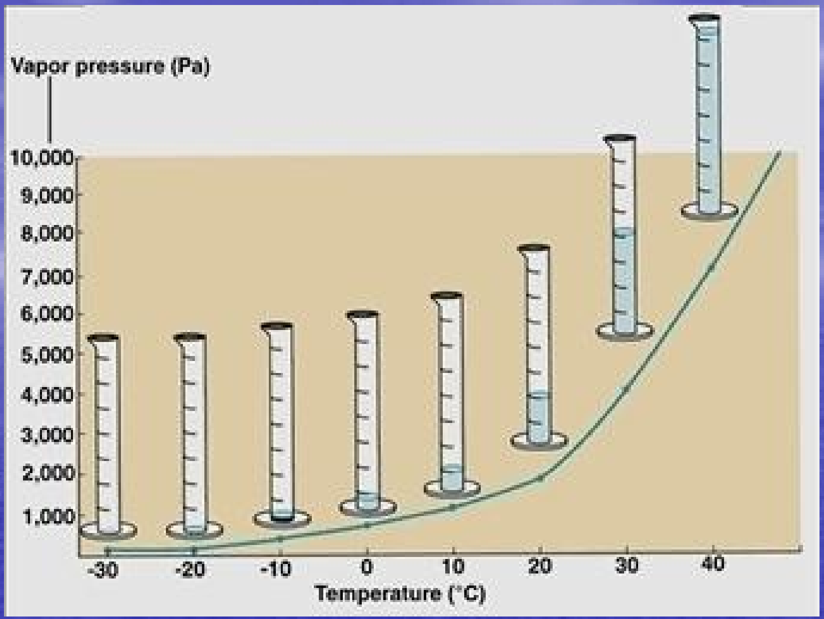
3) High pressure centers have rotating downdrafts  of drying air

4) Low pressure centers have rotating updrafts of moistening air

# Adiabatic Effects of Vertical Air Mass Movement




Temperature and Volume Changes as a Function of Vertical Air Mass Movement = adiabatic cooling (uplift) or warming (downdraft)

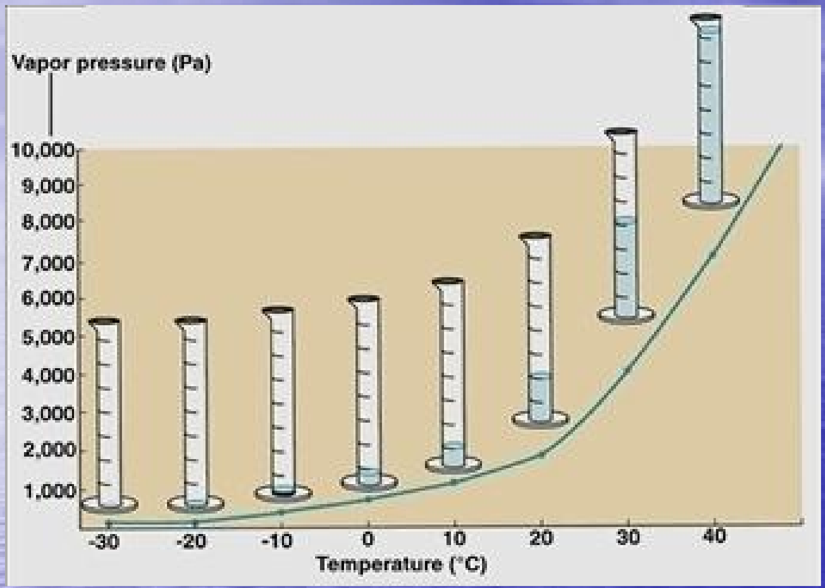



Water Vapor Saturation Level as a Function of Changing Temperature of Air Mass

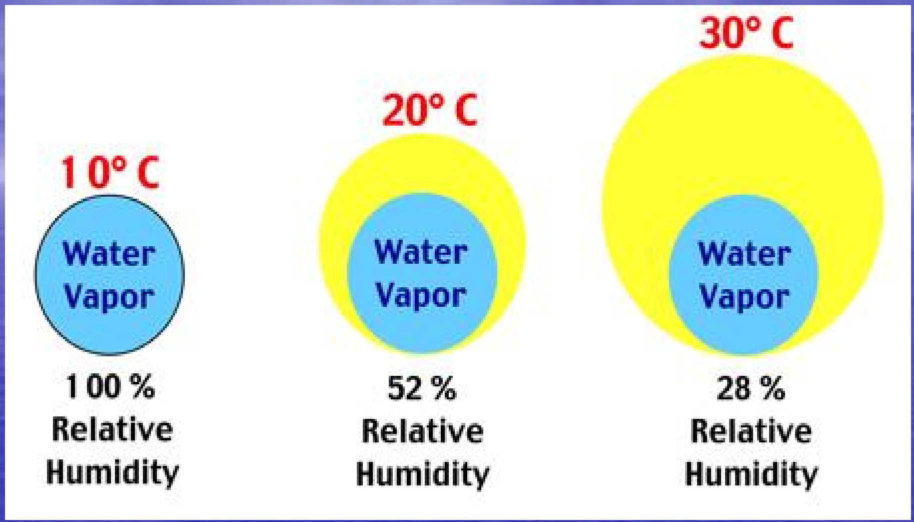
## Key Ideas

- ✓ Ascending (rising) air expands, cools, and becomes moister
- ✓ Descending (falling) air contracts, heats, and becomes dryer
- ✓ Water vapor in rising and cooling air will condense into clouds
- ✓ Further rising and cooling of cloud-rich air will lead to precipitation

# Atmospheric Humidity versus Temp




Maximum Vapor Pressure (Absolute Humidity Limit) for Air Masses of Different Temperatures




Relative Humidity for Air Masses of Different Temperatures with a Given Absolute Amount of Water Vapor

## Key Ideas

- ✓ Ascending (rising) air expands, cools, and becomes moister
- ✓ Descending (falling) air contracts, heats, and becomes dryer
- ✓ Water vapor in rising and cooling air will condense into clouds
- ✓ Further rising and cooling of cloud-rich air will lead to precipitation

# Weather at Divergence and Convergence Zones

## Polar Divergence

- ✓ High evaporation
- ✓ Variable winds
- ✓ Cold, harsh, dry weather

## Subpolar Convergence

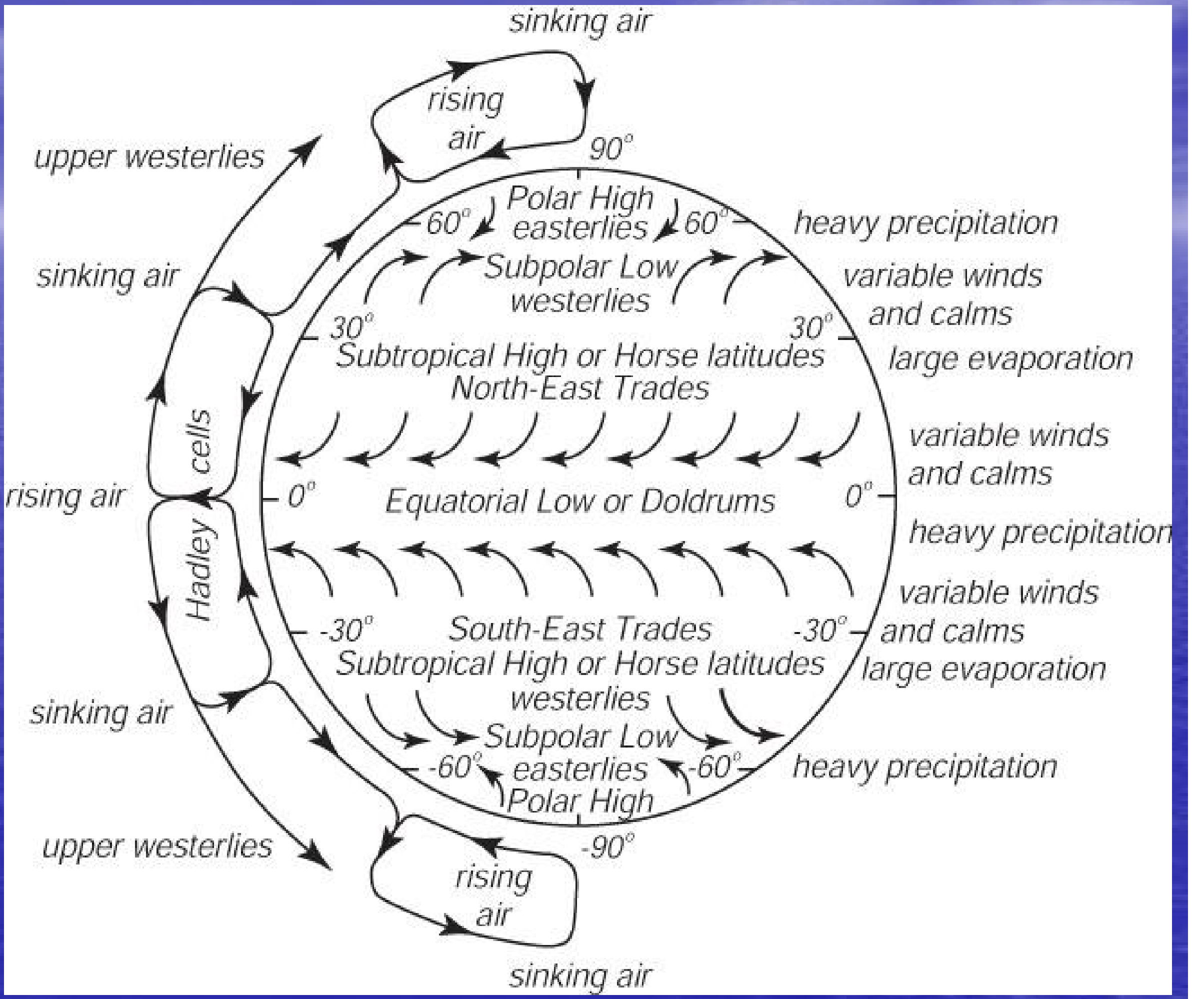
- ✓ Heavy precipitation
- ✓ Winter storm fronts
- ✓ Stormy, wet, cool weather

## Subtropical Divergence

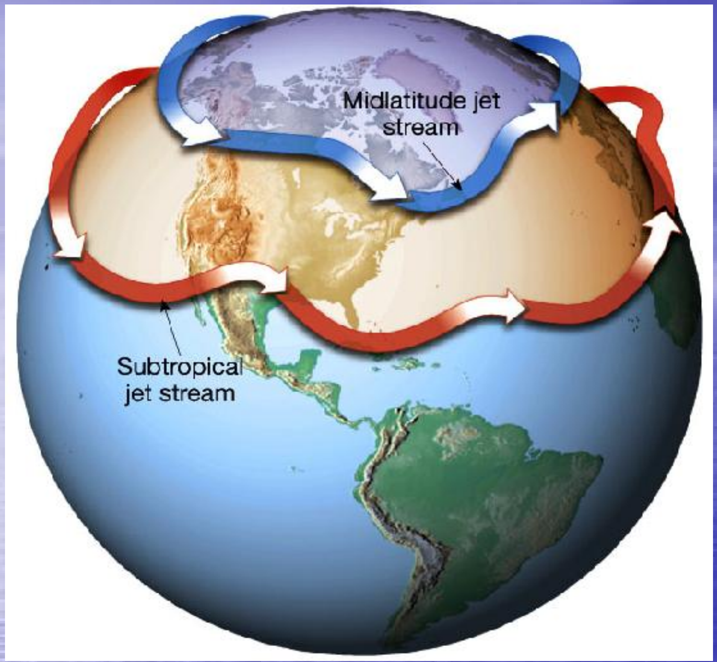
- ✓ High evaporation
- ✓ Variable winds and Calms
- ✓ Warm, mild, dry weather

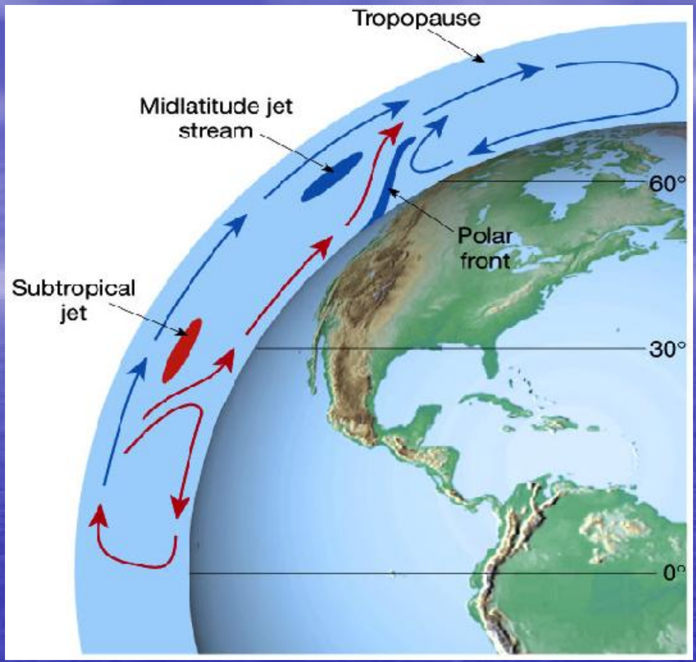
## Tropical Convergence

- ✓ Heavy precipitation
- ✓ Light winds and Calms
- ✓ Tropical cyclone nursery
- ✓ Stormy, wet, hot weather



# The Jet Stream and Pressure Centers




## Key Ideas

- ✓ Narrow, fast-moving, ribbons of high-level wind moving west to east
- ✓ Found between atmospheric cells
- ✓ Controls position and movement of stormy low pressure systems (above troughs) and fair weather high pressure systems (below ridges)

# Land-Sea Breezes Along Coasts

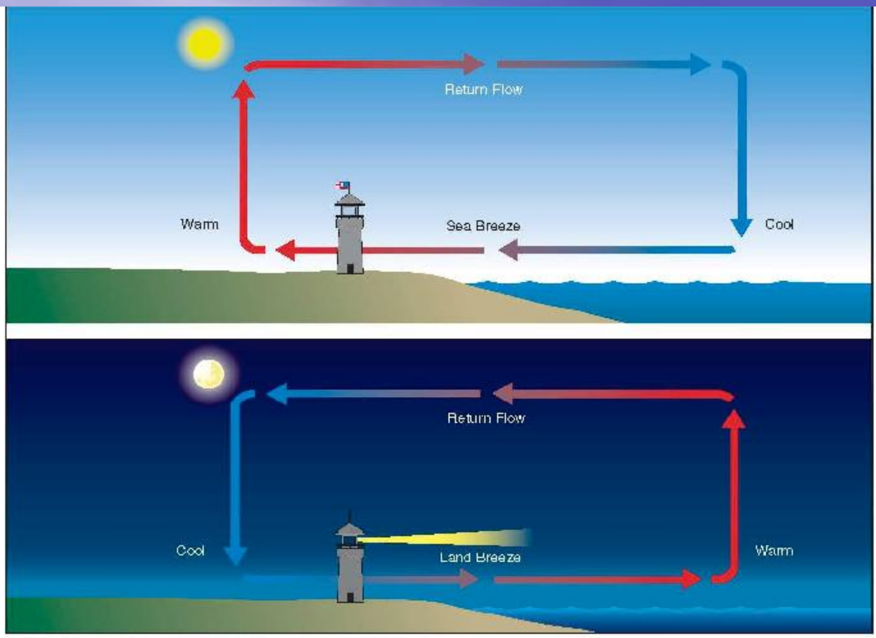
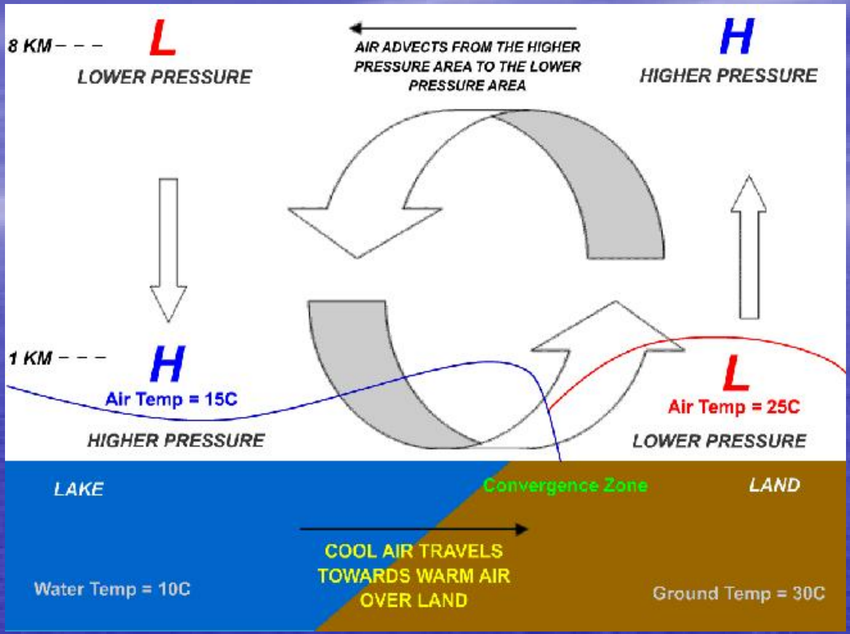
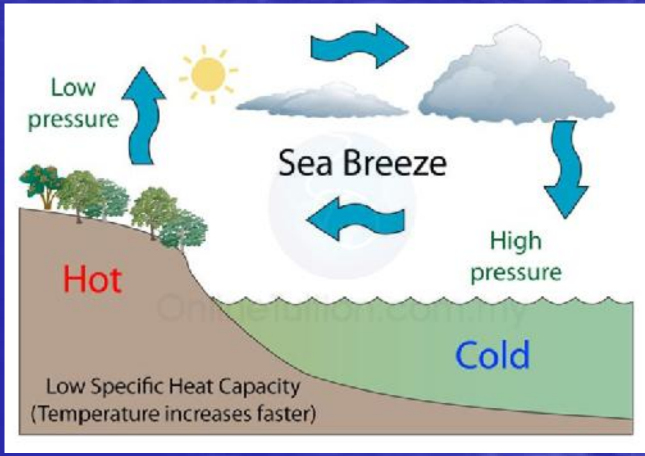



Figure 10-13. Sea breeze and land breeze wind circulation patterns.

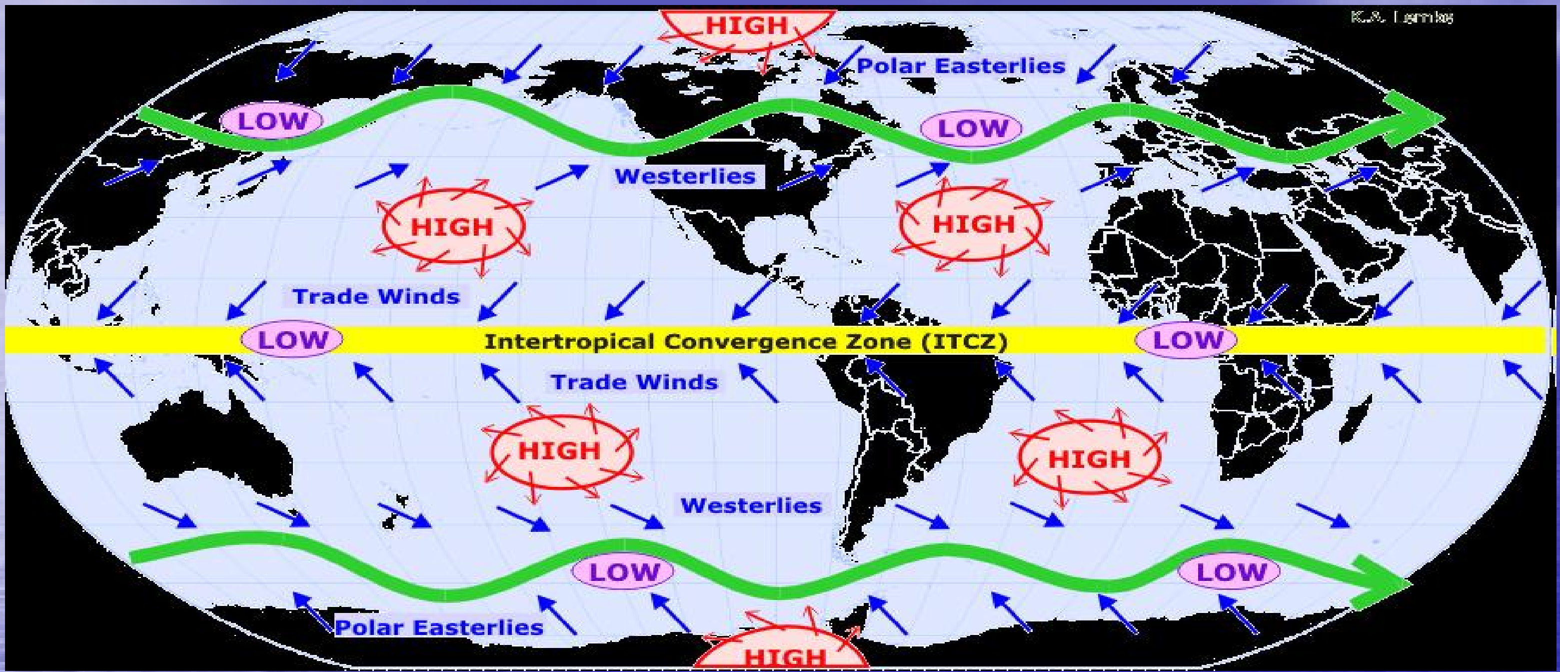



- ✓ Daily reversal of local coastal winds
- ✓ Coastal breeze direction controlled by local differences in atmospheric pressure between air masses over land versus sea
- ✓ Nighttime offshore wind (Land = High; Sea = Low
- ✓ Daytime onshore wind (Land = Low; Sea = High



# *Weather Patterns and Storm Systems*

# Seasons, Surface Winds and Weather



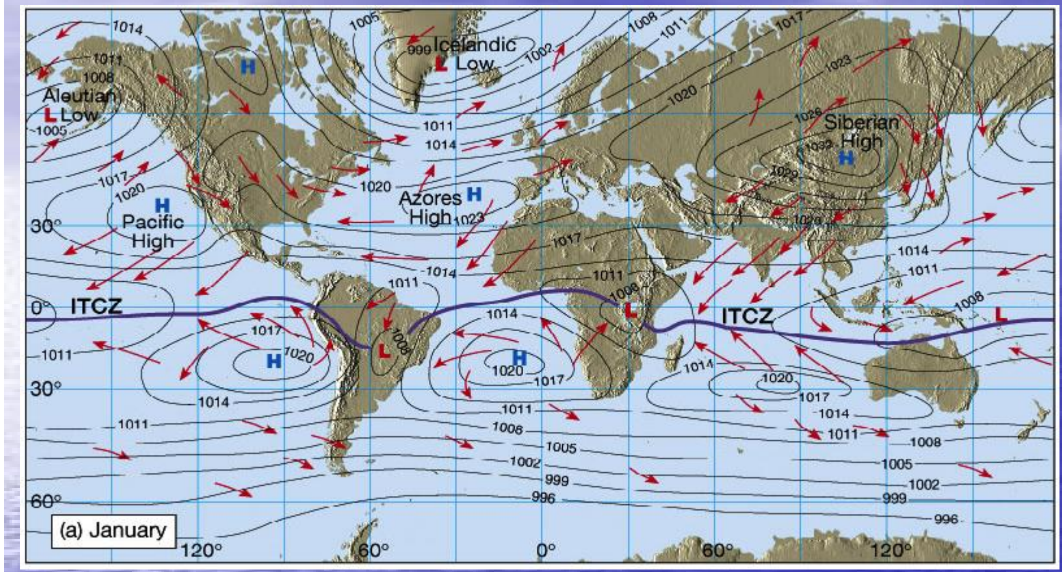

**Key Idea**

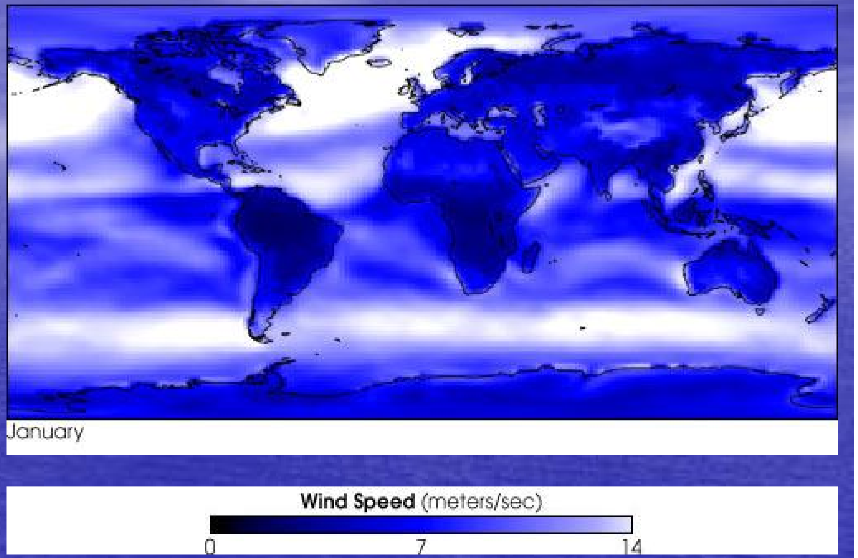
Seasonal changes in Earth's axis in respect to the sun cause latitudinal migrational shifts in several atmospheric elements:

- Pressure centers
- Wind belts
- Jet streams
- Intertropical Convergence Zone (ITCZ)
- Large-scale weather patterns

# Pressure Systems and Wind Patterns

## Averaged **January** Pattern



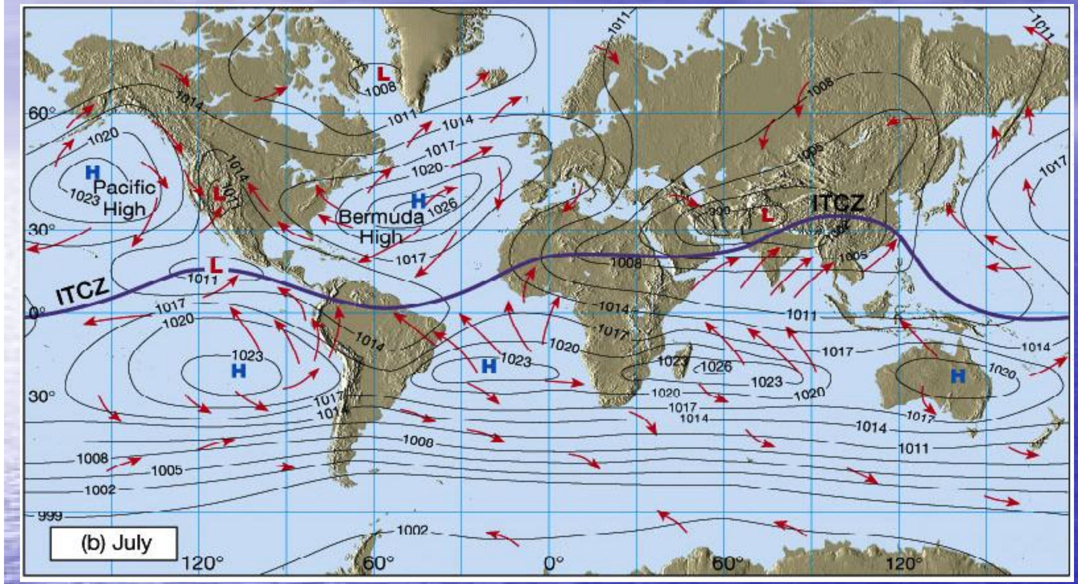



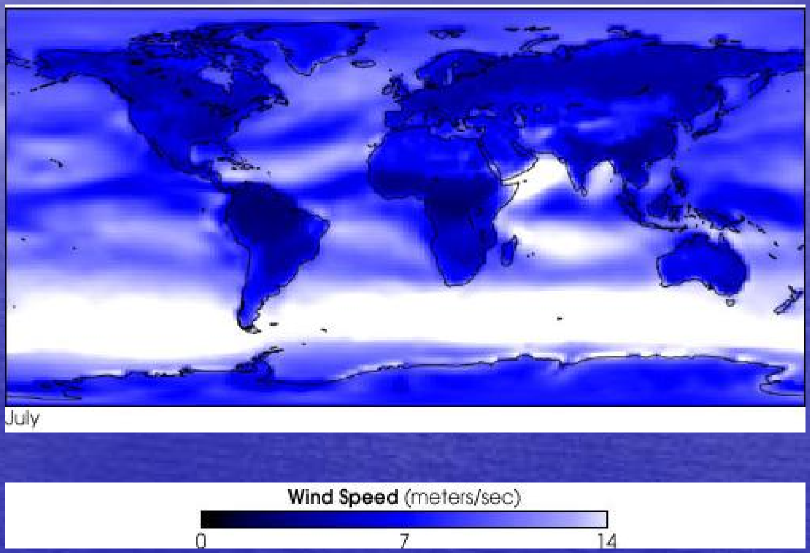

## Key Ideas

- The ITCZ is shifted to its maximum southward position
- Polar lows dominate the northern Pacific and Atlantic Oceans
- Subtropical highs dominate south Pacific and Atlantic Oceans
- Winter in the Northern Hemisphere; summer in the S. Hemi.

# Pressure Systems and Wind Patterns

## Averaged **July** Pattern




## Key Ideas

- The ITCZ is shifted to its maximum northward position
- Subtropical highs sit over the north Pacific and Atlantic Oceans
- Southern Ocean westward wind belt at maximum strength
- Summer in the Northern Hemisphere; Winter in the S. Hemi.

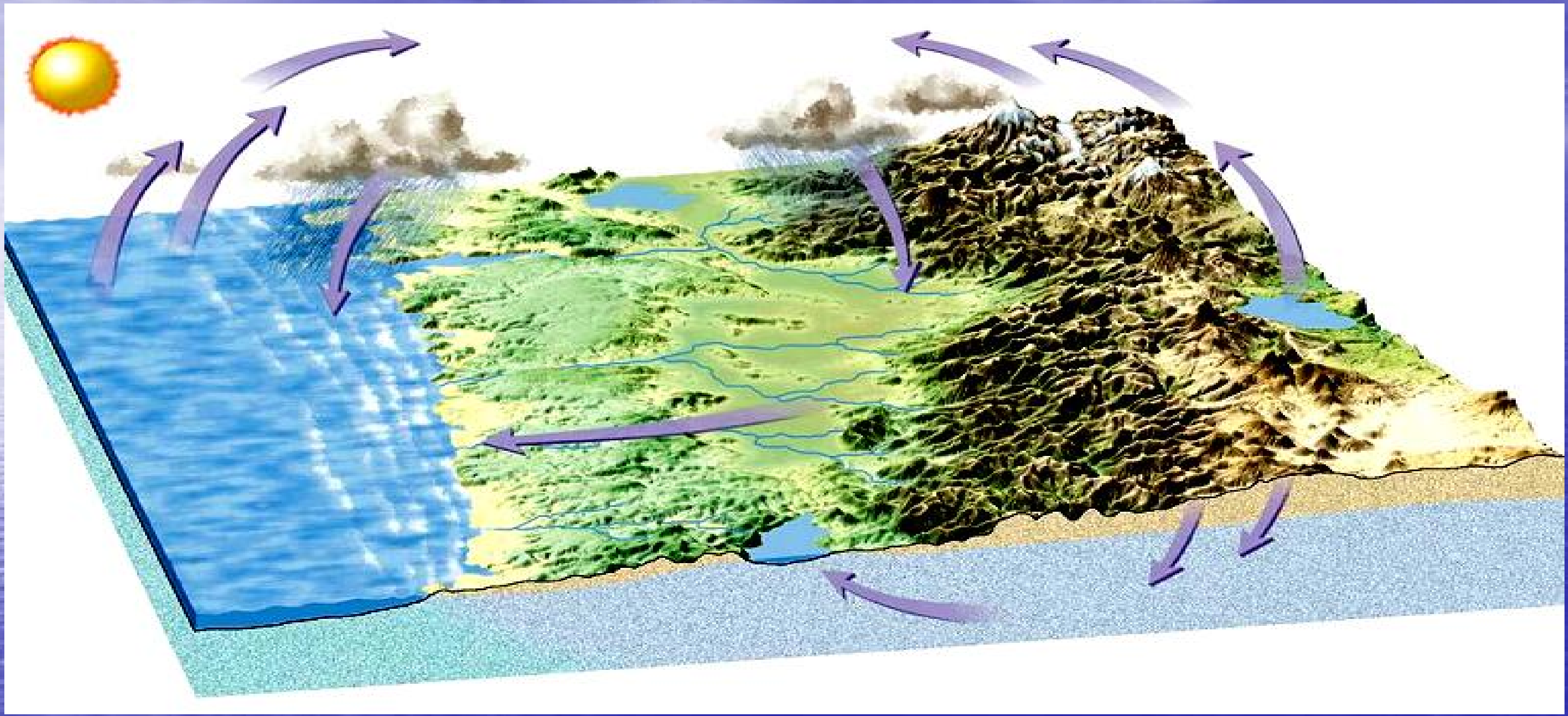
# Weather Systems

Local atmospheric conditions that prevail over a period of days to weeks

# Storm Systems

- Spinning Air Mass Disturbances
  – Tropical Cyclones
  – Extratropical Cyclones

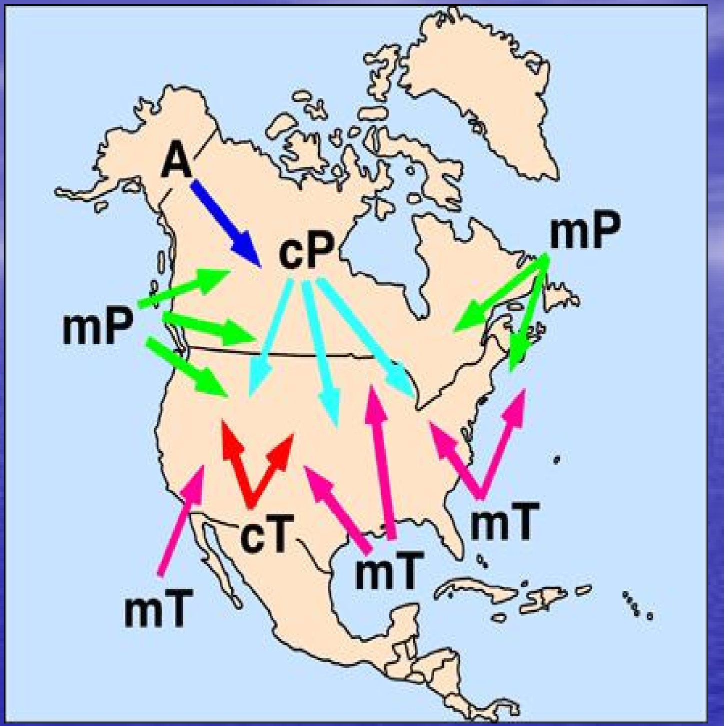
# Solar Energy Powers the Both the Atmospheric and Hydrologic Cycles



**Solar Energy Causes Evaporation of the Ocean Surface Waters**

- ✓ 1 meter of ocean surface is evaporated each year!
- ✓ Most precipitation falls back into the ocean
- ✓ Precipitation over land plays huge part in weathering and erosion

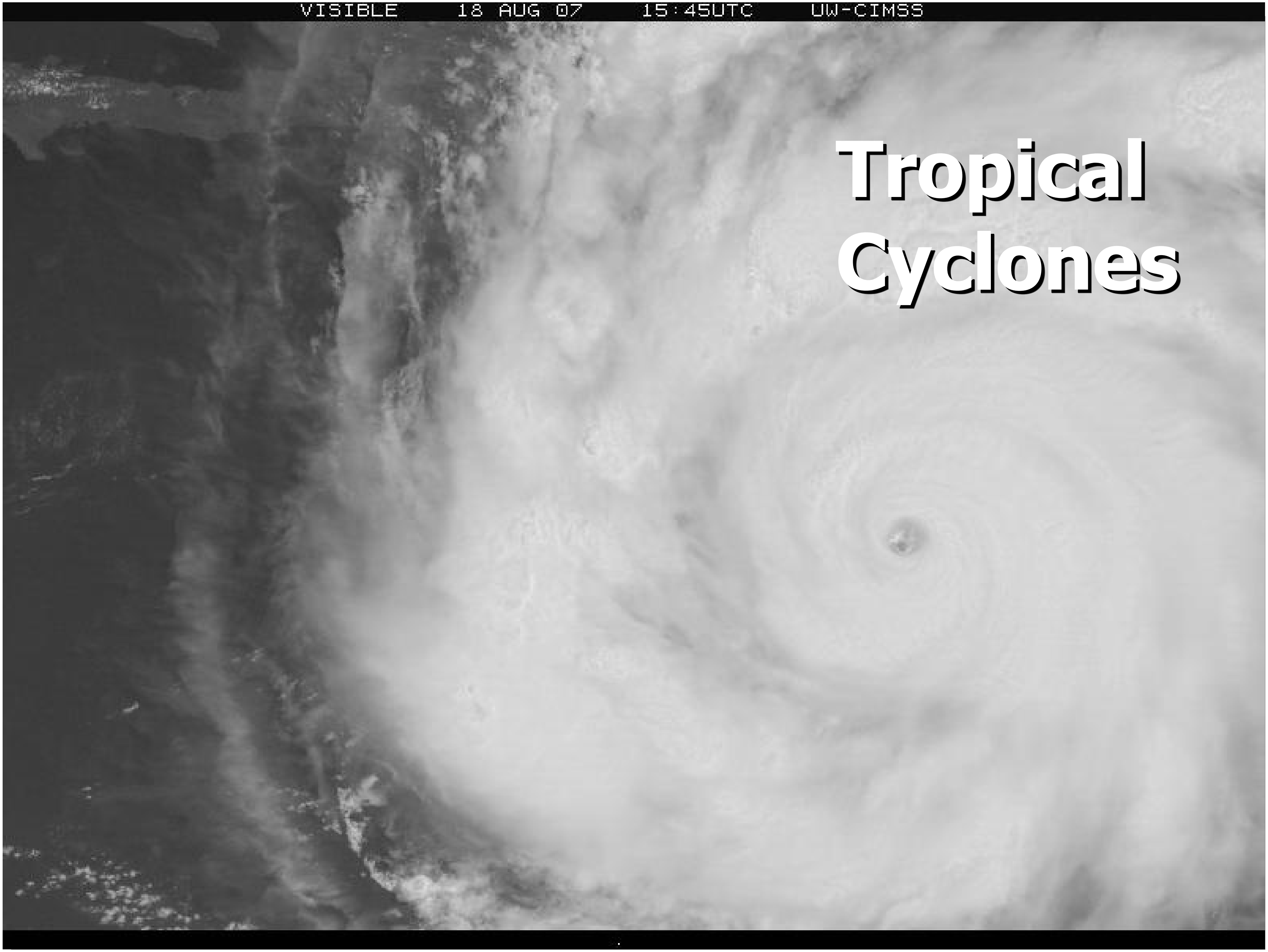
# North American Air Masses


**Several Distinctive Regional Air Masses found Across the Hemisphere**

- ✓ **Each air mass gets its characteristics from the surface beneath it**
- ✓ **Differences in surface type (marine versus continental)**
- ✓ **Differences in surface temperature (equator vs. subtropical vs. polar)**
- ✓ **Each air mass has different density; they do not mix when they collide.**
- ✓ **Stormy weather is the result of rising and colliding air masses.**

# Tropical Cyclones



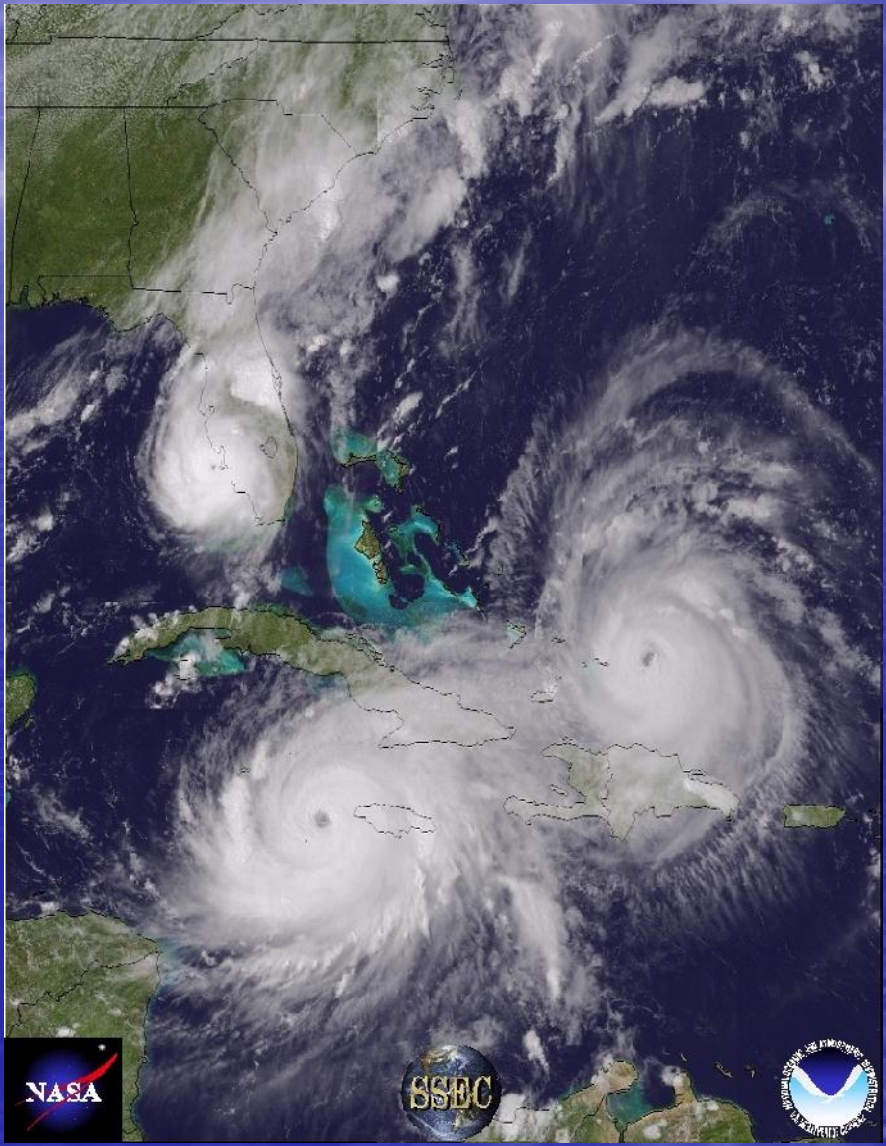
# Tropical Cyclones

1) **Tropical Cyclones** are known as *hurricanes* in the Atlantic Ocean, *typhoons* in the Pacific Ocean and *cyclones* in the Indian Ocean.

2) Very extensive, powerful, and destructive type of storm.

3) This type of storm develops over oceans 8° to 15° North and South of the equator.

4) Hurricanes draw their energy from the warm water of the tropics and latent heat of condensation.



# Necessary Conditions for Cyclone Development:

**1) Must originate over ocean water that is least 26.5 °C.**

- ✓ Hurricanes feed off the latent heat of water – hotter the better!

**2) Have an atmosphere that cools quickly with height.**

- ✓ This creates potentially unstable conditions that builds storms.

**3) Low vertical wind shear.**

- ✓ Winds at all levels of the atmosphere from the ocean up to 30,000 feet or higher are blowing at the same speed and from the same direction.

**4) No closer than 500 kilometers to the equator.**

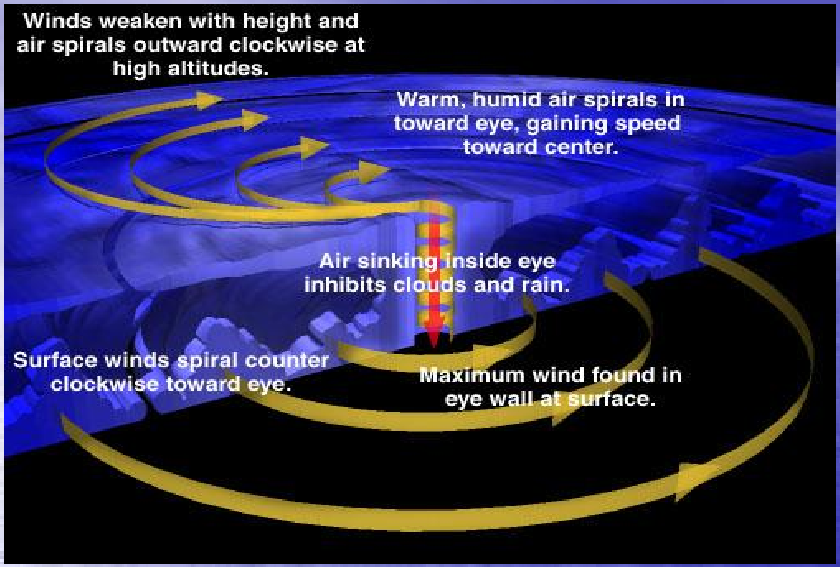
- ✓ The Coriolis Force is too weak close to the equator.
- ✓ It is the Coriolis Force that initially makes the cyclone spiral and maintains the low pressure of the disturbance.

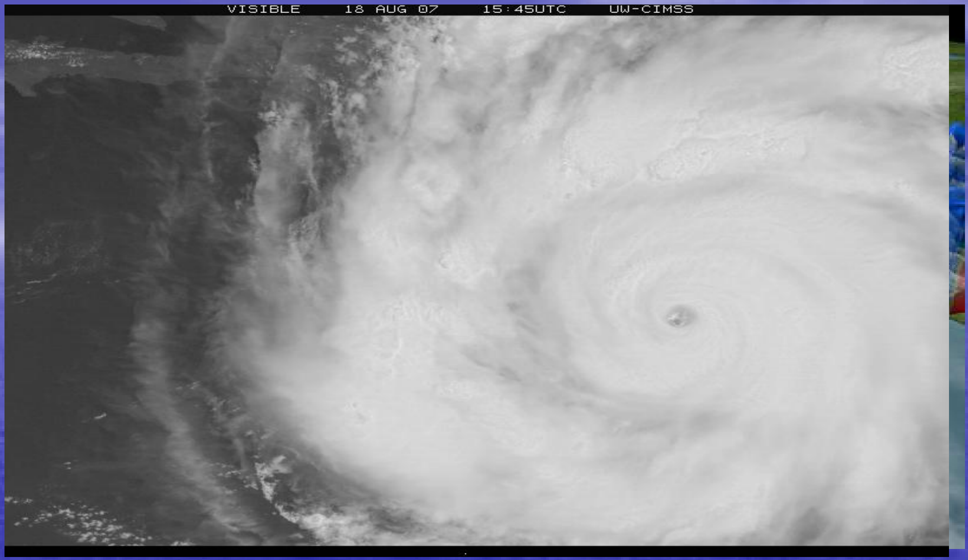
**5) An upper atmosphere high pressure area above the growing storm.**

- ✓ The air in such high pressure areas is flowing outward. This pushes away the air that is rising in the storm, which encourages even more air to rise from the low levels.

**6) Hurricanes will not always form in these conditions. However, a will hurricane only form if these conditions are present.**

# Anatomy and Behavior of a Hurricane




1) Warm, humid surface winds spiral towards eye.
2) Strongest winds occur in the eye wall at the surface.
3) Air in the eye sinks which inhibits wind and cloud formation
4) Body of hurricane divided into concentric rain bands
5) Surface rotation direction depends on hemisphere
6) All hurricanes move toward the west

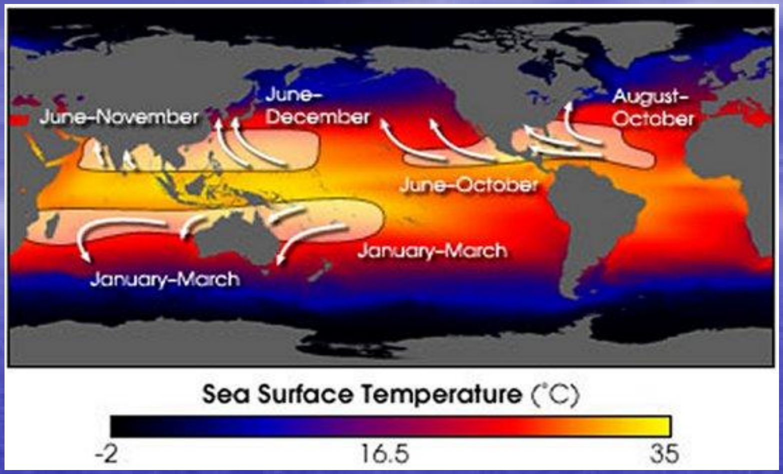
# Life Cycle of Tropical Cyclones

## 1) Formation
- ✓ Tropical Disturbance to Depression
- ✓ Weak to moderate winds
- ✓ Little to no rotation

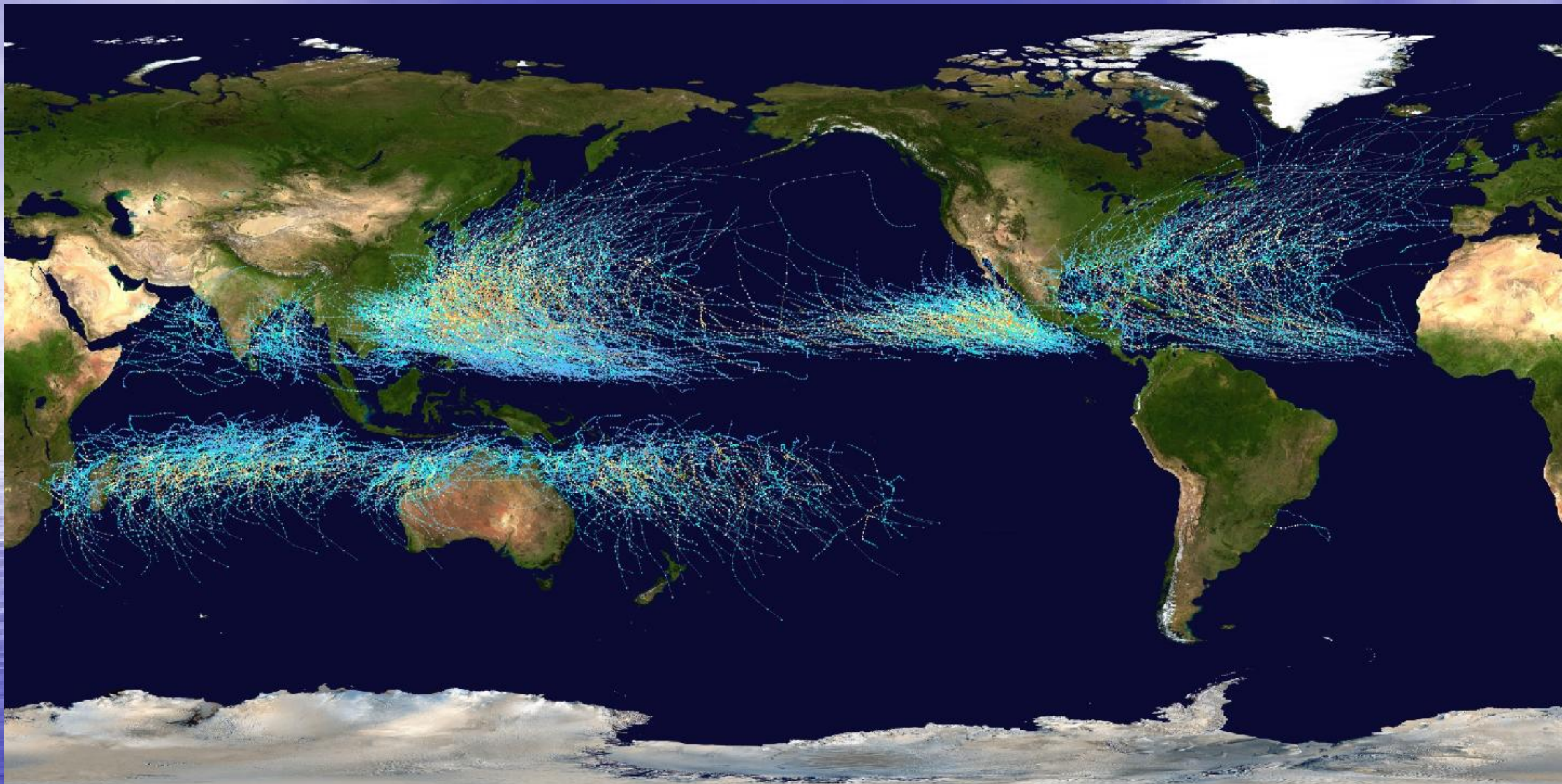
## 2) Prematurity
- ✓ Tropical Storm
- ✓ Moderate to strong winds
- ✓ Moderate rotation

## 3) Full Maturity
- ✓ Hurricane
- ✓ Very Strong winds
- ✓ Rapid rotation with eye

## 4) Decay
- ✓ Dissipation into weaker and weaker system
- ✓ Entire cycle typically lasts between 1 to 2 weeks



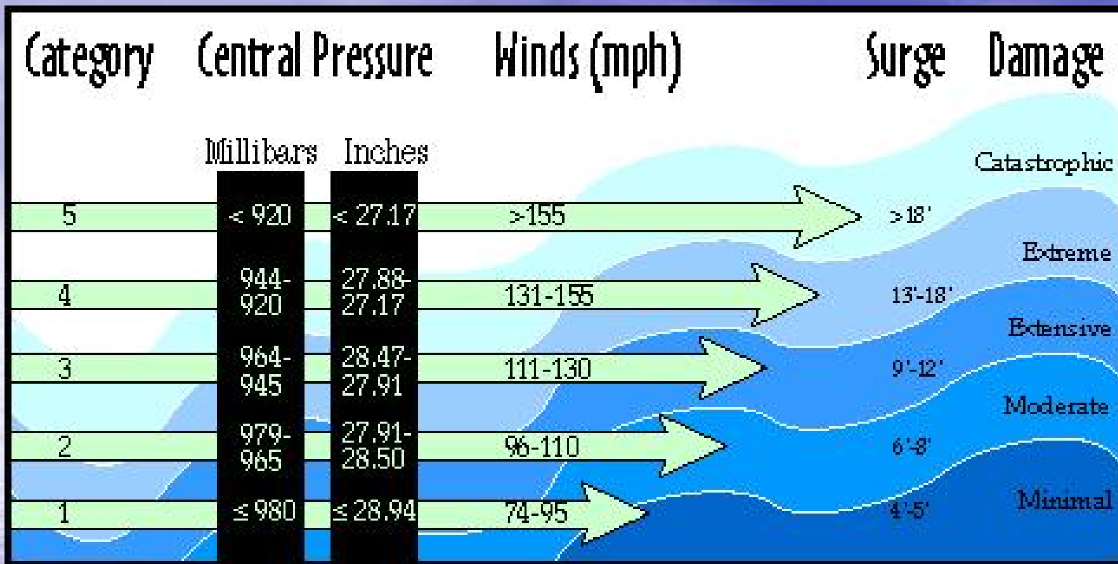

# Global Tropical Cyclone Tracks

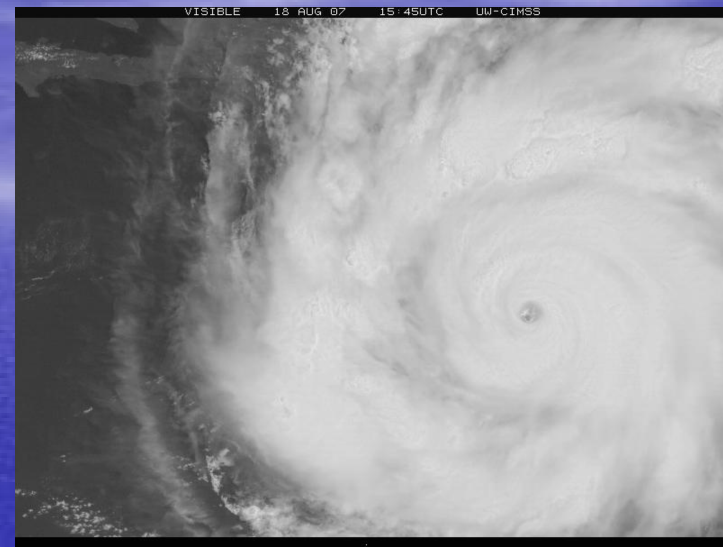


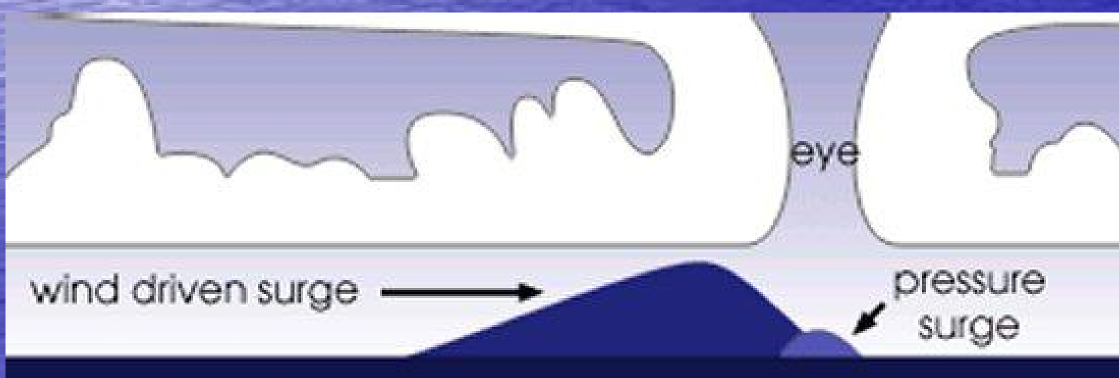
Which ocean basin has the most tracks?  Why?

Which ocean basin has the least tracks?   Why?

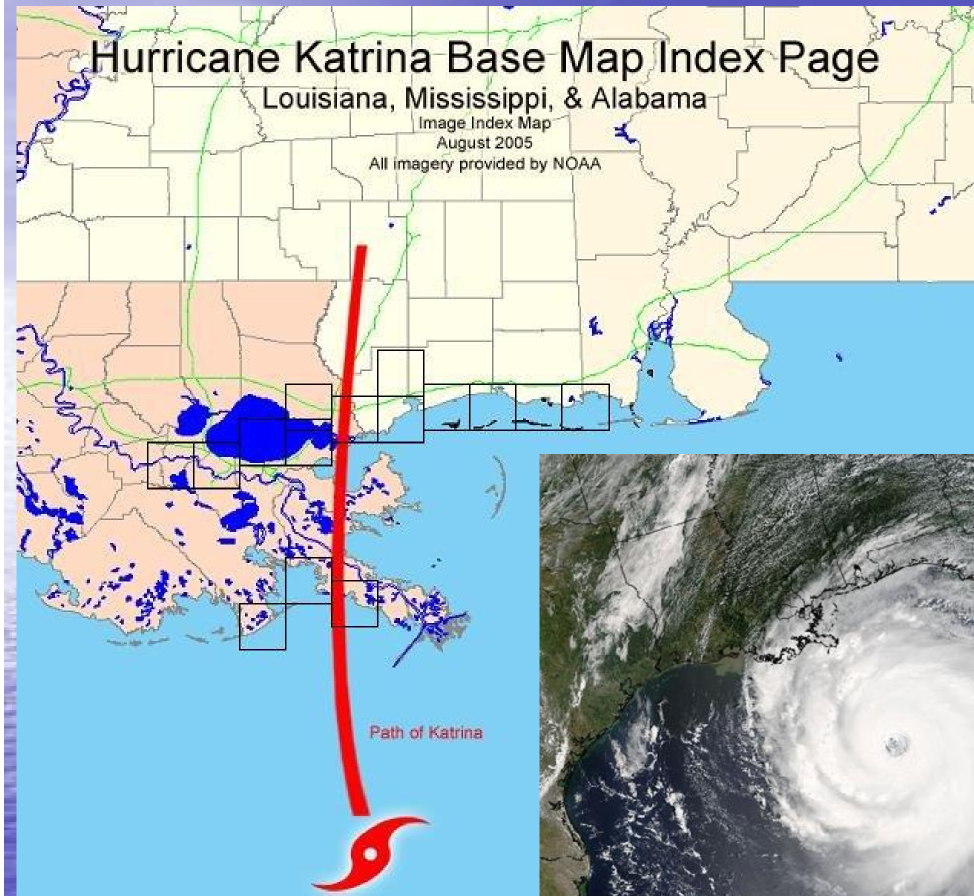
# Hurricane Intensity Scale

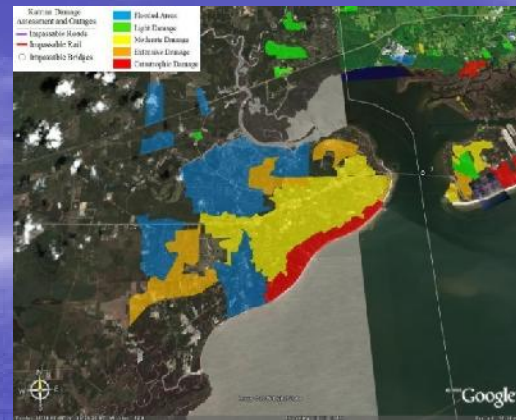


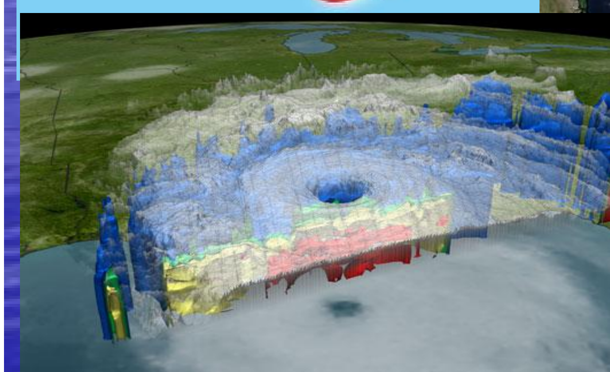



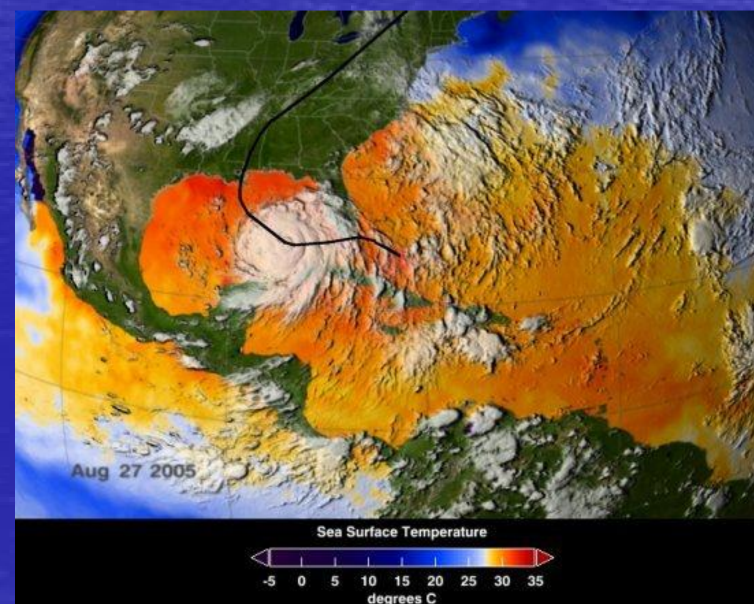
# Hurricane Katrina



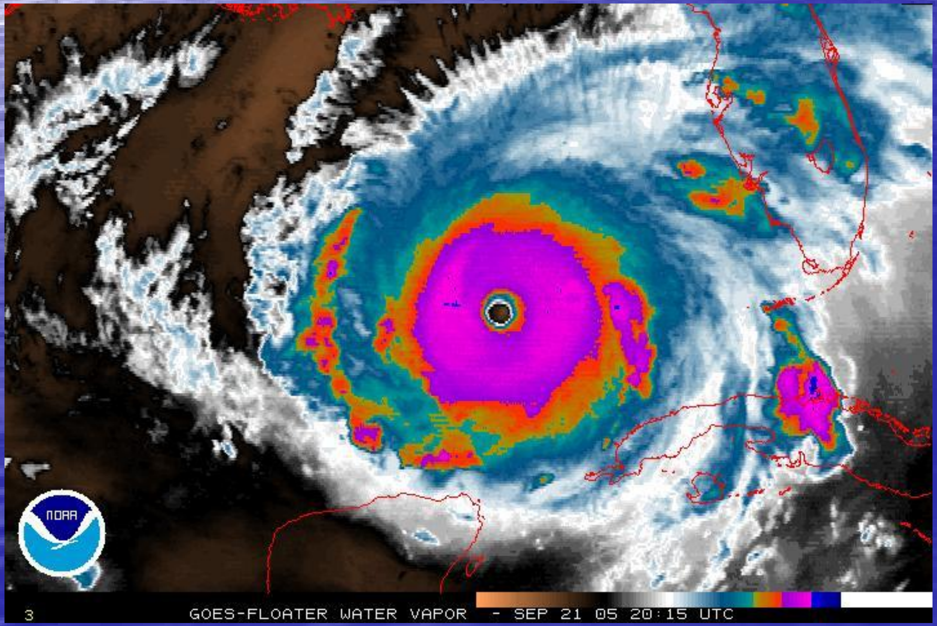






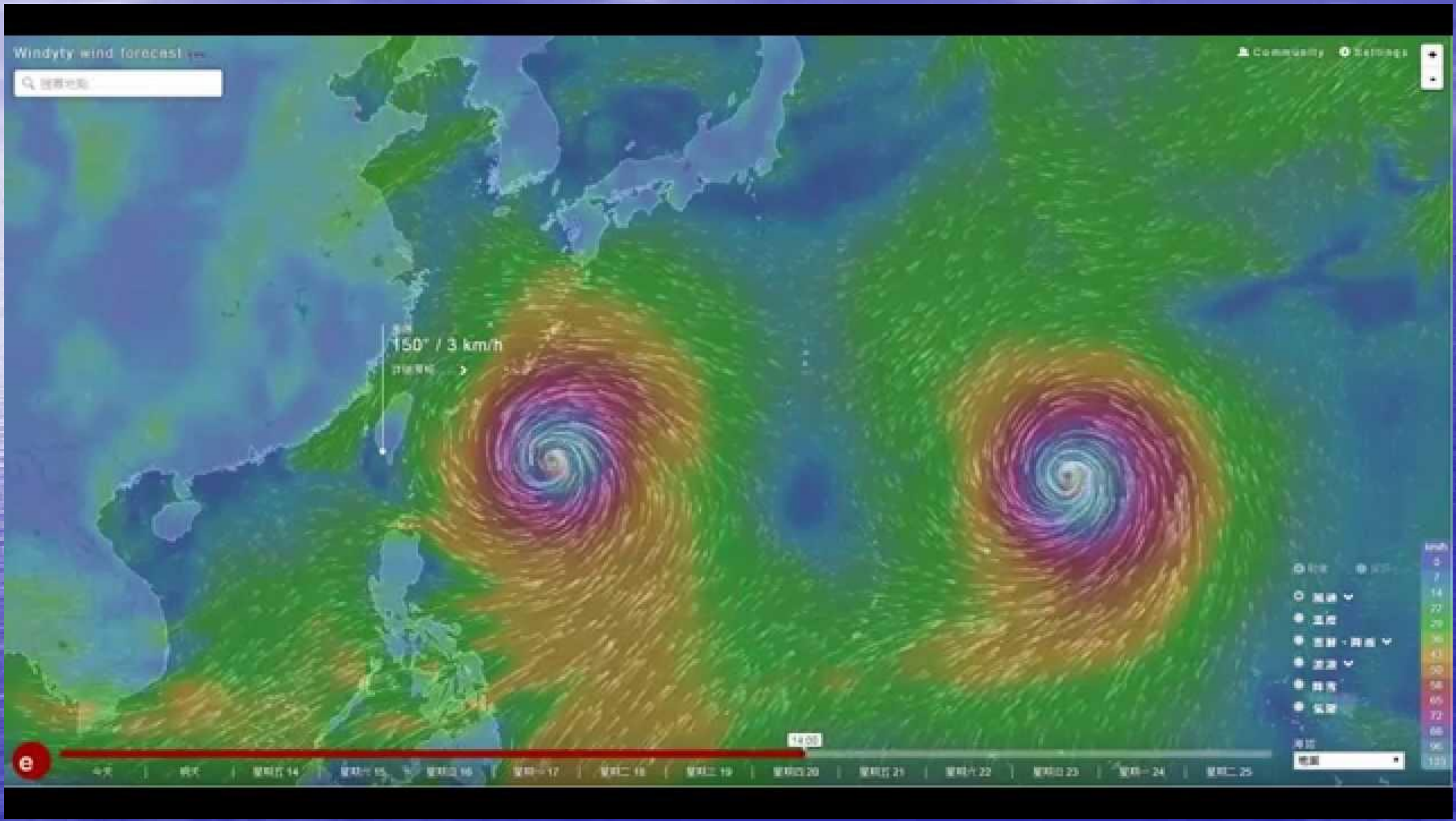
# Hurricane Rita





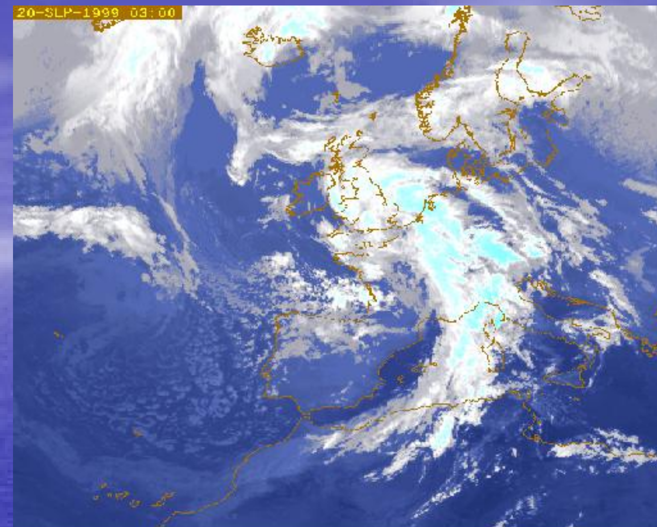

Hurricane Rita was the strongest hurricane ever recorded in the Atlantic Basin

# Real-Time Tropical Cyclones

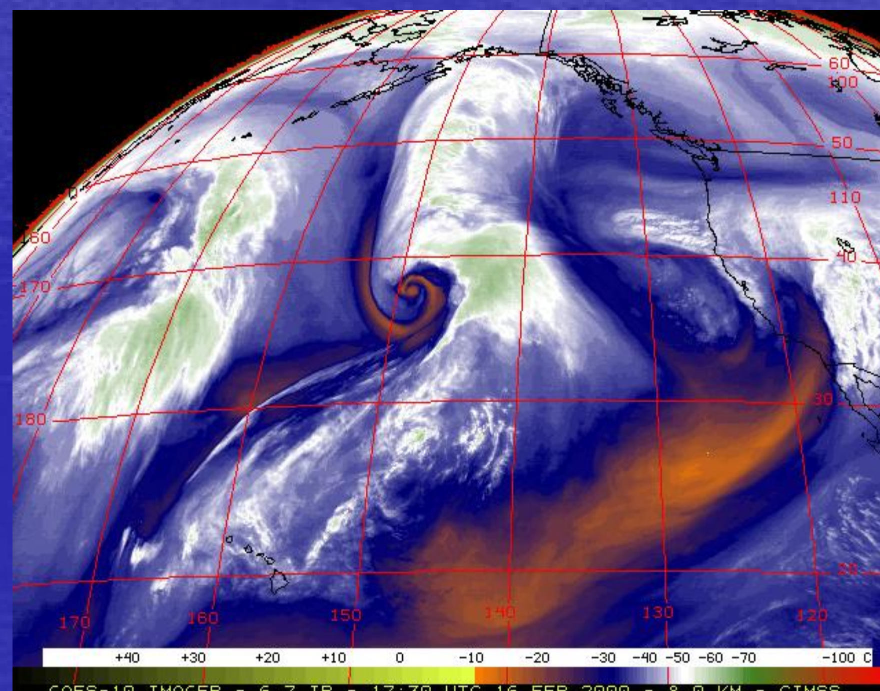



www.windyty.com

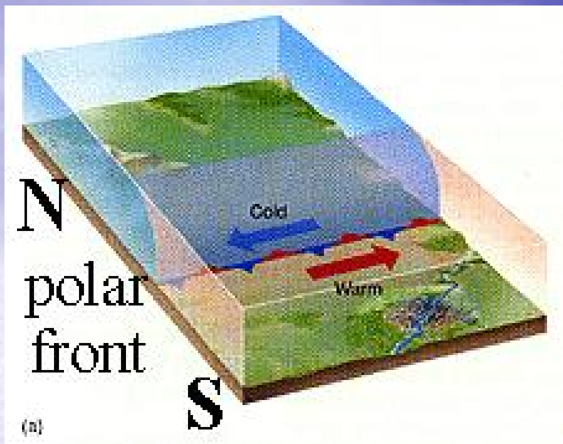
# Mid-Latitude Cyclonic Systems

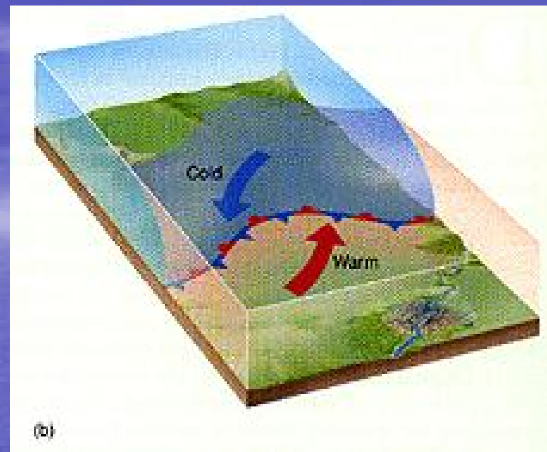

- ✓ A high- to mid-latitude cyclonic low pressure system
- ✓ Typically form from fall to spring
- ✓ IT IS NOT A HURRICANE OR TROPICAL STORM
- ✓ Forms from the swirling convergence of a cold and warm air mass along the polar front
- ✓ Associated with high winds, clouds and precipitation
- ✓ Typical size of mid-latitude cyclone = 1500-5000km in diameter



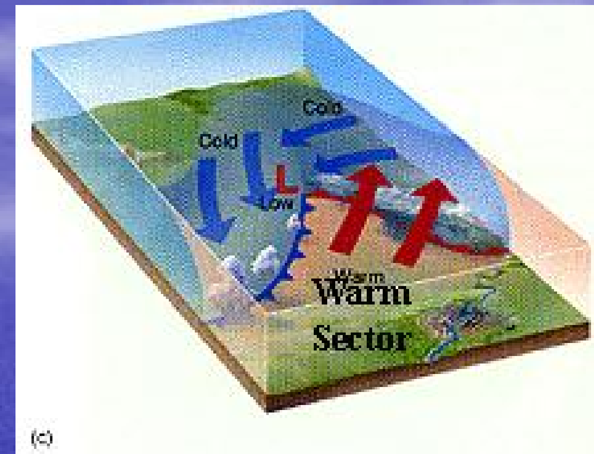
# Development of Mid-Latitude Storm Systems



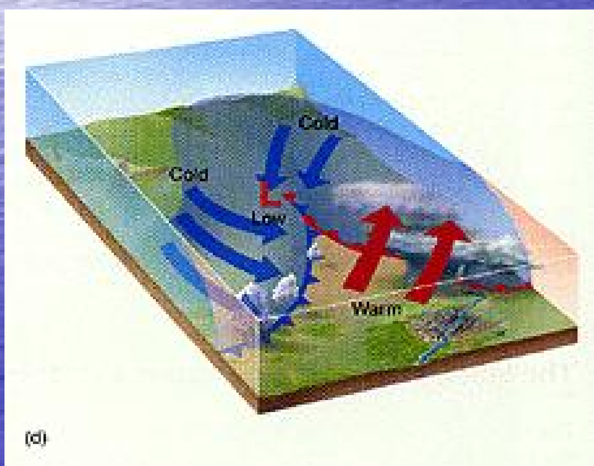

1) Frontal Wave Develops



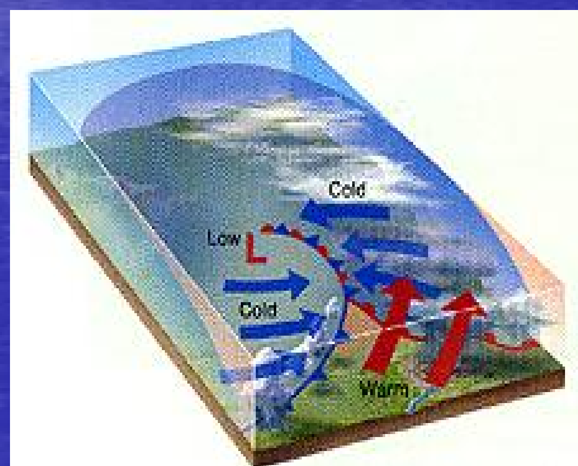

2) Instability “Kink” Forms



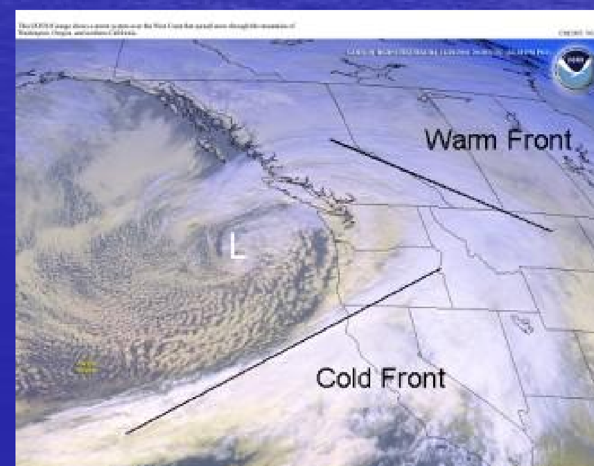

3) Fully-developed Cyclone




4) System Begins to “Occlude”

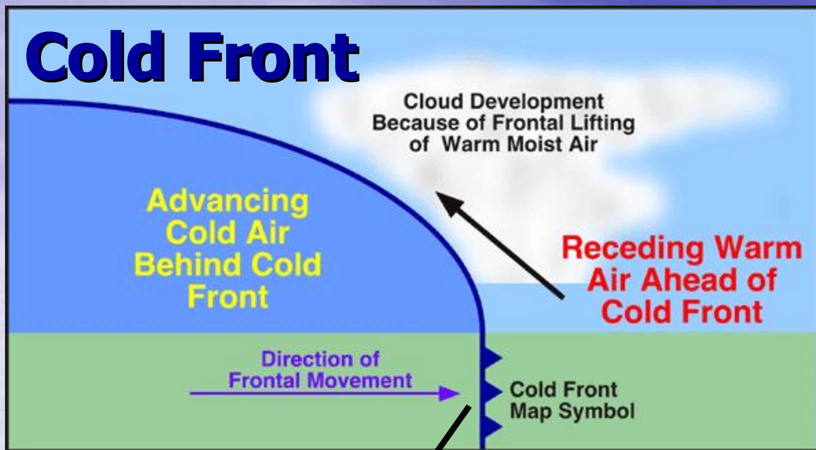


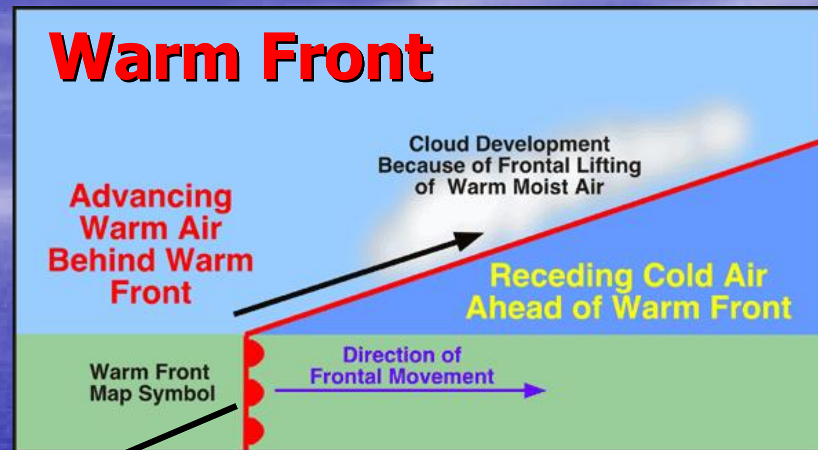

5) Advanced “Occlusion”

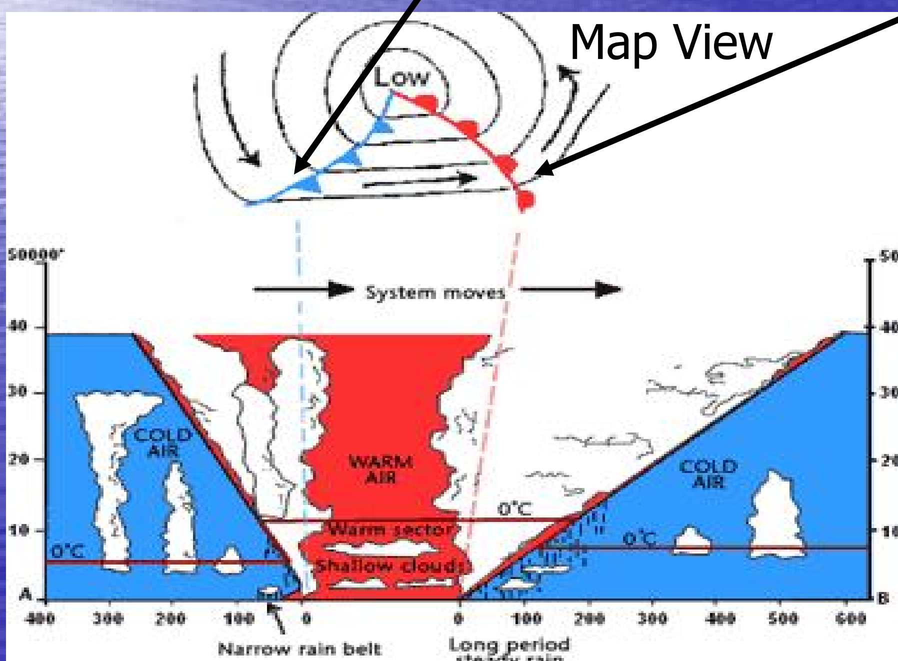



**Example**

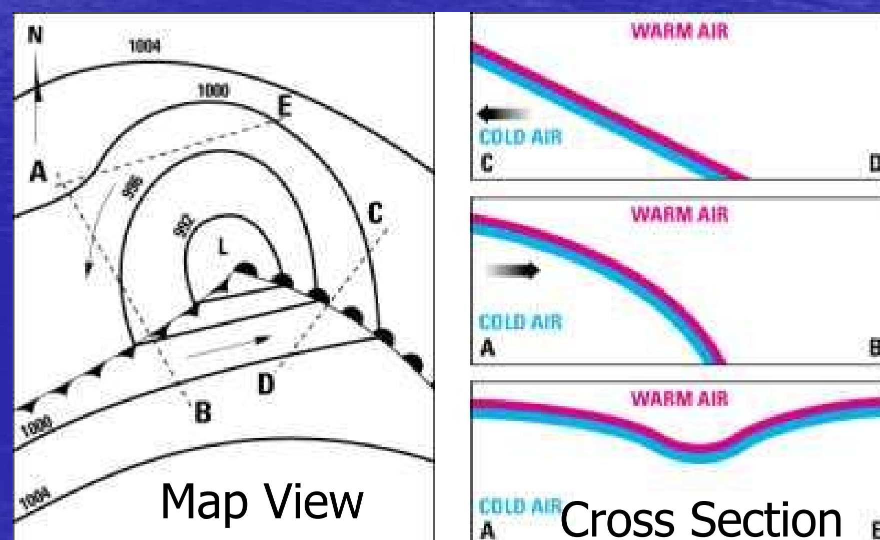
# Cold and Warm Fronts



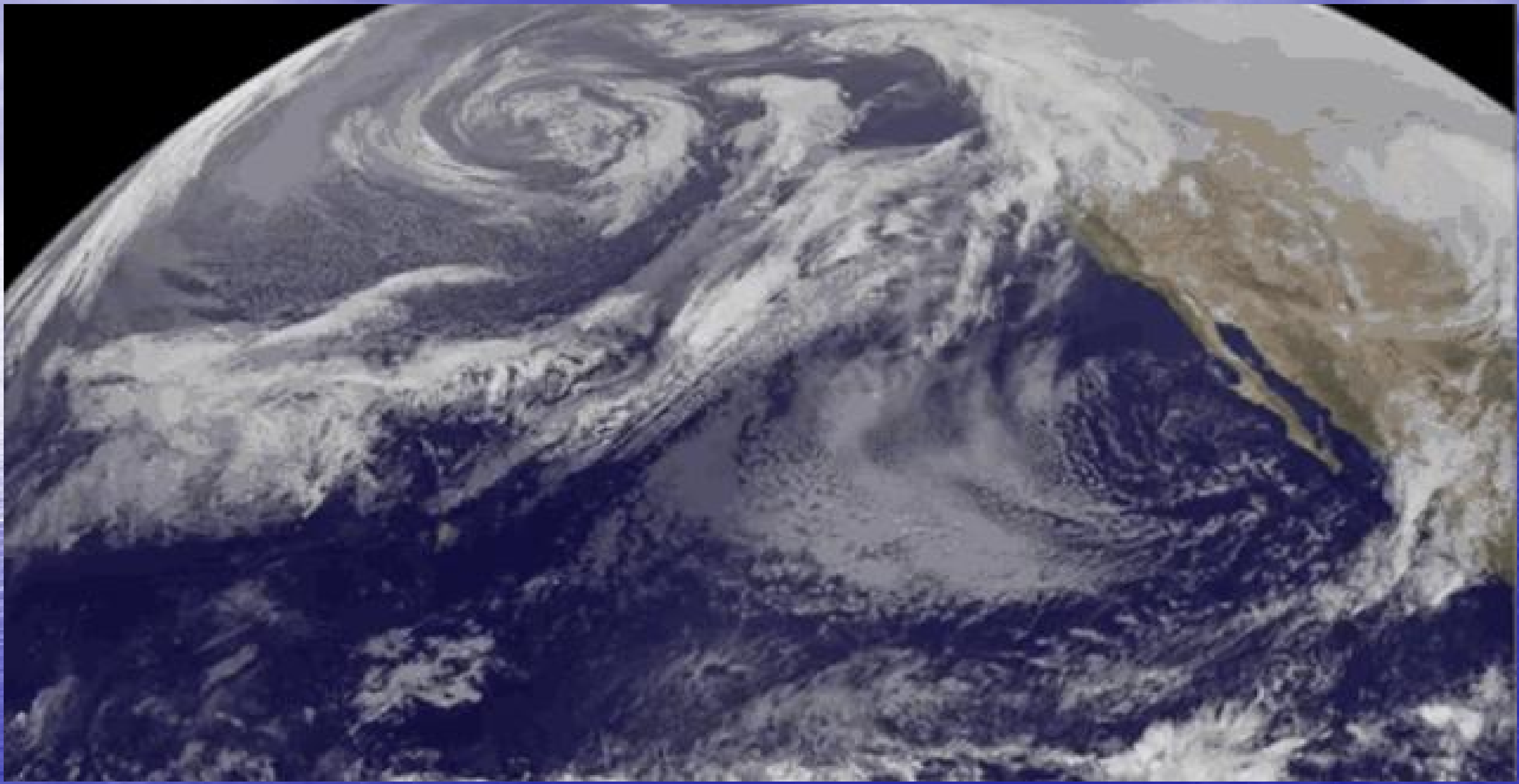




Cross Section View



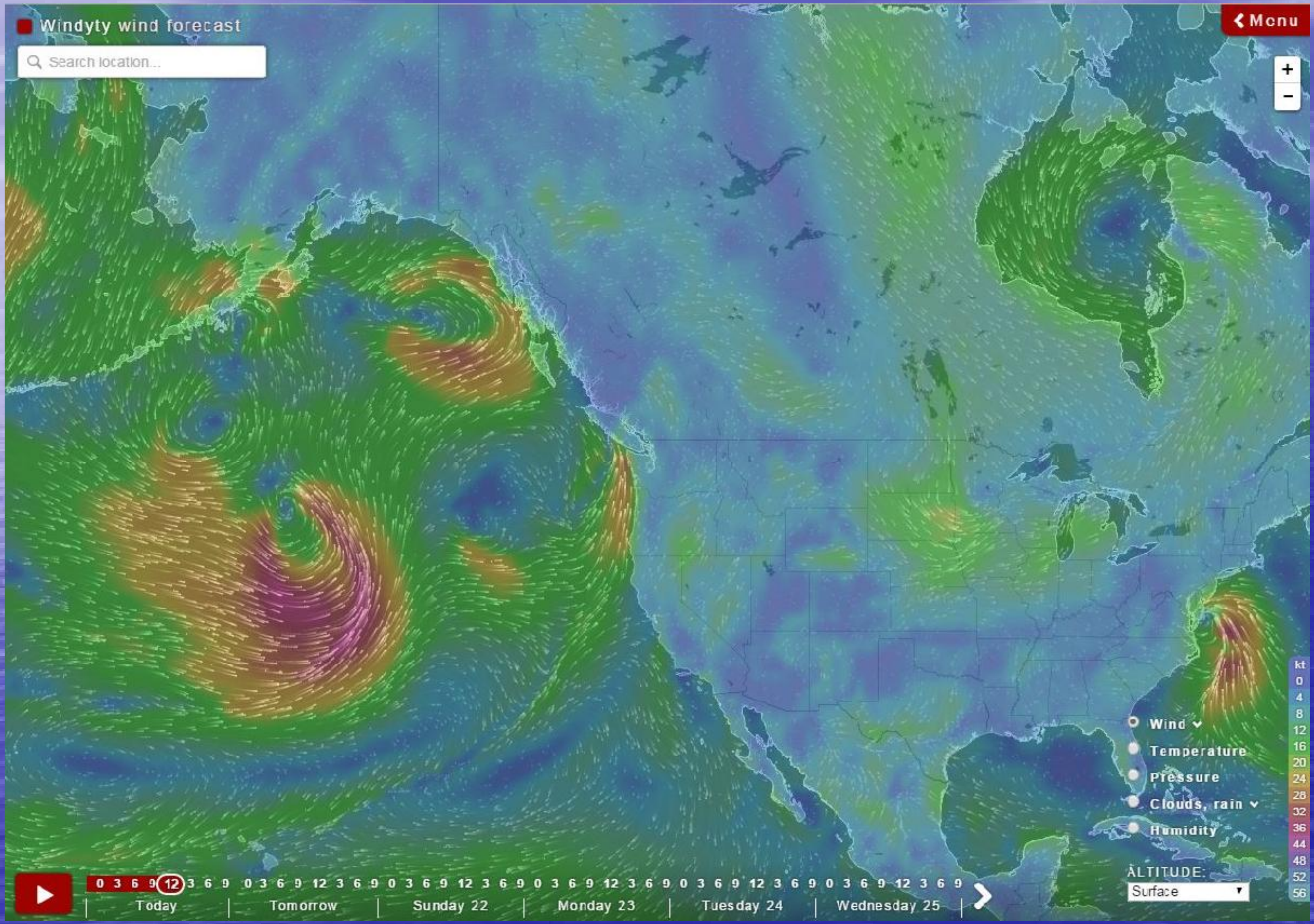
# Spot the Three Frontal Systems -



1) Where are the centers of systems? 2) Centers of low pressure?

3) Sense of rotation?  4) Regions of warm and cold air masses?

# Real-Time Extratropical Cyclones

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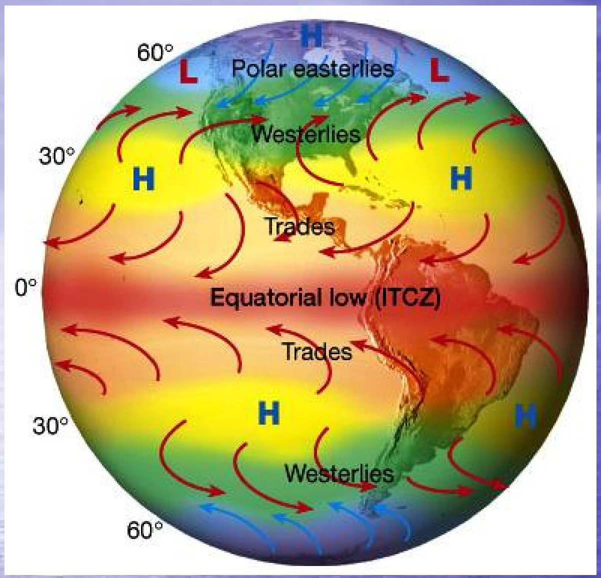
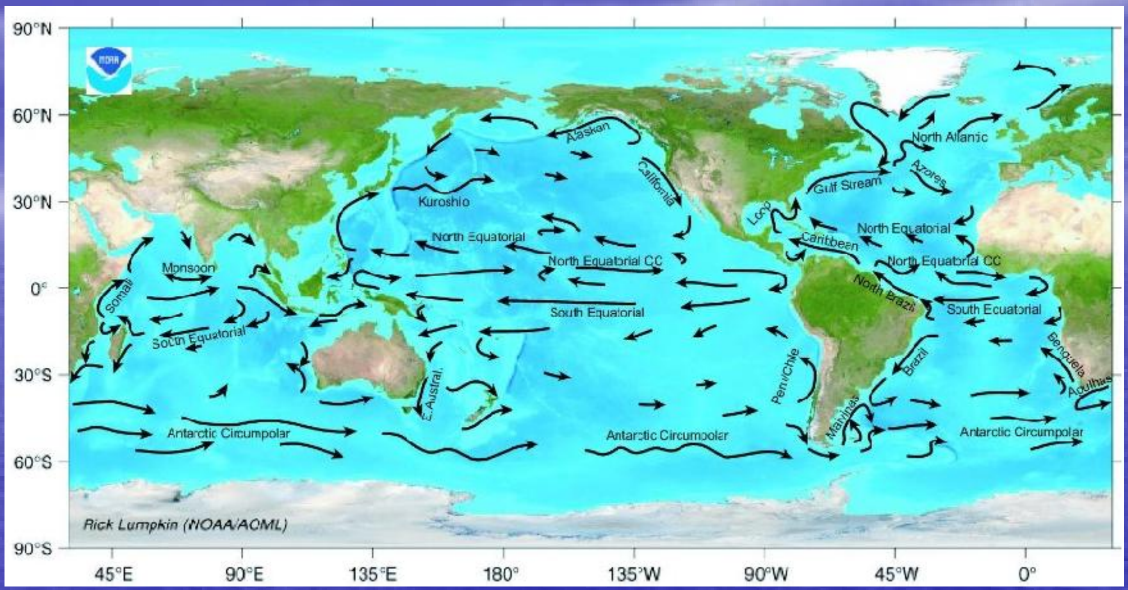
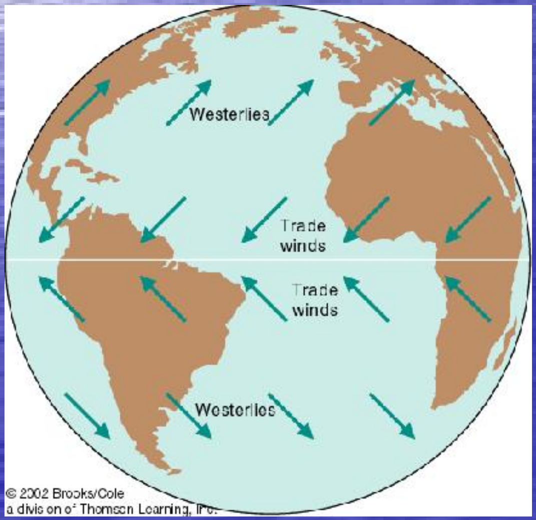
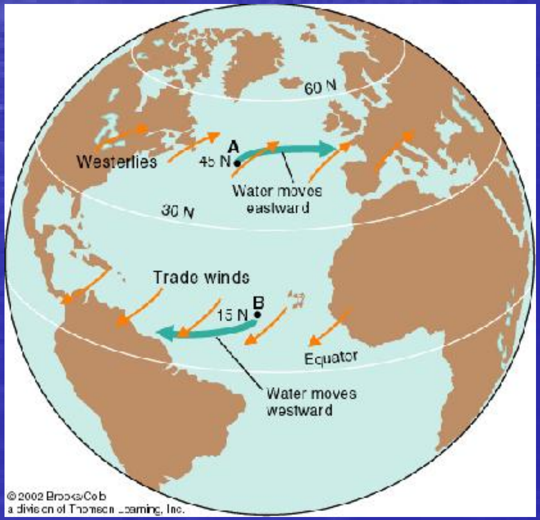
# Development of Ocean Currents



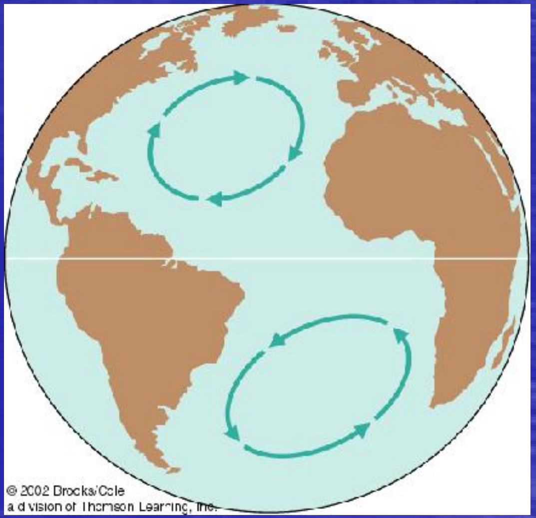




Prevailing Surface Winds

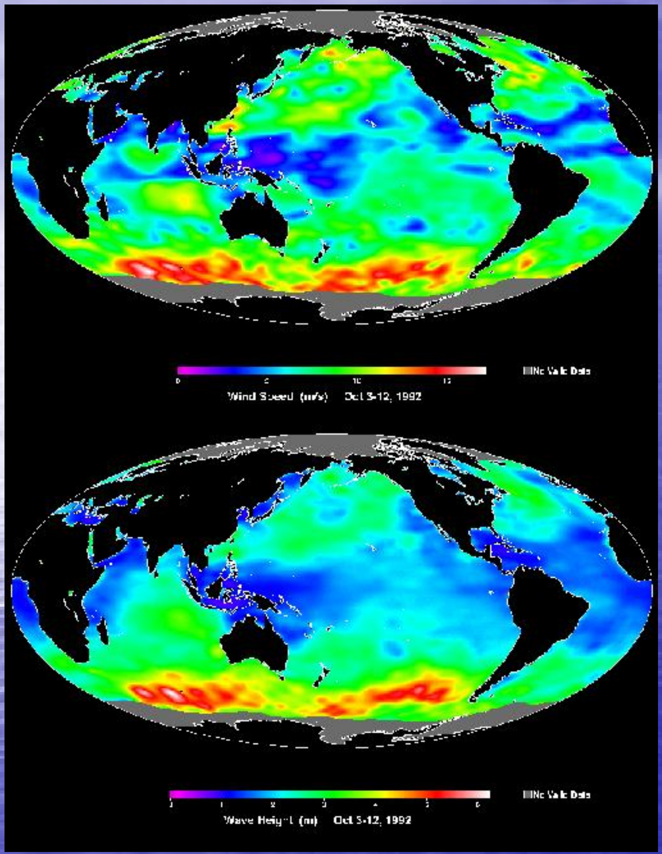



Wind-forced Ocean Currents




Resultant Ocean Gyres

# Wind – Wave Connection




## *Surface Wind Speeds*

- ***Highest = Westerlies***
- ***Lowest = Doldrums/ ITCZ***

## *Wave Heights*

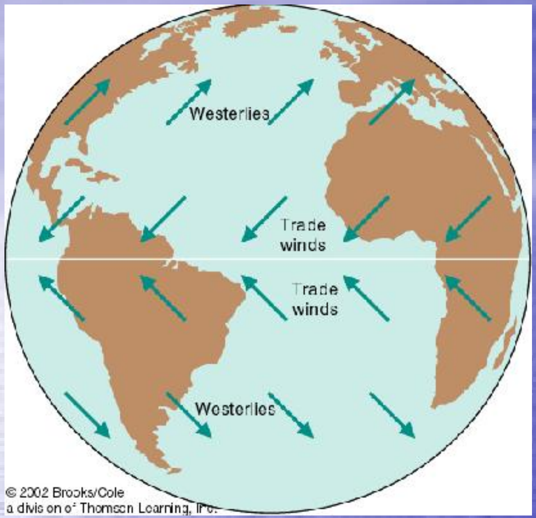
- ***Highest = High Latitude***
- ***Lowest = Low Latitudes***

**KEY POINTS**

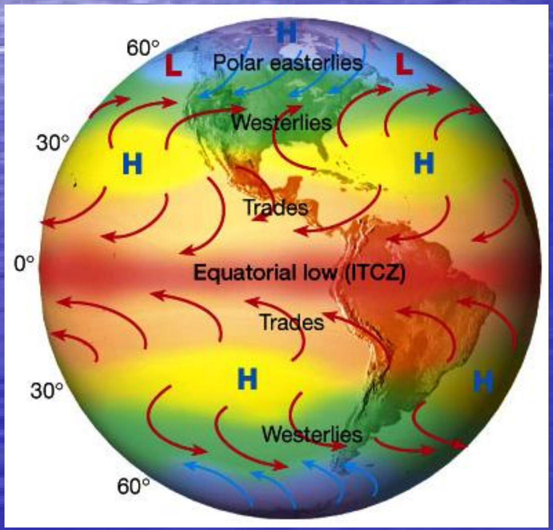
1) Ocean seas and swell are direct result of ocean surface winds

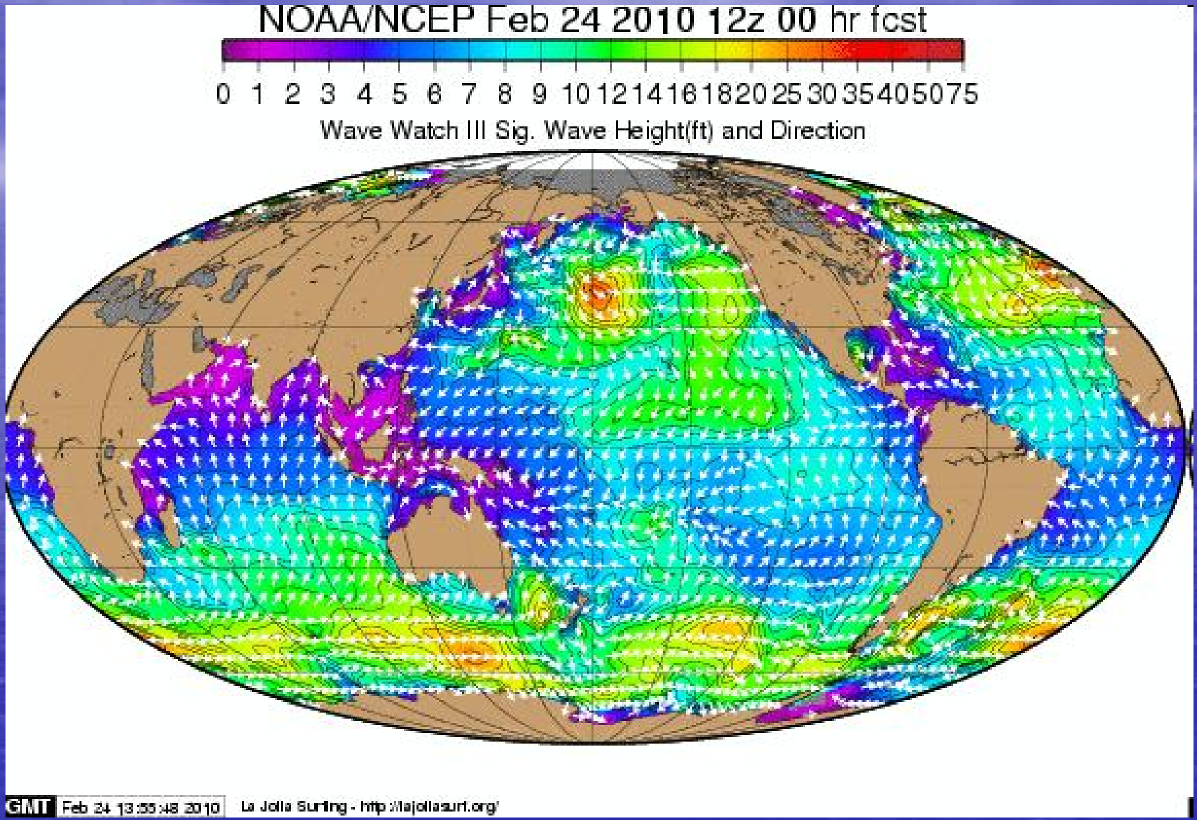
2) The stronger the wind, the larger the seas and swell

# Development of Ocean Wind Waves




**Prevailing Surface Winds**



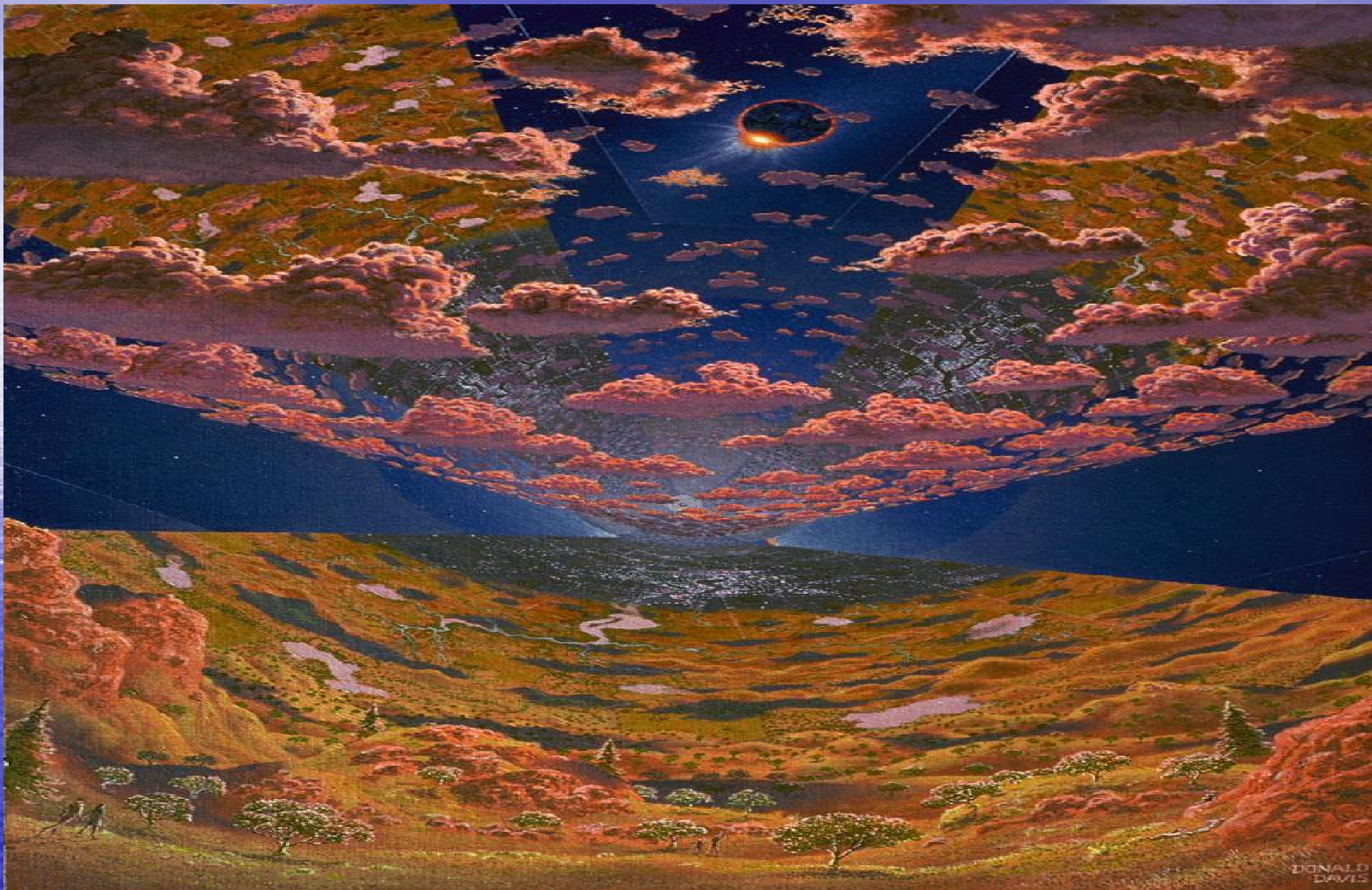

**Resultant Ocean Wind Swell**

# Atmospheric Circulation

## Review of Key Concepts

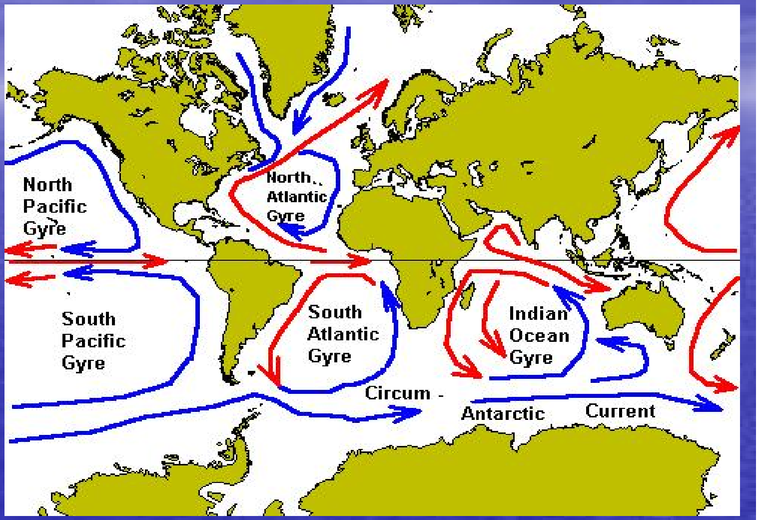
- Earth's atmosphere consists mostly of $N_2$ and $O_2$
- Differential solar heating of Earth's surface produces an over-heated equator and under-heated poles
- Differential solar heating of Earth's surface, coupled with gravity, drives atmospheric convection, i.e. global-scale, circulation system of winds
- The Earth has three major atmospheric circulation cells in each hemisphere – a total of six around the planet
- Earth's rotation causes moving air masses to curve – **left** in the N. Hemisphere and **right** in the S. Hemisphere, a.k.a. the **Coriolis Effect**
- Atmospheric circulation is responsible for the transfer of **2/3rds** of Earth's surface heat from the equator to the poles
- Spinning storm systems are of two types: Tropical and Extra-tropical
- Circulation of atmosphere and ocean moderates Earth's surface temperatures, and shapes weather and climate
- Surface winds and storms generate ocean currents and wind waves

# Discussion

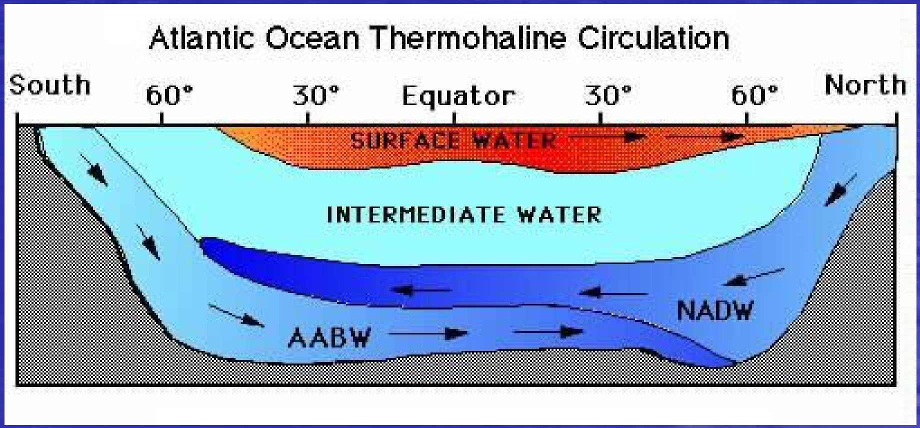


# Preparation for Next Lecture – Ocean Circulation

1) Read Chapter on Ocean Circulation and Currents
2) Review End-of-Chapter Questions and Exercises
3) Review Instructor's classroom website for:
   - ✓ Course Schedule
   - ✓ Lecture Notes
   - ✓ Lecture Presentation




Surface Currents




Deep Currents