Tropical Cyclones: Formation and Conditions

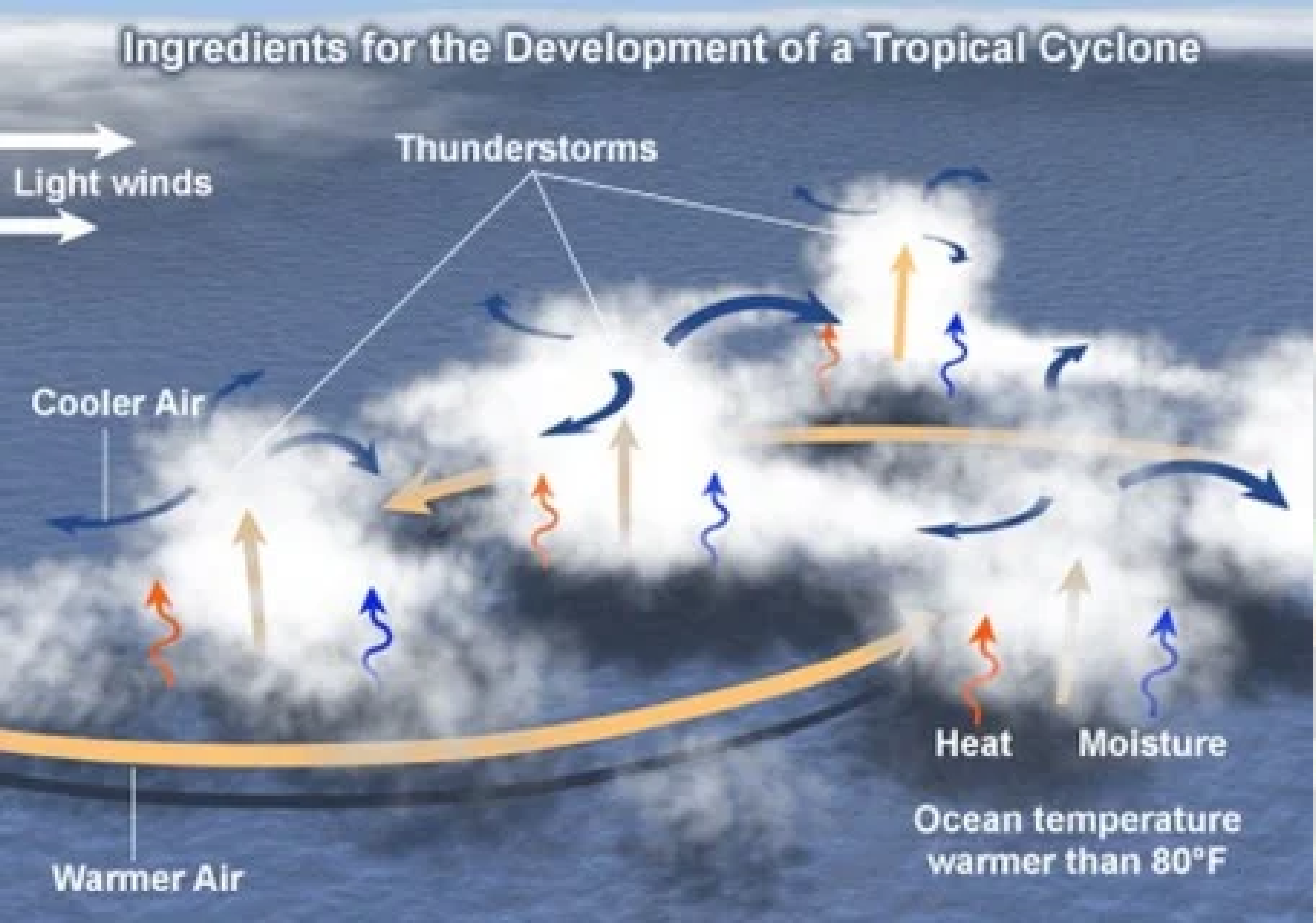
What are Tropical Cyclones?

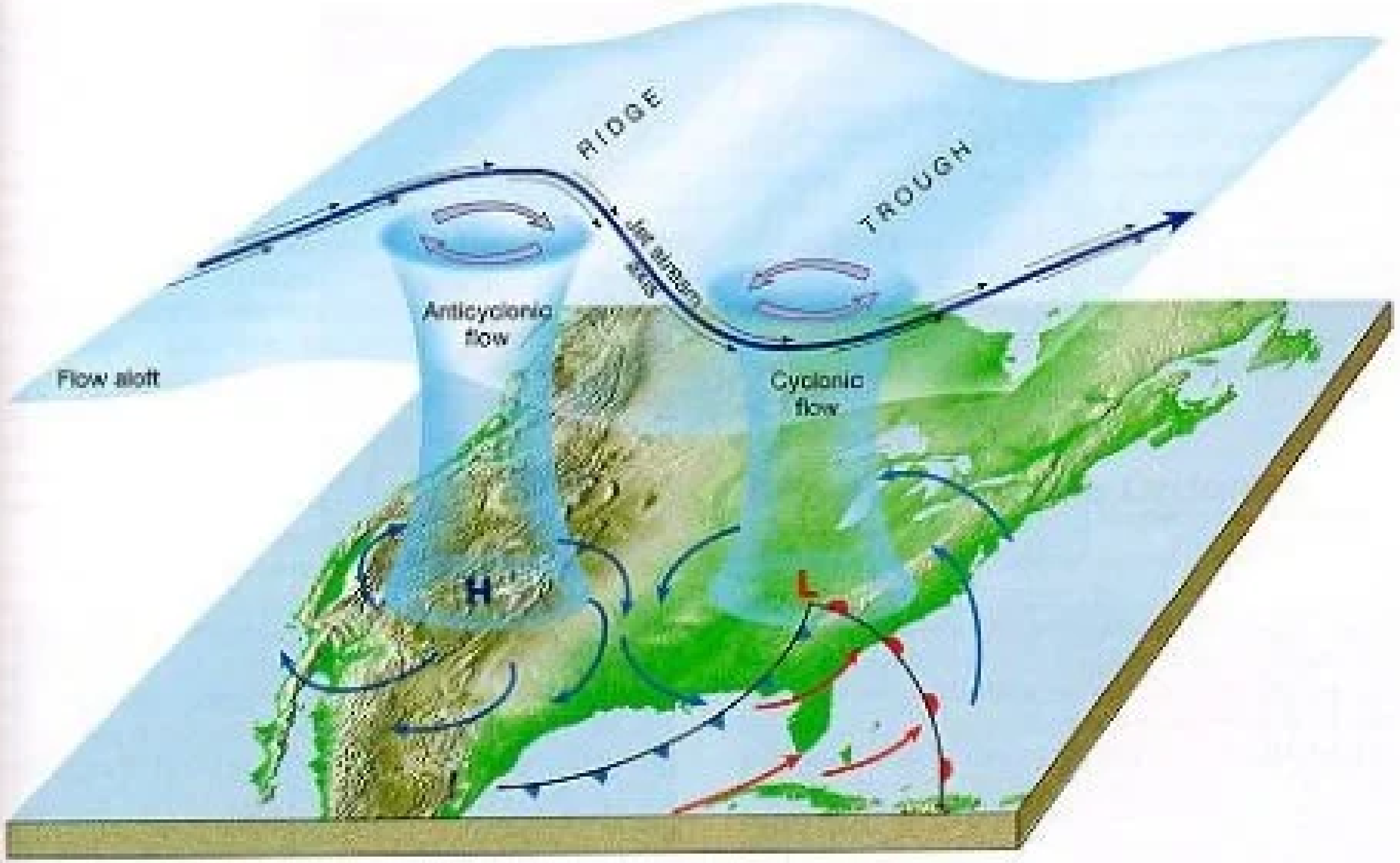
- Violent storms originating over warm tropical oceans
- Move towards coastal areas, causing destruction due to:
- Strong winds (squalls)
- Heavy rainfall (torrential rainfall)
- Storm surges (abnormal rise in sea level)

Characterized by closed circulation of air around a low-pressure center.
Whirling motion results from the rapid upward movement of hot air and Coriolis force.

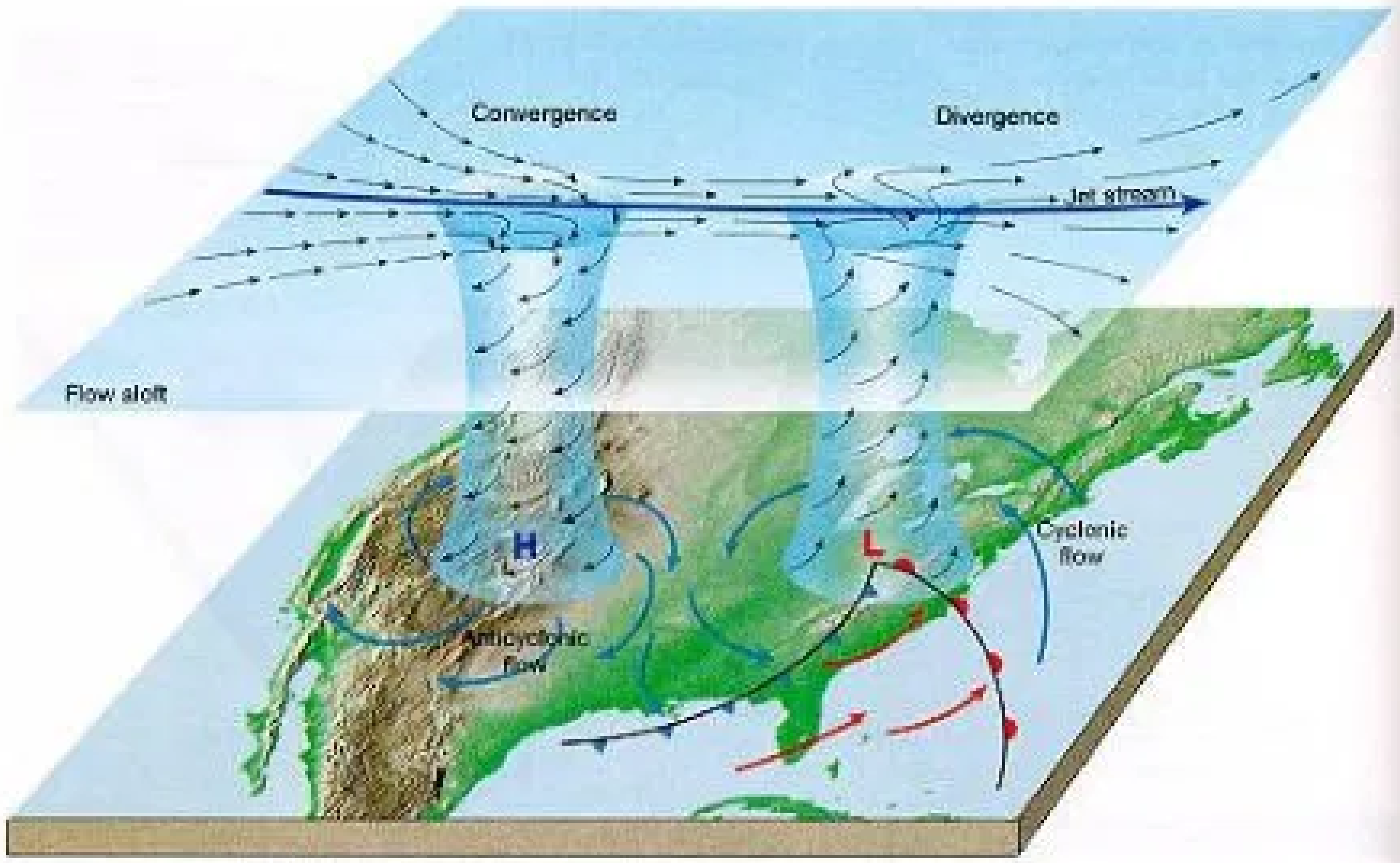
Conditions Necessary for Formation:

- Warm Ocean Waters: Sea surface temperature above 27°C provides energy and moisture.
- Coriolis Force: Sufficient strength to create a cyclonic vortex (zero at the equator, increases with latitude).
- Minimal Vertical Wind Shear: Uniform winds aid cyclone development.
- Pre-existing Low-Pressure Area: Acts as a seed for cyclone formation.
- Upper-Level Divergence: Allows rising air to escape, maintaining low pressure at the center.
- High Humidity: Moisture in the mid-troposphere leads to the formation of towering cumulonimbus clouds.


Ingredients for the Development of a Tropical Cyclone
Light winds
Thunderstorms
Cooler Air
Heat
Moisture
Ocean temperature warmer than 80°F
Warmer Air



Vorticity provided by flow in the jet stream generates cyclonic flow near a trough and anticyclonic flow adjacent to a ridge.



Idealized depiction of the support that divergence and convergence aloft provide to cyclonic and anticyclonic circulation at the surface.

Why Western Ocean Margins are Favored:

- Deep Warm Water: Western tropical oceans have a thicker layer of warm water (due to warm ocean currents) providing ample moisture for cyclone development.
- Cold Currents: Eastern oceans have cooler surface temperatures due to cold currents, hindering cyclone formation.

Why Cyclones Occur Mostly in Late Summers:

- Enhanced Whirling: Doldrums (ITCZ) are farthest from the equator during late summers, promoting stronger cyclonic motion.
- Overheated Air: Warm ocean waters and increased solar radiation create favorable conditions.


ABHIGYAN
ACADEMY

Other Factors:

- Low-Level Disturbances: Pre-existing disturbances (like thunderstorms) act as seeds for cyclones.
- Temperature Contrast: Temperature differences between air masses create instability, aiding cyclone formation.
- Upper Air Disturbance: Remnants of temperate cyclones can trigger tropical cyclone development.
- Upper Tropospheric Divergence: Helps maintain low pressure at the center by removing rising air.
- Humidity: High humidity is needed for cloud formation and energy release through condensation.

Key Points:

- Cyclones are complex weather systems driven by various factors.
- Understanding these factors helps predict and mitigate their impacts.
- Coastal regions are particularly vulnerable to the destructive effects of cyclones and storm surges.

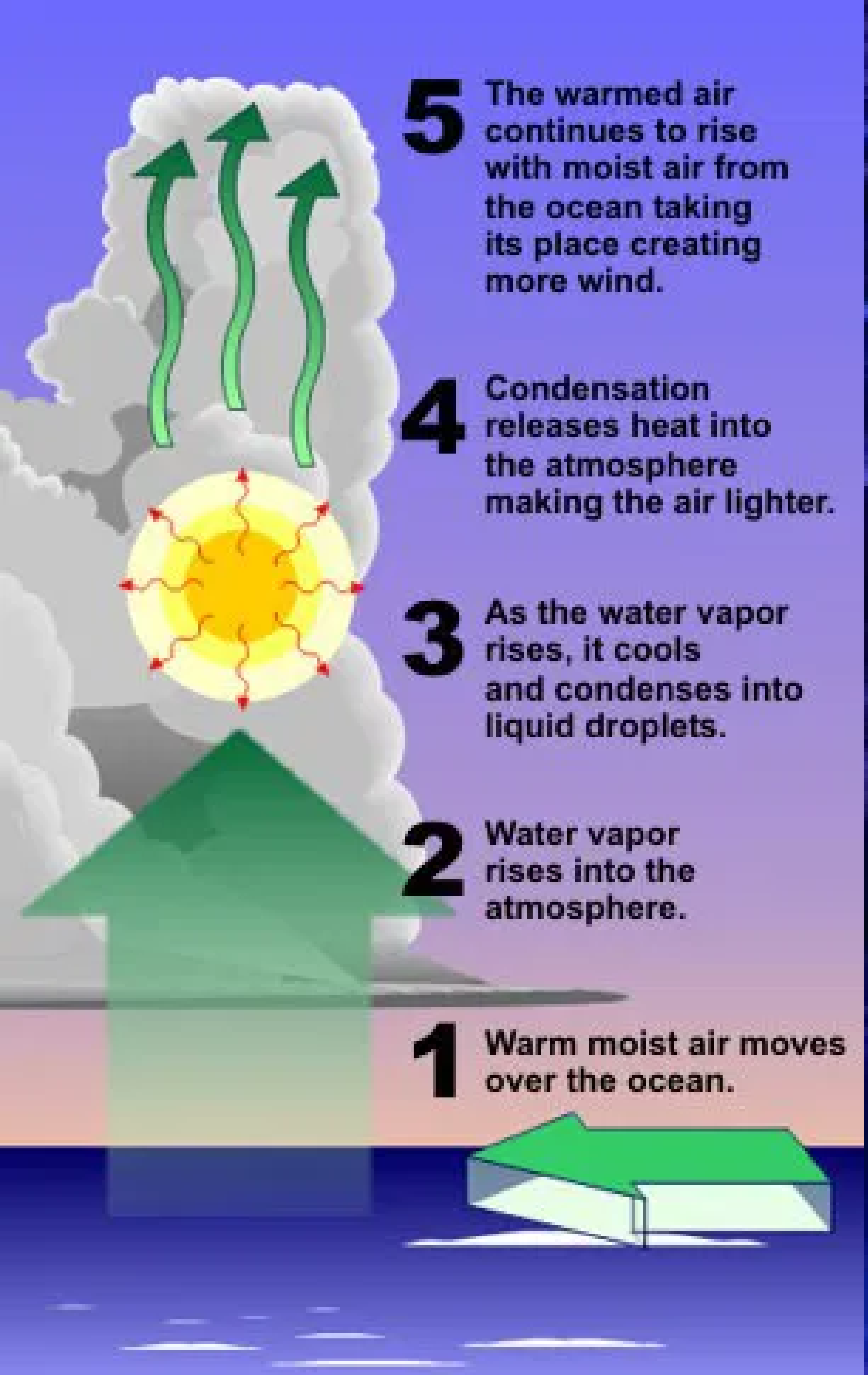
Origin and Development of Tropical Cyclones: Simplified

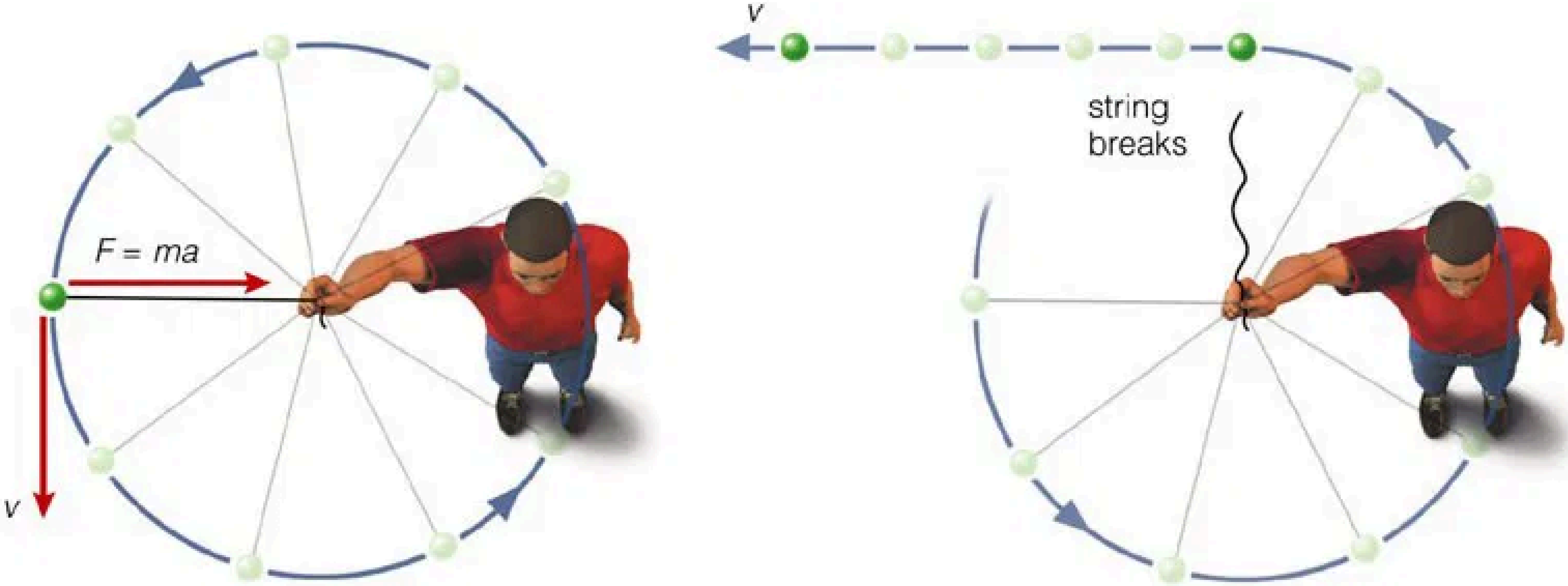
Origin:

- Tropical cyclones form over warm tropical oceans in late summers.
- Strong local updrafts of warm, moist air gain a spinning motion due to the Earth's rotation (Coriolis force).
- Multiple thunderstorms merge to create an intense low-pressure system.

Early Stage:

- Warm, moist air rises, cools, and condenses, releasing heat.
- This heat fuels further rising and creates a low-pressure area, drawing in more air.
- Coriolis force deflects the incoming air, creating a cyclonic vortex (a spiraling column of air).
- The center of the vortex becomes the "eye" - a calm region surrounded by the intense "eye wall."


5 The warmed air continues to rise with moist air from the ocean taking its place creating more wind.
4 Condensation releases heat into the atmosphere making the air lighter.
3 As the water vapor rises, it cools and condenses into liquid droplets.
2 Water vapor rises into the atmosphere.
1 Warm moist air moves over the ocean.


F = ma
v
v
string
breaks

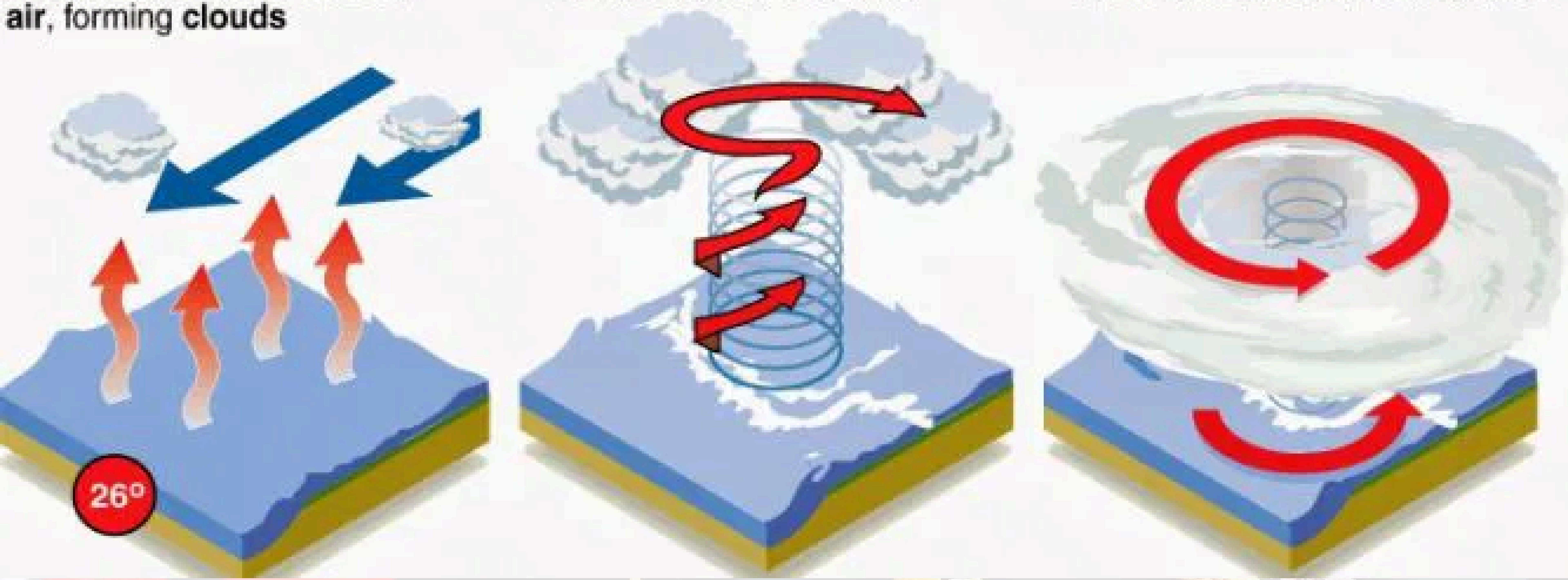
How tropical storms are formed

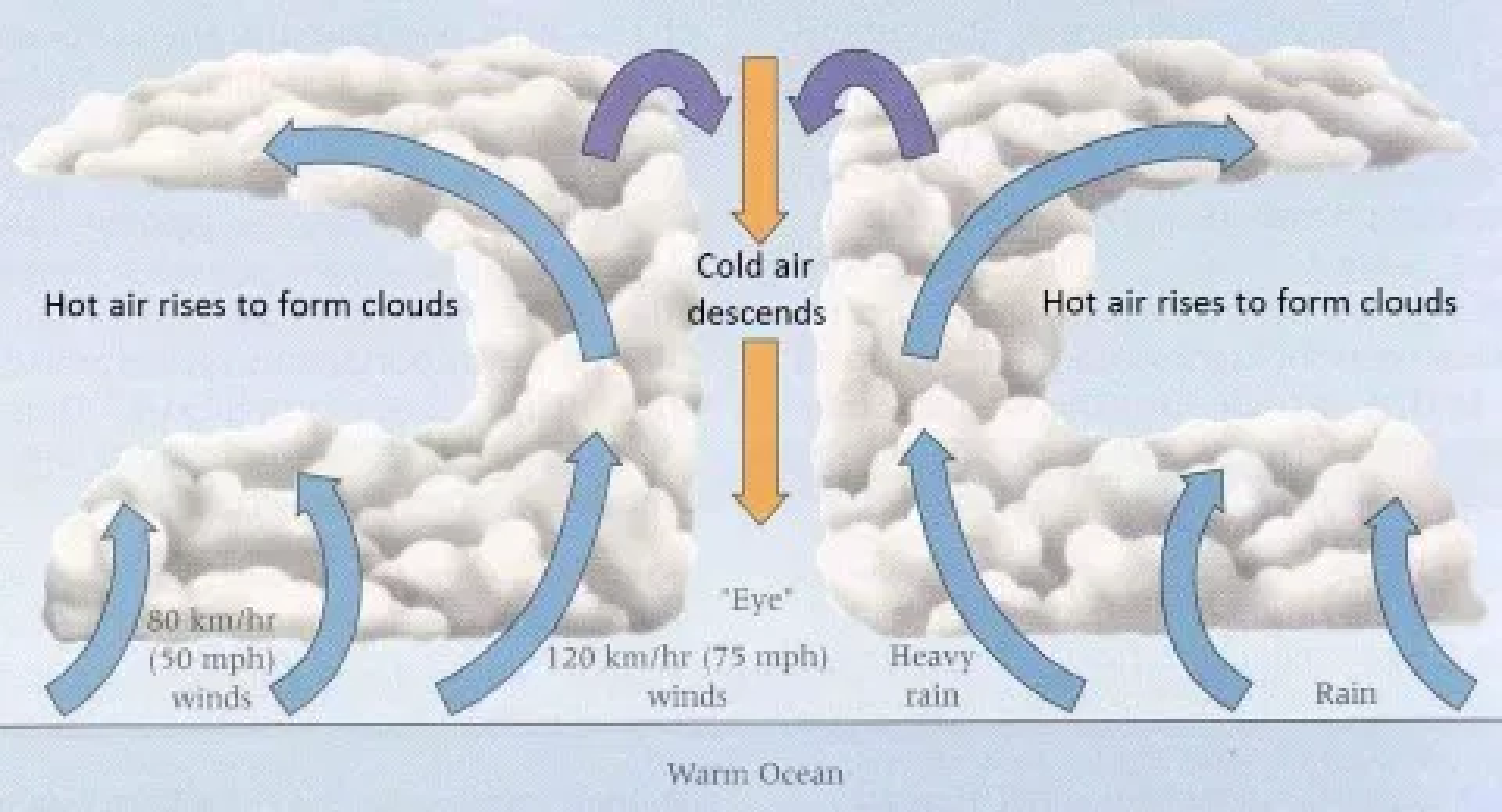
High humidity and ocean temperatures of over 26°C are major contributing factors

Water evaporates from the ocean surface and comes into contact with a **mass of cold air**, forming **clouds**

A **column of low pressure** develops at the centre. **Winds form** around the column

As pressure in the central column (the eye) weakens, the **speed of the wind around it increases**



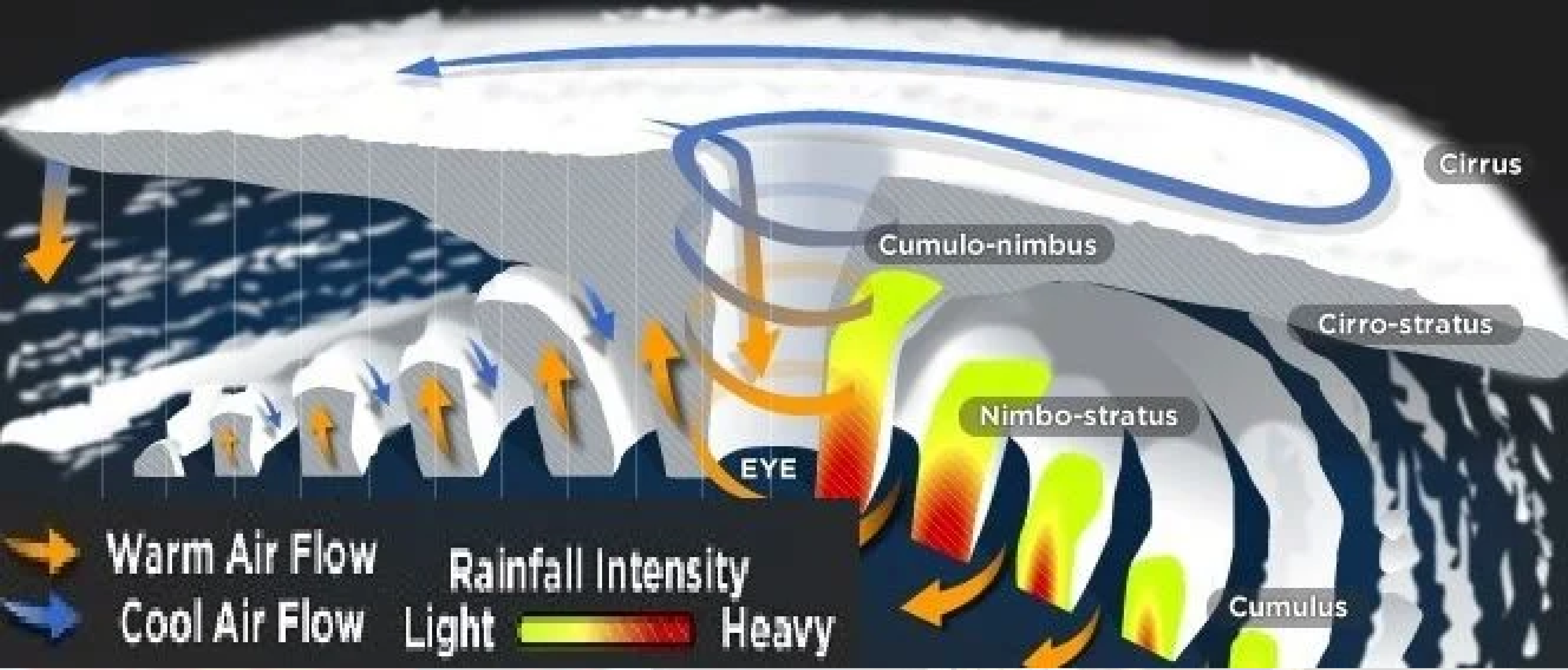

Cold air
descends
Hot air rises to form clouds
Hot air rises to form clouds
"Eye"
80 km/hr
(50 mph)
winds
120 km/hr (75 mph)
winds
Heavy
rain
Rain
Warm Ocean

Mature Stage:

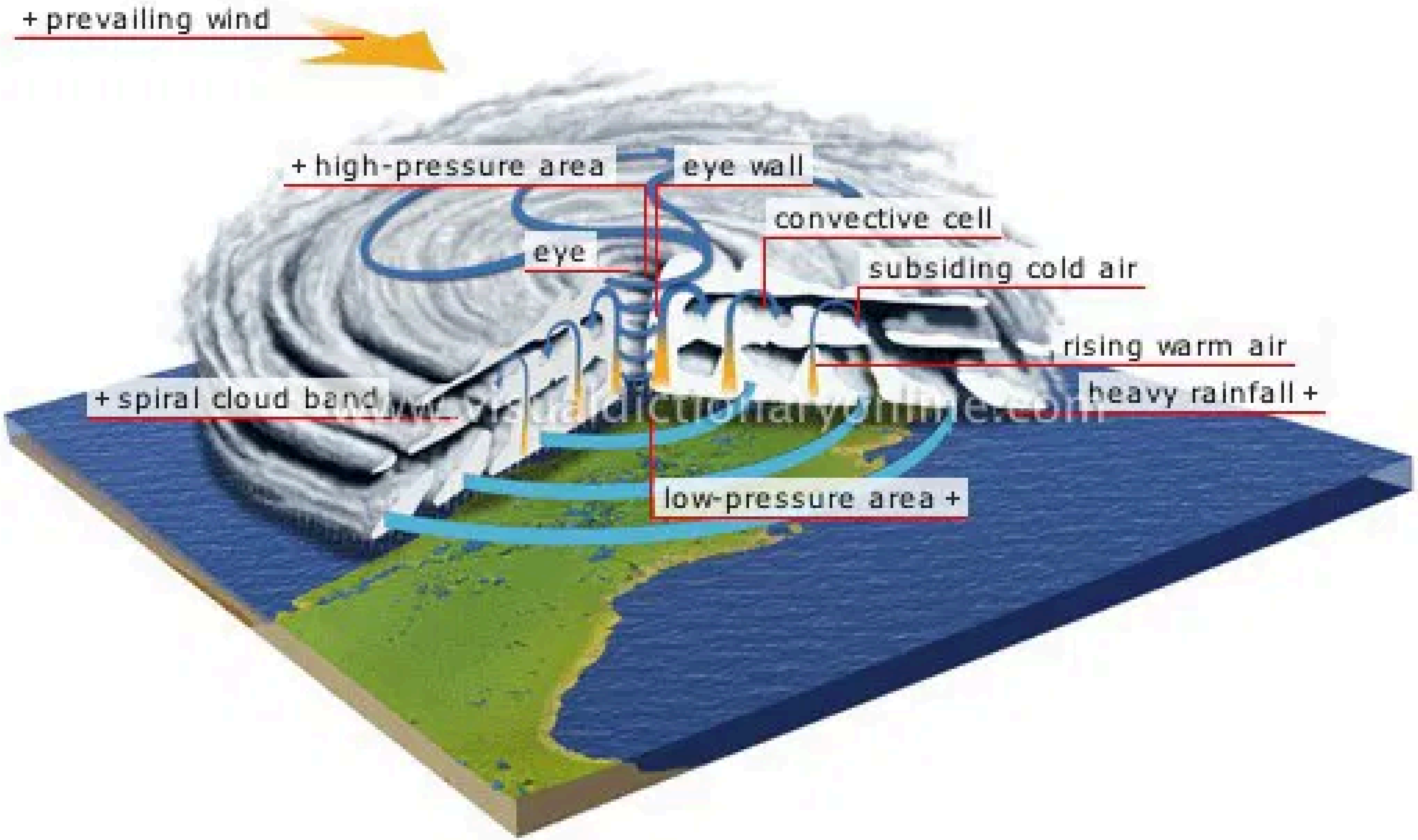
- Spiraling winds create multiple convective cells (areas of rising and sinking air).
- Rain bands (areas of intense rainfall) form under rising air with cumulonimbus clouds.
- Calm regions with subsiding air exist between rain bands.
- Cloud cover is densest at the center and decreases towards the periphery.

Structure of a Tropical Cyclone:

- Eye: Calm center with light winds and clear skies. Lowest surface pressure and warmest temperatures aloft.
- Eye Wall: Surrounds the eye. Area of most intense convection and highest winds.
- Spiral Bands: Long, narrow rain bands spiraling towards the center.
- Areas of maximum low-level convergence and upper-level divergence.



Cirrus
Cumulo-nimbus
Cirro-stratus
Nimbo-stratus
EYE
Cumulus
Warm Air Flow
Cool Air Flow
Rainfall Intensity
Light
Heavy


+ prevailing wind
+ high-pressure area
eye wall
convective cell
eye
subsiding cold air
rising warm air
+ spiral cloud band
heavy rainfall +
low-pressure area +

Vertical Structure:

- Inflow Layer (up to 3 km): Drives the storm by drawing in warm, moist air.
- Mid-Layer (3-7 km): Where the main cyclonic circulation occurs.
- Outflow Layer (above 7 km): Air flows outward in an anticyclonic pattern.

Key Points:

- Cyclones are fueled by warm ocean water and moisture.
- They dissipate when they move over land and lose their moisture source.
- The eye is a calm region surrounded by the intense eye wall.
- Rain bands are areas of heavy rainfall within the cyclone.
- The Coriolis force plays a key role in the cyclone's rotation.

Tropical Cyclones: Categories, Origins, and Characteristics

Categories of Tropical Cyclones

Based on Location and Name:

- South-east Caribbean: Hurricanes
- Philippines, Eastern China, Japan: Typhoons
- Bay of Bengal and Arabian Sea: Cyclones
- South-east African coast and Madagascar-Mauritius islands: Cyclones
- North-west Australia: Willy-willies

Characteristics of Tropical Cyclones

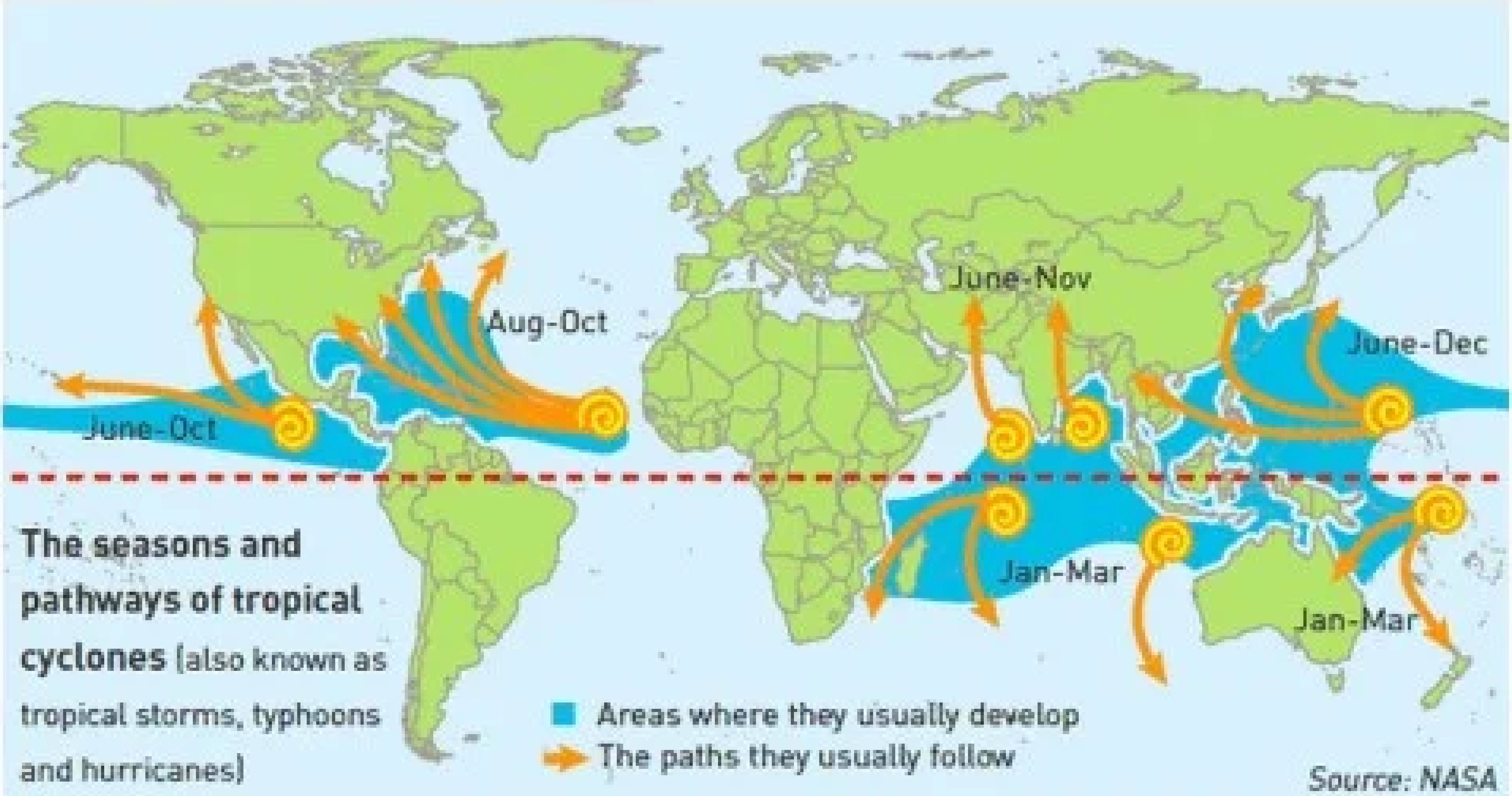
- Size and Shape:

1. Symmetrical elliptical shape (2:3 length to breadth ratio).
2. Compact size, ranging from 80 km near the center to 300-1500 km in diameter.

Cyclone Category	Wind Speed in Km/h	Damage Capacity
01	120-150	Minimal
02	150-180	Moderate
03	180-210	Extensive
04	210-250	Extreme
05	250 +	Catastrophic

Type of Disturbances	Wind Speed in Km/h
Low Pressure	Less than 31
Depression	31-49
Deep Depression	49-61
Cyclonic Storm	61-88
Severe Cyclonic Storm	88-117
Very Severe Cyclone	118-221
Super Cyclone	More than 221

Category	Australian name	US*	NW Pacific	Arabian Sea /Bay of Bengal
-	Tropical low	Tropical depression	Tropical depression	Depression or severe depression
1	Tropical cyclone	Tropical storm	Tropical storm	Cyclonic storm
2	Tropical cyclone	Tropical storm	Severe tropical storm	Severe cyclonic storm
3	Severe tropical Cyclone	Hurricane	Typhoon	Very severe cyclonic storm
4	Severe tropical cyclone	Hurricane	Typhoon	Very severe cyclonic storm
5	Severe tropical cyclone	Hurricane	Typhoon	Super cyclonic storm


June-Oct
Aug-Oct
June-Nov
June-Dec
Jan-Mar
Jan-Mar
The seasons and pathways of tropical cyclones (also known as tropical storms, typhoons and hurricanes)
Areas where they usually develop
The paths they usually follow
Source: NASA

- Wind Velocity and Strength:

1. Higher wind velocity at poleward margins and over oceans.
2. Wind speeds can range from 0 to 1200 km/hour.

- Path of Tropical Cyclones:

1. Start with a westward movement due to Earth's rotation and easterly winds.
2. Turn northwards around 20° latitude due to the Coriolis force.
3. Turn further northeastwards around 25° latitude due to continued Coriolis force deflection.
4. Turn eastwards around 30° latitude due to westerly winds.
5. Eventually lose energy and dissipate due to cooler ocean waters and increased wind shear.

Origin and Development:

- Origin: Multiple thunderstorms merge over warm oceans, creating a low-pressure system.

Early Stage:

1. Warm, moist air rises, cools, and condenses, releasing heat. This heat fuels further rising, creating a stronger low-pressure area.
2. Coriolis force causes the incoming air to spiral, forming a cyclonic vortex.
3. The center becomes the "eye," a calm region surrounded by the intense "eye wall."

Mature Stage:

1. Spiraling winds create multiple convective cells with alternating calm and violent regions.
2. Rain bands form under rising air, bringing intense rainfall.
3. Cloud cover is densest at the center and decreases outward.

Warning and Detection:

1. Monitoring Parameters: Pressure fall, wind velocity increase, storm track.
2. Monitoring Network: Weather stations, islands, radars, aircraft, and satellites.
3. Early Warning: Detection allows for 48-hour advance warnings, enabling preparations like evacuations and securing resources.

Tropical Cyclones: Favorable Conditions for Formation, Stages of Formation & Structure

What is a Storm Surge?

A storm surge is an abnormal rise in sea level caused by a cyclone making landfall.

It leads to seawater flooding coastal areas, causing devastating consequences like:

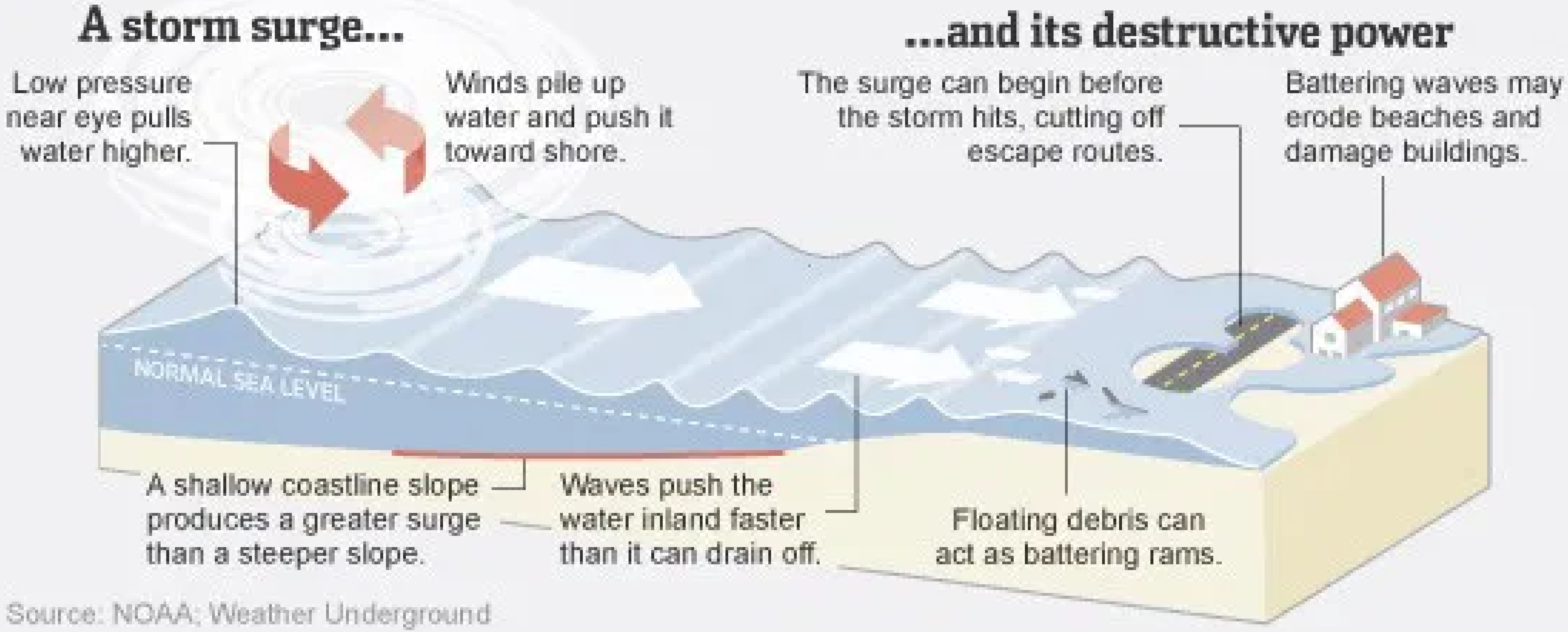
- Loss of life
- Extensive damage to property and crops
- Long-term impact on agriculture due to increased soil salinity

The severity of a storm surge depends on:

- The cyclone's intensity (wind speed and low pressure)
- The shape of the coastline (shallower areas experience higher surges)

What is a Storm Tide?

- A storm tide combines the storm surge with the normal astronomical tide.
- It represents the total water level during a cyclone, potentially causing even greater flooding.



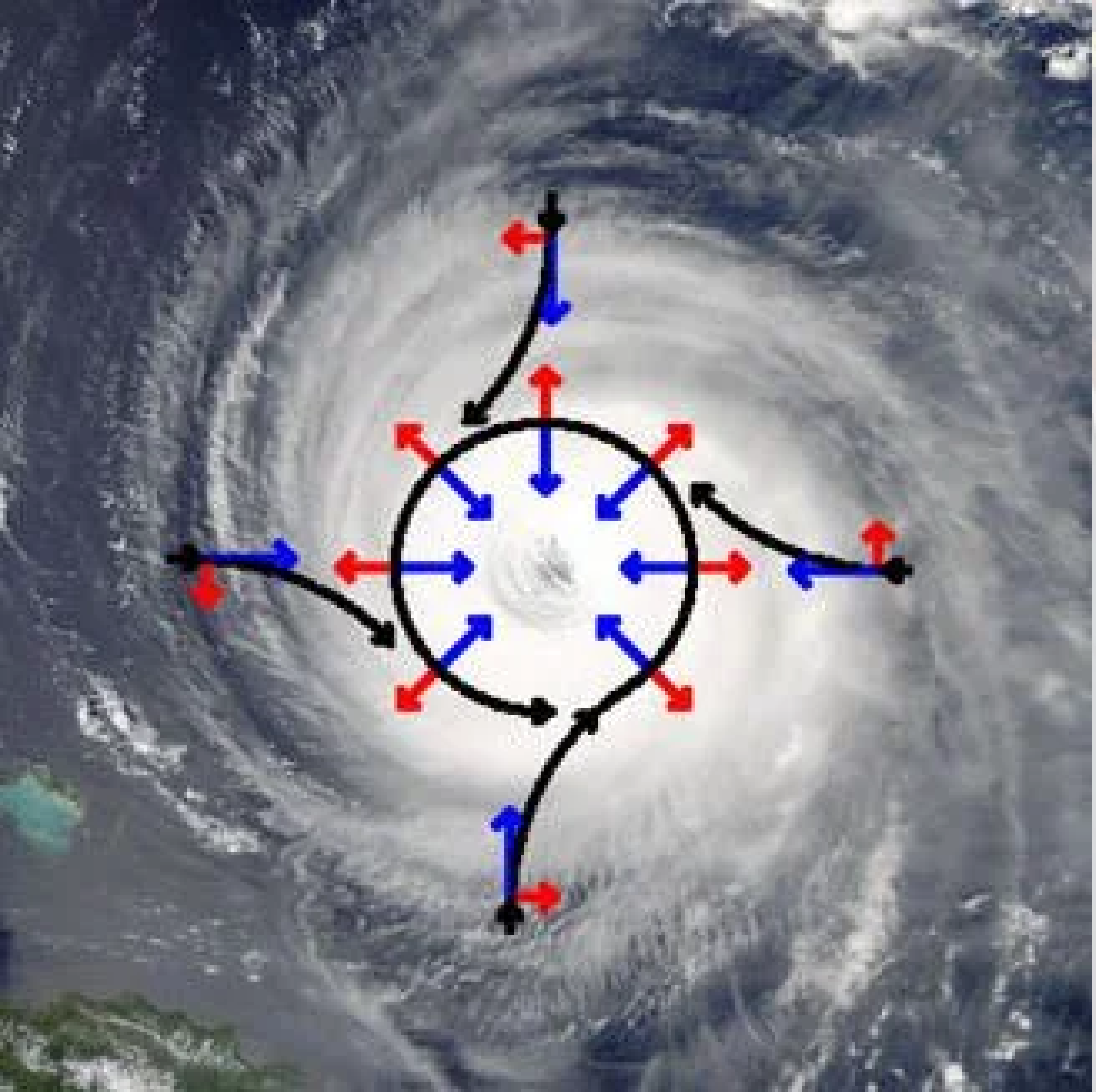
Source: NOAA; Weather Underground

Disaster Potential of Storm Surges

- High Storm Surges: The primary cause of fatalities during cyclones.
- Devastation: Causes widespread flooding, beach erosion, embankment damage, and harm to vegetation.
- Waterborne Diseases: Contamination of drinking water sources leads to outbreaks of diseases.
- Strong Winds (Gales): Uproot trees, damage homes, disrupt communication, and cause further loss of life and property.
- Historical Impact: The Bay of Bengal region has witnessed significant loss of life due to cyclones and storm surges.

Key Takeaway

Storm surges are a major threat during cyclones, causing widespread destruction and loss of life. Understanding the factors that influence storm surges and their potential impacts is crucial for effective disaster preparedness and mitigation in coastal areas.



ABHIGYAN ACADEMY

Why Cyclones Rotate Counter-Clockwise/Clockwise:

Coriolis Force:

- Earth's rotation creates an apparent force that deflects winds.
- Northern Hemisphere: Deflection to the right, causing counter-clockwise rotation in cyclones.
- Southern Hemisphere: Deflection to the left, causing clockwise rotation.

Low-Pressure Systems:

- Air rushes in to fill the low-pressure area at the cyclone's center.
- Coriolis force deflects this air, initiating rotation.

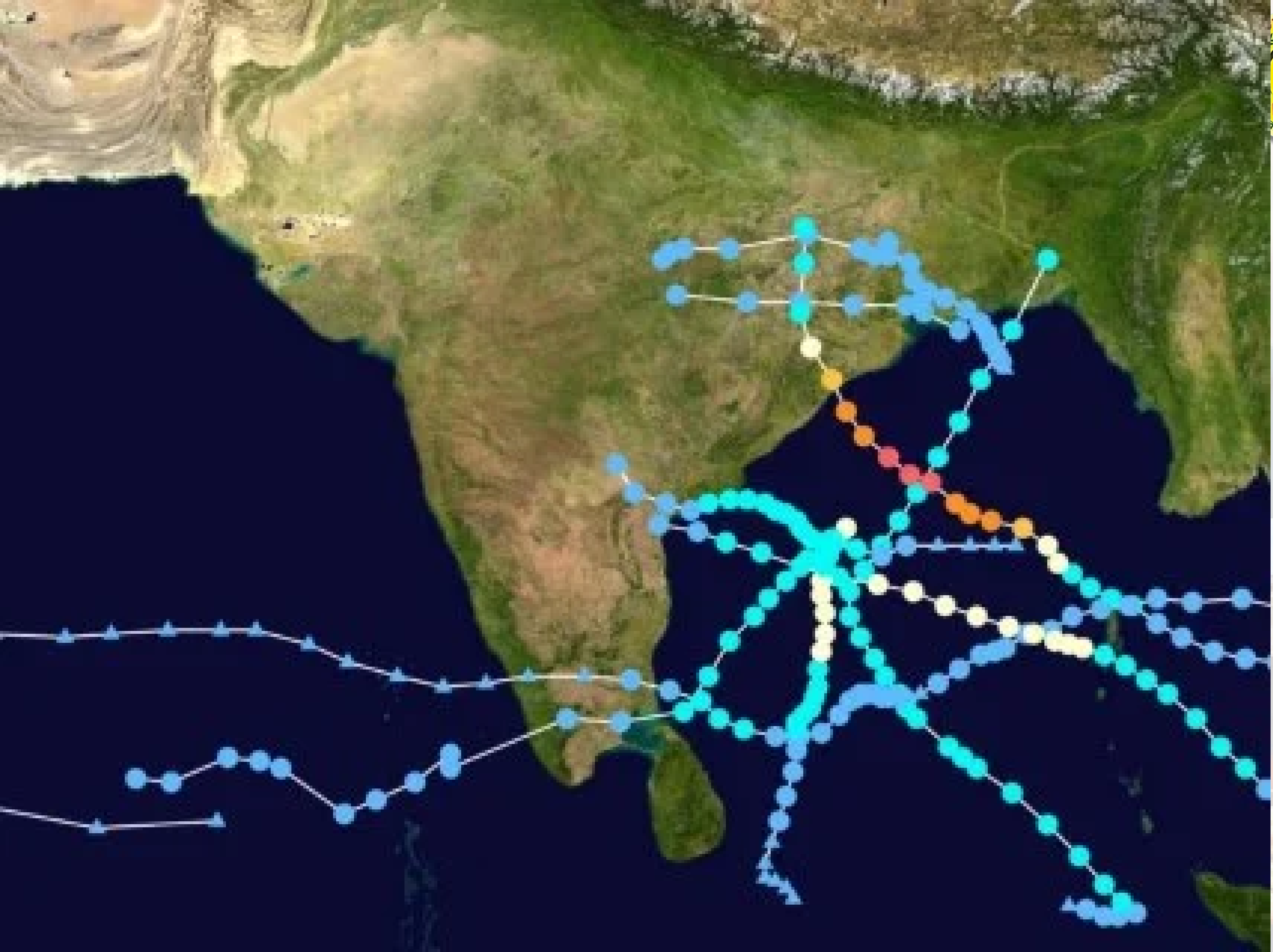
Fewer Cyclones in the Arabian Sea vs. Bay of Bengal:

Bay of Bengal: Receives more cyclones due to:

- Cyclones forming directly over the Bay of Bengal and Andaman Sea.
- Remnants of typhoons from the Northwest Pacific crossing over.

Arabian Sea: Fewer cyclones because:

- Cyclones mainly form directly over the Arabian Sea.
- Remnants of Bay of Bengal cyclones rarely cross over due to weakening over land.
- Cooler sea surface temperatures in the Arabian Sea.



Few Cyclones During Southwest Monsoon:

- Strong Vertical Wind Shear: Westerly winds in the lower troposphere and easterly winds in the upper troposphere create large vertical wind shear. This inhibits cyclone development.
- Shift in Cyclone Formation Zone: The potential zone shifts to the North Bay of Bengal.
- Shorter Oceanic Stay: Depressions formed along the monsoon trough make landfall quickly, limiting their intensification into cyclones.

Tropical Cyclones: Origin, Characteristics, & Monitoring

Origin & Development:

- Originate over warm tropical oceans in late summers.
- Multiple thunderstorms merge, creating a low-pressure system.
- Rising warm air cools, condenses, and releases heat, fueling further rising.
- Coriolis force causes air to spiral, forming a cyclonic vortex.
- Center becomes the "eye" (calm), surrounded by the intense "eye wall."
- Mature stage: spiraling winds create convective cells and rain bands.

Characteristics:

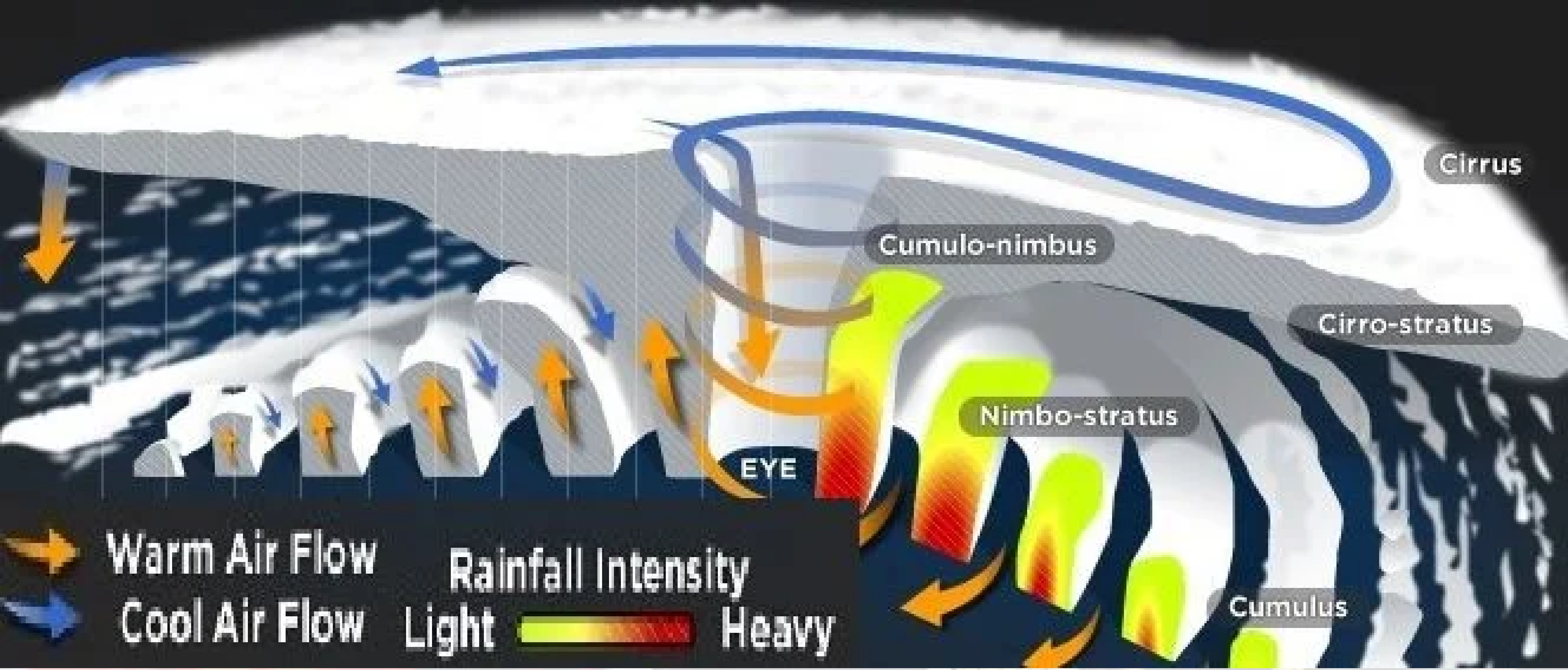
- Shape: Symmetrical elliptical (2:3 length-to-breadth ratio)
- Size: Compact, 80 km near center, can grow up to 1500 km.
- Wind Velocity: Higher at poleward margins and over oceans, ranging from 0-1200 km/hour.
- Path: Typically westward, then north, northeast, and east, dissipating around 30° latitude due to cooler waters and wind shear.

Cyclone Names:

- Vary by region: Hurricanes (Atlantic), Typhoons (W. Pacific), Cyclones (Indian Ocean), Willy-willies (W. Australia).
- In the Indian Ocean, names are contributed by member countries and assigned in order of submission.

Cyclone Frequency:

- Global average: 80 cyclones per year
- North Indian Ocean: 5-6 cyclones per year (4:1 ratio Bay of Bengal to Arabian Sea)
- Bay of Bengal has more cyclones due to warmer waters and typhoon remnants.
- Fewer cyclones during southwest monsoon due to strong wind shear and shorter oceanic stay for depressions.


Cirrus
Cumulo-nimbus
Cirro-stratus
Nimbo-stratus
EYE
Cumulus
Warm Air Flow
Cool Air Flow
Rainfall Intensity
Light
Heavy

Cyclone Monitoring & Warnings:

IMD (India Meteorological Department) monitors cyclones using:

- Weather stations
- Automatic weather stations
- Radar and satellite systems (INSAT)

4-Stage Warning System:

- Pre-Cyclone Watch (72 hours before)
- Cyclone Alert (48 hours before)
- Cyclone Warning (24 hours before)
- Post Landfall Outlook (12 hours before)

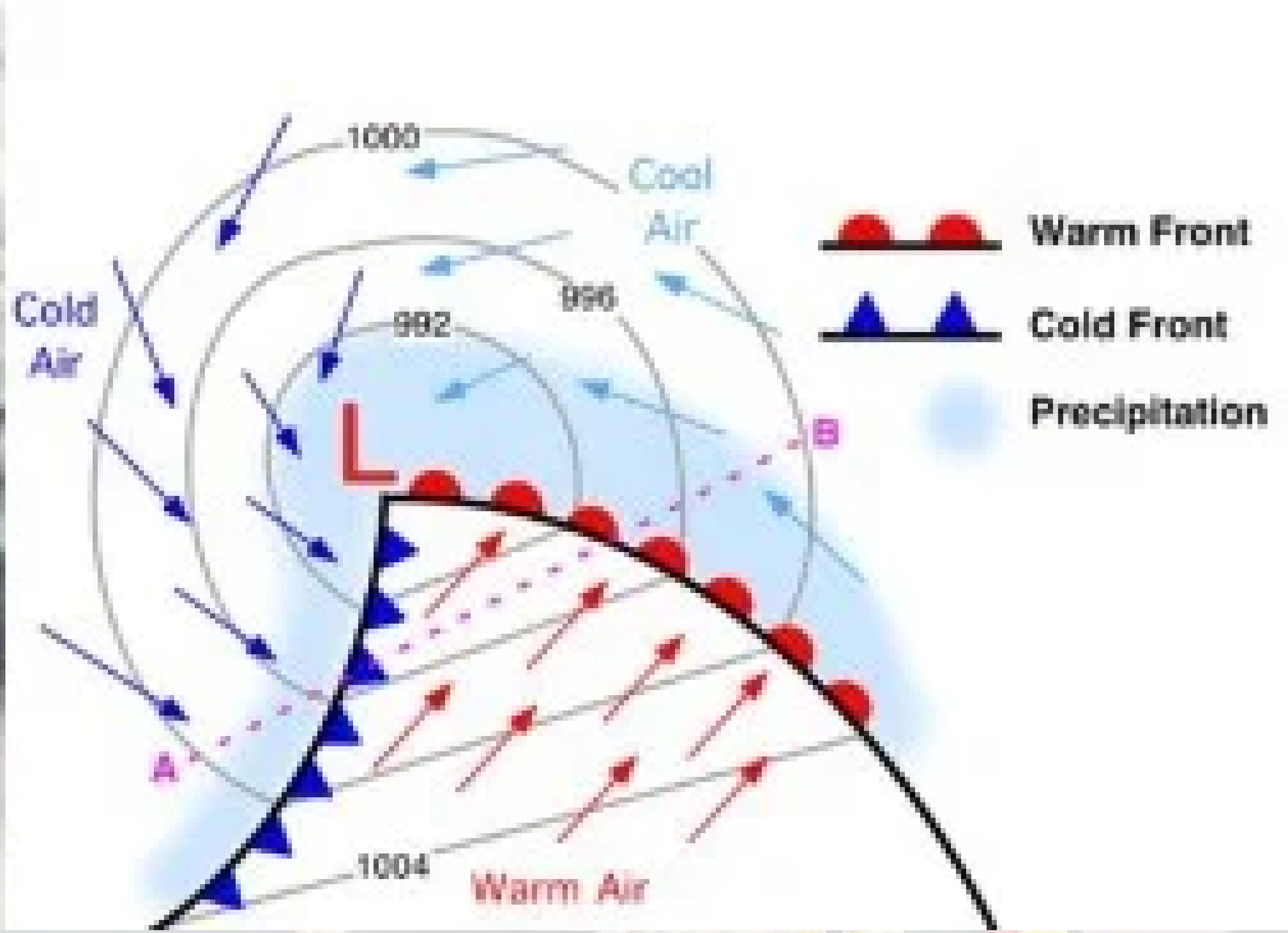
Additional Points:

- Strongest winds are on the right side of the cyclone due to its motion adding to the swirling winds.
- Cyclones crossing 20°N latitude often recurve and become more destructive.
- Upper tropospheric westerly troughs can influence cyclone formation, intensity, and movement.
- Central Dense Overcast (CDO) is the cirrus cloud shield associated with the cyclone's eye and rainbands.
- Various methods have been proposed to modify cyclones, but their effectiveness is debated.

Temperate Cyclones (Mid-Latitude Cyclones, Extra Tropical Cyclones, Frontal Cyclones, Wave Cyclones)

Origin and Development:

- Form in mid and high latitudes (35° to 65° latitude)
- Polar Front Theory: Warm and cold air masses meet, creating a polar front.
- Cold air pushes warm air up, creating a low-pressure area.
- Cyclonic circulation starts due to Earth's rotation and pressure differences.
- Warm and cold fronts develop, leading to precipitation.
- Occlusion occurs as the cold front catches up with the warm front, and the cyclone dissipates.


1000
Cool Air
Warm Front
Cold Air
996
992
Cold Front
Precipitation
L
B
A
1004
Warm Air

Seasonal Occurrence:

- Primarily in winter, late autumn, and spring.
- Associated with rainstorms and cloudy weather.

Distribution:

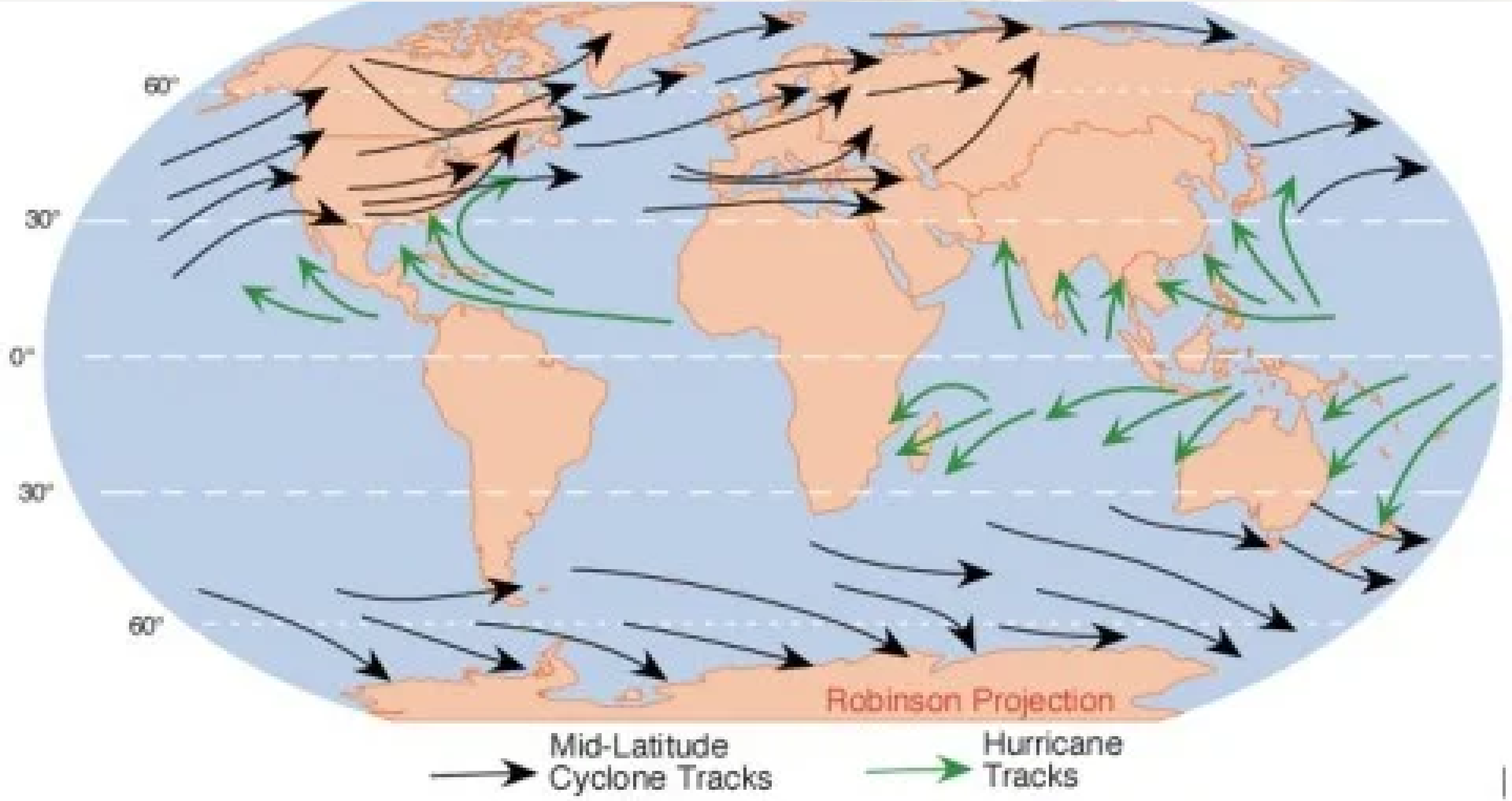
- USA and Canada: Sierra Nevada, Colorado, Eastern Canadian Rockies, Great Lakes.
- Iceland to Barents Sea, Russia, and Siberia.
- Winter storms over the Baltic Sea.
- Mediterranean basin extending to Russia and India (Western Disturbances).
- Antarctic frontal zone.

Characteristics:

- Size and Shape: Asymmetrical, inverted V shape, 500-600 km, can reach 2500 km (Polar Vortex), height 8-11 km.
- Wind Velocity and Strength: Stronger in eastern and southern parts, higher over North America.
- Orientation and Movement:
- Influenced by jet streams, oriented east-west.
- Movement depends on storm front orientation.
- Can move north, south, or east, eventually dissipating.

Structure:

- Northwestern sector: Cold sector
- Northeastern sector: Warm sector



60°
30°
0°
30°
60°
Robinson Projection
Mid-Latitude Cyclone Tracks
Hurricane Tracks

Associated Weather:

- Approach: Falling temperature, wind shifts, halo around sun/moon, cirrus clouds.
- Warm front: Light drizzle turning into heavy rain, rising temperature.
- Cold front: Clear weather, then falling temperature, cloudiness, and rain with thunder.
- Final: Clear weather establishes.

Fujiwhara Effect: Two cyclones can interact and rotate around each other.

Feature	Tropical Cyclone	Temperate Cyclone
Origin	Thermal (warm ocean waters)	Dynamic (Coriolis force, air mass movement)
Latitude	10° - 30° N/S	35° - 65° N/S (more in Northern Hemisphere)
Frontal System	Absent	Present (occluded front)
Formation	Over warm seas (>26-27°C), dissipates on land	Over land or sea
Season	Late summers (Aug-Oct)	Irregular, more in winters
Size	Smaller (100-500 km diameter)	Larger (300-2000 km diameter)
Shape	Elliptical	Inverted V
Rainfall	Heavy, short duration	Slow, continuous, lasting for days/weeks
Wind Velocity & Destruction	High (100-250 kmph), greater destruction from winds, storm surge, and rain	Lower (30-150 kmph), more destruction from flooding

Isobars	Circular, steep pressure gradient	V-shaped, low pressure gradient
Lifespan	Less than a week	2-3 weeks
Path	East-West, turns north at 20° and west at 30°	West-East (westerlies), moves away from equator
Temperature Distribution	Uniform at the center	Varies across sectors
Calm Region	"Eye" at the center	No single calm region
Driving Force	Latent heat of condensation	Density differences in air masses
Influence of Jet Streams	Unclear relationship	Strong influence on formation and path
Clouds	Fewer types (cumulonimbus, nimbostratus)	Variety of clouds at different elevations
Surface Anti-cyclones	Not associated, more destructive	Associated, less destructive
Influence on India	Both coasts affected, east coast more prone	Brings rain to NW India (Western Disturbances)

Geostrophic Wind & Jet Streams: Simplified Notes

Geostrophic Wind:

- Winds in the upper atmosphere (2-3 km above surface) are mostly influenced by pressure gradient force and Coriolis force.
- Pressure gradient force causes air to move from high to low pressure.
- Coriolis force deflects moving air (right in Northern Hemisphere, left in Southern Hemisphere).
- Geostrophic wind occurs when these forces balance, resulting in wind flowing parallel to isobars.

Why Winds Don't Flow Directly from Tropics to Poles:

- Upper-level winds are geostrophic (fast, low friction) and experience strong Coriolis deflection.
- This creates three distinct cells (Hadley, Ferrel, Polar) instead of one large cell.

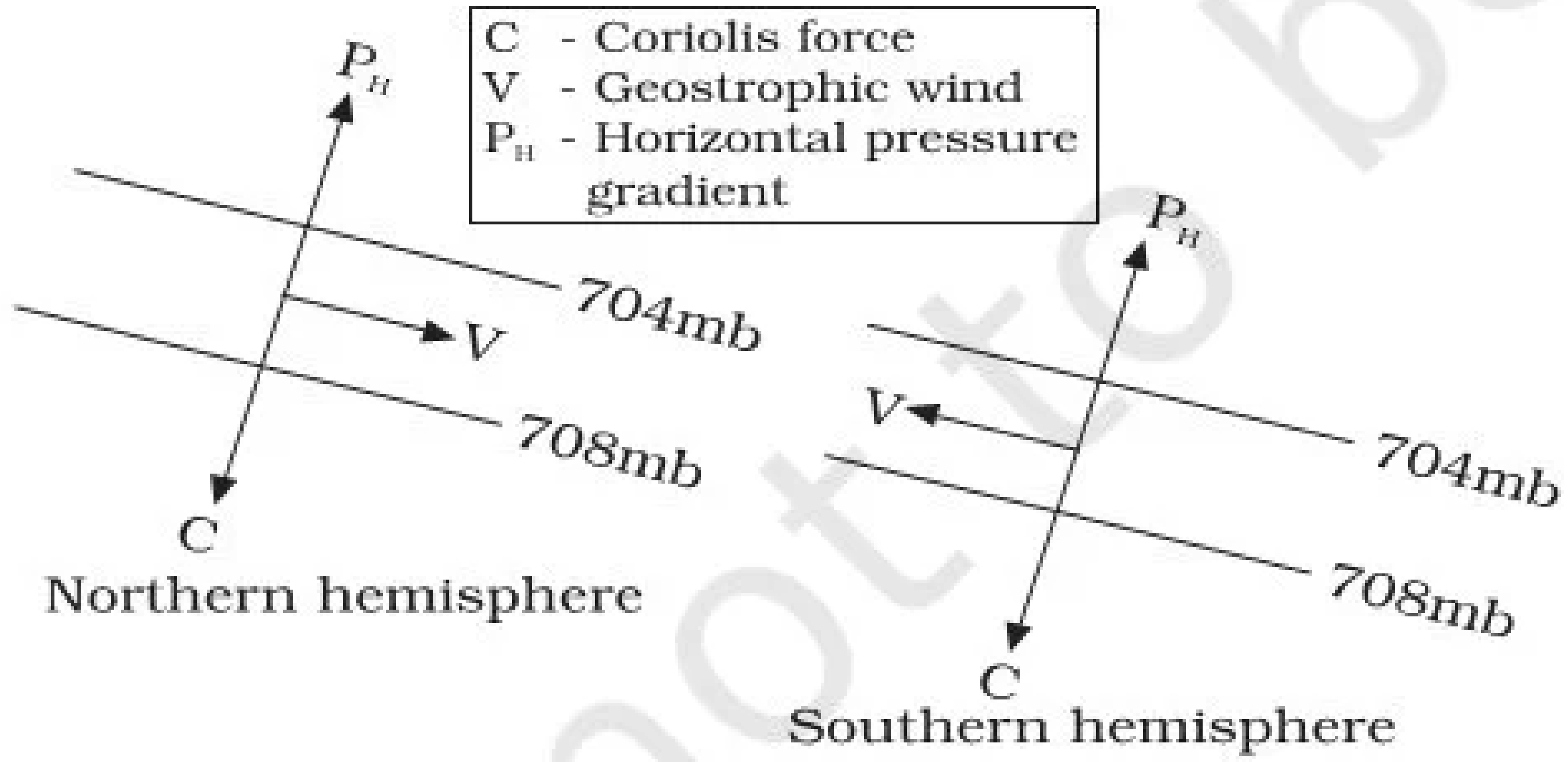
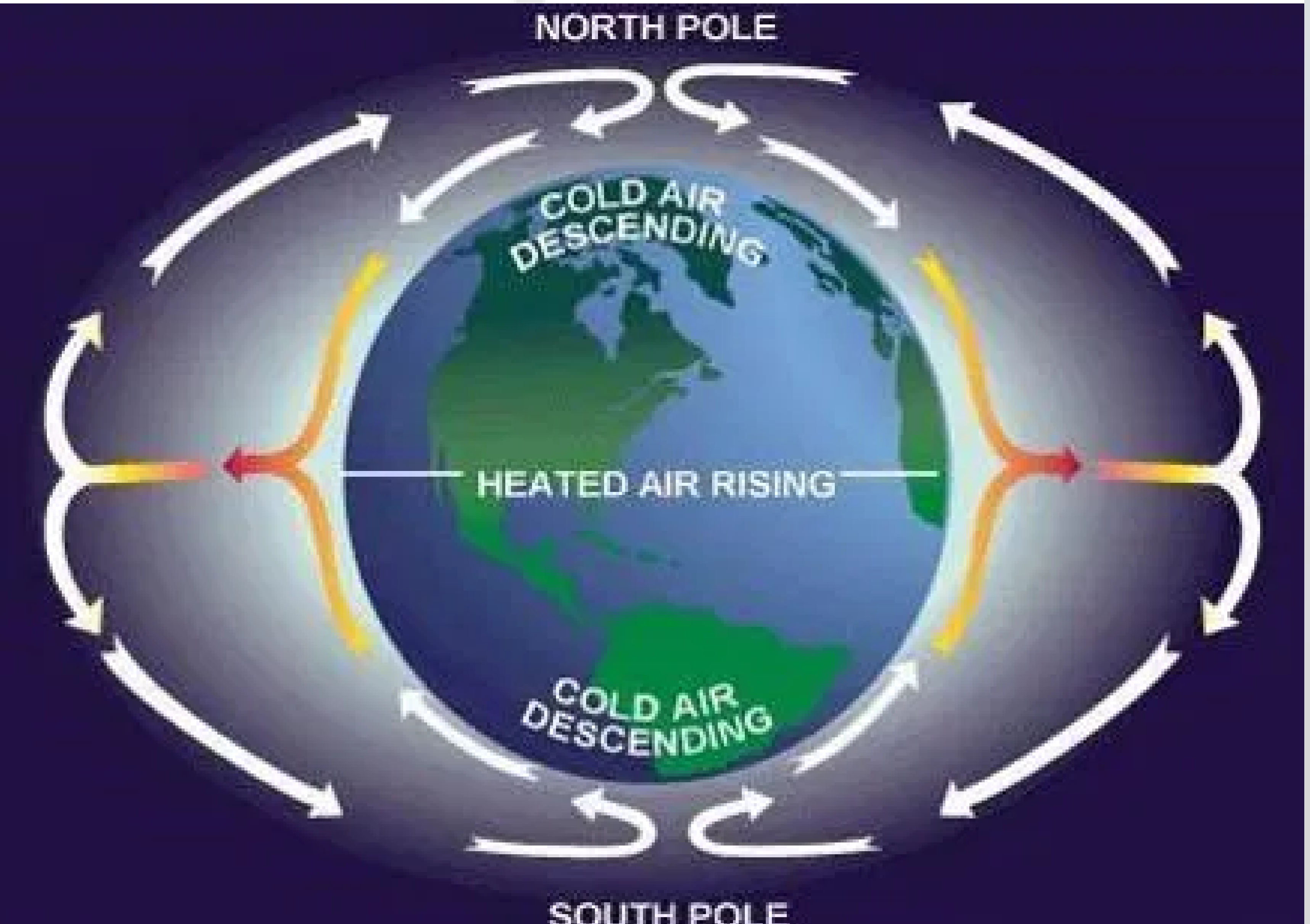


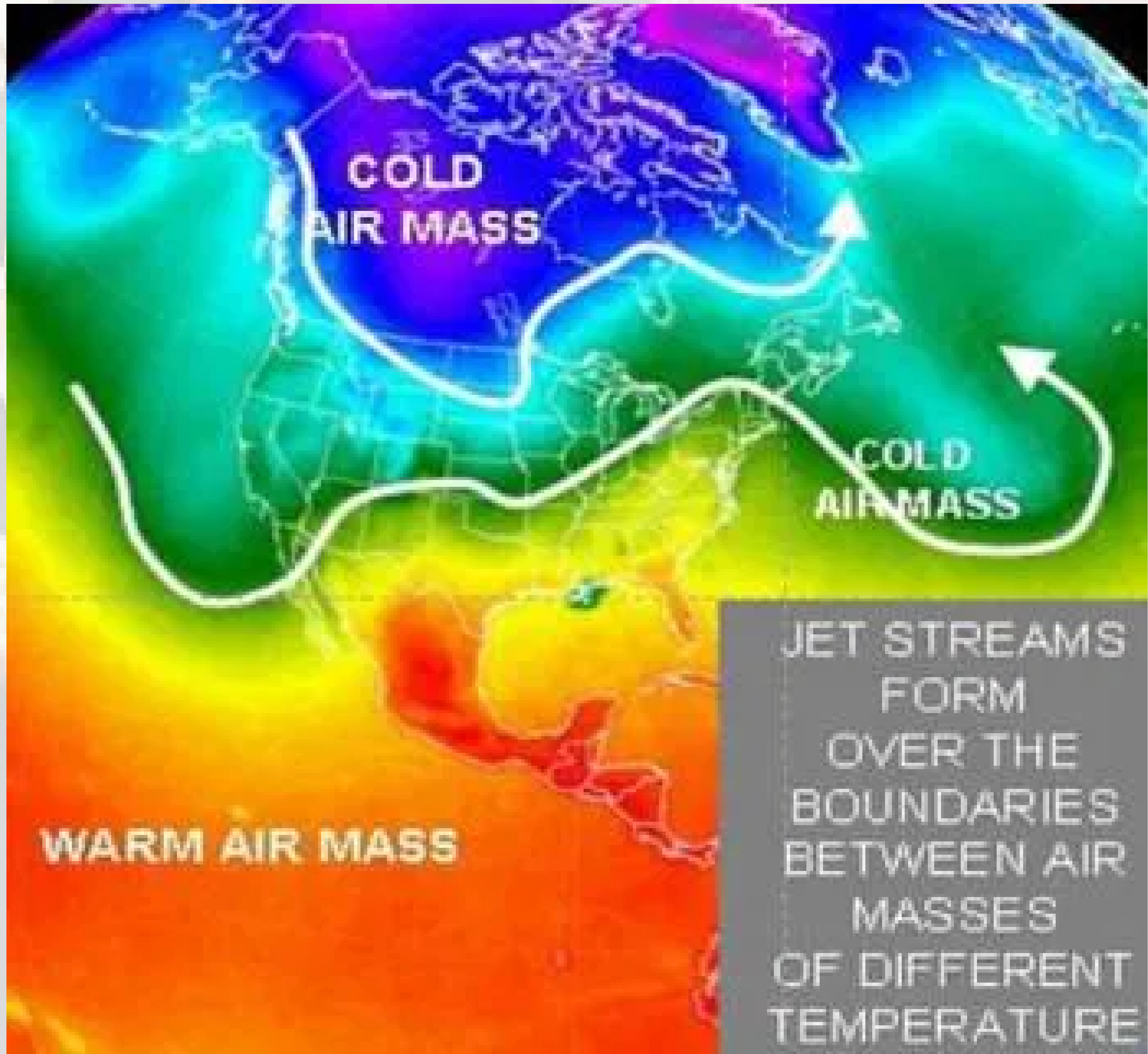
Figure 10.4 : Geostropic Wind



Jet Streams:

- Circumpolar, narrow, concentrated bands of meandering, upper tropospheric, high-velocity, geostrophic winds, bounded by low-speed winds.
- Circumpolar: Circle the Earth around the poles.
- Narrow and Concentrated: 50-150 km wide, air flows towards the stream's axis.
- Meandering: Path becomes wavy when temperature contrast is low.

1. Peaks/Ridges: Meanders towards poles.
2. Troughs: Meanders towards the equator.

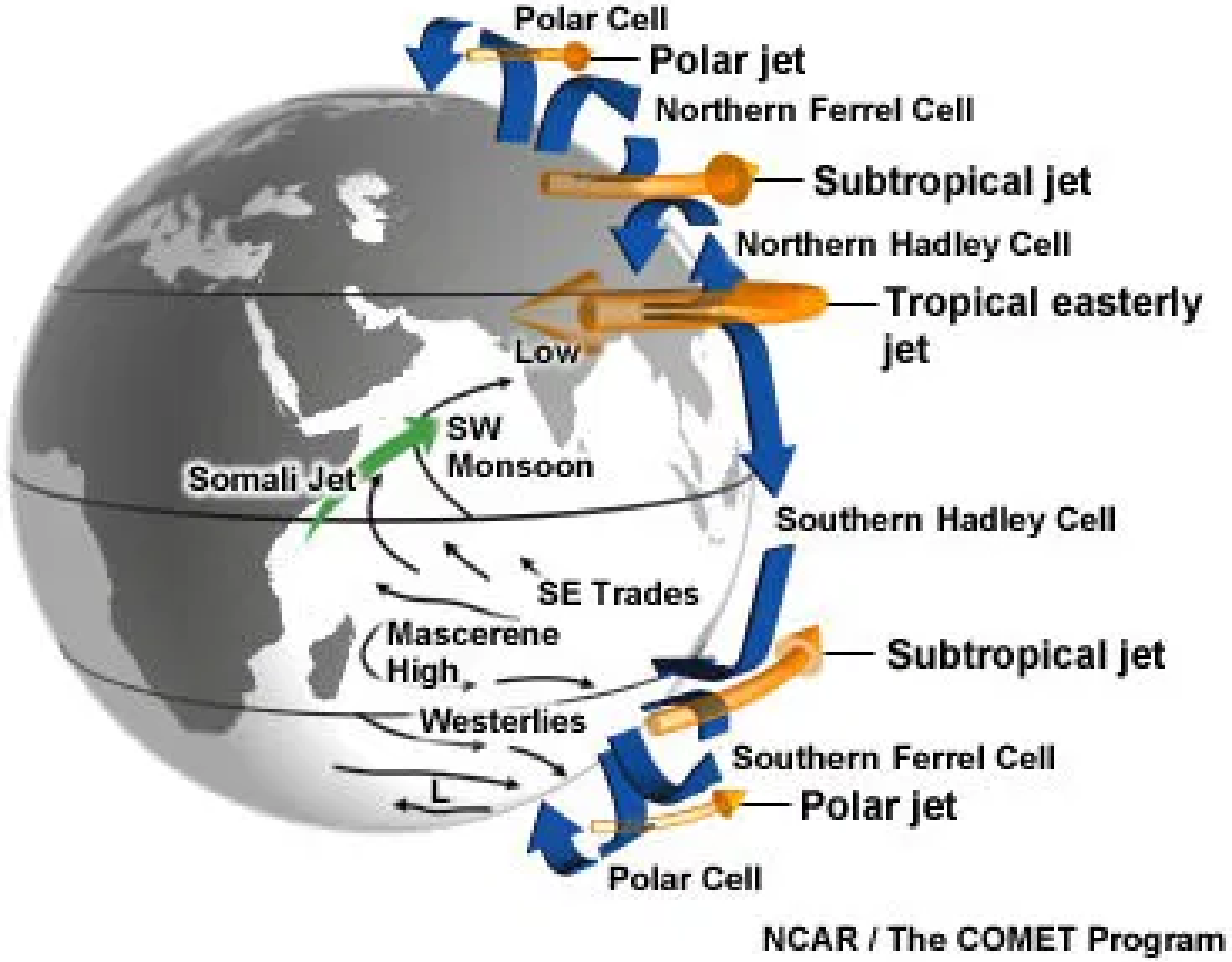


- Upper Tropospheric: Flow just below the tropopause.

1. Polar jet streams: 6-9 km above ground.
2. Sub-tropical jet streams: 10-16 km above ground.
3. Height difference due to thicker troposphere at the equator.

- High Velocity: Caused by increased pressure gradient with altitude, low friction, and temperature differences.
- Geostrophic: Direction determined by pressure gradient and Coriolis forces.
- Bounded by Low-Speed Winds: Surrounding winds are slower.
- Part of Upper-Level Westerlies: Winds flowing from tropics to poles deflect due to Coriolis effect, creating west-to-east flow.


Polar Jet
Sub Tropical Jet

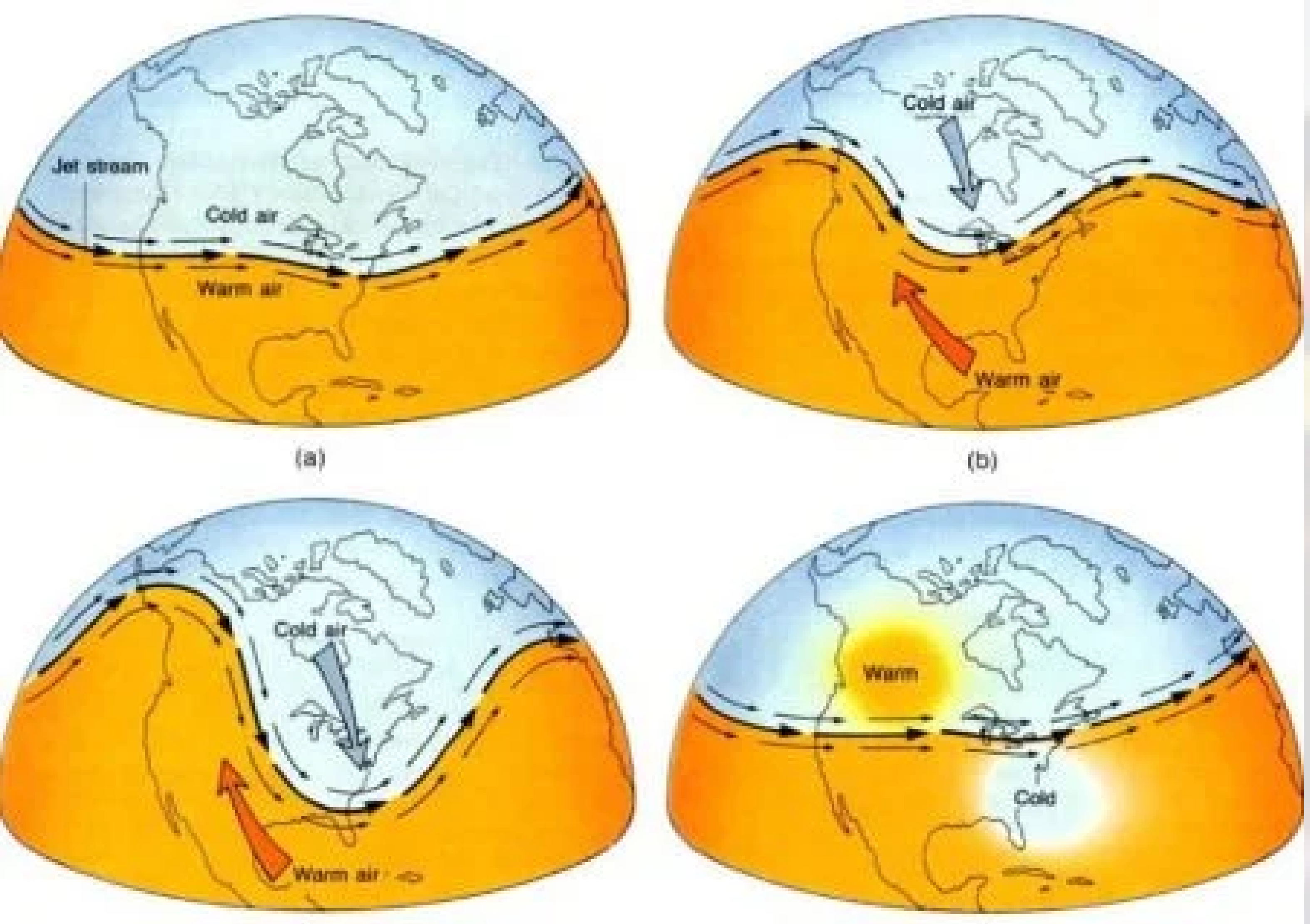

Polar Cell
Polar jet
Northern Ferrel Cell
Subtropical jet
Northern Hadley Cell
Tropical easterly jet
Low
SW Monsoon
Somali Jet
Southern Hadley Cell
SE Trades
Mascerene High
Subtropical jet
Westerlies
Southern Ferrel Cell
L
Polar jet
Polar Cell
NCAR / The COMET Program

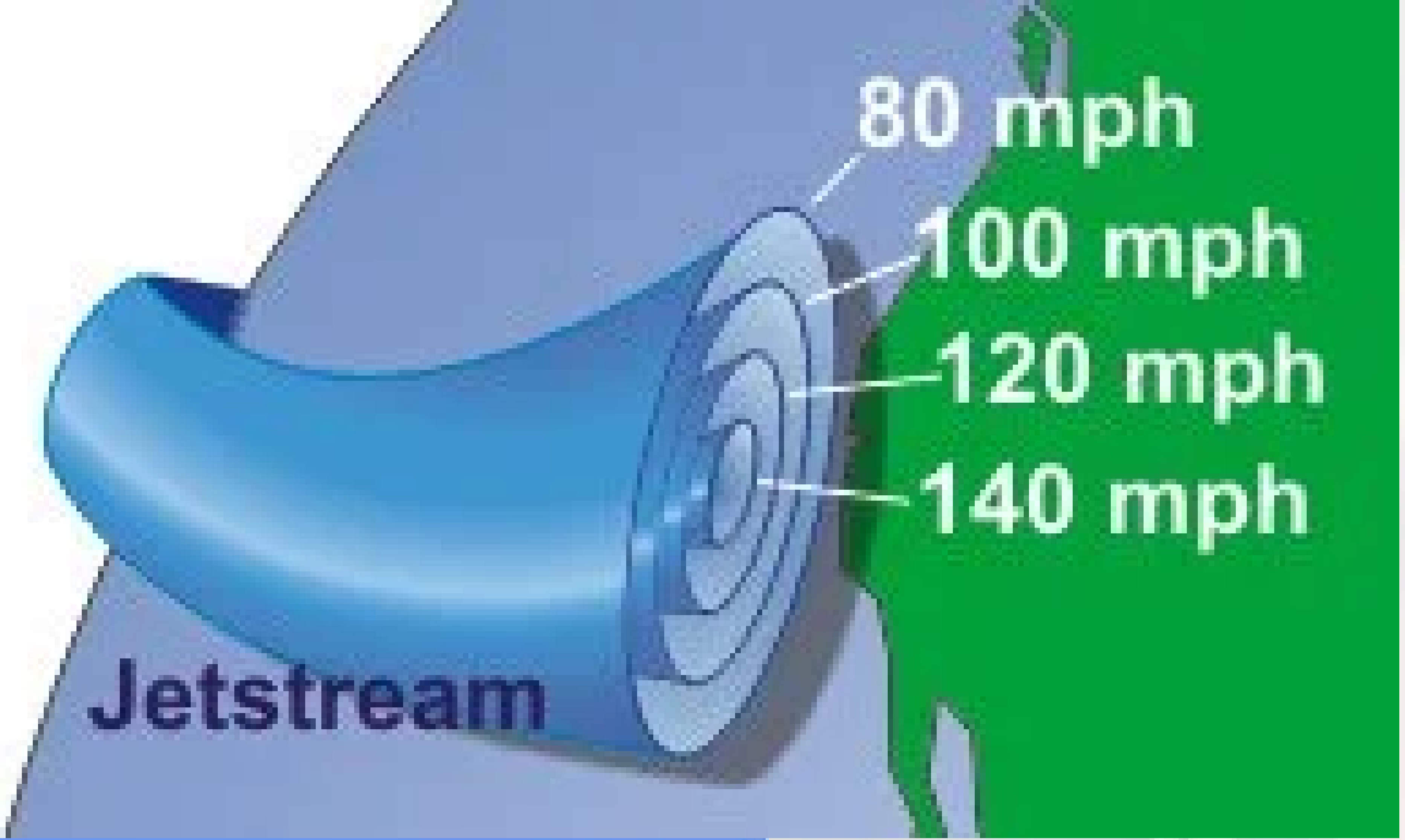
Rossby Waves:

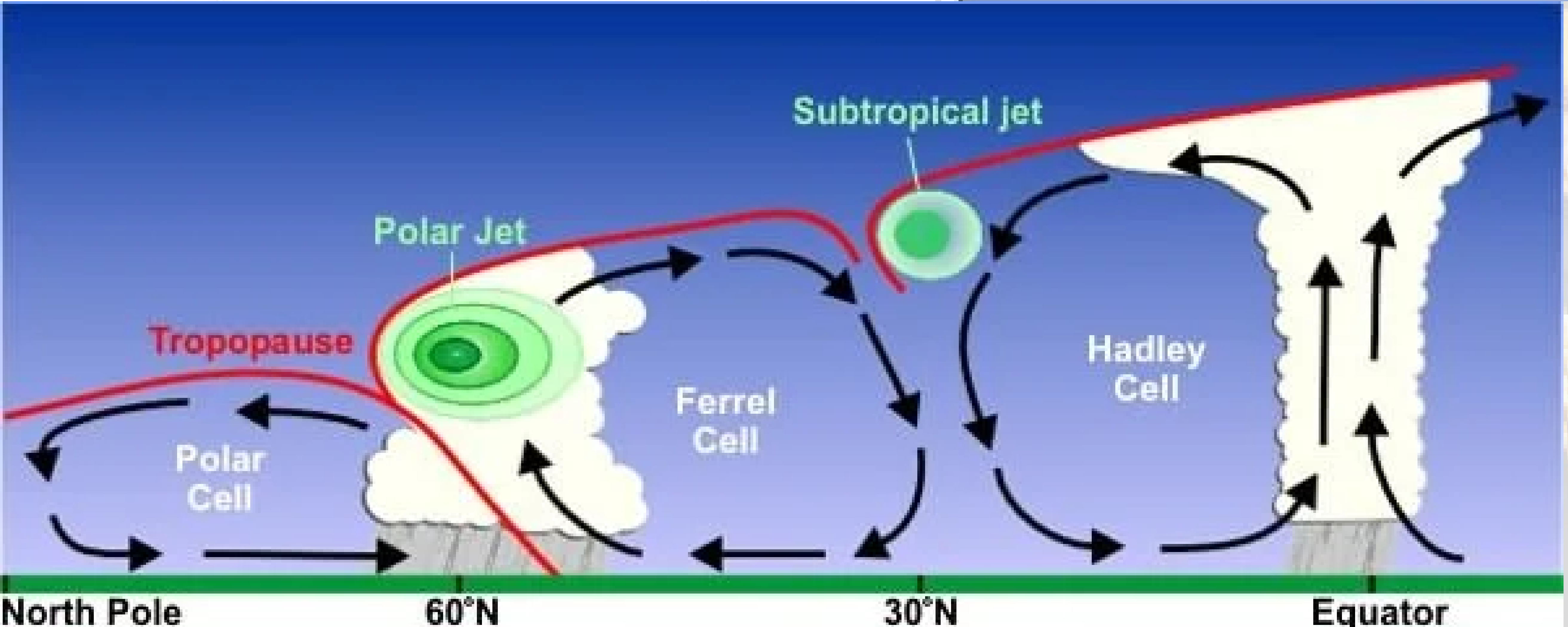
- Meandering jet streams are called Rossby Waves.
- Caused by variations in the Coriolis effect with latitude.
- Explain the formation of low-pressure (cyclones) and high-pressure (anticyclones) systems.

Key Points:

- Geostrophic winds and jet streams are crucial components of atmospheric circulation.
- Their behavior is influenced by pressure gradients, the Coriolis effect, and temperature contrasts.
- Understanding these phenomena helps in weather forecasting and understanding global climate patterns.


Jet stream
Cold air
Warm air
(a)
Cold air
Warm air
(b)
Cold air
Warm air
Warm
Cold


80 mph
100 mph
120 mph
140 mph
Jetstream


Subtropical jet
Polar Jet
Tropopause
Hadley Cell
Ferrel Cell
Polar Cell
North Pole
60°N
30°N
Equator

Subtropical Jet Stream (STJ):

- Formation: Earth's rotation and temperature contrast between tropical and subtropical regions.
- Location: Around 30° latitude in both hemispheres.

Seasonality:

- Nearly continuous in winter.
- Intermittent in the Northern Hemisphere during summer.
- Influence: Can merge with the polar front jet, impacting weather patterns and monsoons.

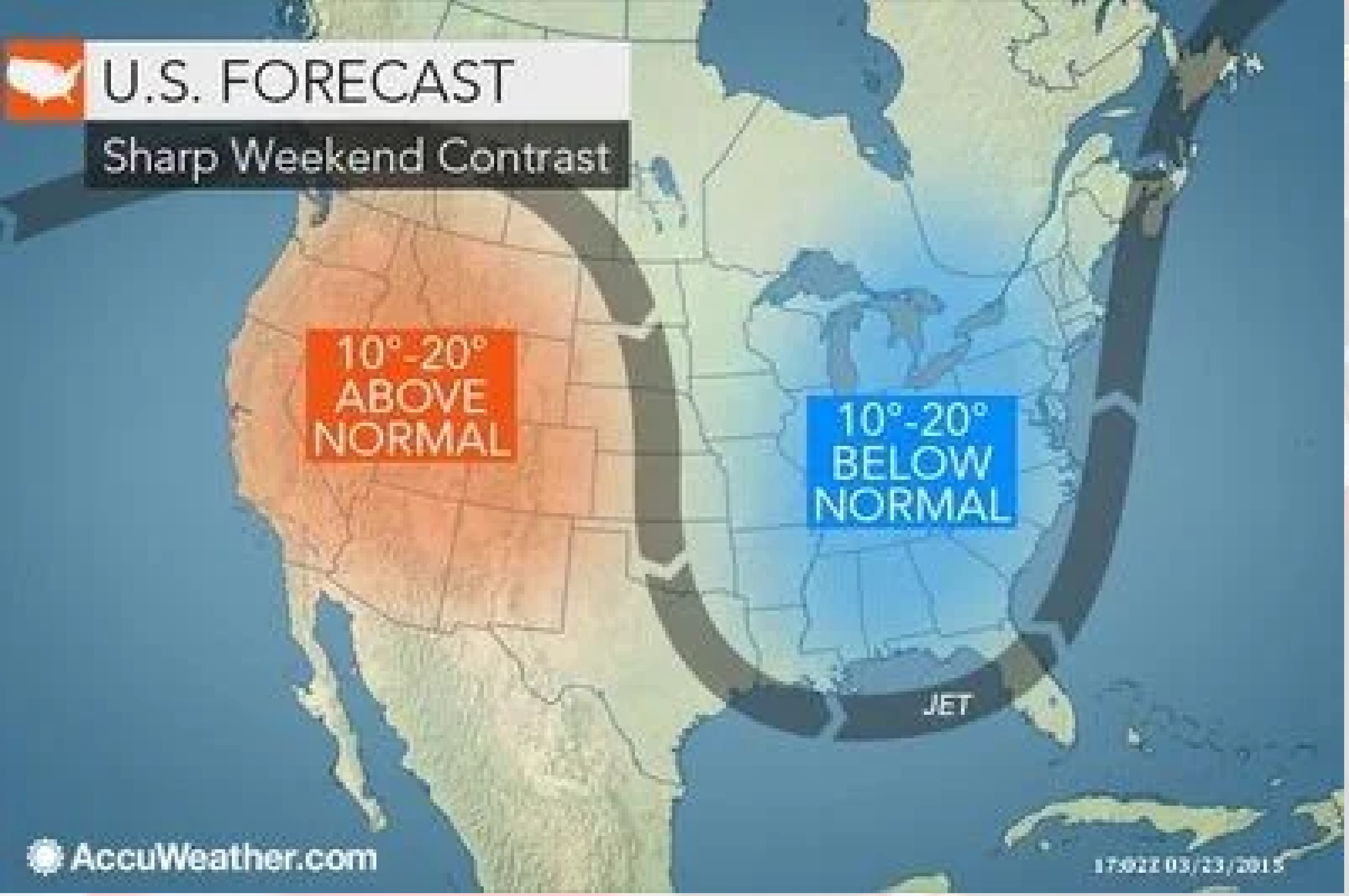
Polar Front Jet (PFJ):

- Formation: Temperature difference, closely related to the polar front.
- Location: More variable position, shifting towards poles in summer and equator in winter.
- Strength: Strong and continuous in winter.
- Influence:

1. Affects weather in regions near 60° latitude.
2. Determines the path, speed, and intensity of temperate cyclones.

Temporary Jet Streams:

- Formation: When wind speeds exceed 94 kph in the upper atmosphere.
- Examples: Somali Jet, African Easterly Jet.


U.S. FORECAST
Sharp Weekend Contrast
10°-20° ABOVE NORMAL
10°-20° BELOW NORMAL
JET
AccuWeather.com
17:02Z 03/23/2015

Tropical Easterly Jet (TEJ):

- Unique to the Northern Hemisphere summer over South Asia and North Africa.
- Enhances convection and rainfall over South India.

Somali Jet:

- Occurs during summer over northern Madagascar and Somalia.
- Major cross-equatorial flow.
- Influences monsoon patterns.

Influence of Jet Streams on Weather:

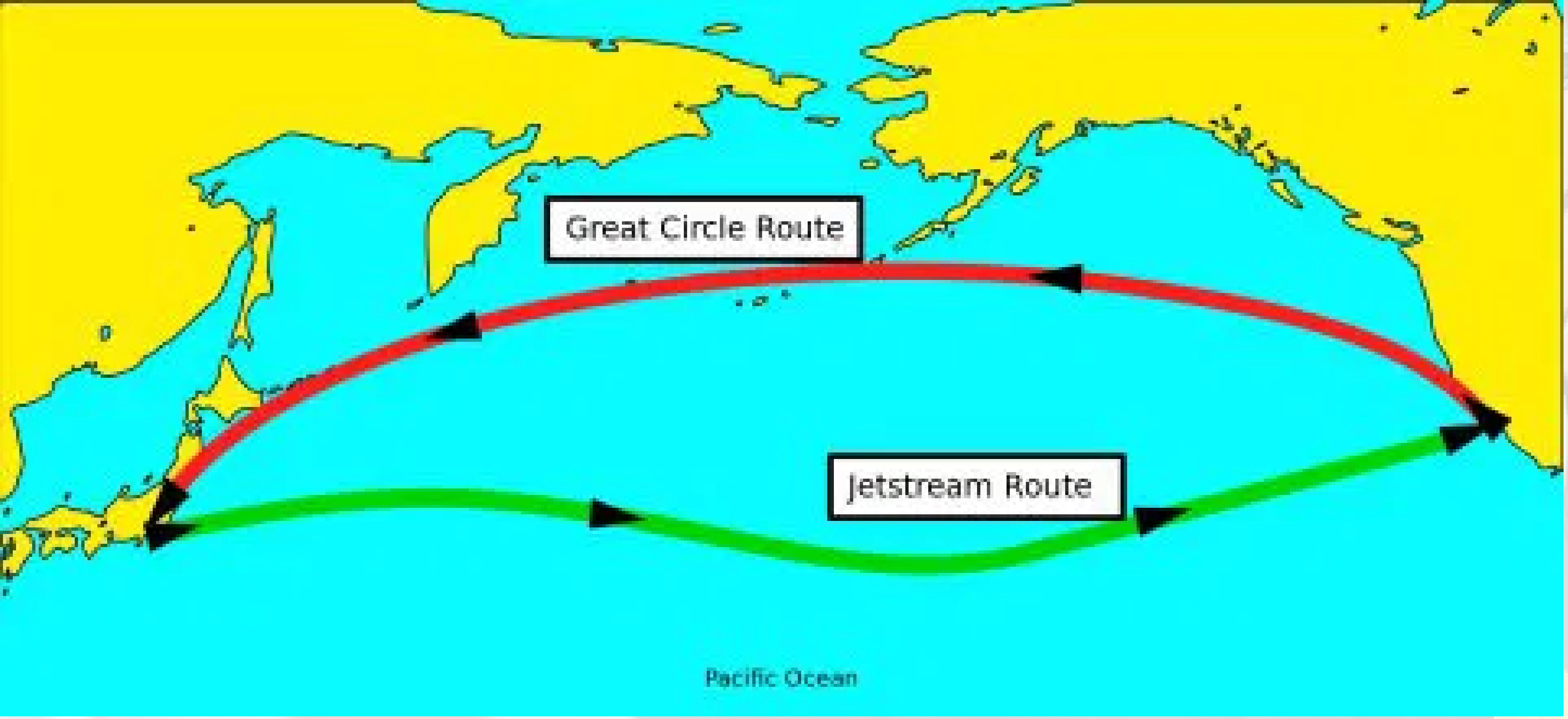
- Heat Balance: Maintains latitudinal heat balance through air mass exchange.
- Weather Disturbances: Influences mid-latitude weather, including severe storms and temperate cyclones.
- Precipitation: Affects the distribution of rainfall from temperate cyclones.
- Monsoons: STJ and temporary jet streams influence Indian and African monsoons.
- Droughts and Floods: Can cause prolonged dry or wet conditions by influencing air mass movement.

Jet Streams and Aviation:

- Favorable: Pilots utilize jet streams for faster travel when flying in the same direction.
- Challenges: Can cause turbulence due to unpredictable movements. Volcanic ash can get trapped in jet streams, affecting air travel.

Key Points:

- Jet streams are high-velocity winds in the upper troposphere.
- They influence weather patterns, including cyclone formation and movement.
- Understanding jet streams is important for aviation and weather forecasting.


Great Circle Route
Jetstream Route
Pacific Ocean