# Meteorology: Weather and Climate

Large Scale Weather Systems
Lecture 1
*Tropical Cyclones: Location and Structure*

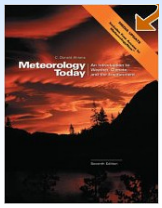
Prof. Roy Thompson Crew building

## Large-scale Weather Systems

- **Tropical cyclones** (1-2)
  - Location, Structure, Life-cycle
  - Formation, Maintenance and Feedback Mechanisms
- **Airmasses** (3-4)
  - Airmasses general characteristics, source regions and modification, airmasses that effect the British Isles
  - Airmasses affecting the British Isles and their properties
- **Fronts** (5-6)
  - Warm, cold, occluded and stationary fronts
- **Mid-latitude depressions and anticyclones** (7-10)
  - Life-cycle of a depression, upper-air flow and 3-D conveyor belt structure
  - Secondary and other types of depressions
  - Anticylones: structure, warm, cold and blocking highs

## Tropical cyclones- lecture 1

- Definition and associated weather
- Locations
  - regions and conditions for formation, pathways and dissipation
- Structure
  - Physical features, airflow, cross-section
- Resources for lectures 1 and 2:

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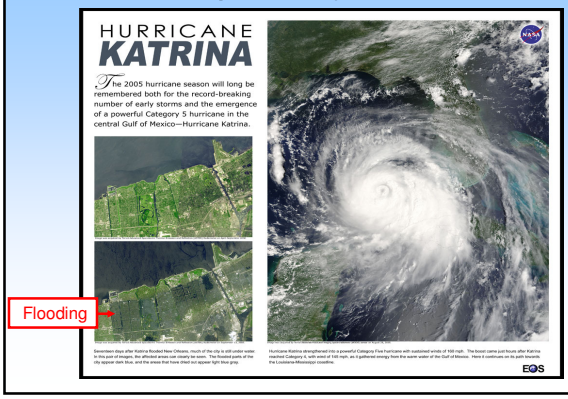
Hurricanes- online meteorology guide:
http://ww2010.atmos.uiuc.edu
NASA:
http://earthobservatory.nasa.gov/Library/Hurricanes/
NOAA:
http://www.aoml.noaa.gov/hrd/tcfaq/tcfaqHED.html

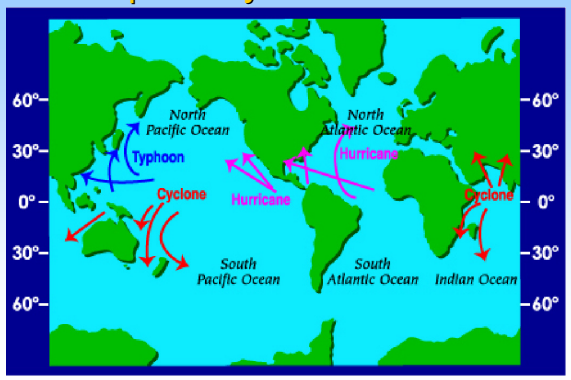
## Tropical Cyclones




## What is a tropical cyclone?

- A tropical cyclone is a non-frontal synoptic scale low-pressure system over tropical waters with organized convection (i.e. thunderstorm activity) and cyclonic surface wind circulation.
- Tropical cyclones:
  - *Called hurricanes* in North and Central America – most powerful storms on earth
  - Called *typhoons* in western north Pacific, known as *cyclones* in Australia and Indian Ocean

## Tropical Cyclone locations



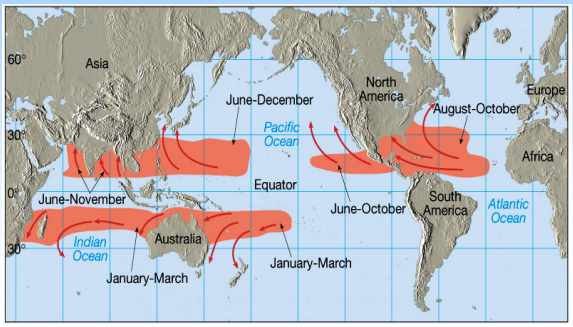
## Tropical cyclones: basics

- Typical synoptic scales of 100's km
- Numbers:
  - Hurricanes: ~5 per/year in Atlantic/Gulf of Mexico
  - ~9 per/year in the East Pacific off Mexico
  - ~16 typhoons per/year in W. Pacific
- Bring:
  - Heavy rains
  - Strong winds (hurricane winds > 74 miles/hr)
  - Storm surges

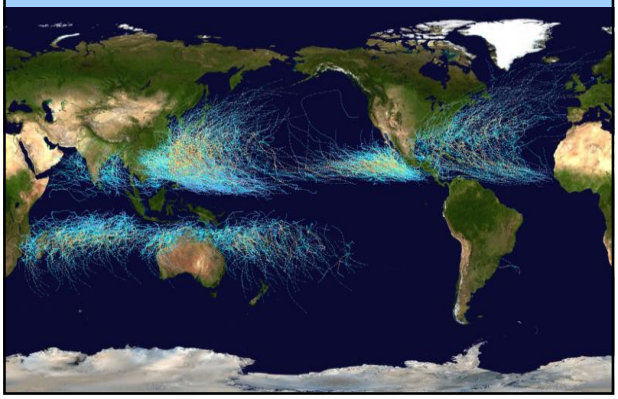
## Tropical cyclones :locations-regions and conditions for formation

## Regions of Formation

- Q. Why do they form only these regions of the tropics and during these periods?



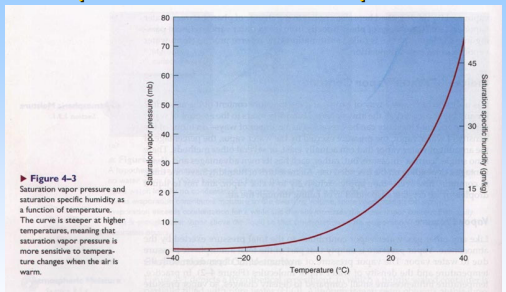

## Hurricane tracks



## Conditions for Tropical Cyclone Formation

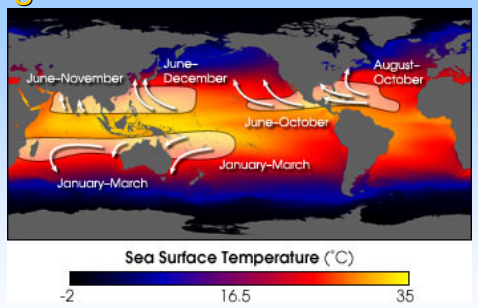
- They form only over oceanic regions with sea-surface temperatures (SSTs) are greater than 26.5oC.
- They do not form within 5 degrees of the equator due to the negligible Coriolis Force there
- They form in regions where vertical wind shear between the surface and upper troposphere is low (less than ~23mph or 10m/s)

## Evaporation and temperature




•Evaporation increases rapidly as temperature increases
•Evaporation =energy in the form of latent heat that fuels the cyclone

## Regions and seasons T>26.5oC

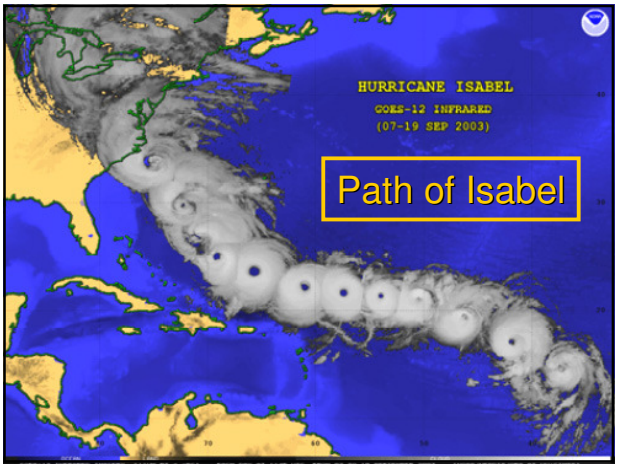



- Orange/yellow regions - tropics between June and December

## Reasons why cyclones do not form in certain tropical regions

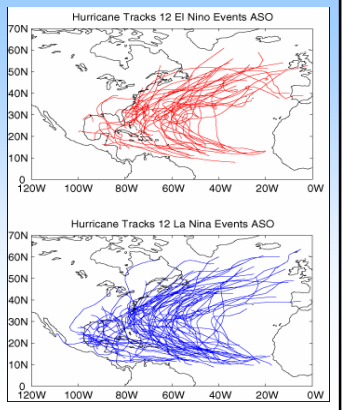
- Cold currents
- Without the Coriolis force, surface winds cannot gain sufficient rotation to converge and the low pressure of the disturbance cannot be maintained
- Large values of vertical wind shear disrupt the formation of a tropical cyclone by interfering with the organization of deep convection around the cyclone centre

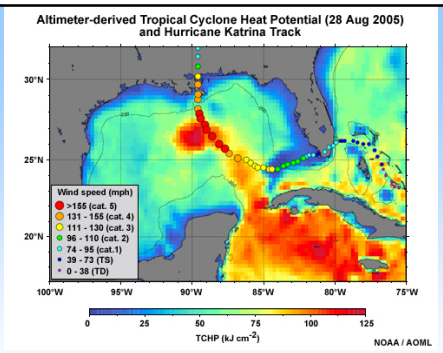
## Tropical cyclones: locations-pathways and dissipation




## Hurricane Paths

- Hurricanes in the N. Atlantic/N. Pacific
  - After formation tropical cyclones movement migrate westward (NW in HH; SW in SH) driven by the easterly or Trade Winds
  - Then steer poleward around the sub-tropical Bermuda High
  - If they move far enough northward into the path of mid-latitude Westerlies, they are then blown eastward
  - Some take erratic paths




Analysis of the altimeter-derived Tropical Cyclone Heat Potential product shows that Katrina encountered a ring of deep warm water associated with the Loop Current coincident with the time period of intensification to a category five hurricane.

## Tropical cyclone dissipation

- Typical lifetime is less than 1 week
- Record hurricane John (1994) -31 days
- Weaken rapidly when they lose their heat source:
  - Reach more northerly locations and cooler waters
  - Travel over land – a) energy source removed b) friction at land-surface decreases surface winds causing central pressure to rise
- Encounter large vertical shear e.g. in mid-latitude jet-stream

## Tropical cyclone: Structure

## Tropical cyclone/Hurricane structure


- Up to 500 km in diameter.
- The "Eye" the most notable feature –clear calm conditions
- The eye is surrounded by the eye wall. The strongest winds and rainfall are located in the eye wall.
- The eye wall is surrounded by spiral rain bands

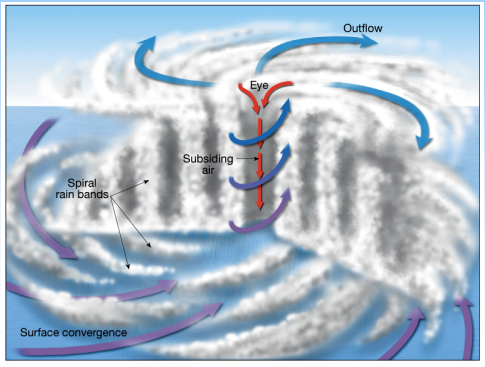
## Structure- physical features

- Eye -a roughly circular area of light winds mostly devoid of clouds.
  - It is the region of lowest surface pressure and warmest temperatures aloft
  - Eyes range in size from 8 km to over 200 km (generally 30-60km) across
- Eye wall -a circular rotating region of intense thunderstorms extending up to the tropopause (~15 km).
  - Area of highest surface winds
- Spiral rain bands – lines of thunderstorms, spiraling anticlockwise (in N. hemisphere)

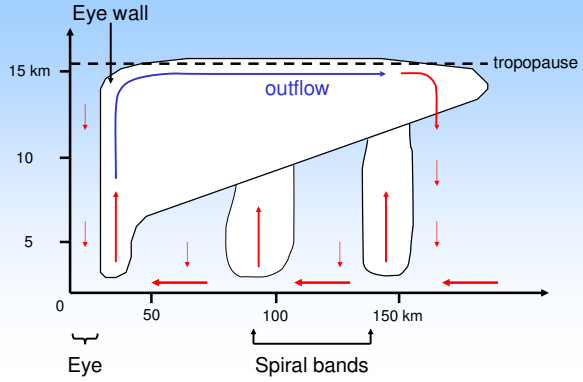
## Structure-airflow

- In the "eye" air is slowly sinking (causes compressional warming and "warm core"
- The eye wall has a net upward airflow as a result of numerous updrafts and downdrafts.
- Near the top of the eye-wall clouds relatively dry air flows outwards from the centre. This diverging air aloft extending outwards for ~100s km. As the outflow reaches the cyclones edges it sinks
- In the spiral rain bands, air converges at the surface, ascends through these bands, diverges aloft, and descends on both sides of the bands.

## Structure-airflow



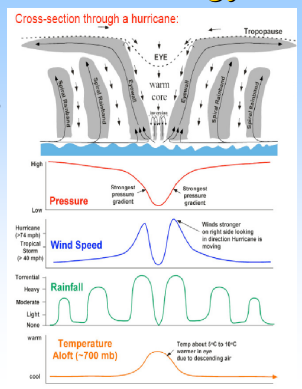
## Vertical cross-section and airflow



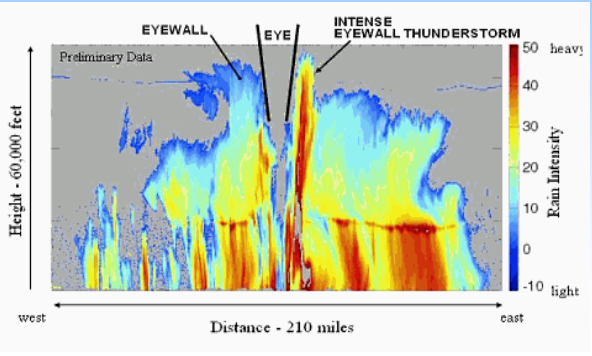

ON HANDOUT

## Cross section-meteorology

- Strong pressure gradient within eyewall
- Responsible for strong hurricane winds. Speed is fastest on "right" side of hurricane: sum of rotational and forward velocity
- Rain occurs in eyewall (heaviest) and spiral rainbands
- Temperatures increase in the eye because of descending air

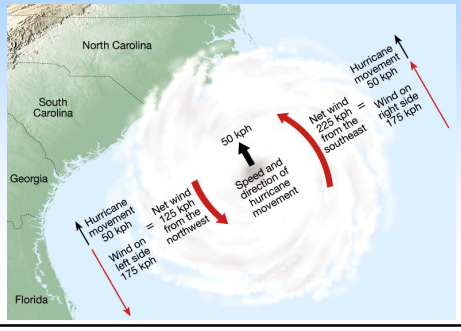



## Radar observations of the Cat 5 storm Emily




## Hurricane –meteorology

- The front right-hand side of a hurricane has the most intense winds and storm surges




## Lecture 1 Summary

- Form in tropical waters with SSTs > 26.5°C, but not within 5°of equator or in areas with large vertical shear
- Dissipate when heat source is lost or encounter large vertical shear
- Structure: eye, eyewall and spiral bands
- Air subsides in the eye creating warm clear conditions
- Eyewall is region of vigorous thunderstorms surface air rises; outflow aloft

## Meteorology: Weather and Climate

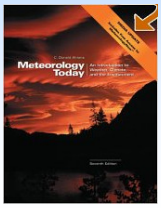
Large Scale Weather Systems
Lecture 2

*Tropical Cyclones: formation,maintenance and feedback mechanisms*

Prof. Roy Thompson, Crew building

## Tropical cyclones- lecture 2

- Development stages, disturbance sources and formation process
- Growth and maintenance through positive feedback mechanisms
- Resources for lectures 1 and 2

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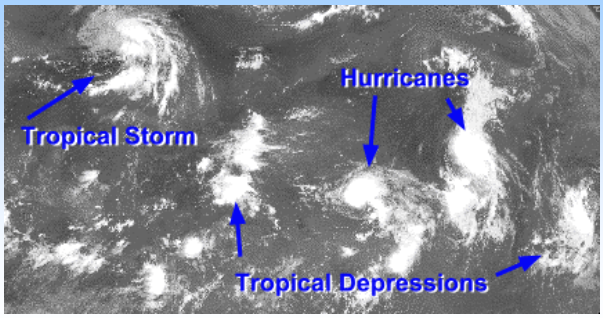
## Tropical cyclone formation and development stages

## Tropical cyclone development

- Stage 1: tropical disturbance
  - a cluster of disorganized thunderstorms w/o rotation over the tropical ocean waters
  - Winds 0-20 kts (23 mph)
- Stage 2: tropical depression
  - organized circulation in the centre of the thunderstorm complex with identifiable surface pressure drop (1 isobar)
  - Winds between 20 and 34 knots (23 - 39 mph).
- Stage 3: tropical storm
  - Thunderstorms becoming organized –closed isobars, cyclonic rotation
  - Winds between 35-64 knots (39-73 mph)
- Stage 4: hurricane
  - Intense, closed cyclonic system around central core
  - Hurricane ≥ 64 kts (74 mph =120 km/h)

## Tropical cyclone development

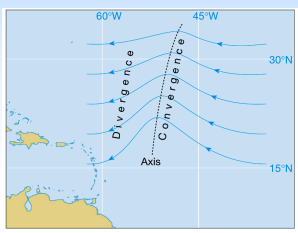



## Sources of tropical disturbances

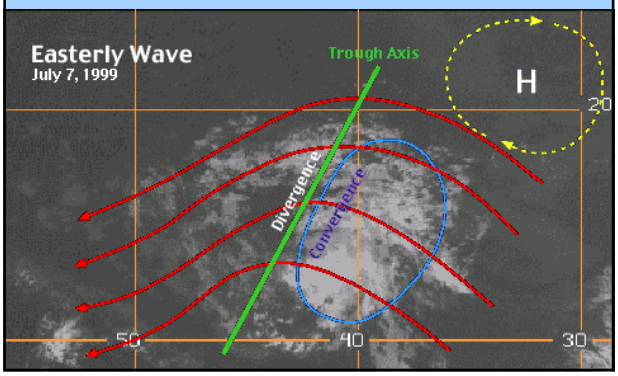
- Easterly waves in trade wind flow- converging winds on the east side of the easterly wave trigger the development of thunderstorms. Most Atlantic hurricanes originate from easterly waves that form over Western Africa
- ITCZ- easterly trade winds converge to trigger numerous thunderstorms in a region called the Intertropical Convergence Zone (ITCZ)
- Mid-latitude cold fronts that have moved south -(e.g. into the Gulf of Mexico, off the East Coast of Florida) cause convergence of air

## Easterly waves

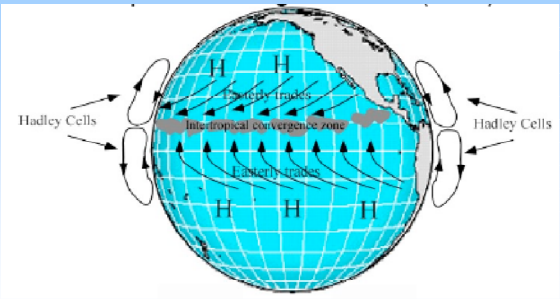
- E*asterly waves* develop as “ripples” in the Trade Winds
- Convergence occurs on the East side of a trough at the surface force
- **Convergence forces air up, creating weak low pressure and thunder storms**
- Waves originate over continents as air moves across mountains/deserts



Tropical cyclones often develop along easterly waves. These waves, or oscillations, in the trade winds move from east to west across the tropics. **Satellite** imagery provides the best view of an easterly wave. As low-level winds enter the trough of the wave, they converge, causing convection.



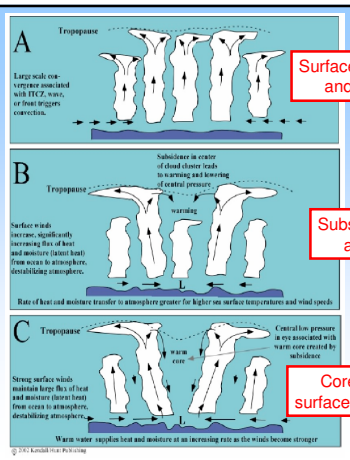

## InterTropical Convergence Zone




- **Easterly trade winds converge near the Equator**
- **Warm moist air rises ⇒ thunderstorms form**

## Formation process

- Surface water evaporates and is convected upward
- Air rises and diverges; some air is forced towards the eye centre, where it sinks
- Compressional heating in the eye creates the warm core and clear conditions
- Divergence aloft and warmer air results in lower surface pressure
- Increased surface pressure gradient yields increased surface winds
- Evaporation increases and the cycle strengthens

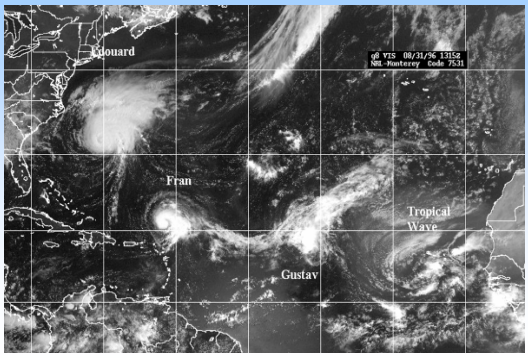



## Summary of Hurricane Formation

**HURRICANE FORMATION**

| Trigger Mechanisms for initial Thunderstorms | Environment required for Hurricane formation | Spin up of thunderstorm clusters into Hurricane |
|---|---|---|
| 1. Intertropical convergence zone<br>2. Easterly waves in trade wind flow<br>3. Cold fronts extending into tropics | 1. Sea surface temp > 27 °C<br>2. Deep layer of warm water<br>3. Weak wind shear<br>4. At least 5° from equator | 1. Wind induced transfer of heat from the ocean to the atmosphere<br>2. Conservation of angular momentum |

## Satellite photo of the tropical N Atlantic on August 31st, 1996



## Tropical cyclone growth and maintenance feedback mechanisms

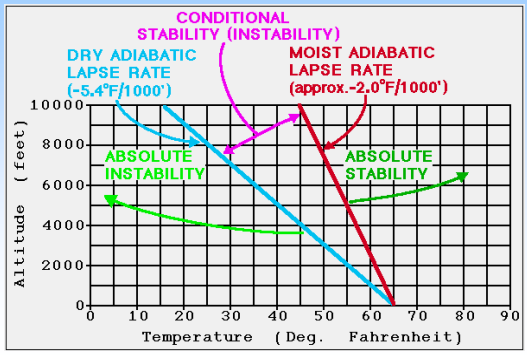
## Growth and Maintenance

- Occurs by means of two positive feedback mechanisms
  - CISK =Conditional instability of the second kind
  - Isothermal warming
- Requires:
  - Evaporation by winds from the ocean surface to the atmosphere
  - Conservation of angular momentum

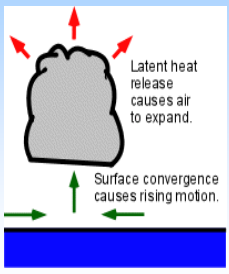
## CISK positive feedback Mechanism

- CISK=Conditional instability of the second kind:
  - low-level convergence in the wind field produces convection and cumulus formation, thereby releasing latent heat.
  - This enhances the convergence and further increases convection ⇒ a positive feedback

## Lapse rates

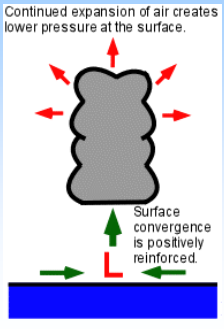



## CISK Mechanism




- Surface air spirals into the centre of a low pressure system creates convergence and forces air to rise in the centre
- This air cools and moisture condenses into clouds and releases latent heat into the air
- This warms the surrounding air
- Since warm air is less dense than cooler air, the warmer air takes up more space. This expansion of this air forces more air outside away from the centre of the storm and the surface pressure (the weight of the air above the surface) decreases.

## CISK Mechanism

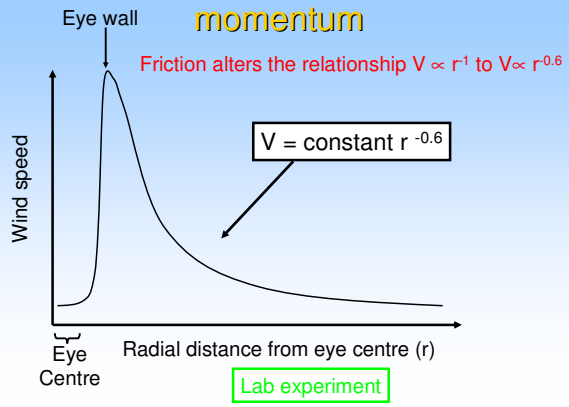



- When the surface pressure decreases, a larger pressure gradient is formed, and more air converges towards the centre of the storm (conservation of angular momentum)
- This creates more surface convergence and causes more warm moist surface air to rise above the surface releasing even more latent heat
- This cycle continuously repeats itself each time intensifying the storm (positive feedback)

## Conservation of angular momentum

- Horizontal pressure gradient at surface ⇒ winds spiral towards low pressure centre
- Conservation of angular momentum ⇒ tangential wind velocity x radial distance from centre = constant or
- V=const. $R^{-1}$ (due to friction $R^{-0.6}$)
- ⇒ air accelerates toward eye centre
- ⇒ greater convergence
- Aids feedback process

## Conservation of angular momentum




## Isothermal warming definition

- Isothermal warming is the addition of heat at constant temperature = energy as air in contact with the ocean surface flows towards the hurricane centre

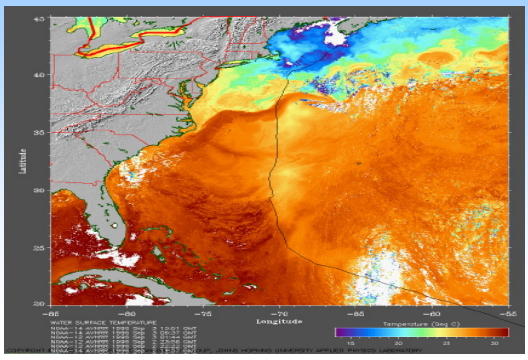
## Isothermal warming positive feedback mechanism

- Air spiralling in towards lower pressures near the surface is made warmer through isothermal warming by contact with the uniformly warm sea-surface
- Warm moist air rises and clouds form and latent heat released
- Air warms and diverges outwards
- Surface pressure falls ⇒ a positive feedback

## Isothermal warming positive feedback mechanism

- Cyclone core behaves as a “heat engine”
  - Heat is taken in at the ocean surface
  - Potential energy converted to kinetic energy (energy of motion)
  - Lost at tropopause through radiative cooling
- A warmer ocean surface
  - greater heat transfer and temperature of hurricane core
  - lower minimum pressure and higher wind speeds
- Core warmth or minimum pressure is a measure of the energy of the cyclone

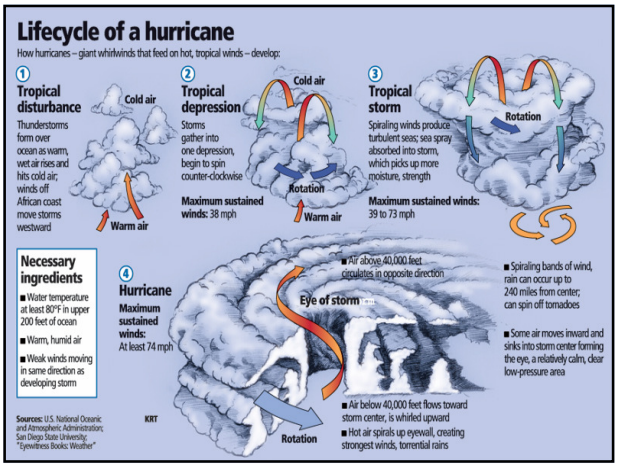
## Hurricane effect on sea surface temperature



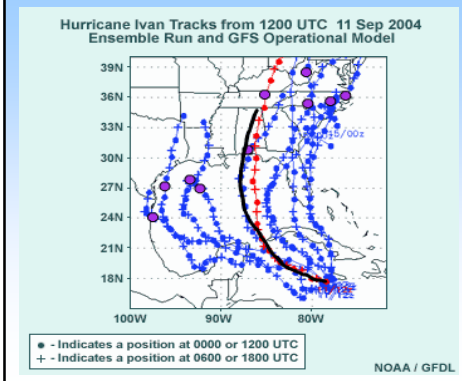
## Tropical cyclone dissipation

## Tropical cyclone dissipation

- Typical lifetime is less than 1 week
- Weaken rapidly when they lose their heat source:
  - Reach more northerly locations and cooler waters
  - Travel over land – a) energy source removed b) friction at land-surface decreases surface winds causing central pressure to rise
- Weaken when they encounter large vertical shear
  - e.g. in mid-latitude jet-stream

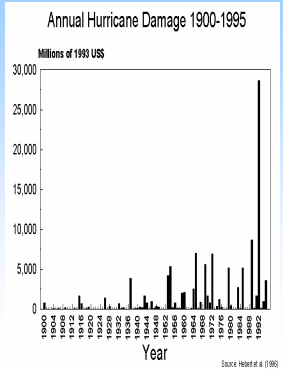


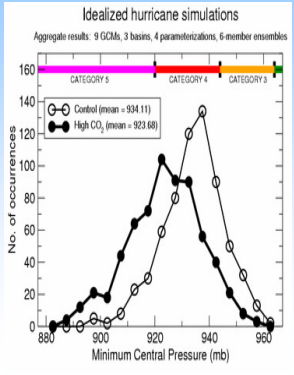

## Prediction is still very difficult




**The 8-day ensemble forecast shows large uncertainties in the path of Hurricane Ivan. Ultimate path in black. Operational path in red. Note tendency for clustering of tracks. 5 members to east, 4 members to west, 1 ensemble member in the middle.**

## Hurricanes and global warming




## Lecture 2 Summary

- 4 development stages from tropical disturbances to hurricanes
- Disturbance sources: easterly waves, ITCZ, mid-lat cold front
- Growth and maintenance occurs through 2 positive feedback mechanisms
  - CISK
  - Isothermal warming
- Essential formation and growth criteria
  - Evaporation from warm ocean surface waters
  - Conservation of angular momentum