Tornado

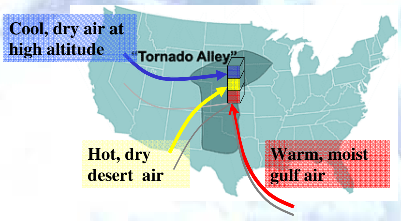
- Spinning column of air
- Associated with strong updraught and turbulence in the atmosphere (e.g. thunderstorms)
- Can last up to an hour or more
- Winds up to 200 miles per hour
- 689 people died from 18 March 1925 tornadoes

A tornado is a rapidly spinning column of air which forms within a parent cumulonimbus cloud. An average width of their destructive path is 50m although can reach 2km wide. They can last from seconds to over an hour, often covering over a few km. The most extreme winds are thought to be over 400 km/hour although this is difficult to measure. More than 50 tornados hit central Oklahoma on 3 May 1999 and 40 people died. Death tolls are lower today than decades ago since forecasting and warnings are far better these days.

The prelude to a tornado is observed as a spinning funnel cloud which becomes a tornado as it extends down to the ground or a water spout when it touches the ocean surface.

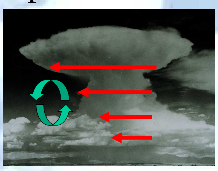
Tornadoes: formation

- Some uncertainty in exact processes!
- Meeting of cold, dry air with warm, moist air (e.g. cold front)

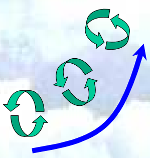


Thunderstorms and tornados are found at the meeting of cold, dry air and warm moist air, for example at a cold front. Particularly violent tornado formation is caused by a warm, moist near-surface flow, hot and dry mid-level flow and cool, dry upper level flow as is commonly the case in "tornado alley" in the American mid-west (e.g. Oklahoma). The local geography is well suited to the formation of intense tornados: for example, when low level moist air from the Gulf to the south east is capped by a layer of hot, dry air blowing on from the higher ground to the south-west, originating from New Mexico, and an upper layer of cold, dry air flows from the Rocky Mountains to the north west. The hot dry air acts to inhibit convection from the low layers while the upper cold layer can potentially allow convection of the warm, buoyant surface layers. When convection occurs it is often explosive and the differing wind directions at different levels initiates spinning motion which is transferred into the vertical by the explosive convection.

Tornadoes: development



- Severe thunderstorm:
  - intense updraughts
  - Change in wind speed with height (sheer)
  - Causes rotation
  - Intense updraughts translate this rotation toward vertical
- Rapid rotation extends downward (funnel cloud)
  - "Touch-down" when funnel cloud reaches surface
  - "Spinning-skater" effect
  - **See diagrams…**

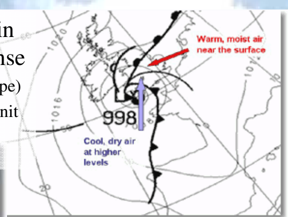


Mixing of similar contrasting air masses on smaller scales can also produce intense squall lines of convection and tornados such as experienced in the UK (e.g. London and Birmingham). Although the tornados are smaller than in the USA, they are actually relatively frequent in the UK.

The exact process for tornado formation is a much researched area; they are thought to form through the mixing of air masses moving in differing directions at different levels that initiate a horizontal roll. These small-scale circulations are then transferred into the vertical by the substantial updraughts found within thunderstorms. Meso-cyclones (air circulating around a local low pressure region within the storm) cause convergence of the air. The spin of the converging air is enhanced by the inflow of air into the localized low pressure just as a spinning skater increases their spin by bringing their arms and legs towards the body. An equilibrium is attained as the pressure gradient force balances the centrifugal force (corriolis force does not act significantly at such small scales although it may influence how much spin is contained in the first place within the cloud system).

Tornadoes in the UK

- Tornadoes frequent in the UK but less intense
  - 50 per year (top in Europe)
  - Highest frequency per unit area in the world!
  - So why have I never seen one?



Birmingham tornado, 28 July 2005

Note: measured using TORRO scale (UK) or Fujita scale (USA)

It is not possible to predict the precise timing and location of tornados since the processes are operating at such a fine scale. However, the large-scale conditions that are conducive for tornado formation can be predicted. For example, while the recent tornado that hit north London was not predicted, the Met Office did send out a warning that conditions were suitable for tornado formation. Precipitation radars can also be used to track particularly intense rainfall which may accompany tornados.

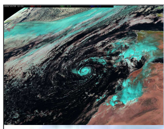
Hurricane

- Tropical Cyclone
  - Hurricane (Atlantic, E. Pacific), Typhoon (West Pacific), or just Cyclone (Indian Ocean)
- Massive low pressure /tropical depression
  - Winds > 39 mph à Tropical Storm
  - Winds > 74 mph à Hurricane/Typhoon
  - Central pressure often can reach below 950 mb
- Massive damage caused including loss of life
- Debate as to their response to global warming

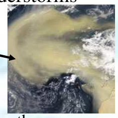
“Hurricanes”, “Typhoons” and “Cyclones” are all names for intense tropical cyclones (like depressions) with low central pressure occurring at low latitudes. The intense winds, heavy rainfall and large tidal surges accompanying tropical cyclones causes substantial damage to societies. For example, in 1995, while thunderstorms (including tornados and hail) caused around 3 billion $ of damage, tropical storms caused nearly 6 billion $ damage.

A tropical cyclone is typically 500-800 km across and 15 km deep.

Hurricane formation



- Solar heating and convergence of trade winds encourage uplift and thunderstorms
- Organisation of thunderstorm clusters
  - Can be linked to African disturbances
  - Formation of low-pressure

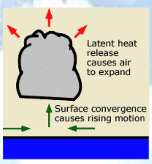


- Triggers for formation of cyclone
  1) Warm ocean (more than 27^{o}C) to ~60m depth
  2) Wind speeds uniform with height (low sheer)
  3) Coriolis Spin: Movement away from the equator
  4) Moist mid-troposphere (3-6 km)
  5) Upper level wind field conducive to outflow

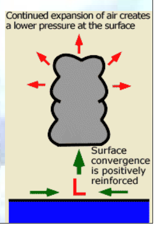
They occur when the upper layers of the ocean are warmest, in late summer, typically when the sea surface temperature is greater than 27ºC. This heat supplies energy for the storm. Also required are large quantities of water vapour, which is well correlated with warm temperatures and provides additional latent energy. Additionally, spin is required: the coriolis force supplies this and explains why such storms do not occur at the equator where the coriolis force is zero.

Instability in the atmosphere is also required; this allows growth of large cumulonimbus clouds. A moist mid-troposphere helps to sustain such disturbances since dry air essentially erodes the cloud formation. Wind sheer (changing wind speed with altitude) can destroy tropical storms since the upper layers become disconnected with lower levels. This is why El Nino events (described later) diminish Hurricane formation since the rearrangement of atmospheric and oceanic circulation during El Nino causes enhanced wind sheer over the Atlantic.

Hurricane Development



- Uplift and convergence of air
- Stronger trade winds
- More evaporation from surface
- Water vapour condenses, releasing more energy
- Feedbacks/vicious circles crucial; research continues to understand processes
- See diagrams…

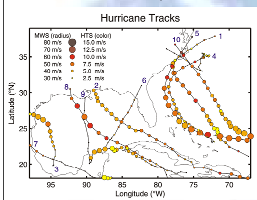


Positive feedbacks also operate to build up the size of tropical storms into full blown cyclones. For example, stronger winds cause more evaporation which results in more latent heating of the atmosphere through condensation, supplying more energy to the storm and therefore increasing wind speed.

At the top of the tropical cyclone, air spirals outwards in contrast to the inward vortex at lower levels; this outflow, modified by the large-scale flow patterns, is also crucial to maintaining an active cyclone. If the upper outflow is larger than the low-level inflow, surface pressure will continue falling and the system will continue to develop.

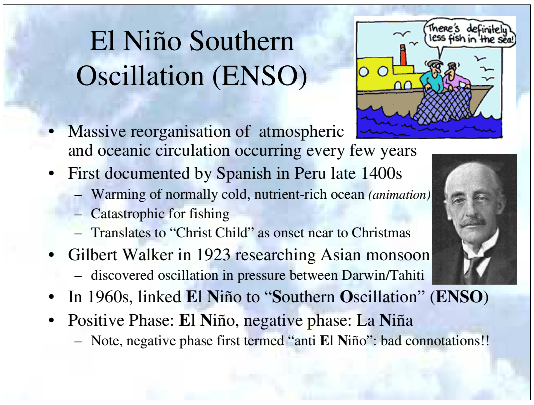
Storm surges are associated with tropical cyclones for two reasons. Firstly, low surface pressure causes a “swell” of water to develop since the weight of air is locally lower. This swell is enhanced by the strong winds and flooding on land is exacerbated by the intense rainfall.

- Up to 800 km across & 15km deep
- Can have sustained winds more than 155 mph (the worst Category 5 storm)
- Low pressure and strong winds à storm surge, high tides
- Warm core: unusual for tropical disturbances à low density
- Tornadoes, heavy rain, flooding

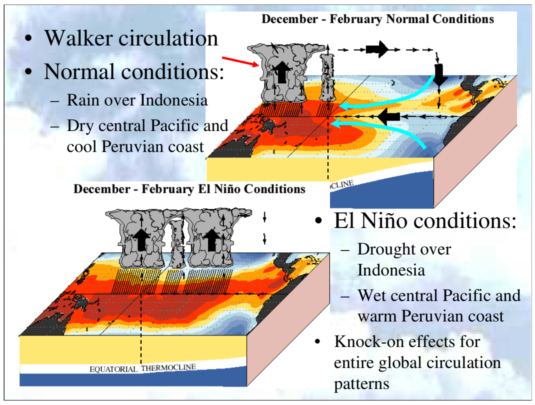


- Prediction: seasonal; climate change?
- Sea surface temperature and other factors
- 24-36 hour hurricane watch
- Usually travel westwards and then pole-ward
- Lose their energy source (warm sea) when they hit land
- Evidence of more Category 5 Hurricanes with warming
- First ever recorded South Atlantic Hurricane 2005

Tropical Cyclones are generally thought likely to become more intense but not more numerous with global warming. This primarily related to the increased atmospheric moisture and the ocean heat content, both of which rise in conjunction with surface temperature. The observational evidence remains inconclusive with only the Atlantic showing clear positive relationships between intensity and ocean temperature and this relationship has not yet been proven to relate to global warming and may be part of a multi-decadal cycle. Part of the ambiguity stems from the lack of records of tropical cyclones over the open ocean decades ago (perhaps some of the observations of past tropical cyclones over open water now lie at the bottom of the ocean!). Nevertheless, the strong theoretical basis for expecting more intense cyclones is compounded by the increase in the population living in zones affected by tropical cyclones.



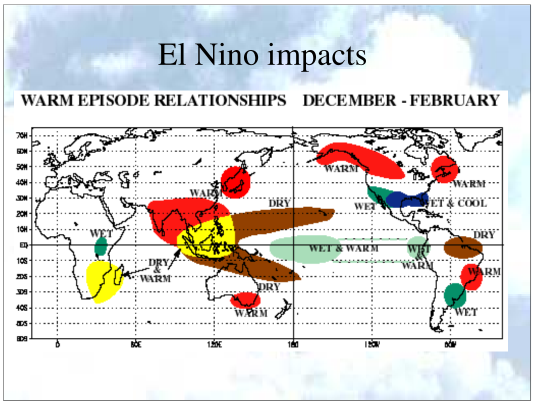
In 1923 Gilbert Walker was assigned to the Indian Meteorological Department to tackle an important problem, namely understanding what determined the Asian monsoon, a source of great economic uncertainty for the region. As part of this research he discovered an oscillation in pressure patterns every few years: when surface pressure is high in the central Pacific, it is low in in the west Pacific and Indian Ocean. This "Southern Oscillation" of these contrasting pressure patterns, while not necessarily exerting a consistent effect on the Indian monsoon, appeared to coincide with large changes in rainfall over the Pacific. These changes were felt particularly strongly in Peru and Ecuador where every few years large increases in ocean temperature coincide with drastic reductions in fish stocks. Here, this phase of the oscillation was termed El Niño, the "little boy" in Spanish, or "Christ Child" since the full impact is usually experienced around Christmas time.



In the late 1960s, a link between the Southern Oscillation and El Niño was proposed and today the El Niño/Southern Oscillation is referred to as ENSO with El Niño being the positive phase. Initially, the negative phase was termed anti-El Niño; this was quickly dropped since the El Niño can also be translated as "the Christ child"! The term used to describe the negative phase of ENSO is "La Niña".

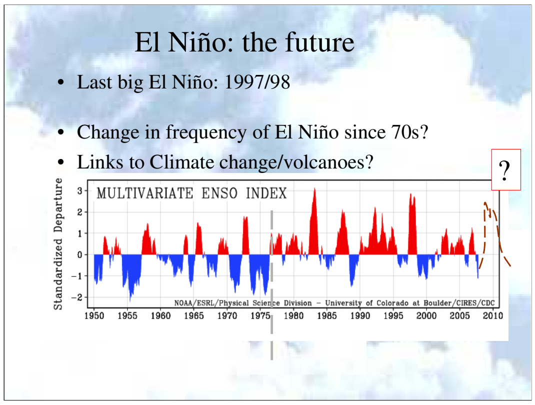
ENSO is a variability of the atmospheric and oceanic circulation in the Pacific that is so substantial that it affects global weather patterns. Normal conditions result in a convergence of the trade winds in the west Pacific and a build up of warm ocean water, both of which are conducive for convection and high rainfall (and low surface pressure).

In the east Pacific, colder, nutrient-rich water from higher latitudes and from depth flows in resulting in high ocean productivity and the suppression of convective rainfall here.



In La Niña there is a break-down of the usual westerly flow and the warm west Pacific and associated convective rainfall spill back across into the central Pacific. This initiates drought over the west Pacific region (e.g. Darwin, Australia), a wet central Pacific and warmer, less fertile waters over the east Pacific close to Peru.

Since the atmospheric and ocean circulations are so strongly perturbed, the entire global atmospheric circulation is modified and substantial changes in weather patterns are experienced across the globe. For example, El Niño is generally associated with a wet California while the reverse is true in La Niña. The last major El Niño was in 1997/98; we experienced a weak El Niño in 2006 while a weak La Niña is currently underway (2007) which may explain the dryness in California, possibly along with the influence of global warming.



In 2005/6, models predicted neutral conditions for 2006/07. In fact we experienced a weak El Niño followed by La Niña. Predictions of this oscillation are still in their infancy and research is ongoing. Nevertheless, climate models tend to show an increasing frequency of El Niño in the future.

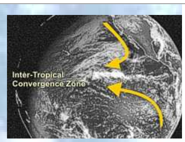
Observations also suggest a "climate shift" around 1976/77 after which the frequency and intensity of El Niño appeared to change. It is also possible that sudden kicks to the system can initiate an El Niño that would otherwise have occurred a little later. For example the El Chichon volcanic eruption was shortly followed by a strong El Niño. There is no way to prove any link at present since models probably do not resolve aspects of the oscillation well enough and this hampers both seasonal prediction as well as long term regional climate prediction.

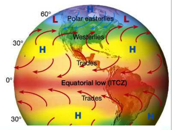
Monsoon

- From Arabic “mausam”
  - meaning season
  - seasonal change; primarily dry to wet season
- Indian monsoon well known
  - Northward migration of cloud & rain every summer
  - Also other Asian regions and W. African monsoon
- Essential for agriculture
  - Accurate prediction is required but problematic
  - Links to El Niño/La Niña and climate change?

The energy balance of the Earth results in a band of buoyant, ascending air near to the equator where the trade winds converge. This is called the Inter-Tropical Convergence Zone and is associated with convective rainfall. Since this band of wet weather follows behind the maximum input of solar radiation which oscillates between the tropics of Cancer to the north and Capricorn to the south, there are many regions which experience wet and dry seasons. Where the transition from wet to dry is particularly strong, for example due to feedbacks involving the heating of the hot dry land and changes in surface radiative and latent heat fluxes, the onset of the rains is termed Monsoon. While the Asian monsoon is the best known, there are also other monsoons, for example the west African monsoon which affects the Sahel.

Monsoon: mechanisms



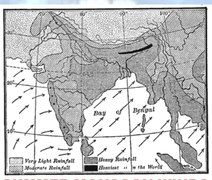


- Solar heating maximum drifts north & south
- Ocean heats up more slowly than land
  - Movement of Inter-Tropical Convergence Zone (ITCZ) lags maximum heating
- Dry land heats up extremely strongly
- Shape of continents and their albedo crucial

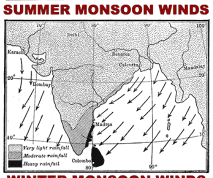
Although the reasons for the onset of the monsoon rains are well understood, reasons for yearly changes in the intensity of the monsoon have been under active research, ever since the time of Gilbert Walker. This is particularly important since when the monsoon is too strong flooding will occur while when the monsoon fails the land is parched. Both situations impact agriculture adversely and cause human suffering and pressure on the environment.

Indian Monsoon

- Indian monsoon:
  - Late May – early June: often a spectacular burst
  - Northerly flow blocked by Tibetan highlands
  - Warm, moist south-westerly flow dominates
  - Sri Lanka: double rainy season (350 mm per month in both May and October)



SUMMER MONSOON WINDS



WINTER MONSOON WINDS