

- Tropical cyclone motion
- Seasonal and interannual variability

Goal: Understand how tropical cyclones move and how they vary on different timescales

“Cork in a stream?”

- Tropical cyclones are known to move in response to environmental influences such as other disturbances
- To what extent is “passive advection”, or environmental steering, important?
- Cyclone advection by the environment is related to mean winds through a deep layer
 - Average over, say, 850-200 mb, or 500 mb motion averaged over a radius centered on the storm

Barotropic, nondivergent potential vorticity

For a barotropic fluid layer of depth h , the potential vorticity q is:

$$q = \frac{\zeta + f}{h}$$

If q is conserved along a flow path:

$$\frac{dq}{dt} = h^{-1} \left[\frac{d(\zeta + f)}{dt} - h^{-1}(\zeta + f) \frac{dh}{dt} \right] = 0$$

By the continuity equation $\frac{dh}{dt} + h \nabla_H \cdot \mathbf{v} = 0$ so for a nondivergent flow $\frac{dh}{dt} = 0$ and:

$$\begin{aligned} h^{-1} \left[\frac{d(\zeta + f)}{dt} - h^{-1}(\zeta + f) \frac{dh}{dt} \right] = 0 &\Rightarrow \frac{d(\zeta + f)}{dt} = 0 \\ &\Rightarrow \frac{\partial \zeta}{\partial t} + \mathbf{v} \cdot \nabla_H (\zeta + f) = 0 \end{aligned}$$

That is, at a fixed location, the time-rate of change in relative vorticity is equal to the advection of absolute vorticity.

The β -Effect (I)

Scale analysis suggests that advection of relative vorticity $-\mathbf{v} \cdot \nabla_H \xi$ is typically larger than advection of planetary vorticity $-\mathbf{v} \cdot \nabla_H f$ in the tropics. However, the latter is not negligible: it gives rise to perturbations to tropical cyclone motion known as the β -Effect or β -gyres.

To illustrate the β -Effect, we first consider the case of cyclone in zero background flow. The total wind and vorticity fields at any point in time will consist of a symmetric part, i.e., the cyclonic vortex, in the azimuthal direction of cylindrical coordinates, and an asymmetric part (from the β -Effect).

$$\frac{\partial}{\partial t} (\xi_s + \xi_a) = -(\mathbf{v}_s + \mathbf{v}_a) \cdot \nabla_H (\xi_s + \xi_a) - (\mathbf{v}_s + \mathbf{v}_a) \cdot \nabla_H f$$

In the above equation, symmetric wind advection of symmetric relative vorticity is:

$$\mathbf{v}_s \cdot \nabla_H \xi_s = v \cdot \frac{1}{r} \frac{\partial}{\partial \phi} \xi_s = v \cdot \frac{1}{r} \frac{\partial}{\partial \phi} \left[\frac{1}{r} \frac{\partial (rv)}{\partial r} \right] = 0$$

In the absence of background flow, with $f = 0$, there would be no propagation, as expected.

The β -Effect (II)

Ignoring the terms we anticipate should be small gives:

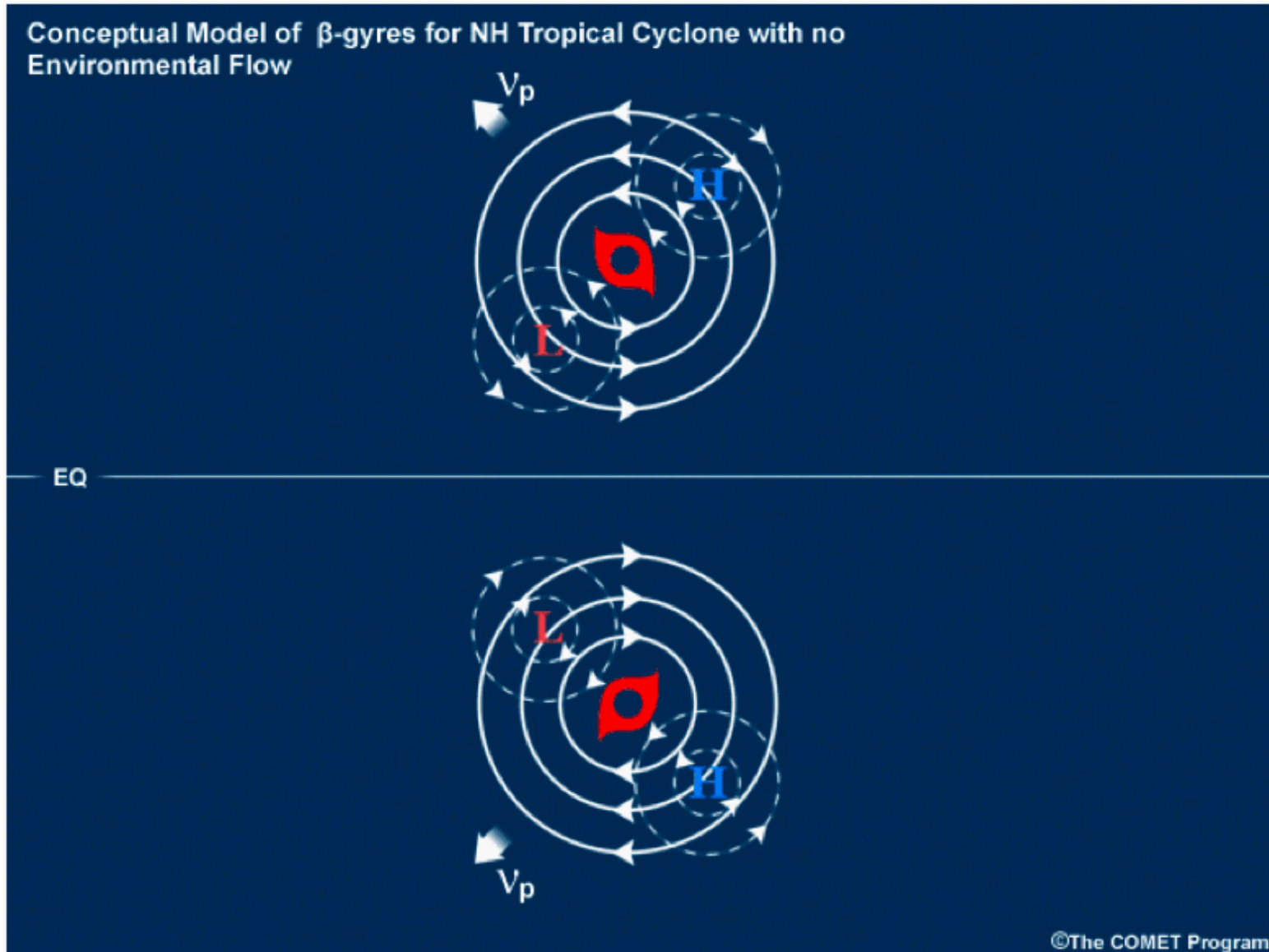
$$\frac{\partial}{\partial t}(\zeta_s + \zeta_a) \approx -v_a \cdot \nabla_H \zeta_s - v_s \cdot \nabla_H \zeta_a - v_s \cdot \nabla_H f$$

The first two terms on the RHS are advection of the cyclonic vortex by the β -gyres and advection of the β -gyres by the cyclonic vortex. For an initially symmetric state with f varying in the north-south direction, the small time limit behavior is:

$$\frac{\partial}{\partial t} \zeta_a \approx -v_s \cdot \nabla_H f$$

For definiteness, consider a NH cyclone. To the east of the storm center, the above equation produces anticyclonic vorticity (f increases poleward) and cyclonic vorticity to the west. As time evolves, advection by the symmetric flow translates the gyres cyclonically to positions NE and SW of the center and with β -drift to the NW.

Illustration of the β -Effect for the no background flow



Results from numerical simulations

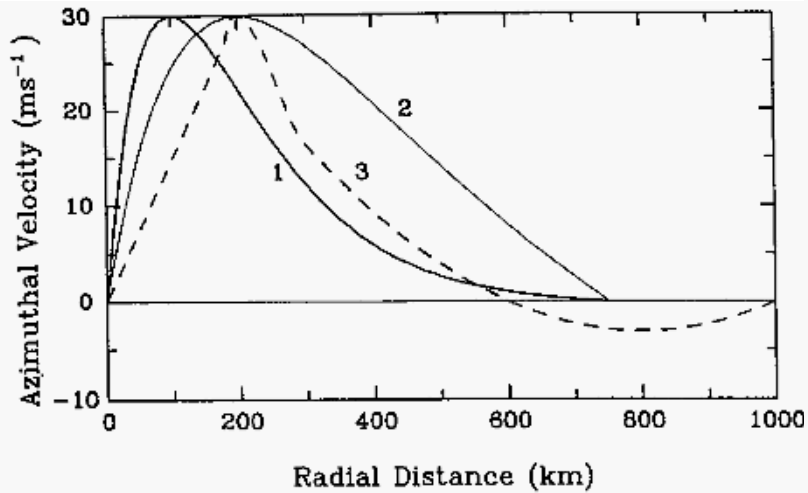


FIG. 1. Azimuthal wind profiles of initial symmetric vortices in three experiments. Thin solid, thick solid, and dashed lines are for cases 1, 2, and 3, respectively.

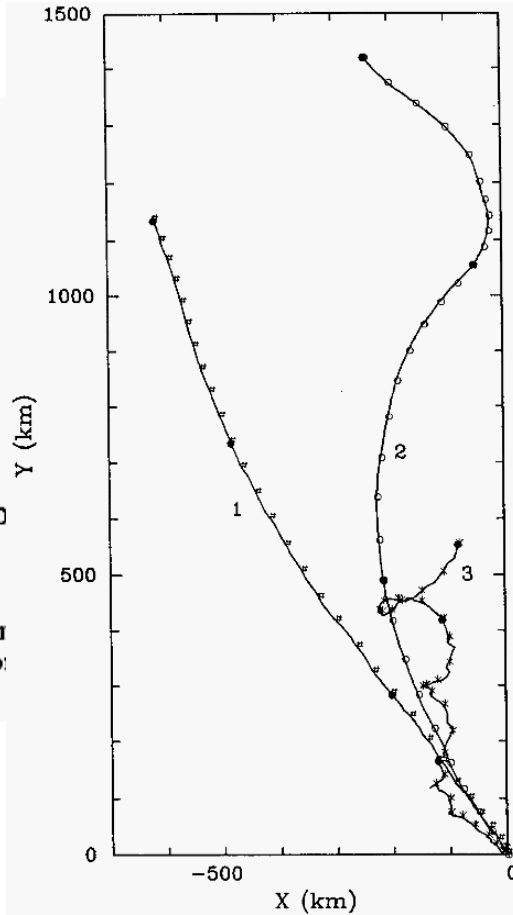


FIG. 2. The vortex tracks at 6-hour intervals for cases 1 (#), 2 (O), and 3 (*). The closed dots denote positions of the vortex center every 60 hours.

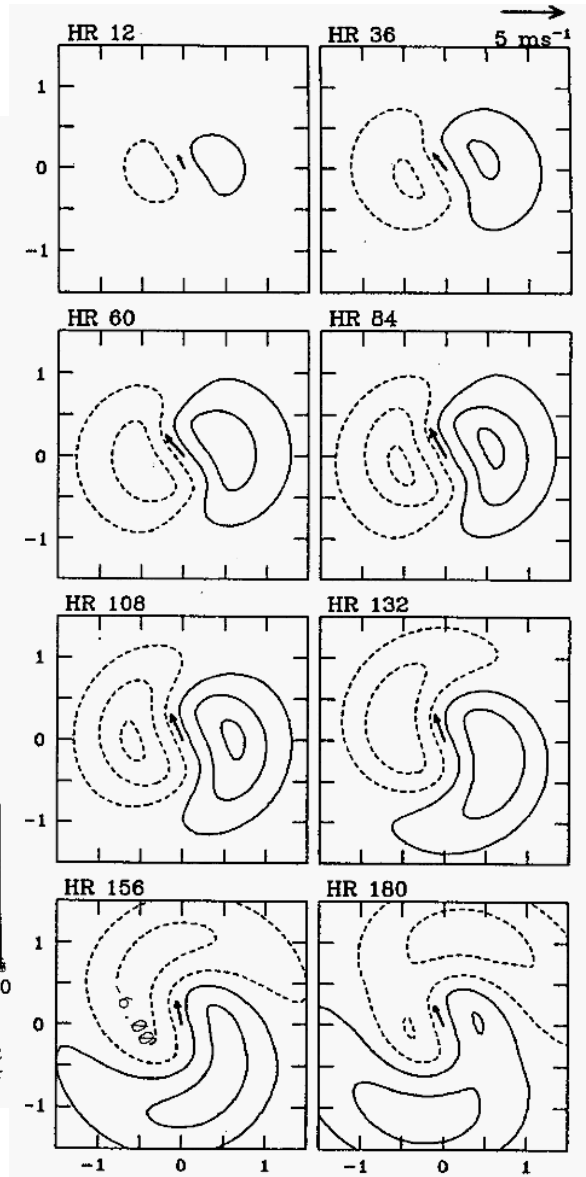
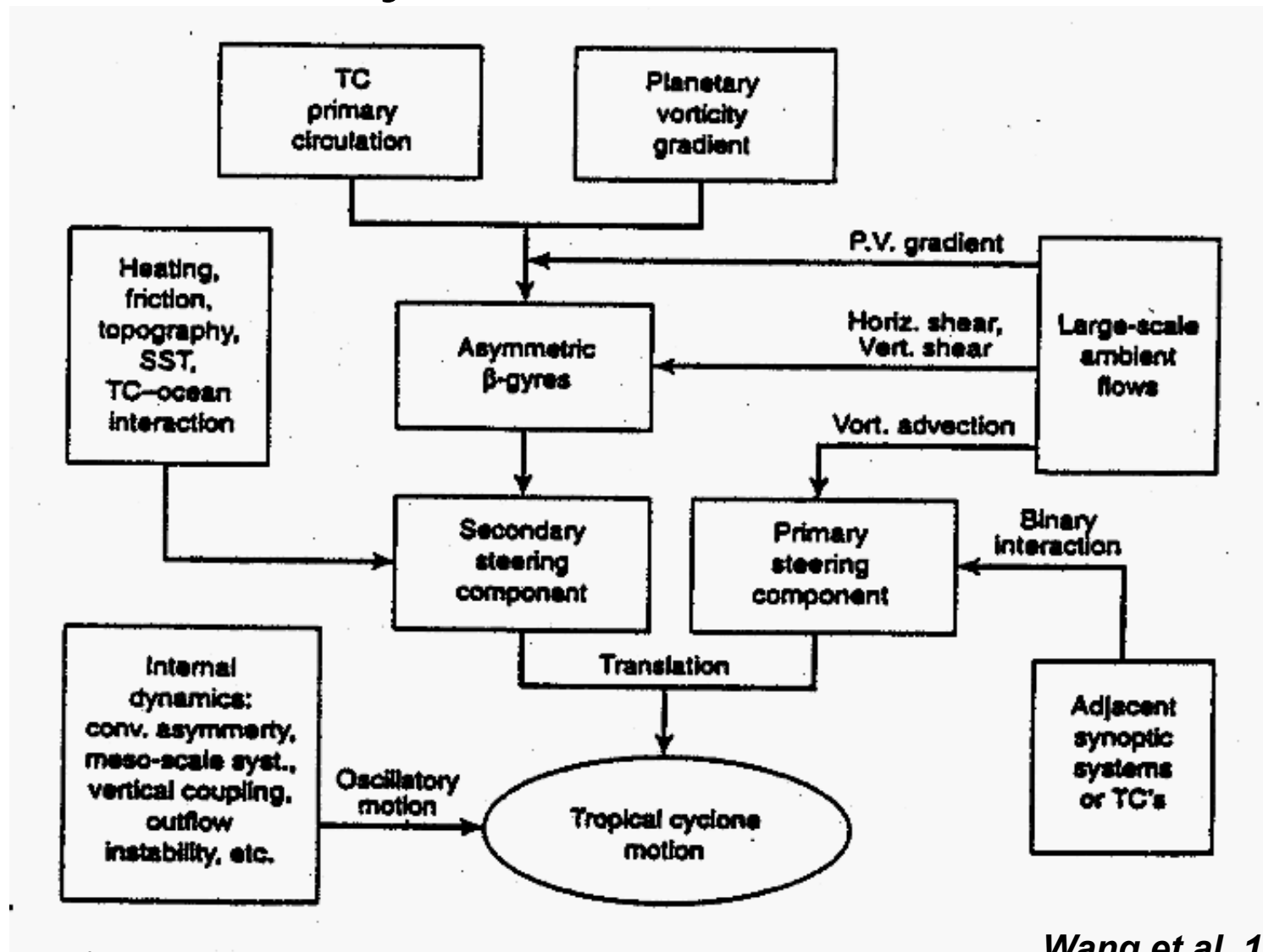


FIG. 3. The streamfunctions of the beta gyres at every 12 hours with a contour interval of $4 \times 10^5 \text{ m}^2 \text{ s}^{-1}$ for case 1. The arrow at the vortex center denotes the drifting velocity of the vortex. Abscissa and ordinate units are 1000 km.

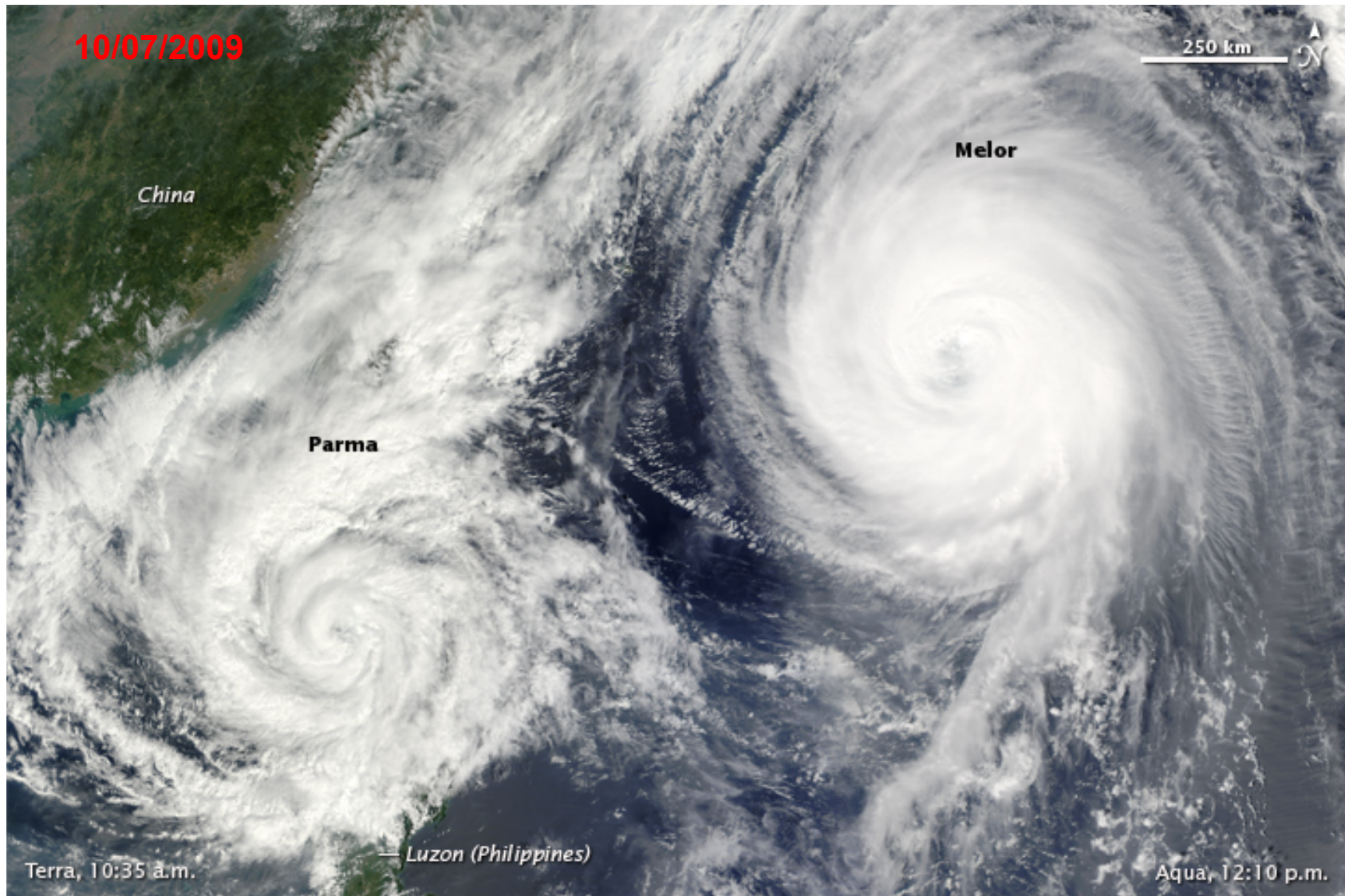
Summary of impacts on tropical cyclone motion



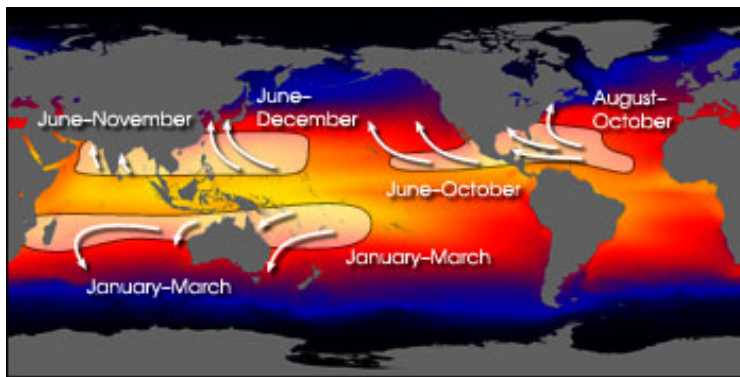
Interactions of tropical cyclones: the Fujiwhara Effect

- As two cyclones approach, their mutual cyclonic circulations may interact
- The Fujiwhara effect is observed to take place once every 1.5x year in the western Pacific and once every 3 years in the Atlantic
- Large angular rotations occur when the cyclonic centers are separated by 1300-1400 km
- The interactions are size dependent: e.g., if a large and small cyclone interact, the smaller one will orbit around the larger one and may be absorbed

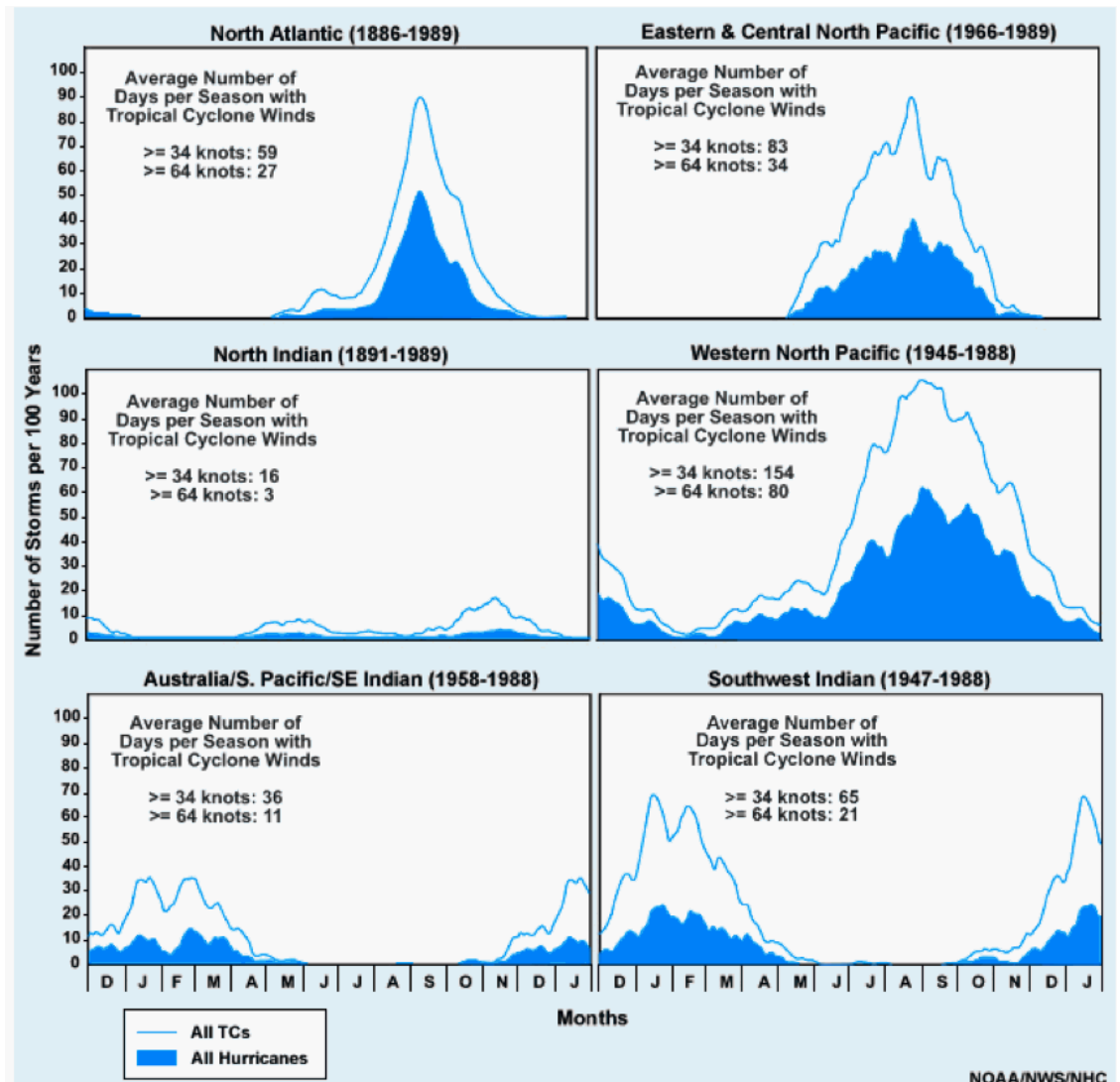
Super Typhoon Melor and TS Parma



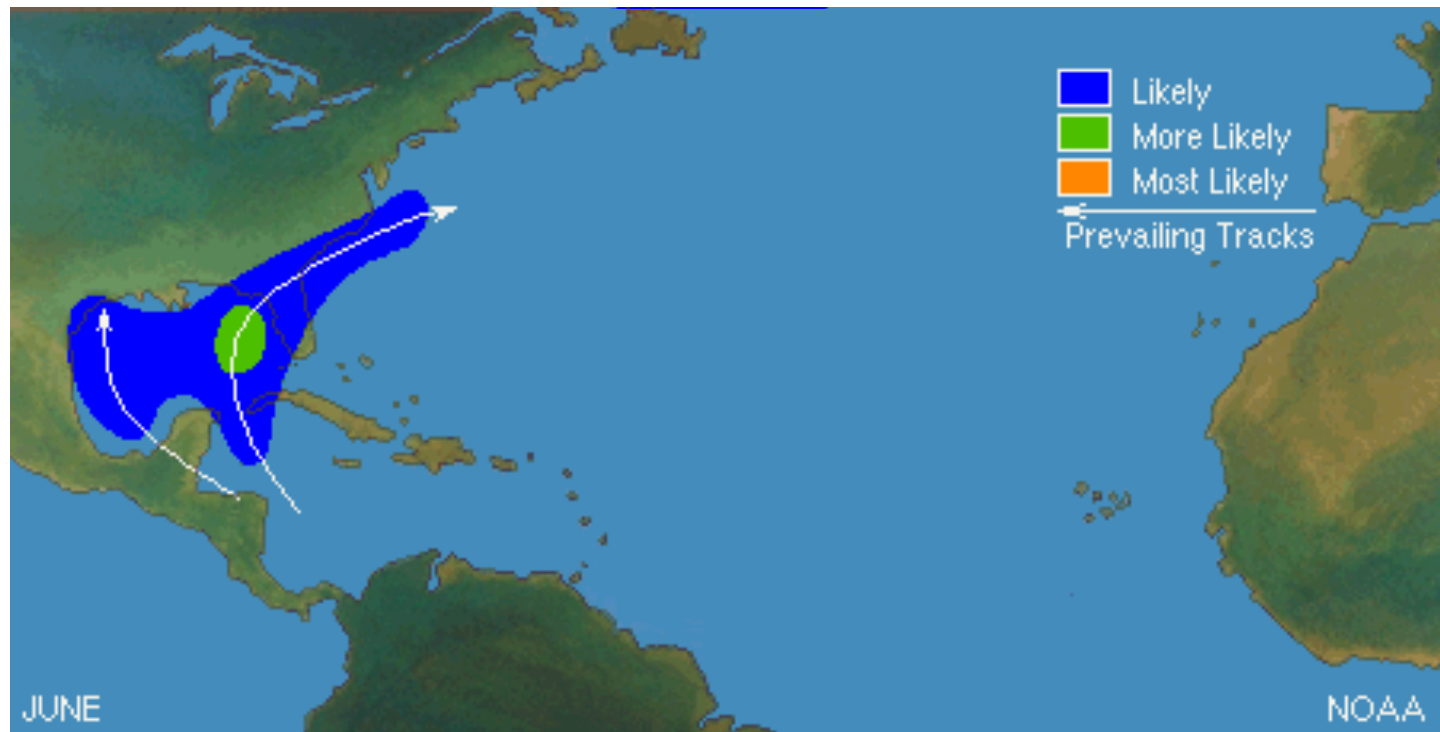
Seasonality of tropical cyclones by cyclogenesis region



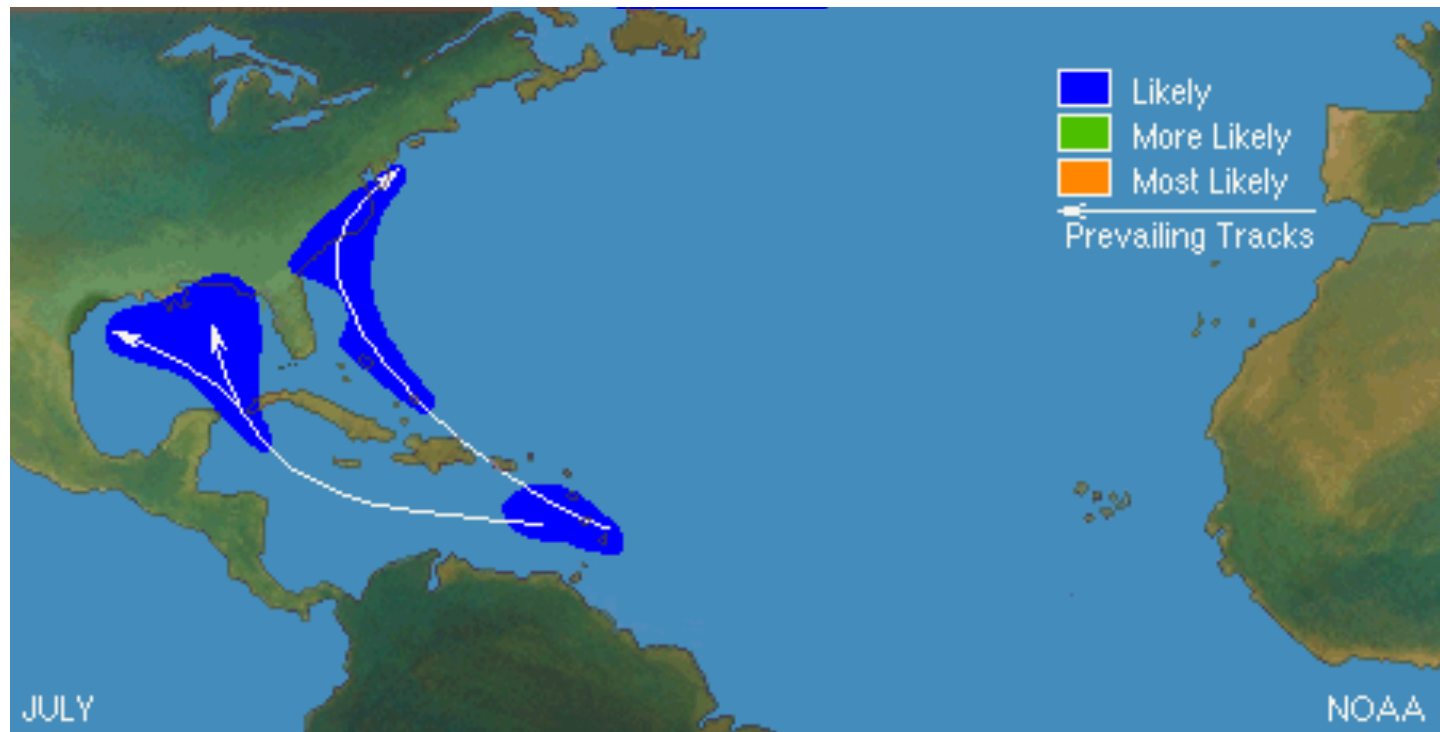
Sea Surface Temperature (°C)



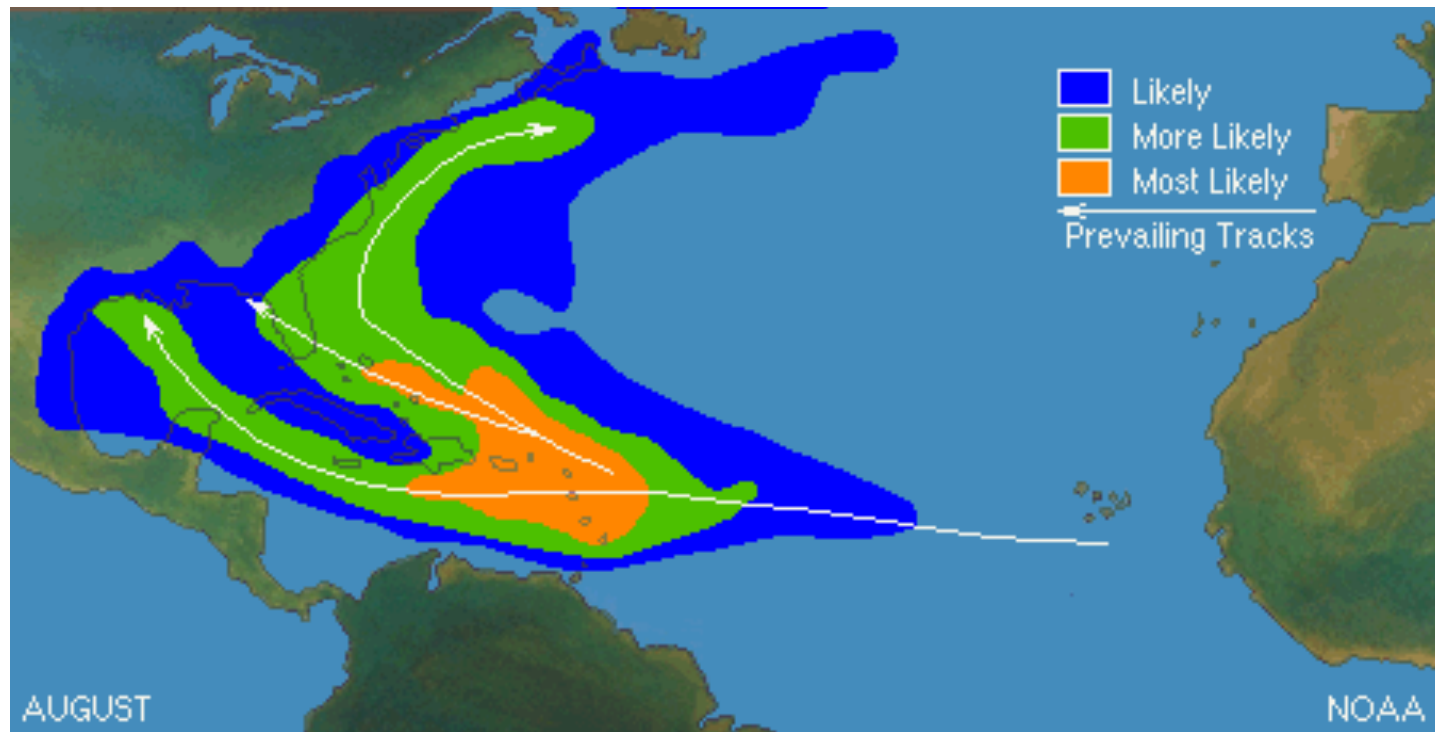
Where do Atlantic hurricanes typically head?



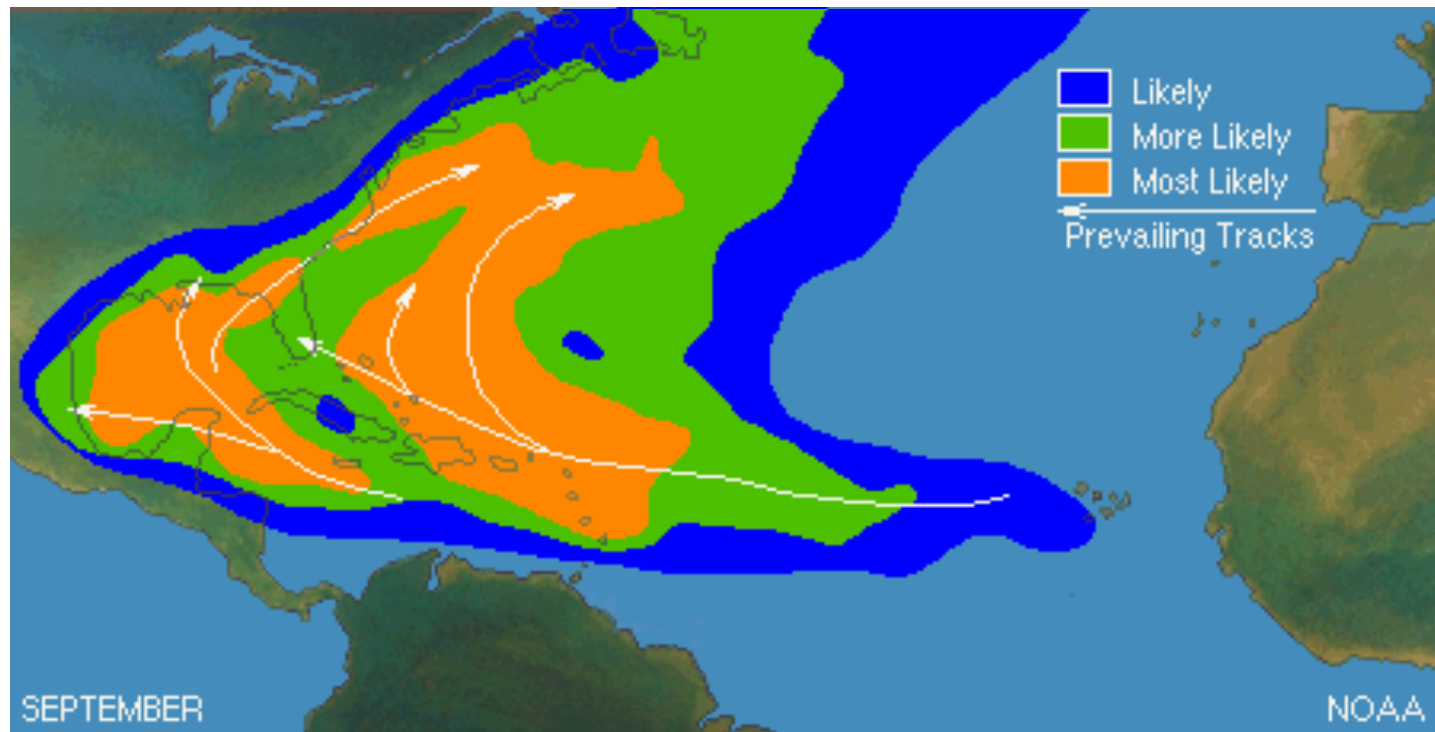
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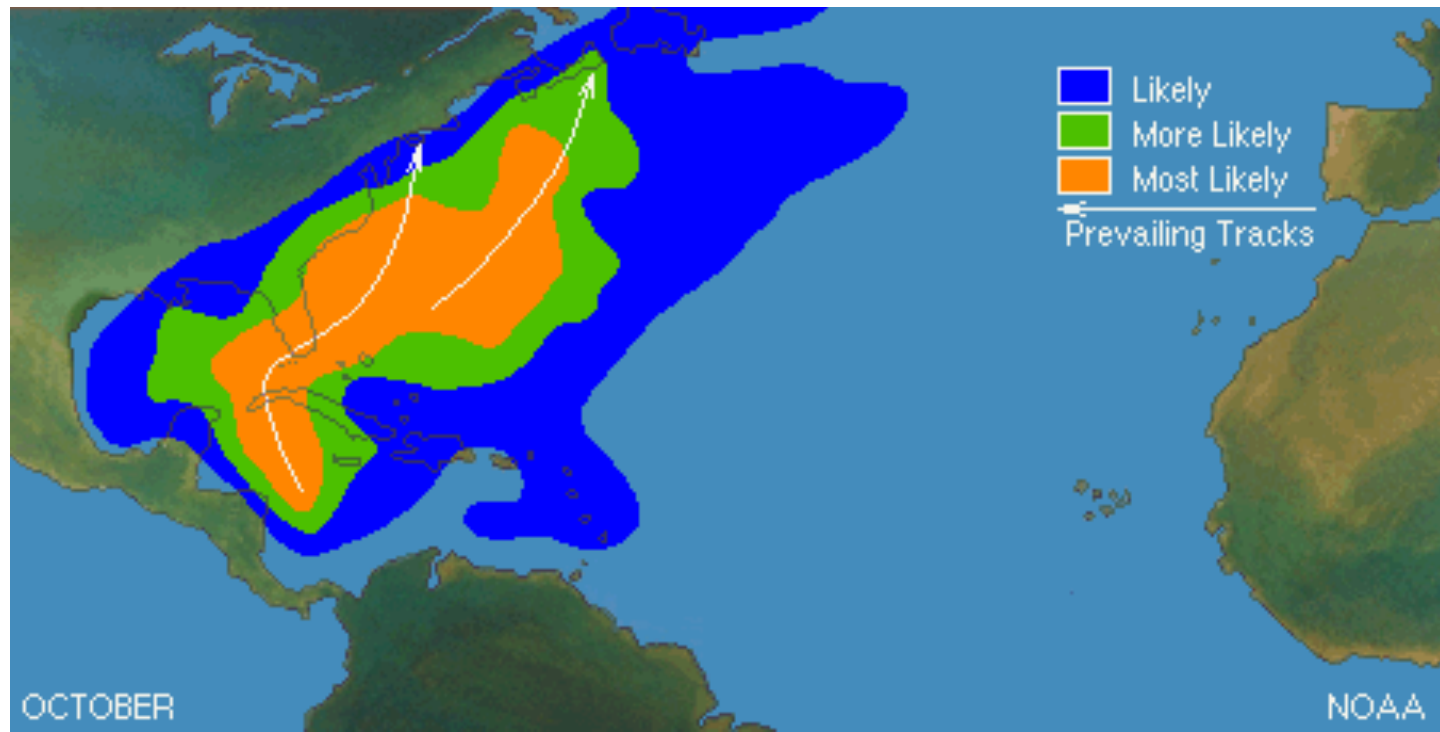
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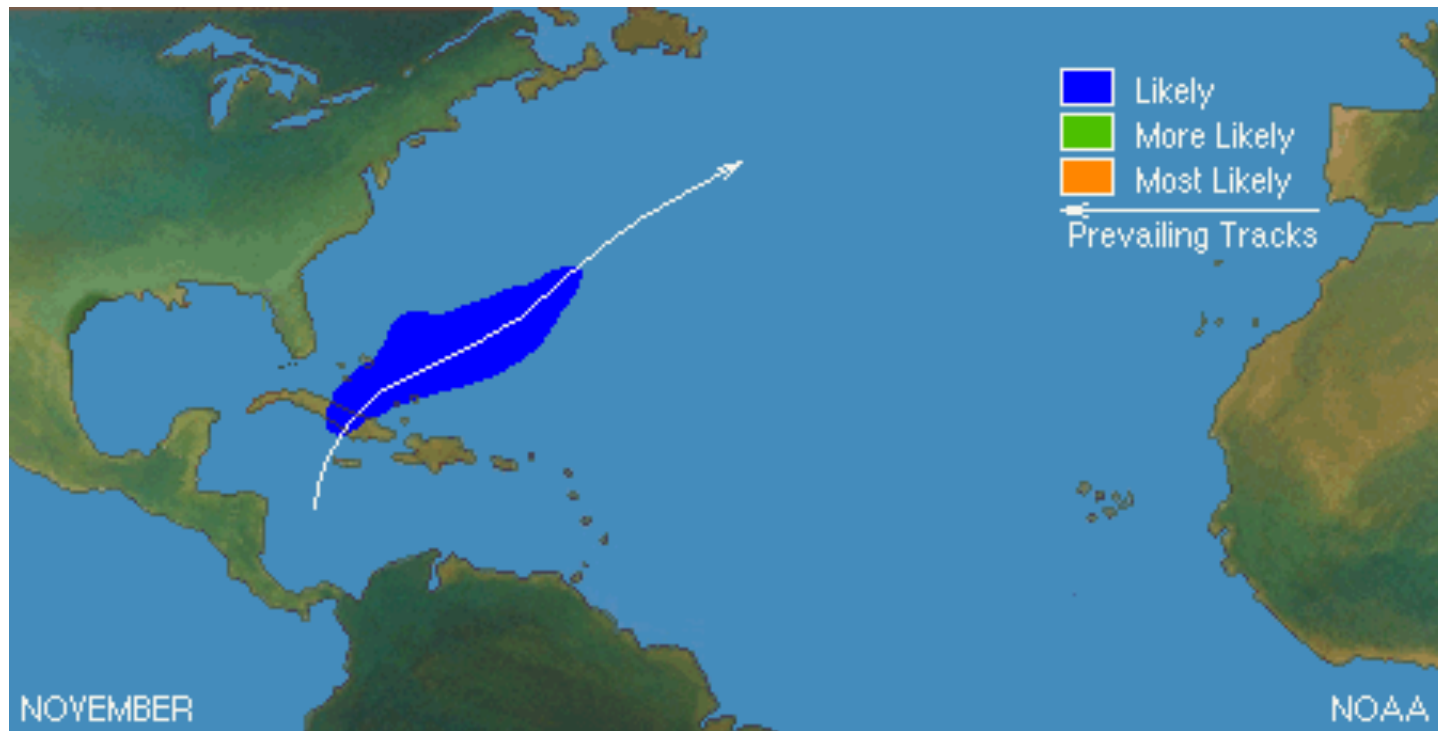
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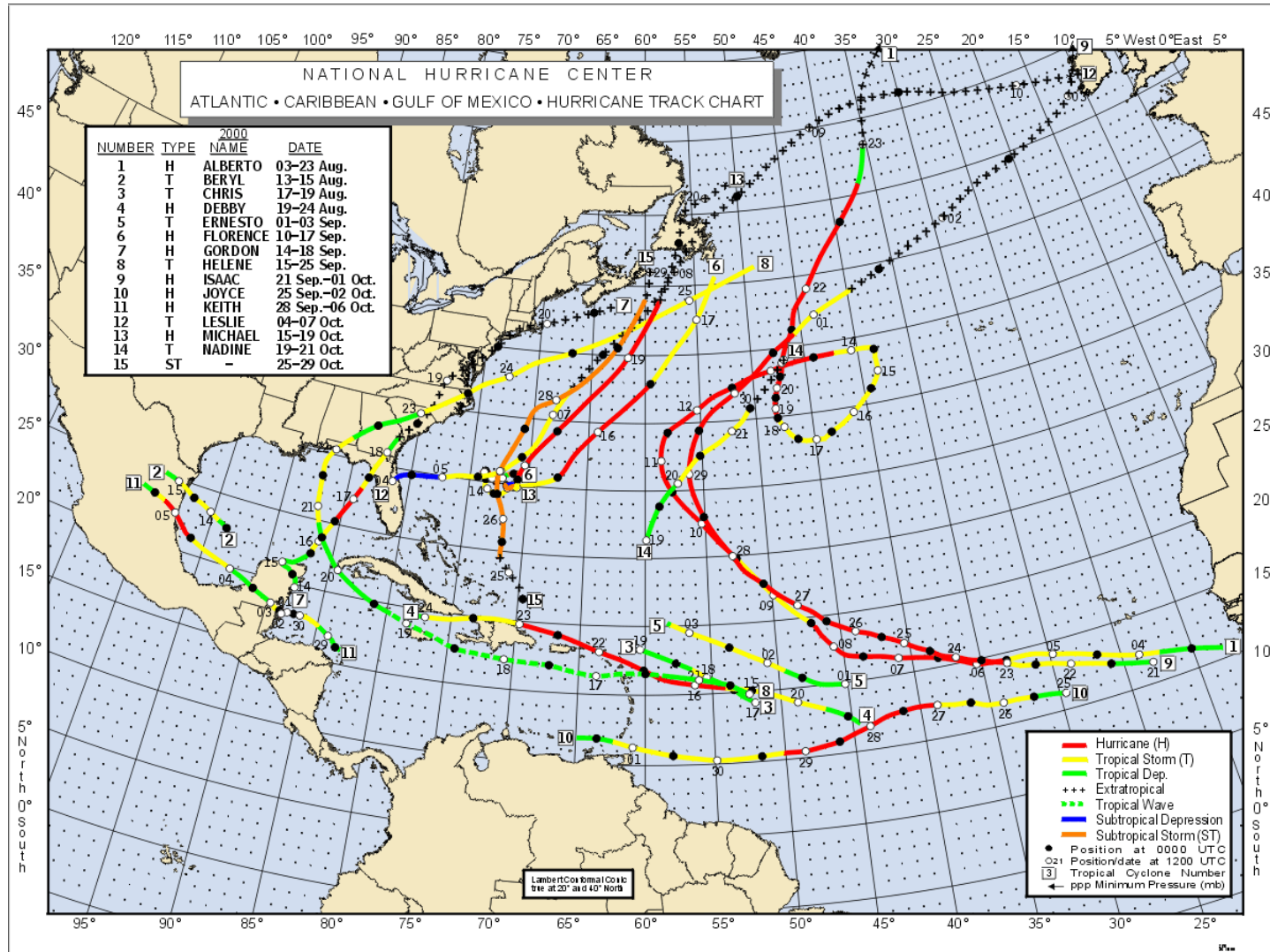
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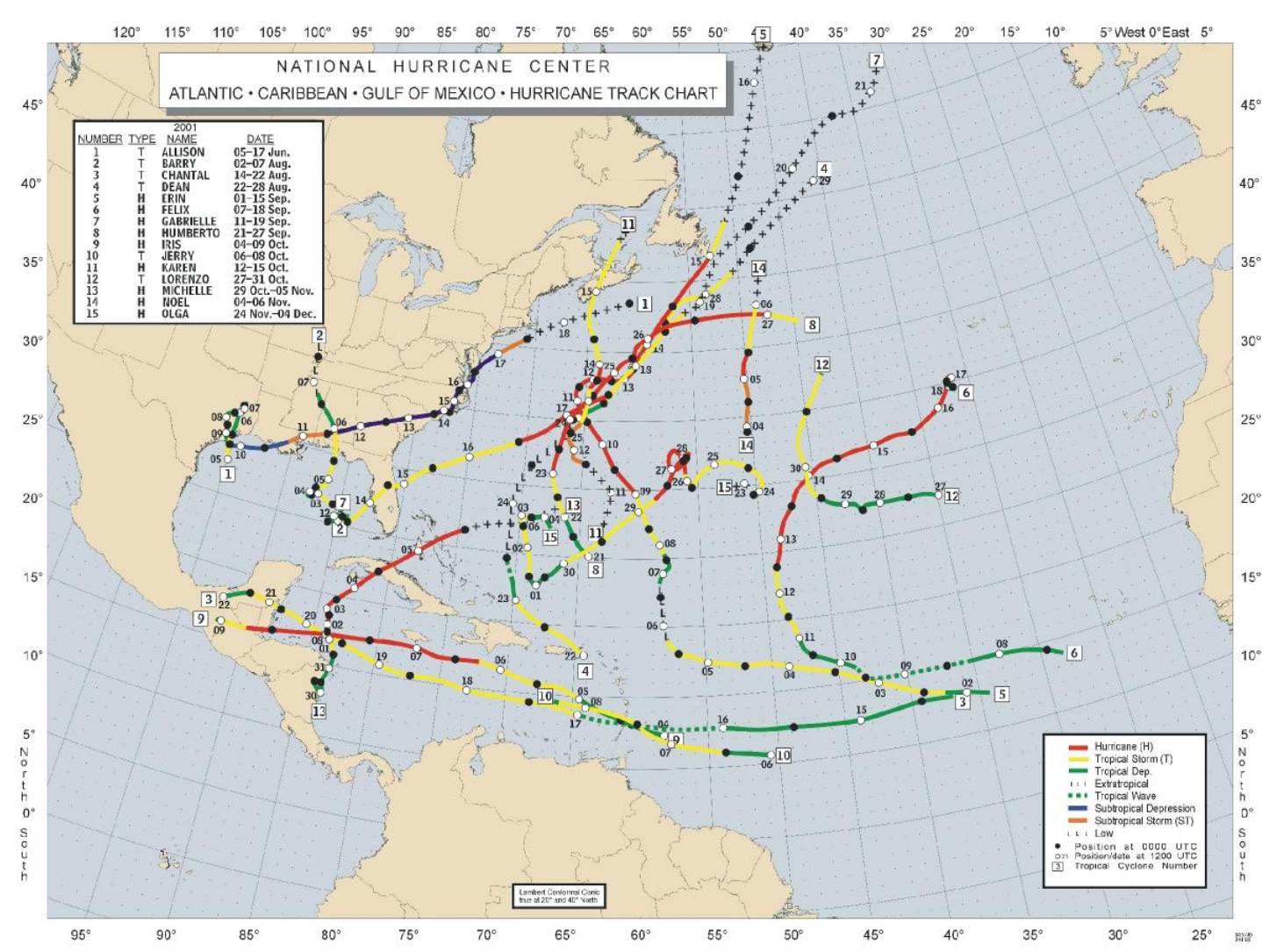
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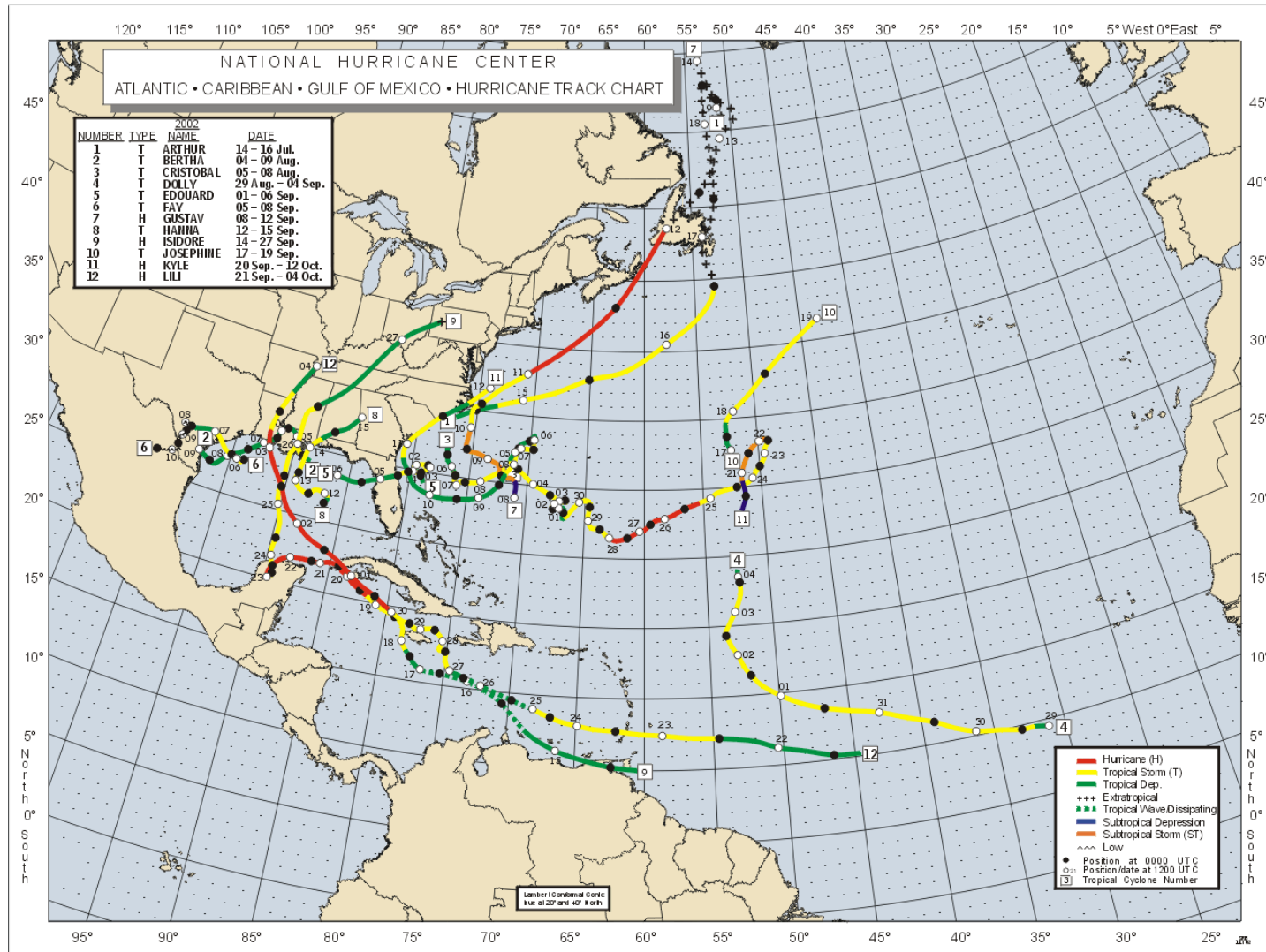
Atlantic Hurricane Tracks (00-08)



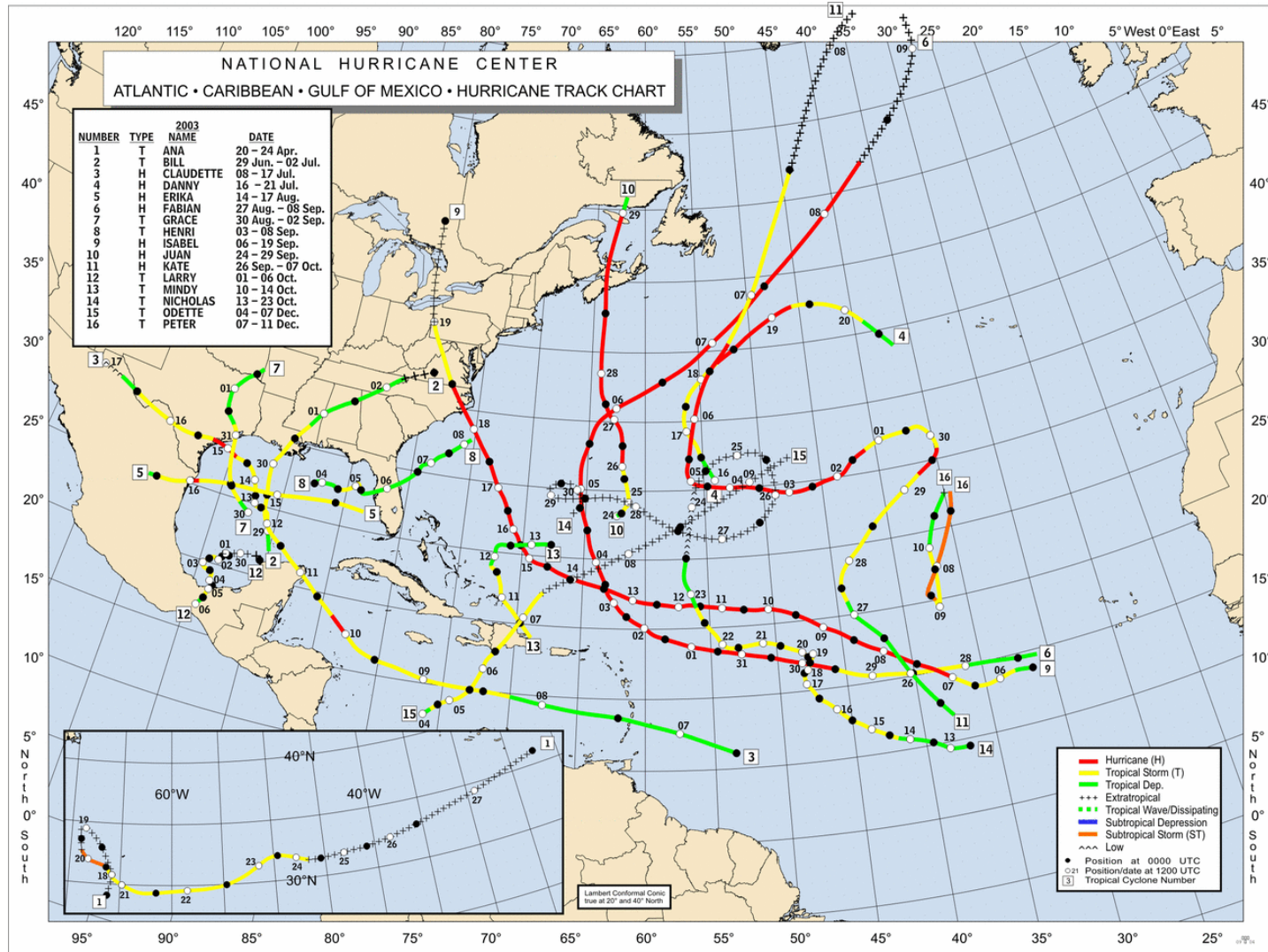
Atlantic Hurricane Tracks (00-08)



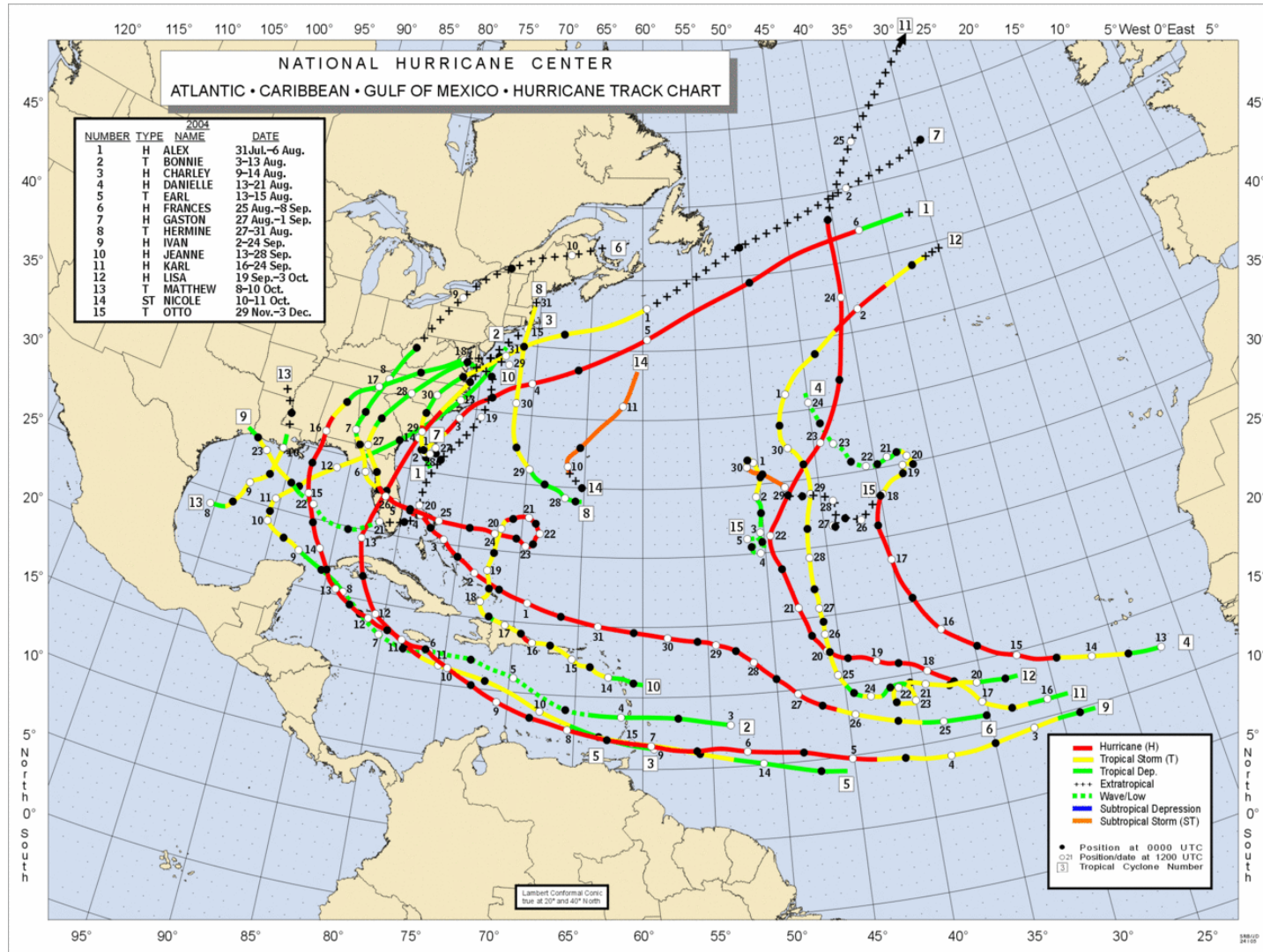
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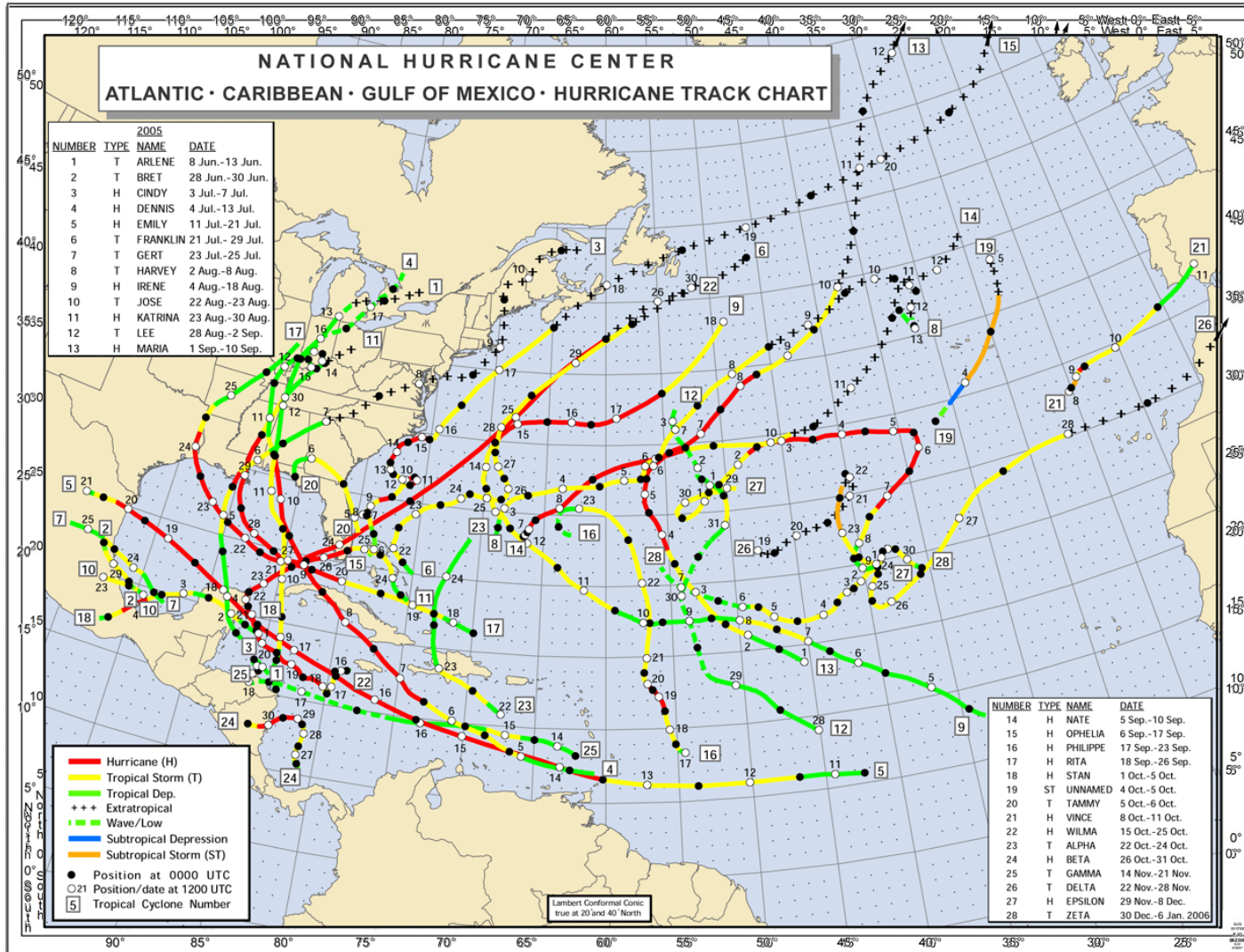
Atlantic Hurricane Tracks (00-08)



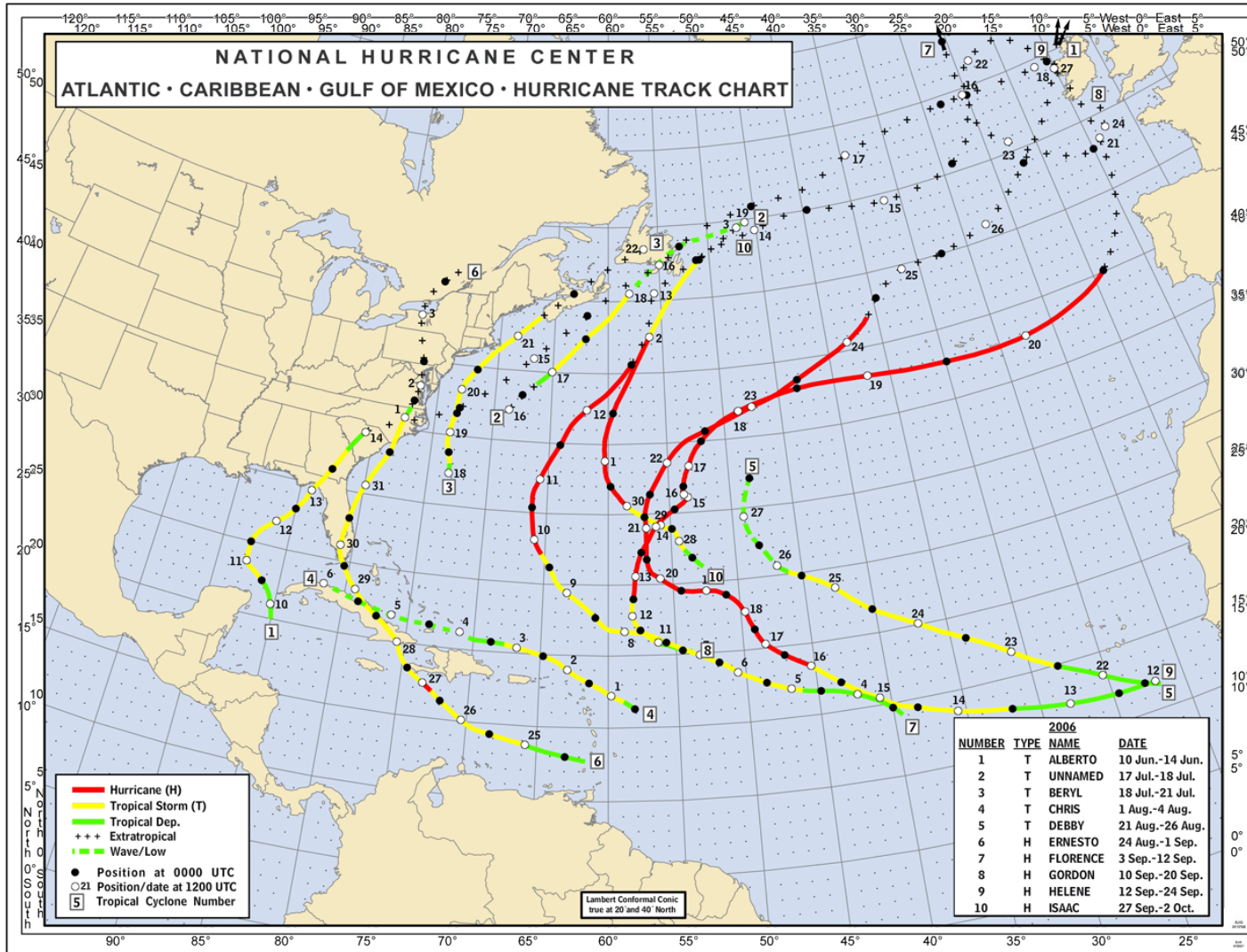
Atlantic Hurricane Tracks (00-08)



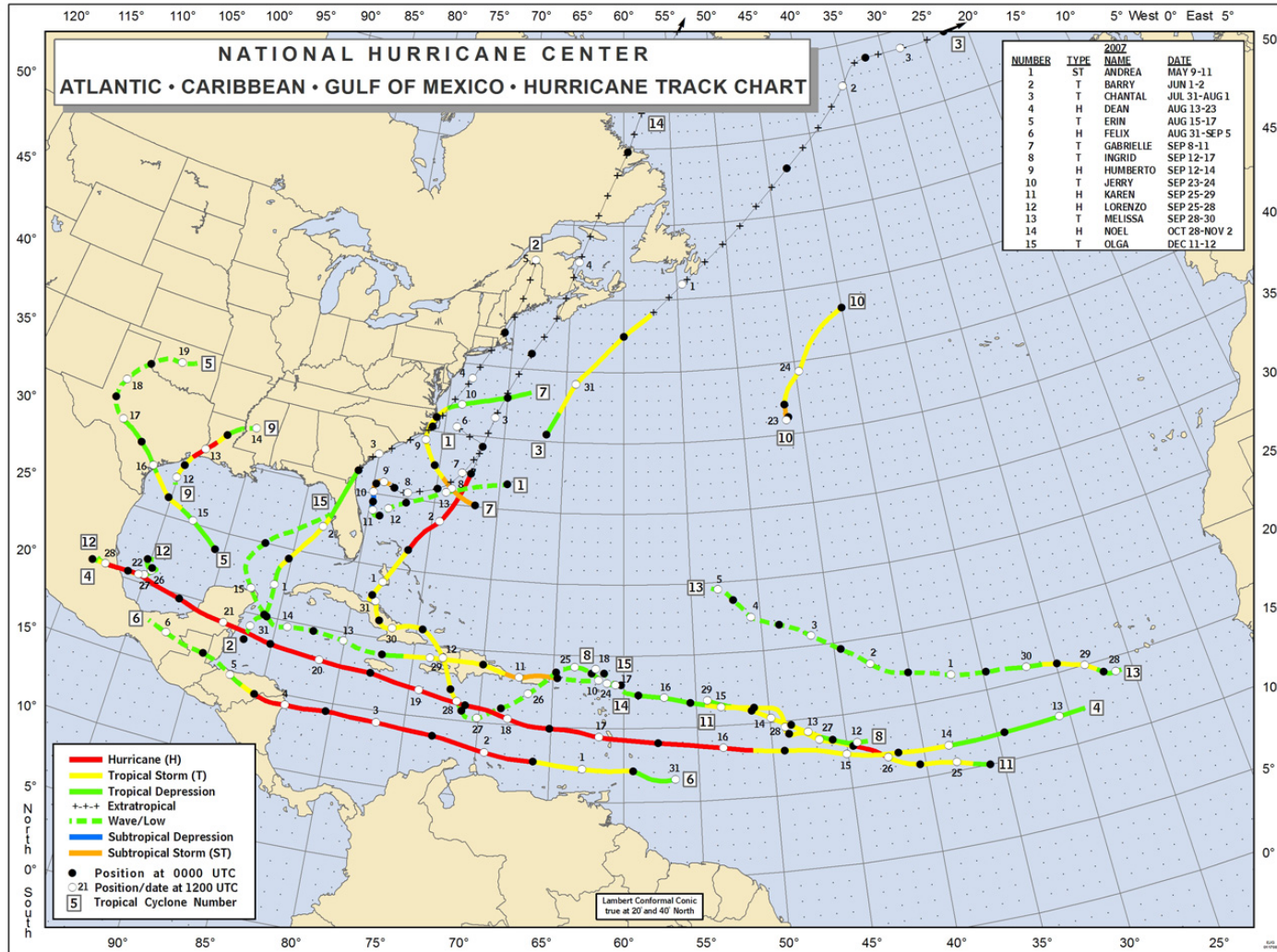
Atlantic Hurricane Tracks (00-08)



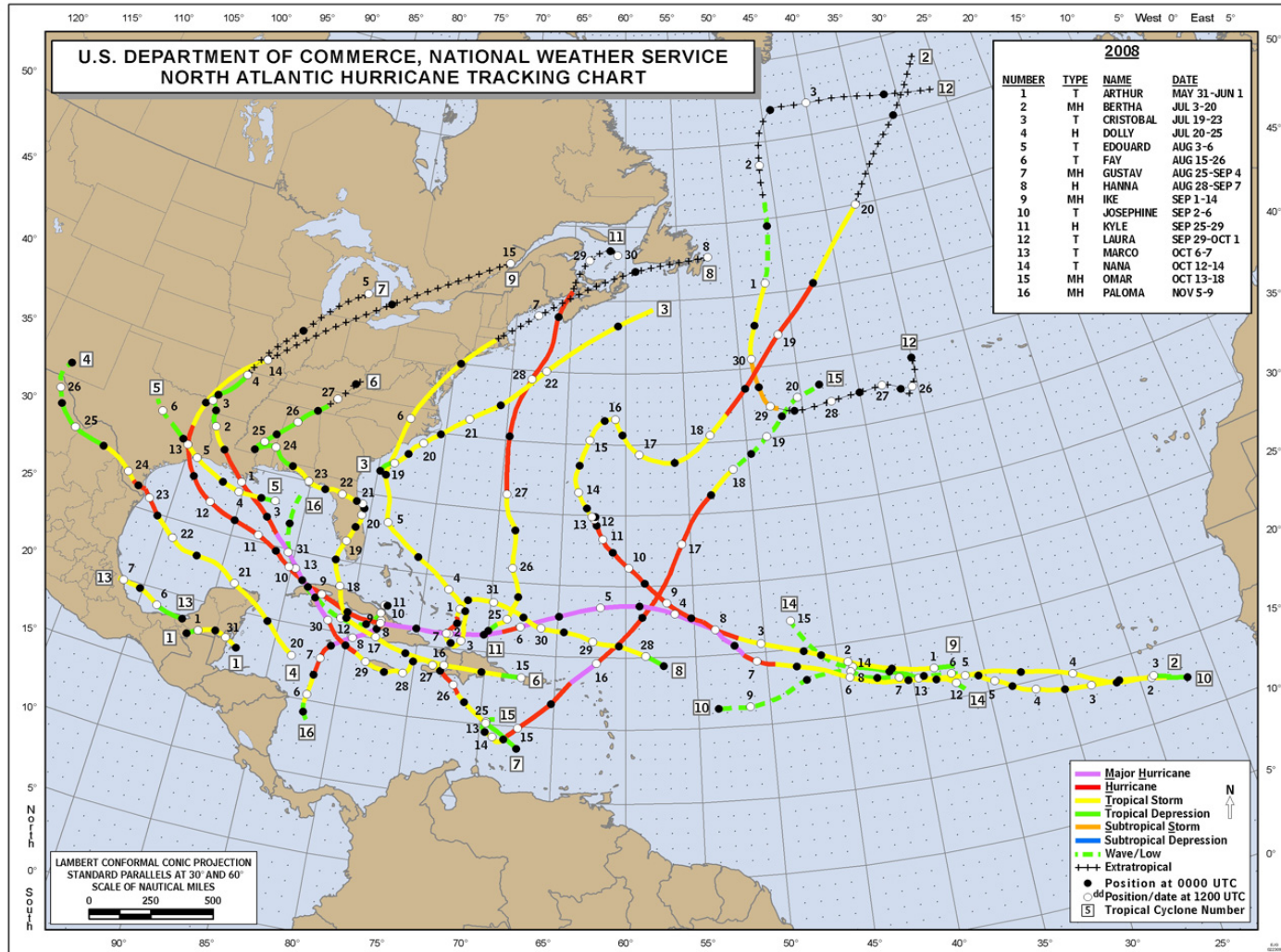
Atlantic Hurricane Tracks (00-08)



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Intraseasonal modulation: MJO

Composite evolution of 200hPa velocity potential anomalies ($10^5 \times \text{m}^2/\text{s}$) and points of origin of tropical systems that developed into hurricanes/typhoons

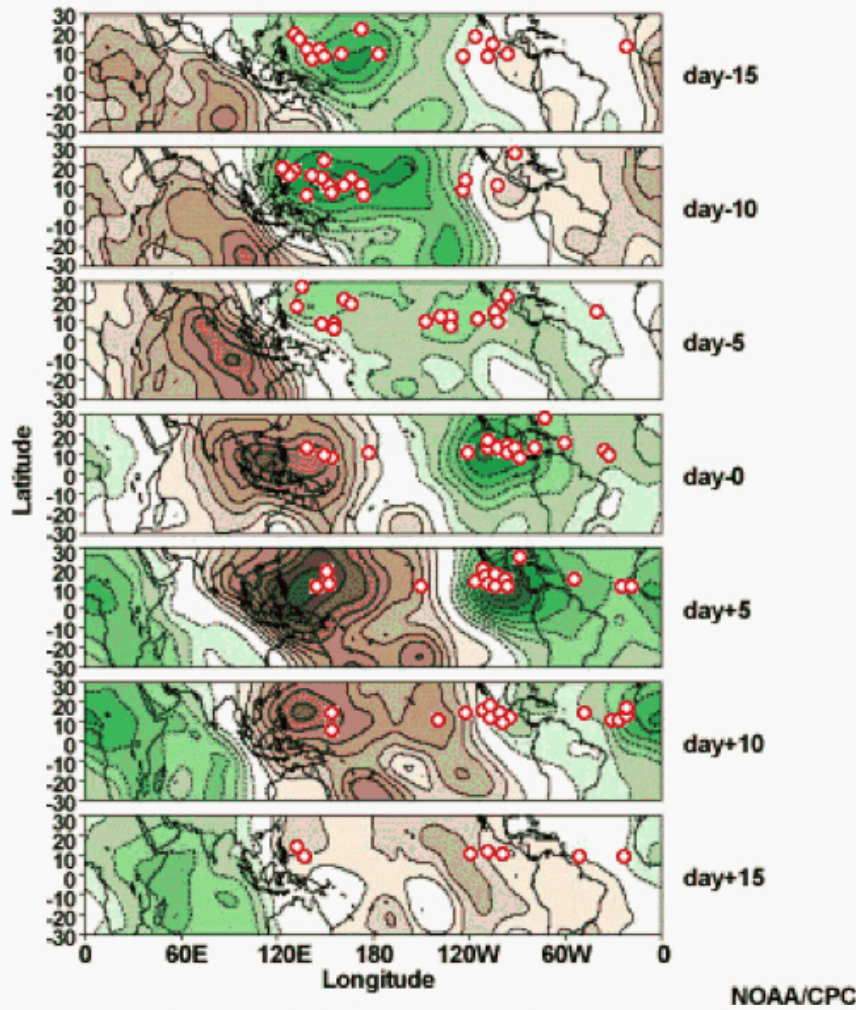
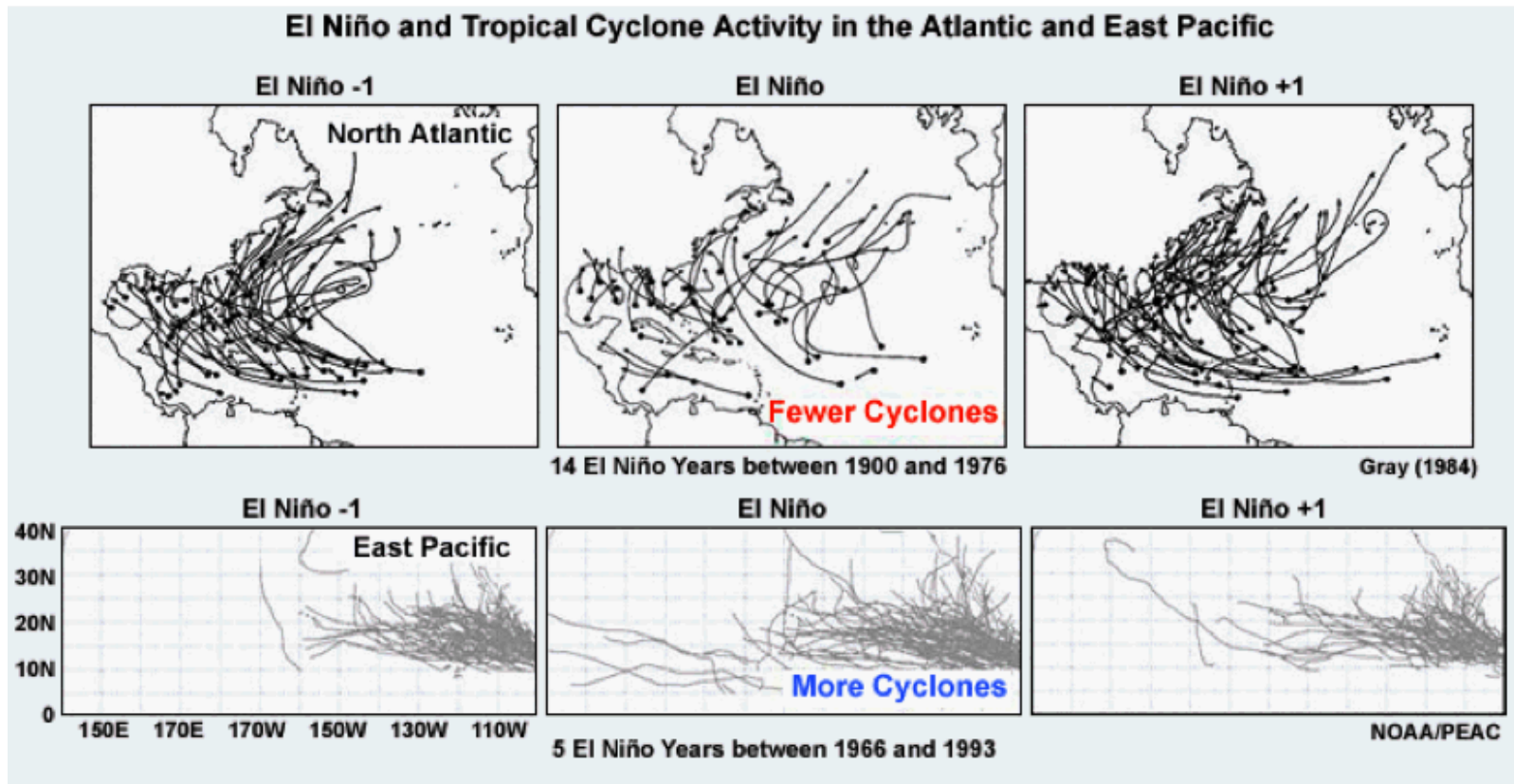


Fig. 10.68. Points of origin of tropical systems that developed into tropical cyclones (red circles) relative to phases of the MJO. The MJO cycle is identified here by the 200 hPa velocity potential anomalies ($10^5 \times \text{m}^2 \text{s}^{-1}$); green is the peak and dark brown is the lull.

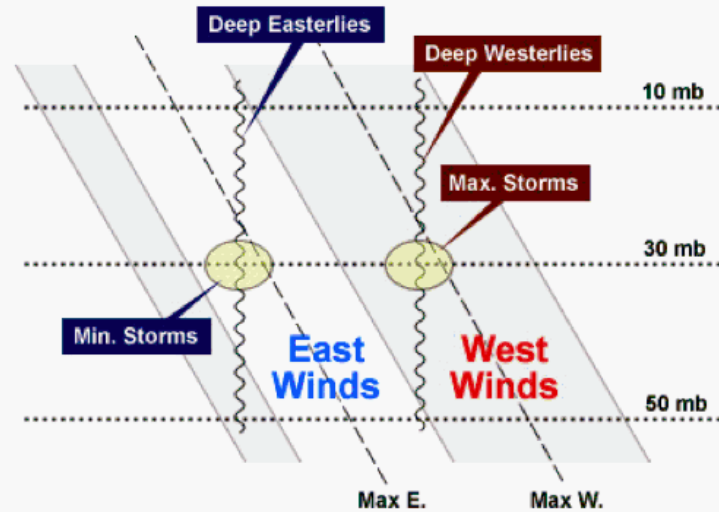
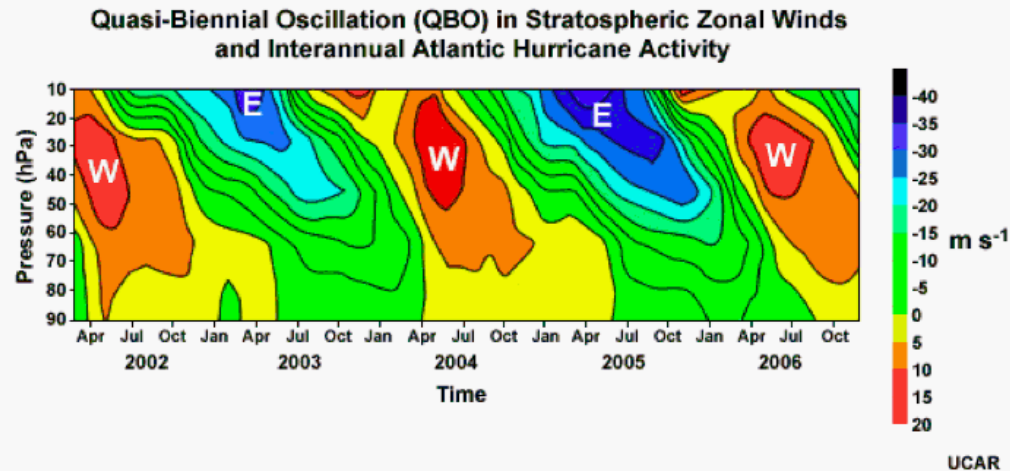
- Active phases of the MJO are associated with increased incidence of tropical cyclogenesis
- One possible source of this increase is increasing convective organization, resulting in moistening of the troposphere through cloud detrainment, creating a more favorable environment
- Organized convection has greater low-level vorticity, decreasing the local Rossby radius of deformation and potentially providing seed disturbances
- Active phases of the MJO may also provide background for interactions with easterly waves

Interannual modulation: ENSO



- The increase to SST and weakening of vertical wind shear in the central and eastern Pacific and central/western Indian Ocean during El Niño events appears to favor more tropical cyclone activity in these regions
- By contrast, cooling of SST in the western Pacific and increase in vertical wind shear in the western Pacific and Atlantic during El Niño events appears to decrease tropical cyclone activity in these regions

Interannual modulation: QBO



Adapted from Gray 1984

Fig. 10.71. The 10-50hPa stratospheric zonal wind (upper) and typical variation when the 30hPa westerly winds are becoming stronger (wavy lines in grey shaded region) and Atlantic hurricane activity is enhanced. Hurricane activity is suppressed during the easterly wind phase of the QBO (lower, unshaded region). Lower panel is adapted from Gray (1984).¹⁶²

Global warming and tropical cyclones (I)?

Summary Statement on Tropical Cyclones and Climate Change

The surfaces of most tropical oceans have warmed by 0.25 – 0.5 degree Celsius during the past several decades. The Intergovernmental Panel on Climate Change (IPCC) considers that the likely primary cause of the rise in global mean surface temperature in the past 50 years is the increase in greenhouse gas concentrations.

The global community of tropical cyclone researchers and forecasters as represented at the 6th International Workshop on Tropical Cyclones of the World Meteorological Organization has released a statement on the links between anthropogenic (human-induced) climate change and tropical cyclones, including hurricanes and typhoons. This statement is in response to increased attention on tropical cyclones due to the following events:

- a) There have been a number of recent high-impact tropical cyclone events around the globe. These include 10 landfalling tropical cyclones in Japan in 2004, five tropical cyclones affecting the Cook Islands in a five-week period in 2005, Cyclone Gafilo in Madagascar in 2004, Cyclone Larry in Australia in 2006, Typhoon Saomai in China in 2006, and the extremely active 2004 and 2005 Atlantic tropical cyclone seasons - including the catastrophic socio-economic impact of Hurricane Katrina.
- b) Some recent scientific articles have reported a large increase in tropical cyclone energy, numbers, and wind-speeds in some regions during the last few decades in association with warmer sea surface temperatures. Other studies report that changes in observational techniques and instrumentation are responsible for these increases.

Global warming and tropical cyclones (II)?

Consensus Statements by International Workshop on Tropical Cyclones-VI (IWTC-VI) Participants

1. Though there is evidence both for and against the existence of a detectable anthropogenic signal in the tropical cyclone climate record to date, no firm conclusion can be made on this point.
2. No individual tropical cyclone can be directly attributed to climate change.
3. The recent increase in societal impact from tropical cyclones has largely been caused by rising concentrations of population and infrastructure in coastal regions.
4. Tropical cyclone wind-speed monitoring has changed dramatically over the last few decades, leading to difficulties in determining accurate trends.
5. There is an observed multi-decadal variability of tropical cyclones in some regions whose causes, whether natural, anthropogenic or a combination, are currently being debated. This variability makes detecting any long-term trends in tropical cyclone activity difficult.
6. It is likely that some increase in tropical cyclone peak wind-speed and rainfall will occur if the climate continues to warm. Model studies and theory project a 3-5% increase in wind-speed per degree Celsius increase of tropical sea surface temperatures.
7. There is an inconsistency between the small changes in wind-speed projected by theory and modeling versus large changes reported by some observational studies.
8. Although recent climate model simulations project a decrease or no change in global tropical cyclone numbers in a warmer climate, there is low confidence in this projection. In addition, it is unknown how tropical cyclone tracks or areas of impact will change in the future.
9. Large regional variations exist in methods used to monitor tropical cyclones. Also, most regions have no measurements by instrumented aircraft. These significant limitations will continue to make detection of trends difficult.
10. If the projected rise in sea level due to global warming occurs, then the vulnerability to tropical cyclone storm surge flooding would increase.