



TROPICAL CYCLONE GENESIS

Todd B. Kimberlain and Richard J. Pasch

**WMO RA-IV Workshop on Hurricane
Forecasting & Warning**

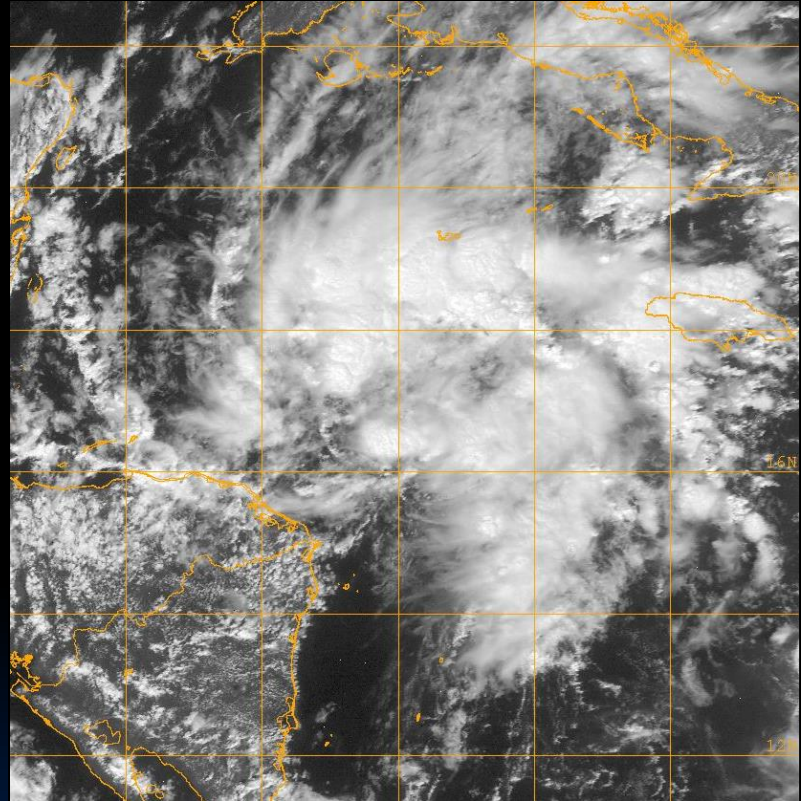
7 March 2017

Outline / Topics

- Climatology
- Large-scale conditions associated with tropical cyclone (TC) formation
- Relation to ENSO, intraseasonal variability
- Theories of genesis
- Meso-scale aspects of genesis
- TC genesis in global models
- Web sites of genesis parameters
- Operational (NHC) genesis forecasting
- Forecast exercise

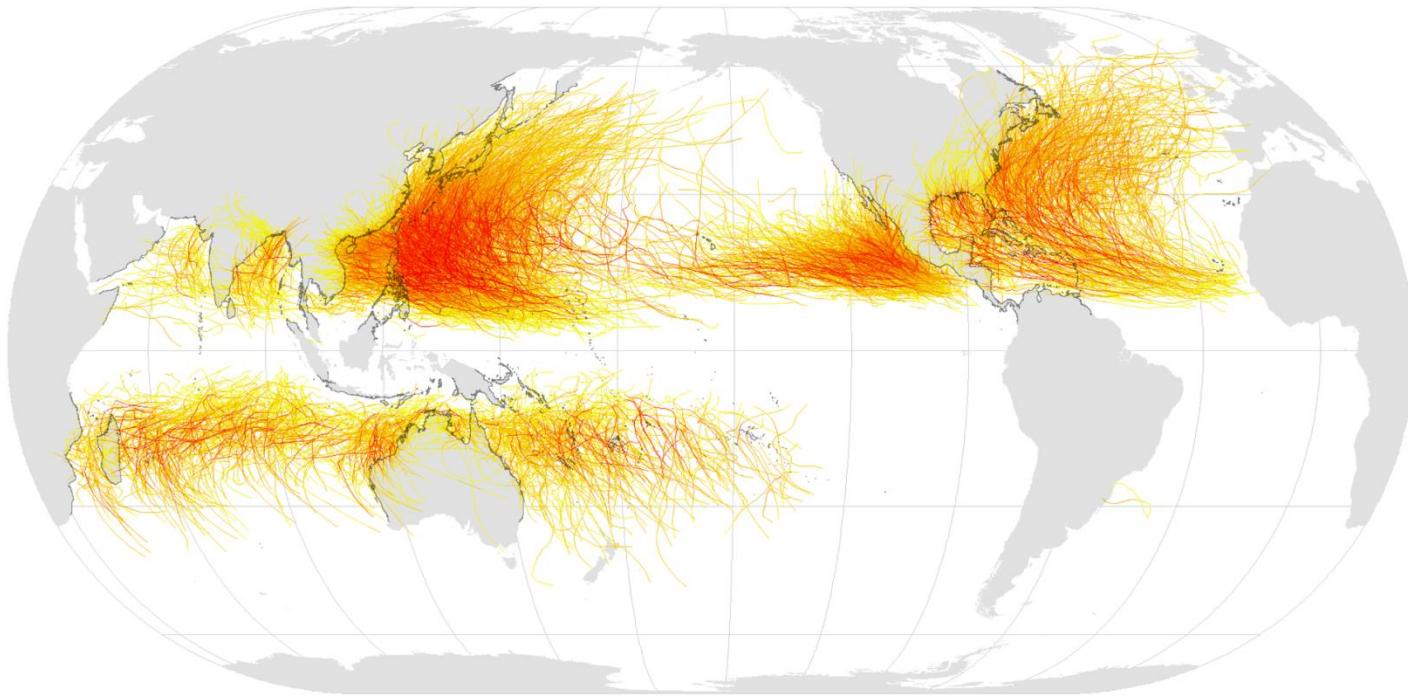
WMO Definition of a Tropical Cyclone:

“A warm-core, non-frontal synoptic-scale cyclone, originating over tropical or subtropical waters, with organized deep convection and closed surface wind circulation about a well-defined center.”



Principal Areas of Tropical Cyclone Formation

Tropical Cyclones, 1945–2006



Saffir-Simpson Hurricane Scale:

tropical
depression

tropical
storm

hurricane
category 1

hurricane
category 2

hurricane
category 3

hurricane
category 4

hurricane
category 5

Factors Governing the Climatology of Tropical Cyclone Formation in the Atlantic Basin

- In the long-term mean, typically, there is a lag between the occurrence of the most favorable thermodynamic conditions (in terms of static stability) and the most favorable dynamical conditions (in terms of vertical wind shear).
- The atmosphere tends to be more unstable later in the season.
- The vertical shear tends to be weaker earlier in the season.

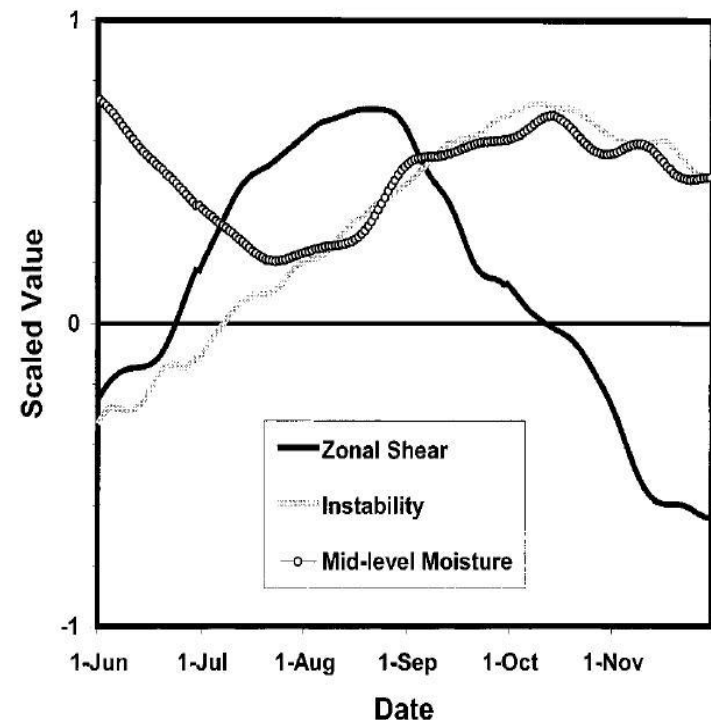
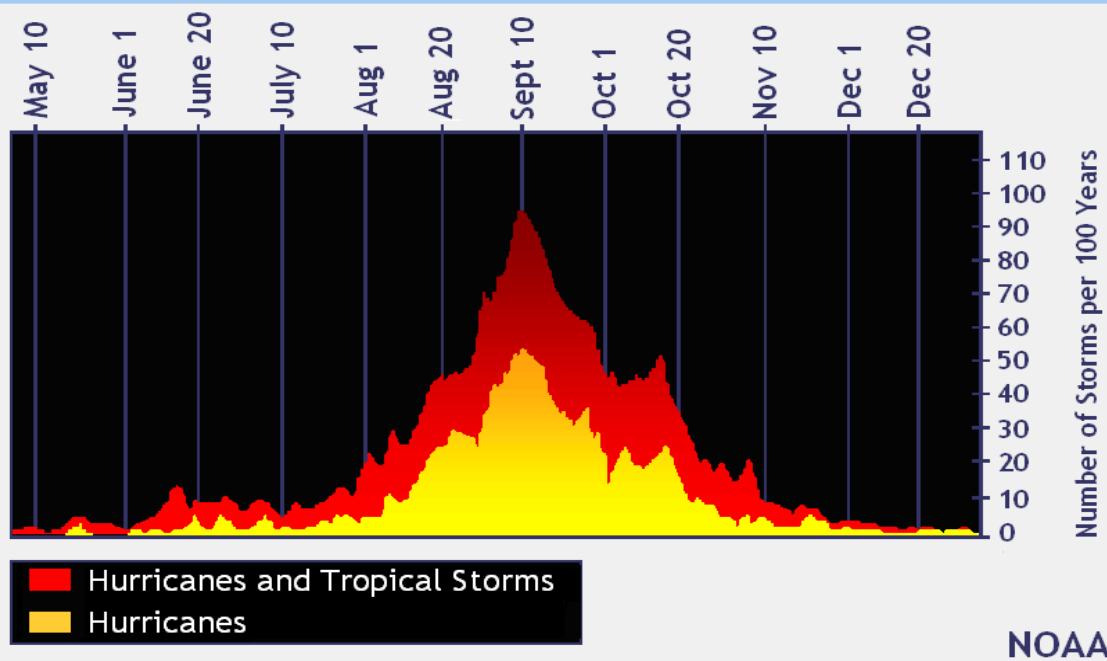
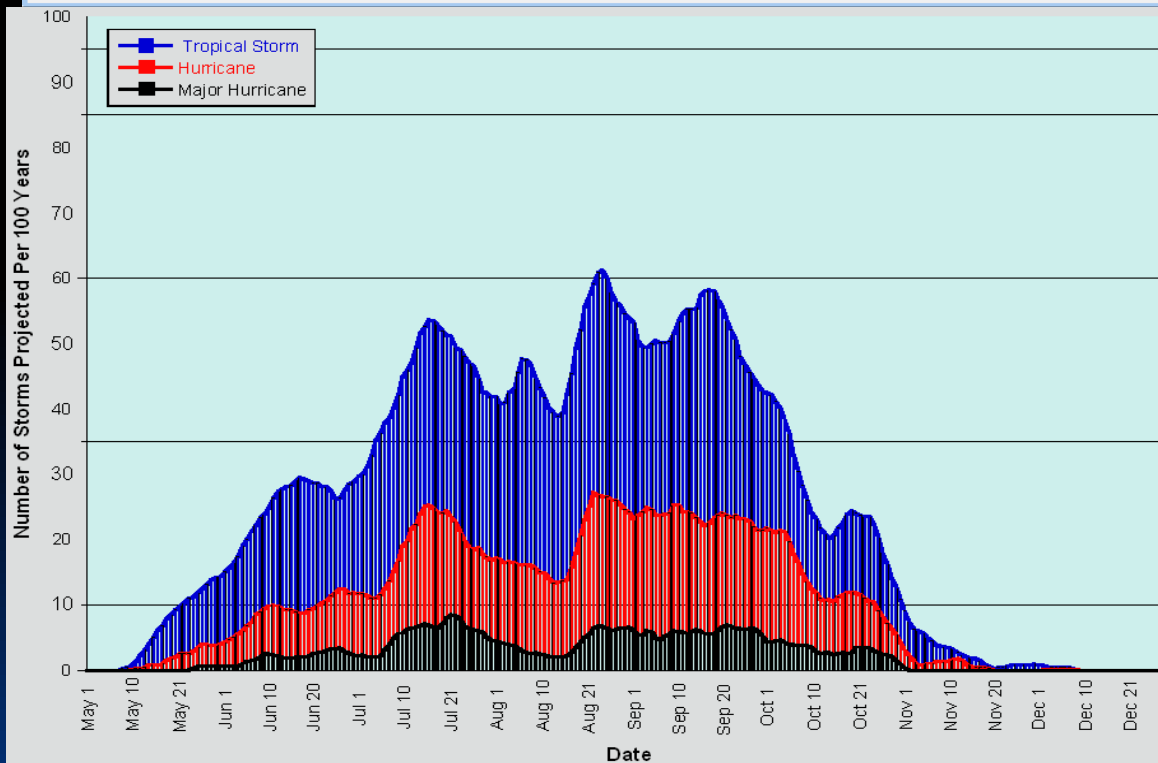


FIG. 7. Climatological time series of the scaled shear, instability, and moisture variables.



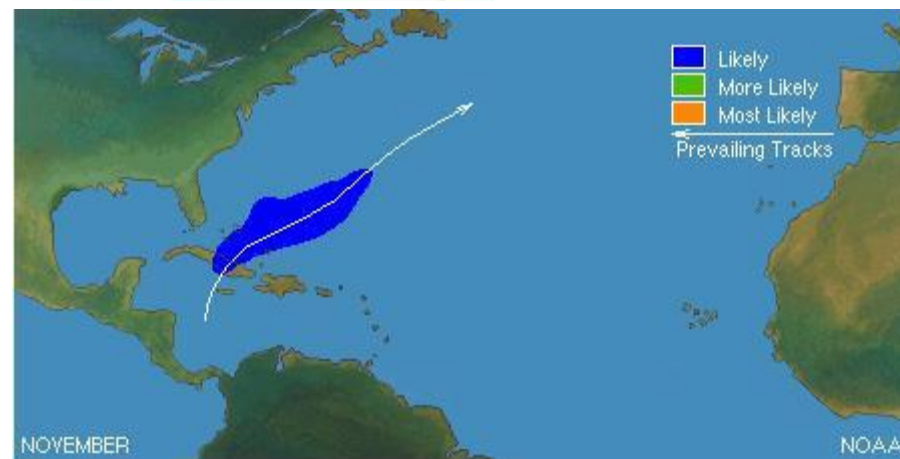
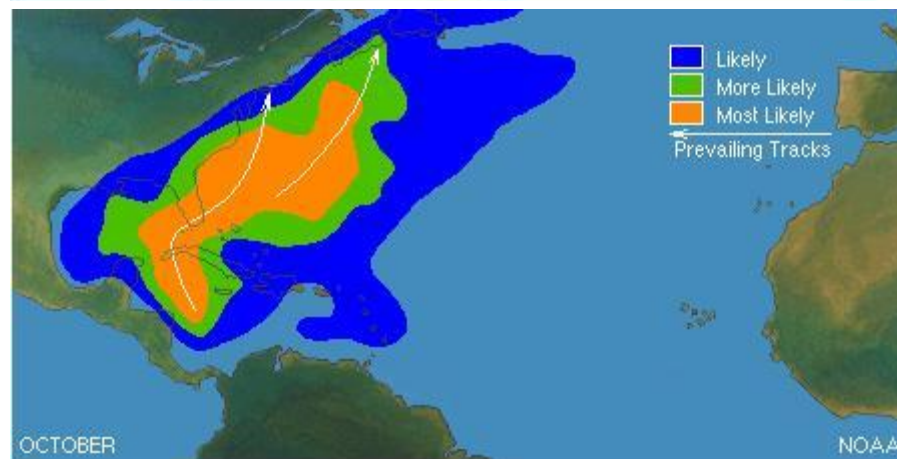
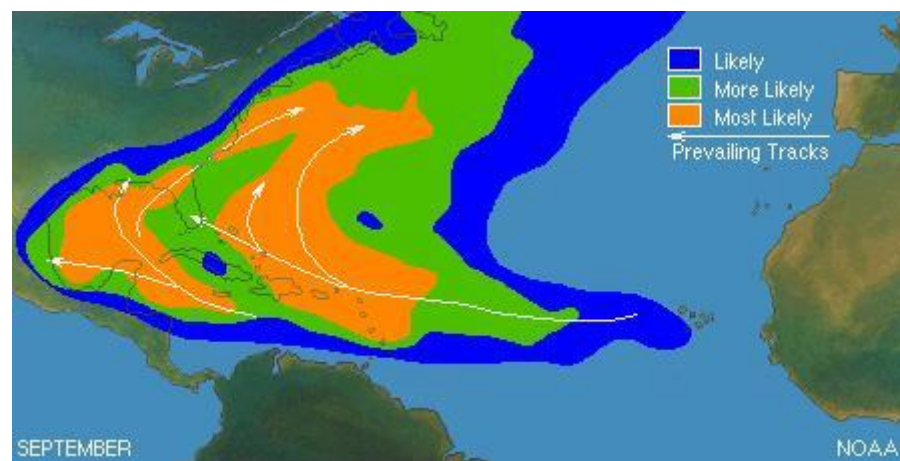
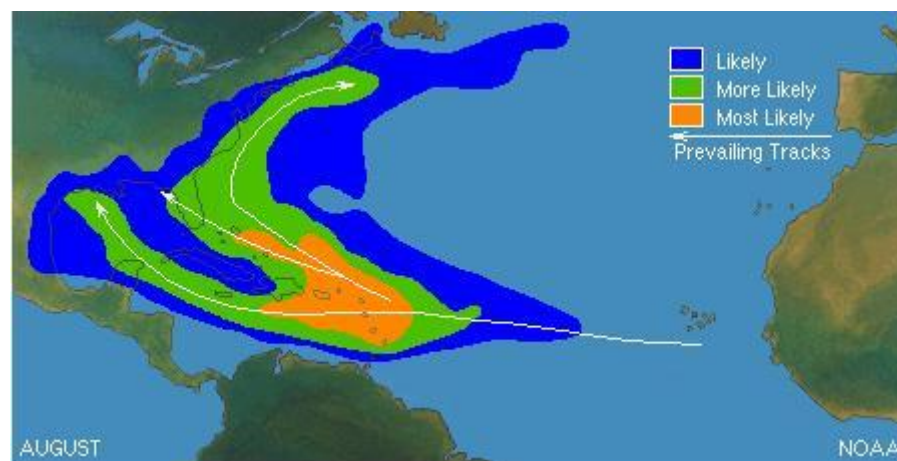
Atlantic

**Highly peaked
with a secondary
peak in mid-
October**



**Eastern North
Pacific**

**Bimodal
distribution**

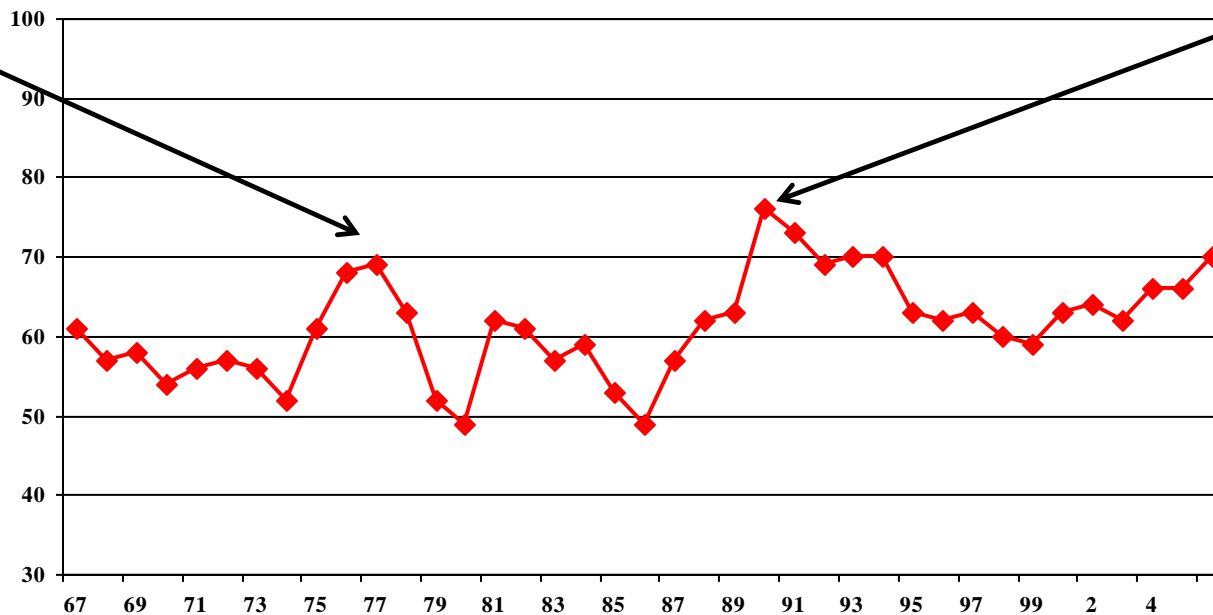


Interannual variability of the frequency of Atlantic tropical waves, 1967-2005

Inactive year

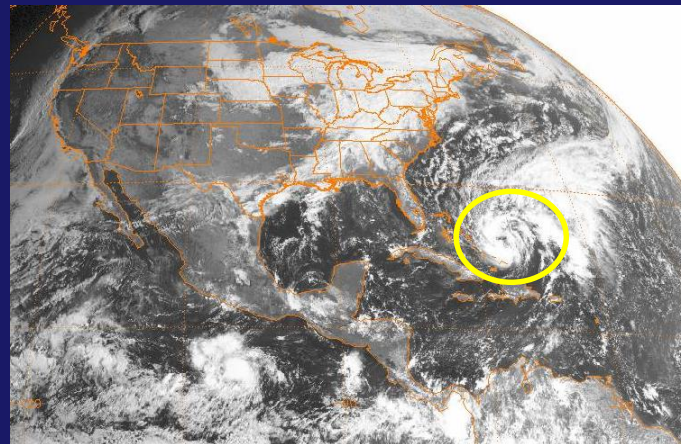
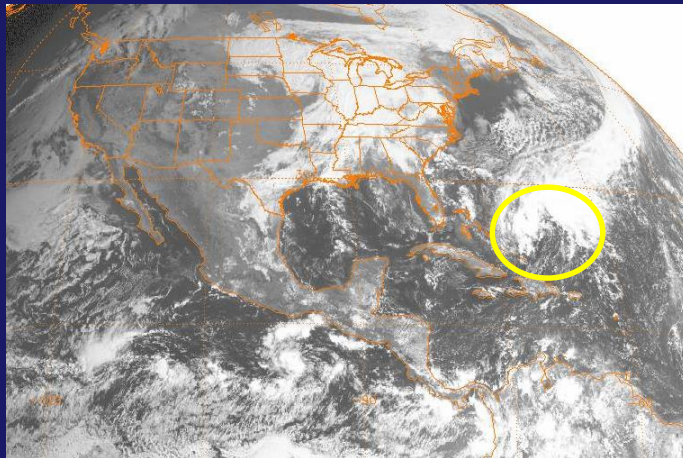
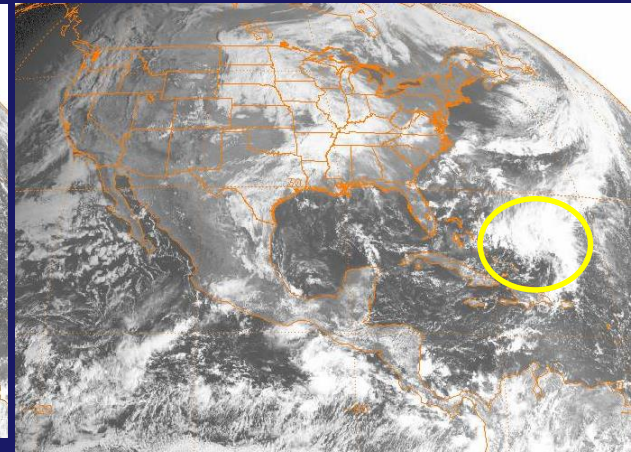
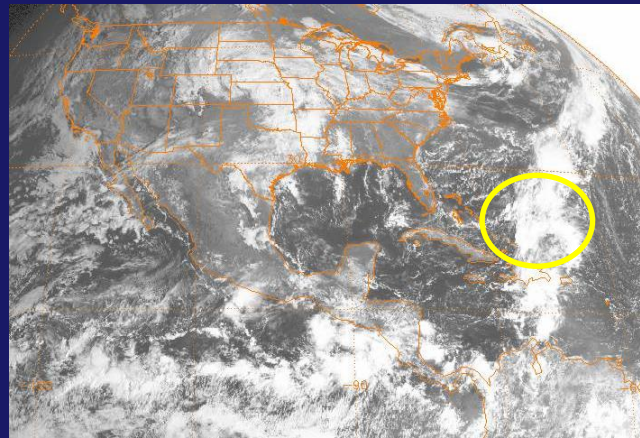
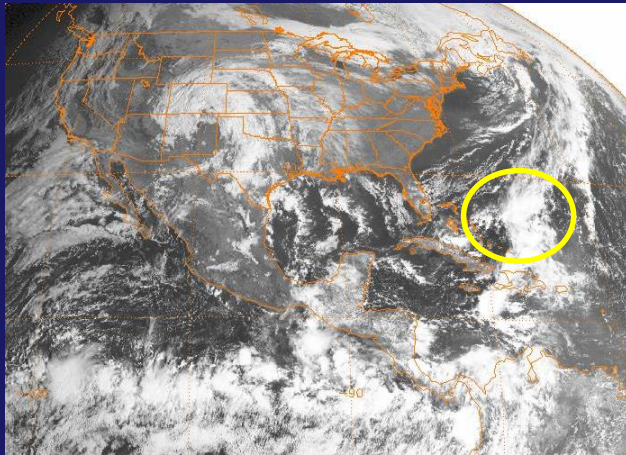
Tropical waves

Inactive year



Note that TC genesis is not a function of the number of available disturbances.

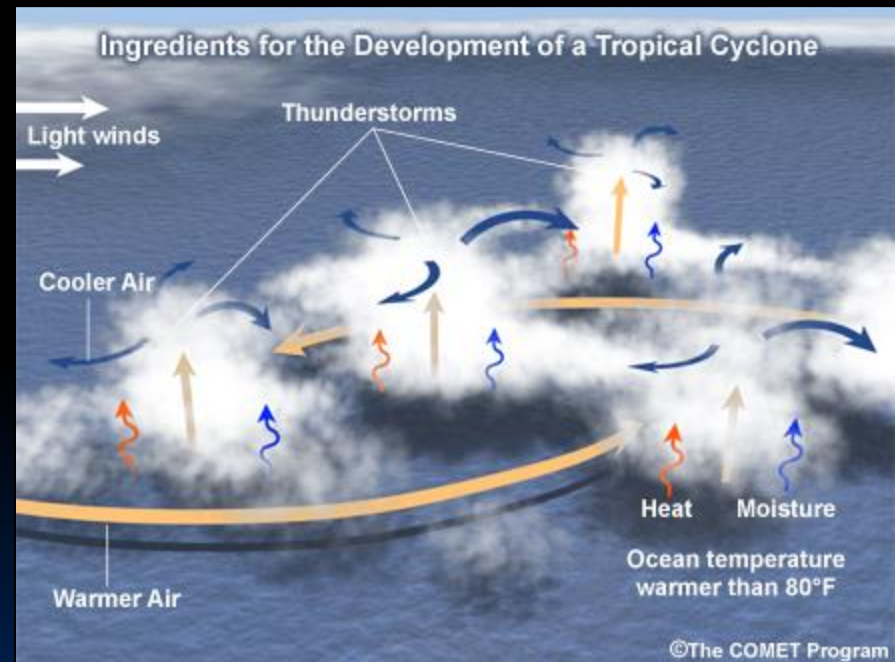
Typical Non-Tropical TC formation in the North Atlantic



Large-Scale Conditions and Other Characteristics Associated with TC Formation

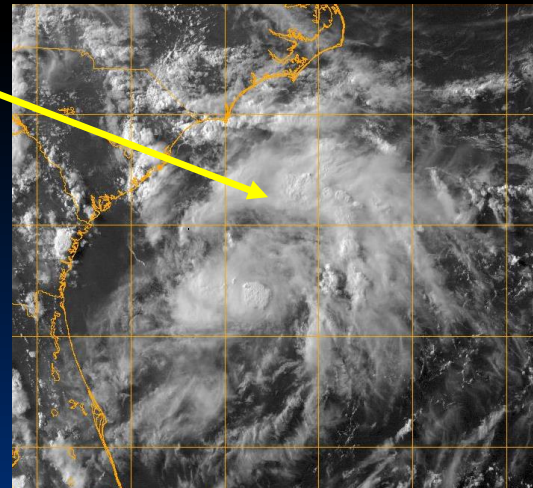
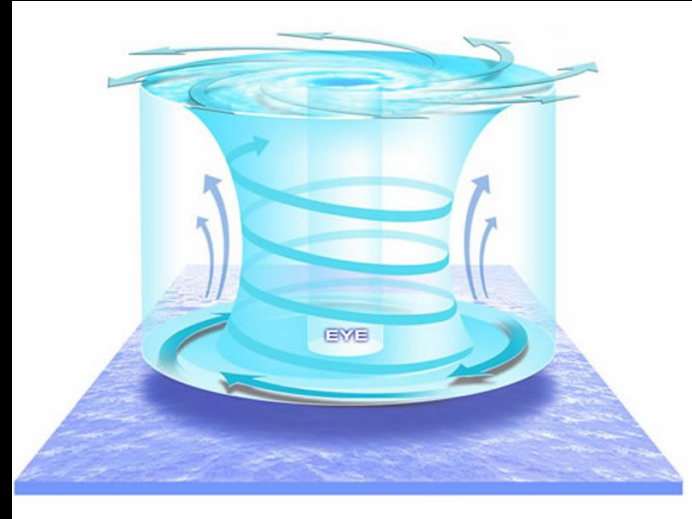
Necessary but not sufficient conditions!

- A pre-existing disturbance containing abundant deep convection
- Latitudes poleward $\sim 5^\circ$
- Adequate ocean thermal energy
 - SST $> 26^\circ\text{C}$ extending to a depth of 60 m
- A “sufficiently” unstable atmosphere & deep layer of moist air
- Small vertical shear of the horizontal wind



Large-Scale Conditions and Other Characteristics Associated with TC Formation (cont'd)

- Upper-tropospheric anticyclonic outflow over the area
- Enhanced lower tropospheric relative vorticity
- Appearance of curved banding features in the deep convection
- Falling surface pressure: **24-hour** pressure changes (falls) of usually **3 mb** or more



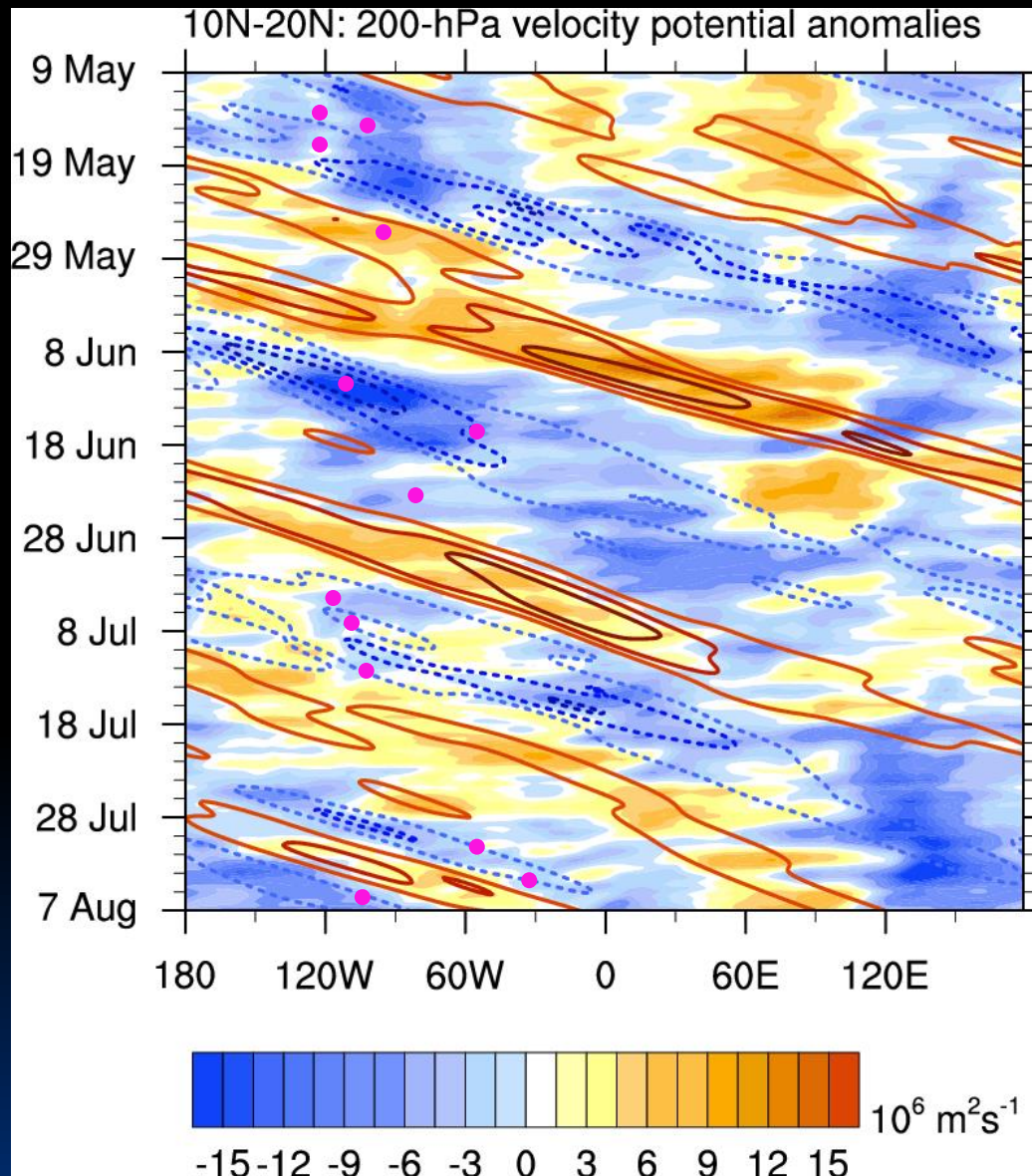
“We observe universally that tropical storms form only within pre-existing disturbances...An initial disturbance therefore forms part of the starting mechanism. A weak circulation, low pressure and a deep moist layer are present at the beginning. The forecaster need not look into areas which contain no such circulations.”

Herbert Riehl (1954)

Important Intraseasonal Predictors for 5-Day Genesis Forecasts

Blue—
favorable
upper-level
conditions
(lower
shear and
more
unstable)

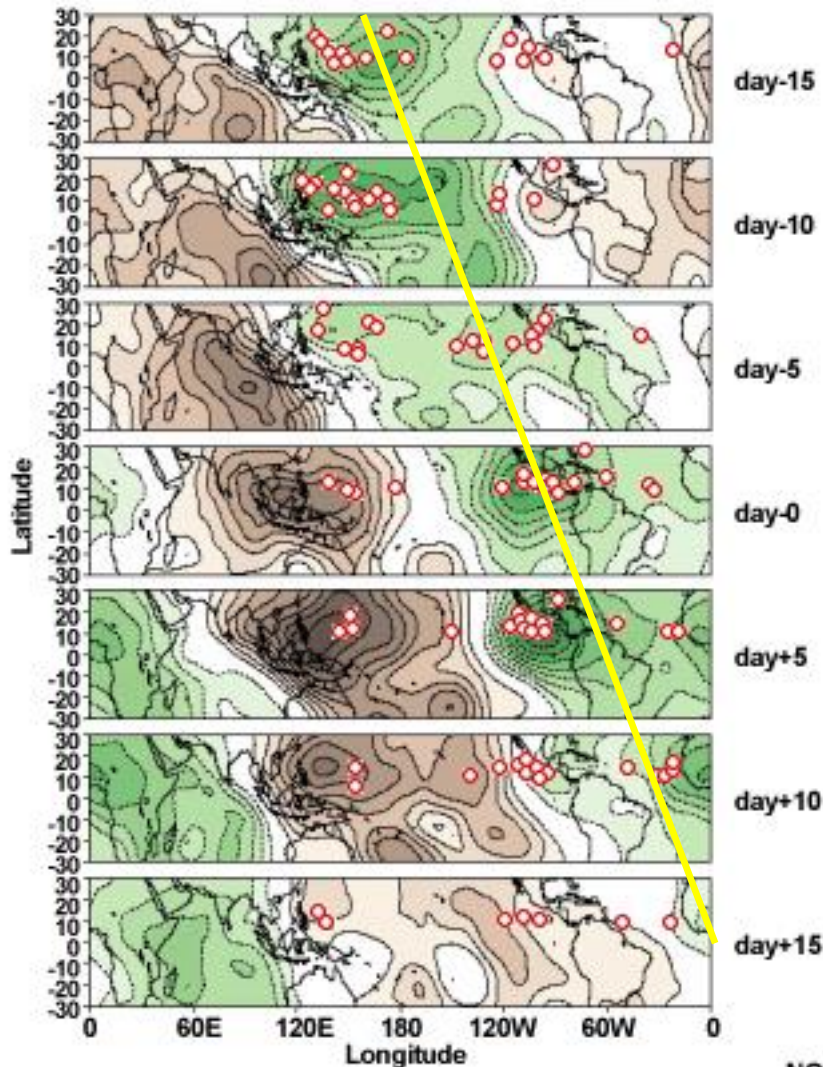
Magenta
dots are TC
genesis
points in
early 2012



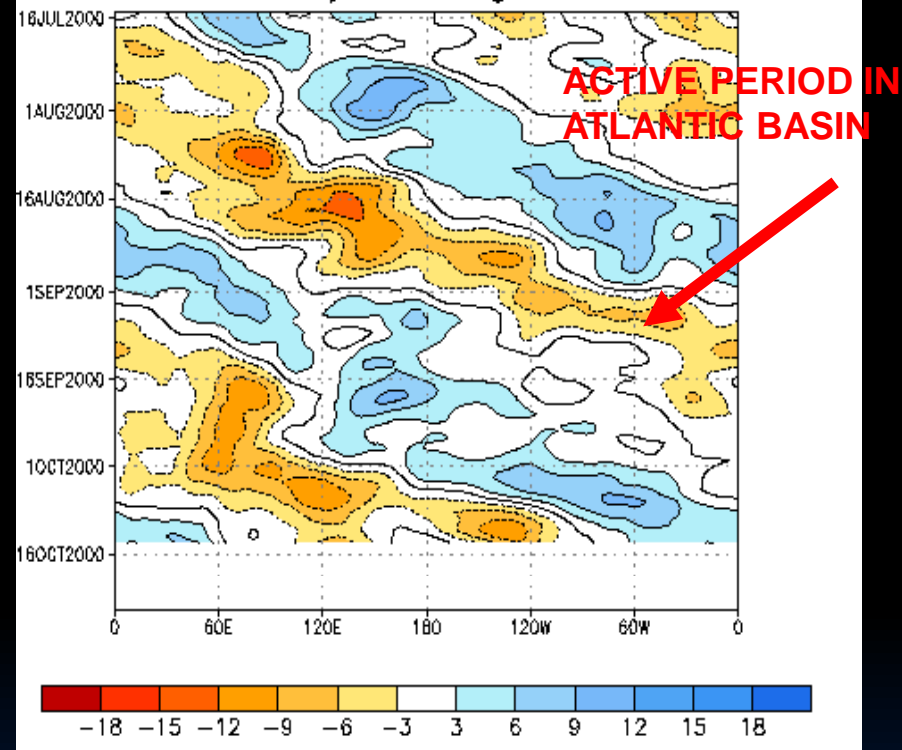
Diagnostic
tools involving
the MJO and
other
intraseasonal
oscillations are
becoming
increasingly
important but
are still used
qualitatively

MADDEN-JULIAN OSCILLATION: RELATED TO INTRASEASONAL VARIABILITY IN TC ACTIVITY?

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

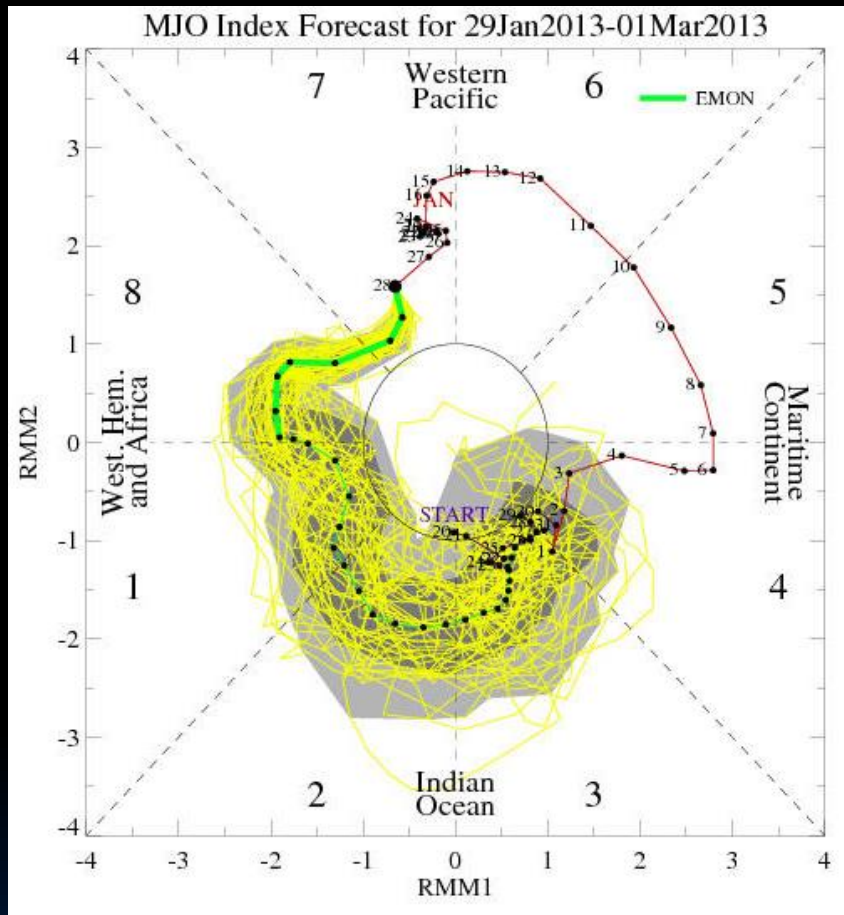


200-hPa Velocity Potential Anomaly: 5N-5S
5-day Running Mean

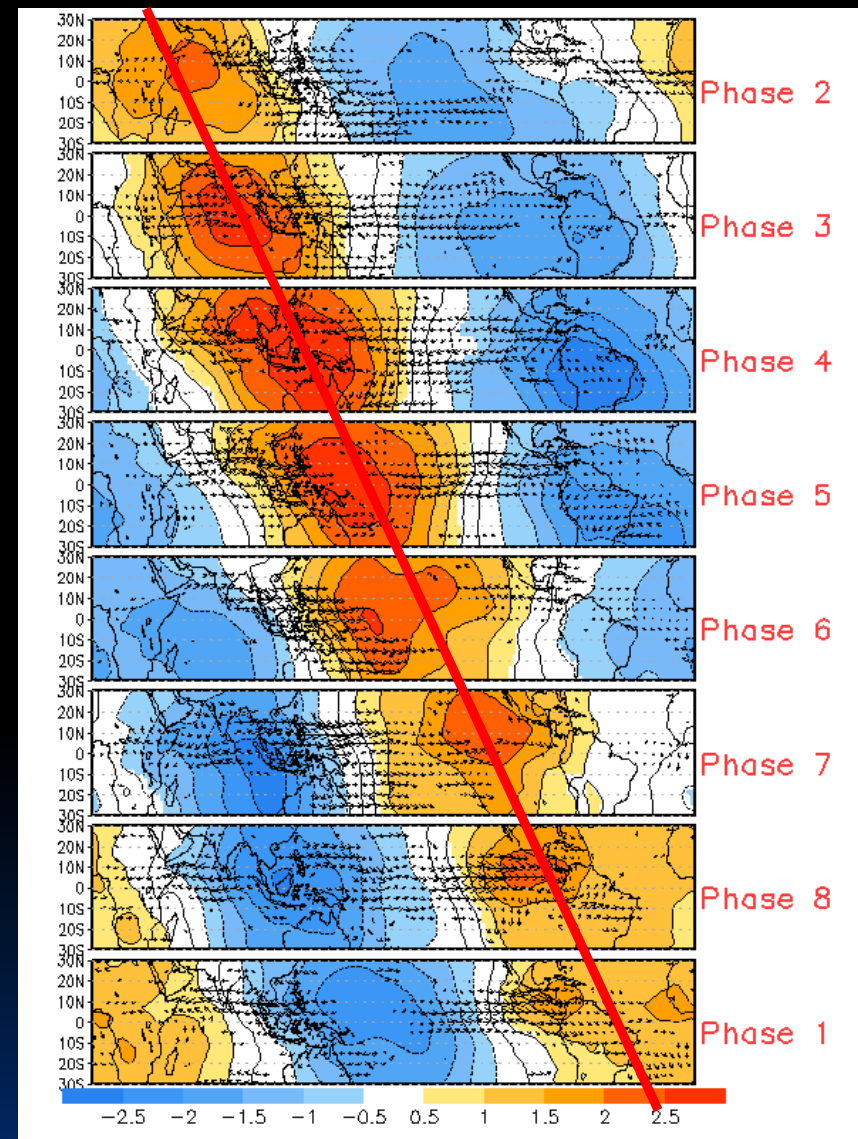


200 MB VELOCITY
POTENTIAL 5°N-5°S 5-
DAY RUNNING MEAN

A Tool for Tracking and Forecasting the MJO

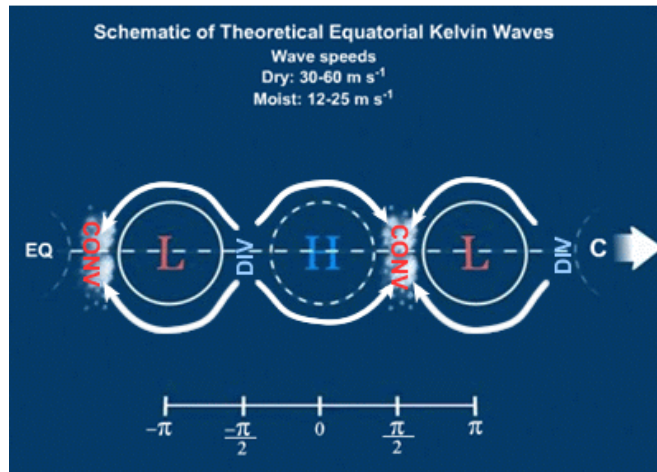


- Conceptual model showing idealized phases of MJO progression
- Phases 8 through 3 most active phases for the Atlantic

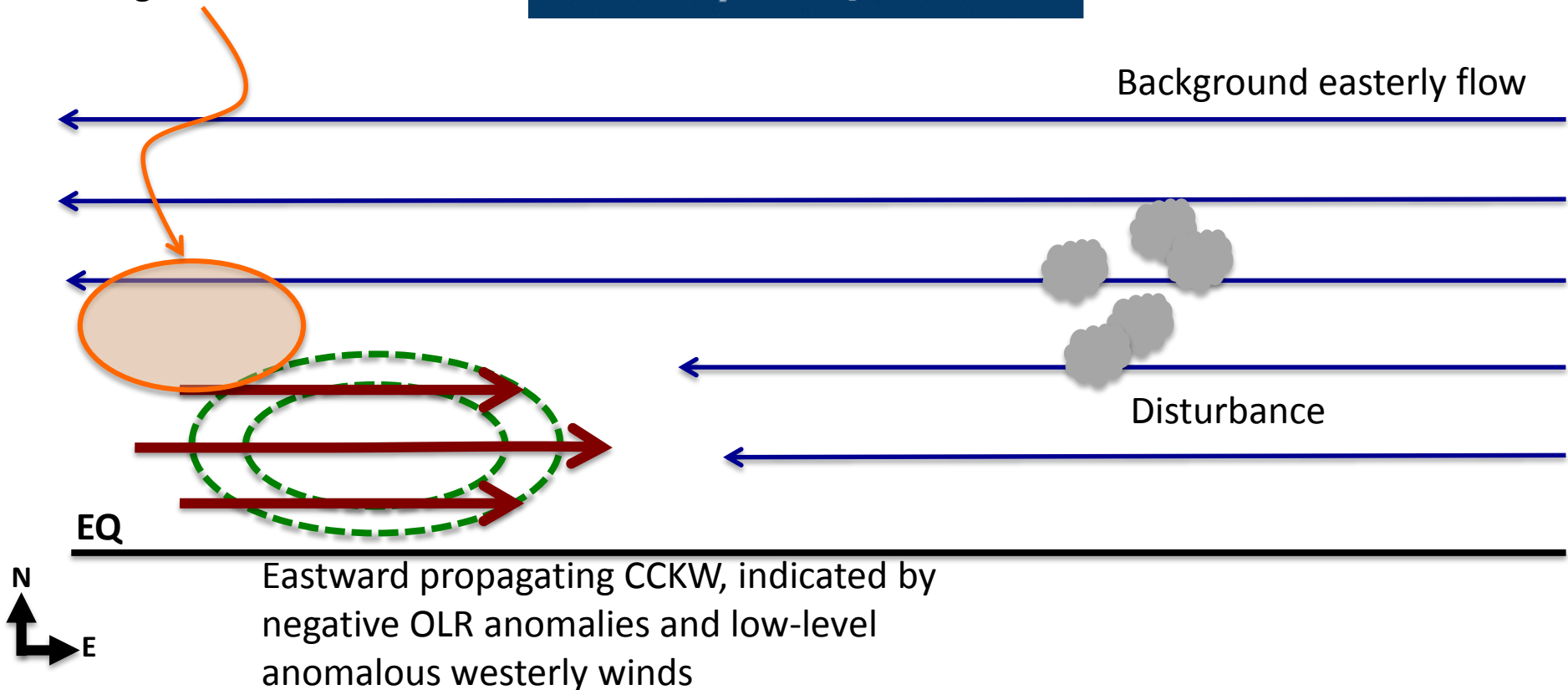


Idealized CCKW-influenced TC genesis

Day -2

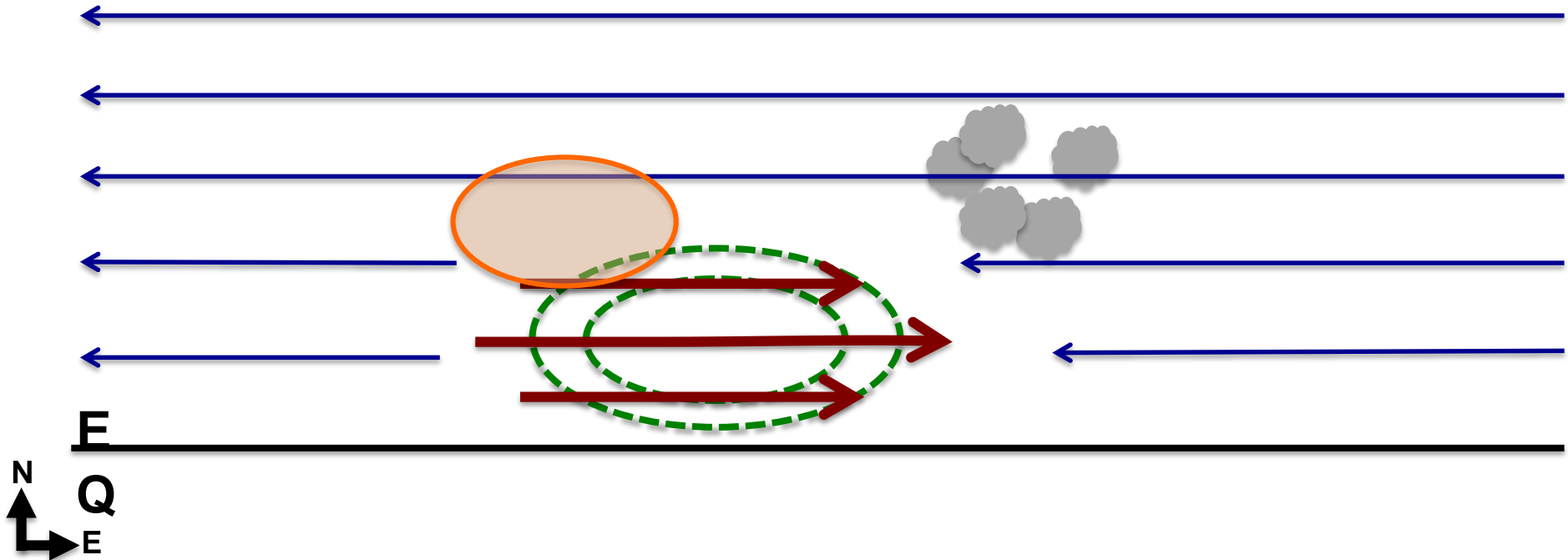


Region of enhanced
cyclonic vorticity
generation



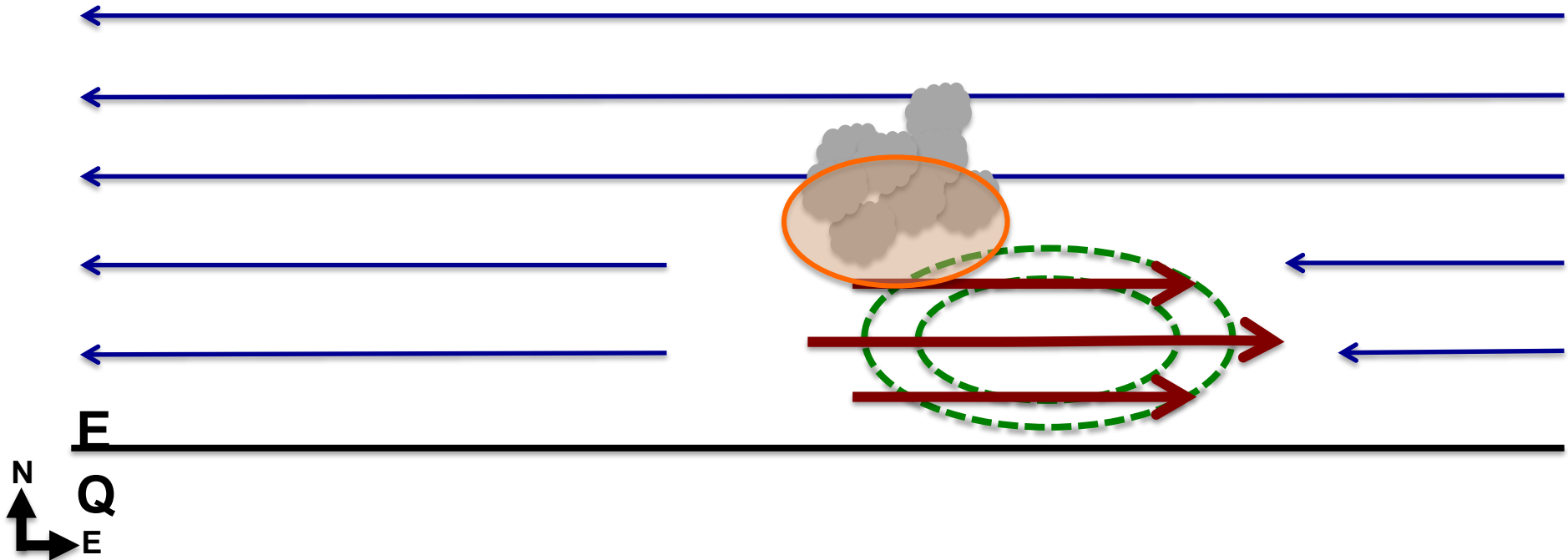
Idealized CCKW-influenced TC genesis

Day -1



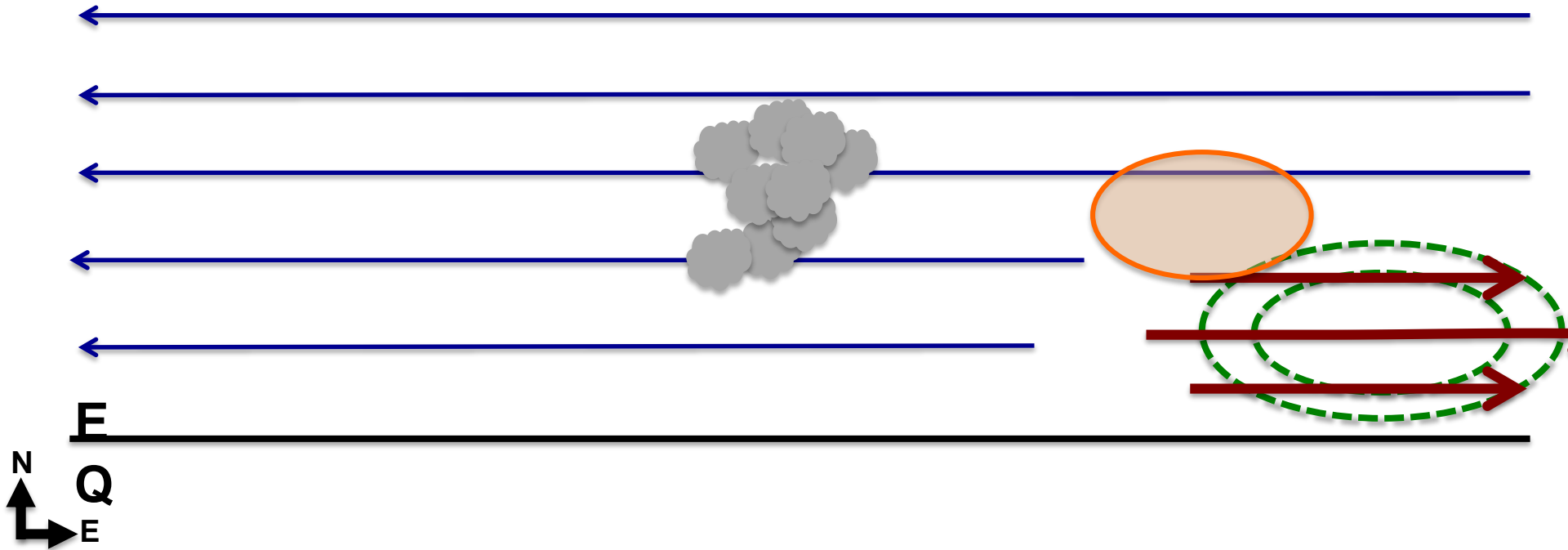
Idealized CCKW-influenced TC genesis

Day 0



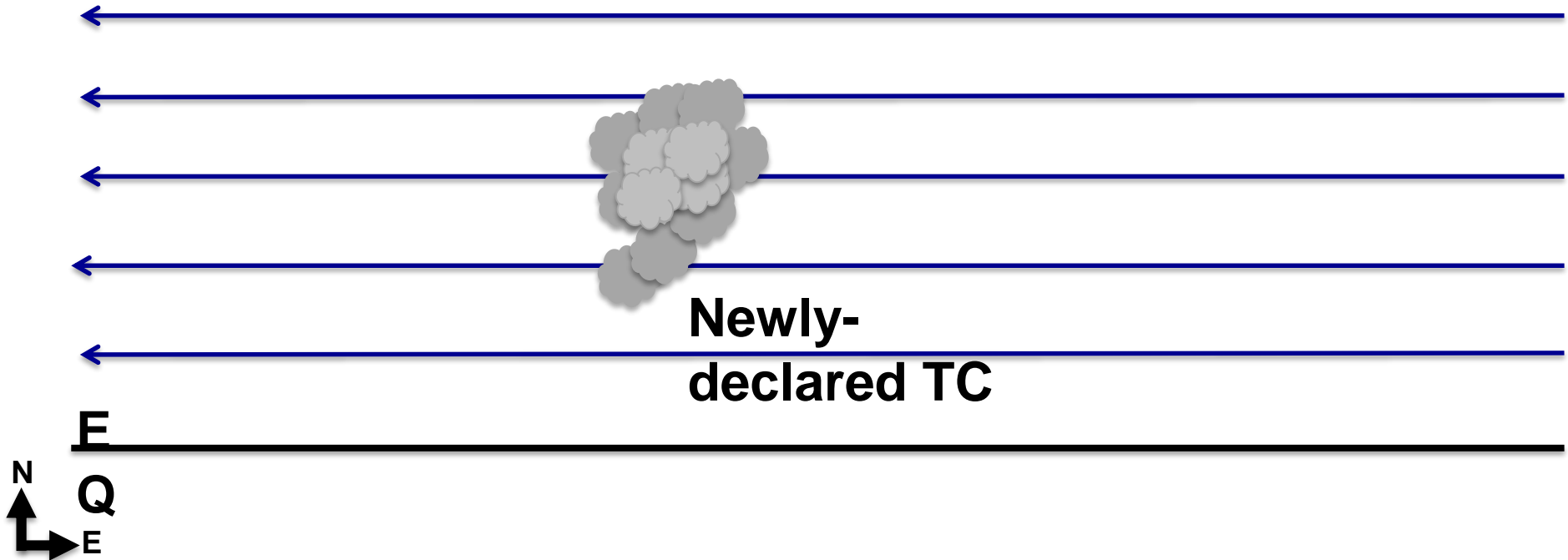
Idealized CCKW-influenced TC genesis

Day +1



Idealized CCKW-influenced TC genesis

Day +2



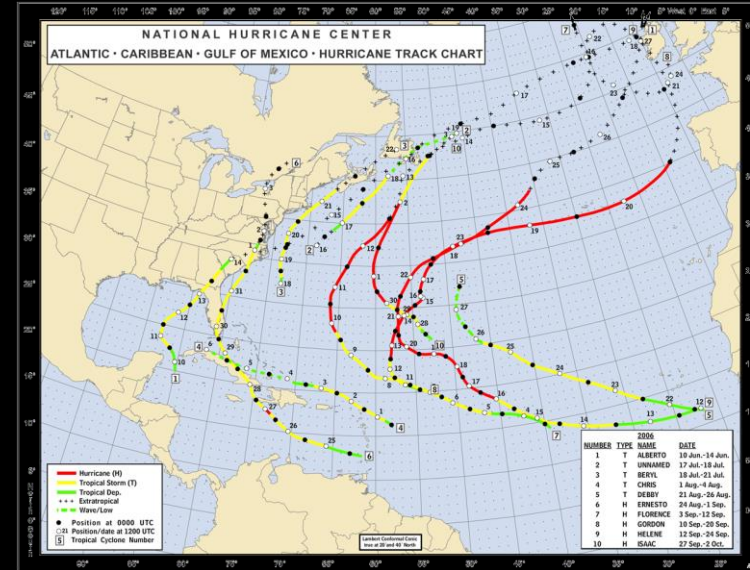
How are Intraseasonal Oscillations Used at NHC?

- Used as a way to increase forecaster confidence in a given situation if conceptual model of CCKWs and genesis matches model solutions.
- Any adjustments to 5-day genesis probabilities based on intraseasonal signals are small and subjectively determined.
- Global models handle the MJO much more accurately than individual CCKWs, and thus the forecaster can add value to the deterministic models.
- No operational standard on use of CCKW in genesis forecasts (about half of forecasters use it).

Influence of El Niño/La Niña on TC Genesis

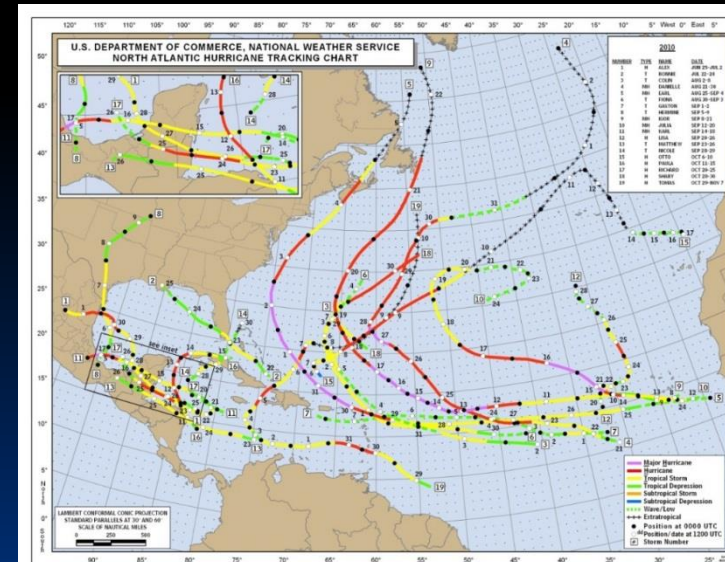
- During El Niño episodes, *fewer* TCs form over the deep tropical Atlantic and Caribbean; tendency for more to form at subtropical latitudes. The opposite generally occurs during La Niña years.

**2006
(El Niño)**



- In the eastern North Pacific, El Niño typically *enhances* TC activity, with a tendency for stronger hurricanes during El Niño (e.g., 1997, 2006).

**2010
(La Niña)**



2 Formal Theories of TC Genesis

- CISK (Ooyama, Charney and Eliassen)
- WISHE (Emanuel)

CISK

Acronym for:

Conditional **I**nstability of the **S**econd **K**ind

- A cooperative feedback between small-scale convection (frictionally-induced convergence and latent heat release) and the larger-scale circulation (a growing disturbance)
- A simplified linear theory which assumes that flow is in gradient balance
- When latent heat release balances surface frictional dissipation, the cyclone maintains its intensity

NOTE: ALTHOUGH THIS THEORY IS FREQUENTLY ATTACKED, IT STILL HAS SOME INTUITIVELY APPEALING ASPECTS!

LARGE-SCALE WAVE

CISK

LOW-LEVEL CYCLONIC
VORTICITY

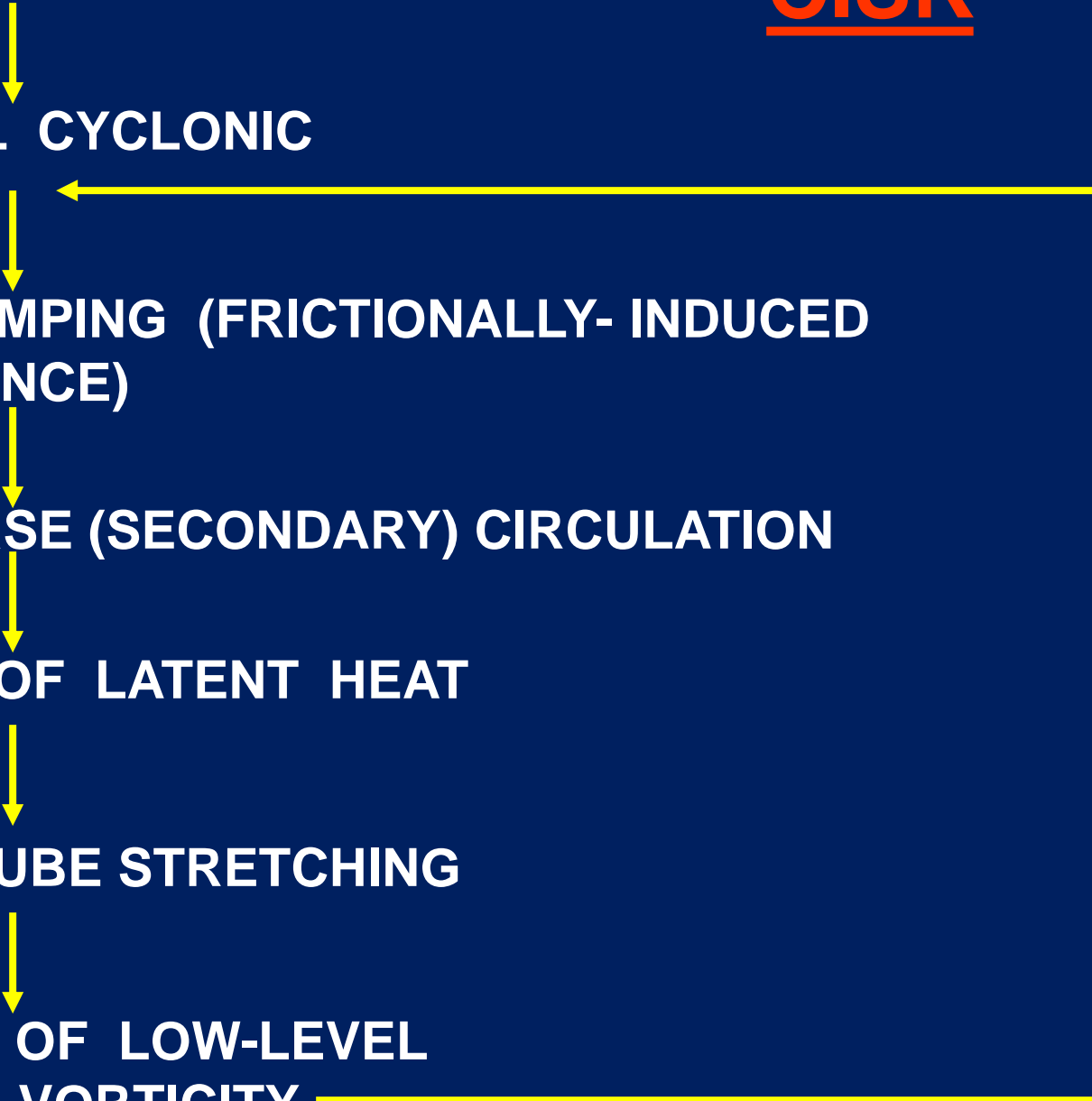
EKMAN PUMPING (FRICTIONALLY- INDUCED
CONVERGENCE)

TRANSVERSE (SECONDARY) CIRCULATION

RELEASE OF LATENT HEAT

VORTEX TUBE STRETCHING

INCREASE OF LOW-LEVEL
CYCLONIC VORTICITY



CISK Schematic

a

Convection grows stronger as more moisture flows into surface low

Latent heat release causes air to expand and surface low to strengthen

Incipient disturbance

Frictional convergence of moisture causes rising motion

©The COMET Program

b

Air flows outwards and Coriolis turning forms upper anticyclone

Stronger convection gives more latent heat

As surface low strengthens, moist frictional convergence, convection and surface low have positive feedback to each other

Winds strengthen as low develops; frictional convergence

©The COMET Program

“The more fundamental question about the CISK concept is how can cooperation between cyclone-scale and convective-scale circulations produce their simultaneous development including the formation and intensification of a warm core? It is difficult to see how it can happen because, if there are no sources, θ_e is simply redistributed by these motions individually, and therefore by the total motion, without creating a new maximum. Conditional instability simply converts the vertical variation of θ_e to the horizontal variation while the mass distribution in θ_e space is conserved. Any instability that changes this distribution, therefore, inevitably involves processes other than cooperation between cyclone-scale circulation and convective clouds. Since the cooperation alone does not produce new instability, the concept of CISK as distinguished from the usual conditional instability can hardly be justified.”

(Arakawa, 2004 *J. Climate*)

This suggests that another mechanism for TC genesis, that involves thermodynamics and a source of heat, should be invoked.

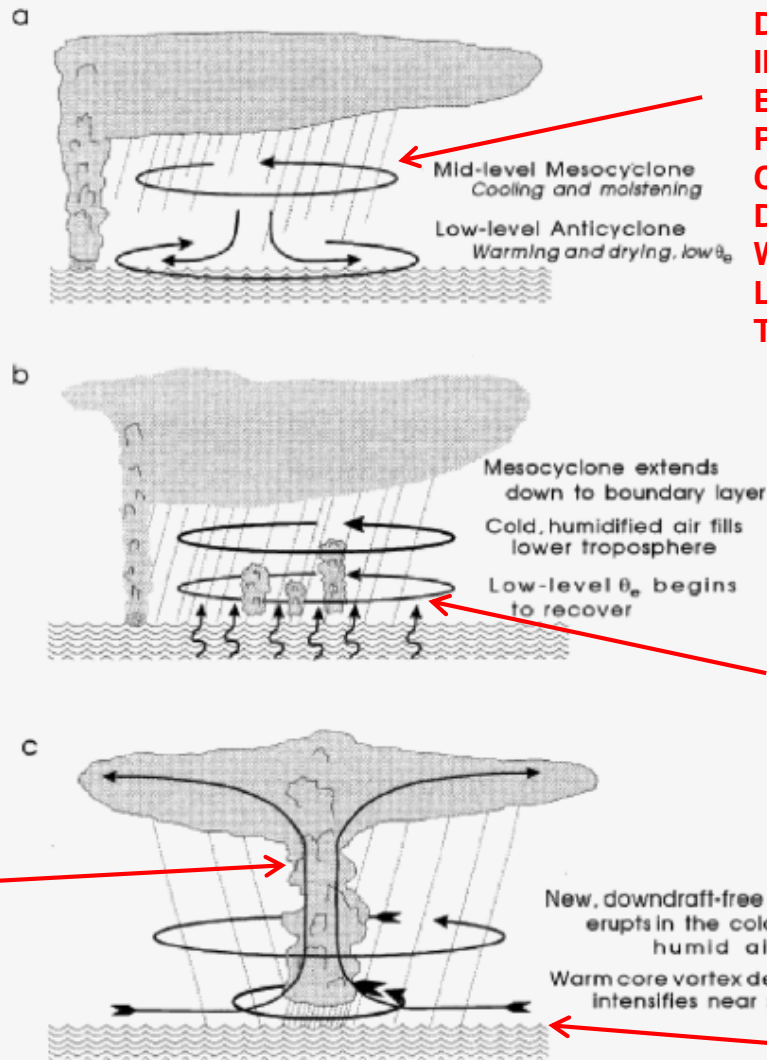
WISHE is such a mechanism.

WISHE

Wind **I**nduced **S**urface **H**eat **E**xchange

- Heat release and instability in the free troposphere is governed by the evaporation of moisture from the sea (i.e., the extraction of energy from the underlying ocean surface)
- Evaporation is primarily determined by the magnitude of the surface winds

WISHE



DEEP CONVECTION,
INITIATED THROUGH
EKMAN PUMPING, WILL
PRODUCE
CONVECTIVE-SCALE
DOWNDRAFTS THAT
WILL STABILIZE THE
LOWER LAYER OF
THE ATMOSPHERE

THE
TROPOSPHERE
MUST BECOME
NEARLY
SATURATED IN
THE VORTEX CORE

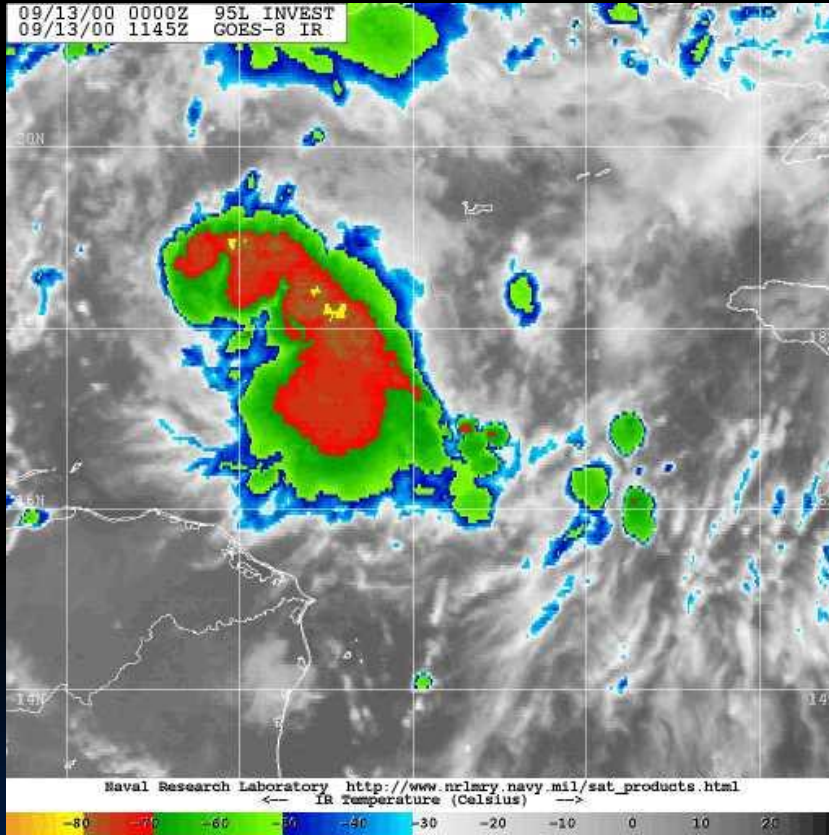
THE ENHANCED
SURFACE FLUXES
ASSOCIATED
WITH STRONG
SURFACE WINDS
NEAR THE CORE
CAN INCREASE
THE SUBCLOUD
MOIST STATIC
ENERGY.

Figure 8. Conceptual model of tropical cyclogenesis from a preexisting MCS. (a) Evaporation of stratiform precipitation cools and moistens the upper part of the lower troposphere; forced subsidence leads to warming and drying of the lower part. (b) After several hours there is a cold and relatively moist anomaly in the whole lower troposphere. (c) After some recovery of the boundary layer θ_e , convection redevelops (From Bister and Emanuel 1997, Copyright American Meteorological Society).

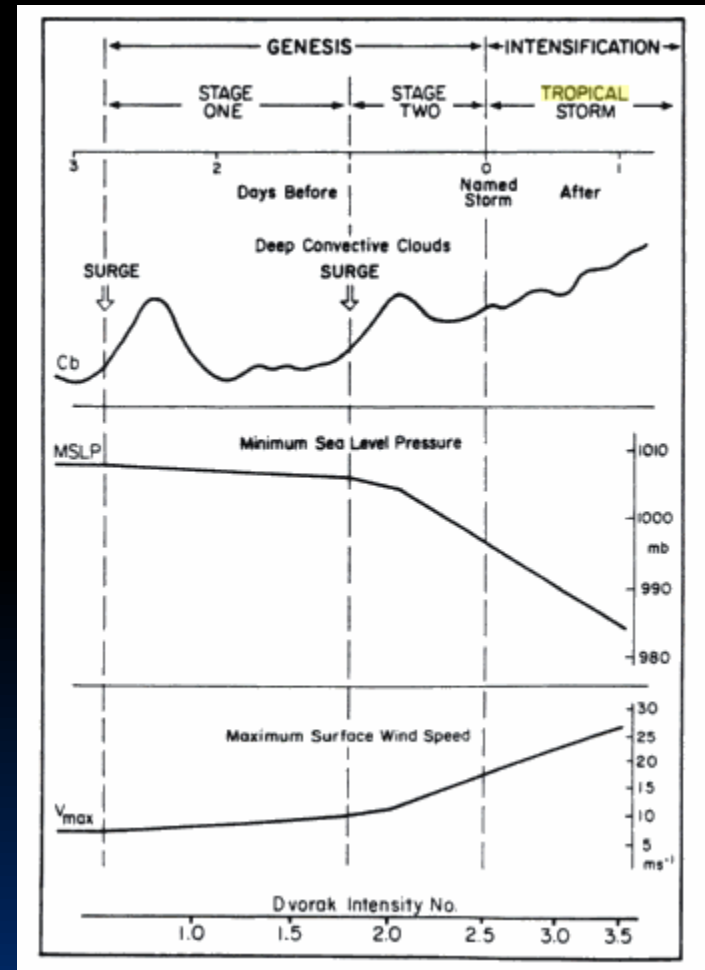
CONVECTION
CAN INCREASE
THE
TEMPERATURE
OF THE
VORTEX CORE.
IN A MOIST
TROPICAL
ATMOSPHERE,
THE WISHE
PROCESS CAN
ACT AS A
POSITIVE
FEEDBACK TO
THE WARM-
CORE
CYCLONE.

Stage 1-Stage 2 Genesis

INNER CORE MAY ORIGINATE AS A MID-LEVEL MESO-VORTEX (NEAR 700 MB) THAT FORMS IN ASSOCIATION WITH A MESOSCALE CONVECTIVE SYSTEM (MCS)



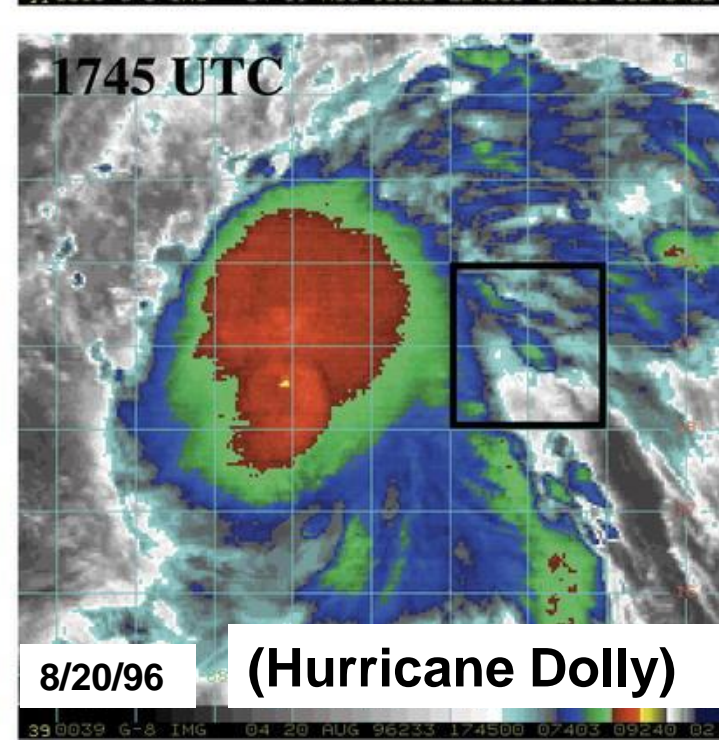
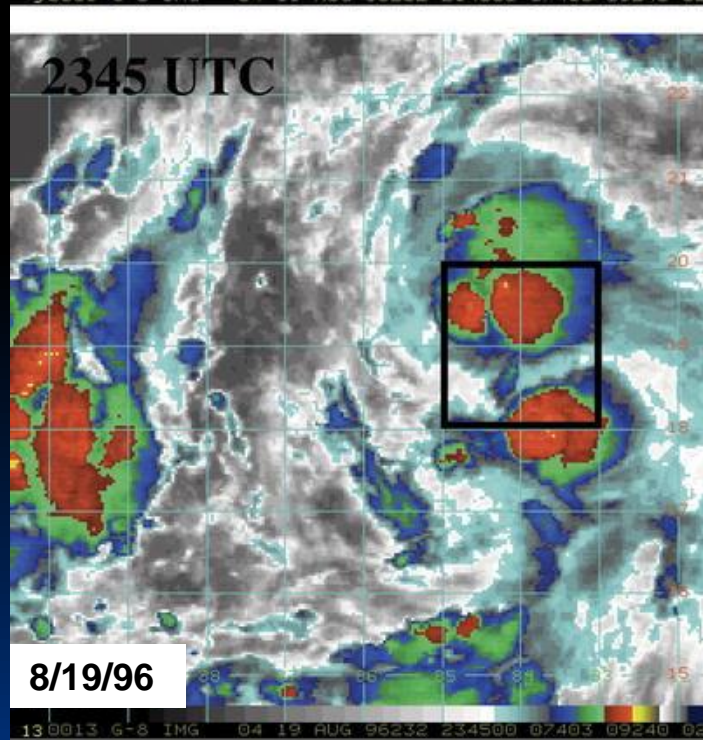
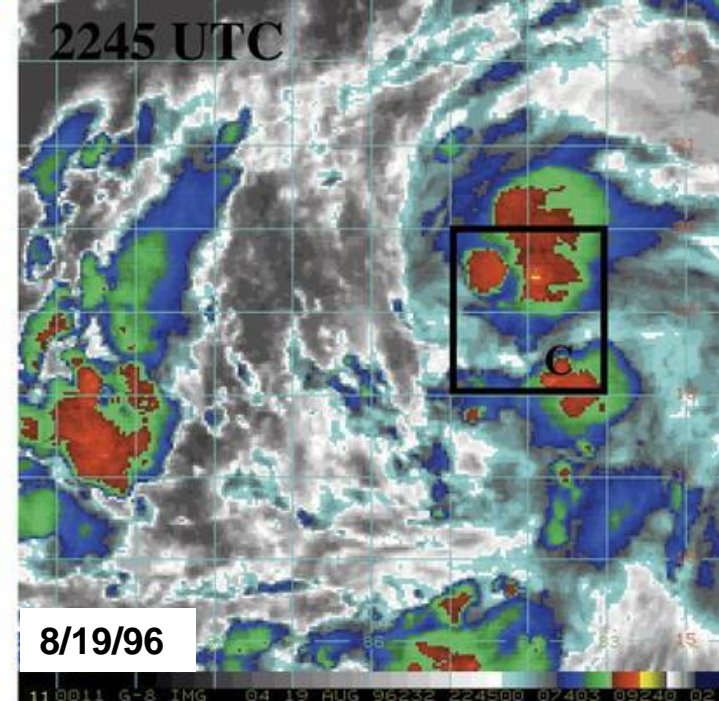
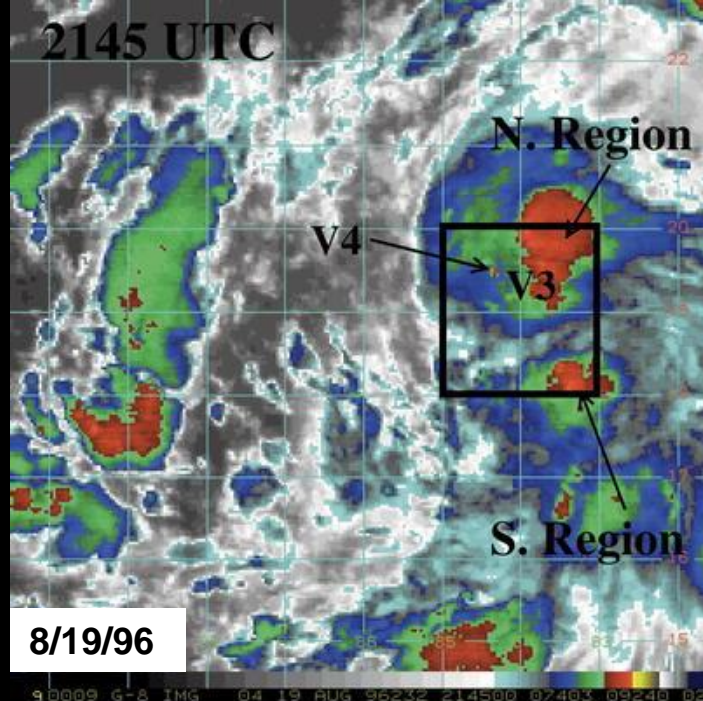
**PRE-GORDON DISTURBANCE, 9/13/00
1145 UTC (~24 HOURS PRIOR TO
GENESIS)**

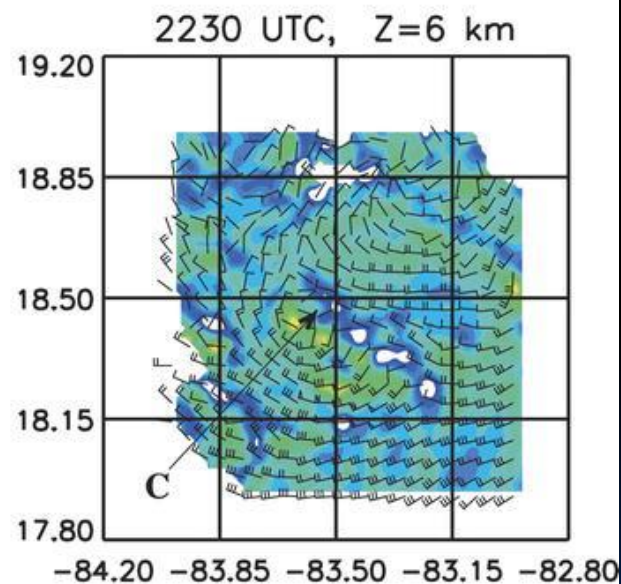
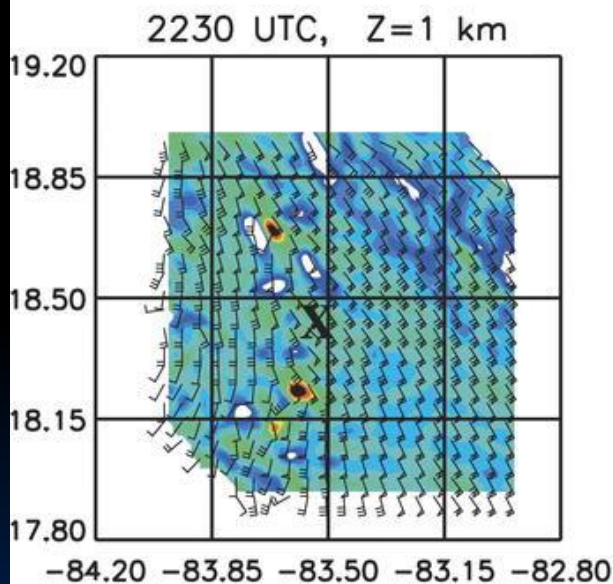
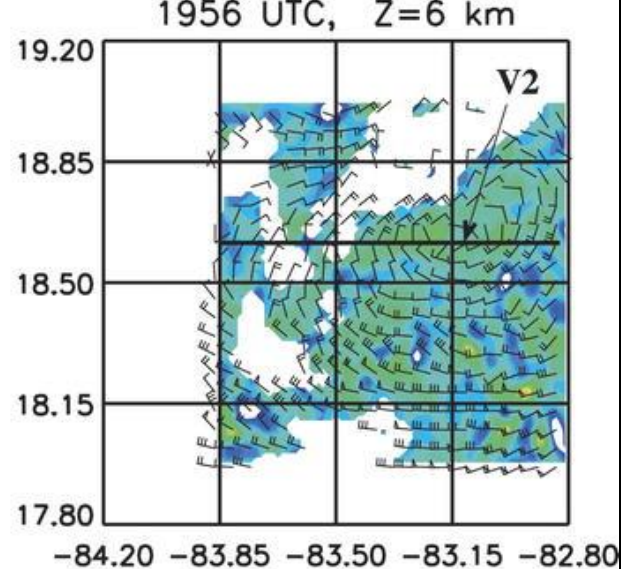
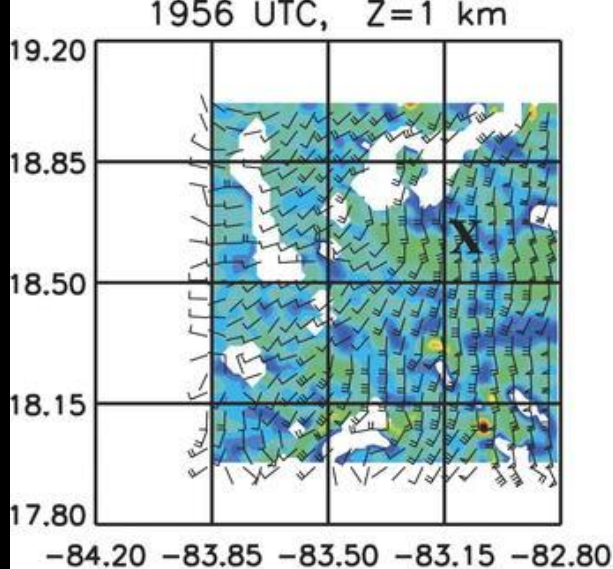


Zehr (1992)

Multiple mid-level mesoscale vortices during genesis stage.

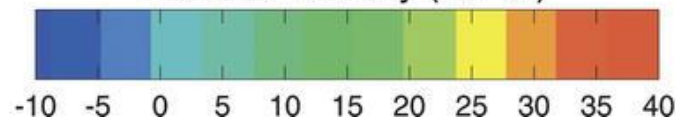
(Reasor et al. 2005 *J. Atmos. Sci.*)





WIND AND VORTICITY WITHIN SOUTHERN CONVECTIVE REGION, 8/19/96

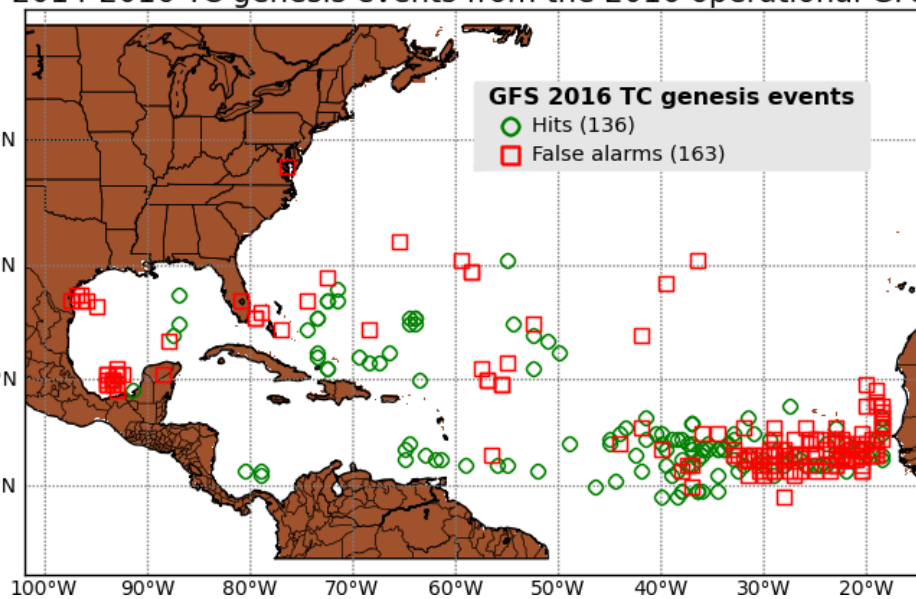
Relative Vorticity (10^{-4} s^{-1})



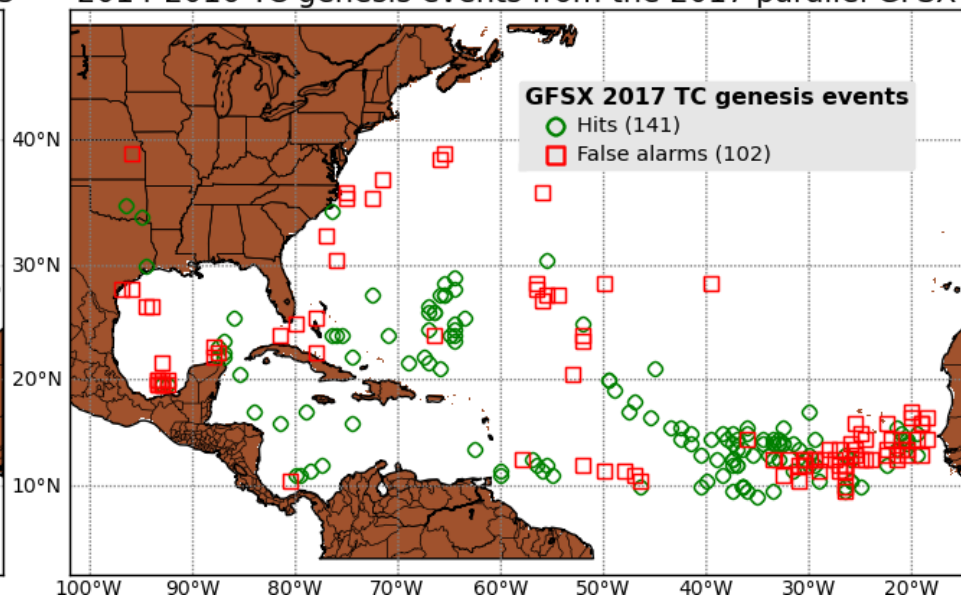
Use of global models relevant for TC genesis forecasting:

- Global models, especially the ECMWF, GFS, and UKMET along with their ensembles are our primary tool for predicting TC genesis.
- The forecaster looks for consistency among the different models, as well as run-to-run consistency, to assess the likelihood of genesis.
- Recent upgrades to the ECMWF have probably improved that model's performance, but changes to the GFS have apparently degraded its ability to forecast genesis, especially in the eastern North Pacific.
- The UKMET model has a high detection rate for genesis but also has an abundance of "false alarms". Therefore, when we see no development in the UKMET forecast, the probability of genesis is low.
- Of all the global models used by the NHC, the Canadian global model typically shows the highest number of false alarms.

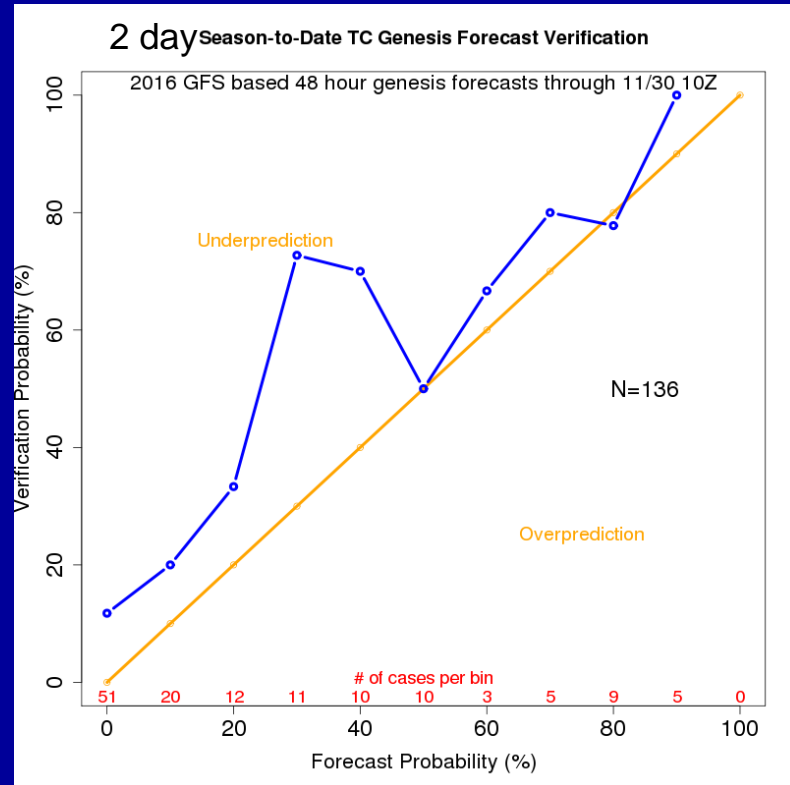
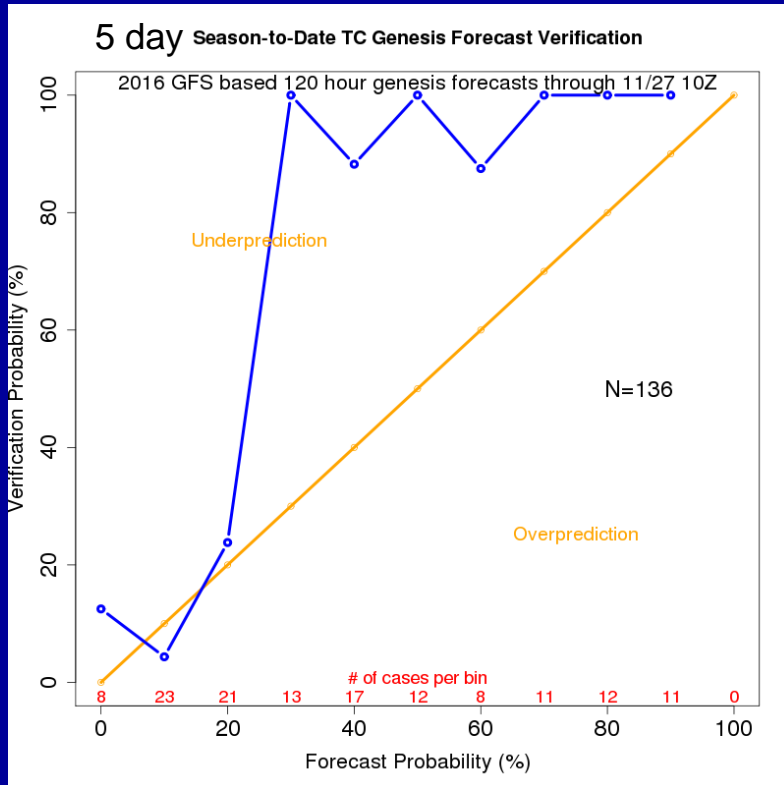
2014-2016 TC genesis events from the 2016 operational GFS



2014-2016 TC genesis events from the 2017 parallel GFSX

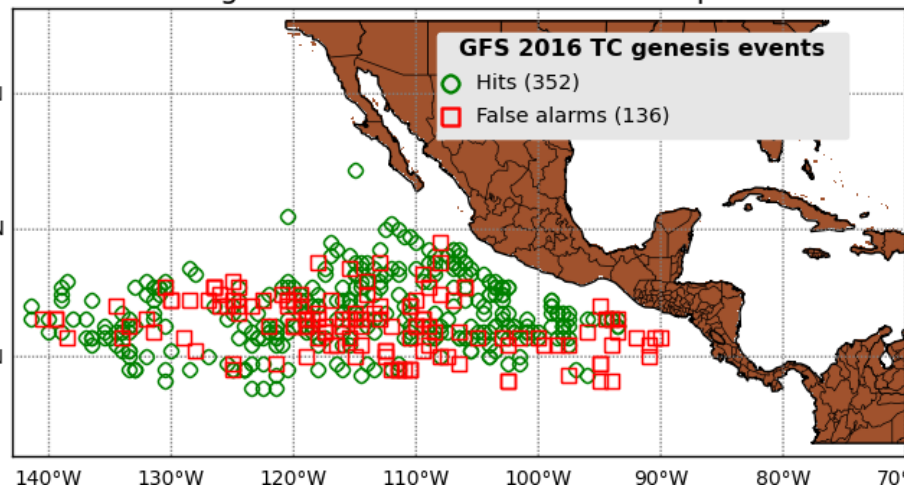


Atlantic genesis forecasts

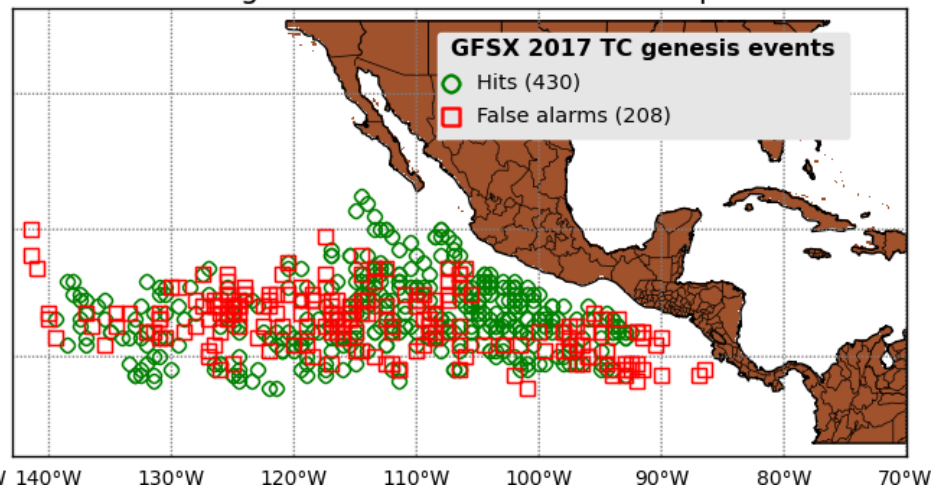


- 5 day forecasts had a huge underprediction bias
- 2 day is better, but only 20 forecasts all year in the high category from the model (NHC issued ~50 based on all guidance including non-NCEP models)

2014-2016 TC genesis events from the 2016 operational GFS



2014-2016 TC genesis events from the 2017 parallel GFSX

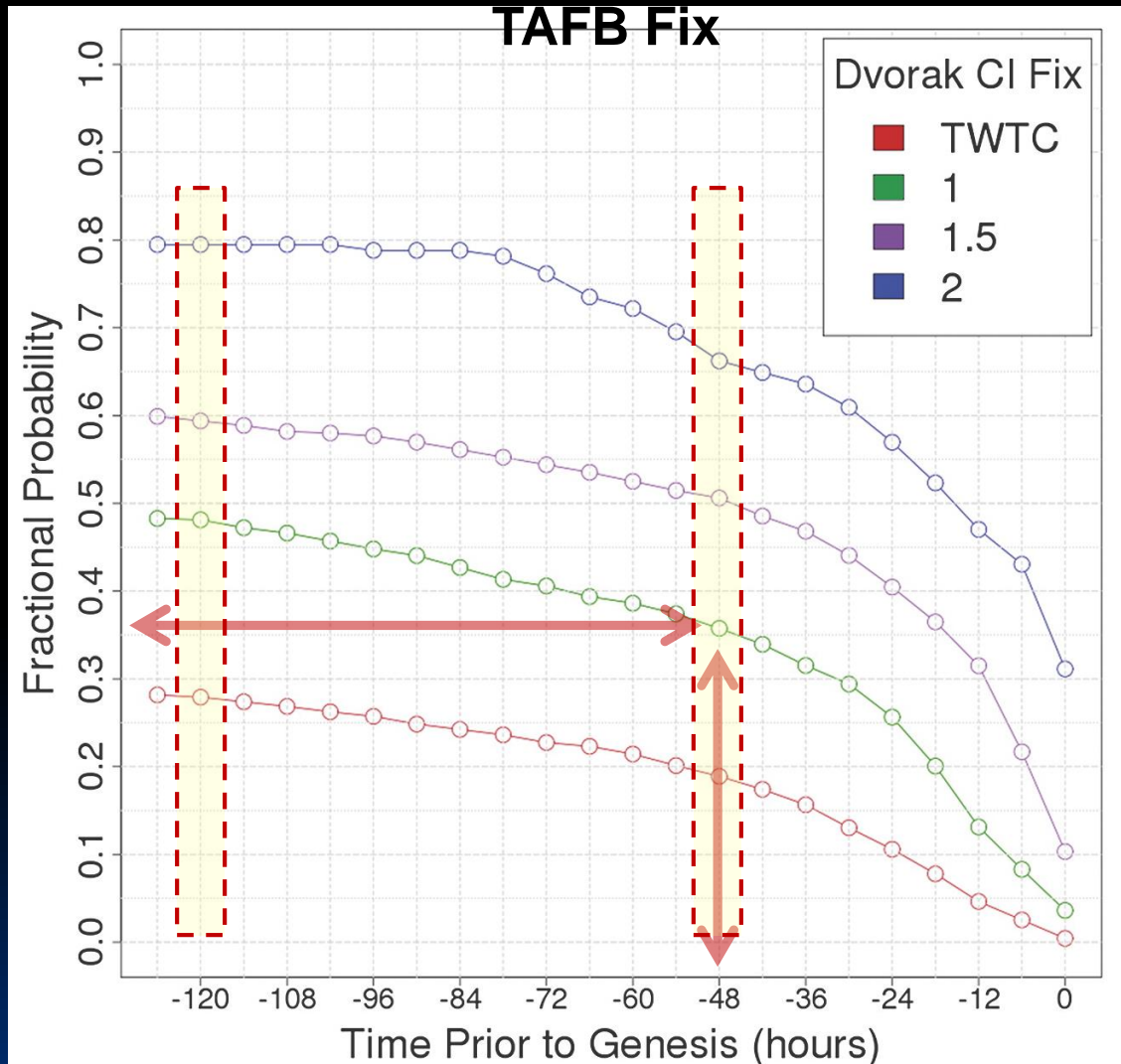


Web site for monitoring real-time model forecasts
of cyclogenesis:

<http://www.emc.ncep.noaa.gov/gmb/tpm/emchurr/tcgen/>

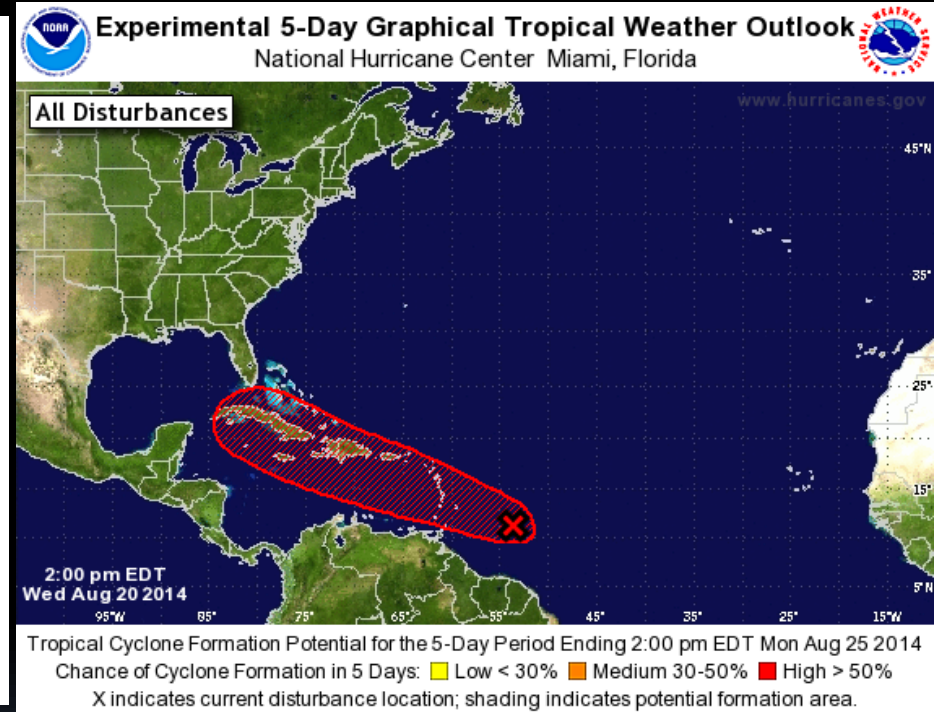
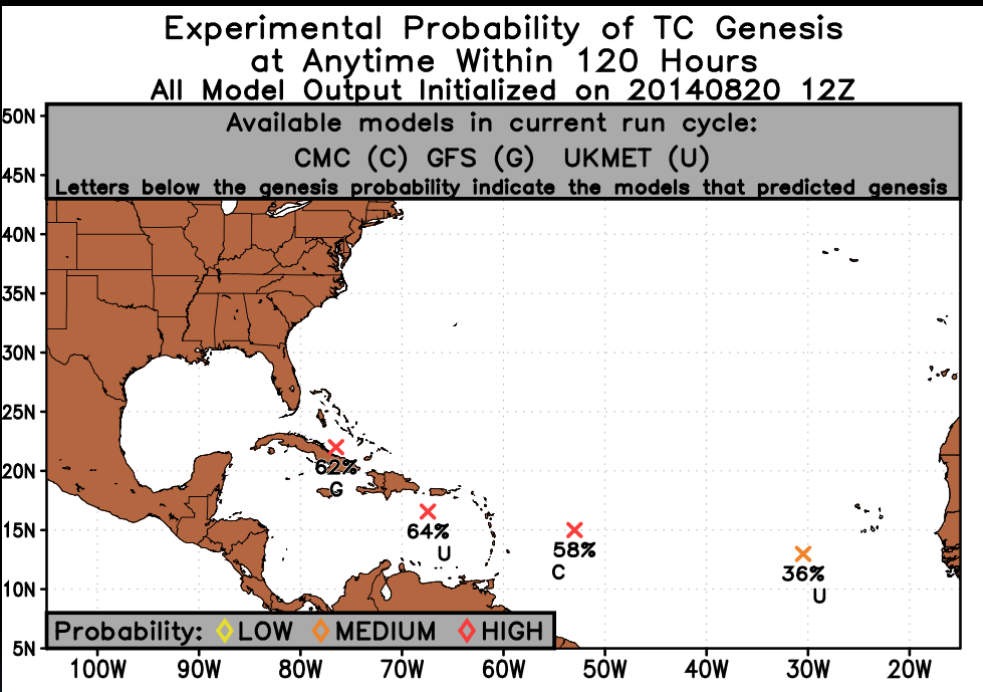
Genesis Probability by Dvorak Number

- Uses Dvorak intensity estimates from all invests/disturbances (both developing and non-developing) from 2001-2011.
- Example: Invest with a 1.0 TAFB CI Number has 35% chance of genesis within 48 h.
- Real-time guidance at moe.met.fsu.edu/genesis
- More information in Cossuth et al. (2013)



FSU Guidance

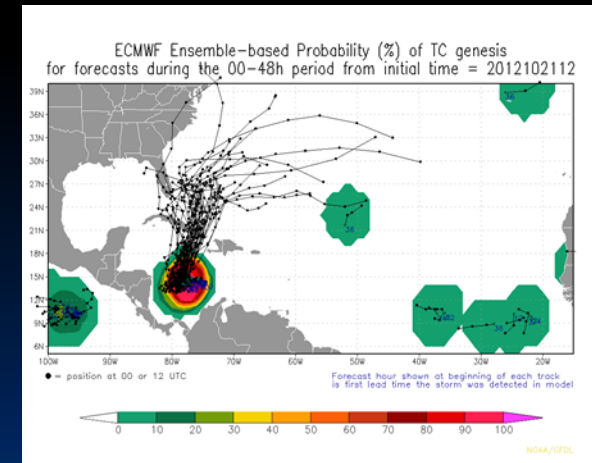
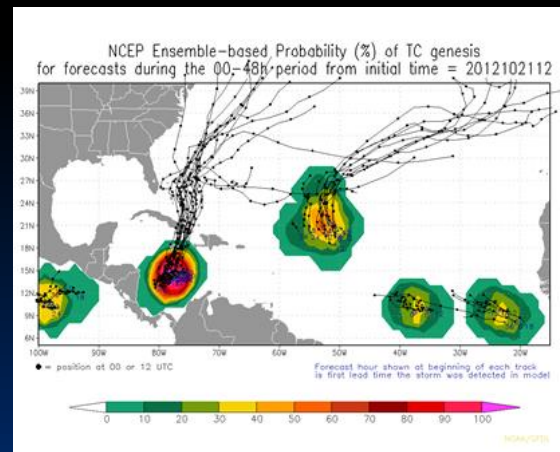
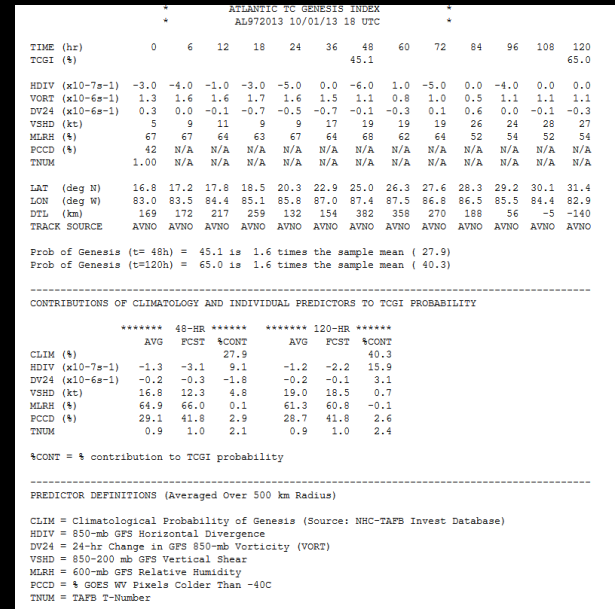
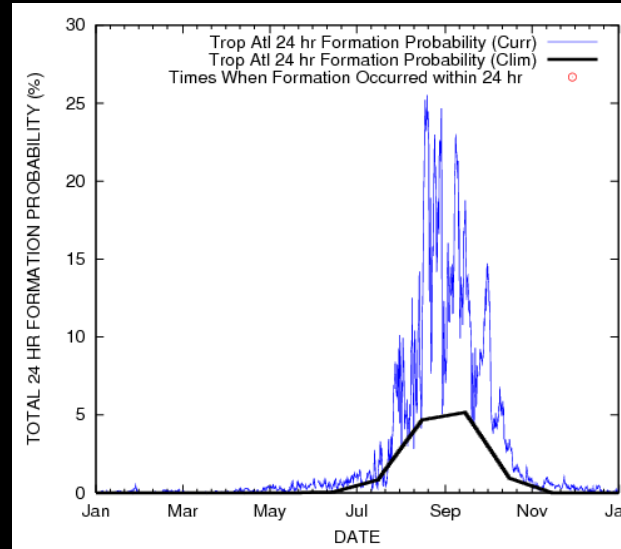
(<http://moe.met.fsu.edu/modelgen>)



- Best objective genesis guidance to date
- Uses statistics on dynamical model forecasts of genesis to develop probabilities
- Multi-model consensus gives most reliable forecasts
- Scheme provides guidance on many more systems than are mentioned in the TWO

Other Tools

- CIRA Tropical cyclone-based formation probabilities
- Ensemble-based probabilities generated (use consensus of this?)
- Several projects (e.g. Joint Hurricane Testbed), with the goal to provide objective genesis guidance

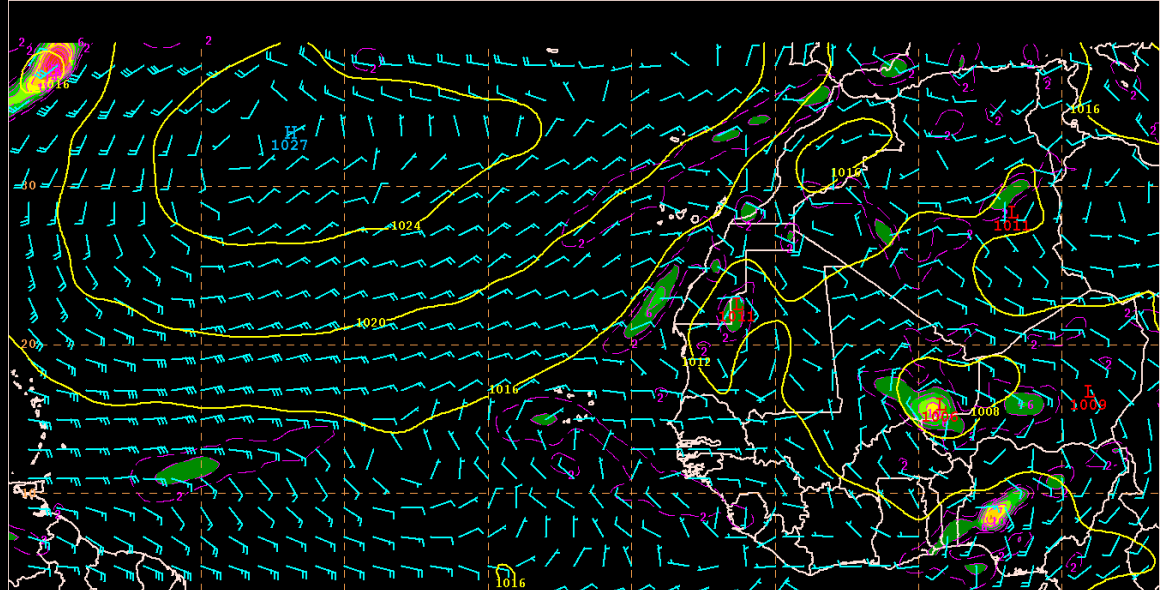


**Excerpted from the TWO at
1800 UTC 8/26/14:**

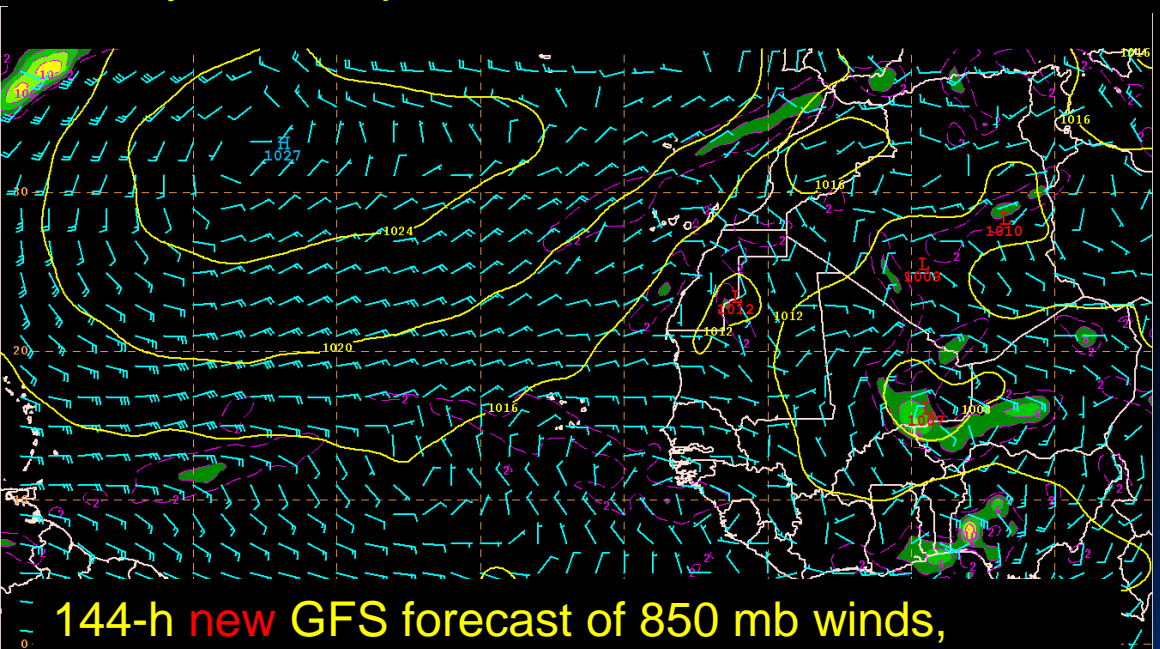
**“A tropical wave is forecast
to move off the west coast
of Africa late this week.
Conditions appear to be
favorable for some
development thereafter
while the system moves
westward at 10 to 15 mph
across the eastern Atlantic.**

*** Formation chance through
48 hours...low...near 0
percent.**

*** Formation chance through
5 days...medium...40
percent.”**

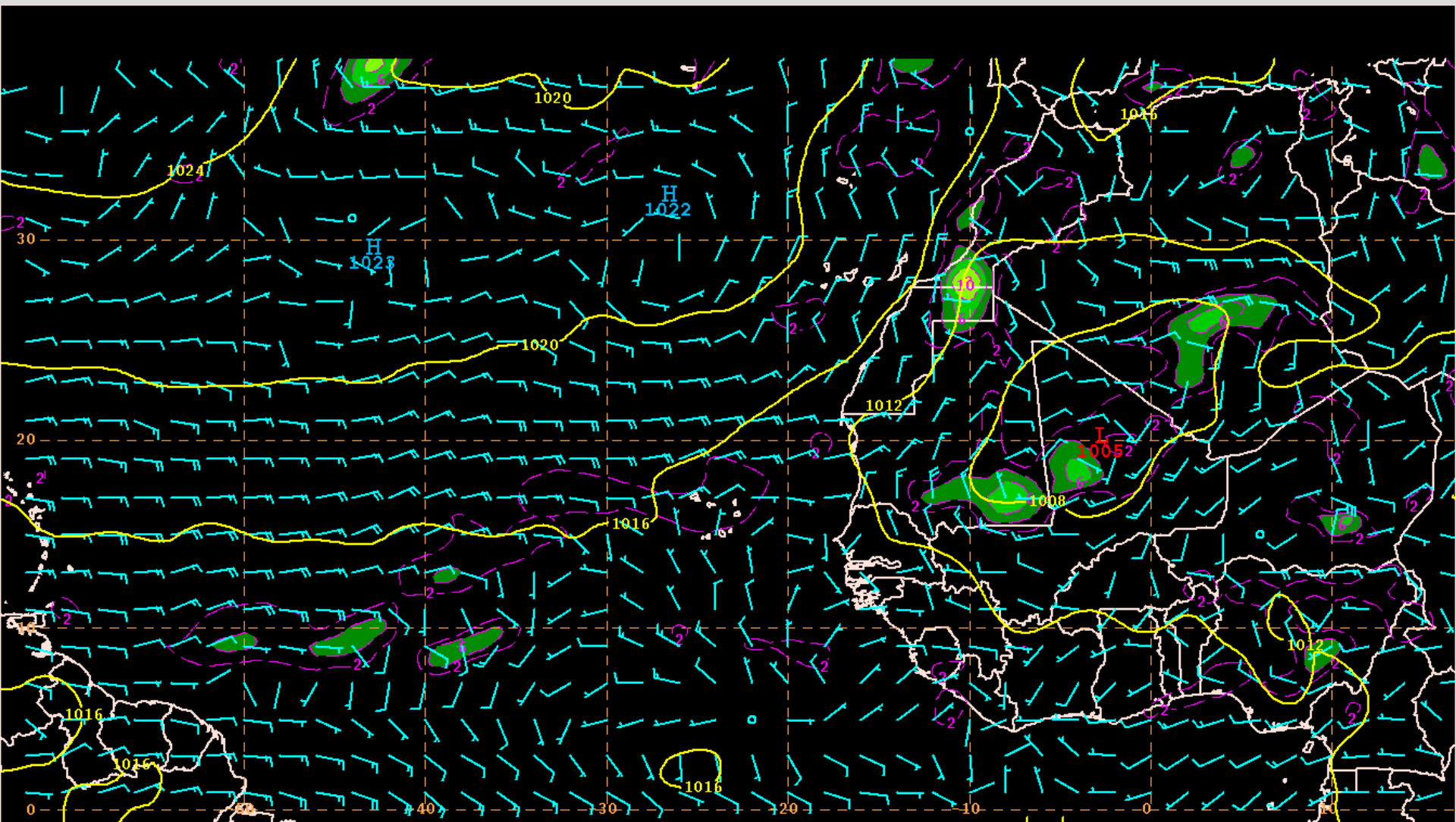


**144-h operational GFS forecast of 850 mb winds,
vorticity, and msfp from 1200 UTC 8/26/14**



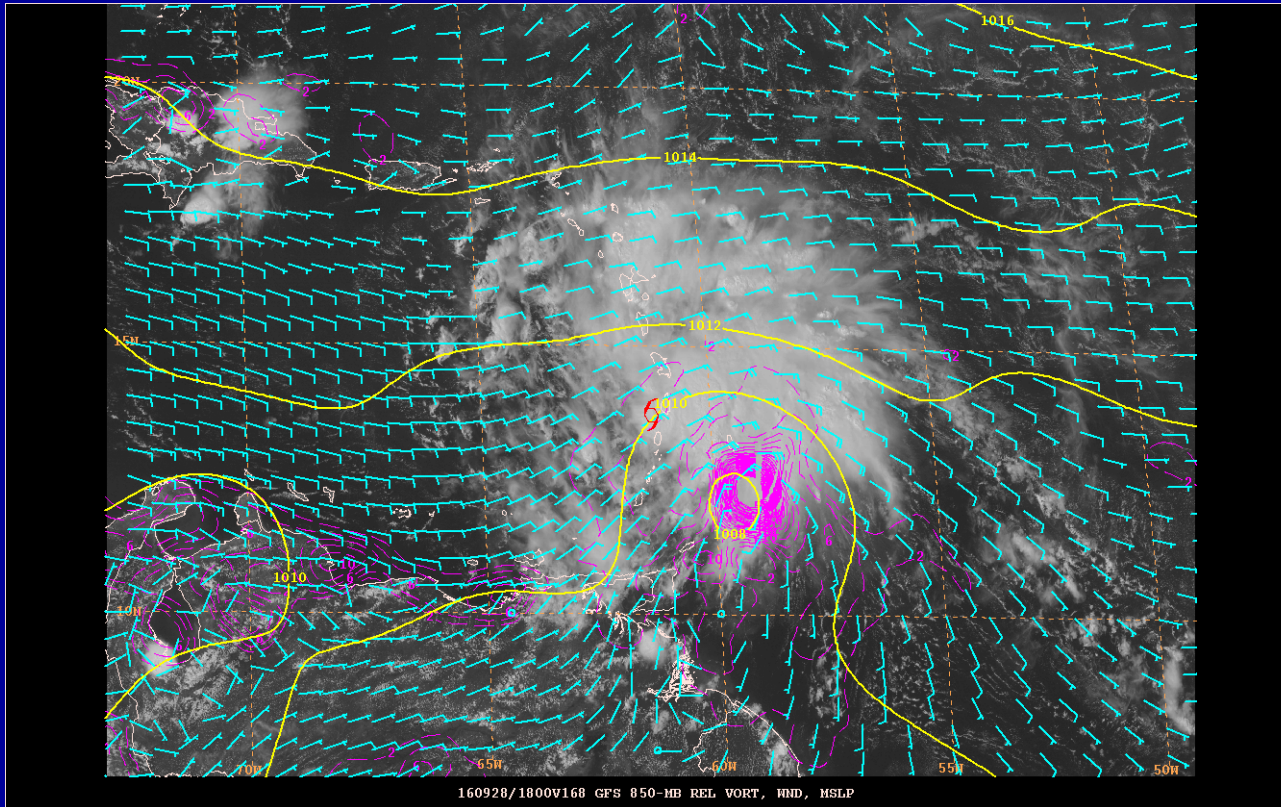
**144-h new GFS forecast of 850 mb winds,
vorticity, and msfp from 1200 UTC 8/26/14**

Verifying 850 mb winds, vorticity, and mslp for 120 h: nada!



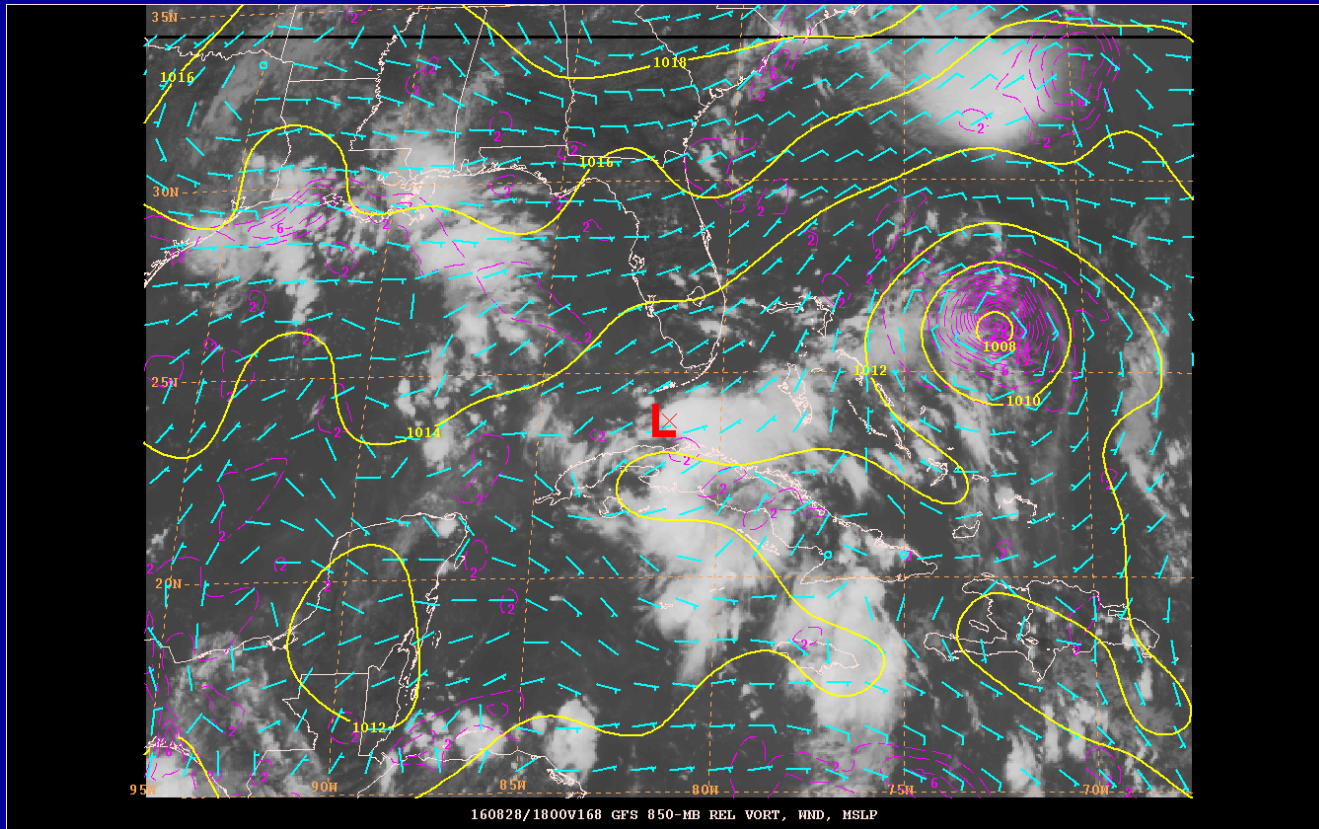
140831/1200V000 GFS 850-MB WIND (KT), 850-MB REL VORT, AND MSLP

GFS genesis forecasts for Matthew



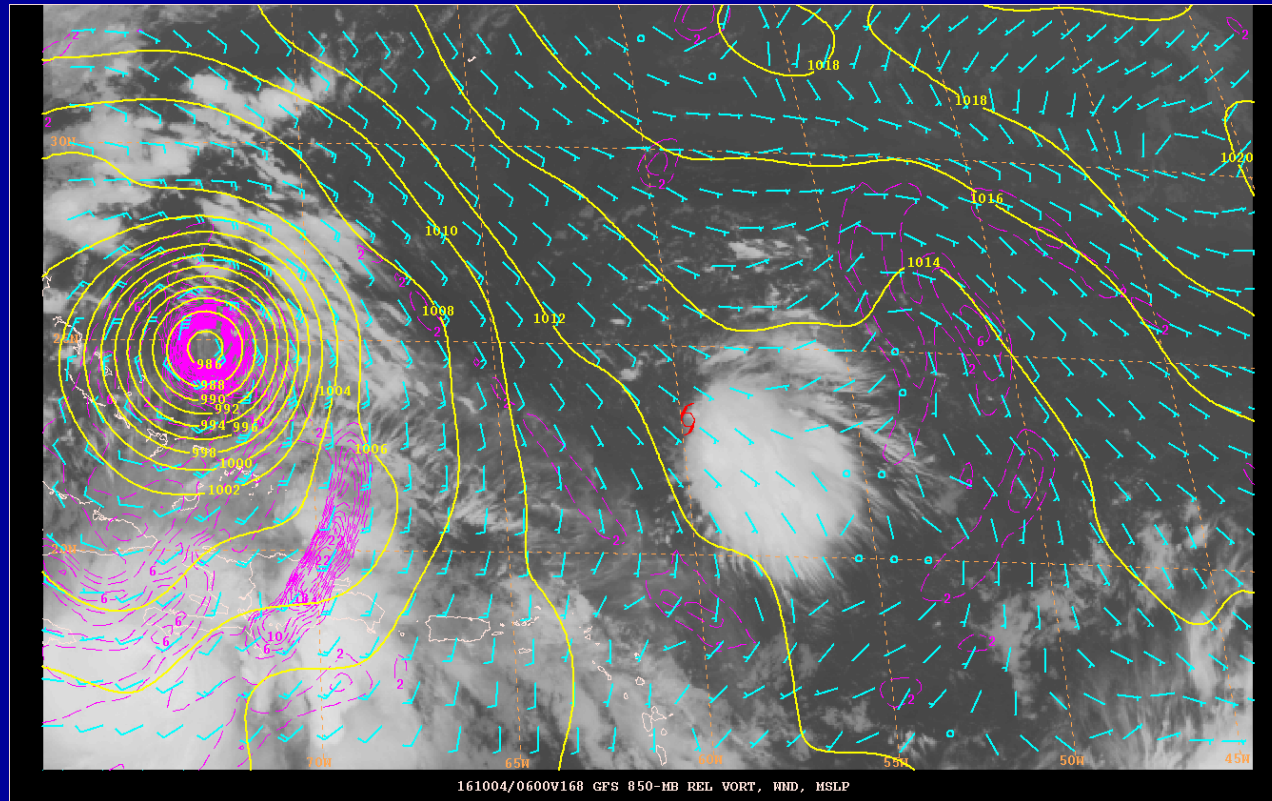
One of the best performances of the year, particularly in a geographic region where the GFS has historically struggled

GFS genesis forecasts for Hermine



Mixed performance, wrong location at first, then only signal < 2 days from formation

GFS genesis forecasts for Nicole



Probably the worst performance of the year, virtually no signal

NHC Tropical Weather Outlook

- General assessment of activity in the tropics
- Assesses tropical cyclone formation potential during the next 5 days
- Chance of formation during the first 48 hours and the entire 5-day period are provided

Issued at 0000 UTC, 0600 UTC,
1200 UTC, 1800 UTC

Tropical Weather Outlook Text

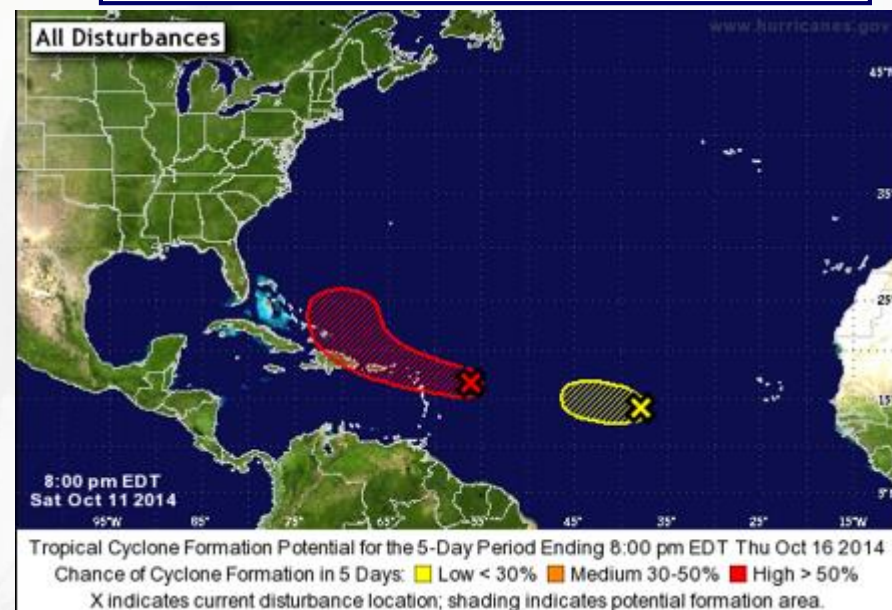
TROPICAL WEATHER OUTLOOK
NWS NATIONAL HURRICANE CENTER MIAMI FL
800 PM EDT THU OCT 9 2014

For the North Atlantic...Caribbean Sea and the Gulf of Mexico:

1. Shower and thunderstorm activity, associated with a broad surface low pressure area and an upper-level low, continues to gradually organize several hundred miles north-northeast of the northern Leeward Islands. Environmental conditions appear generally conducive for additional development, and a tropical or subtropical depression could form during the next day or two while the system moves northwestward or north-northwestward at about 10 mph.

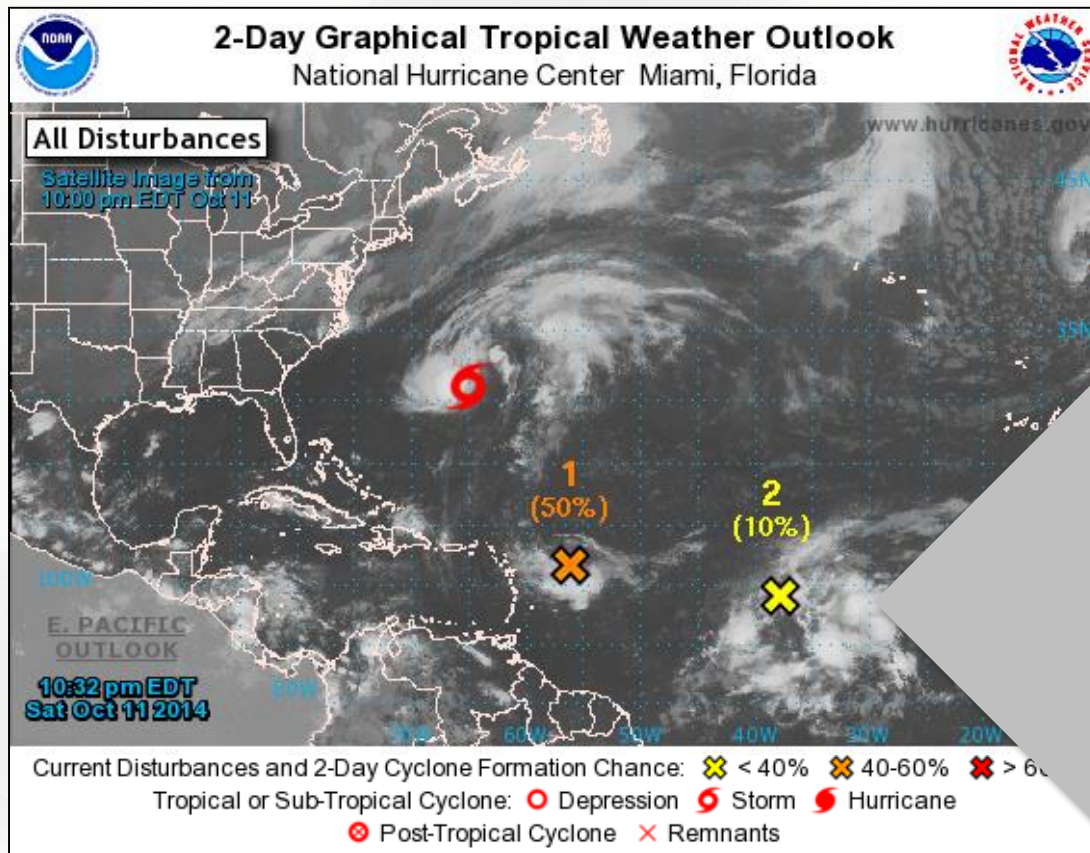
- * Formation chance through 48 hours...high...60 percent.
- * Formation chance through 5 days...high...60 percent.

Forecaster Cangialosi



Graphical Tropical Outlook

2-Day Formation Chance



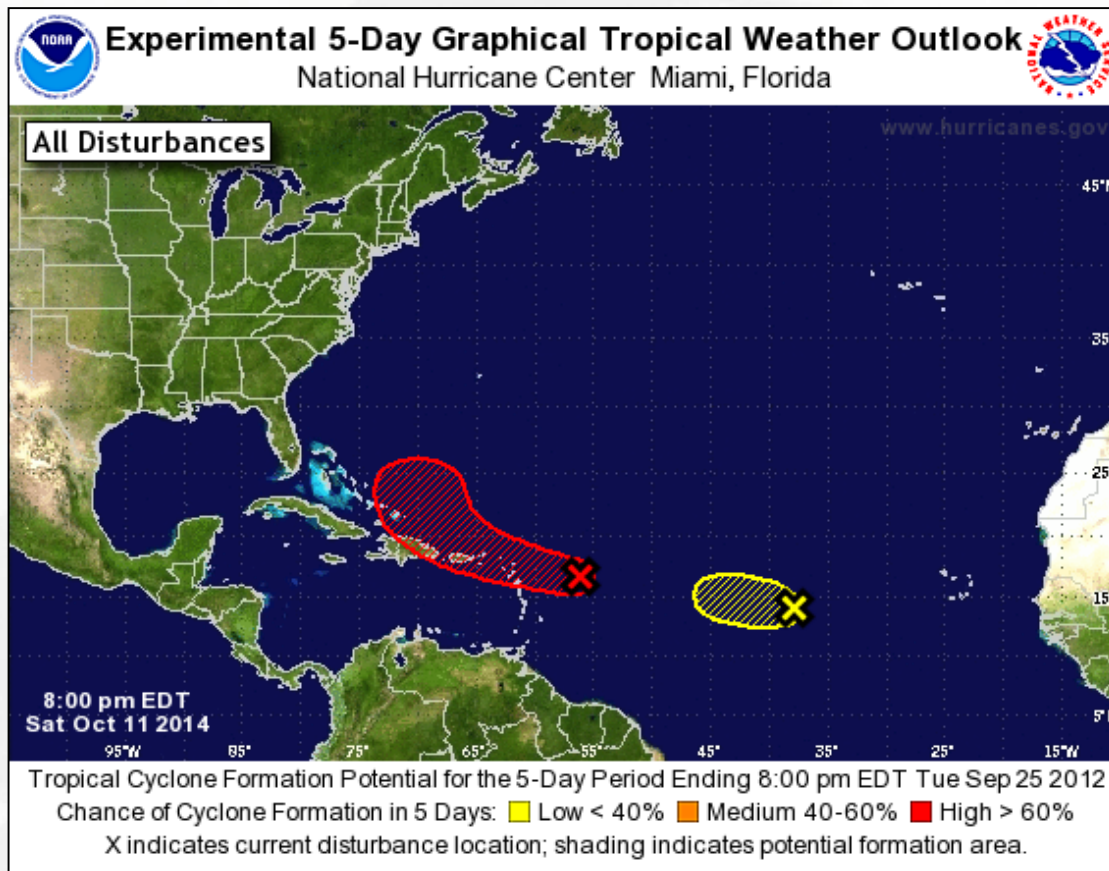
Identifies current location of disturbed weather (discussed in the Tropical Weather Outlook)

Formation chance during the next 48 hours

- Categorical (Low, Medium, and High)
- Probabilities

Graphical Tropical Outlook

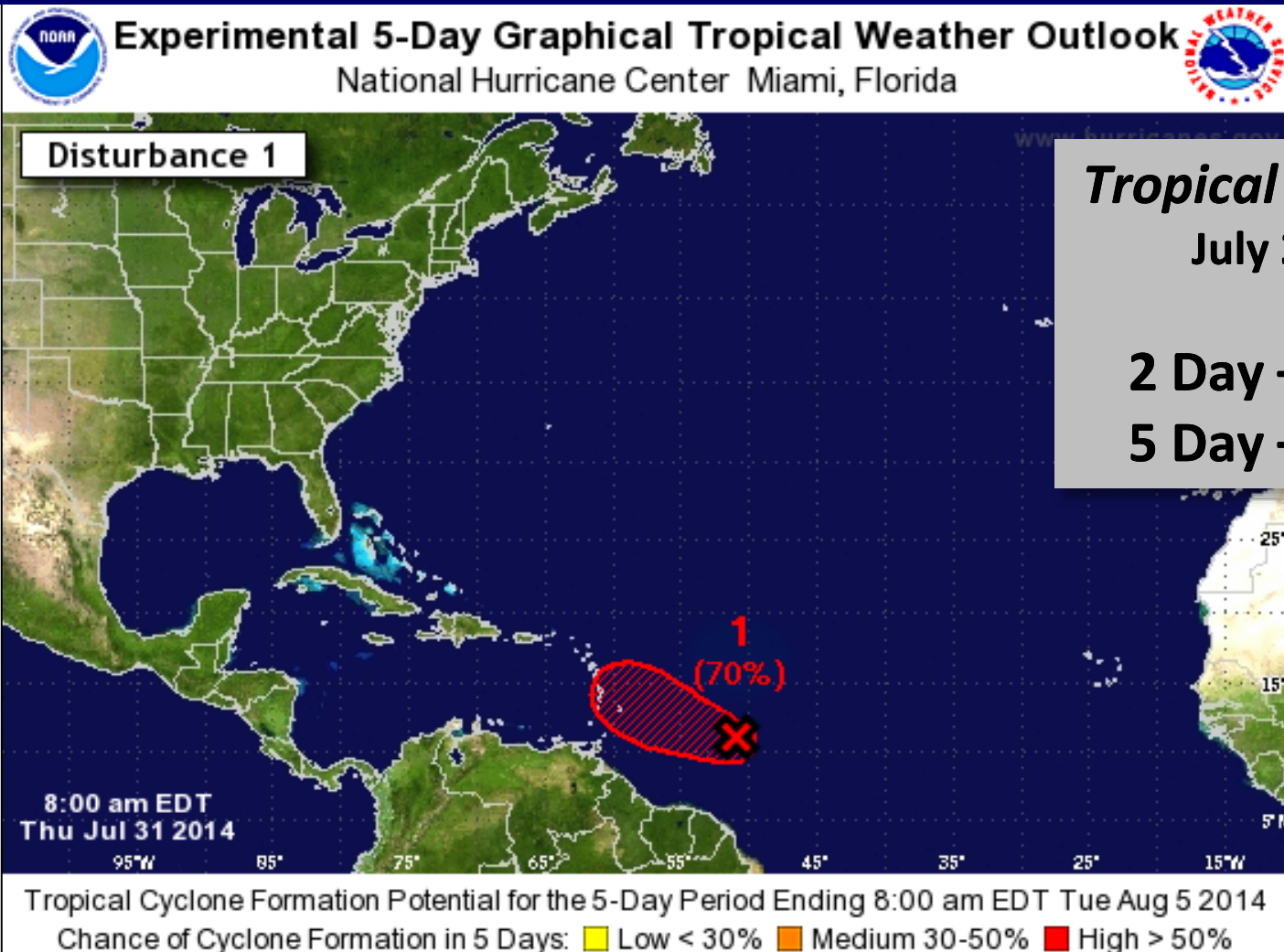
5-Day Formation Potential



- Shows formation potential during the next 5 days
- Initial location of disturbance (X) indicated, if existing at issuance time
- Shading represents potential formation area
- Active tropical cyclones not shown
- Graphic will show the location of active tropical cyclones beginning in 2017

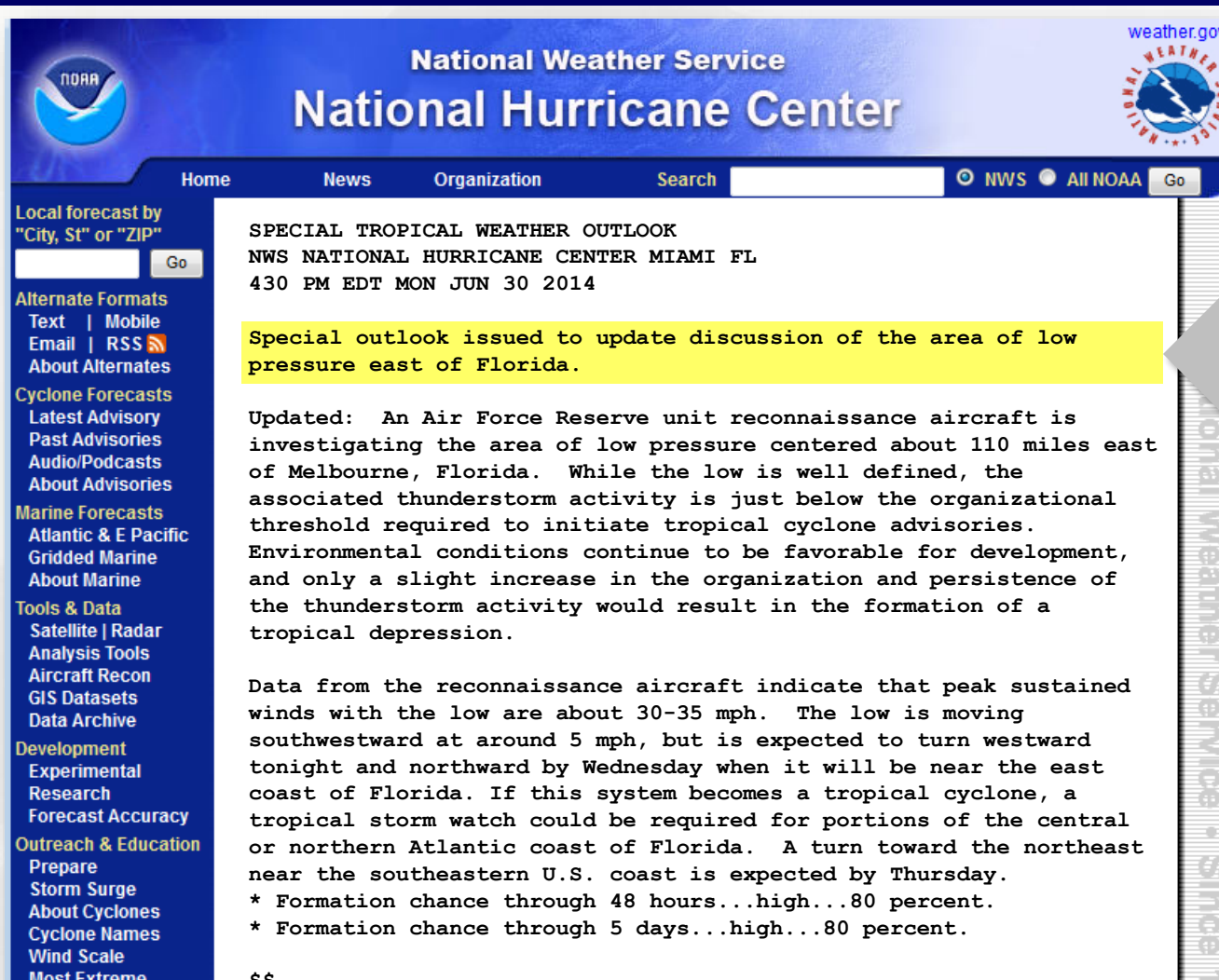
Situational Awareness

Graphical Tropical Outlook



Special Tropical Outlook

Significant or unexpected changes.



The screenshot shows the National Weather Service National Hurricane Center website. The header includes the NOAA logo, the text "National Weather Service National Hurricane Center", and the "weather.gov" logo. A navigation bar contains links for Home, News, Organization, Search, NWS, All NOAA, and a Go button. On the left, there are links for Local forecast by "City, St" or "ZIP", Alternate Formats (Text, Mobile, Email, RSS, About Alternates), Cyclone Forecasts (Latest Advisory, Past Advisories, Audio/Podcasts, About Advisories), Marine Forecasts (Atlantic & E Pacific, Gridded Marine, About Marine), Tools & Data (Satellite, Radar, Analysis Tools, Aircraft Recon, GIS Datasets, Data Archive), Development (Experimental, Research, Forecast Accuracy), and Outreach & Education (Prepare, Storm Surge, About Cyclones, Cyclone Names, Wind Scale, Most Extreme).

SPECIAL TROPICAL WEATHER OUTLOOK
NWS NATIONAL HURRICANE CENTER MIAMI FL
430 PM EDT MON JUN 30 2014

Special outlook issued to update discussion of the area of low pressure east of Florida.

Updated: An Air Force Reserve unit reconnaissance aircraft is investigating the area of low pressure centered about 110 miles east of Melbourne, Florida. While the low is well defined, the associated thunderstorm activity is just below the organizational threshold required to initiate tropical cyclone advisories. Environmental conditions continue to be favorable for development, and only a slight increase in the organization and persistence of the thunderstorm activity would result in the formation of a tropical depression.

Data from the reconnaissance aircraft indicate that peak sustained winds with the low are about 30-35 mph. The low is moving southwestward at around 5 mph, but is expected to turn westward tonight and northward by Wednesday when it will be near the east coast of Florida. If this system becomes a tropical cyclone, a tropical storm watch could be required for portions of the central or northern Atlantic coast of Florida. A turn toward the northeast near the southeastern U.S. coast is expected by Thursday.

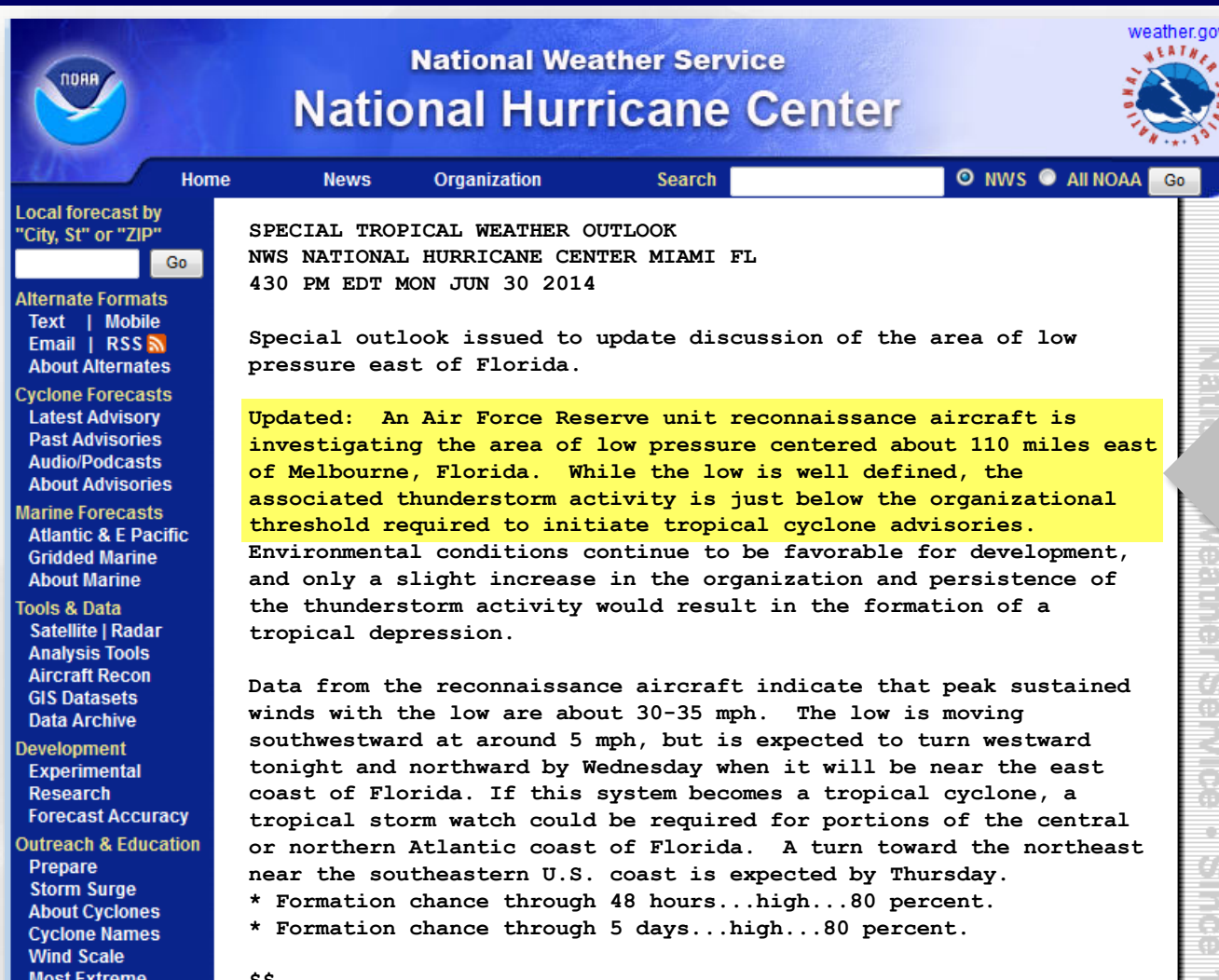
- * Formation chance through 48 hours...high...80 percent.
- * Formation chance through 5 days...high...80 percent.

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What is the special outlook issued for?

Special Tropical Outlook

Significant or unexpected changes.



The screenshot shows the National Weather Service National Hurricane Center website. The header includes the NOAA logo, the text "National Weather Service National Hurricane Center", and the "weather.gov" logo. Navigation links for Home, News, Organization, and Search are present. A local forecast input field is on the left. The main content area displays a "SPECIAL TROPICAL WEATHER OUTLOOK" issued from the NWS National Hurricane Center Miami FL at 430 PM EDT on Monday, June 30, 2014. The outlook discusses a low pressure system east of Florida, with an updated section highlighted in yellow stating that an Air Force Reserve unit reconnaissance aircraft is investigating the area. The outlook also mentions that environmental conditions are favorable for development and that a tropical storm watch could be required for portions of the central or northern Atlantic coast of Florida. Data from the reconnaissance aircraft indicates peak sustained winds of about 30-35 mph, moving southwestward at around 5 mph, but expected to turn westward tonight and northward by Wednesday. The outlook concludes with formation chances of 80 percent through 48 hours and 80 percent through 5 days.

SPECIAL TROPICAL WEATHER OUTLOOK
NWS NATIONAL HURRICANE CENTER MIAMI FL
430 PM EDT MON JUN 30 2014

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Updated: An Air Force Reserve unit reconnaissance aircraft is investigating the area of low pressure centered about 110 miles east of Melbourne, Florida. While the low is well defined, the associated thunderstorm activity is just below the organizational threshold required to initiate tropical cyclone advisories.

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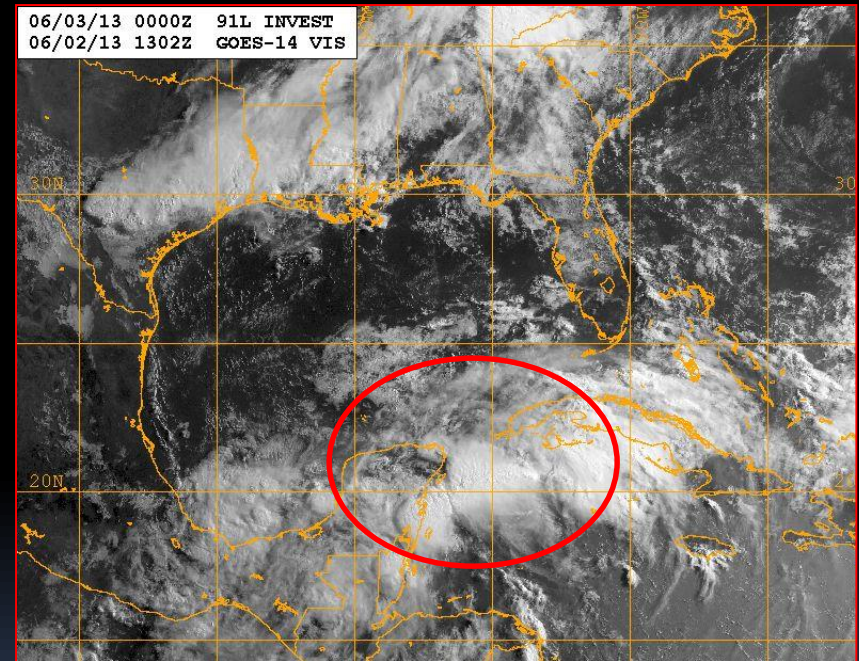
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What's the new information?
Aircraft?



NHC “Invest” Systems

- NHC opens “invests” to monitor suspicious weather systems more carefully
- There are no standards for opening invests unlike for initiating a tropical cyclone package – based on forecaster prerogative
- Guidance is typically run when a cloud system center is apparent (but not always!)
- Users are reminded to be extremely cautious about using parameters associated with particular “invests” in decision-making

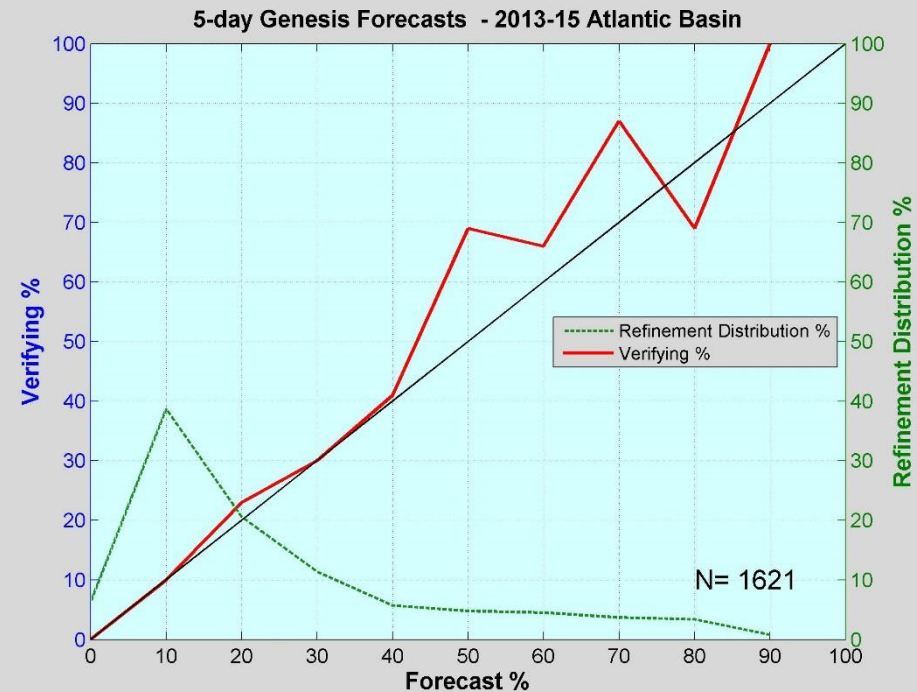
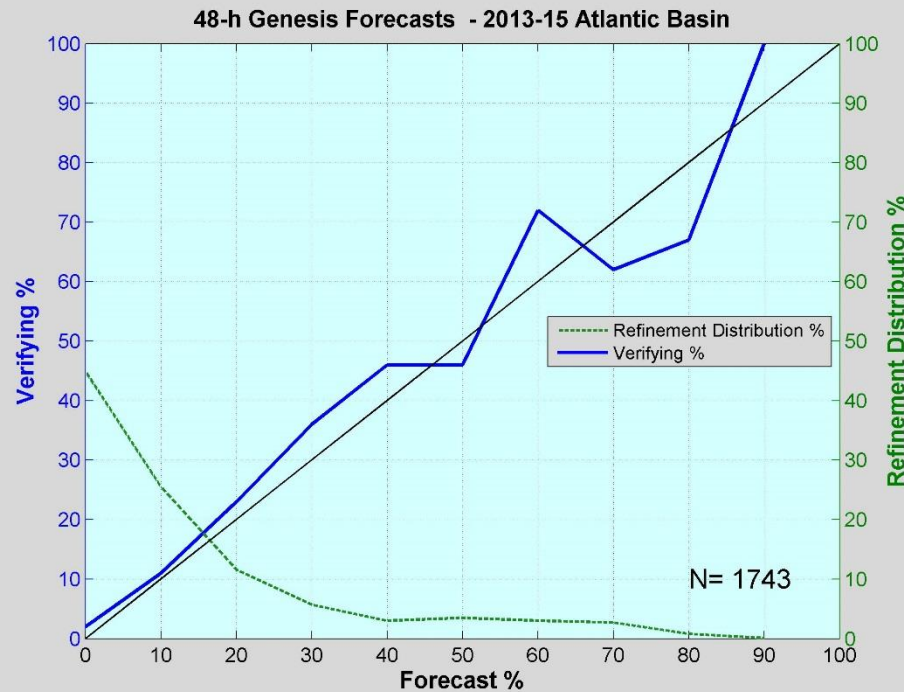


Forecasts and Warnings for Potential Tropical Cyclones

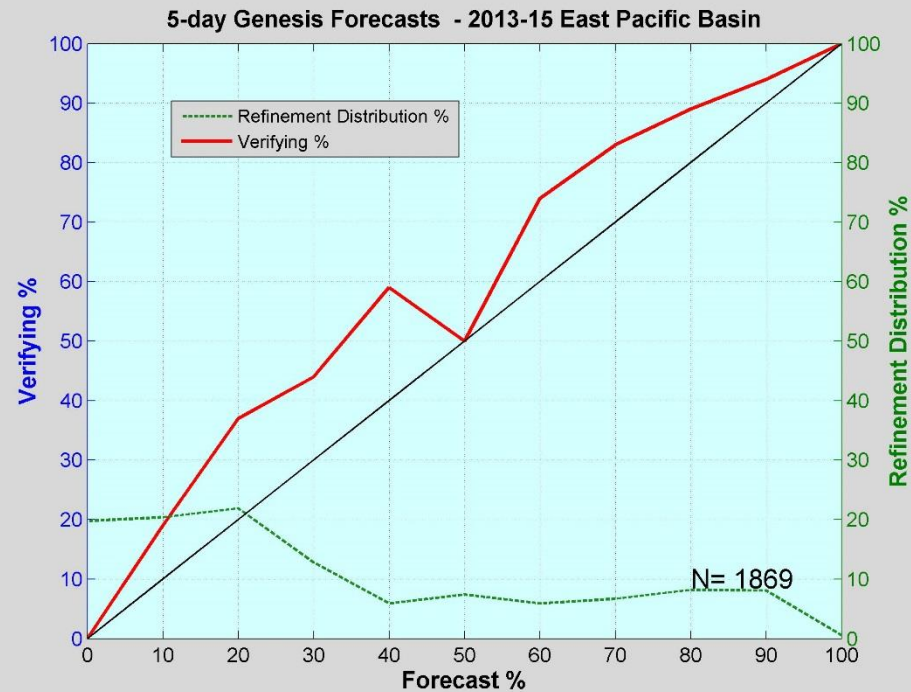
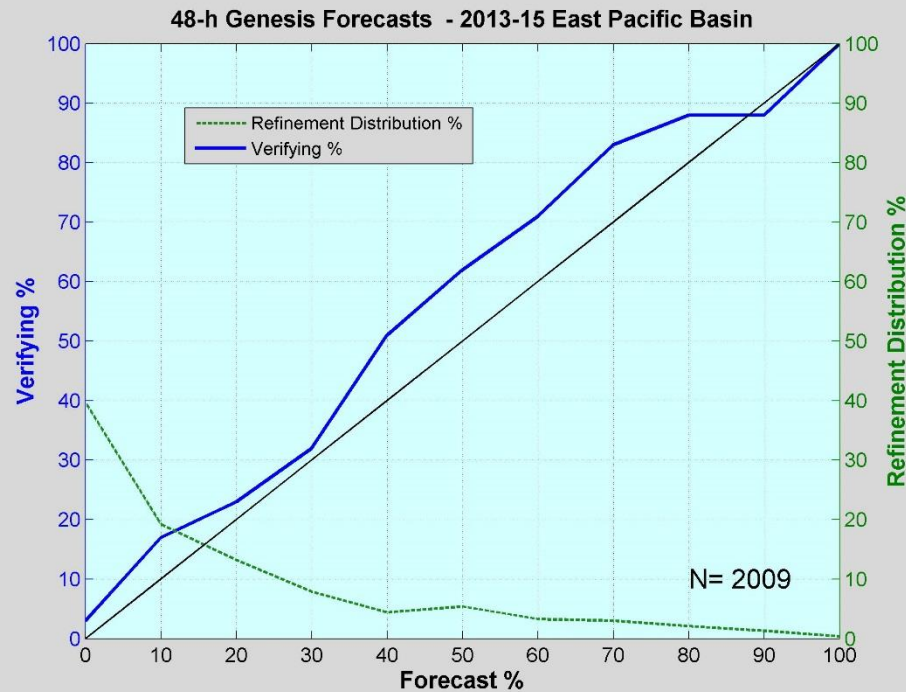
- Broaden the definition of tropical storm and hurricane watches and warnings to allow their use for disturbances
- Regular watch/warning criteria would apply
 - Watch – possible within 48 h
 - Warning – expected within 36 h
- Issued through the standard suite of NHC advisory products
 - *Potential Tropical Cyclone*
 - Current numbering system (for depressions) would apply
 - System is referenced, but no longer described, in the Tropical Weather Outlook



Verification Results of 2- and 5-Day Genesis Forecasts - Atlantic



Verification Results of 2- and 5-Day Genesis Forecasts - Pacific



Out of ~60 tropical waves transiting the Atlantic basin each season, less than 1/10 develop. Why?

- A) Waves lose convection off of Africa due to cool waters and have less potential for development
- B) many of them are too close to the equator
- C) environmental factors are generally marginally conducive for development
- D) Waves are closely spaced together and constructively interfere with one another
- E) Both A and C

The Atlantic basin is a marginal basin for TCs

- A) True
- B) False

The instability over the Atlantic basin is greatest:

- A) Late in the hurricane season
- B) Early in the hurricane season
- C) Early to mid hurricane season
- D) None of the above

As a general rule, pressures falls of what magnitude, associated with a tropical disturbance, are indicative that TC genesis is imminent ?

- A) 1 mb/24 h
- B) 2 mb/24 h
- C) 3 mb/24 h or more
- D) 0.5 mb/24 h

Stage 1 of TC genesis results in the formation of what phenomenon:

- A) Disorganized convection
- B) An upper-level anticyclone
- C) Often a large burst of convection
- D) A mesoscale convective vortex
- E) C and D

If the 2- and 5-day genesis probabilities are equal in the TWO, what does this mean?

- A) TC genesis, if it occurs, is likely to occur within 2 days
- B) TC genesis, if it occurs, is likely to occur within 5 days
- C) TC genesis, if it occurs, is likely to occur within 3 to 5 days
- D) TC genesis, if it occurs, is likely to occur in a few hours

The opening of an “invest” system signifies that:

- A) NHC is on the verge of issuing TC advisories on that system
- B) NHC wishes to monitor a particular system of interest more carefully
- C) NHC intends to increase the genesis probabilities of this system soon
- D) NHC knows very precisely where and how strong the invest system is

About what percentage of Atlantic TCs form from non-tropical sources each season:

- A) 10%
- B) 50%
- C) 25%
- D) 5%

The requirement that a TC has organized deep convection is:

- A) an objective criterion that can be proven
- B) somewhat subjective
- C) arbitrary and a man-made definition
- D) B and C

Forecast Exercise