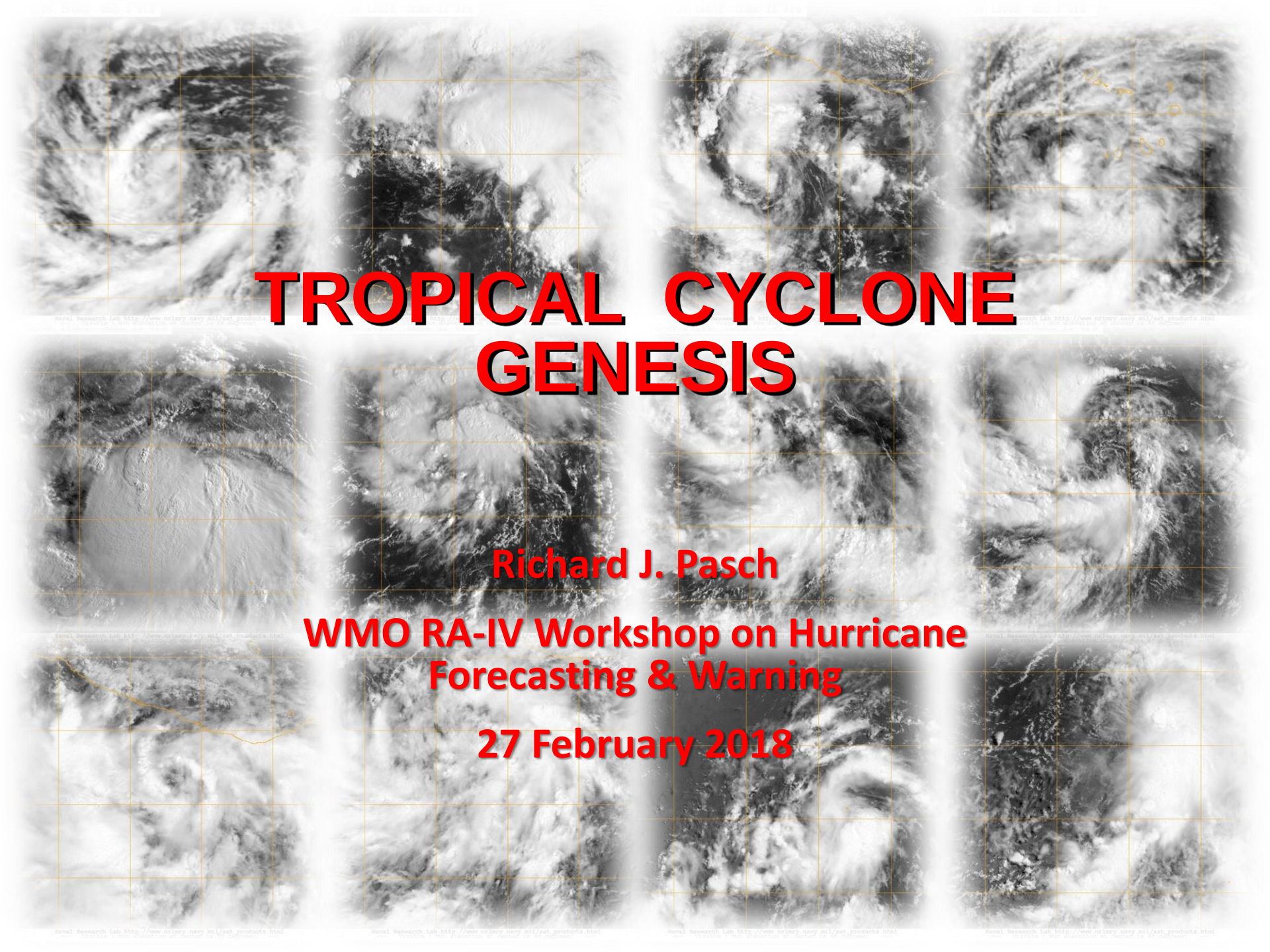


TROPICAL CYCLONE GENESIS

Richard J. Pasch

WMO RA-IV Workshop on Hurricane Forecasting & Warning

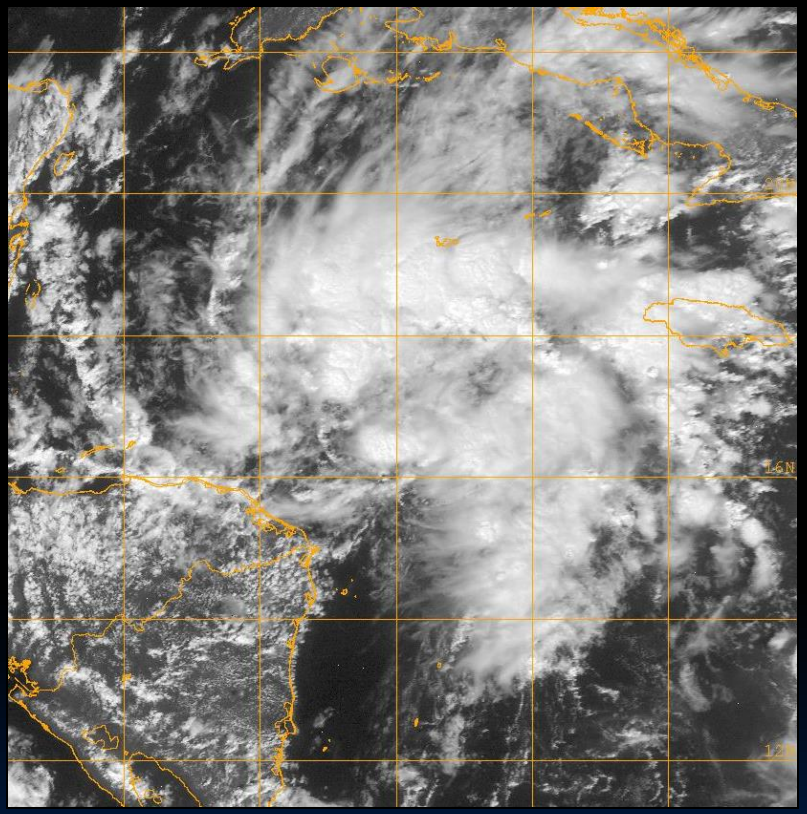
27 February 2018

Outline / Topics

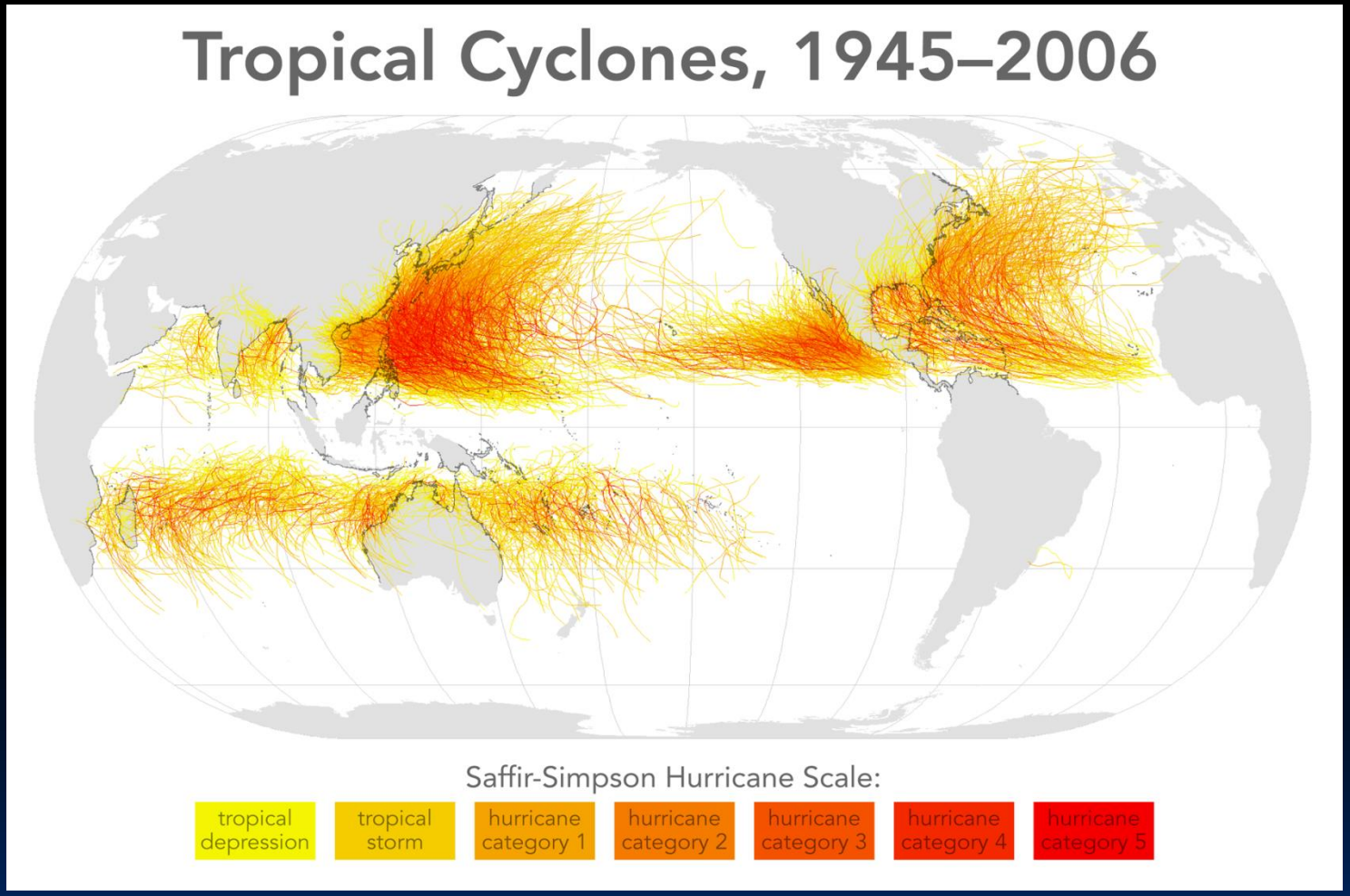
- Climatology
- Large-scale conditions associated with tropical cyclone (TC) formation
- Relation to ENSO, intraseasonal variability
- Theories of genesis
- Meso-scale aspects of genesis
- TC genesis in global models
- Web sites of genesis parameters
- Operational (NHC) genesis forecasting
- Forecast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



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.

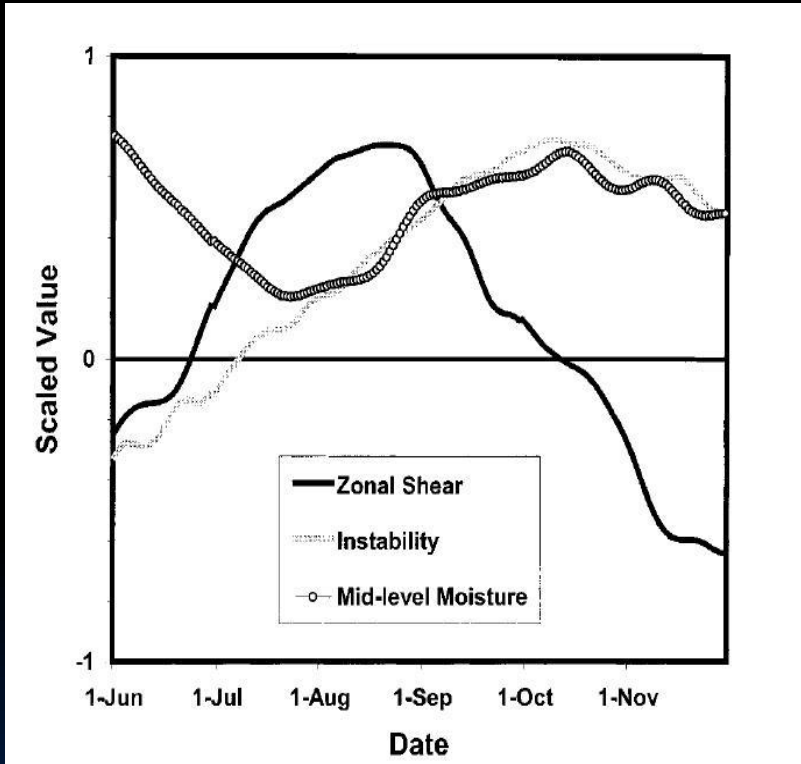
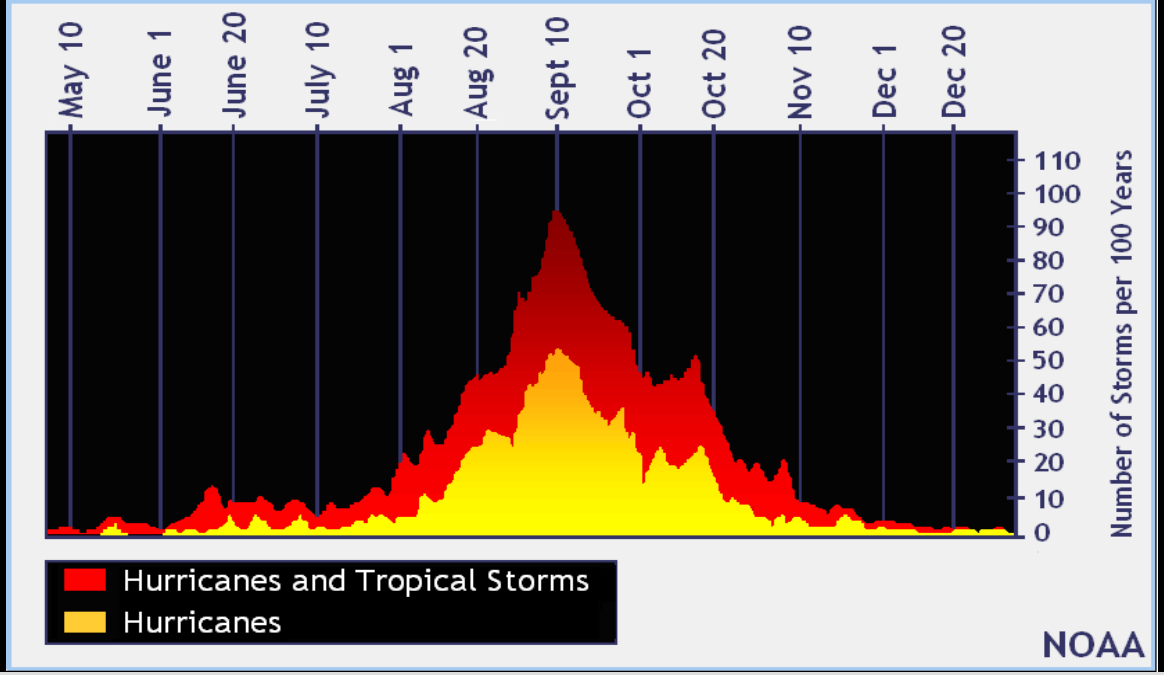
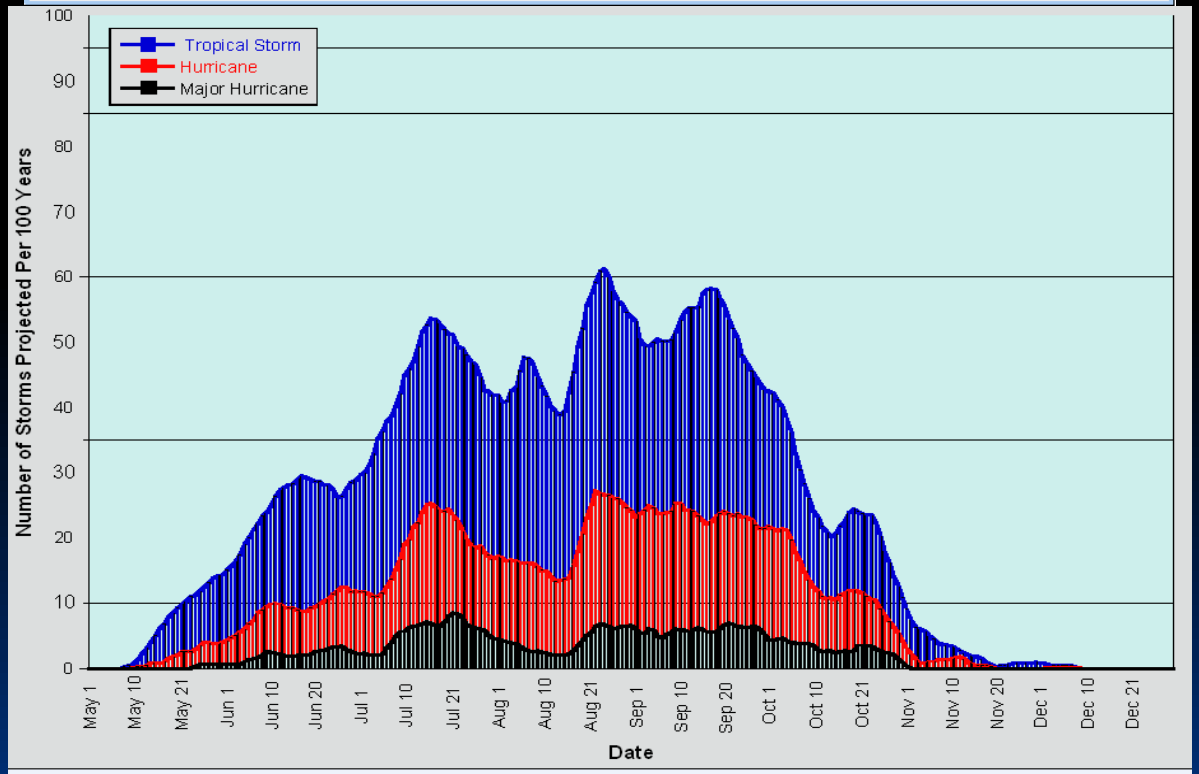


FIG. 7. Climatological time series of the scaled shear, instability, and moisture variables.



Atlantic

Highly peaked with a secondary peak in mid-October

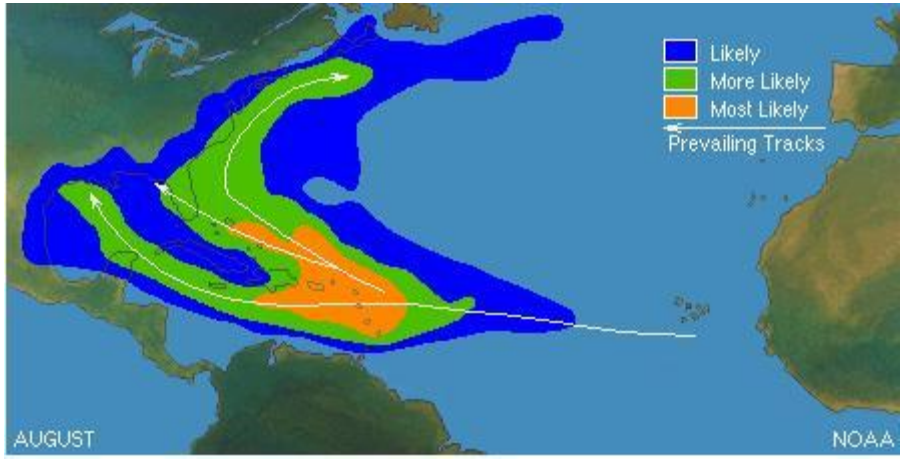


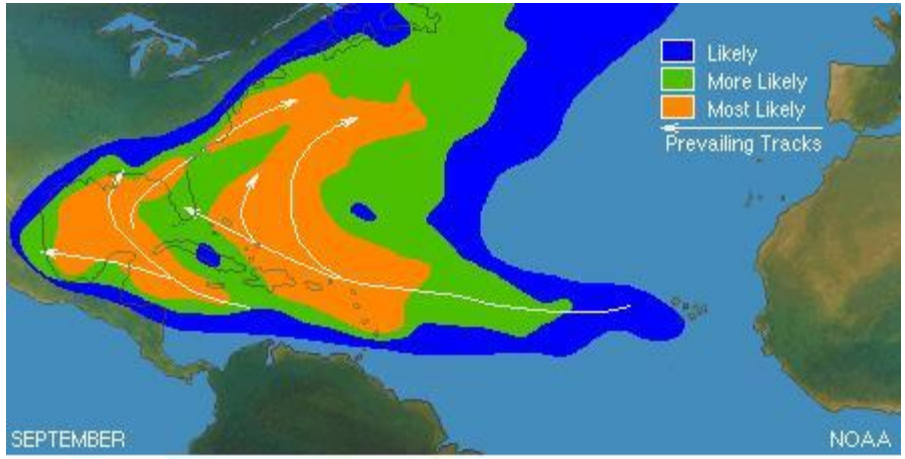
Eastern North Pacific

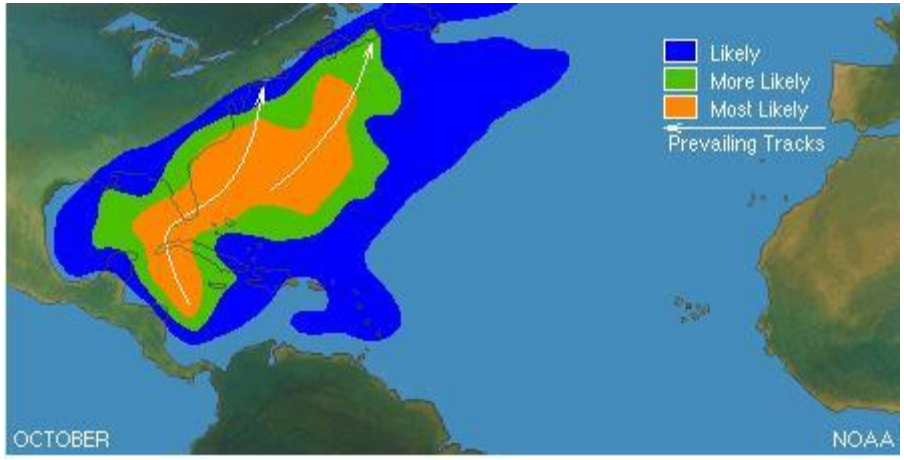
Bimodal distribution

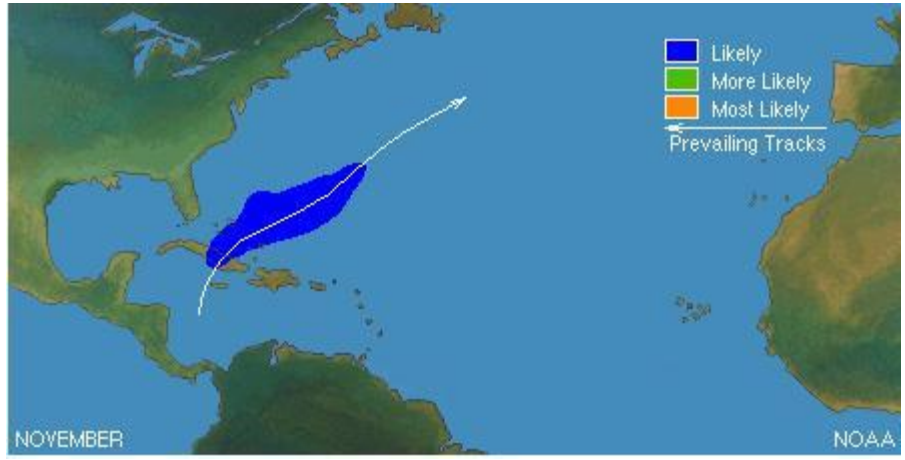

Likely
More Likely
Most Likely
Prevailing Tracks
JUNE
NOAA


Likely
More Likely
Most Likely
Prevailing Tracks
JULY
NOAA


Likely
More Likely
Most Likely
Prevailing Tracks
AUGUST
NOAA


Likely
More Likely
Most Likely
Prevailing Tracks
SEPTEMBER
NOAA

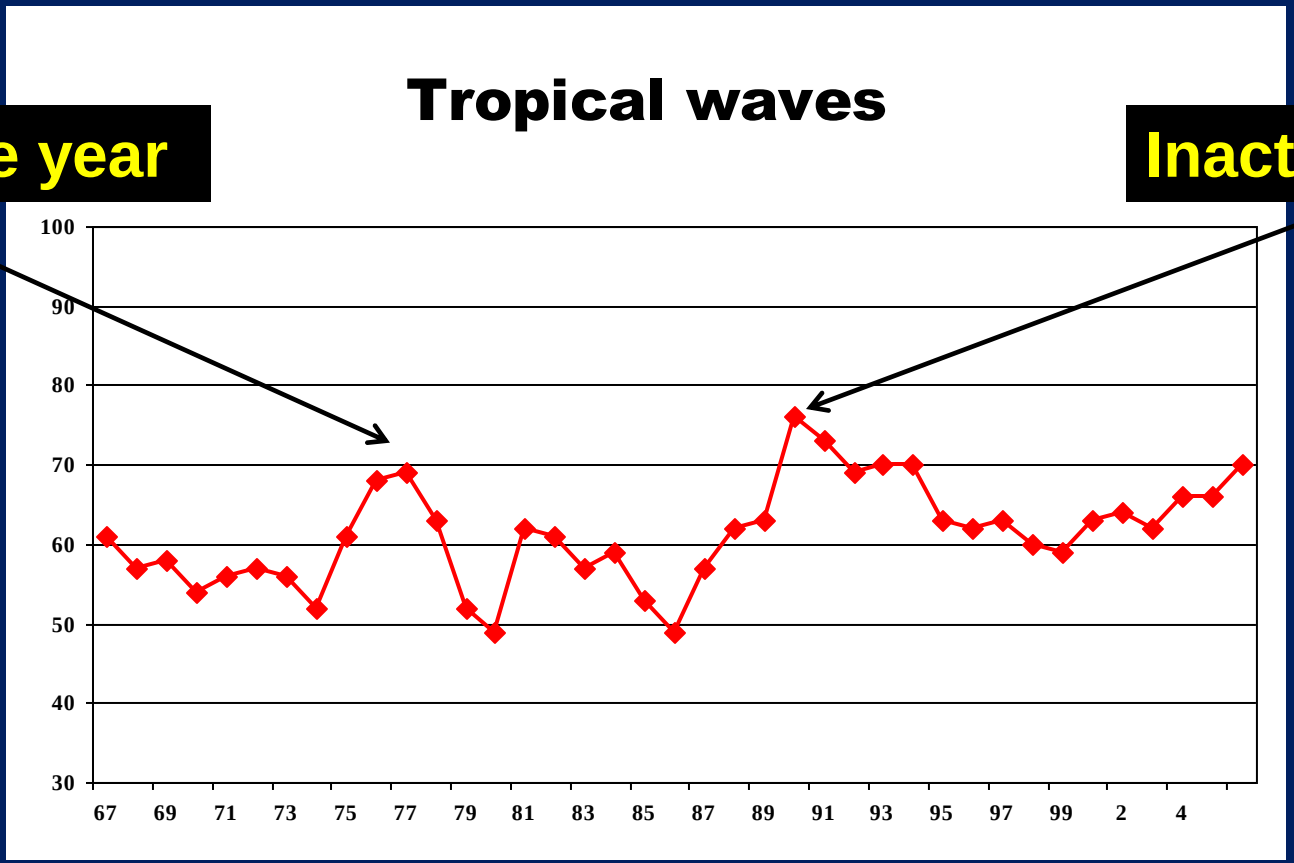

Likely
More Likely
Most Likely
Prevailing Tracks
OCTOBER
NOAA


Likely
More Likely
Most Likely
Prevailing Tracks
NOVEMBER
NOAA

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

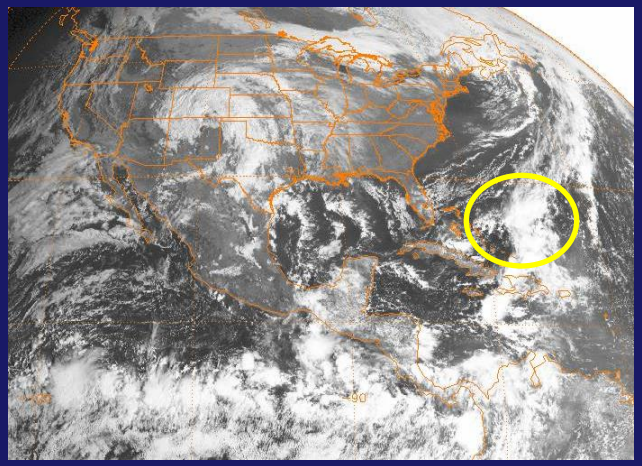
Inactive year

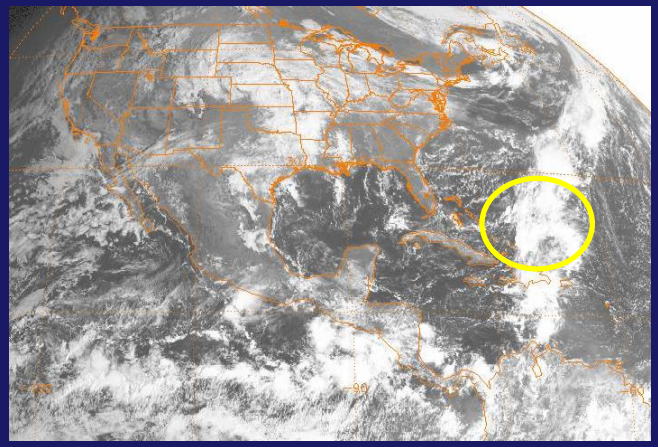
Inactive year

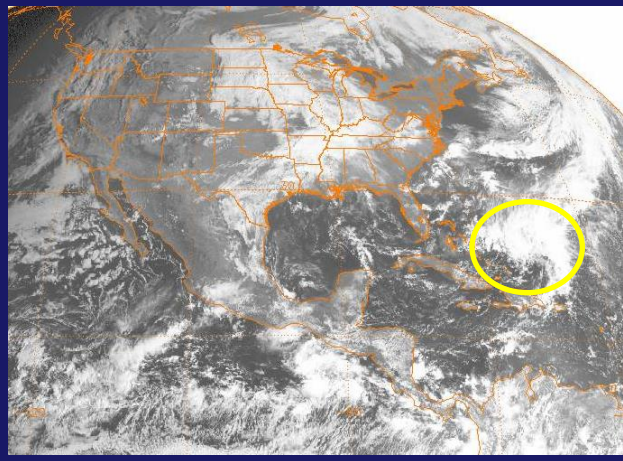


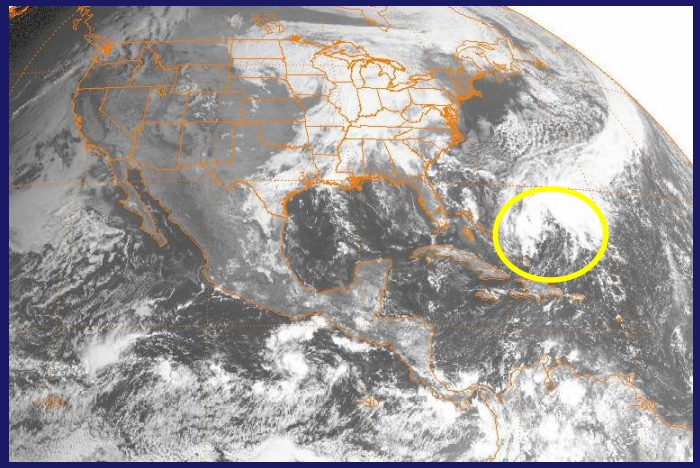
Note that TC genesis is ***not*** a function of the number of available disturbances.

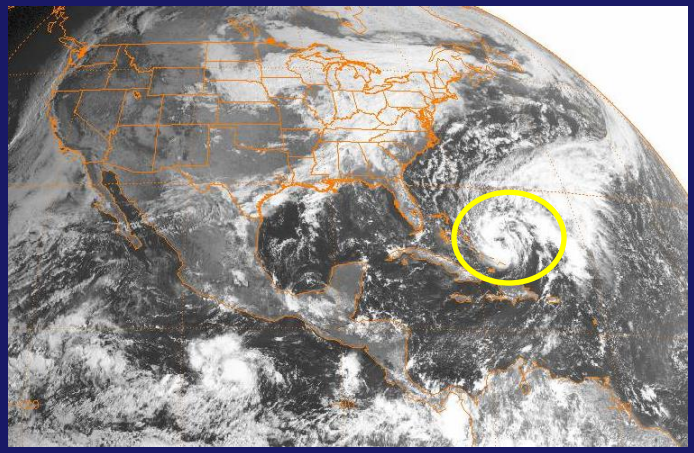
Typical Non-Tropical TC formation in the North Atlantic (fronts, upper-level lows)









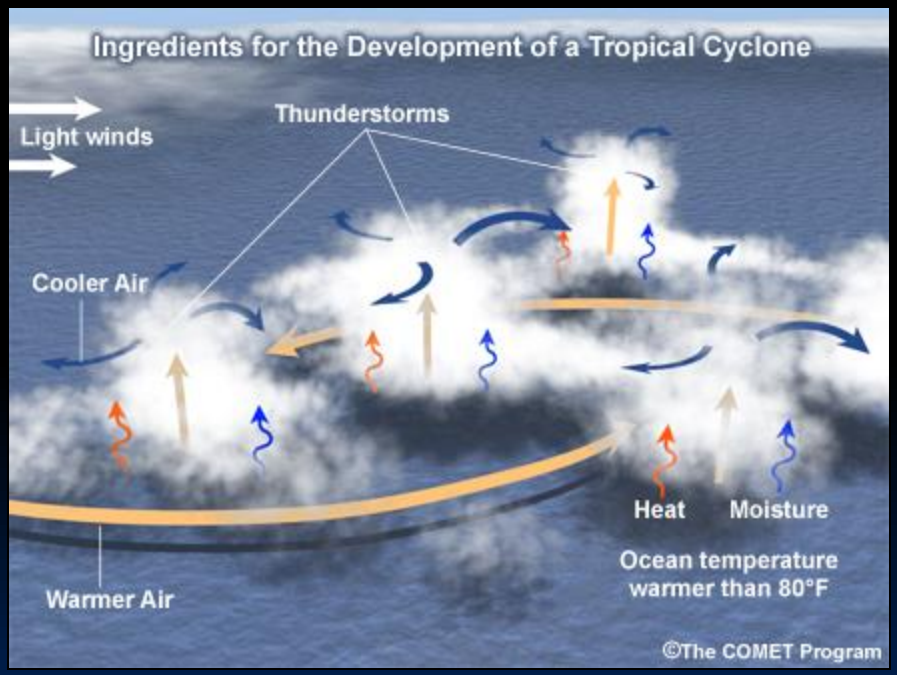


On average, about 25% of Atlantic TCs form from non-tropical sources

Large-Scale Conditions and Other Characteristics Associated with TC Formation

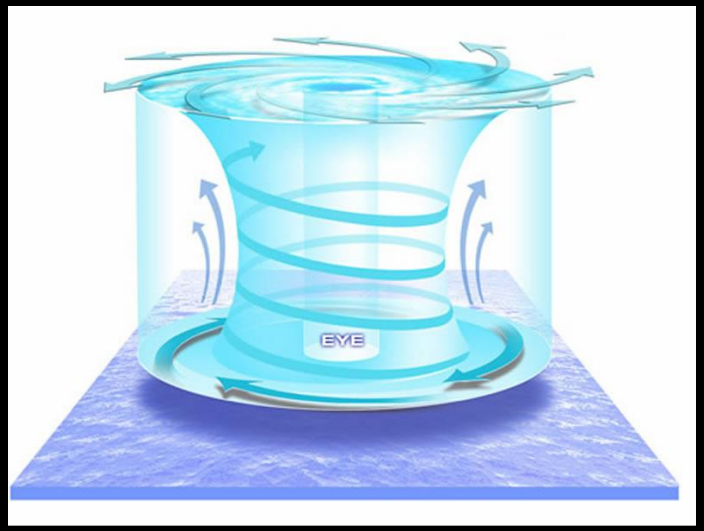
Necessary but not sufficient conditions!

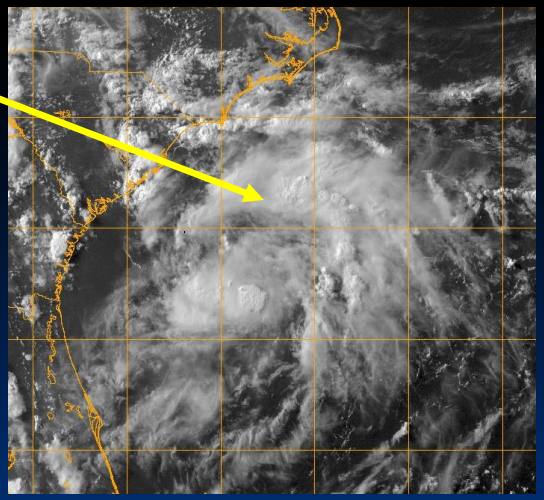
- A pre-existing disturbance containing abundant deep convection
- Latitudes poleward ~5º
- Adequate ocean thermal energy
  - SST > 26ºC extending to a depth of 60 m
- A "sufficiently" unstable atmosphere & deep layer of moist air
- Small vertical shear of the horizontal wind



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



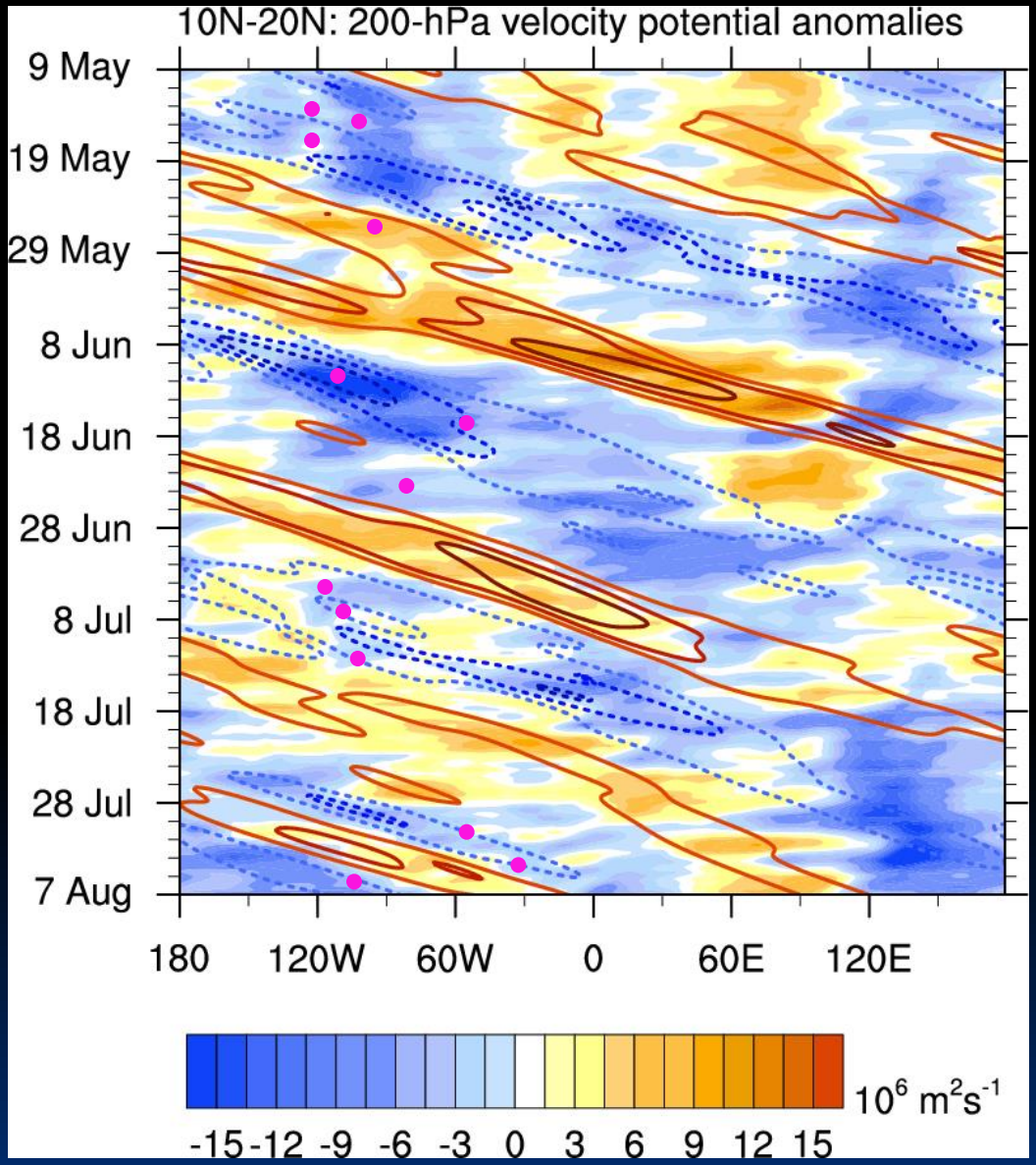


"We observe universally that tropical storms form only within pre-existing disturbances…An initial disturbance therefore forms part of the starting mechanism. A weak circulation, low pressure and a deep moist layer are present at the beginning. The forecaster need not look into areas which contain no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

Herbert Riehl (1954)

Important Intraseasonal Predictors for 5-Day Genesis Forecasts

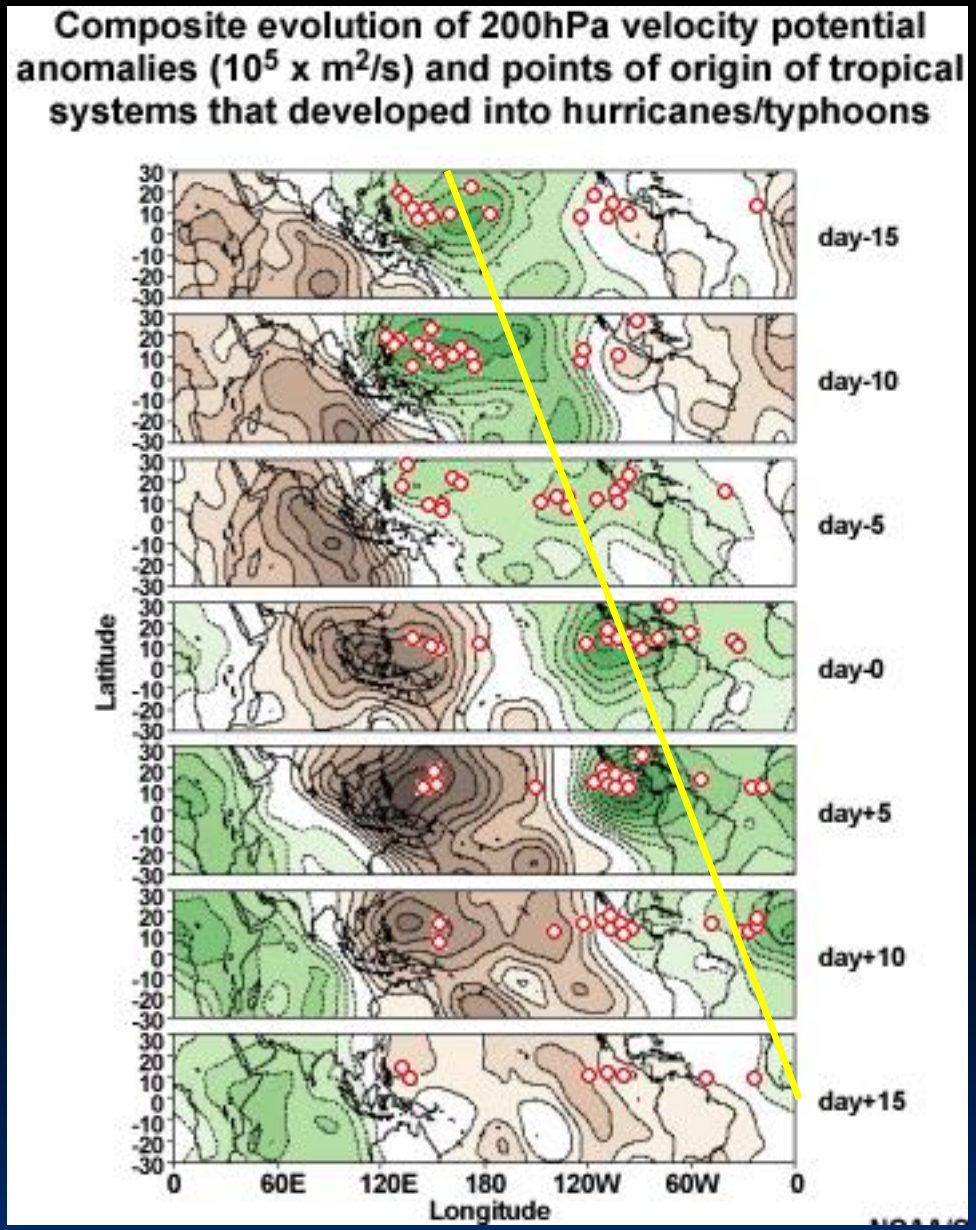
Blue–favorable upper-level conditions (lower shear and more unstable)

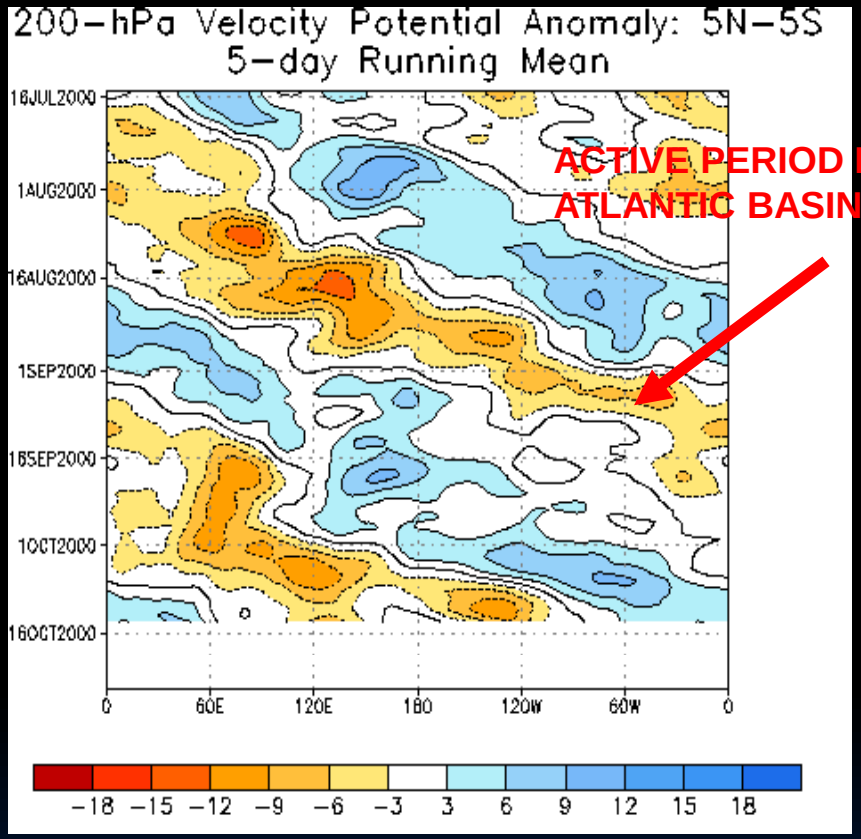


Magenta dots are TC genesis points in early 2012

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

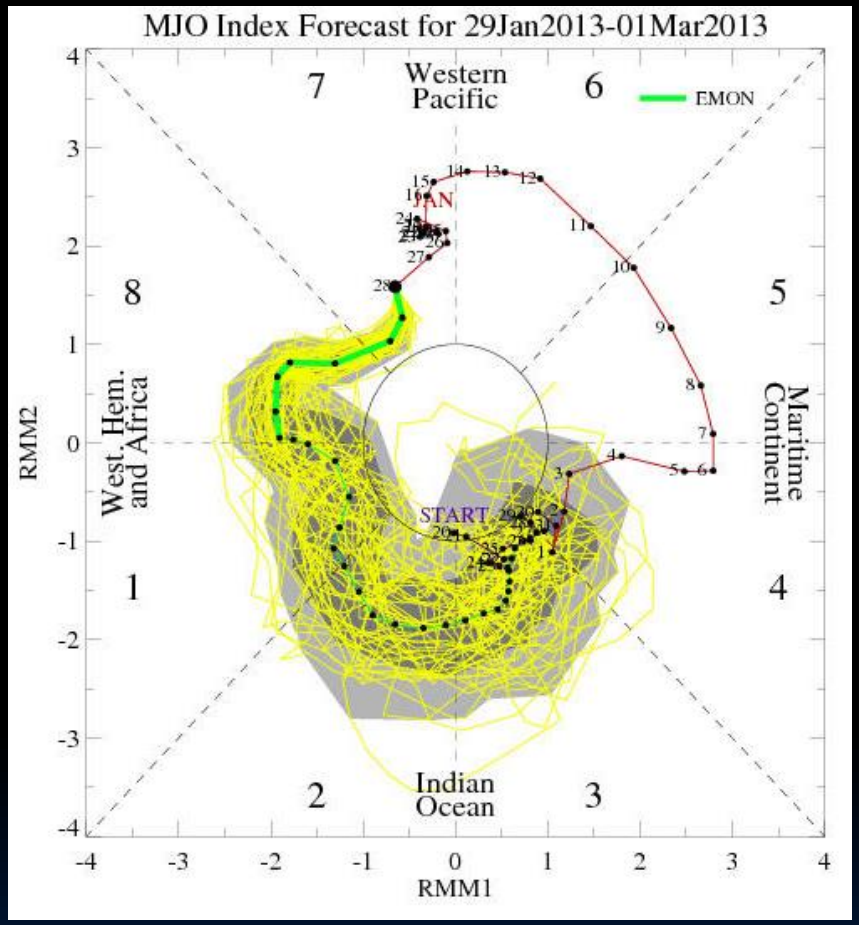
MADDEN-JULIAN OSCILLATION: RELATED TO INTRASEASONAL VARIABILITY IN TC ACTIVITY?

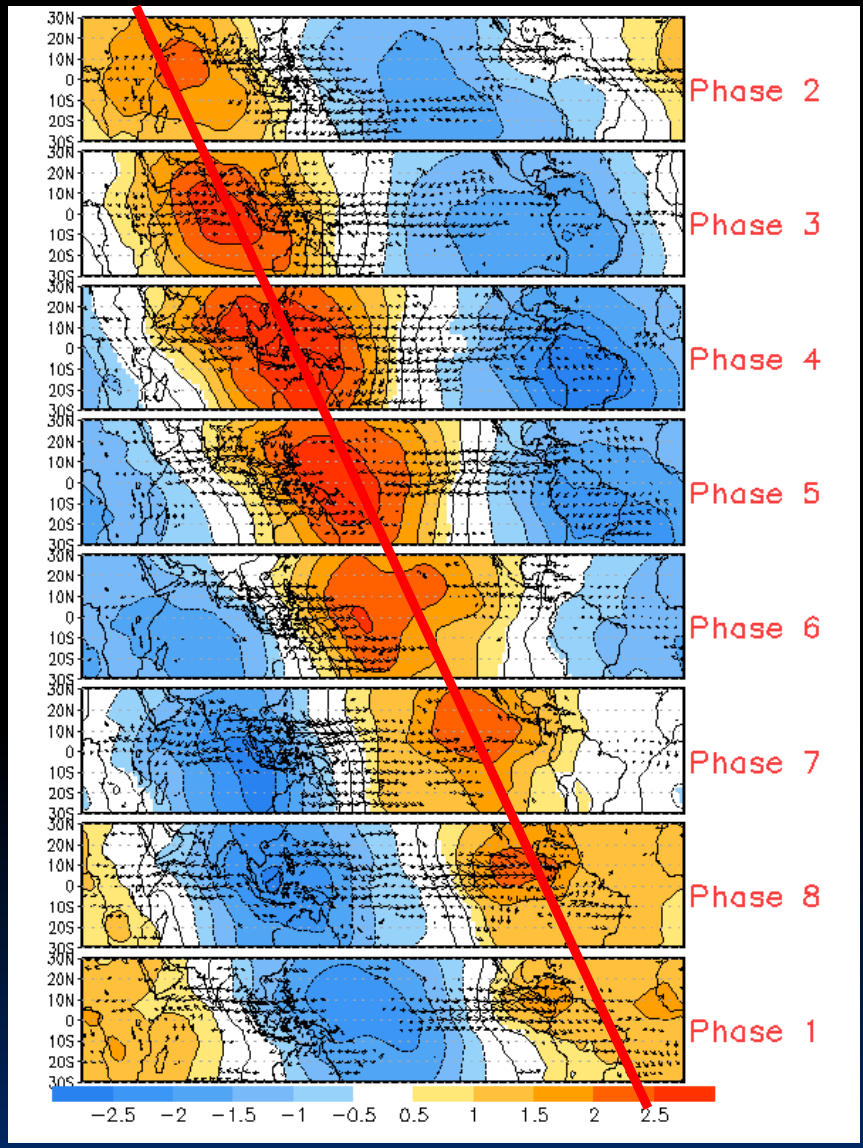




200 MB VELOCITY POTENTIAL 5°N-5°S 5-DAY RUNNING MEAN

A Tool for Tracking and Forecasting the MJO

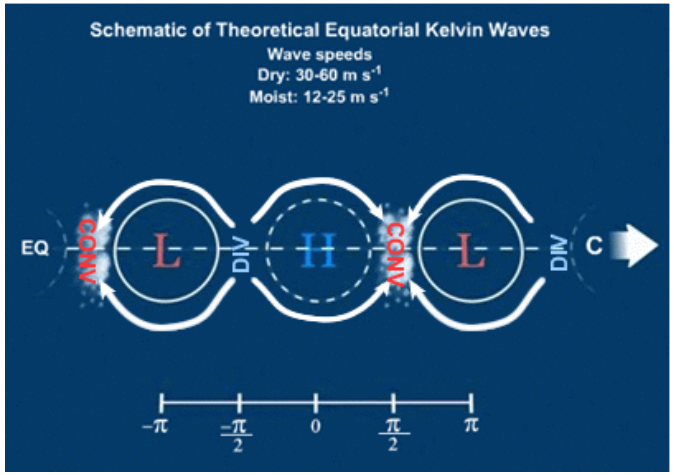




- Conceptual model showing idealized phases of MJO progression
- Phases 8 through 3 most active phases for the Atlantic

Idealized CCKW-influenced TC genesis

Day -2



Region of enhanced cyclonic vorticity generation

Background easterly flow

Disturbance

EQ

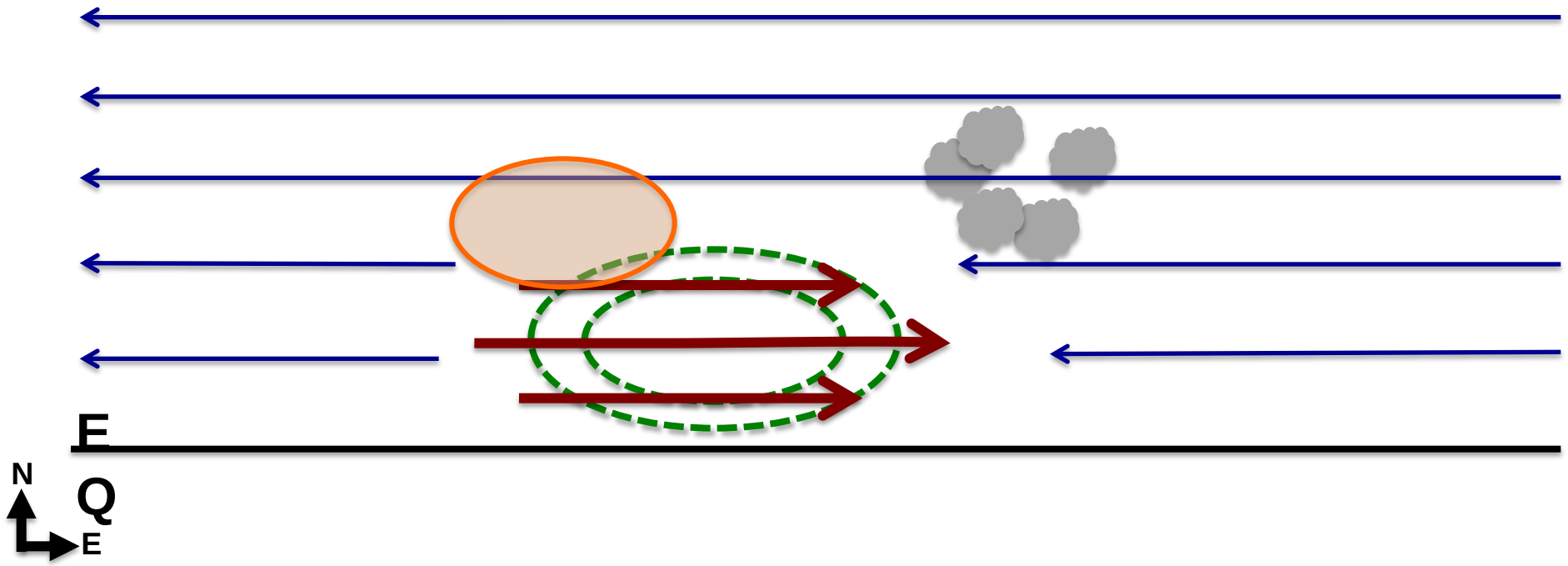
Eastward propagating CCKW, indicated by negative OLR anomalies and low-level anomalous westerly winds

N

E

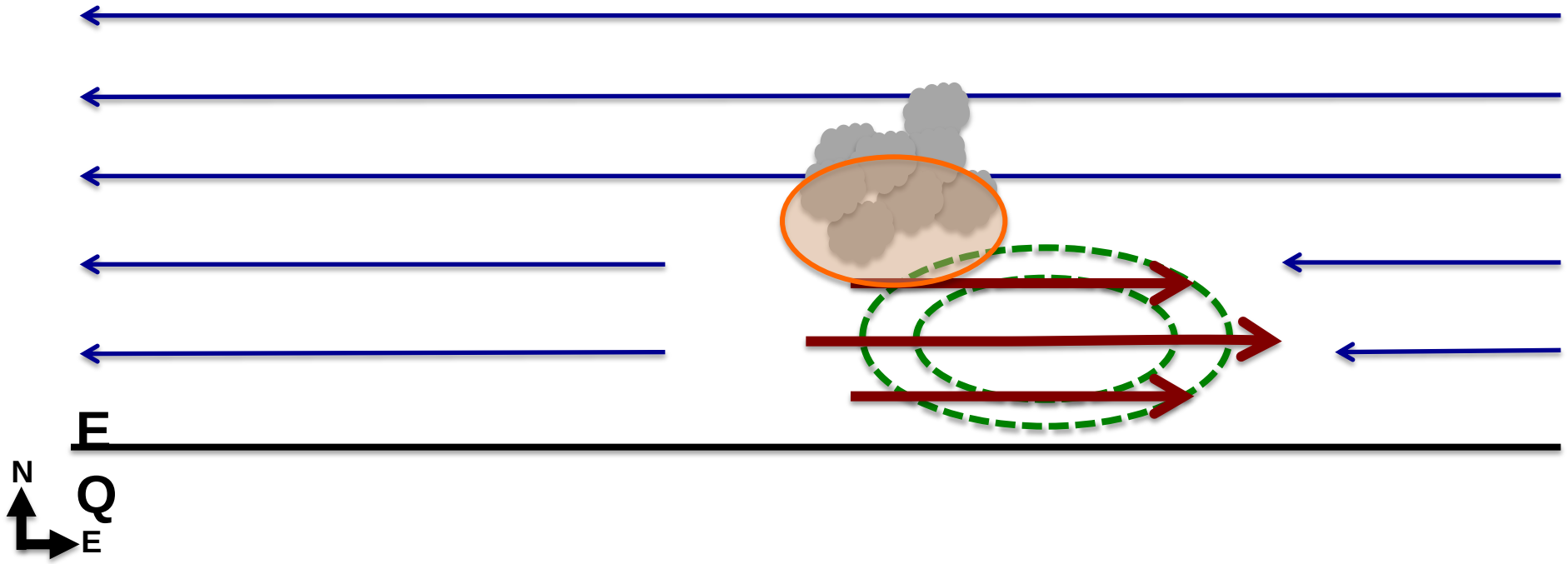
Idealized CCKW-influenced TC genesis

Day -1



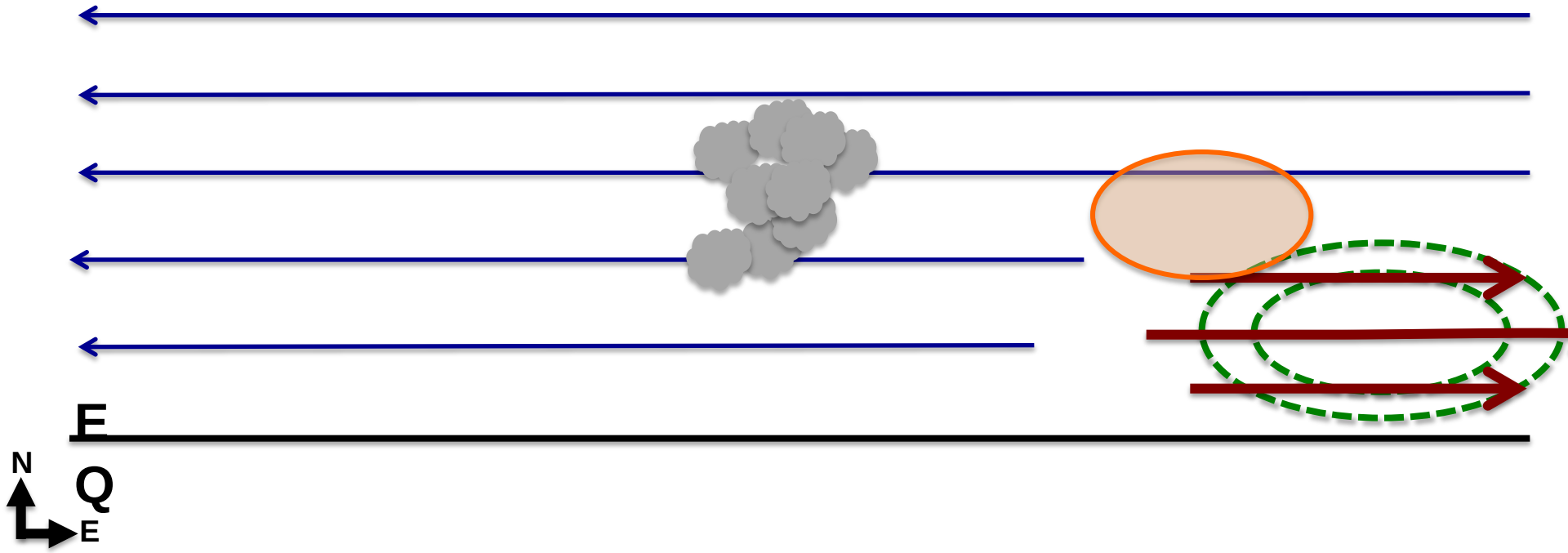
Idealized CCKW-influenced TC genesis

Day 0



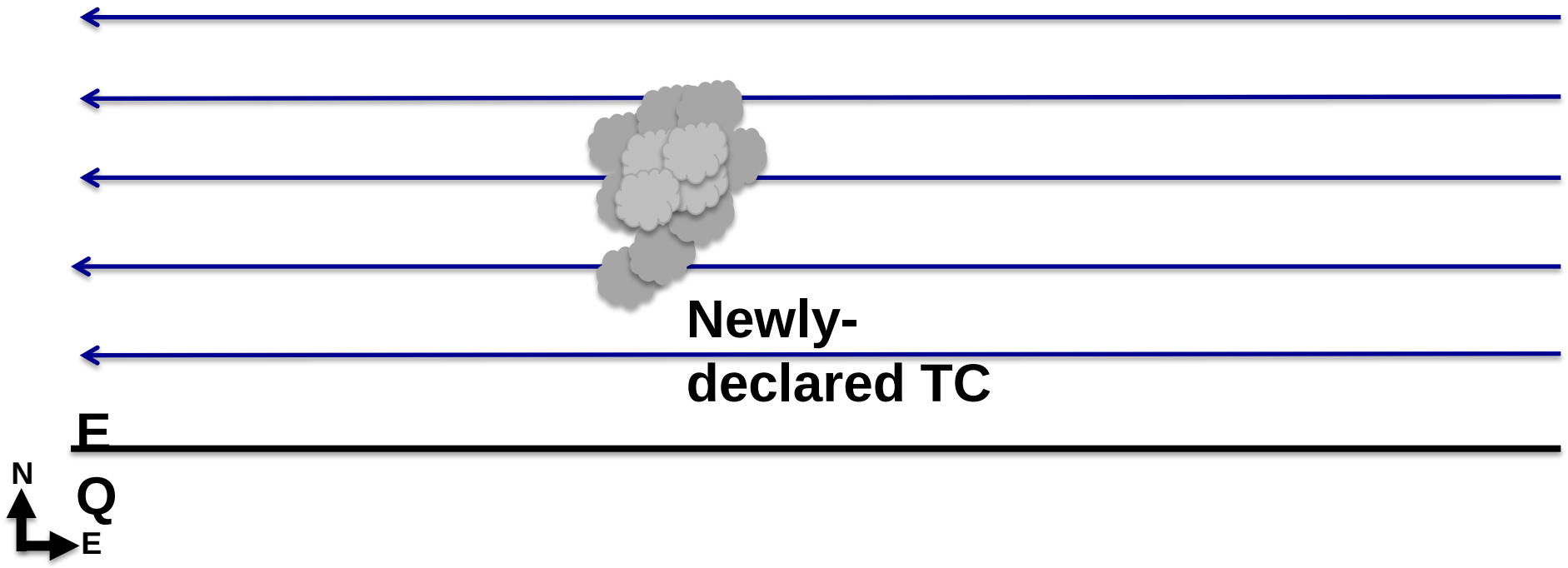
Idealized CCKW-influenced TC genesis

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.

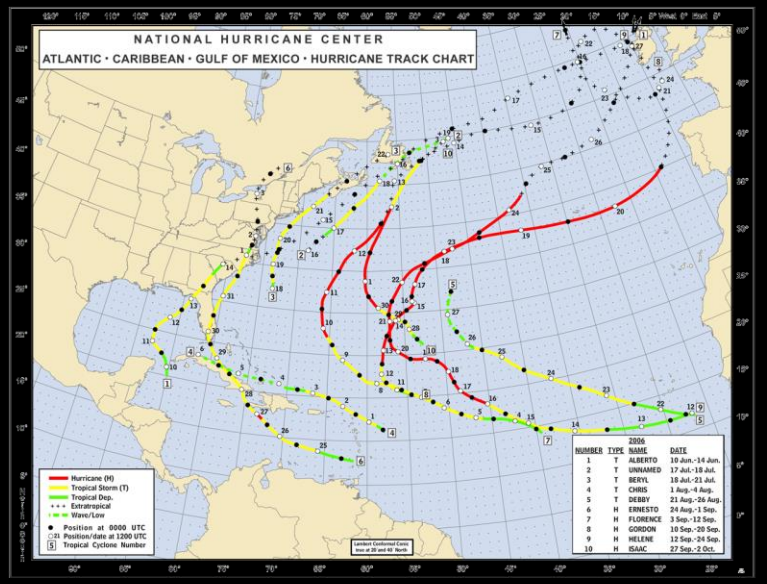
- No operational standard on use of CCKW in genesis forecasts (about half of forecasters use it).

Influence of El Niño/La Niña on TC Genesis

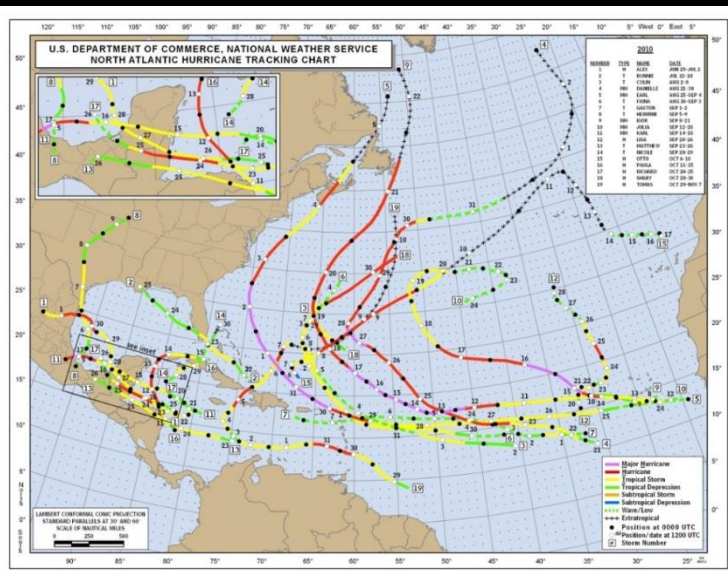
• During El Niño episodes, *fewer* TCs form over the deep tropical Atlantic and Caribbean; tendency for more to form at subtropical latitudes. The opposite generally occurs during La Niña years.

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

2006 (El Niño)



2010 (La Niña)



2 Formal Theories of TC Genesis

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

CISK

Acronym for:

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

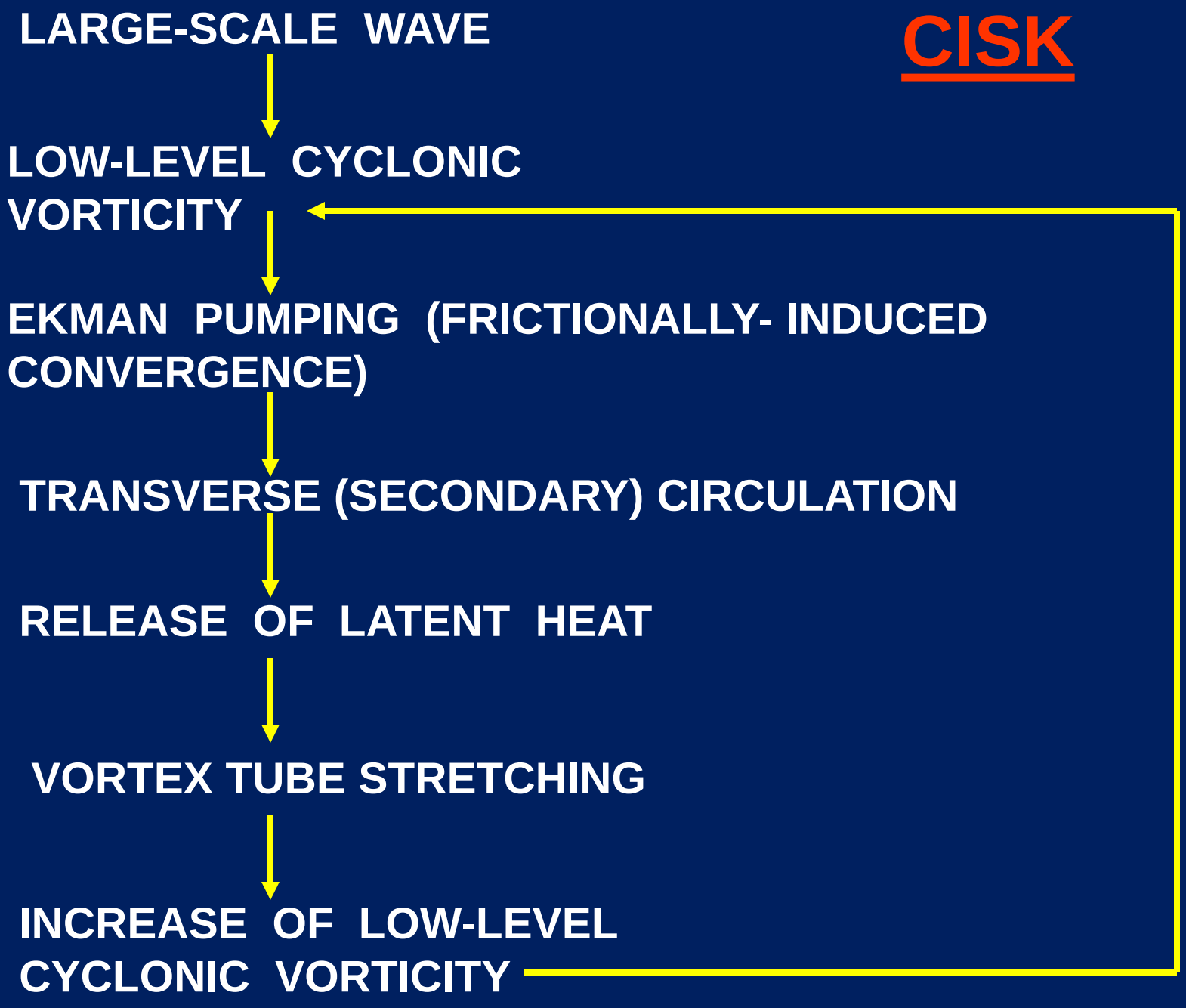
- A cooperative feedback between small-scale convection (frictionally-induced convergence and latent heat release) and the larger-scale circulation (a growing disturbance)

- A simplified linear theory which assumes that flow is in gradient balance

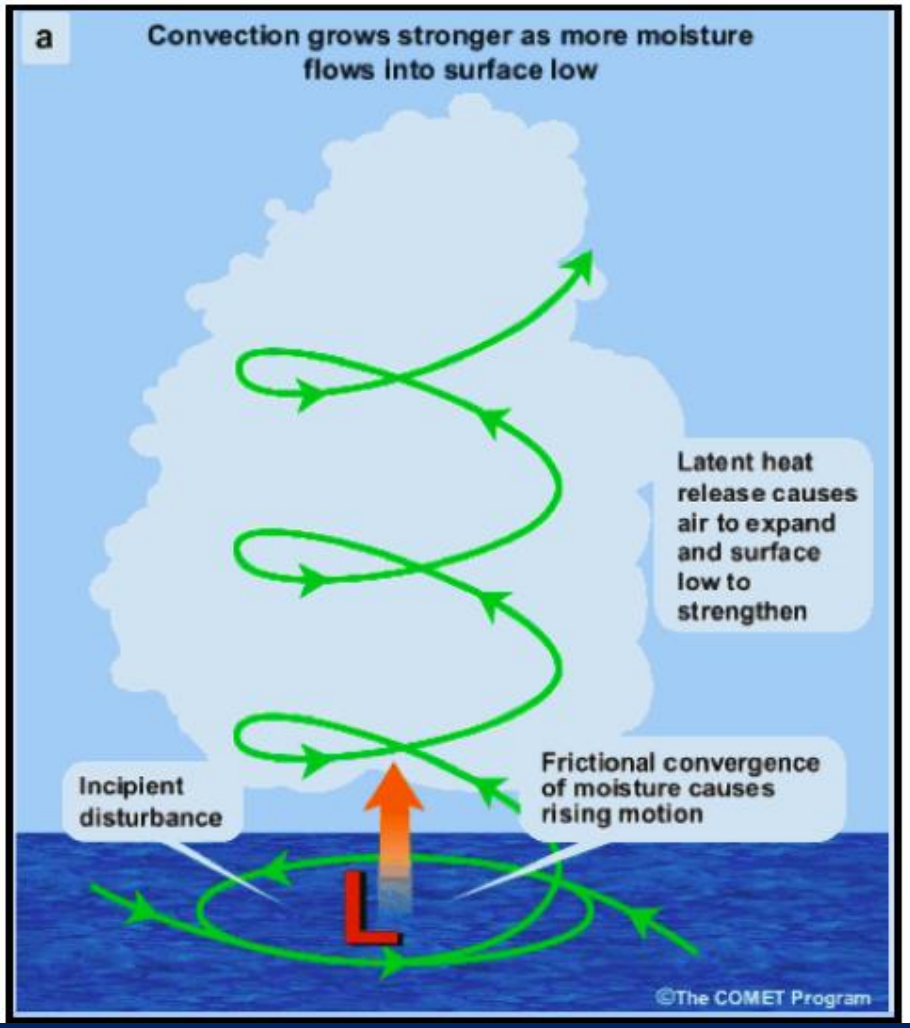
- When latent heat release balances surface frictional dissipation, the cyclone maintains its intensity

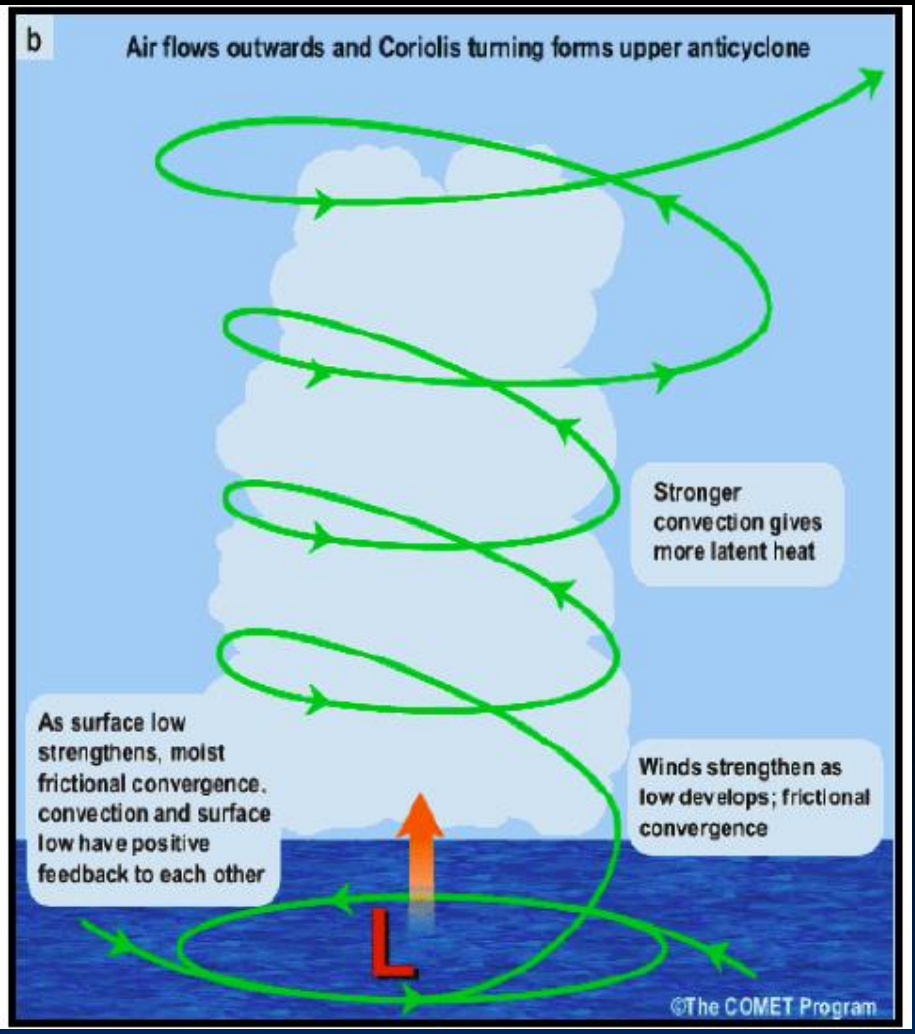
NOTE: ALTHOUGH THIS THEORY IS FREQUENTLY ATTACKED, IT STILL HAS SOME INTUITIVELY APPEALING ASPECTS!

CISK


LARGE-SCALE WAVE
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





“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

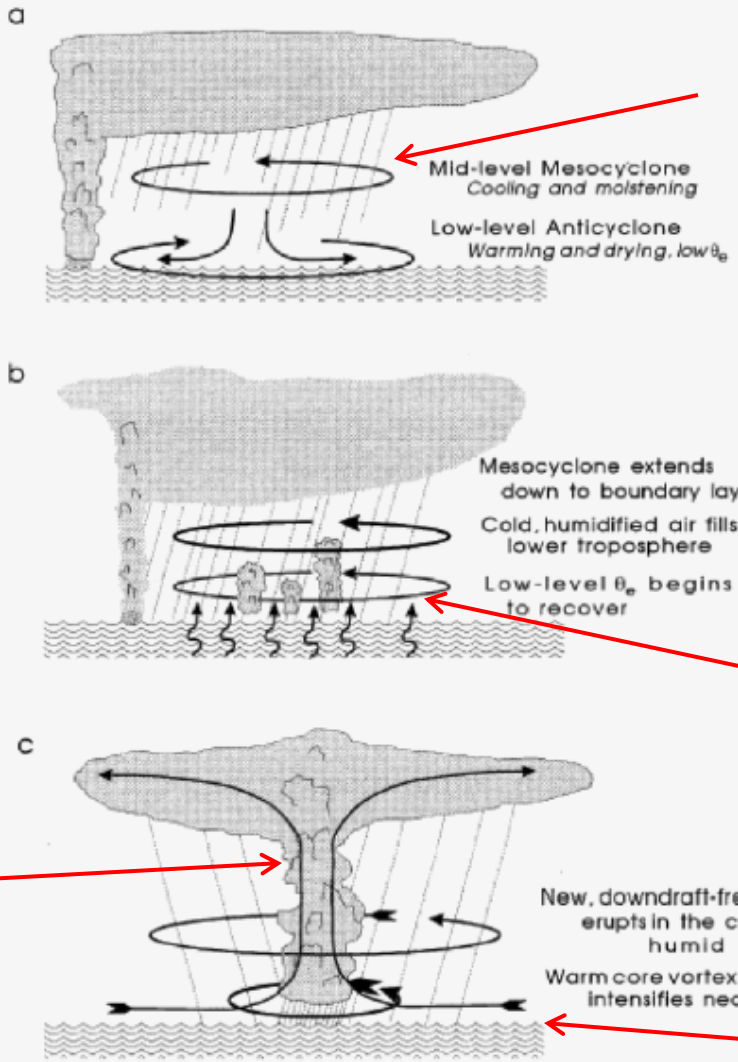


Figure 8. Conceptual model of tropical cyclogenesis from a preexisting MCS. (a) Evaporation of stratiform precipitation cools and moistens the upper part of the lower troposphere; forced subsidence leads to warming and drying of the lower part. (b) After several hours there is a cold and relatively moist 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).

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

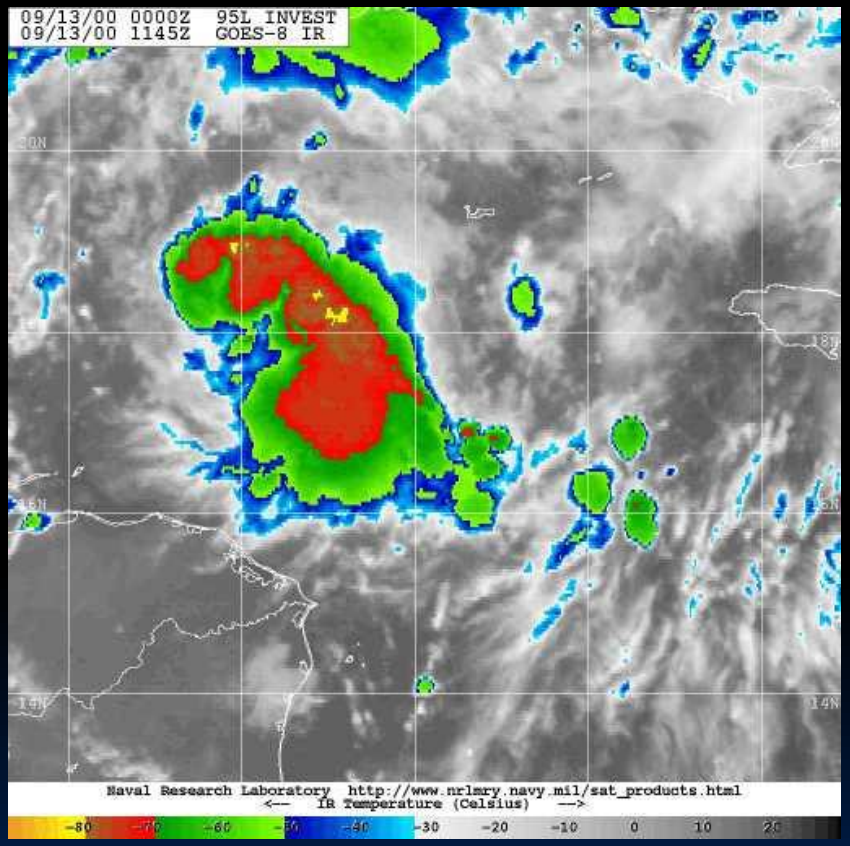
THE TROPOSPHERE MUST BECOME NEARLY SATURATED IN THE VORTEX CORE

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.

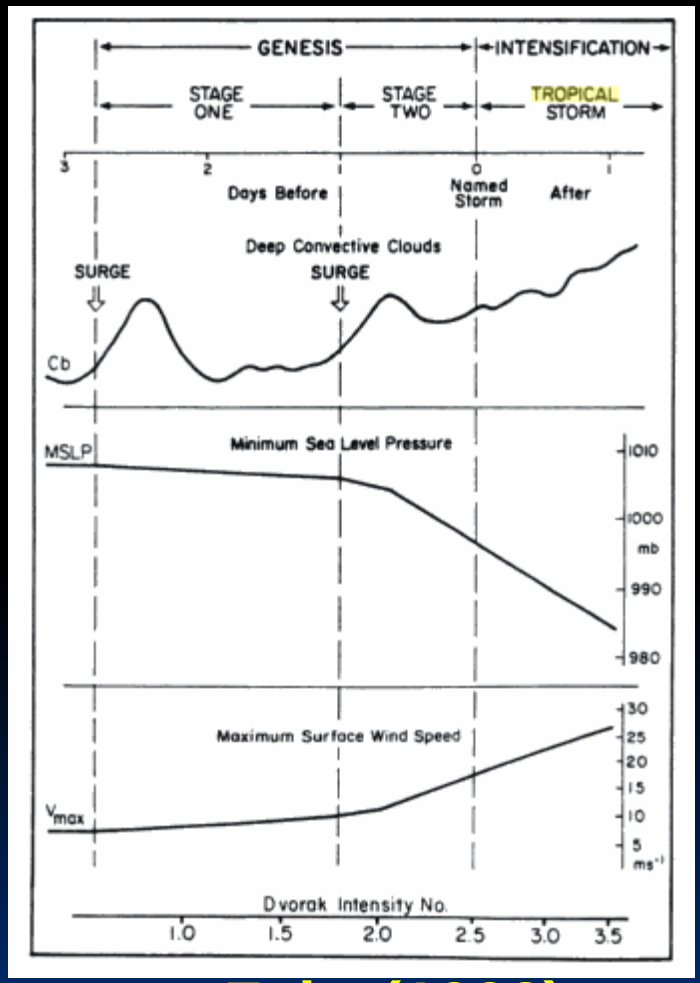
THE ENHANCED SURFACE FLUXES ASSOCIATED WITH STRONG SURFACE WINDS NEAR THE CORE CAN INCREASE THE SUBCLOUD MOIST STATIC ENERGY.

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)



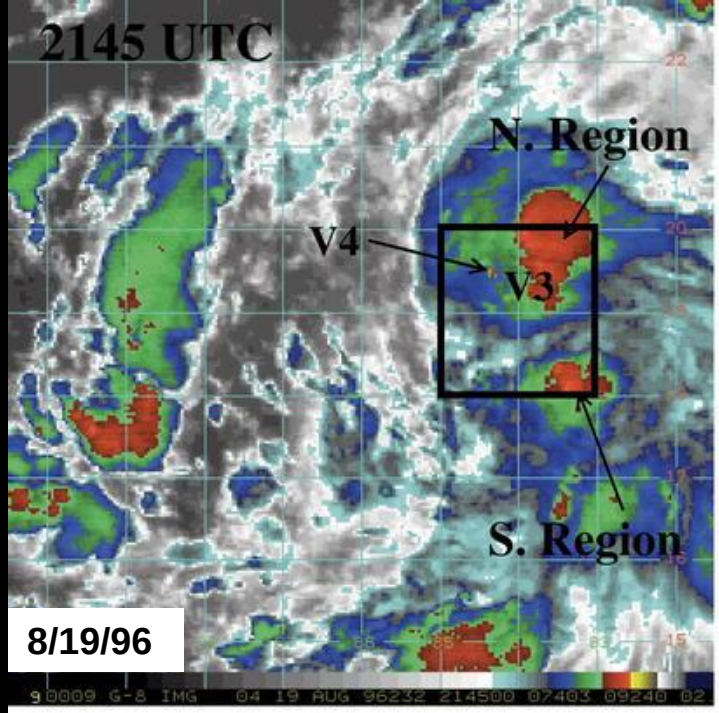
PRE-GORDON DISTURBANCE, 9/13/00 1145 UTC (~24 HOURS PRIOR TO GENESIS)

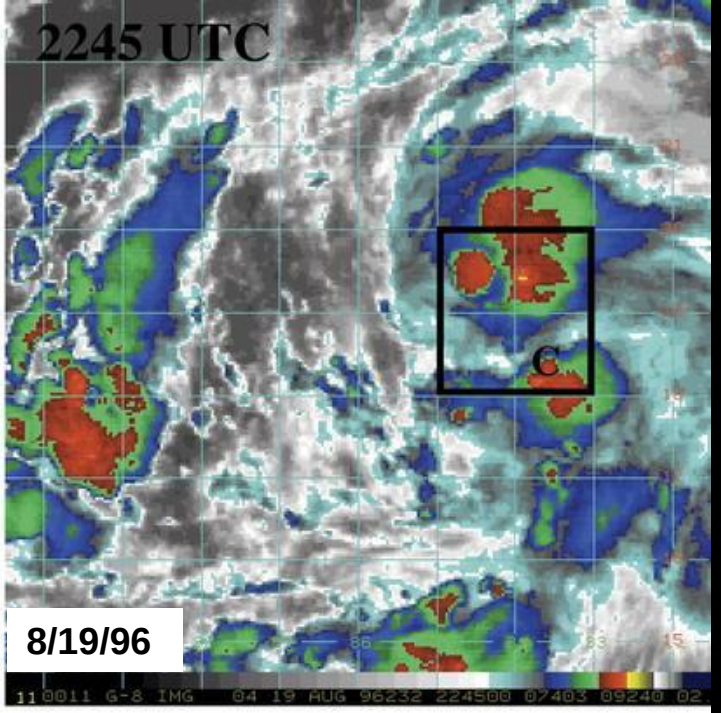


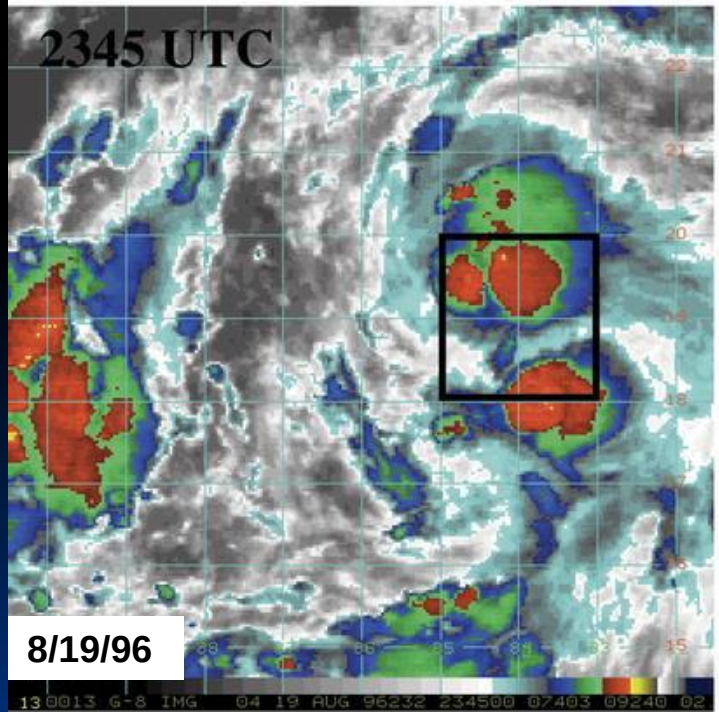
Zehr (1992)

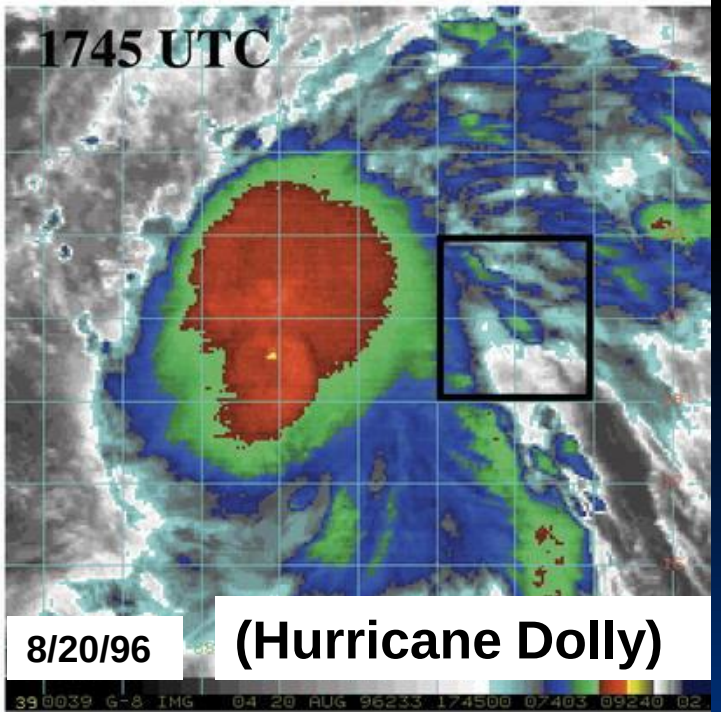
Multiple mid-level mesoscale vortices during genesis stage.

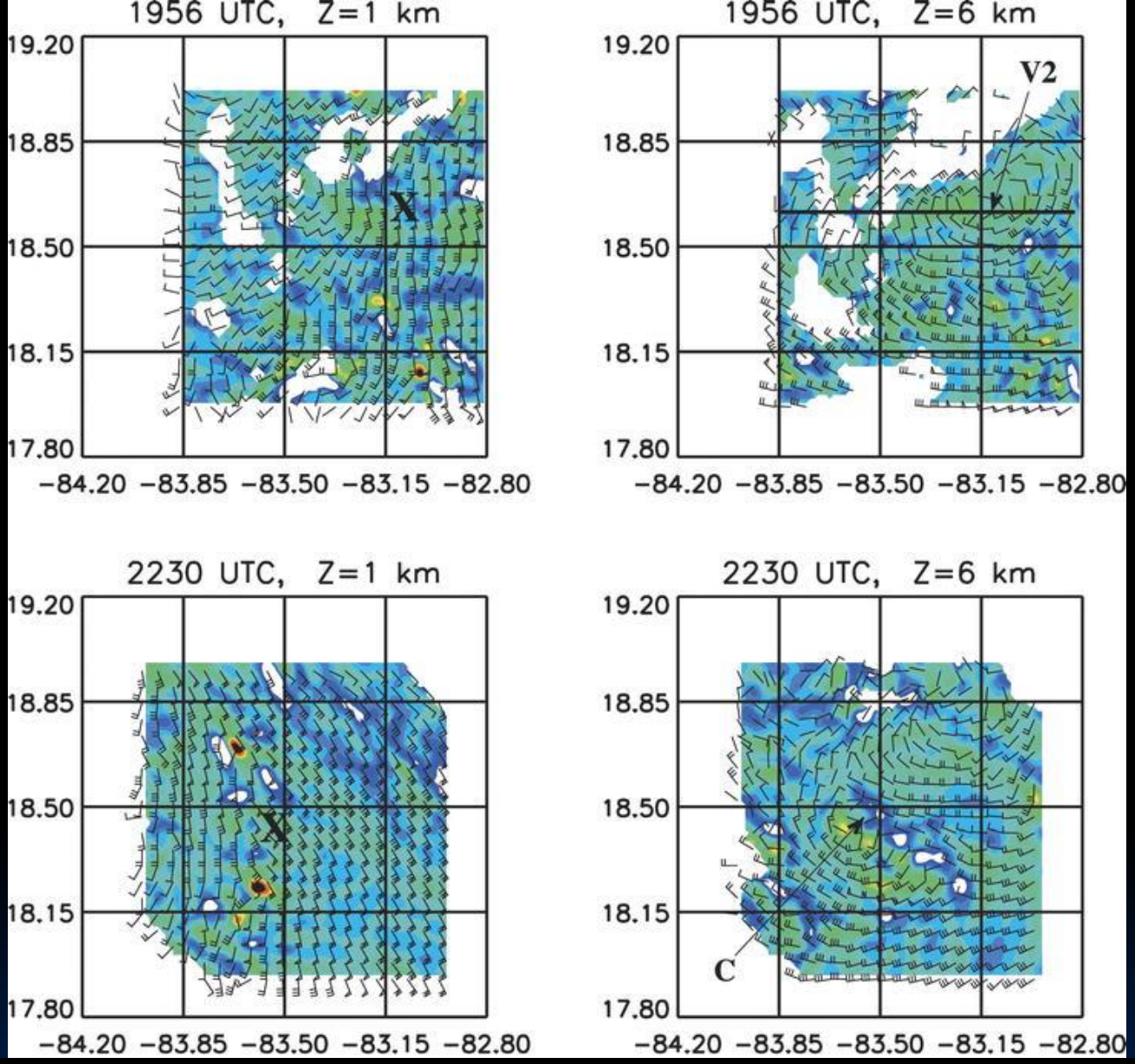
(Reasor et al. 2005 *J. Atmos. Sci.*)







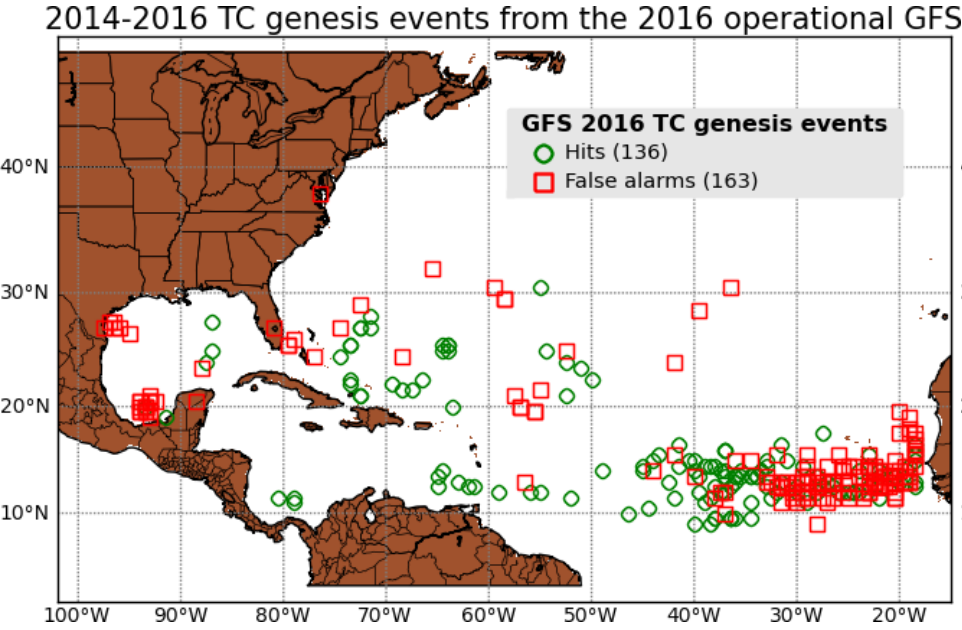


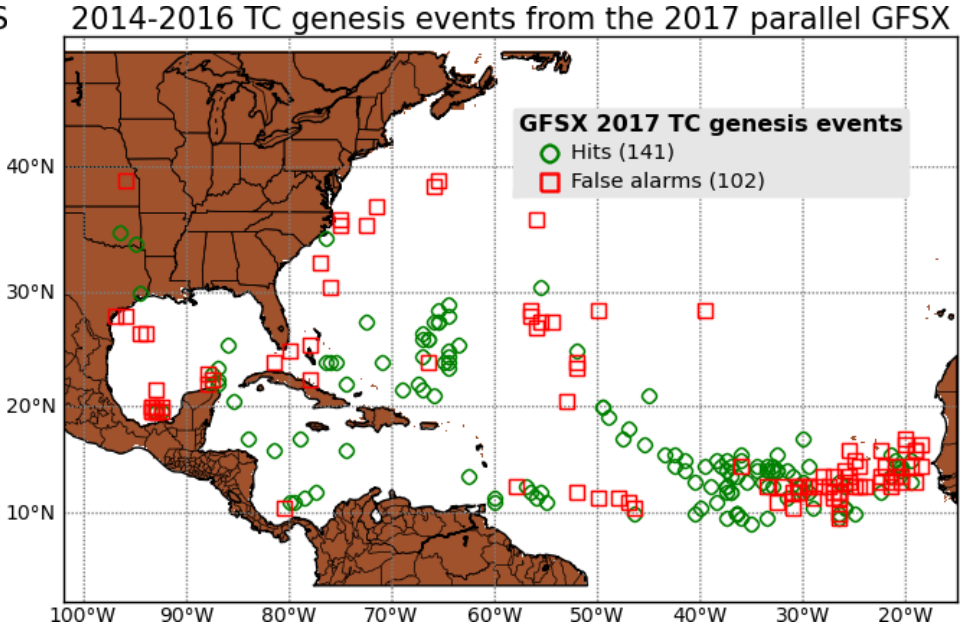


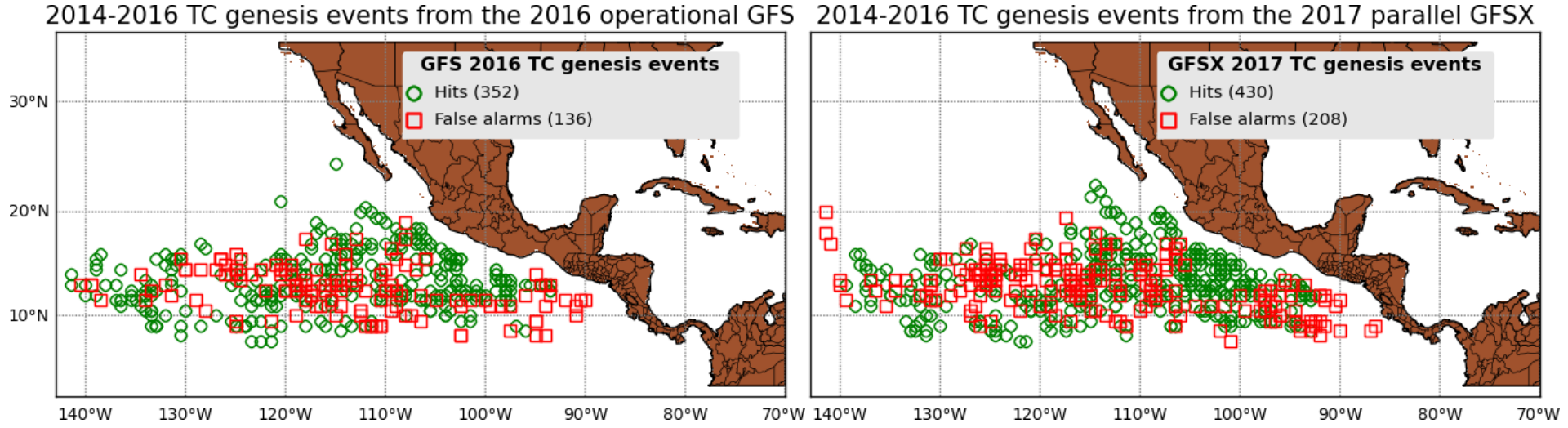
WIND AND VORTICITY WITHIN SOUTHERN CONVECTIVE REGION, 8/19/96

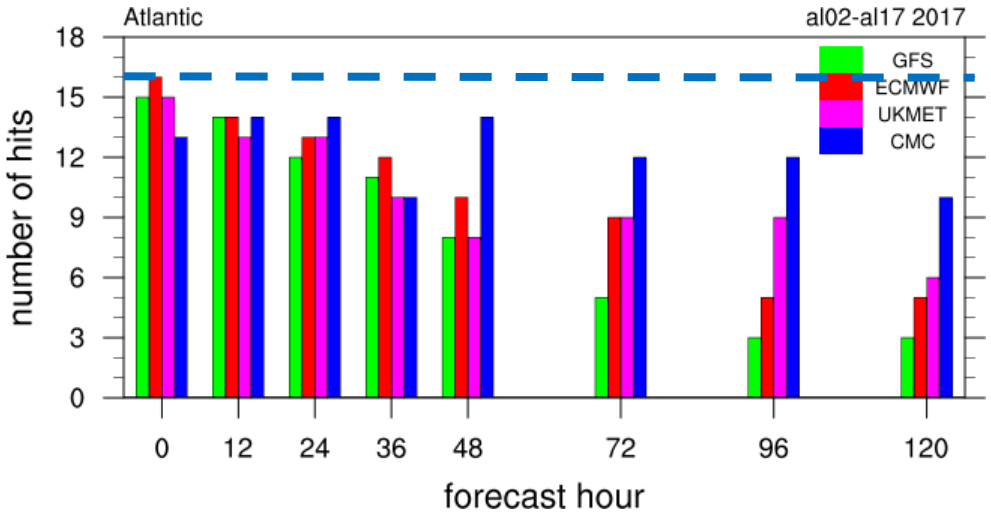
Use of global models relevant for TC genesis forecasting:

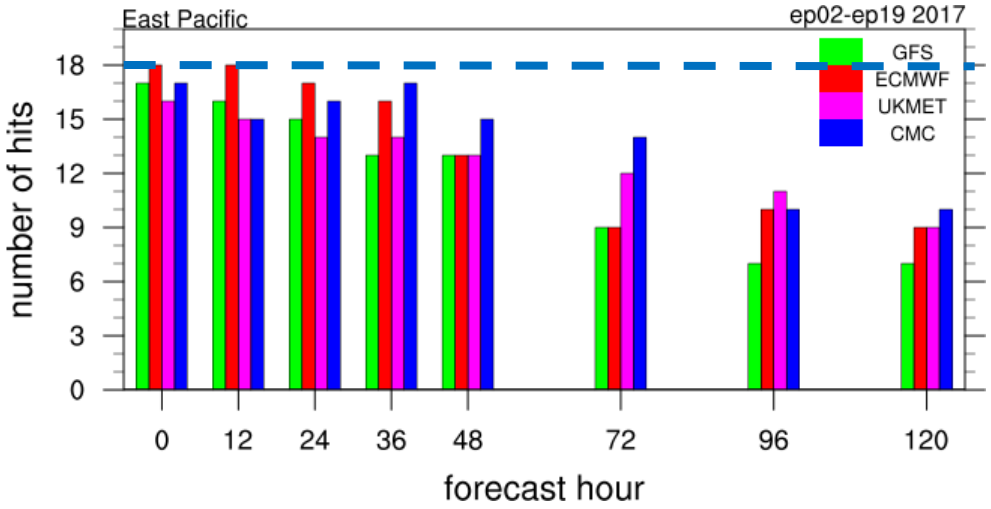
- Global models, especially the ECMWF, GFS, and UKMET along with their ensembles are our primary tool for predicting TC genesis.
- The forecaster looks for consistency among the different models, as well as run-to-run consistency, to assess the likelihood of genesis.
- Recent upgrades to the ECMWF have probably improved that model's performance, but changes to the GFS have apparently degraded its ability to forecast genesis.
- 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
GFS 2016 TC genesis events
Hits (136)
False alarms (163)
40°N
30°N
20°N
10°N
100°W
90°W
80°W
70°W
60°W
50°W
40°W
30°W
20°W


2014-2016 TC genesis events from the 2017 parallel GFSX
GFSX 2017 TC genesis events
Hits (141)
False alarms (102)
40°N
30°N
20°N
10°N
100°W
90°W
80°W
70°W
60°W
50°W
40°W
30°W
20°W


2014-2016 TC genesis events from the 2016 operational GFS
GFS 2016 TC genesis events
Hits (352)
False alarms (136)
30°N
20°N
10°N
140°W
130°W
120°W
110°W
100°W
90°W
80°W
70°W
2014-2016 TC genesis events from the 2017 parallel GFSX
GFSX 2017 TC genesis events
Hits (430)
False alarms (208)
140°W
130°W
120°W
110°W
100°W
90°W
80°W
70°W



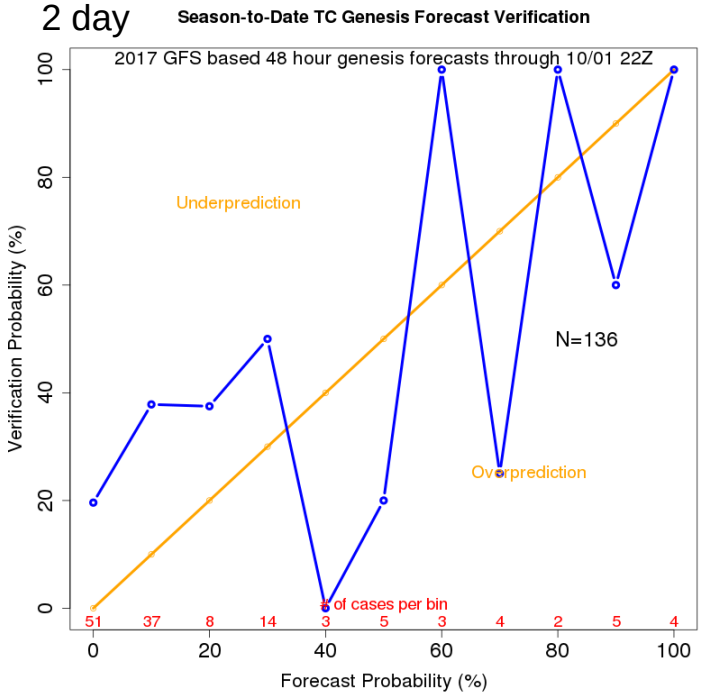


GFS Genesis Problems

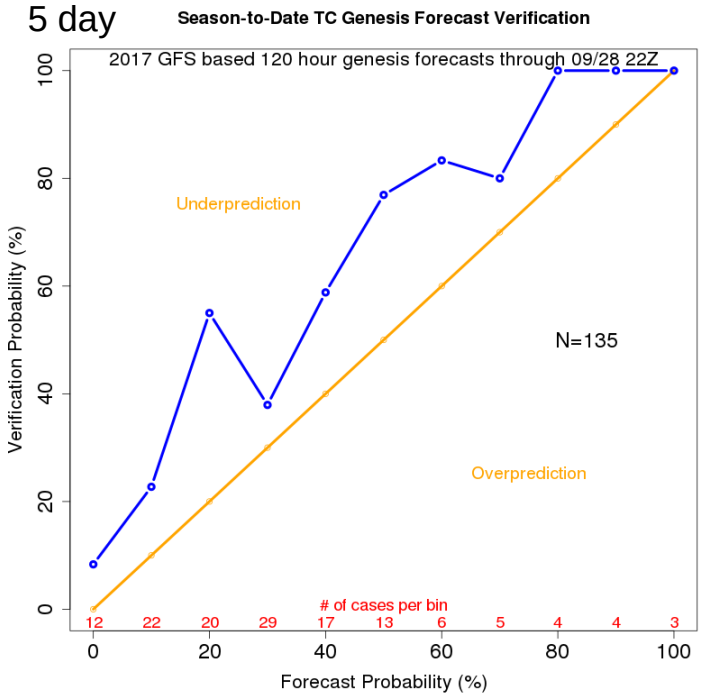
- 2017 GFS had issues with under-predicting genesis at longer time ranges in both basins
  - Atlantic: GFS hit 3 of 16 genesis events at 120 h (19%)
  - East Pacific: GFS hit 7 of 18 genesis events at 120 h (39%)
- GFS forecast only half of Atlantic TC formations 48 h in advance
- East Pacific better in the short range – GFS hit 13 out of 18 events at 48 h (72%)

Atlantic GFS Genesis Forecasts

2 day



5 day



2-day "High" Forecasts
GFS: 15
NHC: 45

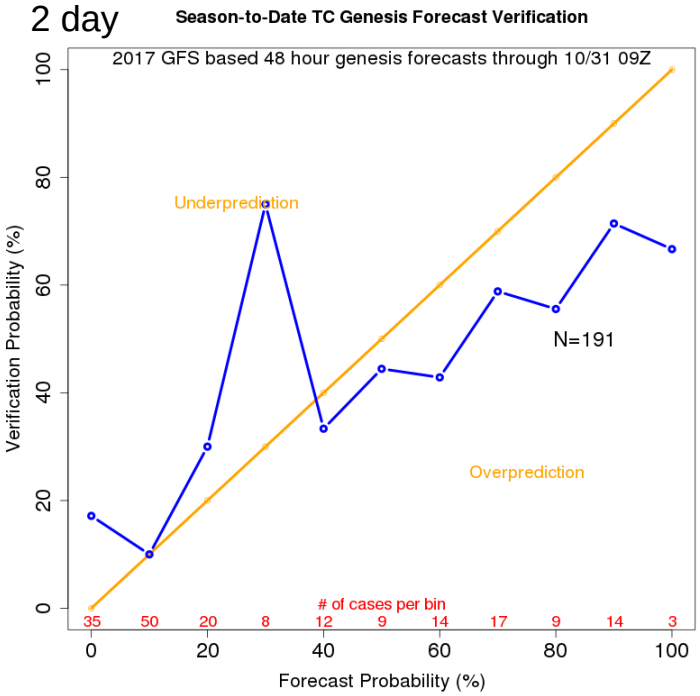
5-day "High" Forecasts
GFS: 16
NHC: 89

Preliminary results courtesy of Dan Halperin

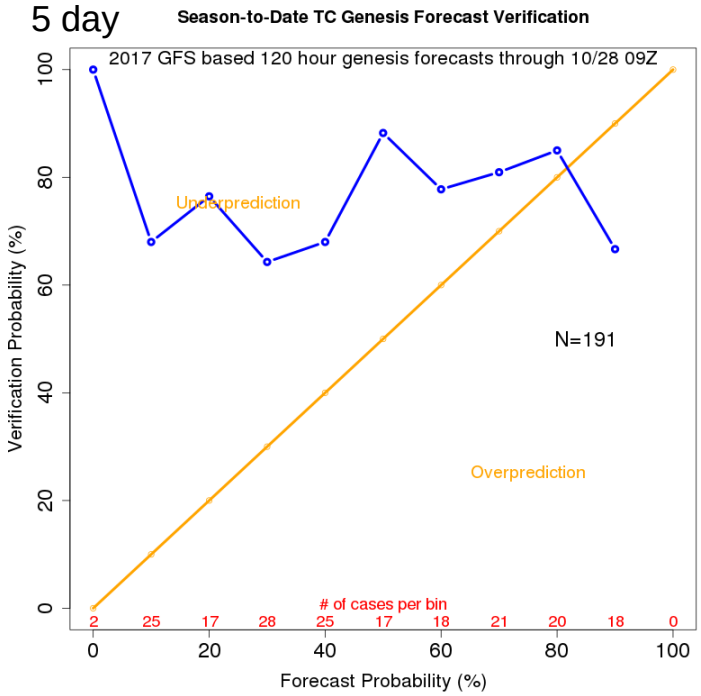
- 2-day GFS genesis forecasts had a lot of noise – low probabilities had an under-forecast bias; sample quite small at 40% and above
- 5-day results smoother, but persistent 10-20% under-forecast bias for most probabilities

East Pacific GFS Genesis Forecasts

2 day



5 day



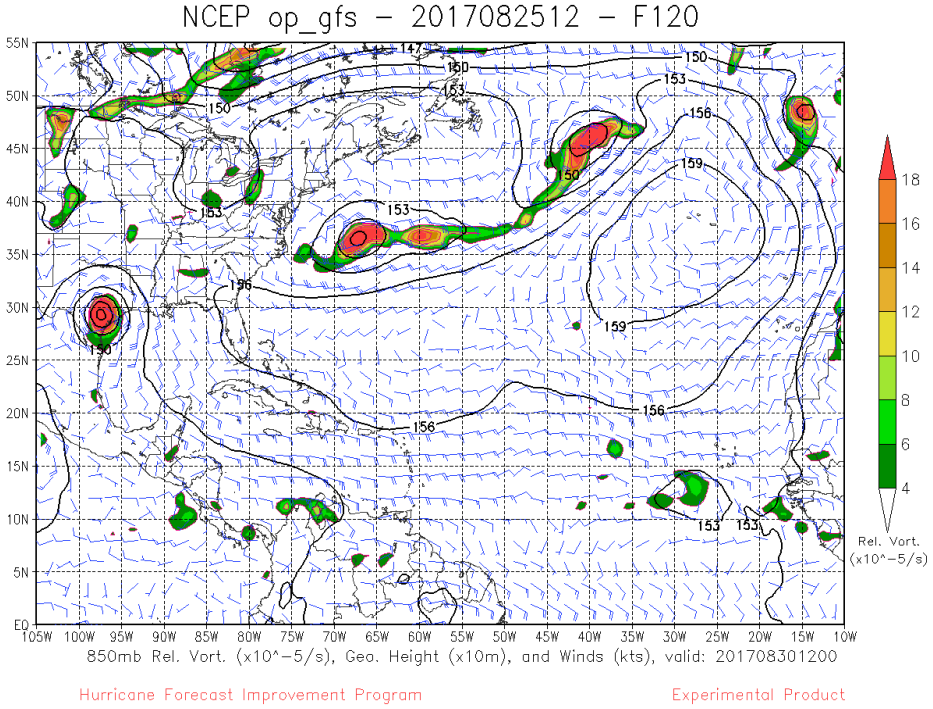
2-day "High" Forecasts
GFS: 43
NHC: 52

5-day "High" Forecasts
GFS: 59
NHC: 111

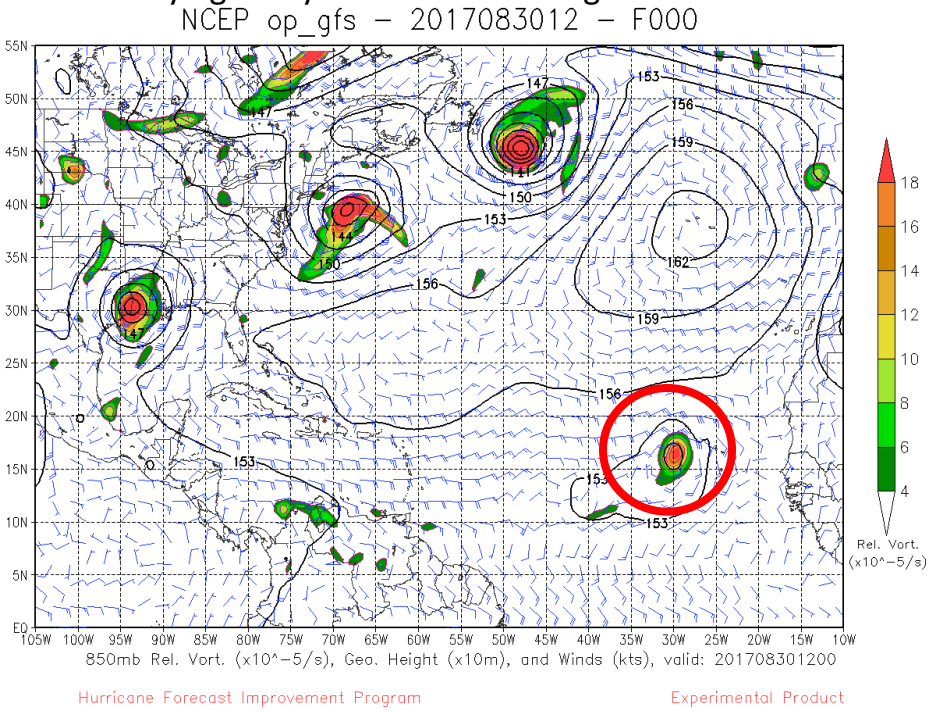
Preliminary results courtesy of Dan Halperin

- 2-day GFS genesis forecasts generally OK, but a big low bias around 30%
- 5-day results terrible – huge under-forecasts at low to medium probability ranges!

GFS Genesis Example – Irma

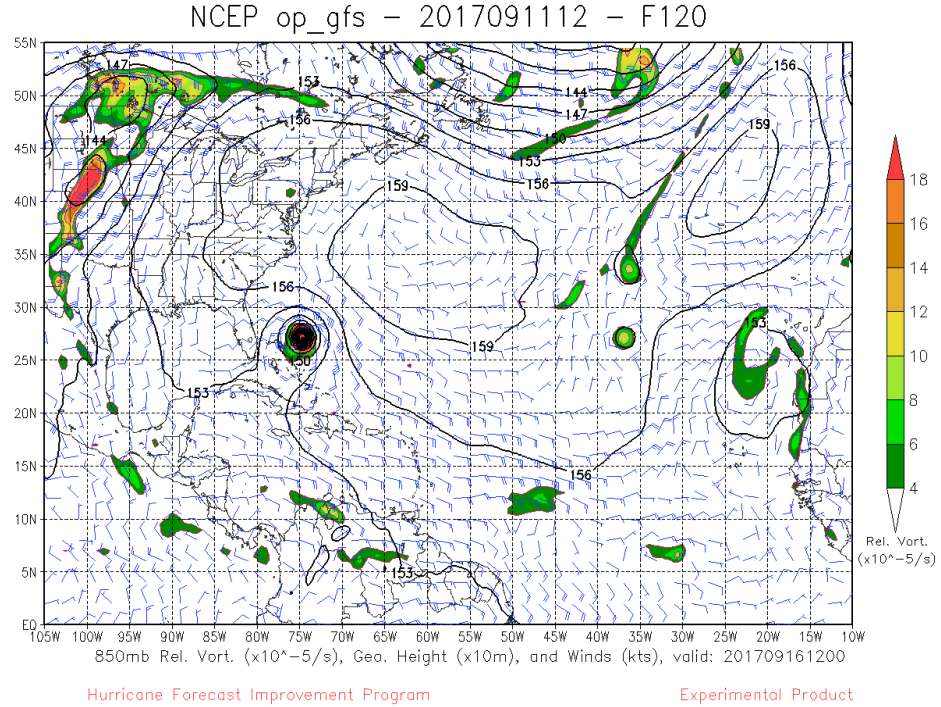


Verifying Analysis – 12 UTC 30 August 2017

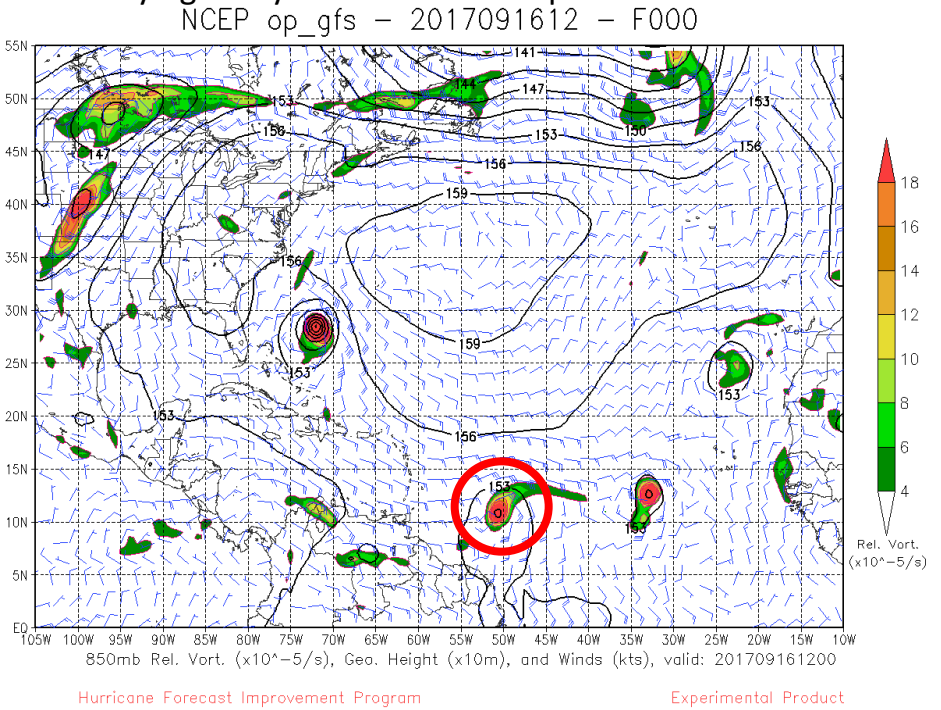


Some signal early (4-5 days), but signal weakened inside of 60 hours until genesis

GFS Genesis Example – Maria

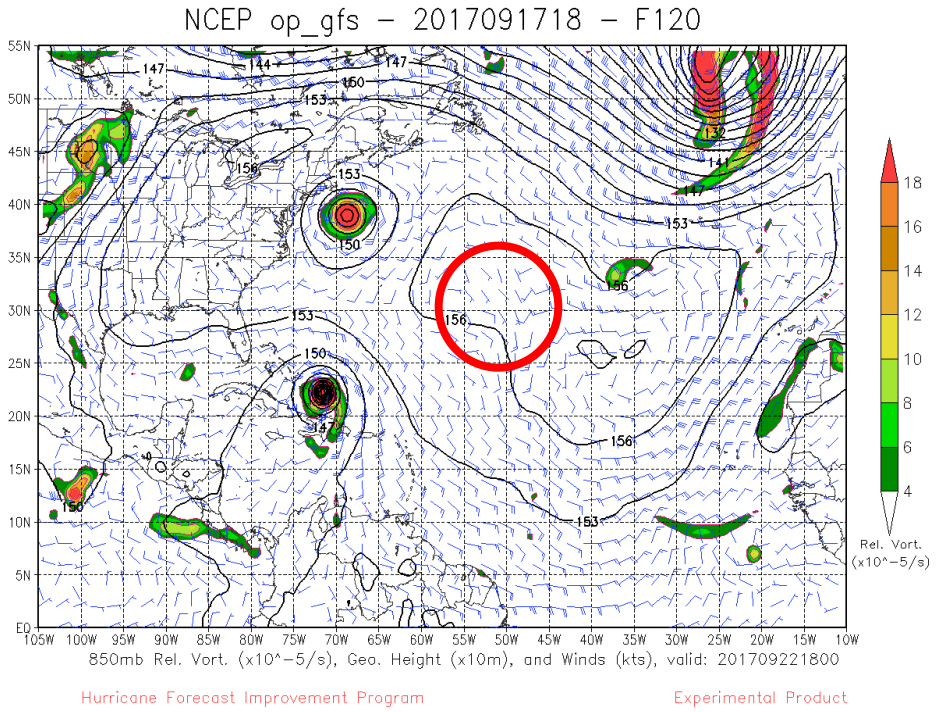


Verifying Analysis – 12 UTC 16 September 2017

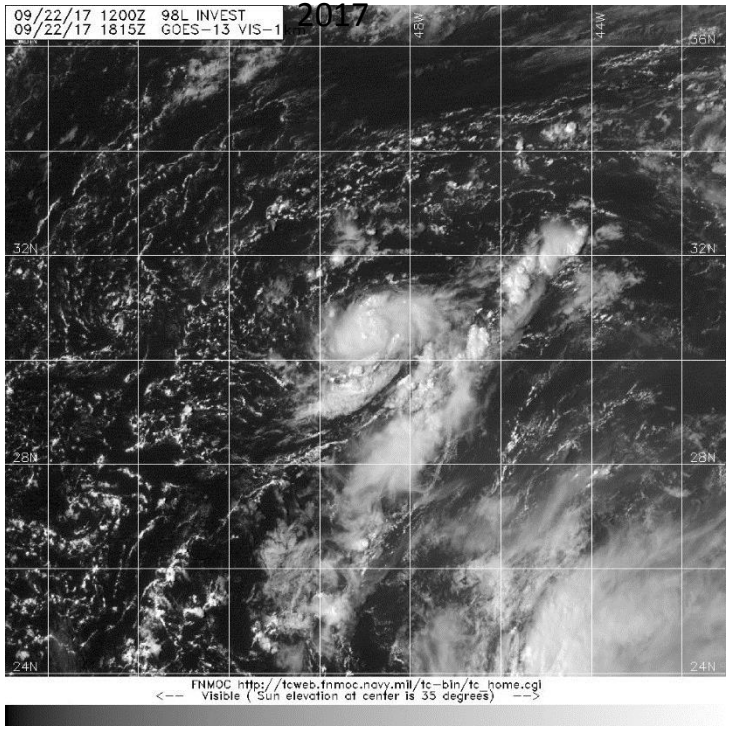


Weak/No signal until 42 h prior to genesis

GFS Genesis Example – Lee (Genesis #2)



GOES-13 Visible Imagery – 1815 UTC 22 September 2017



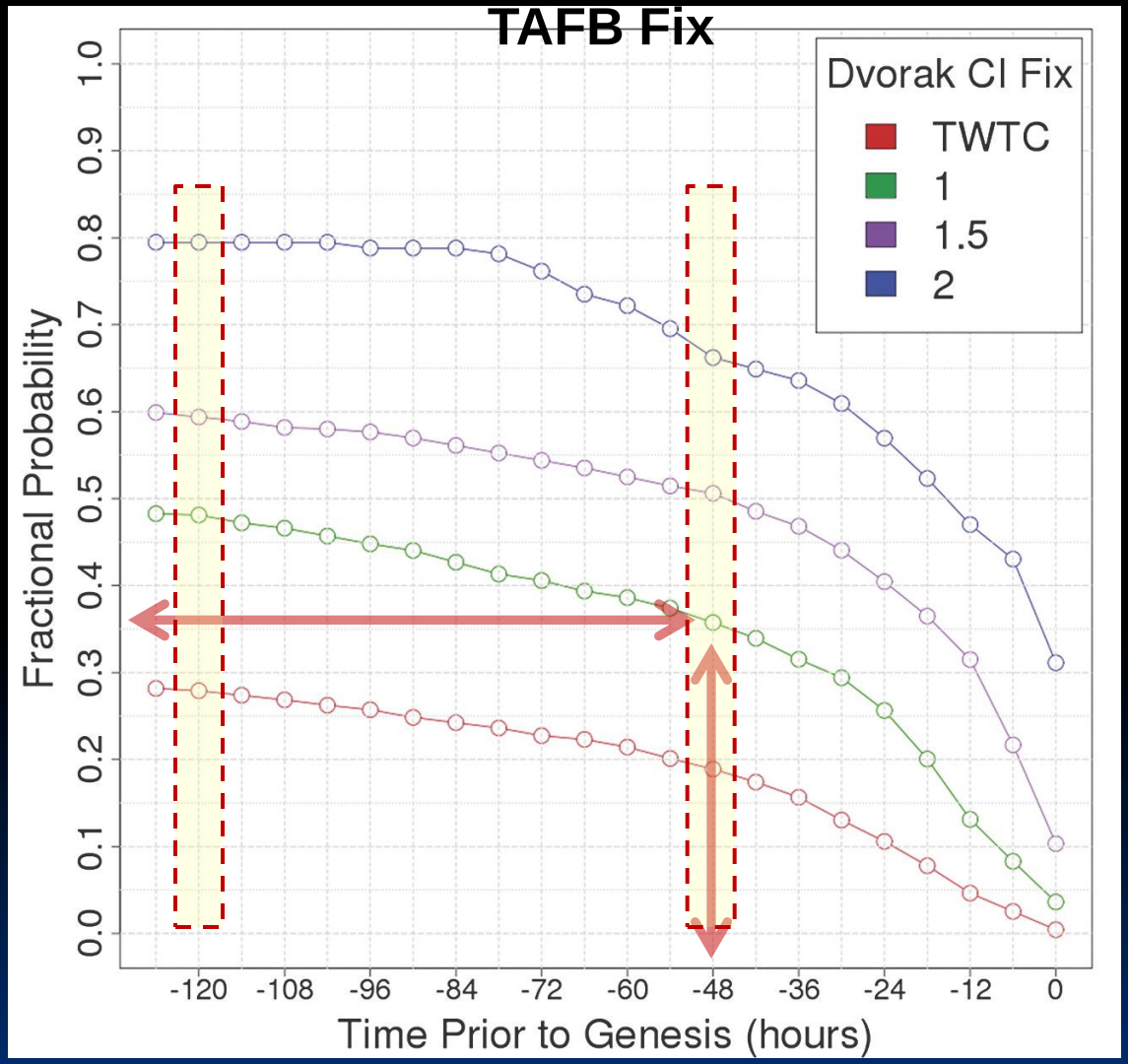
Little/No Signal Prior to Genesis

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

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

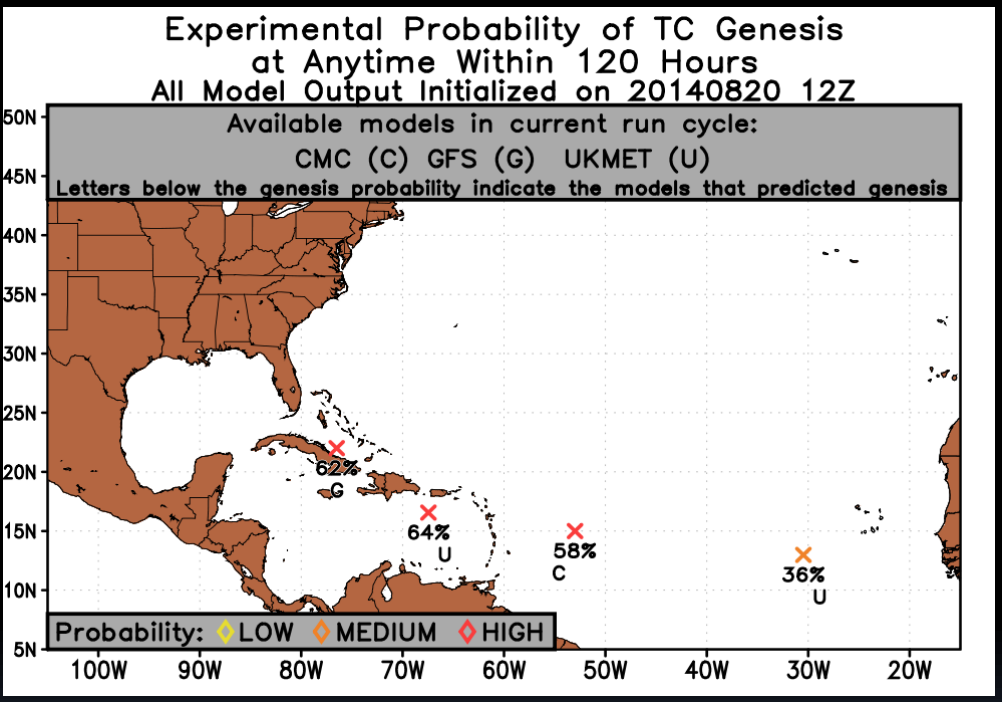
Genesis Probability by Dvorak Number

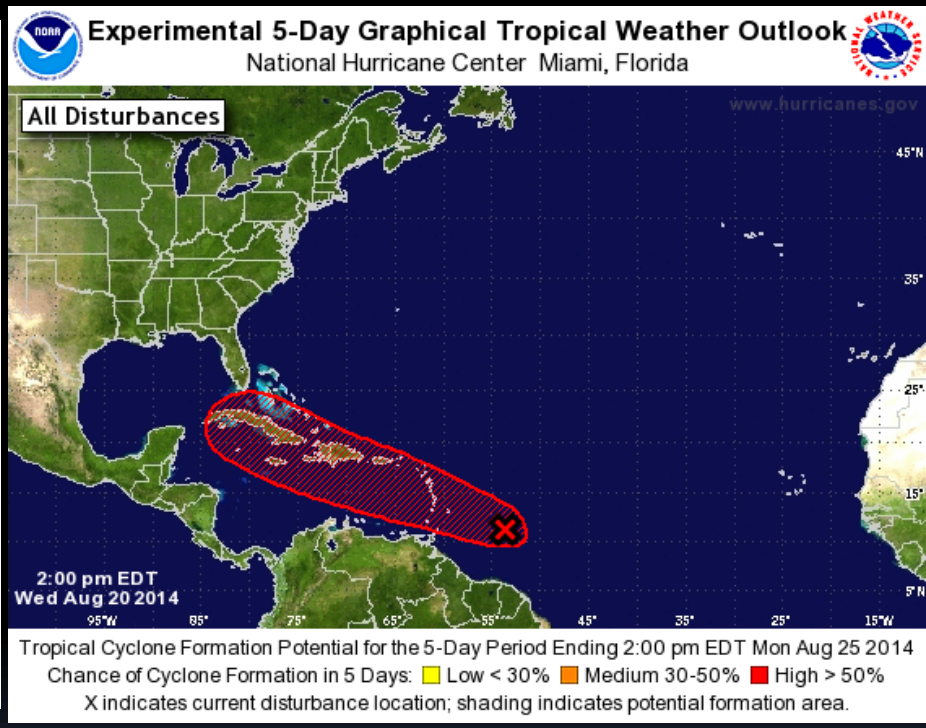
- Uses Dvorak intensity estimates from all invests/disturbances (both developing and non-developing) from 2001-2011.
- Example: Invest with a 1.0 TAFB CI Number has 35% chance of genesis within 48 h.
- Real-time guidance at moe.met.fsu.edu/genesis
- More information in Cossuth et al. (Wea. & Forecasting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



FSU Guidance

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

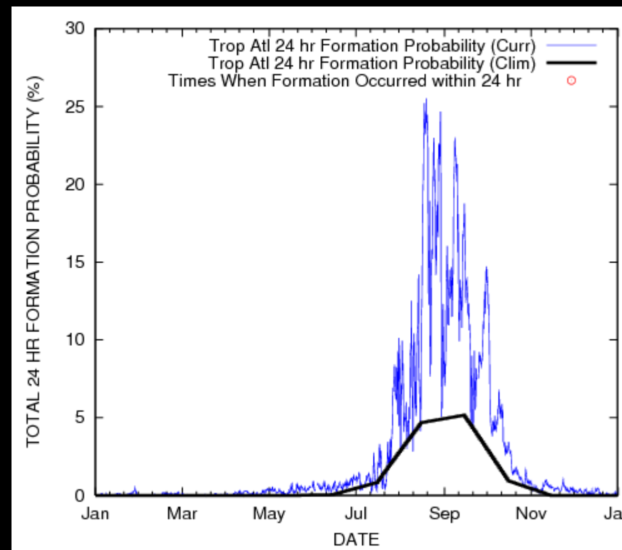


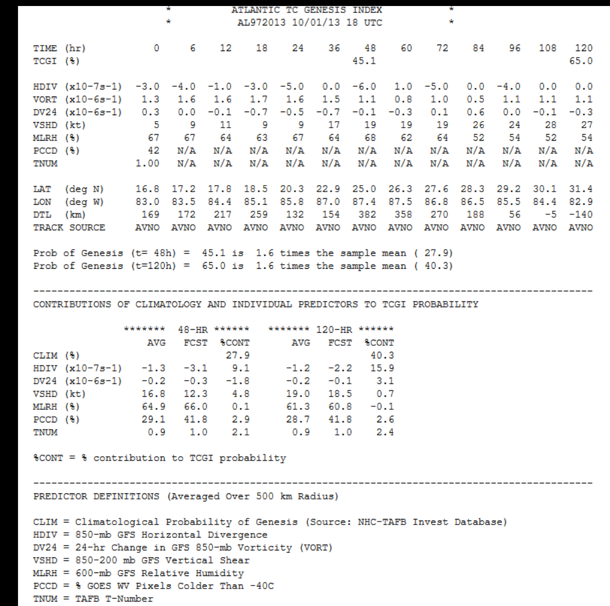


- **Best objective genesis guidance to date**
- **Uses statistics on dynamical model forecasts of genesis to develop probabilities**
- **Multi-model consensus gives most reliable forecasts**
- **Scheme provides guidance on many more systems than are mentioned in the TWO**

Other Tools

- **CIRA Tropical cyclone-based formation probabilities: http://www.ssd.noaa.gov/PS/TROP/TCFP/index.html**
- **Ensemble-based probabilities generated (use consensus of this?)**
- **Several projects (e.g. Joint Hurricane Testbed), with the goal to provide objective genesis guidance**





* ATLANTIC TC GENESIS INDEX *
* AL972013 10/01/13 18 UTC *

TIME (hr)	0	6	12	18	24	36	48	60	72	84	96	108	120
TCGI (%)							45.1						65.0
HDIV (x10-7s-1)	-3.0	-4.0	-1.0	-3.0	-5.0	0.0	-6.0	1.0	-5.0	0.0	-4.0	0.0	0.0
VORT (x10-6s-1)	1.3	1.6	1.6	1.7	1.6	1.5	1.1	0.8	1.0	0.5	1.1	1.1	1.1
DV24 (x10-6s-1)	0.3	0.0	-0.1	-0.7	-0.5	-0.7	-0.1	-0.3	0.1	0.6	0.0	-0.1	-0.3
VSHD (kt)	5	9	11	9	9	17	19	19	19	26	24	28	27
MLRH (%)	67	67	64	63	67	64	68	62	64	52	54	52	54
PCCD (%)	42	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
TNUM	1.00	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
LAT (deg N)	16.8	17.2	17.8	18.5	20.3	22.9	25.0	26.3	27.6	28.3	29.2	30.1	31.4
LON (deg W)	83.0	83.5	84.4	85.1	85.8	87.0	87.4	87.5	86.8	86.5	85.5	84.4	82.9
DTL (km)	169	172	217	259	132	154	382	358	270	188	56	-5	-140
TRACK SOURCE	AVNO	AVNO	AVNO	AVNO	AVNO	AVNO	AVNO	AVNO	AVNO	AVNO	AVNO	AVNO	AVNO

Prob of Genesis (t= 48h) = 45.1 is 1.6 times the sample mean (27.9)
Prob of Genesis (t=120h) = 65.0 is 1.6 times the sample mean (40.3)

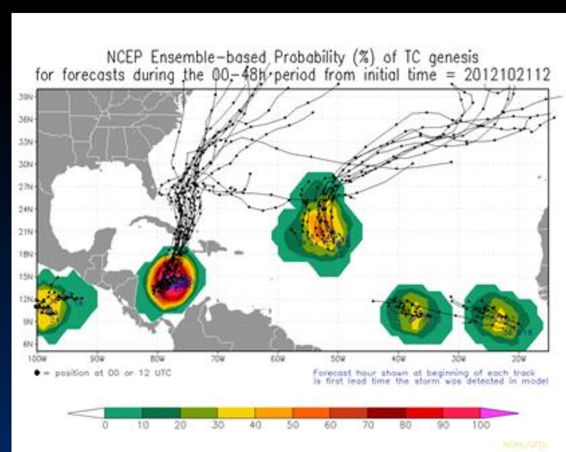
CONTRIBUTIONS OF CLIMATOLOGY AND INDIVIDUAL PREDICTORS TO TCGI PROBABILITY

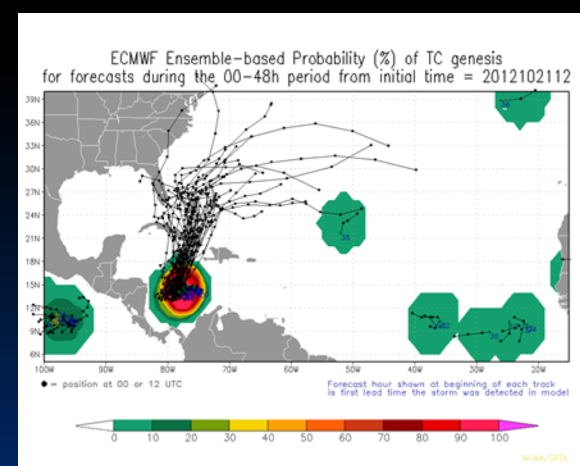
	******* 48-HR ******			******* 120-HR ******		
	AVG	FCST	%CONT	AVG	FCST	%CONT
CLIM (%)			27.9			40.3
HDIV (x10-7s-1)	-1.3	-3.1	9.1	-1.2	-2.2	15.9
DV24 (x10-6s-1)	-0.2	-0.3	-1.8	-0.2	-0.1	3.1
VSHD (kt)	16.8	12.3	4.8	19.0	18.5	0.7
MLRH (%)	64.9	66.0	0.1	61.3	60.8	-0.1
PCCD (%)	29.1	41.8	2.9	28.7	41.8	2.6
TNUM	0.9	1.0	2.1	0.9	1.0	2.4

%CONT = % contribution to TCGI probability

PREDICTOR DEFINITIONS (Averaged Over 500 km Radius)

CLIM = Climatological Probability of Genesis (Source: NHC-TAFB Invest Database)
HDIV = 850-mb GFS Horizontal Divergence
DV24 = 24-hr Change in GFS 850-mb Vorticity (VORT)
VSHD = 850-200 mb GFS Vertical Shear
MLRH = 600-mb GFS Relative Humidity
PCCD = % GOES WV Pixels Colder Than -40C
TNUM = TAFB T-Number





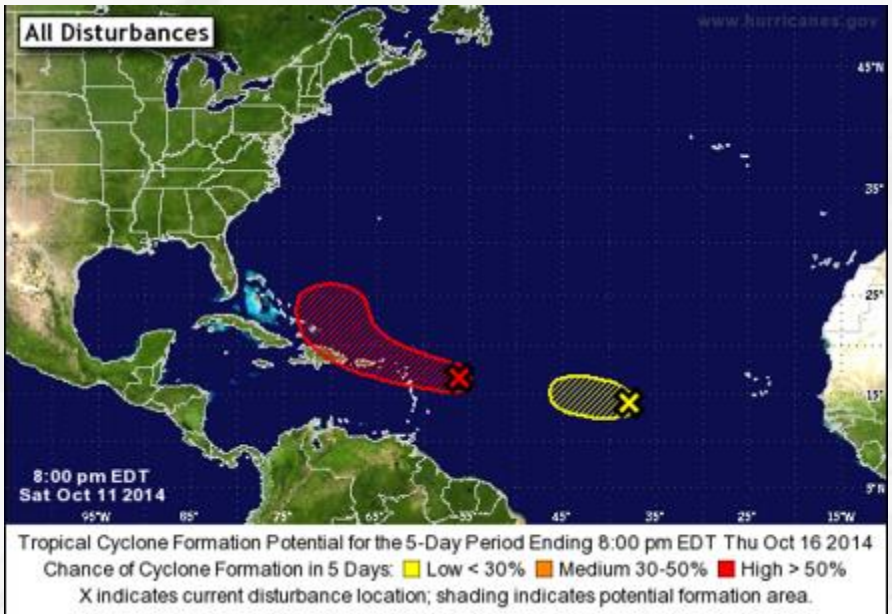
NHC Tropical Weather Outlook

- 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

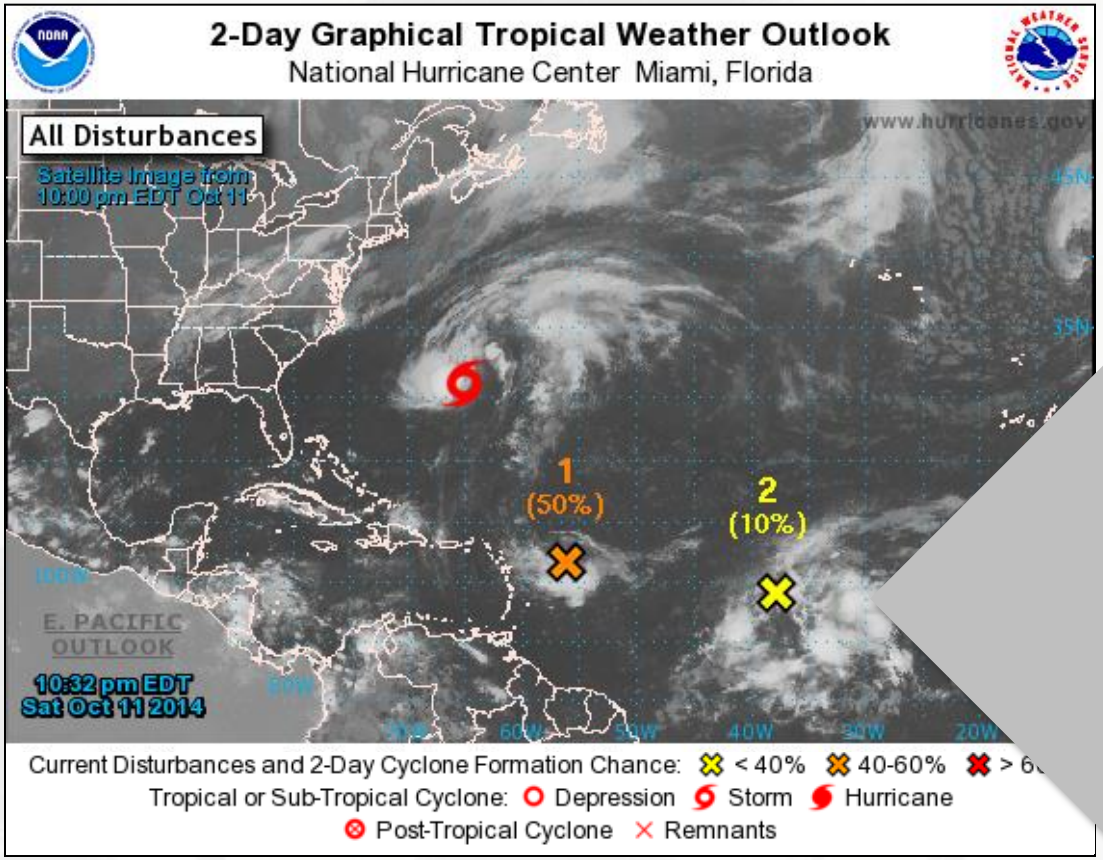
Tropical Weather Outlook Text

```
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



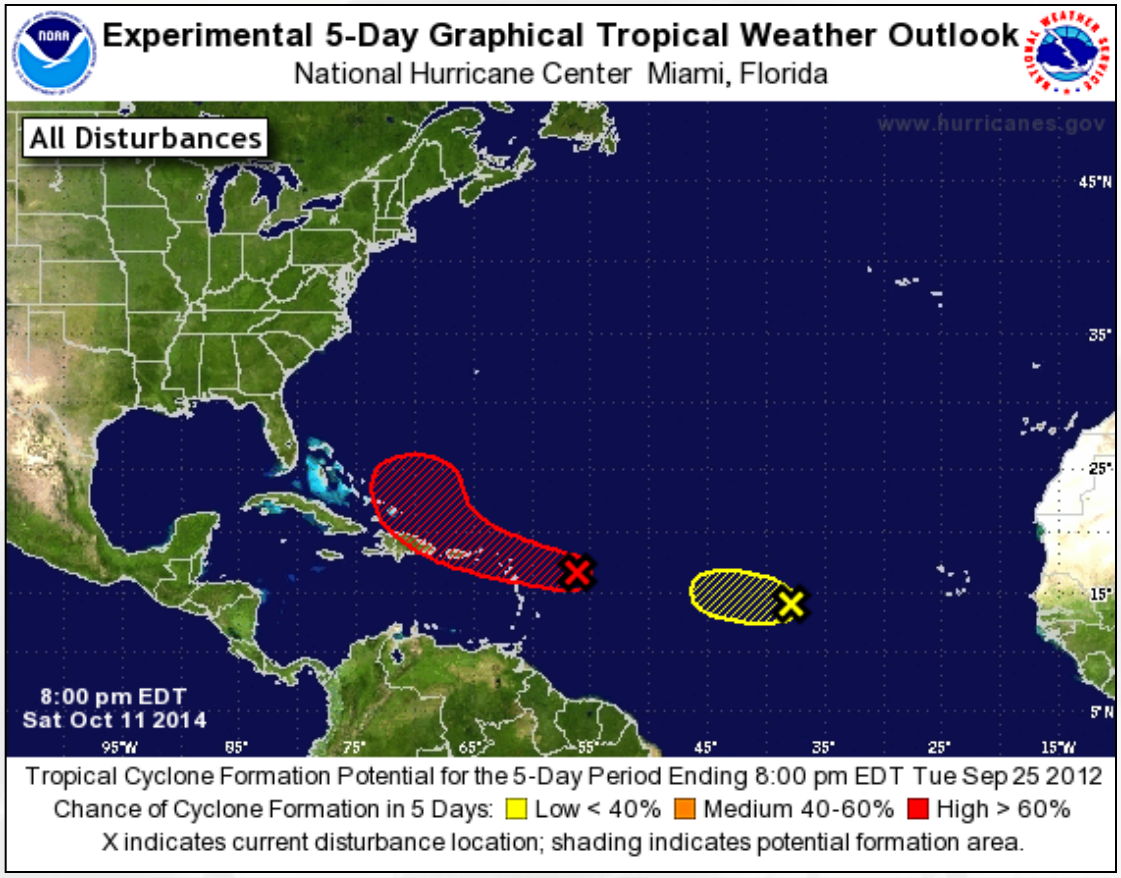
Identifies <u>current</u> location of disturbed weather
(discussed in the Tropical Weather Outlook)

Formation chance during the next 48 hours

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

Graphical Tropical Outlook

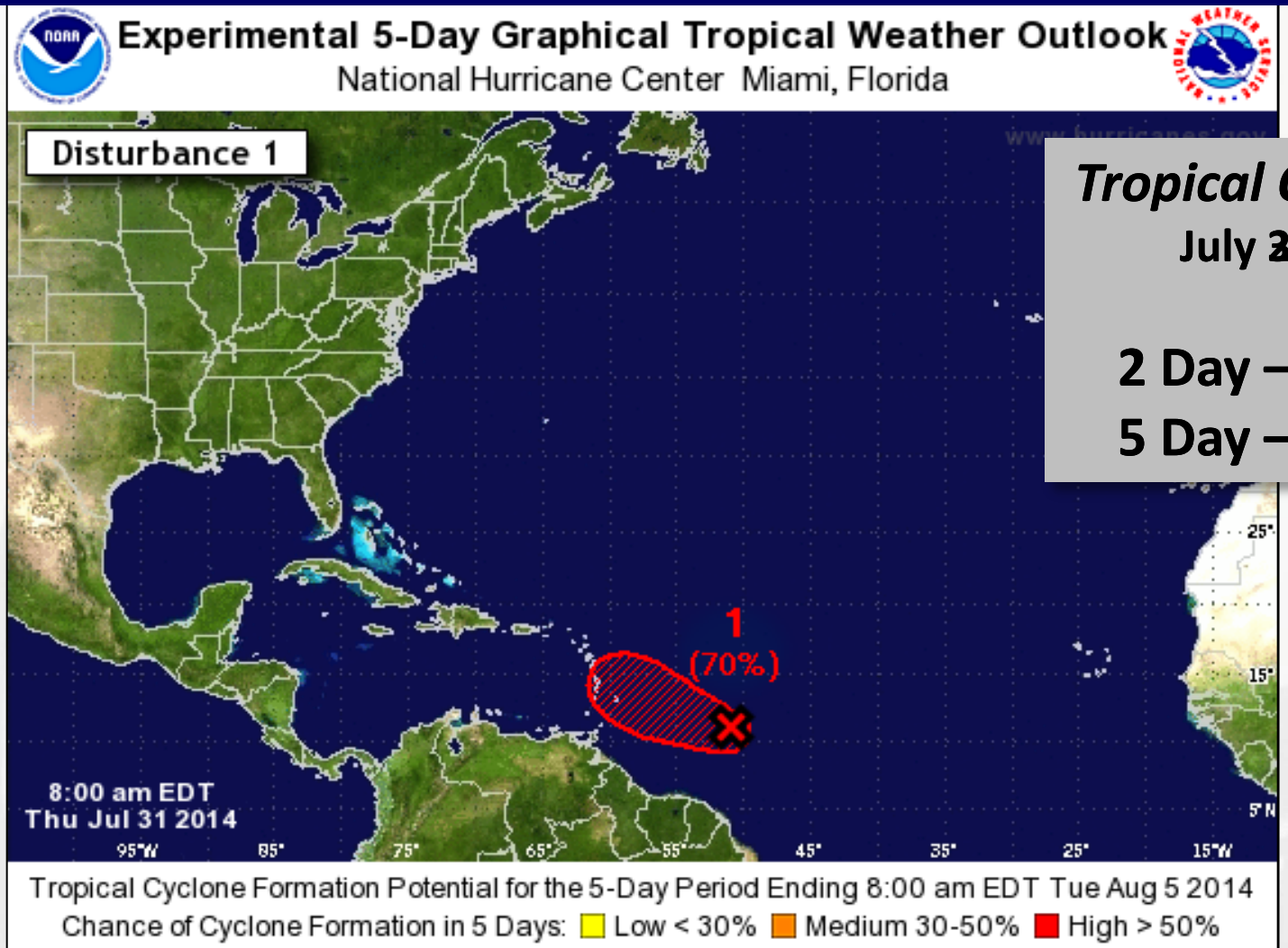
5-Day Formation Potential



- 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



Tropical Outlook

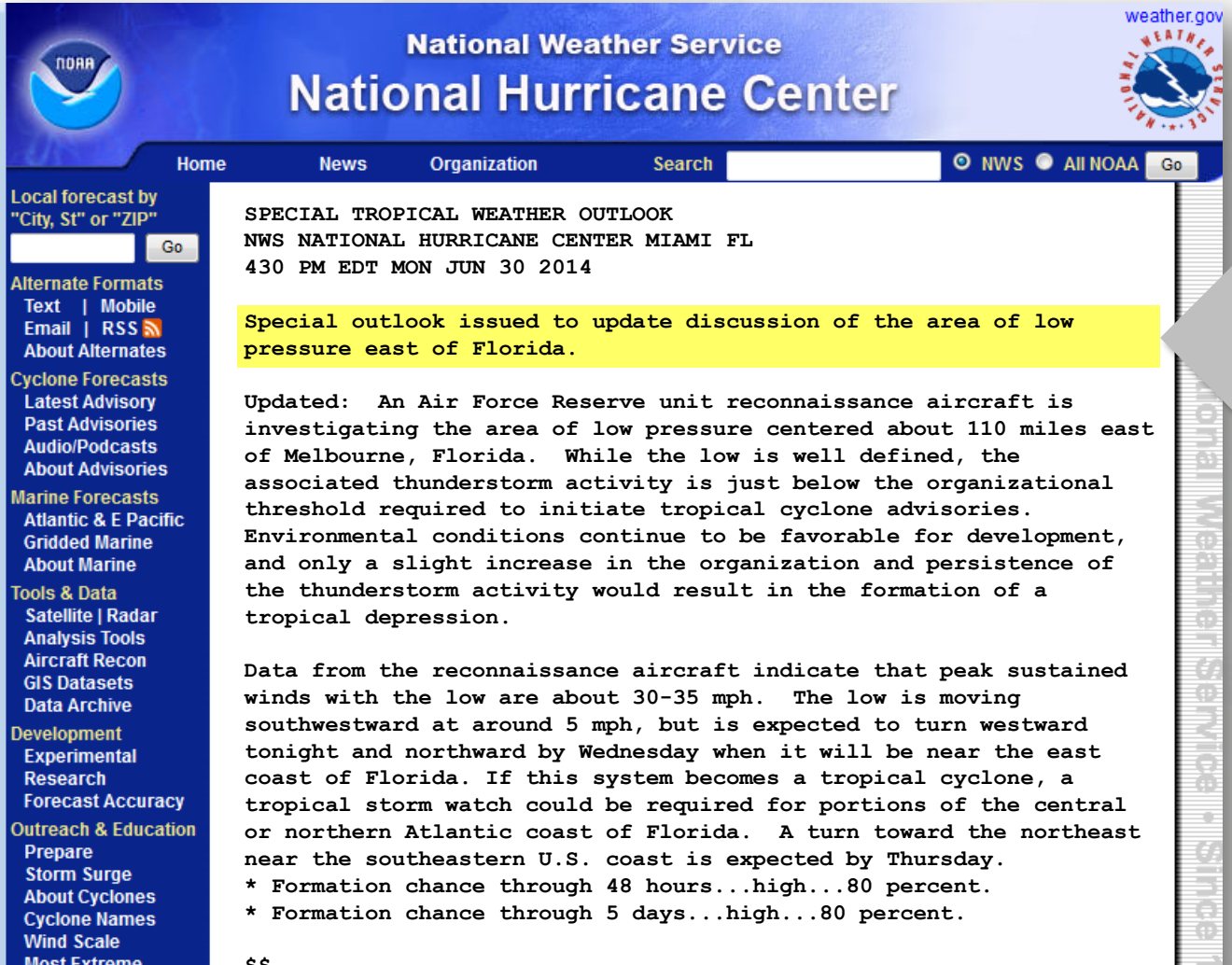
July 28 @ 8am

2 Day – 30%

5 Day – 70%

Special Tropical Outlook

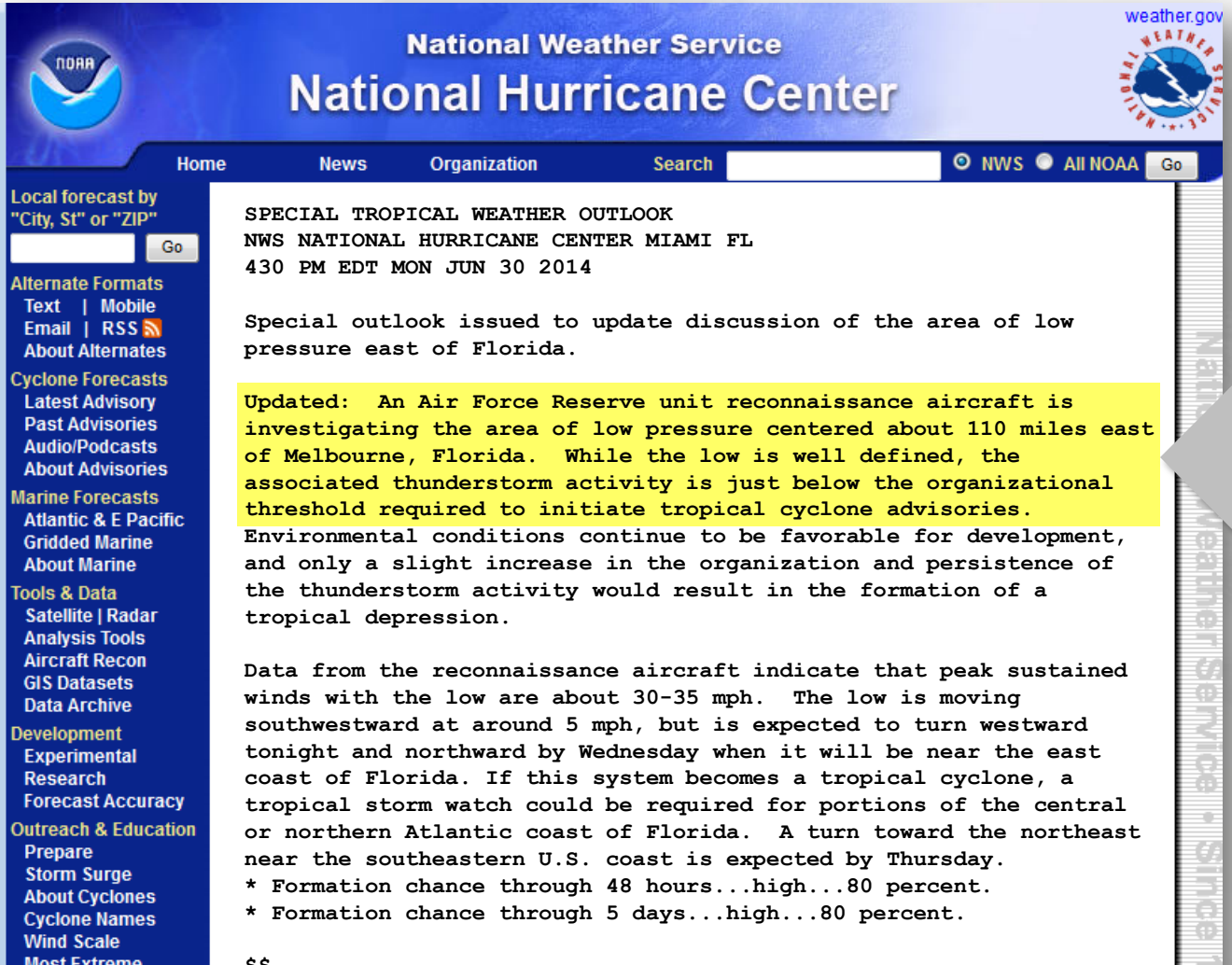
Significant or unexpected changes.



What is the special outlook issued for?

Special Tropical Outlook

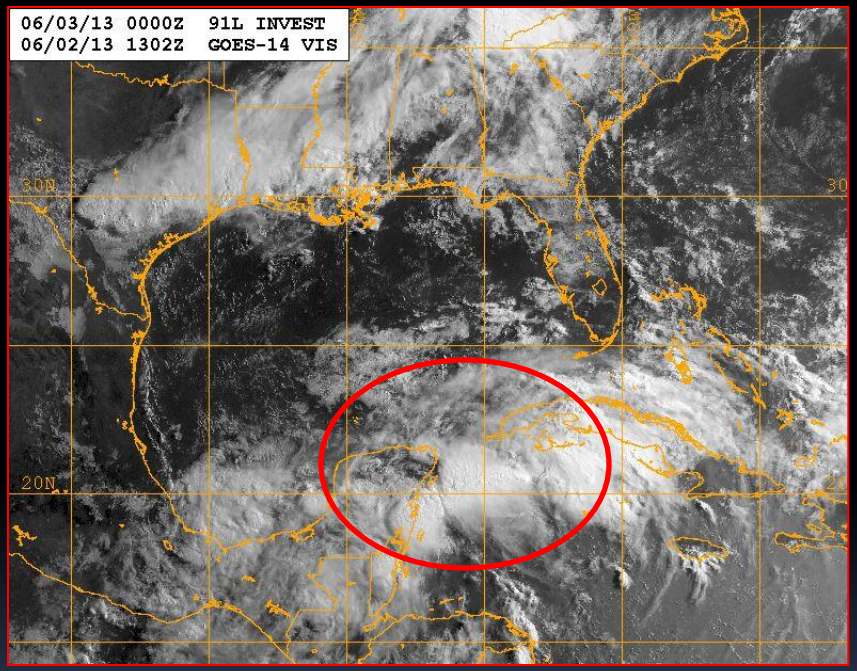
Significant or unexpected changes.



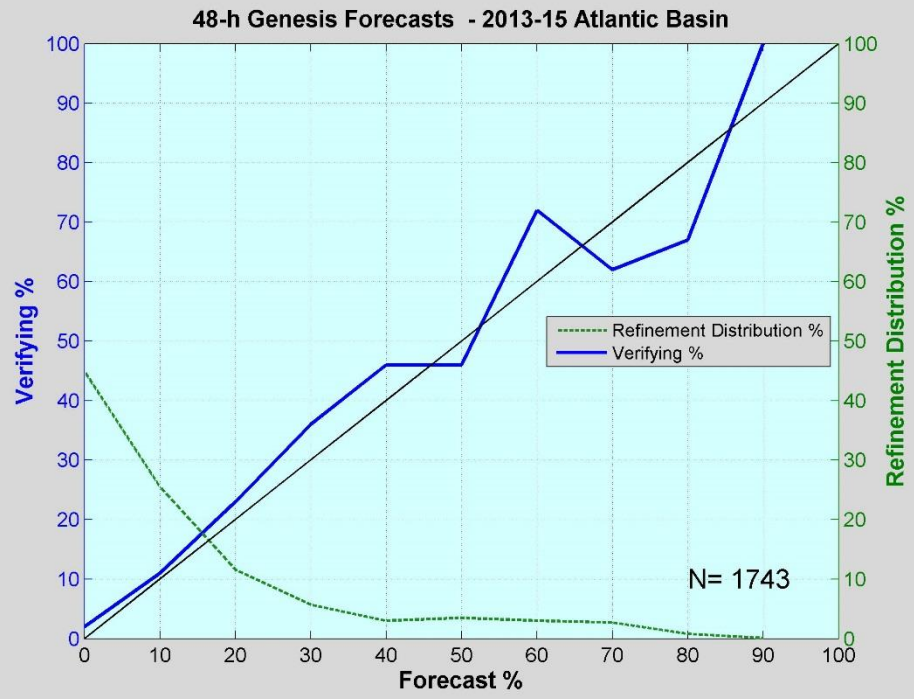
What's the new information? Aircraft?

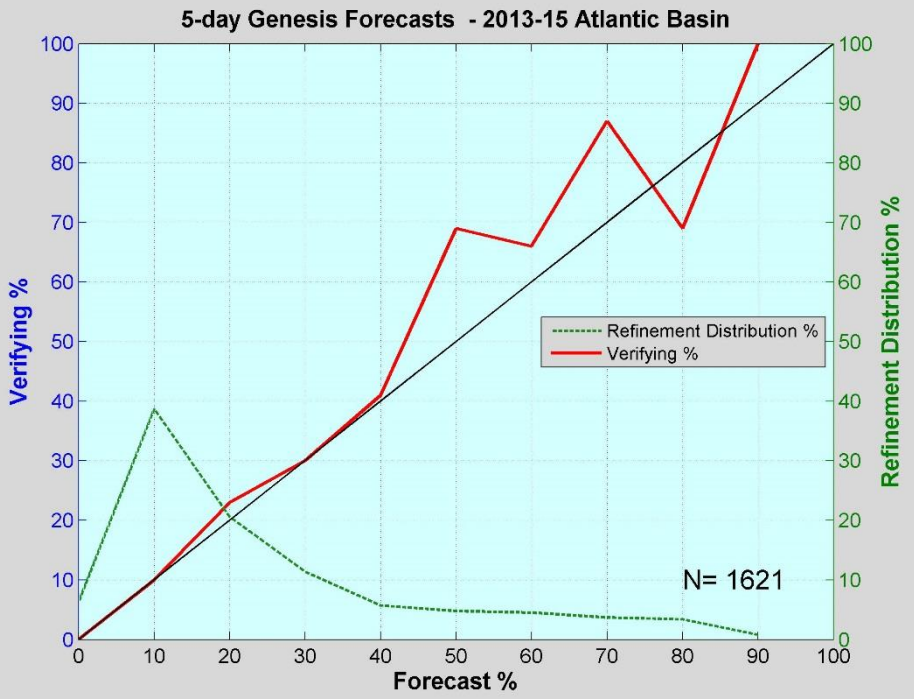
NHC "Invest" Systems

- 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

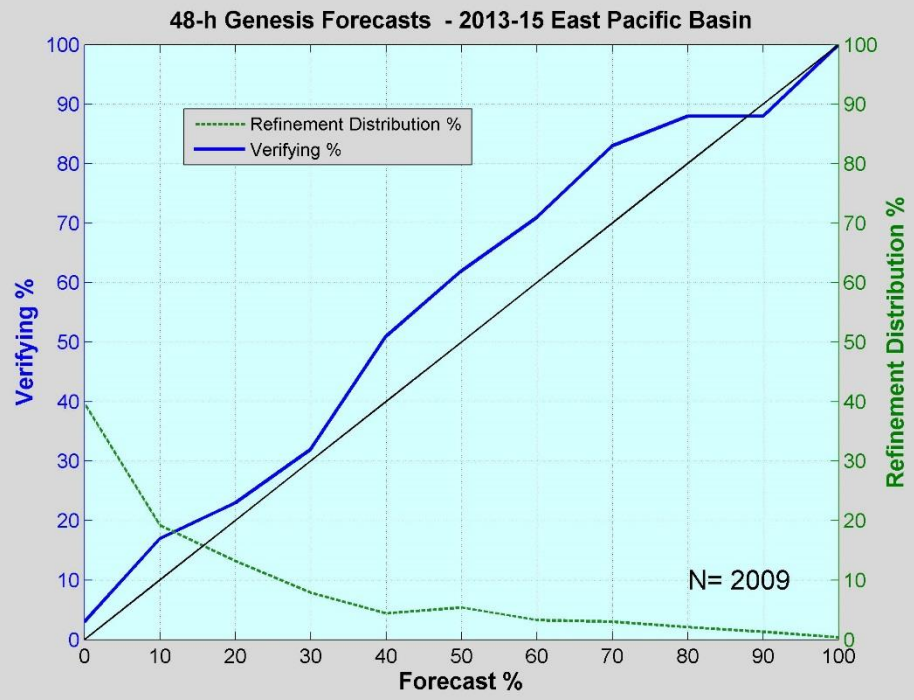


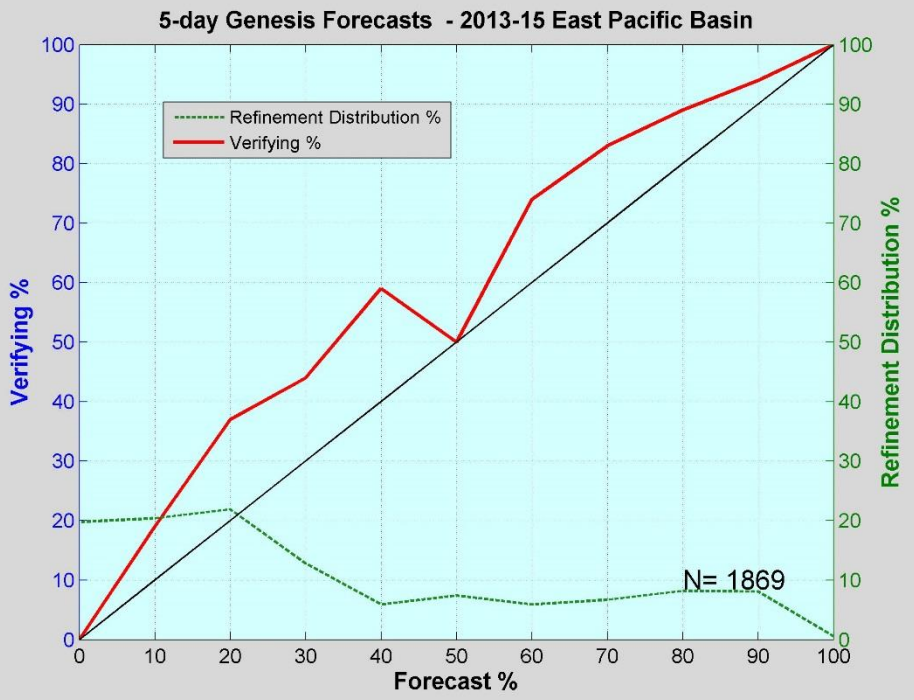
Verification Results of 2- and 5-Day Genesis Forecasts - Atlantic





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