Development and application of an extended range probabilistic ensemble hurricane forecast system

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Benefits of Extended Range Forecast System

- Provide additional lead-time for disaster mitigation
- Support adaptive policies for managing energy resources
- Support hedging strategies (financial, retail) based on probabilistic forecasts
- Fleet support, ocean routing

Operational Ensemble Hurricane Forecasting System

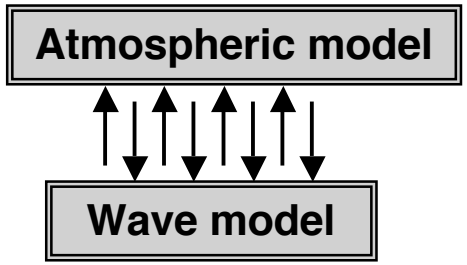
- GaTech/CFAN have been providing operational forecasts for a client in the energy sector since 2007
- 1-15 day, monthly, and seasonal forecasts based primarily on the ECMWF modeling system
- Ensemble-based probabilistic forecasts of tracks and genesis, plus intensity and size forecasts

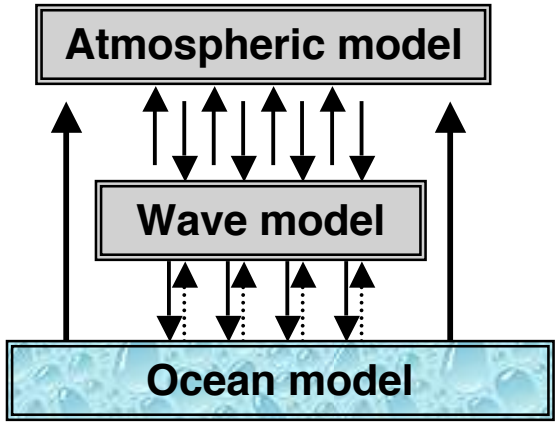
ECMWF: Weather and Climate Dynamical Forecasts

Product

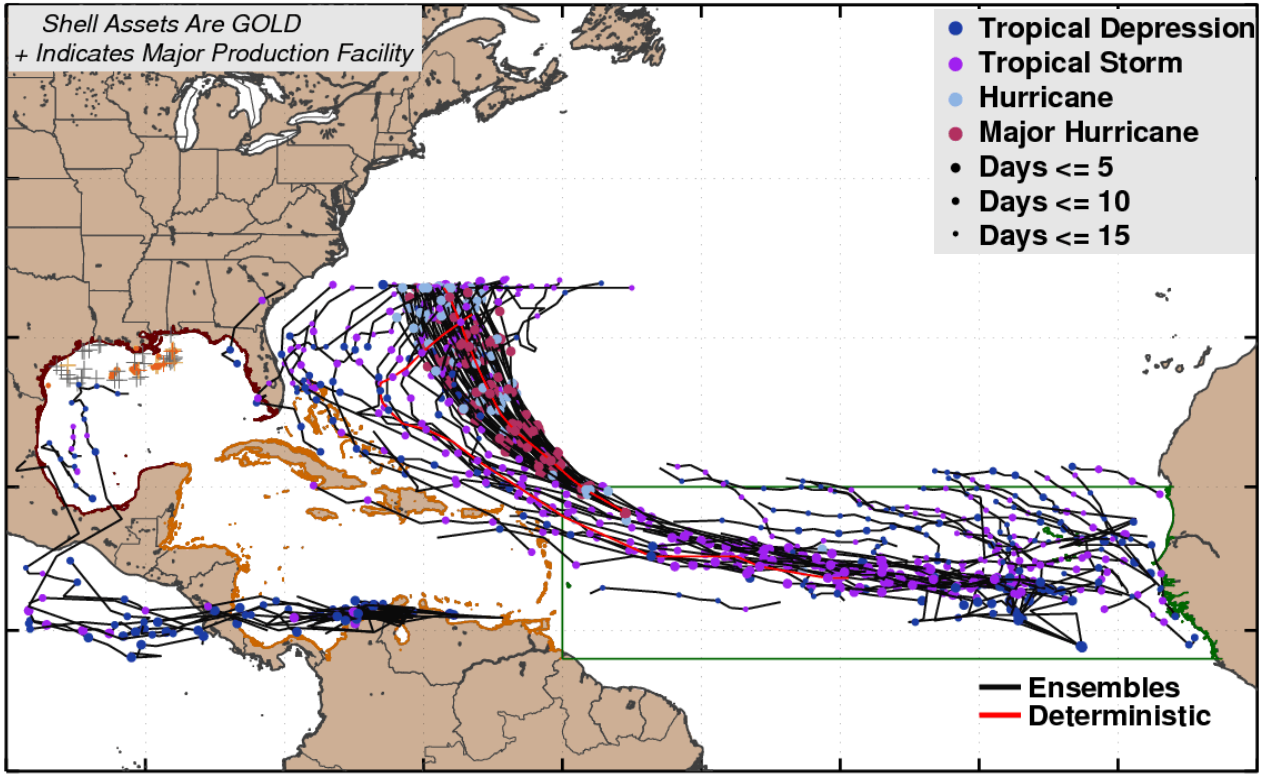
Medium-Range Forecasts	Monthly Forecast	Seasonal Forecasts
Day 1-15	Day 10-32	Month 2-7
51 ensemble mem	51 ensemble mem	40 ensemble mem
30 km resolution	80 km resolution	120 km resolution

Tool





Tracking Methodology



Variables Used in TC Tracking Scheme:

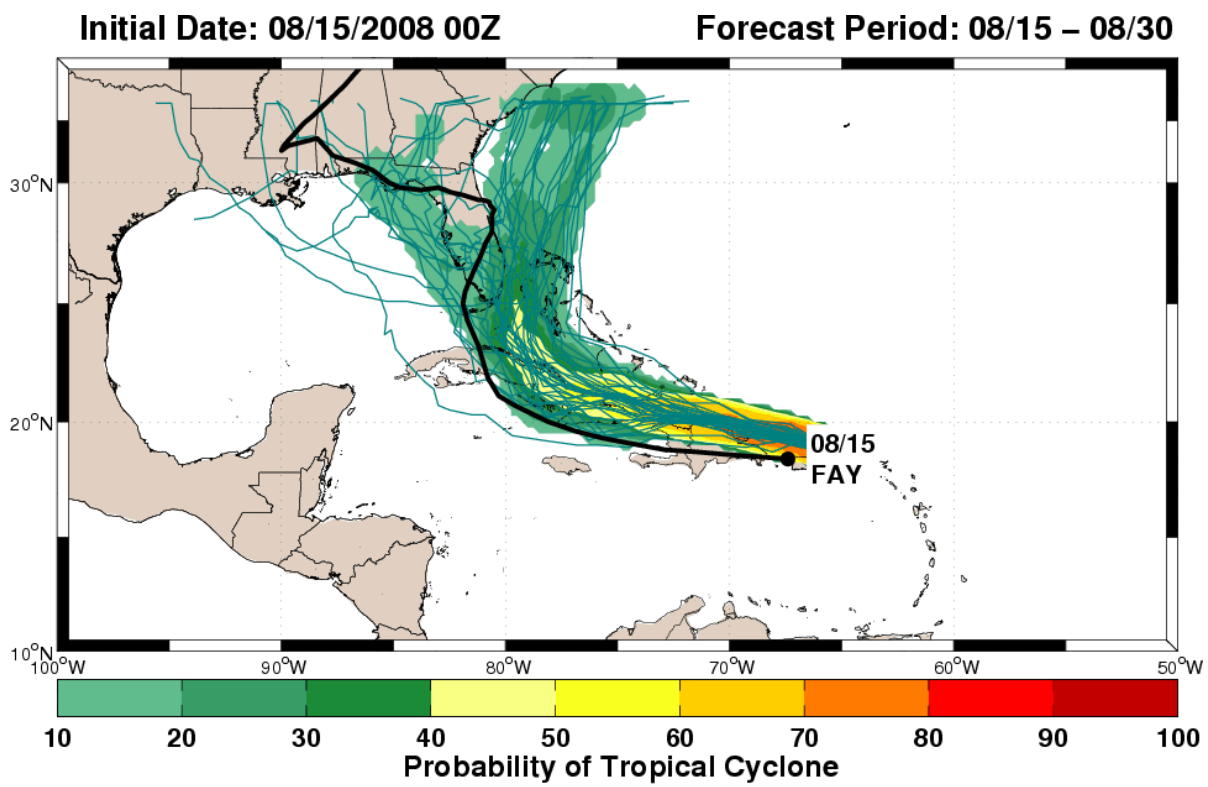
- 850 hPa Relative Vorticity
- Mean Sea Level Pressure
- 500-200 hPa Temperature
- 1000-200 hPa Thickness

Modified from Vitart (1997)

Tracking Adjustments

Correct for:

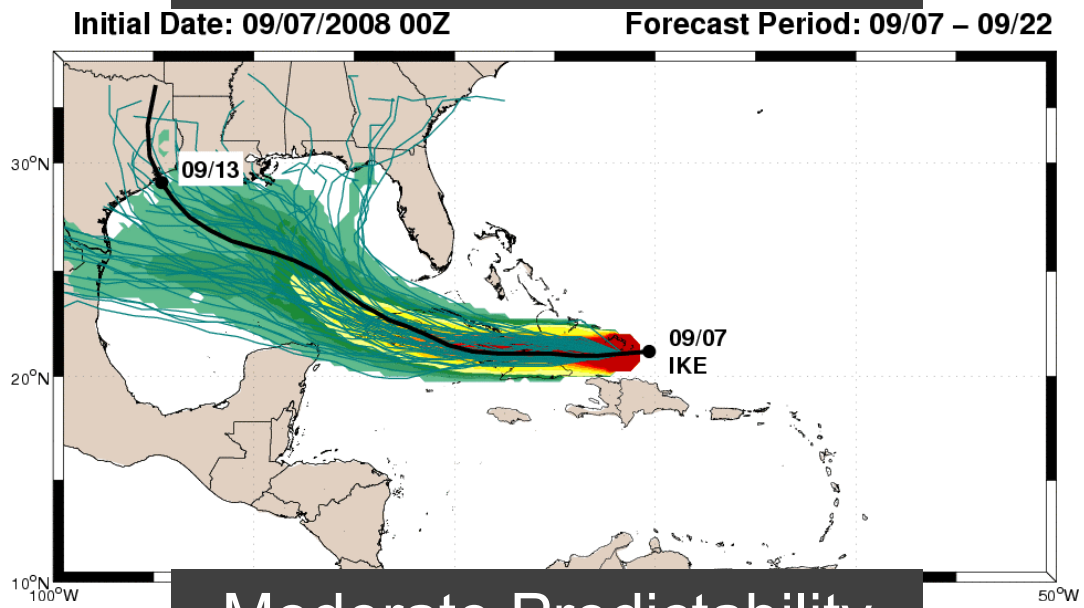
- Time delay in receiving, processing data
- Statistical along-track errors
- Statistical cross-track errors



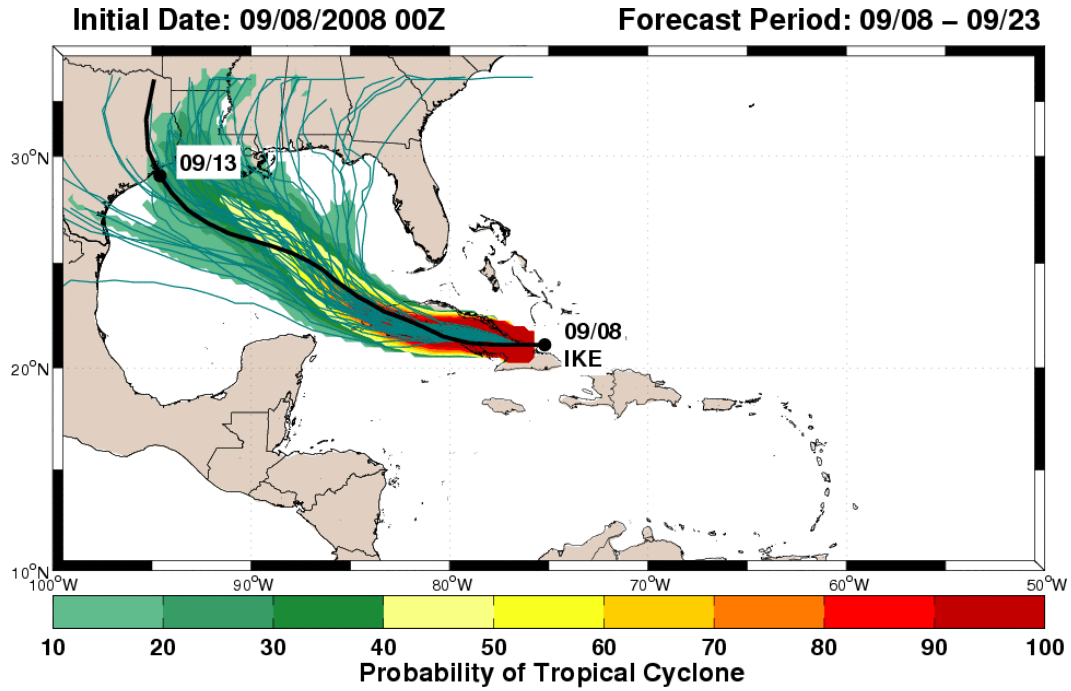
Hurricane Ike

Statistical adjustments to ensemble track forecasts allow us to *dynamically* constrain the cone of uncertainty

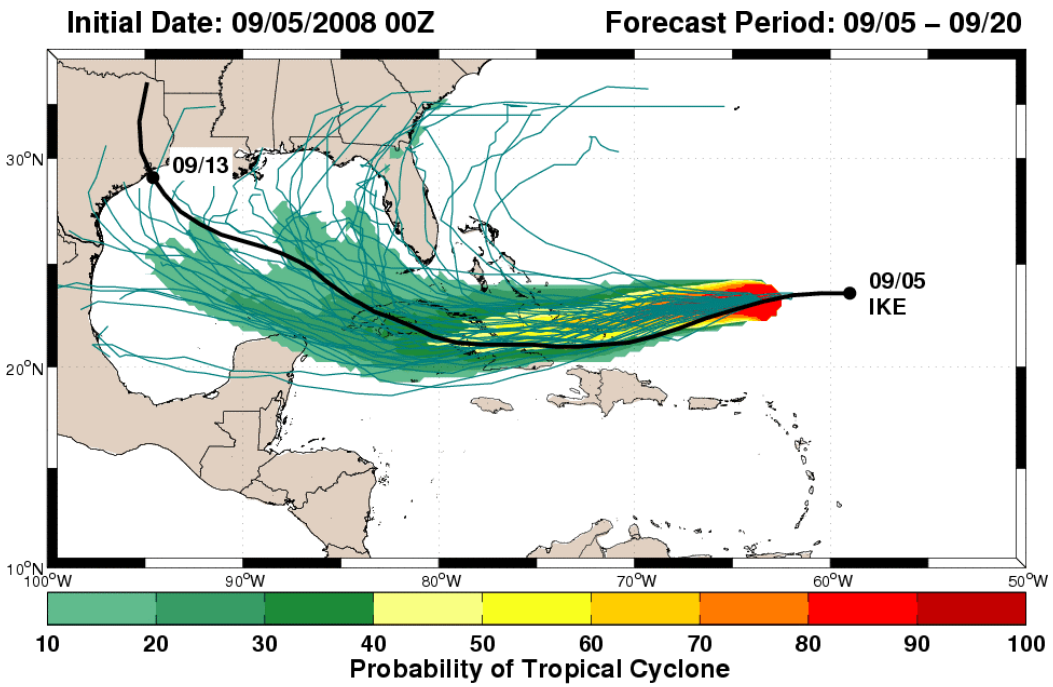
Low Predictability

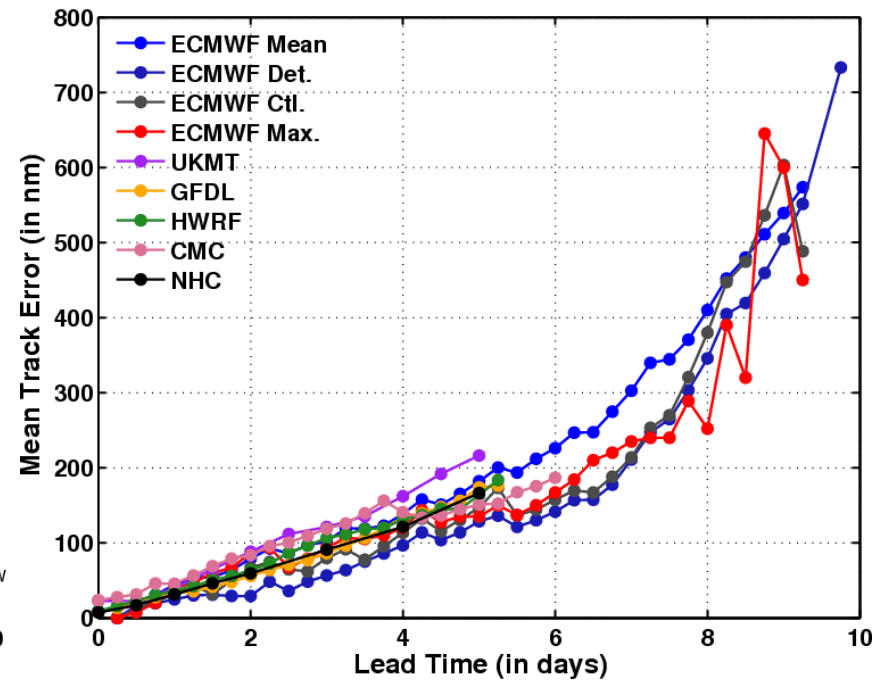


Moderate Predictability



Track Verification: Ike 2008

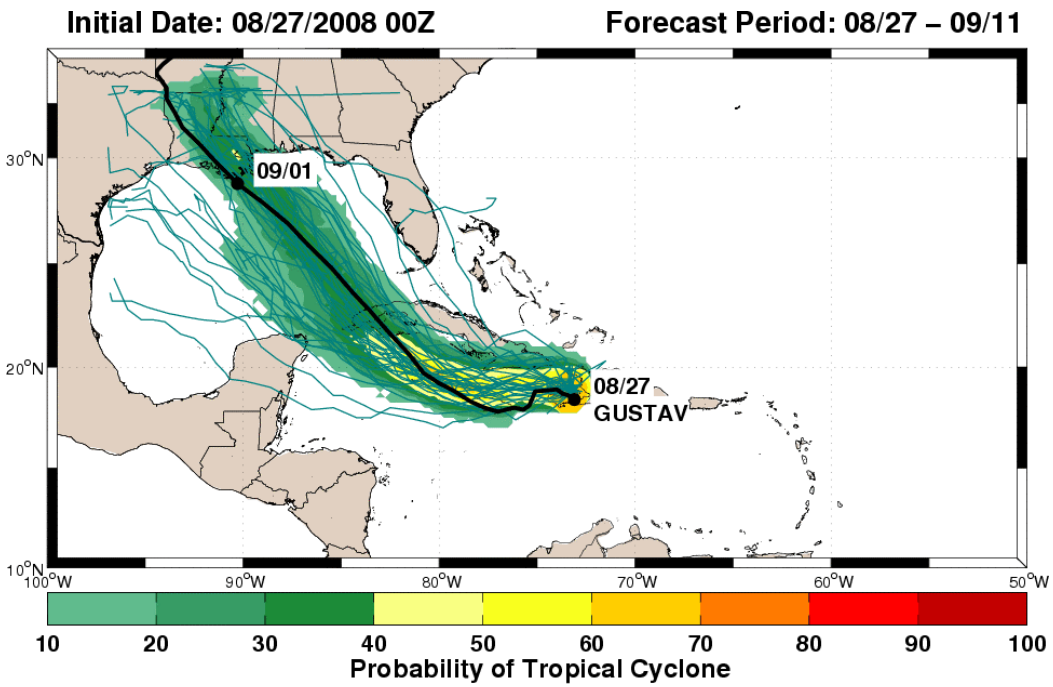


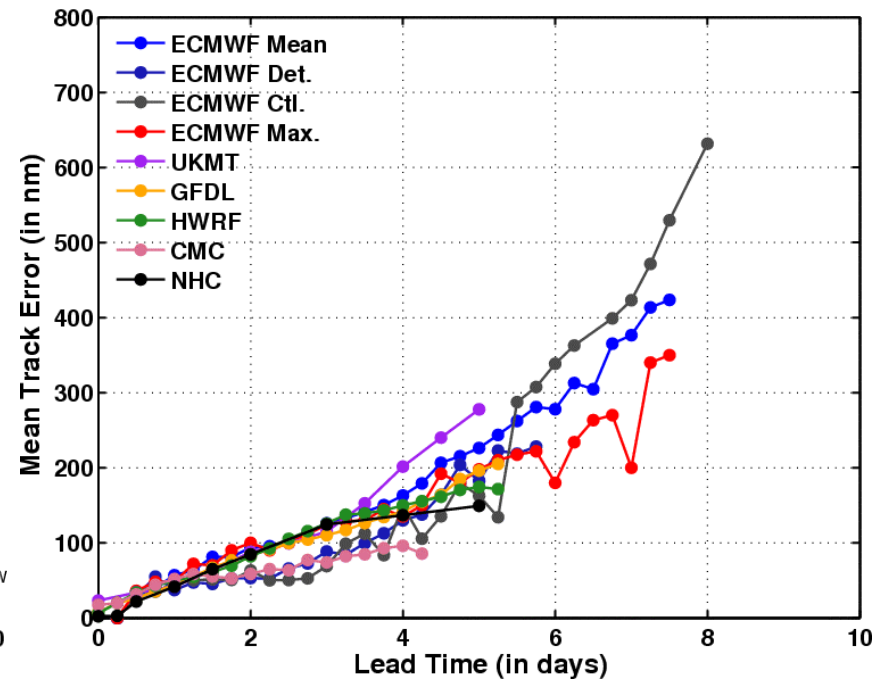


Bias-adjusted ECMWF provided superior track forecasts over the HWRF/GFDL models and the National Hurricane Center

For Days 4+, maximizing the ECMWF ensemble spatial PDF produced the best long-range track forecast

Track Verification: Gustav 2008



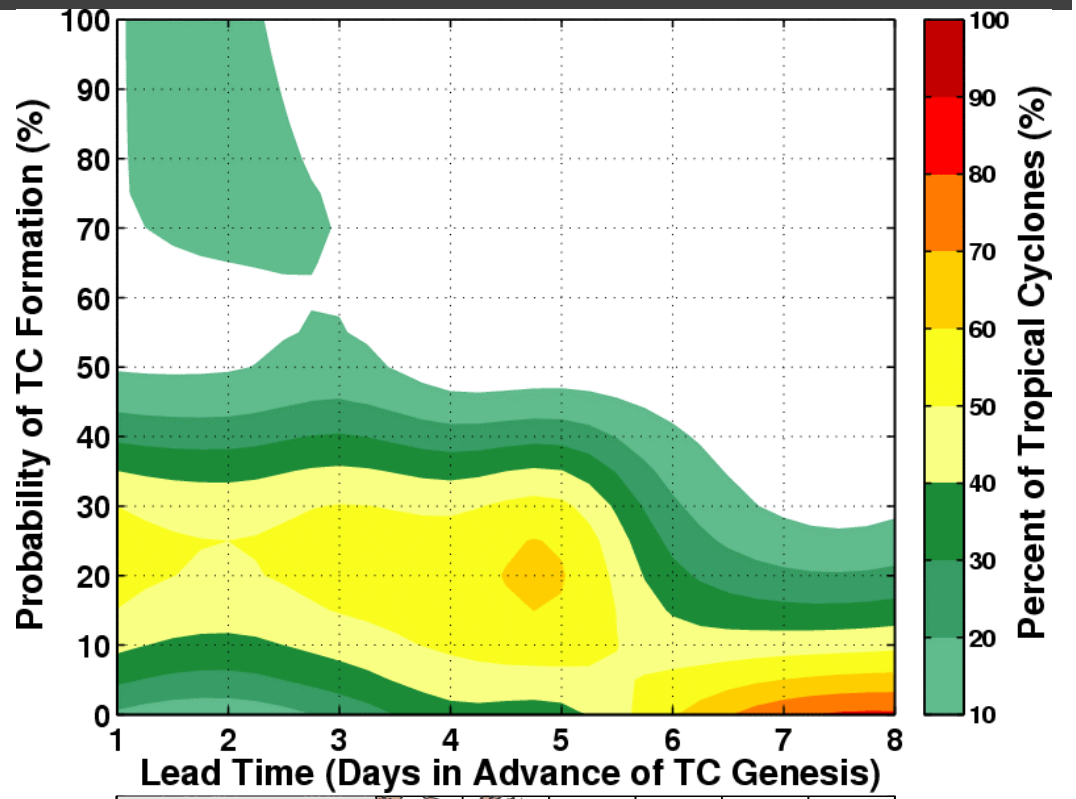


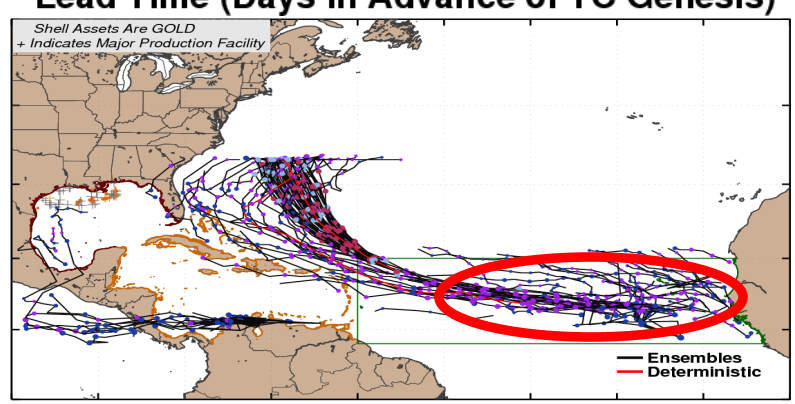
ECMWF deterministic and CMC models provided best 1-3 day forecast

Maximizing the ECMWF ensemble spatial PDF causes track errors to grow less rapidly than using ensemble mean or deterministic forecast

Genesis Verification for ECMWF Tracks

- During 2007-2008, TC genesis rarely exceeded 25% probability within 1-5 days of TC formation
- If timing/location criteria of TC genesis loosened, genesis is more common at the 50% level within 5 days
- The limited reliability of the ECMWF EPS genesis necessitates a *statistical TC genesis model*



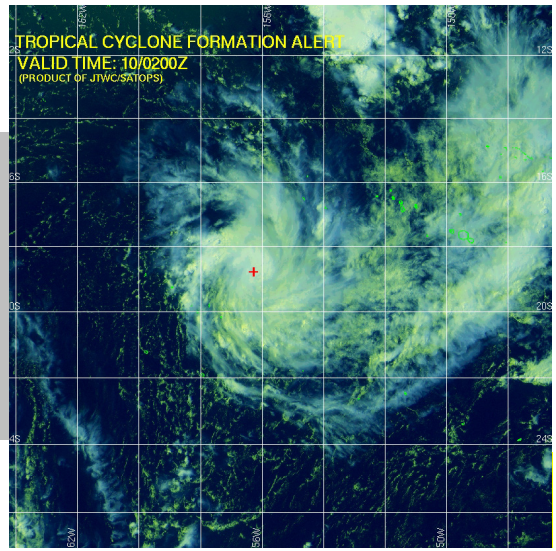


Forecasting Tropical Cyclogenesis

<u>Large-Scale Environment</u> (*Predictability: Days 1-10+*)
(e.g. low wind shear, vertical ascent, high specific humidity, easterly waves, thermodynamic instability)

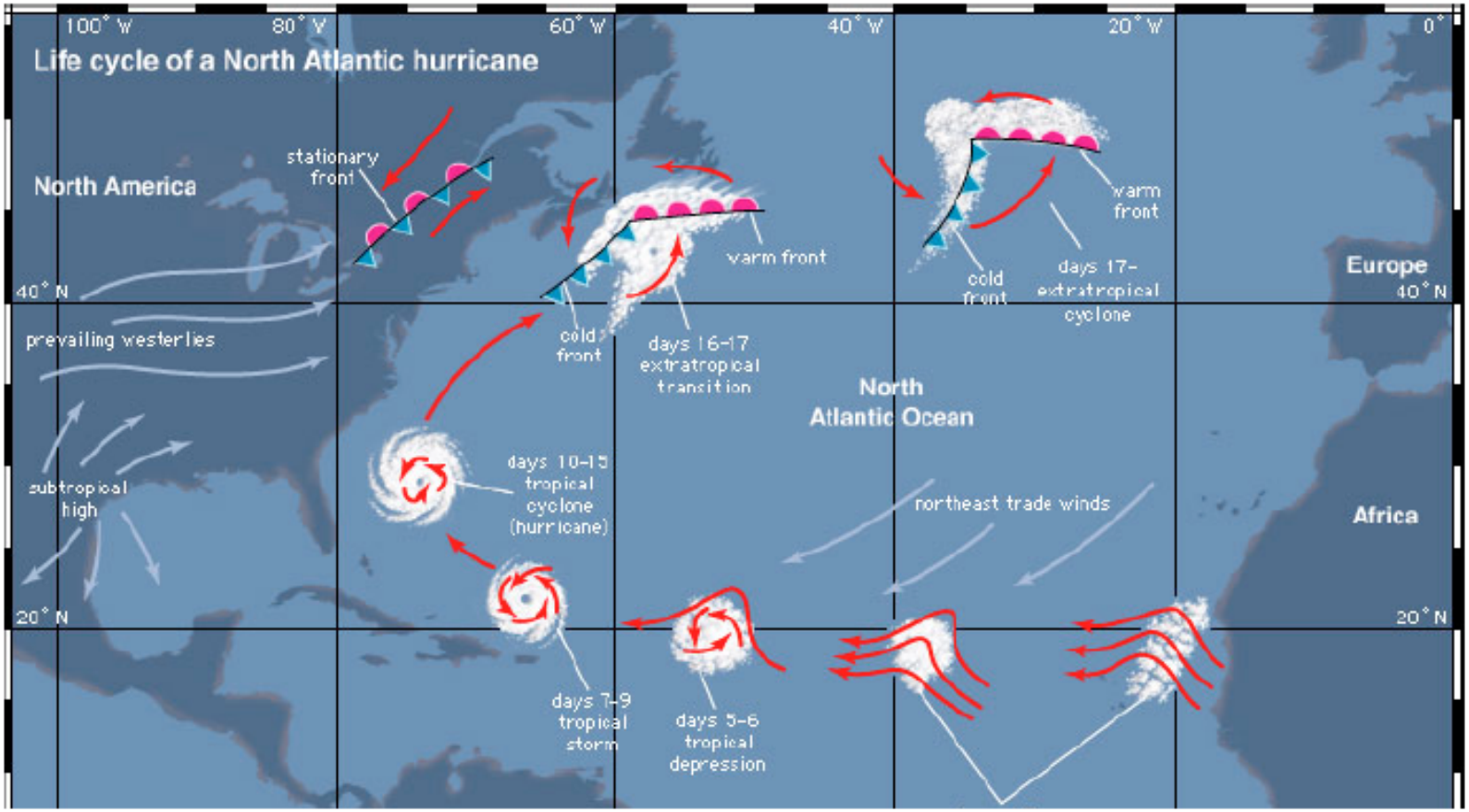
<u>Internal Mesoscale Dynamics</u> (*Predictability: Days <2*)
(e.g. vortical hot towers , MCV, convective processes)

<u>Tropical Cyclogenesis Prediction</u>
- Satellite: Dvorak T-Numbers (Days <2)
- NWP predictions for large-scale environment and African Easterly Waves (Days 2+)



African Easterly Waves (AEW)

- ~2 AEWs/week during hurricane season
- About 60% of TS and Cat 1-2 hurricanes originate from AEWs.
- Nearly 85% of major hurricanes originate from AEWs.



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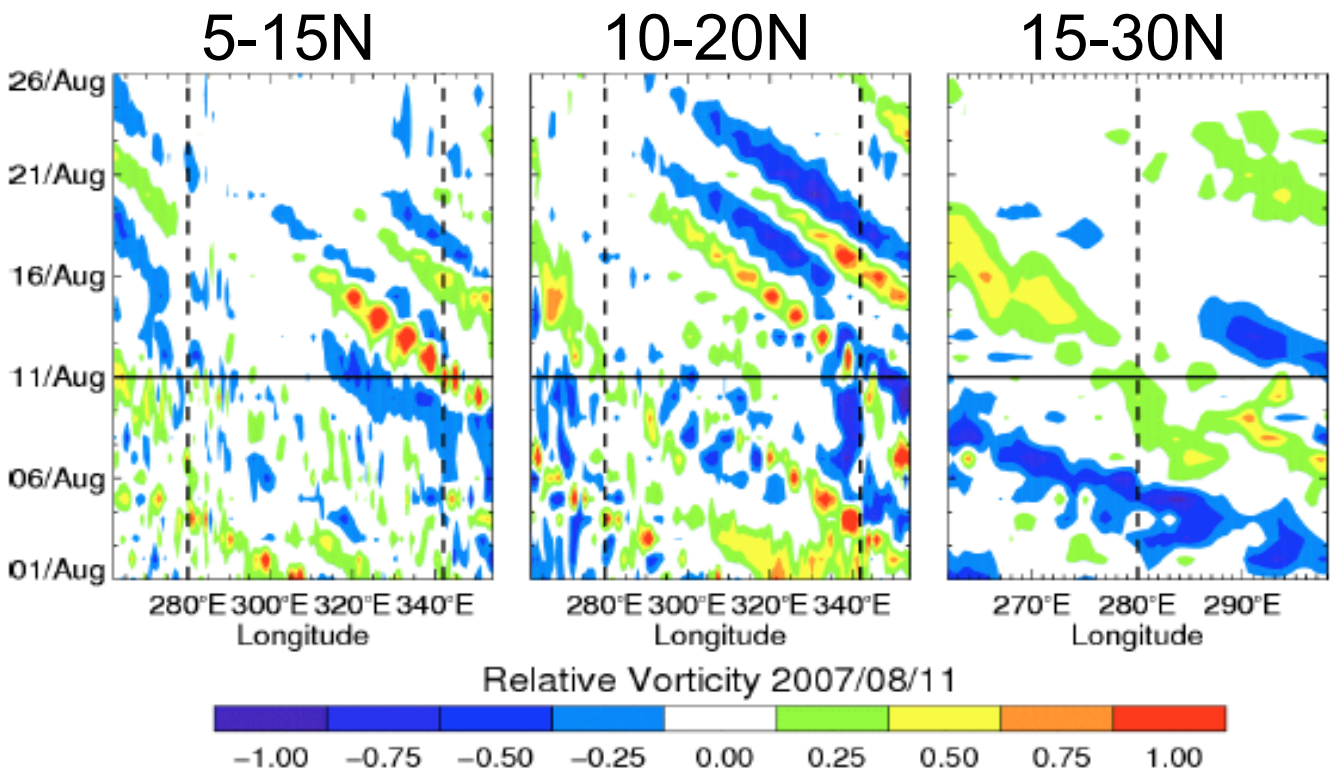
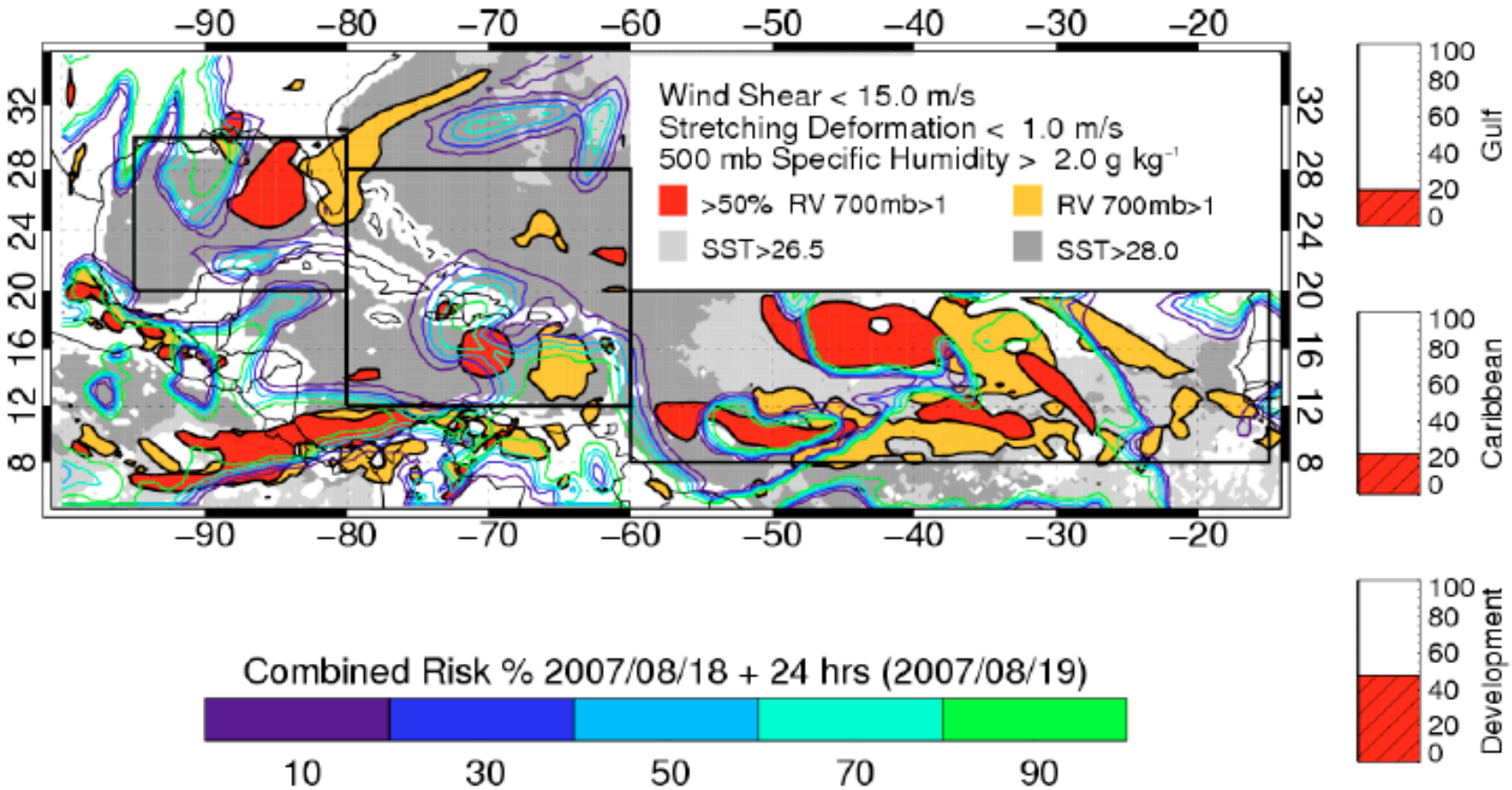
Easterly Wave Tracking Algorithm



- Based on Hovmöller method
- Fourier filtered 2-6 day positive westward vorticity anomalies
- Recursive algorithm to identify grid points neighboring maximum anomalies

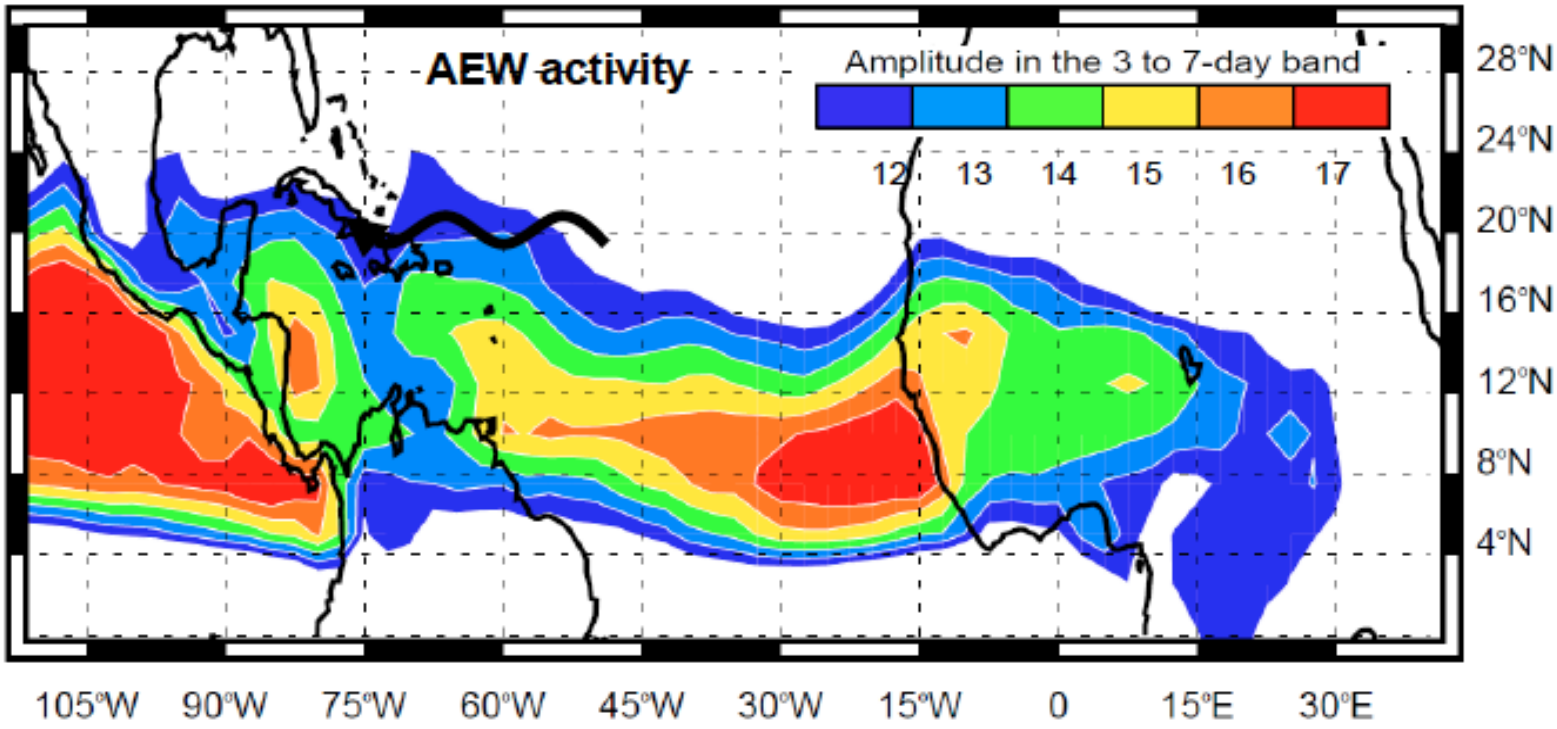
Combined Genesis Risk (2007-2008)

Regions where different conditions favorable for the intensification of tropical storms occurred at the same time



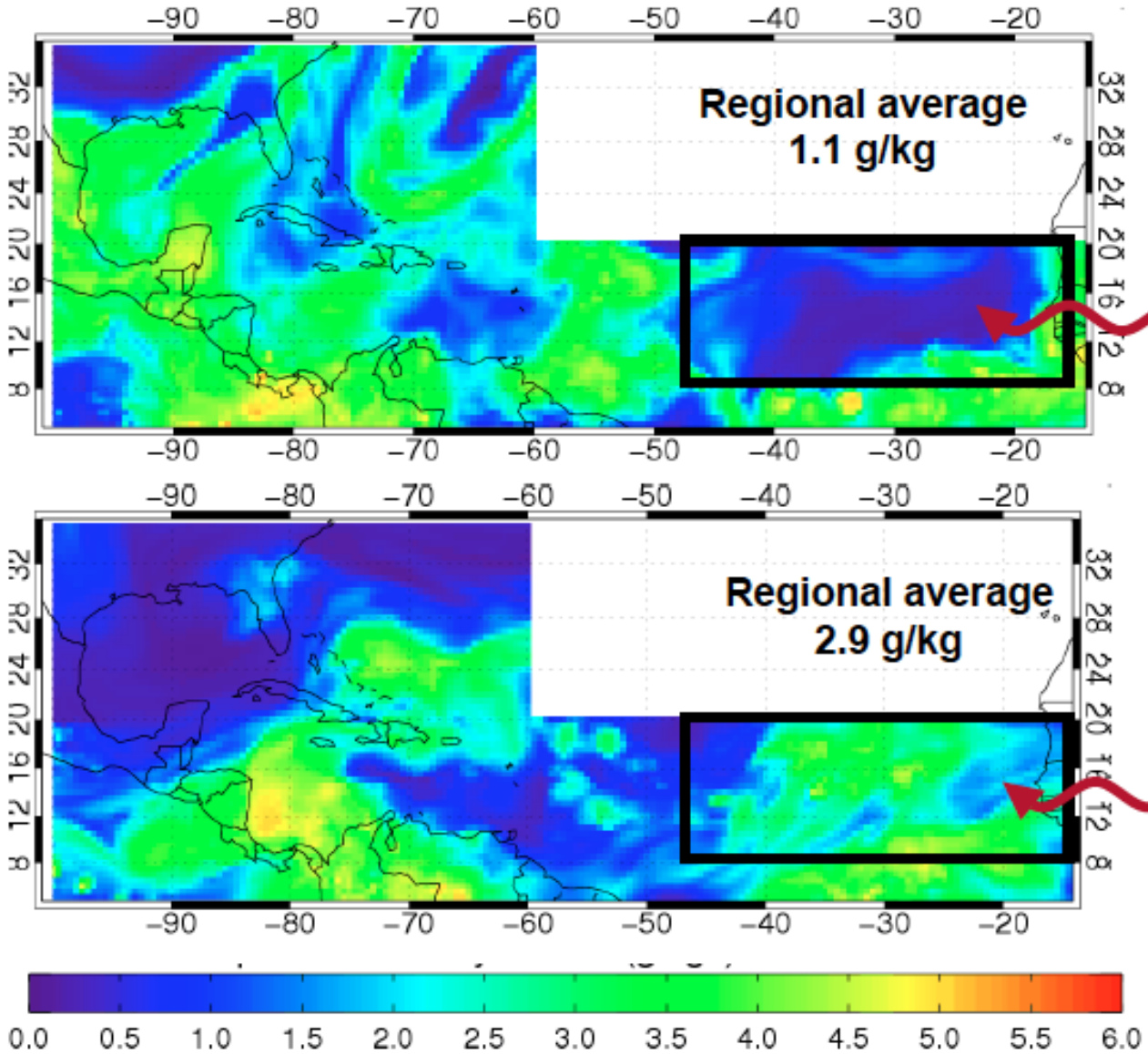
Agudelo, Hoyos, Curry, Webster (2010) *Clim. Dyn.*, in press

New Genesis Risk from African Easterly Waves (AEW)



From studies of AEW climatology we know the likelihood of an AEW becoming a Tropical Cyclone given the values of different tropical storm related variables in a specific region (e.g. MDR).

Example: Specific Humidity

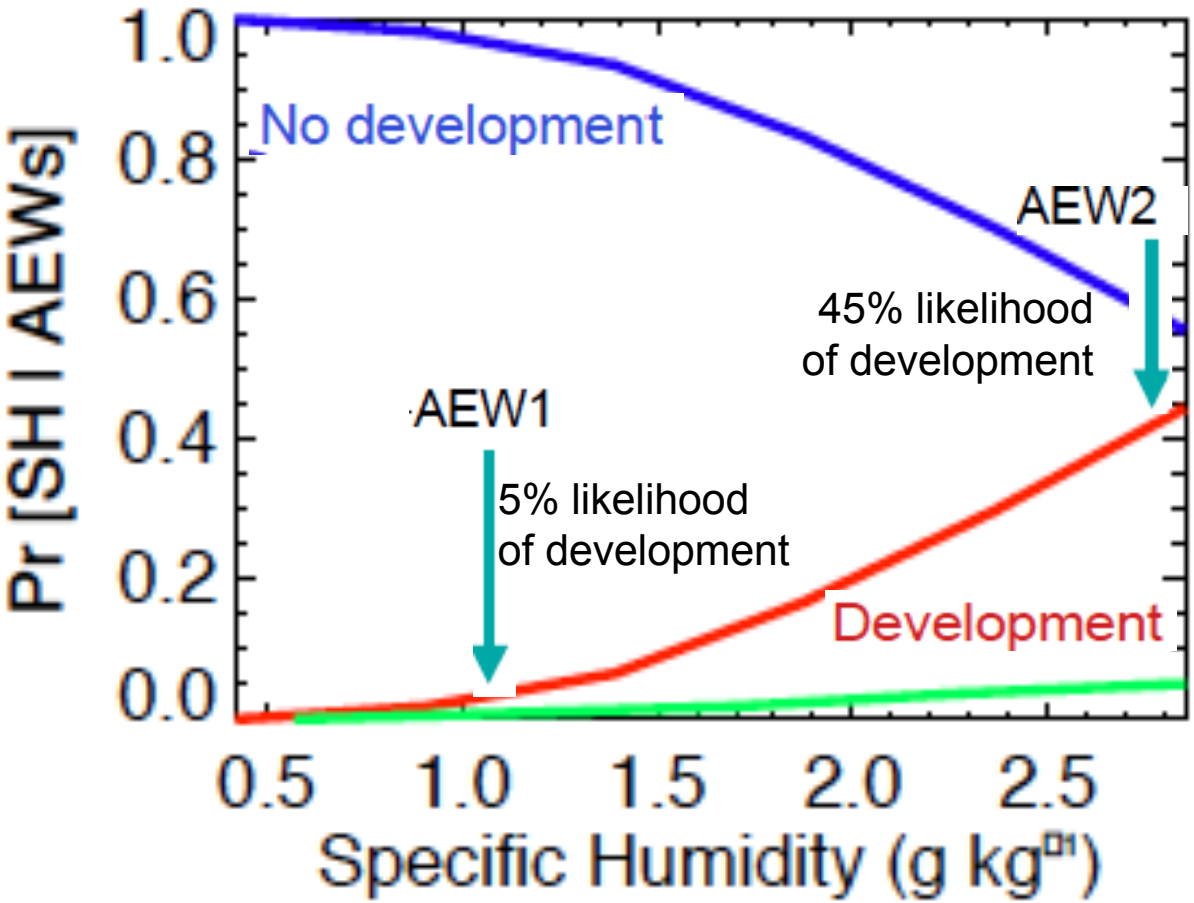


Assume we have two AEWs

AEW1 enters a dry environment in the MDR

AEW2 enters a moist environment in the MDR

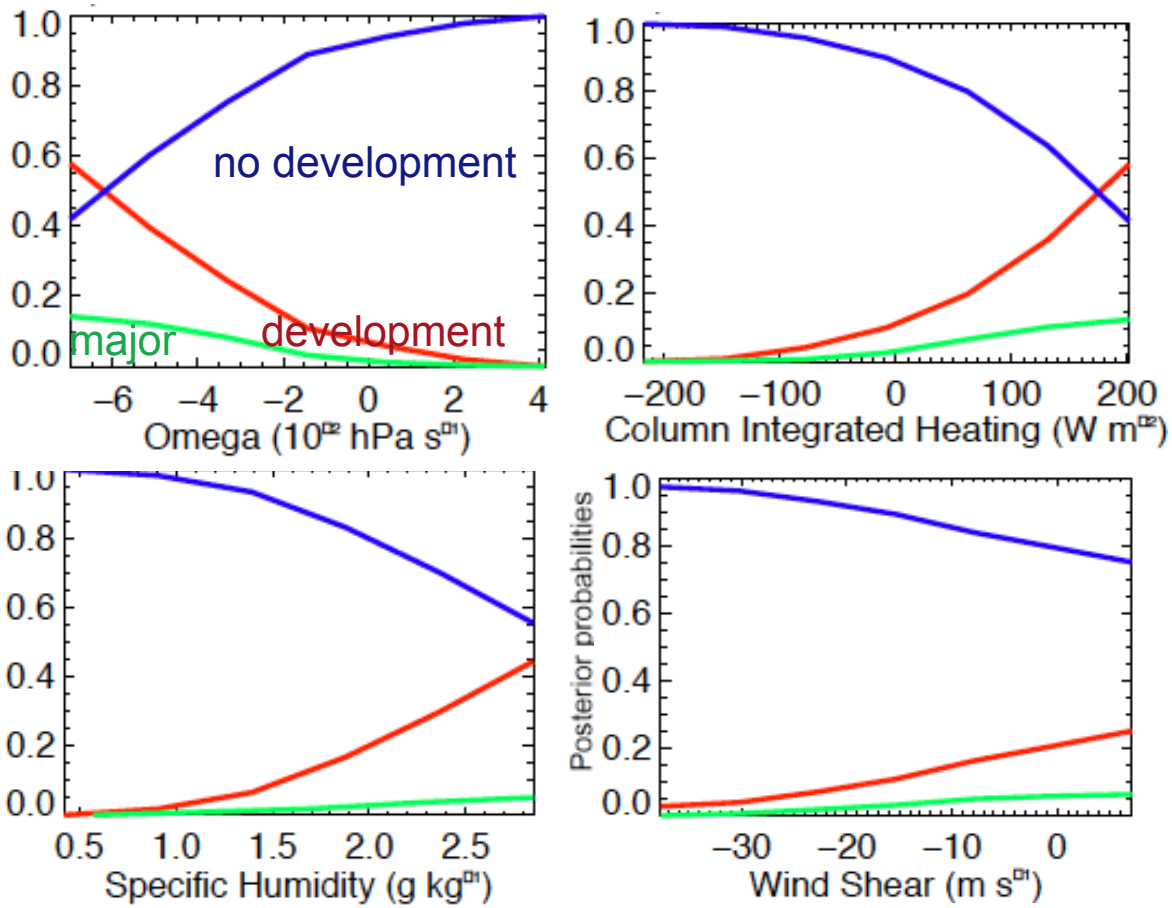
Average Specific Humidity values in the MDR the week prior to genesis are used to the obtain the probability of development of each wave



Same procedure is followed for relevant environmental variables

Agudelo, Hoyos, Curry, Webster (2010) *Clim. Dyn.*, in press

Overall Genesis Probability



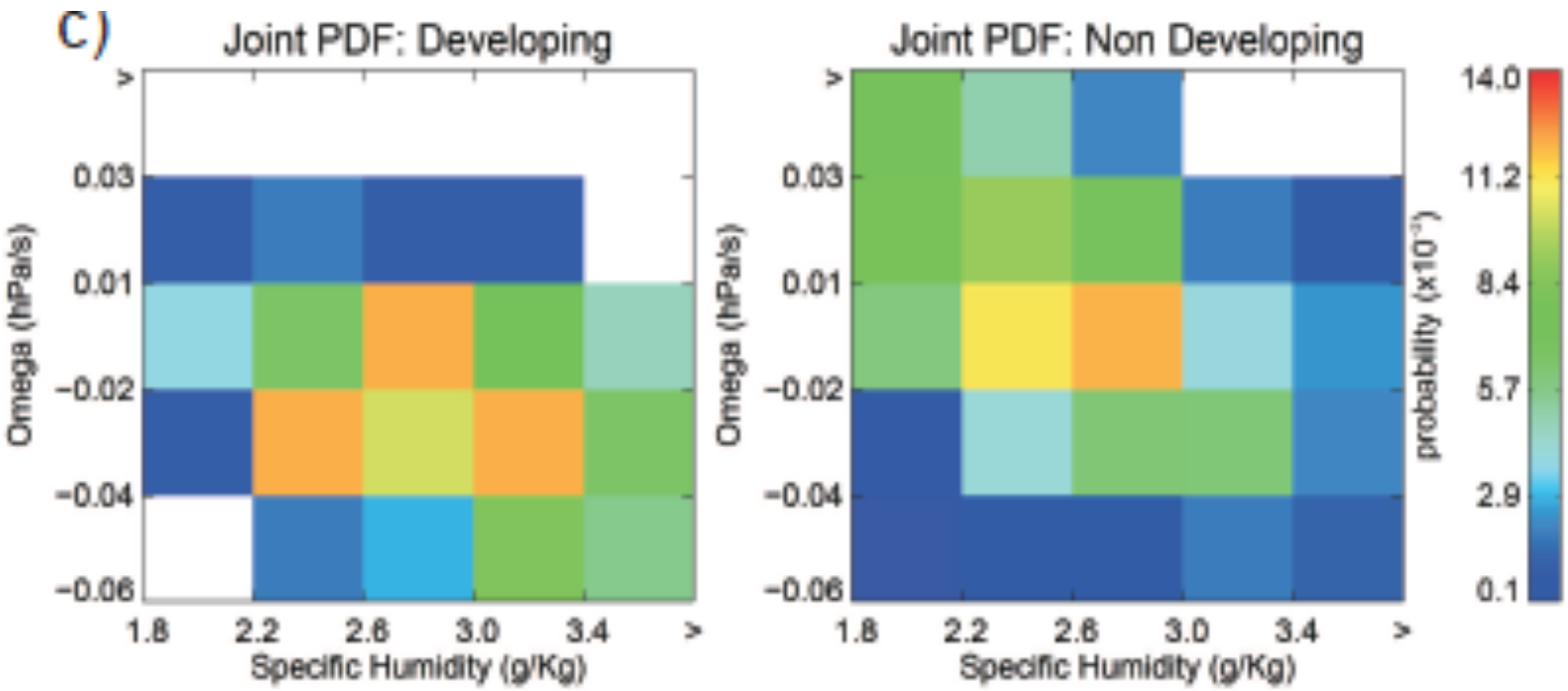
To estimate the overall genesis probability, the set of probabilities for all variables considered is evaluated against all historical sets, and reclassified *('bias corrected')* to obtain a a unique genesis probability

This procedure is repeated for each ensemble member as wells for the ensemble mean and control run to obtain a distribution of genesis probabilities.

Agudelo, Hoyos, Curry, Webster (2010) Clim. Dyn., in press

Bivariate probabilities

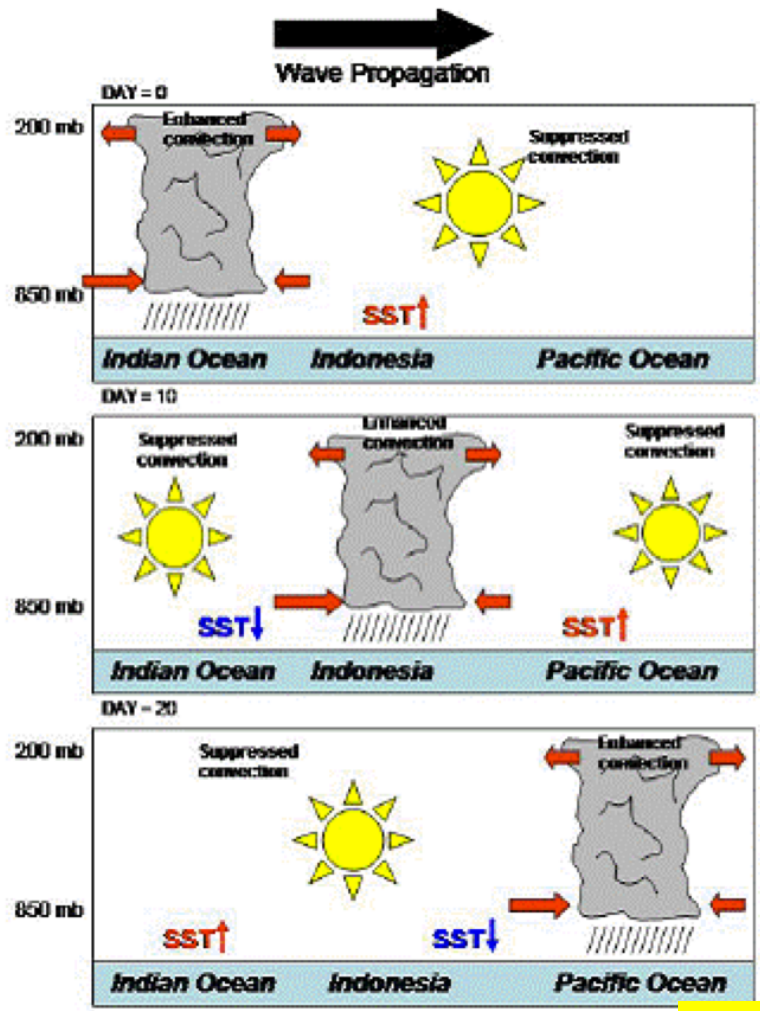
A similar genesis probability is obtained using bivariate distributions



This method allows a better assessment of covariability, however bivariate distributions are not as robust as univariate PDF. Both estimations of genesis risk are complementary.

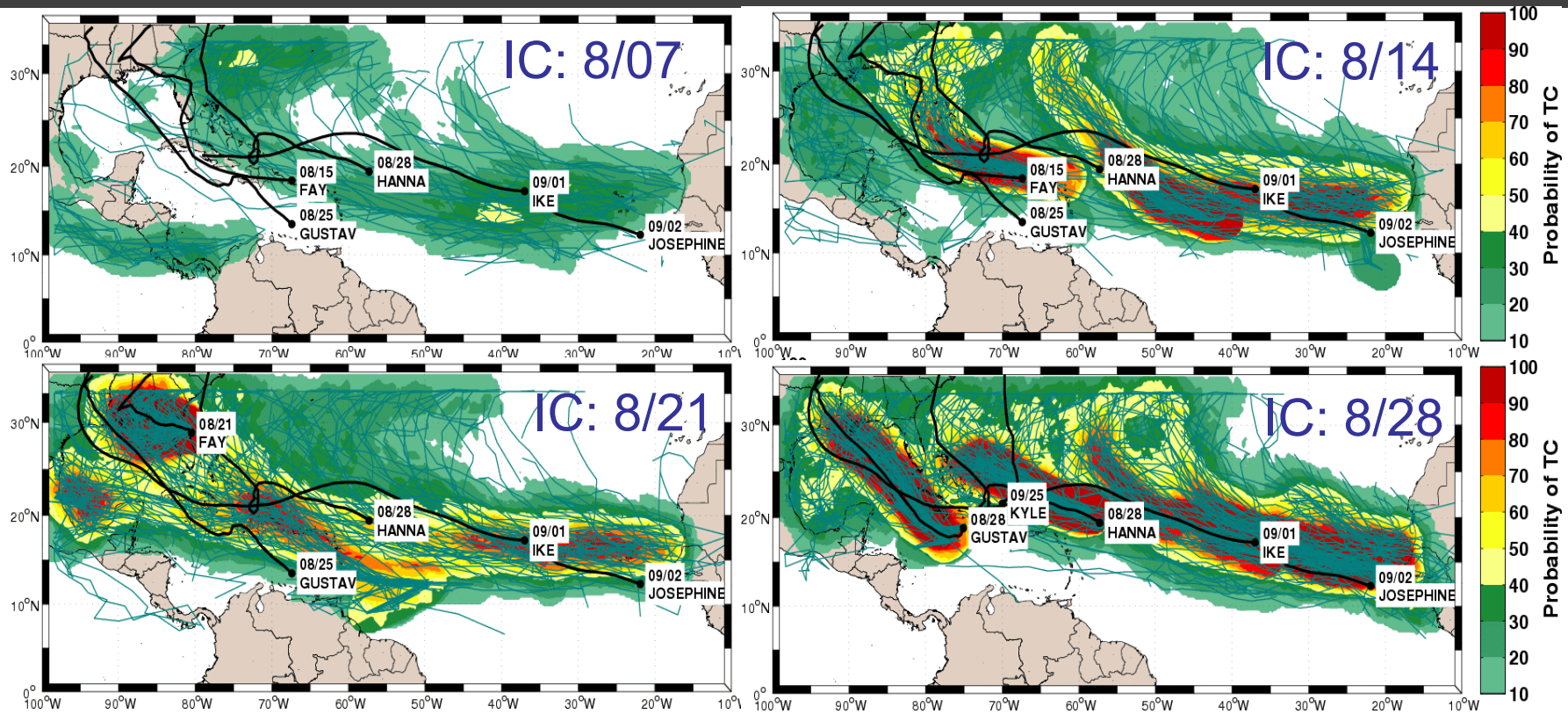
Beyond Two Weeks …

- Predictability Basis for Intraseasonal Forecasts?
  - Some atmospheric memory from initial conditions
  - Ocean circulation changes begin to force atmospheric variability
  - Predictability modulated by the location and amplitude of the Madden-Julian Oscillation



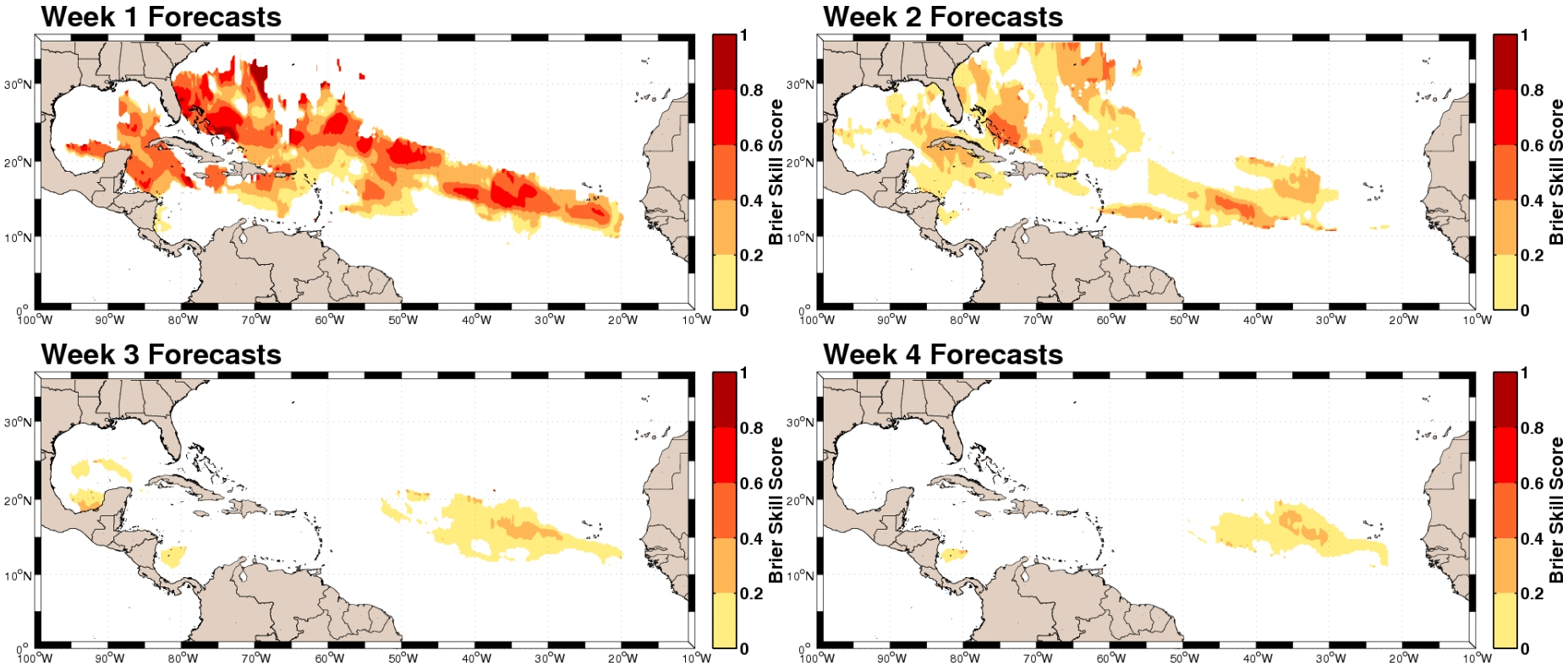
http://www.calclim.dri.edu/ccda/images/mjo.gif

Monthly Projections: August 2008



Tropical Cyclone	Formation Date	Landfall Date
Fay	Aug. 15th	FL; Aug. 18th
Gustav	Aug. 24th	LA; Sept. 1st
Hanna	Aug. 28th	NC; Sept. 5th
Ike	Sept. 3rd	TX; Sept. 13th

ECMWF Monthly TC Forecast



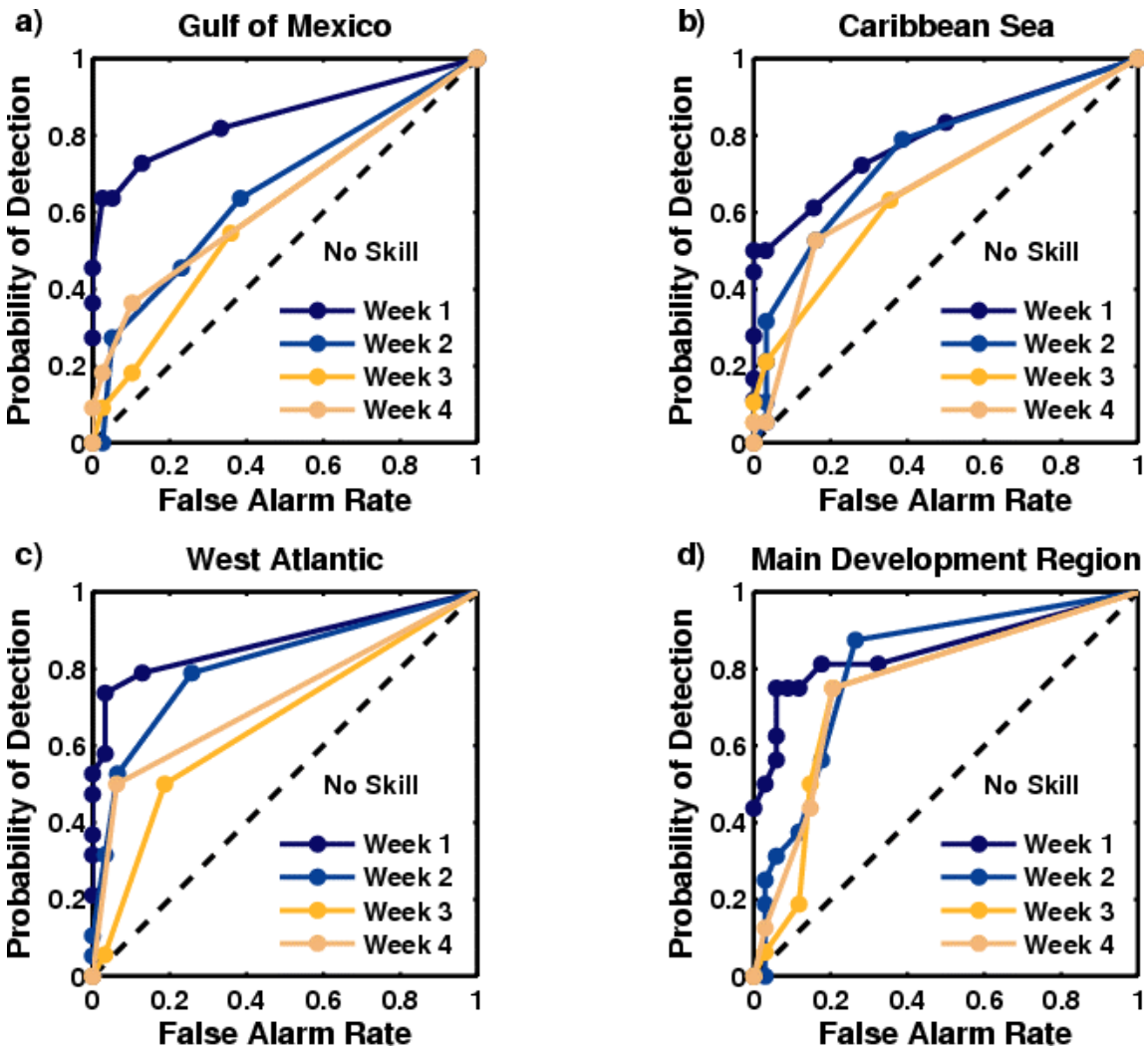
- Reference Forecast: Climatology (1970-2000)
- Regions with forecast skill include:
  - **Northern Caribbean** (Weeks 1-2)
  - **Western Subtropical Atlantic** (Weeks 1-2)
  - **Main Development Region** (Weeks 1-4)

$$Brier\ Skill\ (BS) = \frac{1}{N}\sum_{i=1}^{N}(p_i - o)^2$$

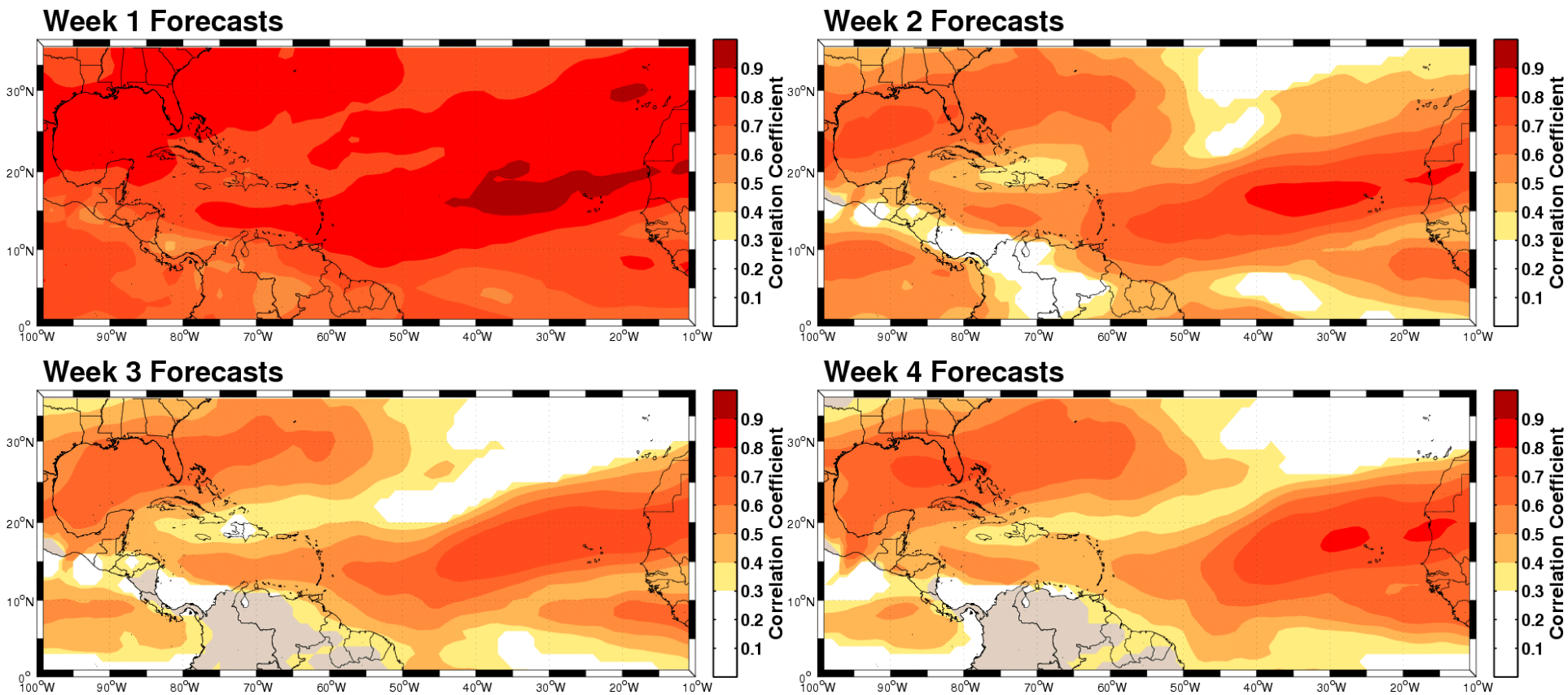
$$Brier\ Skill\ Score = 1 - \frac{BS}{BS_{ref}}$$

ECMWF Relative Operating Characteristic

- The ROC compares hit rates vs false alarm rates as a function of increasing probability levels
- For Weeks 1-2, the West Atlantic and MDR have high ROC scores (0.8)
- For Weeks 3-4, all regions feature forecast skill with higher ROC scores in the MDR (0.75) than in other regions



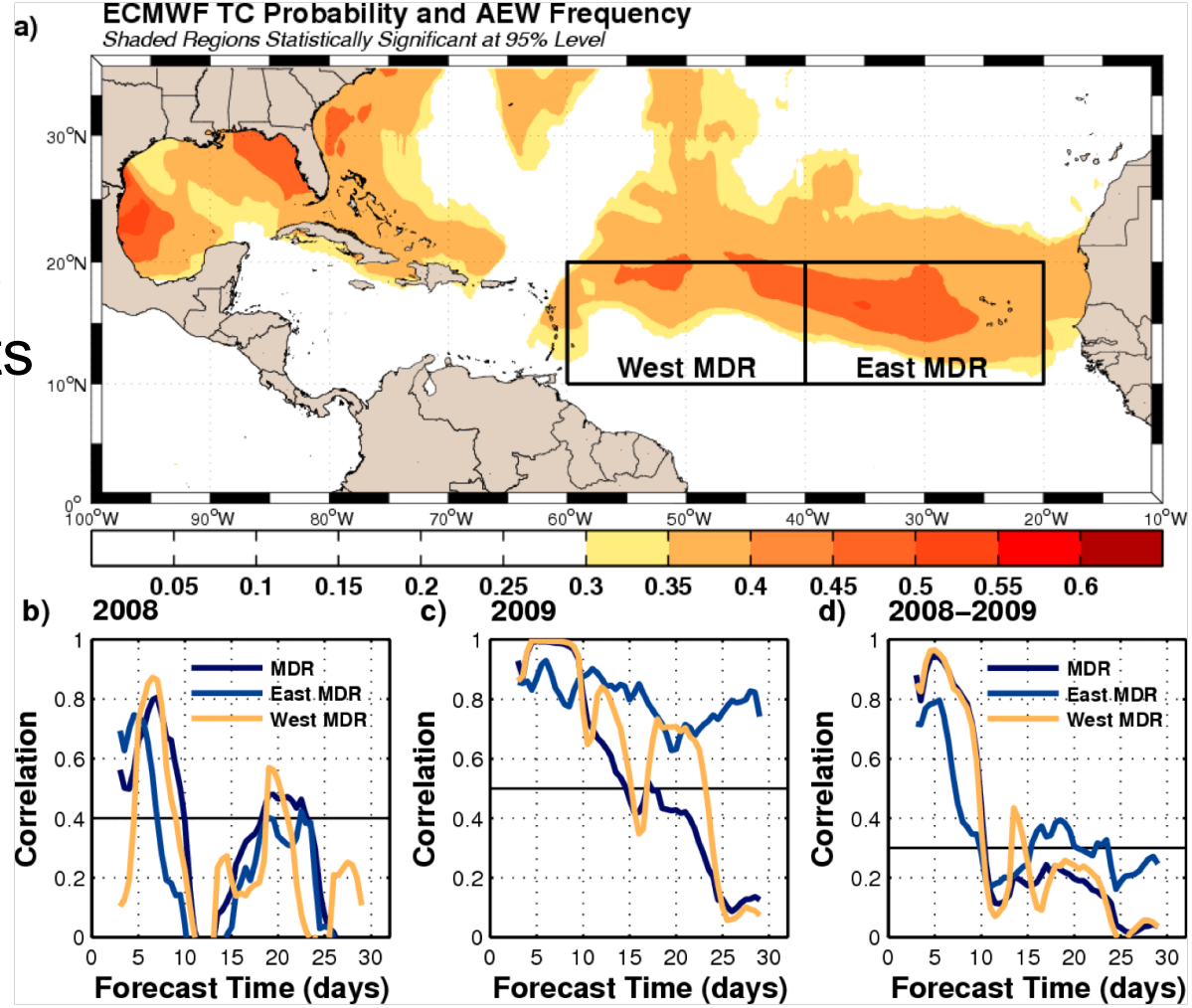
Large-Scale Environment: Deep-Layer Vertical Wind Shear



- ECMWF Monthly is skillful at forecasting deep-layer vertical shear in the Gulf of Mexico and Main Development Region
- Weak correlation in Caribbean tied to variability in TUTT strength

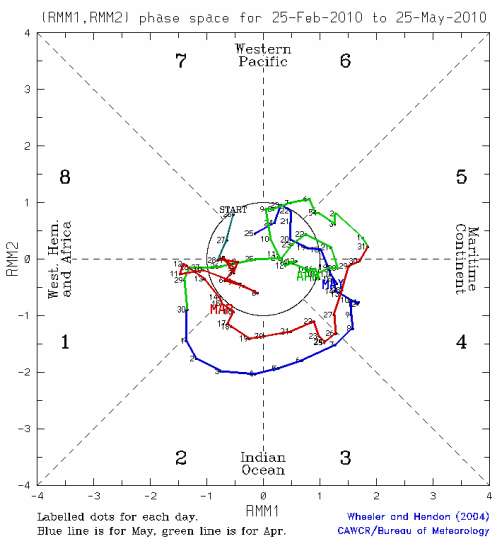
Large-Scale Environment: Variability in African Easterly Waves

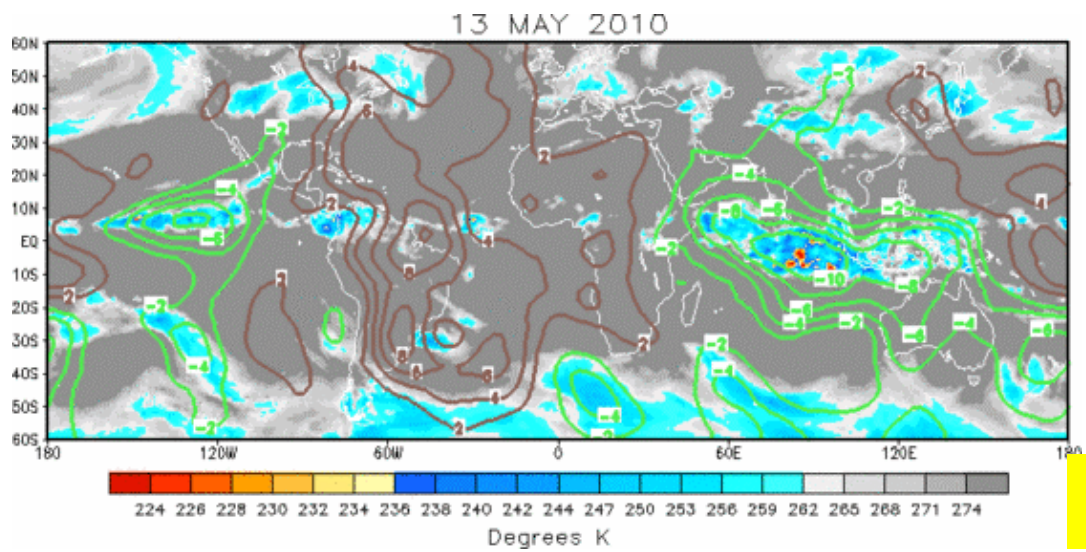
- Frequency of easterly waves explains about 10-20% of the variance in ECMWF TC forecasts
- Spatial pattern of covariability coincides with regions of positive Brier skill scores



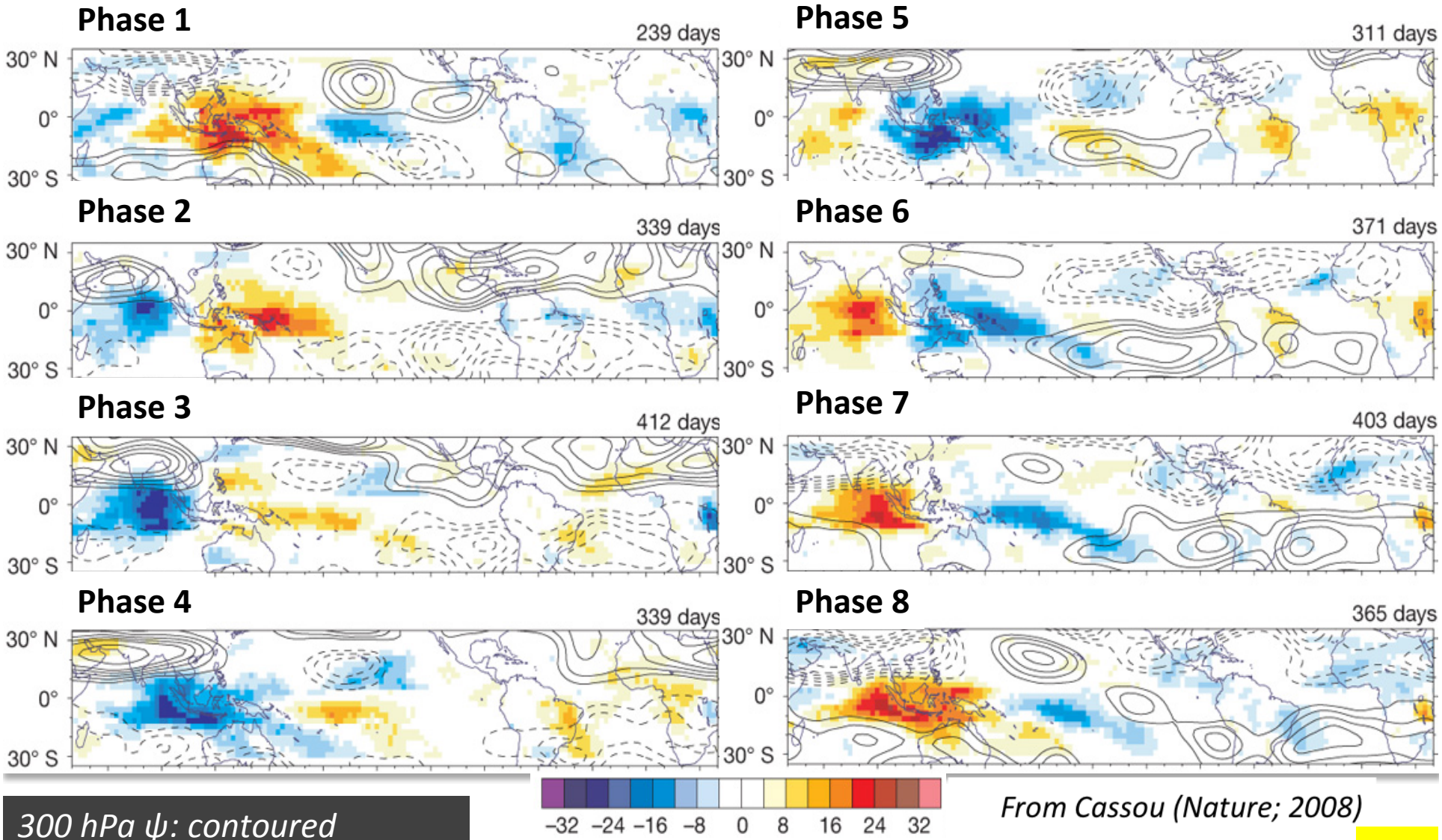
The Madden-Julian Oscillation (MJO)

- MJO is a 30-60 day oscillation in the Tropics
- Near-global scale, quasi-periodic eastward disturbance in surface pressure, tropospheric temperature, and zonal winds across equatorial belt
- Dominant mode of tropical variability on time scales in excess of 1 week but less than 1 season





Sensitivity to the Madden-Julian Oscillation

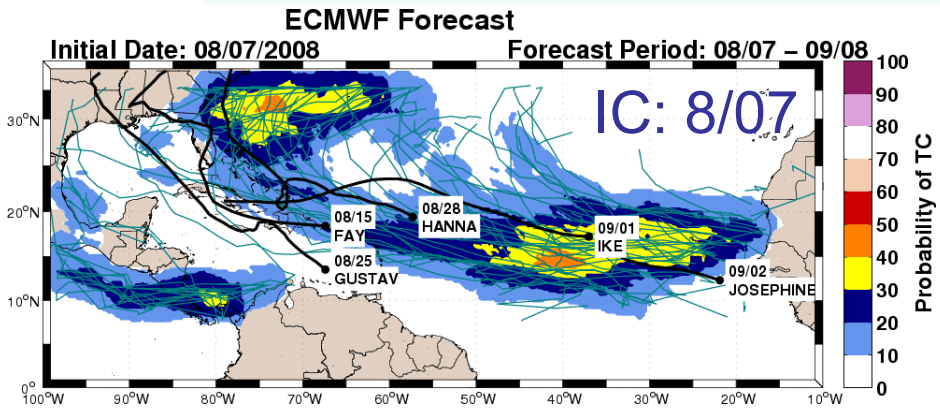


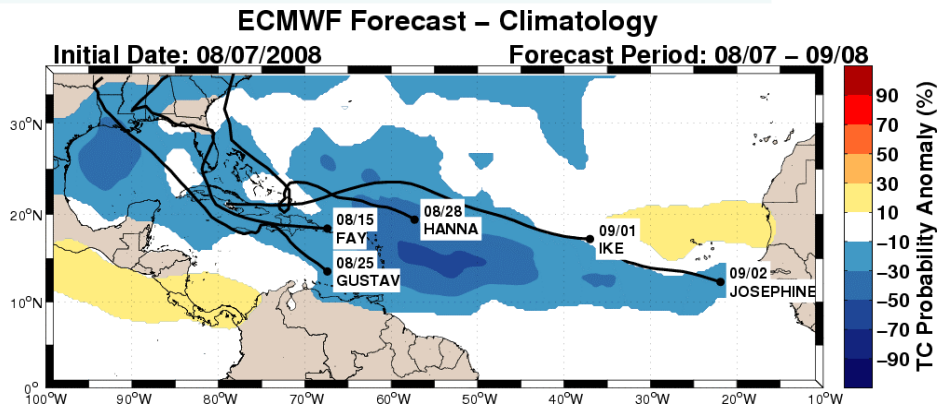
300 hPa ψ: contoured
OLR Anomalies: shaded

From Cassou (Nature; 2008)

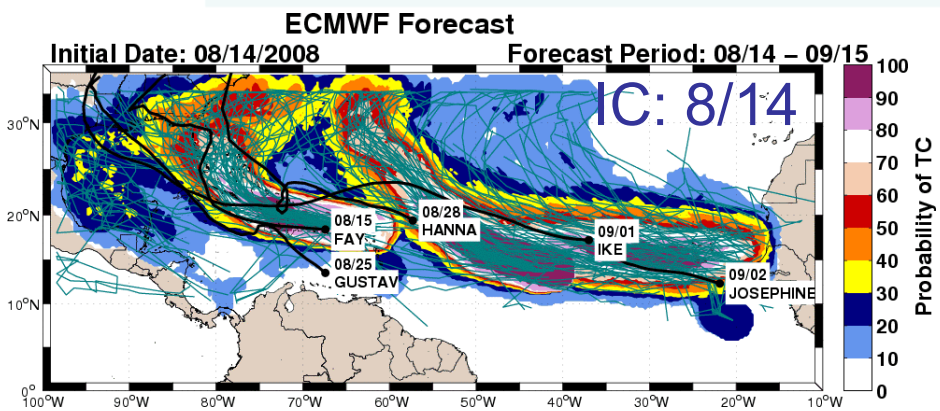
Example: ECMWF Monthly TC Forecasts

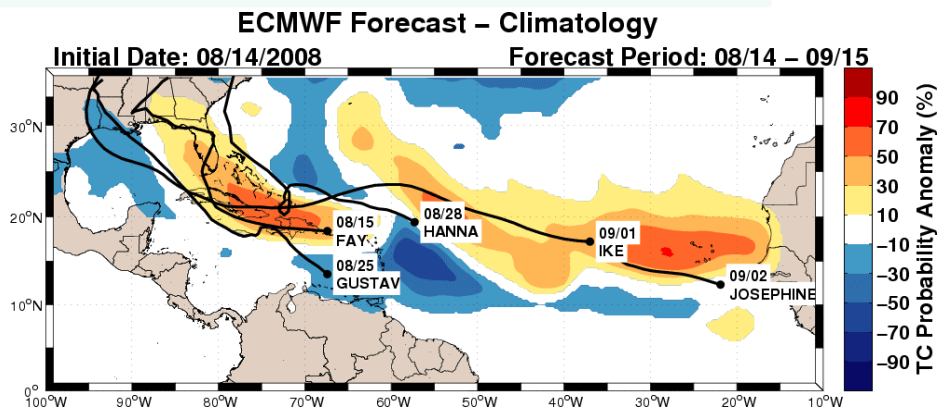
Weak Amplitude MJO @ Model Initialization



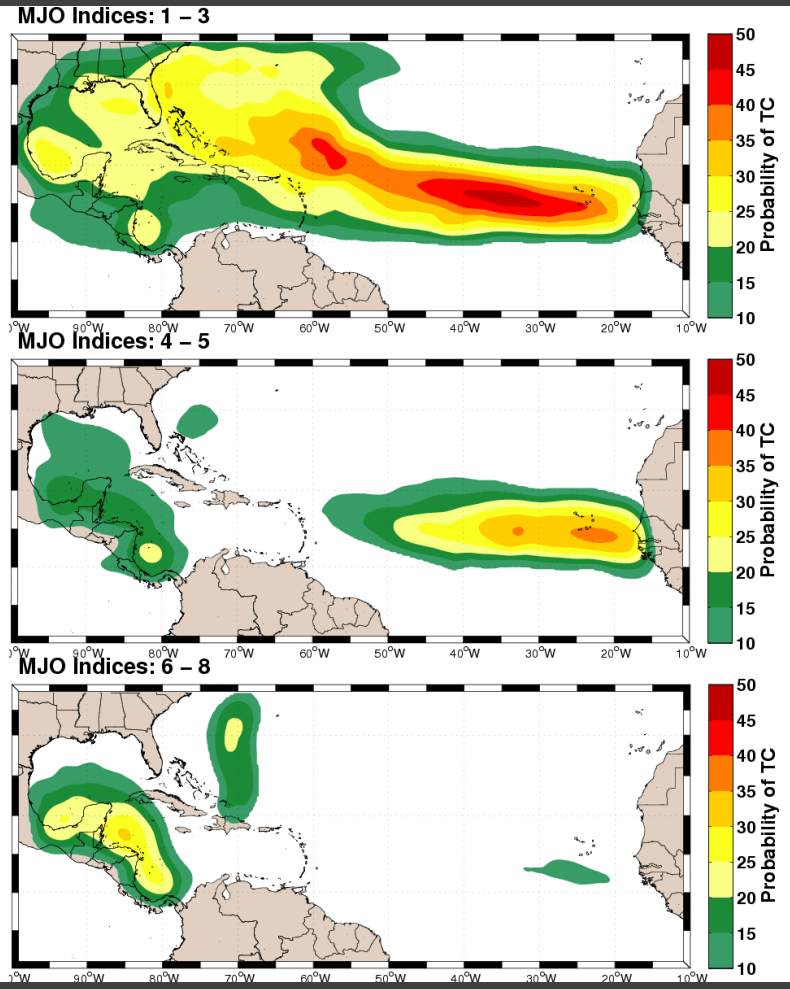


Strong Amplitude MJO @ Model Initialization



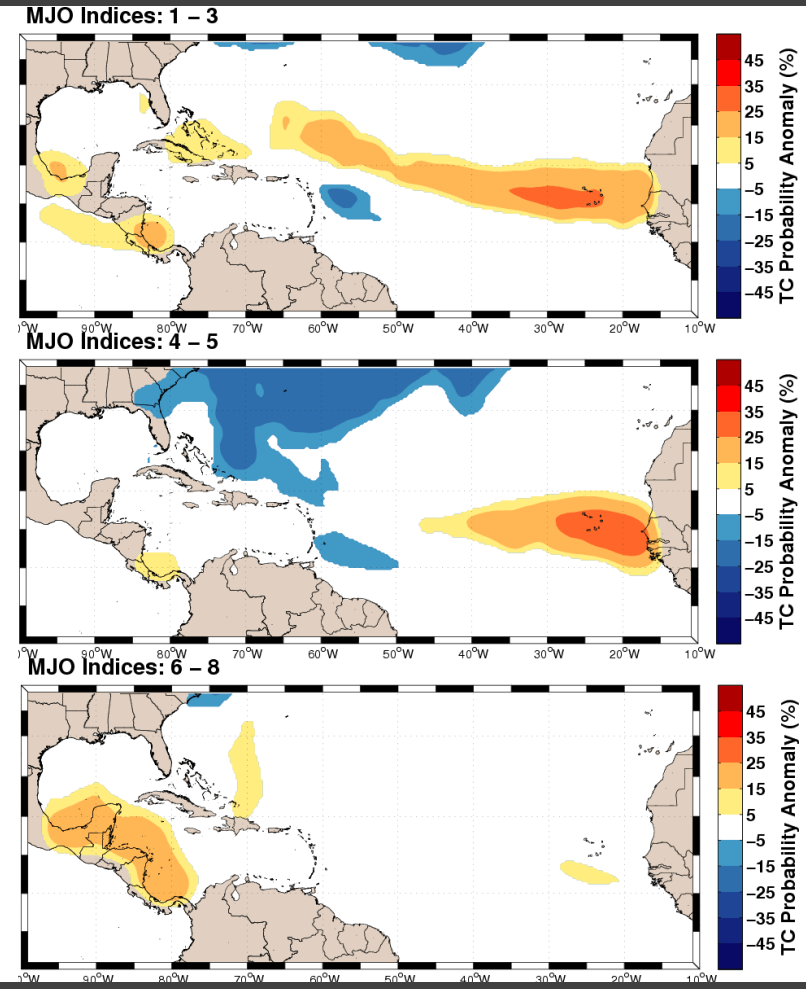


TC Probability: Full 32 Days



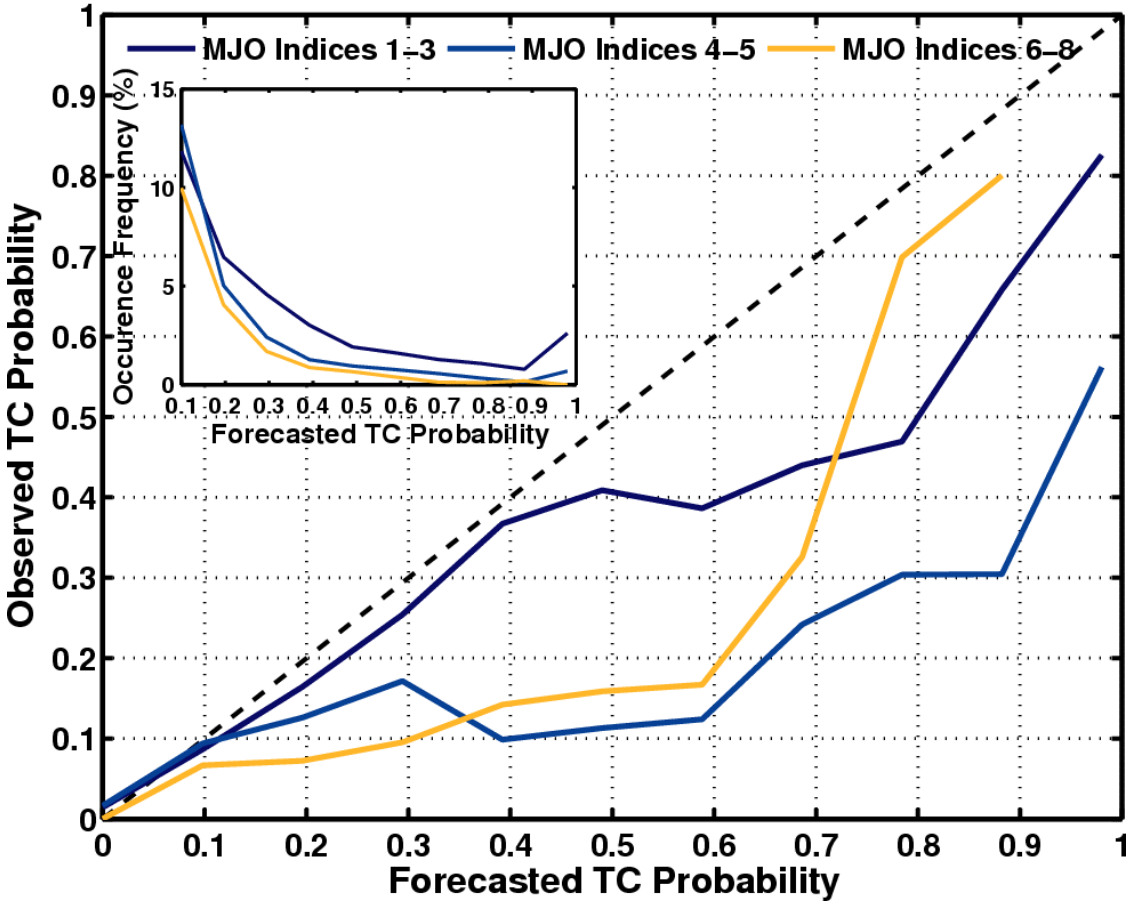
When active MJO (>1 SD) is centered in the **Indian Ocean** (**Western Hemisphere**) at model initialization, TC activity in the North Atlantic is **enhanced** (**suppresed**)

TC Anomaly: Full 32 Days



MJO phasing and intensity modulates 10-30% of TC probability forecasts for the Main Development Region and western Caribbean/southern Gulf of Mexico

Reliability of ECMWF TC Forecasts



Basis for the bias-adjustment & forecast confidence in the real-time forecast scheme of intraseasonal TC activity

- Most consistent forecasts occur when MJO centered initially in the Indian Ocean and amplitude > 1σ
- When MJO located elsewhere (or amplitude is < 1σ), reliability of the ECMWF Monthly Forecast is limited

Summary: Subseasonal Forecasts

- ECMWF monthly forecasts show ability to isolate active/break periods for TC activity regionally on intraseasonal time scales
- TC predictability tied to deep-layer wind shear forecasts and the frequency of easterly waves
- Genesis of TCs in the MDR from easterly waves has predictability through three weeks
- Improvements on intraseasonal time scales awaits better model simulations of the MJO
- Initial phase of the MJO explains 10-30% of total variance in TC forecasts across the MDR and western Caribbean
  - MJO phasing and amplitude modulates reliability of the predictions

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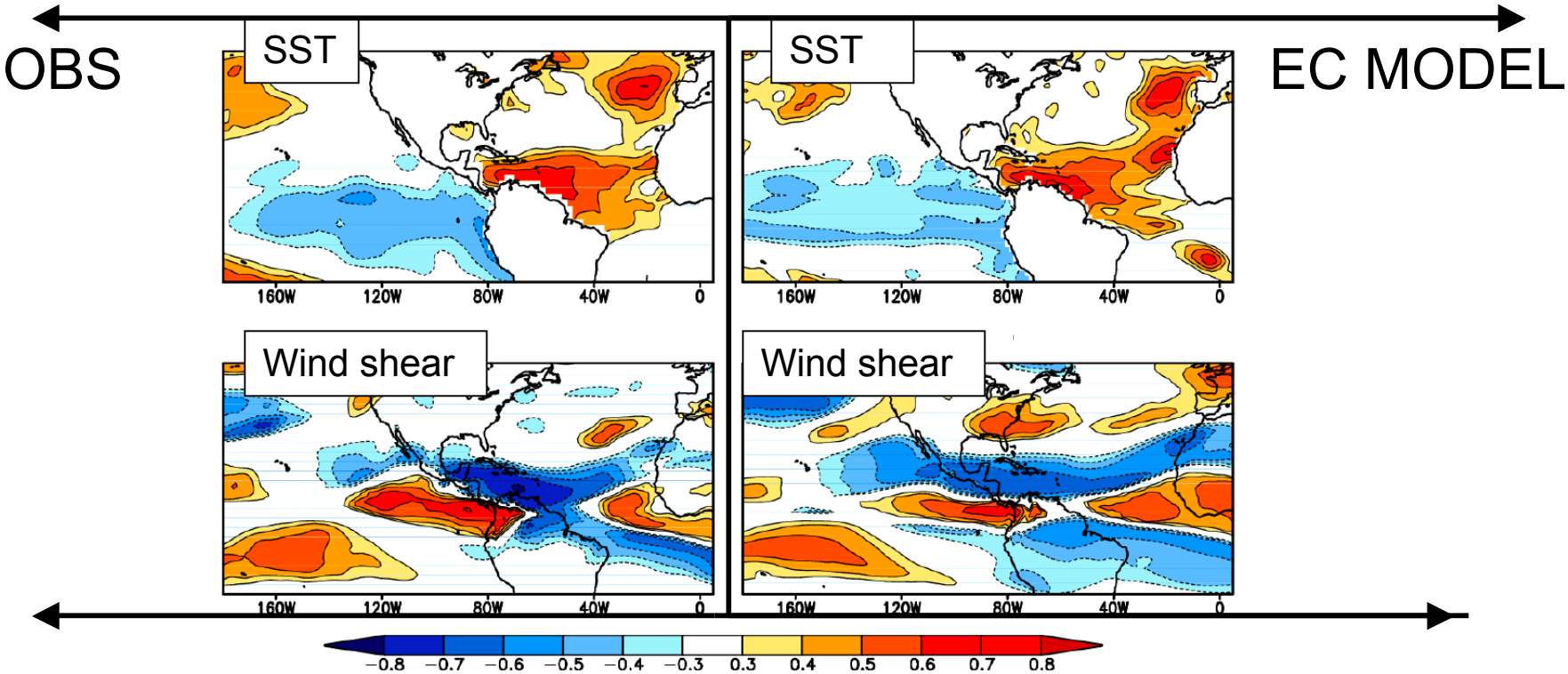
Seasonal NATL TC forecasts

– Statistical/dynamical scheme based upon ECMWF seasonal forecasts

Correlations of Observed and Modeled Fields with # Hurricanes



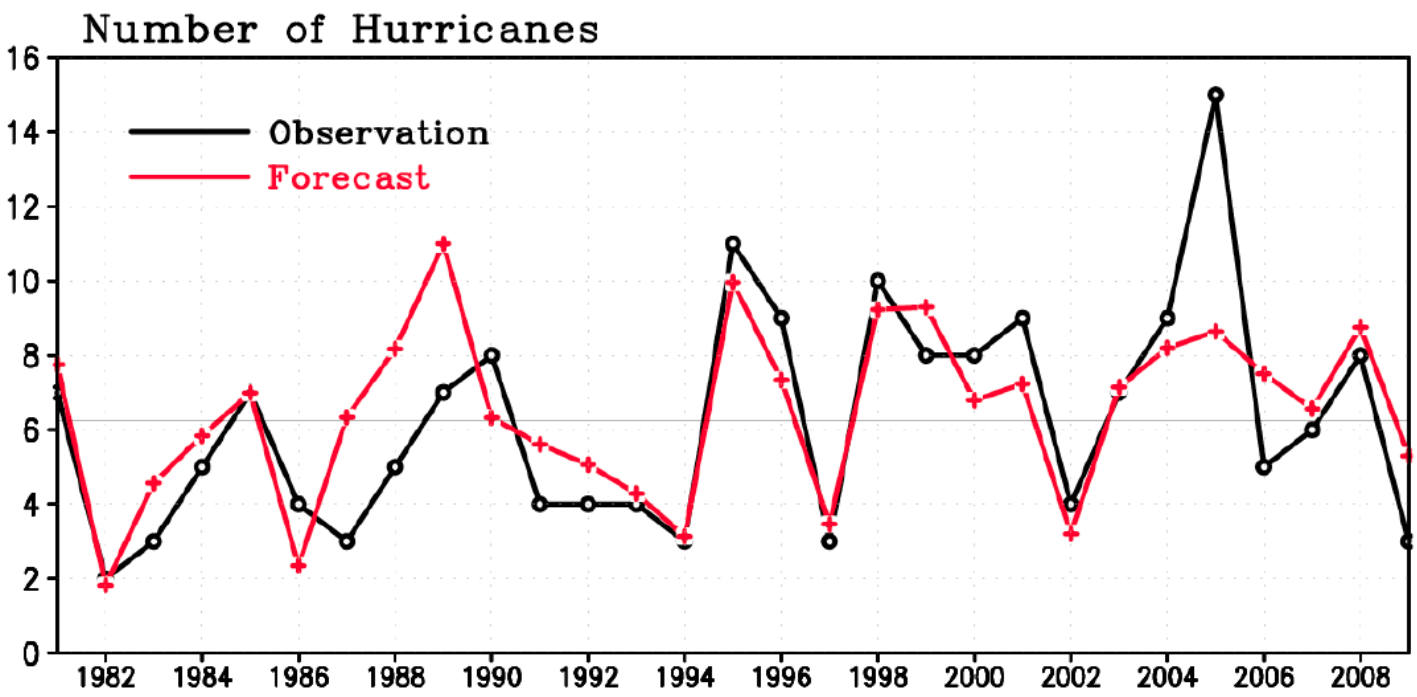
ECMWF System 3 model and observations have similar correlations with number of NATL hurricanes.

	Wind shear	MDR SST	NATL SST	NINO 3 SST	AMM
Correlation:	-0.81	0.61	0.68	-0.48	0.76

Best combination: predictors

Kim and Webster 2010

Hybrid prediction scheme:



- Uses linear regression (observations and hurricane number) to define predictors and regression coefficients.
- Uses forecasts of predictors to determine seasonal hurricane number

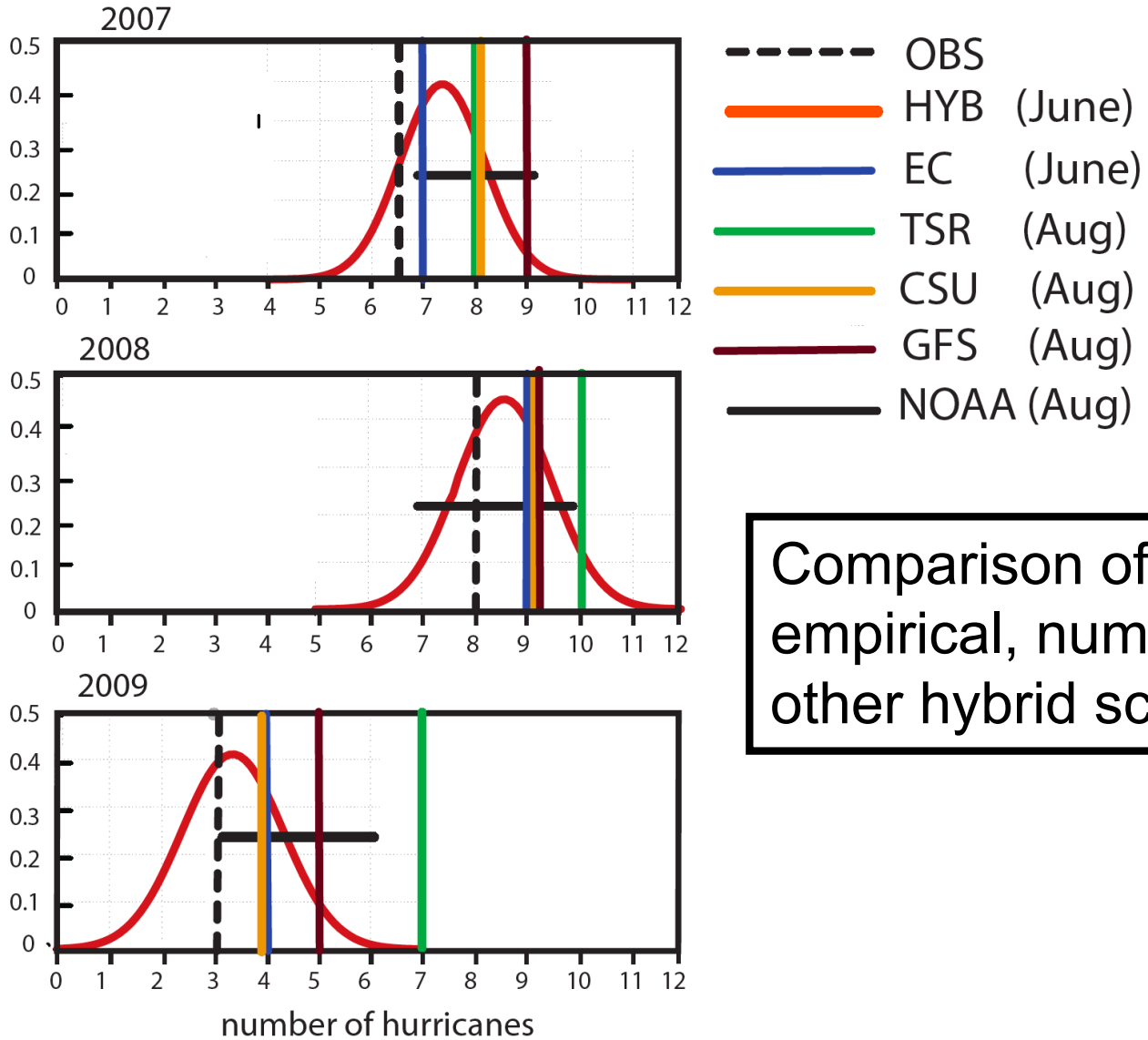
(prior to 2007, only 11 ensemble members)

JUNE HYBRID FORECASTS v ECMWF & NOAA

YEAR	OBS	HYB	NOAA	EC
Issued		Jun	Aug	Jun
2002	4	3	4-6	5
2003	7	8	7-9	8
2004	9	7	6-8	5
2005	15	9	9-11	8
2006	5	8	7-9	13
2007	6	7	7-9	7
2008	8	8	7-10	9
2009	3	4	3-6	4
RMSE		2.6 29 yr: 2.1	2.2	4.1

- Hybrid system has value added over EC forecasts
- Note longer lead time over NOAA forecasts

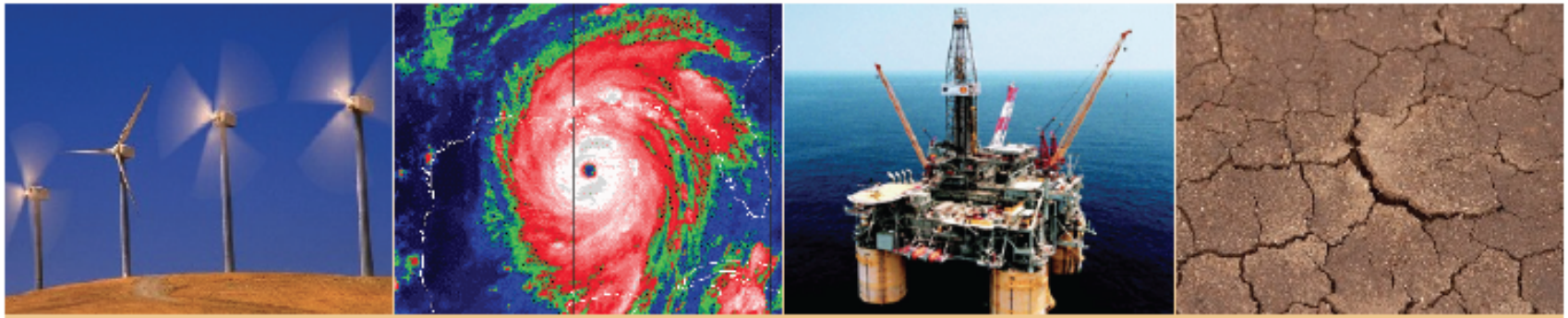
Comparison 2007-9 with 41 ensemble members



Comparison of Hybrid with empirical, numerical and other hybrid schemes

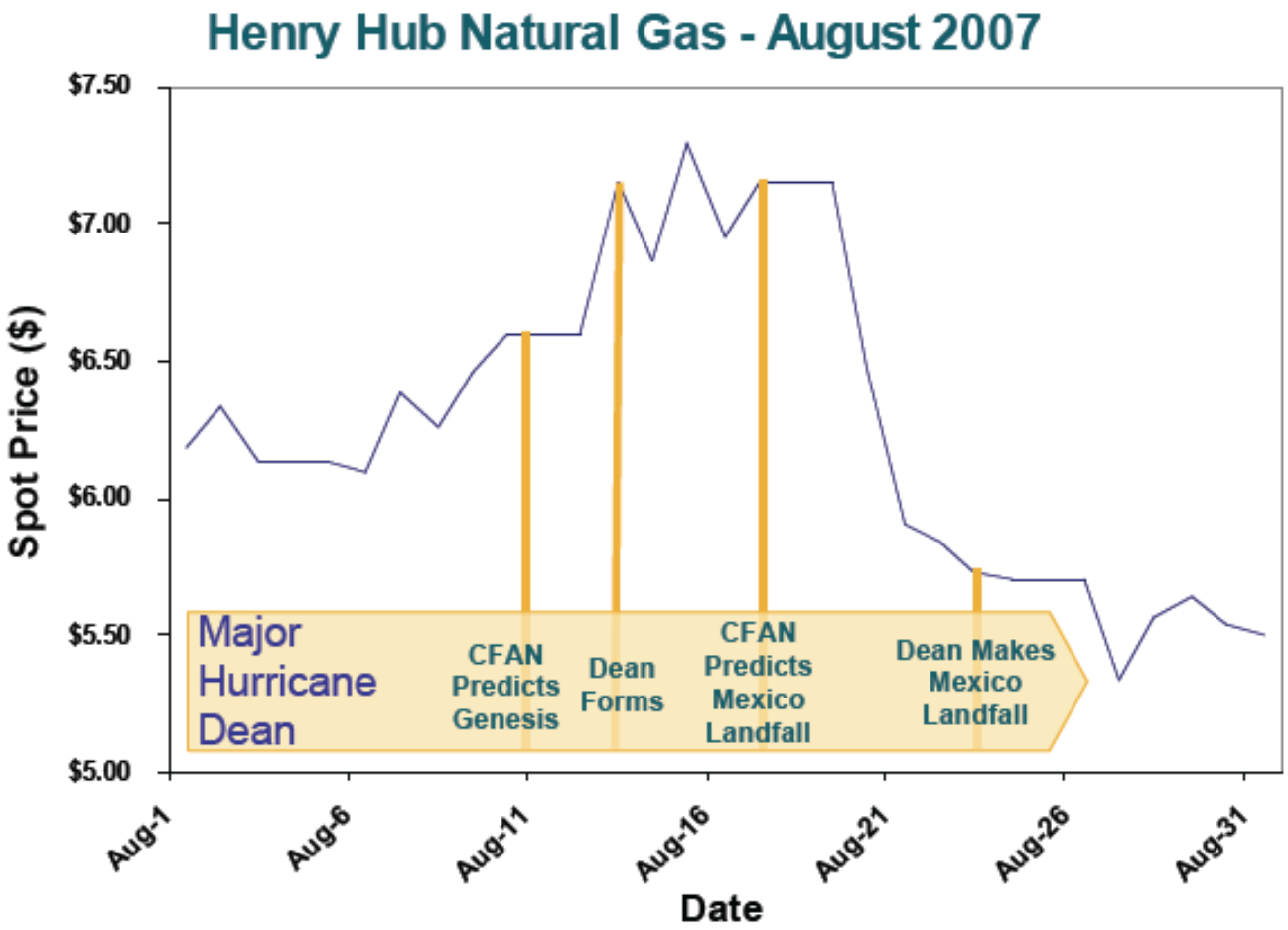
Climate Forecast Applications Network (CFAN)

December 10th 2009 – Atlanta, GA



Enabling superior risk management & decision making for your organization through innovative weather and climate tools

Supporting Decisions



Customized Products

- Weather/Climate Forecasting
  - Days to months
  - Adapted to exposure areas
  - Linked to key analytics
- Climate Impact Assessments
  - Identify organizational exposure
  - Assess adaptation options