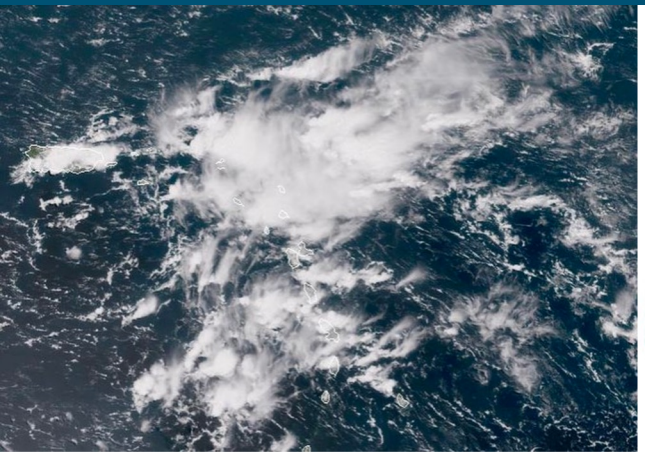
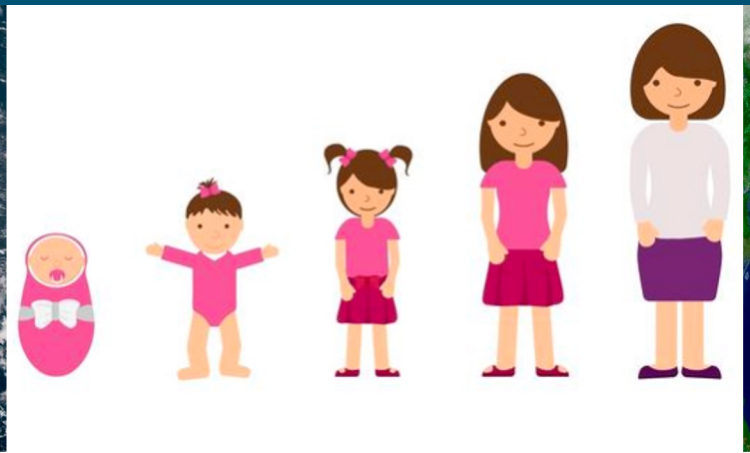
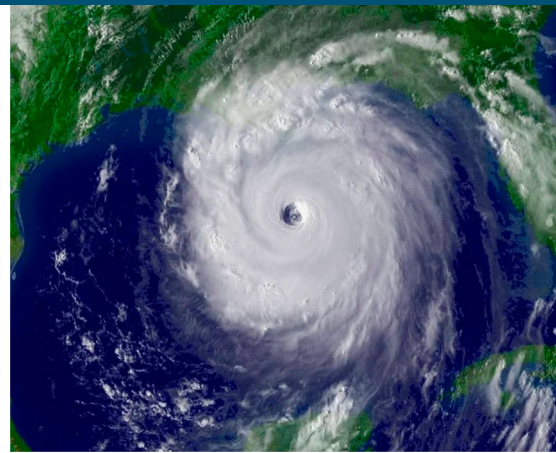
Links between African Easterly Waves and Hurricanes

Alyssa M. Stansfield, PhD
Tropical Meteorology
Guest Lecture | April 26, 2023

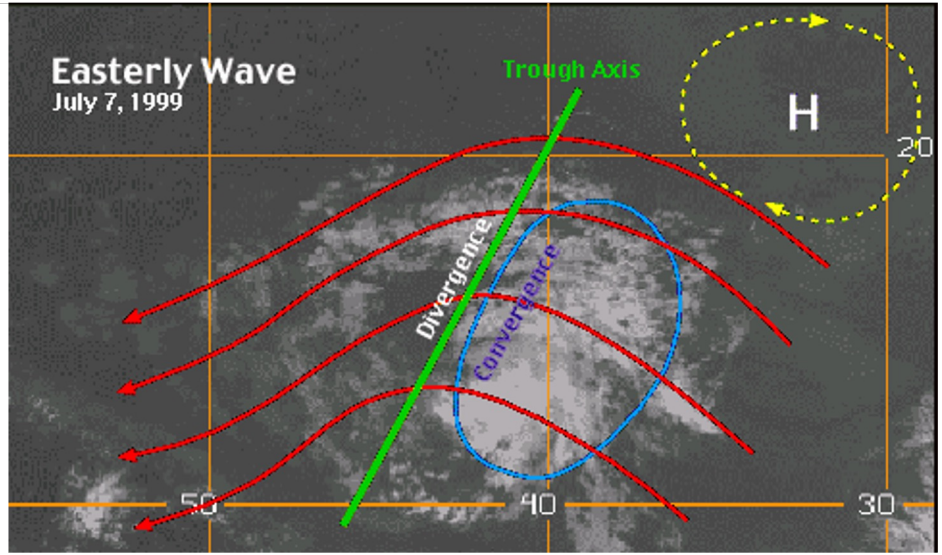




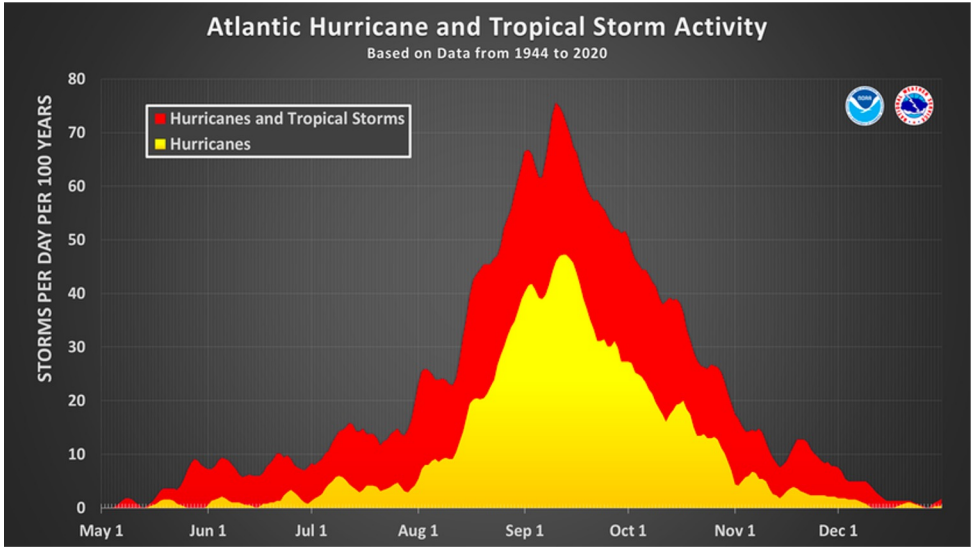


African Easterly Waves

- Synoptic-scale quasi-periodic perturbations that move westward off the coast of northern Africa
  - Wavelengths: 2,000-4,000 km
  - Period: 3-5 days
  - Speed: 5-10 m/s
  - Enhance convective activity by inducing convergence to the east of the trough axis

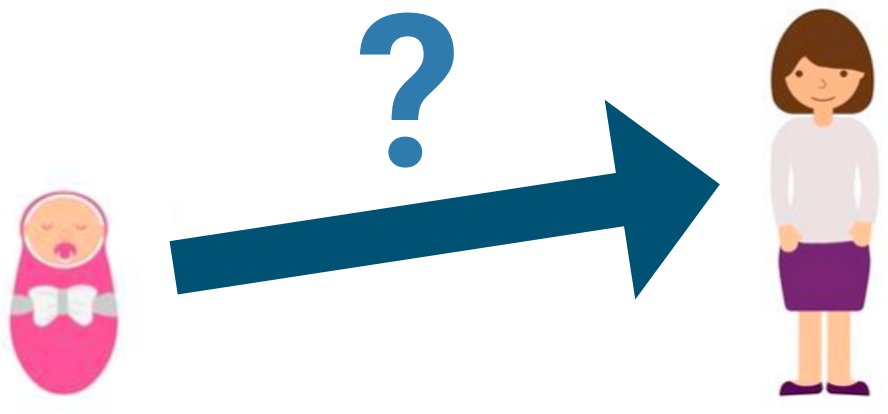


Hurricanes



- Organized, rotating low-pressure systems with maximum sustained near-surface winds of at least 74 mph
  - Lifetime: Few days to multiple weeks
  - Translation speed: 0-15 m/s
  - Diameter range: 200-1,000 km

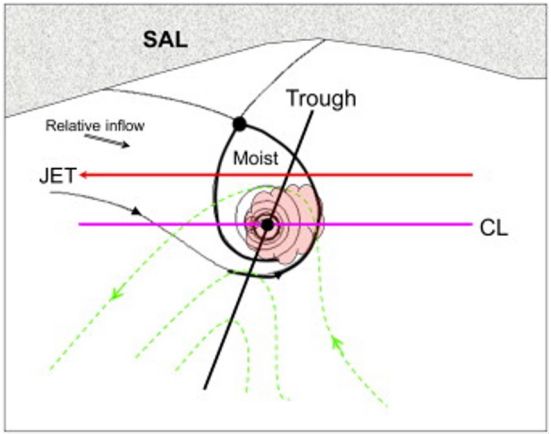
How exactly do AEWs form into tropical cyclones? What controls the number of AEW to TC transitions each year?



The “marsupial paradigm”

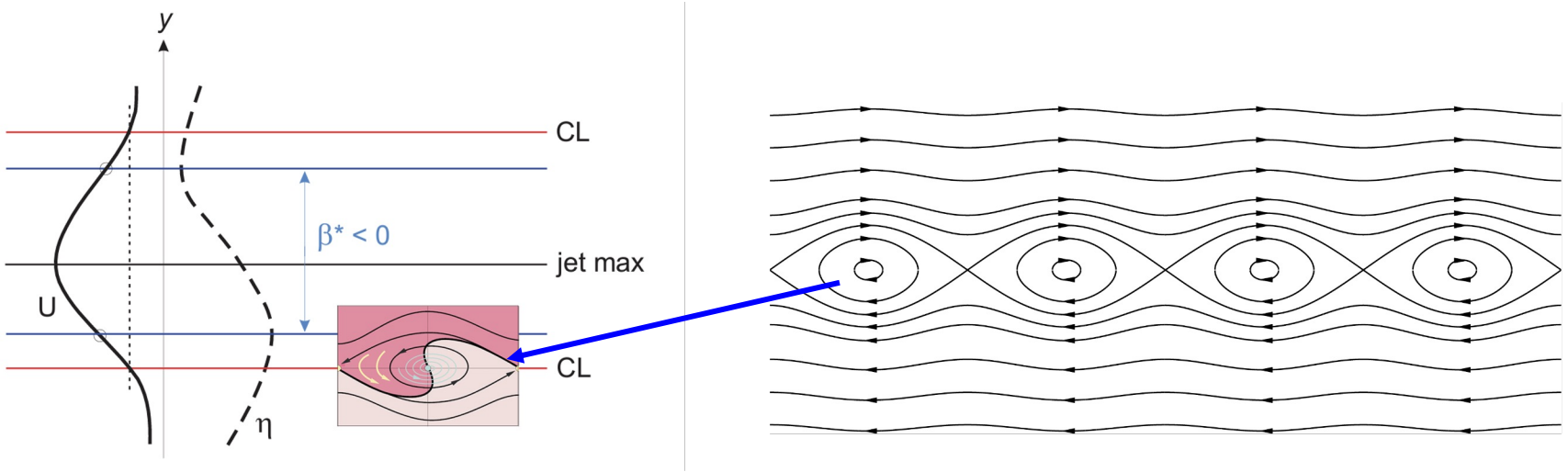
Marsupial: a type of mammal that is not completely developed when it is born and is carried around in a pouch on the mother's body, where it is fed and protected until it is completely developed

Theory to describe transition from easterly wave to tropical depression whereby the easterly wave can “create a **closed gyre or ‘pouch’** and subsequently within the pouch, a proto-vortex or ‘embryo’ favorable for hurricane formation.”



Kelvin's Cat's Eye in Streamflows

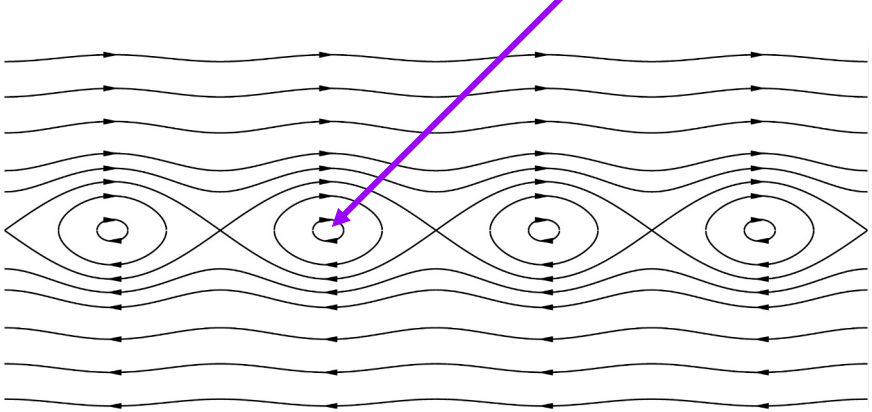
In flow with easterly jet, critical layer (or latitude) occurs where the zonal wind speed = phase speed of the easterly waves. When **viewed from frame of reference moving at phase speed**, there are cutoff stagnation points in the streamflow.



Dunkerton, T. J., Montgomery, M. T., and Wang, Z.: Tropical cyclogenesis in a tropical wave critical layer: easterly waves, Atmos. Chem. Phys., 9, 5587–5646, https://doi.org/10.5194/acp-9-5587-2009, 2009.

The “marsupial pouch”

Environmental flow moves around closed-off stagnation points (i.e., the “pouch”)



*Remember flow only appears this way in Lagrangian perspective moving at phase speed of waves, not Eulerian perspective

Dunkerton, T. J., Montgomery, M. T., and Wang, Z.: Tropical cyclogenesis in a tropical wave critical layer: easterly waves, Atmos. Chem. Phys., 9, 5587–5646, https://doi.org/10.5194/acp-9-5587-2009, 2009.

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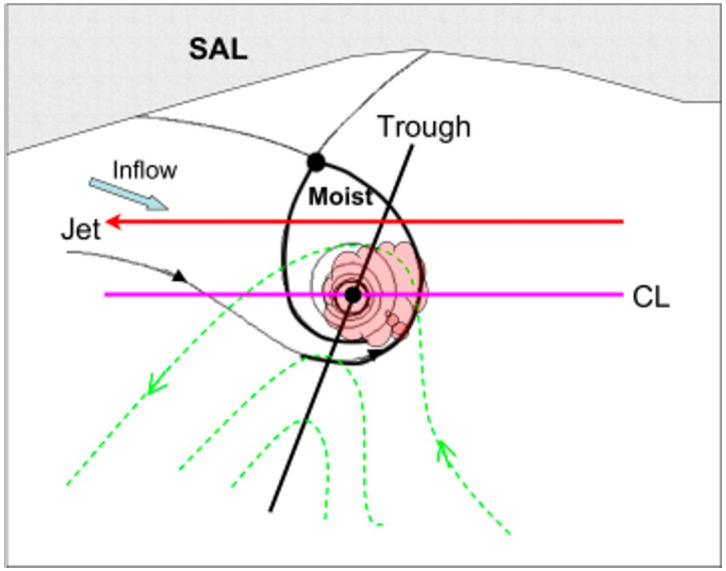
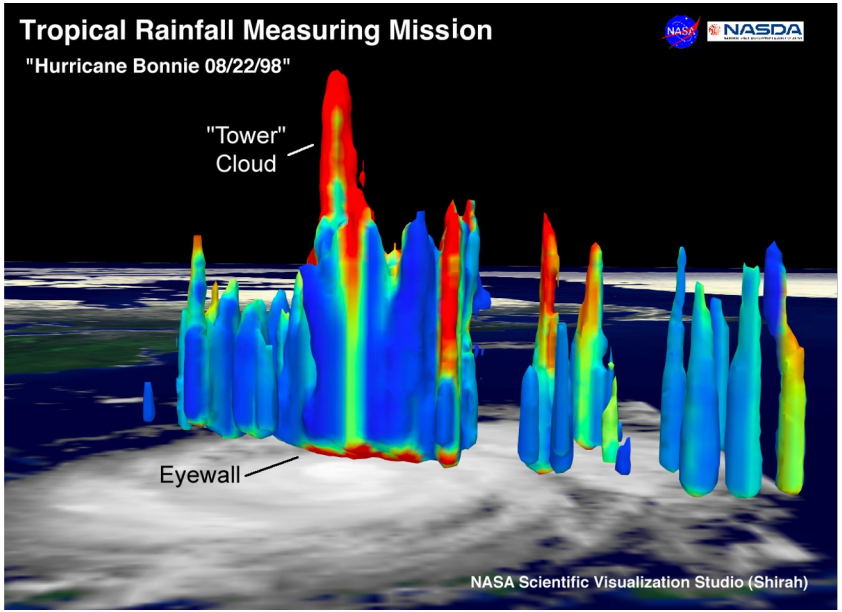


- The closed circulation associated with the *pouch tends to protect the air within it* from hostile environmental air (e.g., relatively dry air from the Saharan Air Layer)
  - Moist air within the pouch supports convection
- TC genesis preferentially occurs at the intersection of the critical latitude and the trough axis
  - When tropical depression develops a strong enough circulation, it gains a northward component of motion (due to beta drift) and separates from its pouch

Dunkerton, T. J., Montgomery, M. T., and Wang, Z.: Tropical cyclogenesis in a tropical wave critical layer: easterly waves, Atmos. Chem. Phys., 9, 5587–5646, https://doi.org/10.5194/acp-9-5587-2009, 2009.

Bottom-Up Genesis Theory



- Convection within pouch creates vertical profile of heating with maximum in lower to mid-troposphere
  - More like deep convection heating profile instead of top-heavy profile that dominates most of tropics
- Deep convective heating profile favors low-level convergence and vorticity amplification through vortex stretching
  - Multiple individual deep, rotating convective updrafts (known as vortical hot towers or VHTs) develop within the wave's pre-existing cyclonic vorticity and eventually consolidate together to form a surface circulation center

Hendricks, E. A., M. T. Montgomery, and C. A. Davis, 2004: The Role of "Vortical" Hot Towers in the Formation of Tropical Cyclone Diana (1984). *J. Atmos. Sci.*, **61**, 1209–1232, https://doi.org/10.1175/1520-0469(2004)061<1209:TROVHT>2.0.CO;2.

Top-Down Genesis Theory

1. Mergers of multiple MCSs in the wave increase the size and strength of the mid-level vortex, which then induces a surface circulation through vortex stretching

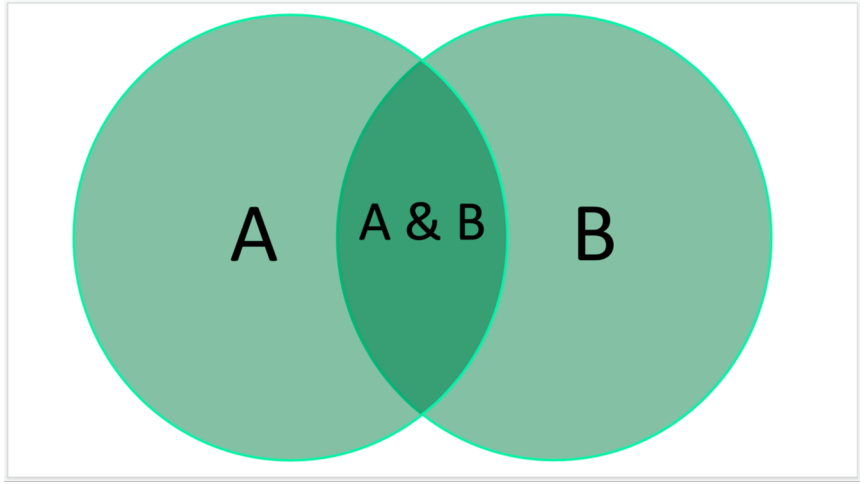
Ritchie, E. A., and G. J. Holland, 1997: Scale Interactions during the Formation of Typhoon Irving. *Mon. Wea. Rev.*, **125**, 1377–1396, https://doi.org/10.1175/1520-0493(1997)125<1377:SIDTFO>2.0.CO;2.

2. Existing MCSs in the wave moisten and cool the mid and lower troposphere through evaporation of precipitation, leading to a cold-core mid-level vortex which then expands downward towards the surface
    - Vortex enhances sea surface fluxes and cold core lowers values of equivalent

Bister, M., and K. A. Emanuel, 1997: The Genesis of Hurricane Guillermo: TEXMEX Analyses and a Modeling Study. *Mon. Wea. Rev.*, **125**, 2662–2682, https://doi.org/10.1175/1520-0493(1997)125<2662:TGOHGT>2.0.CO;2.

Which Genesis Theory is correct?

- Probably both
  - Some storms probably develop bottom-up and some top-down
  - Depending on type of pre-existing disturbance, genesis location, environment, random chance, etc…
- There are observational and modeling studies that support both theories!



Why is TC genesis still not well understood?

- Operational efforts (e.g., hurricane hunter flights) usually target mature TCs
- Lack of in-situ observations over remote tropical oceans
- Small-scale processes and interactions are difficult to observe and model

PREDICT Field Campaign (2010)

PRE-Depression Investigation of Cloud-Systems in the Tropics

- Field campaign involving 25 flights into North Atlantic tropical disturbances to explore TC genesis
  - Collected profiles of pressure, temperature, water vapor, and wind and microphysics measurements (e.g., liquid water content, CCN, aerosols)

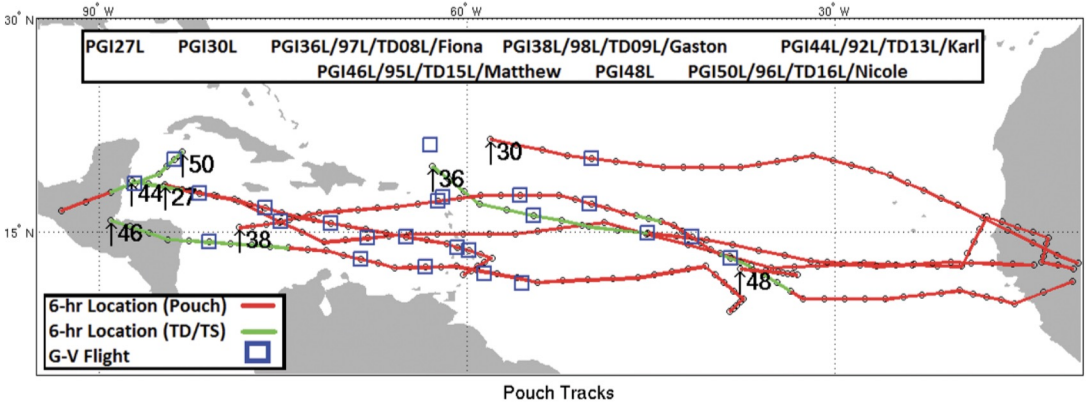
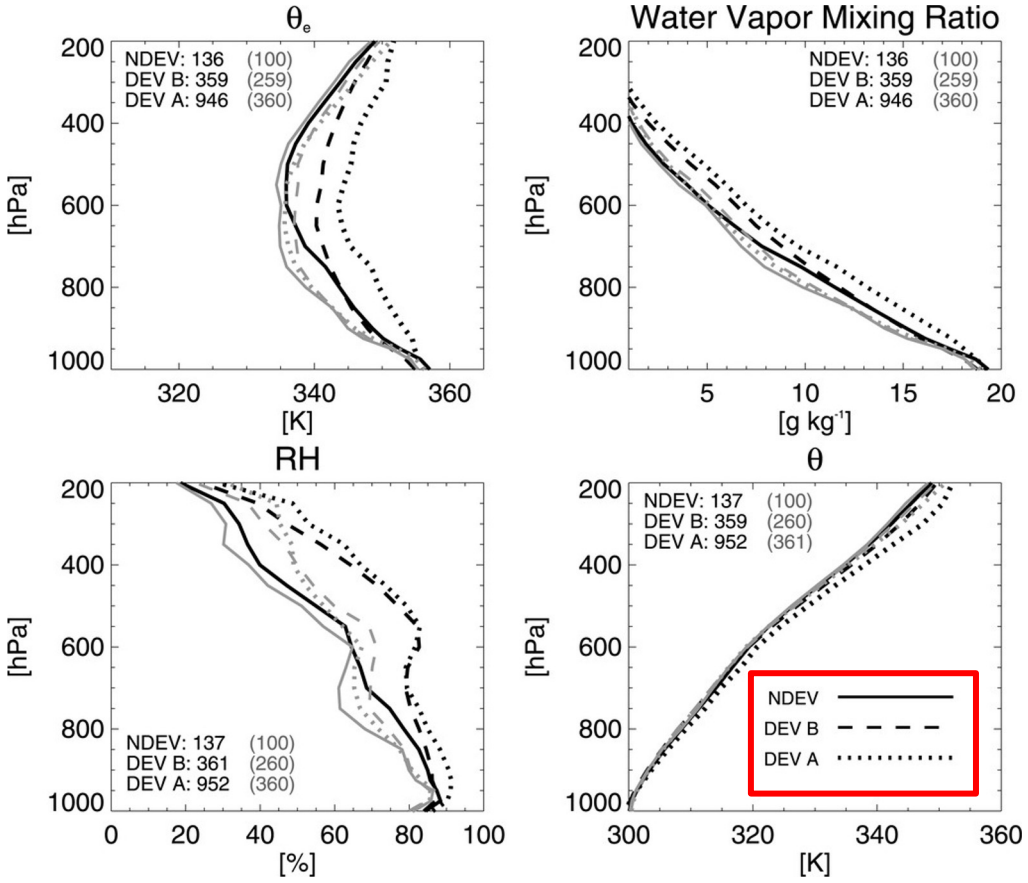


Fig. 11. Pouch tracks for systems that were flown by the GV during PREDICT. The values at the track endpoints indicate the PGI number designations.

Montgomery, M. T., and Coauthors, 2012: The Pre-Depression Investigation of Cloud-Systems in the Tropics (PREDICT) Experiment: Scientific Basis, New Analysis Tools, and Some First Results. *Bull. Amer. Meteor. Soc.*, **93**, 153–172, https://doi.org/10.1175/BAMS-D-11-00046.1.

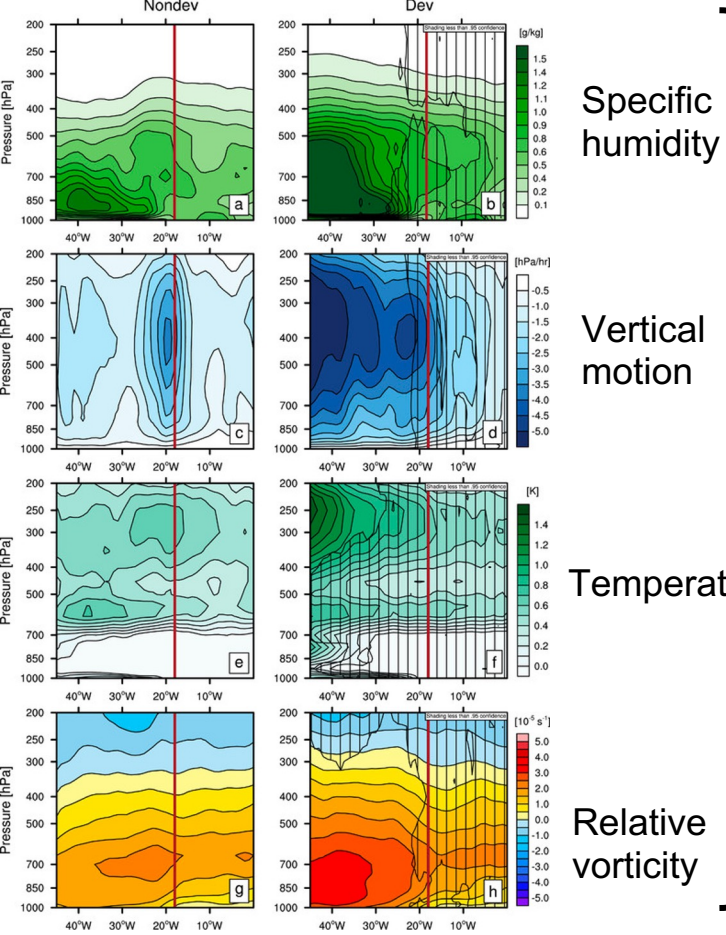
- Larger differences in moisture-related variables than for potential temperature
- Developing systems (pre-genesis) have higher RH, larger WVMR, and higher equivalent potential temperature than non-developing systems

- Larger differences between non-developing and developing for inner-core profiles than environment profiles
- Environment and inner-core profiles most similar for non-developers (protecting "pouch" is weaker?)



Black profiles: inner core (0-3°)
Gray profiles: environment (3-7°)

Zawislak, J., and E. J. Zipser, 2014: Analysis of the Thermodynamic Properties of Developing and Nondeveloping Tropical Disturbances Using a Comprehensive Dropsonde Dataset. *Mon. Wea. Rev.*, **142**, 1250–1264, https://doi.org/10.1175/MWR-D-13-00253.1.



Specific humidity

Vertical motion

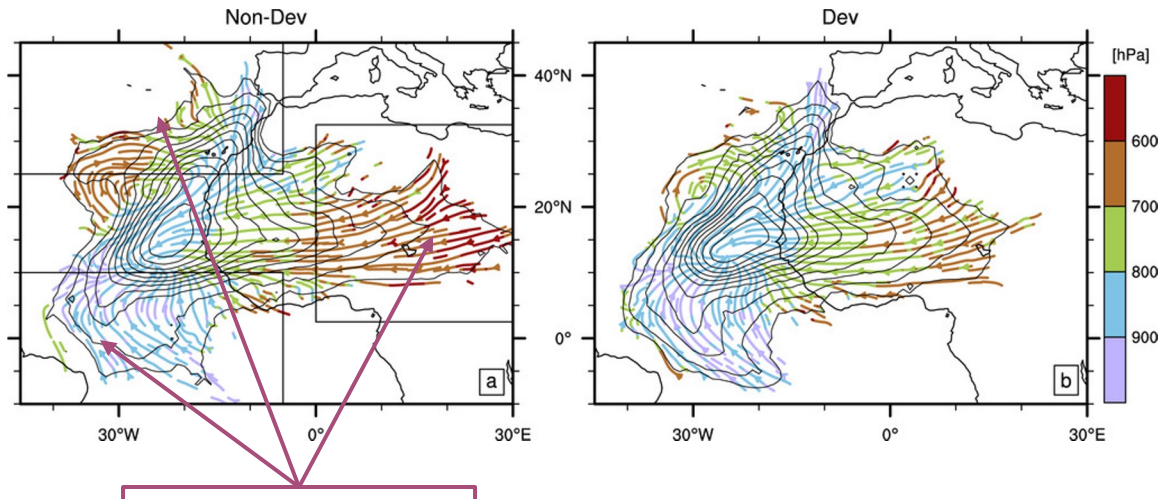
Temperature

Relative vorticity

-Evolution of trough-centered variables for favorable waves only
-Hatched regions = not statistically significantly different from non-developing composite
-Brown line = approximate location of west African coast

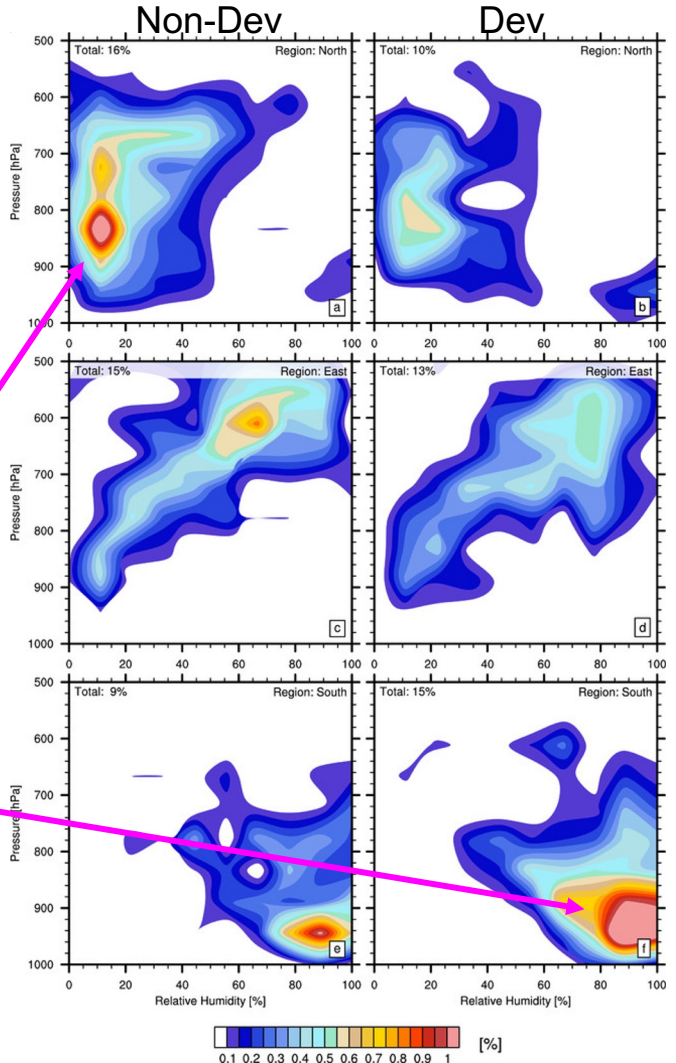
- Non-developers weaken rapidly after moving over ocean
- Moisture, vorticity, temperature, and upward motion increase for both composites, but much more for developers

Brammer, A., and C. D. Thorncroft, 2015: Variability and Evolution of African Easterly Wave Structures and Their Relationship with Tropical Cyclogenesis over the Eastern Atlantic. *Mon. Wea. Rev.*, **143**, 4975–4995, https://doi.org/10.1175/MWR-D-15-0106.1.



3 main regions of inflow for both developers and non-developers

1. Non-developers have more relatively dry air flowing in from mid-troposphere North region
2. Developers have more relatively moist air flowing in from low-levels from the South region



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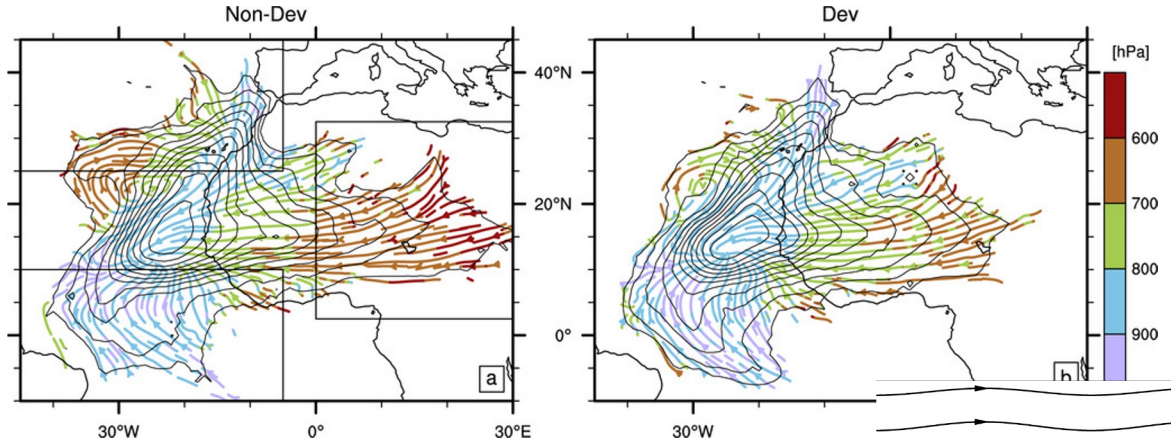
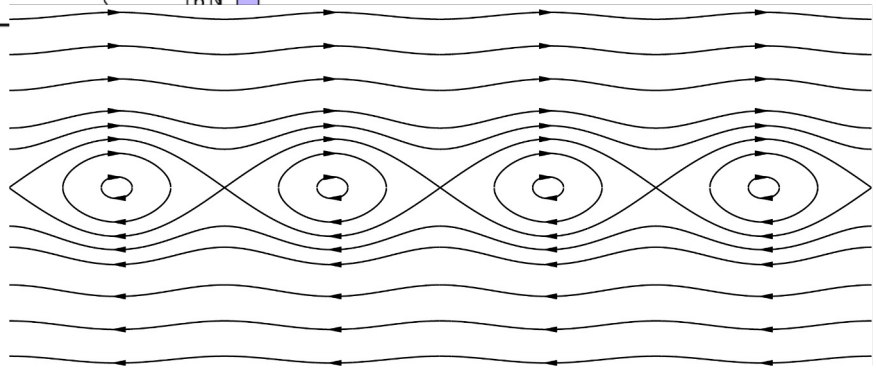
Do inflow focused results from Brammer and Thorncroft (2015) conflict with marsupial pouch paradigm?





Do inflow focused results from Brammer and Thorncroft (2015) conflict with marsupial pouch paradigm?

Not really. Some reasoning:

- In real world, pouches are not going to be perfectly “sealed off” from environmental flow
- Kelvin’s cat’s eye develops around vertical level of African Easterly Jet, so low-levels in trough still susceptible to environment
  - Perhaps developing waves have re-circulating air over larger vertical extent?
- As waves move westward, they tend to develop stronger low-level circulation and then could be less susceptible to inflowing air
  - This study only looked at waves near African coast, so this sensitivity may be limited to waves in this region

So on small-scale, TC genesis is still not completely understood….

But what about on larger (seasonal to climate) timescales?

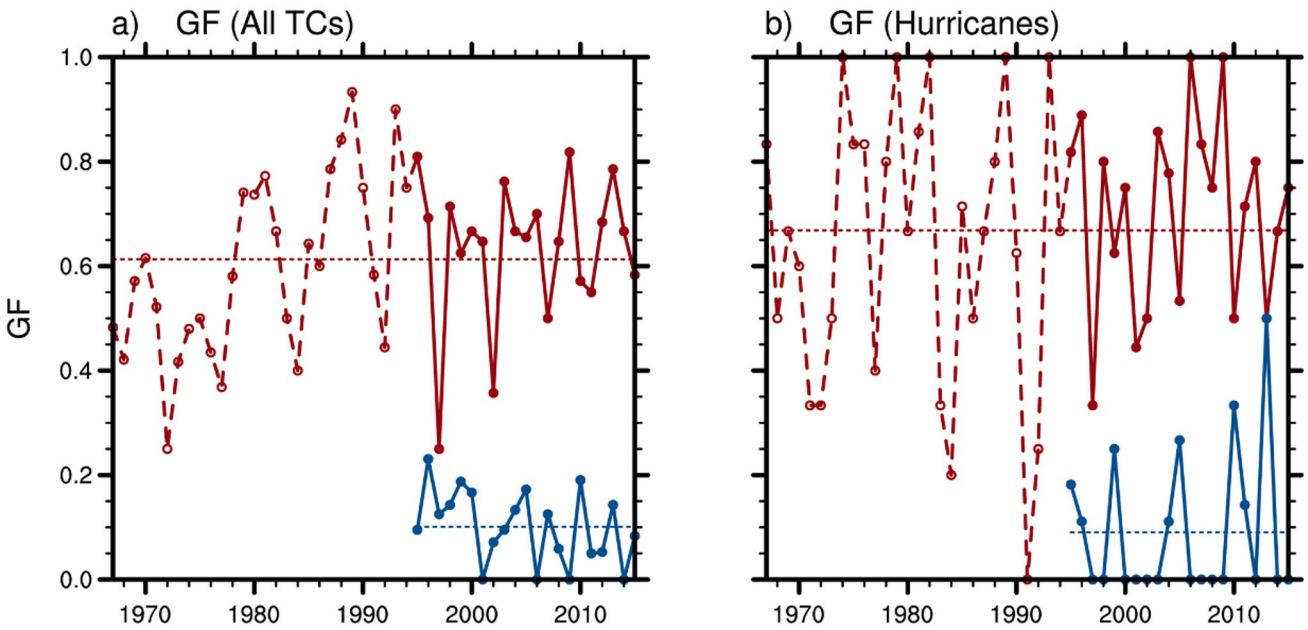
What percentage of North Atlantic TCs every year have origins related to AEWs?

~75% of N. Atlantic tropical cyclones have origins related to AEWs

~81% of hurricanes

Russell, J. O., Aiyyer, A., White, J. D., and Hannah, W. (2017), Revisiting the connection between African Easterly Waves and Atlantic tropical cyclogenesis, *Geophys. Res. Lett.*, 44, 587– 595, doi:10.1002/2016GL071236.

How many TCs form from AEWs?



GF = Genesis fraction

- Plenty of interannual variability, more for hurricanes vs all TCs

Russell, J. O., Aiyyer, A., White, J. D., and Hannah, W. (2017), Revisiting the connection between African Easterly Waves and Atlantic tropical cyclogenesis, *Geophys. Res. Lett.*, 44, 587– 595, doi:10.1002/2016GL071236.


What percentage of AEWs turn into North Atlantic TCs?

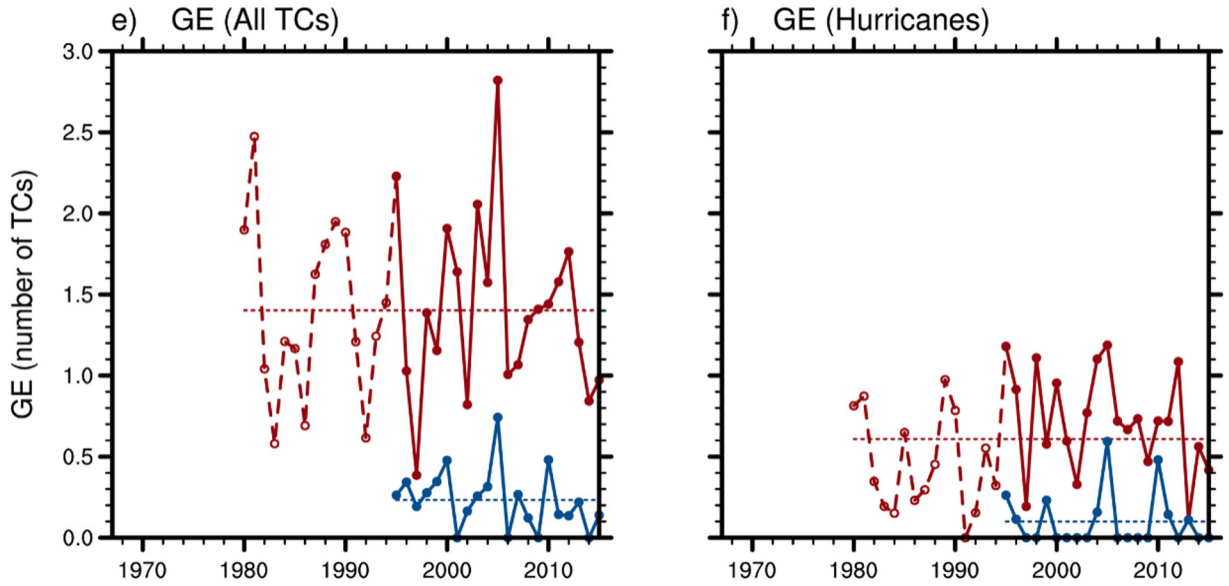
~14% of AEWs turn into tropical cyclones

~3% into major hurricanes

Agudelo, P.A., Hoyos, C.D., Curry, J.A. *et al.* Probabilistic discrimination between large-scale environments of intensifying and decaying African Easterly Waves. *Clim Dyn* 36, 1379–1401 (2011). https://doi.org/10.1007/s00382-010-0851-x

How many AEWs form into TCs?

GE (genesis efficiency) = genesis number/seasonal-mean EKE



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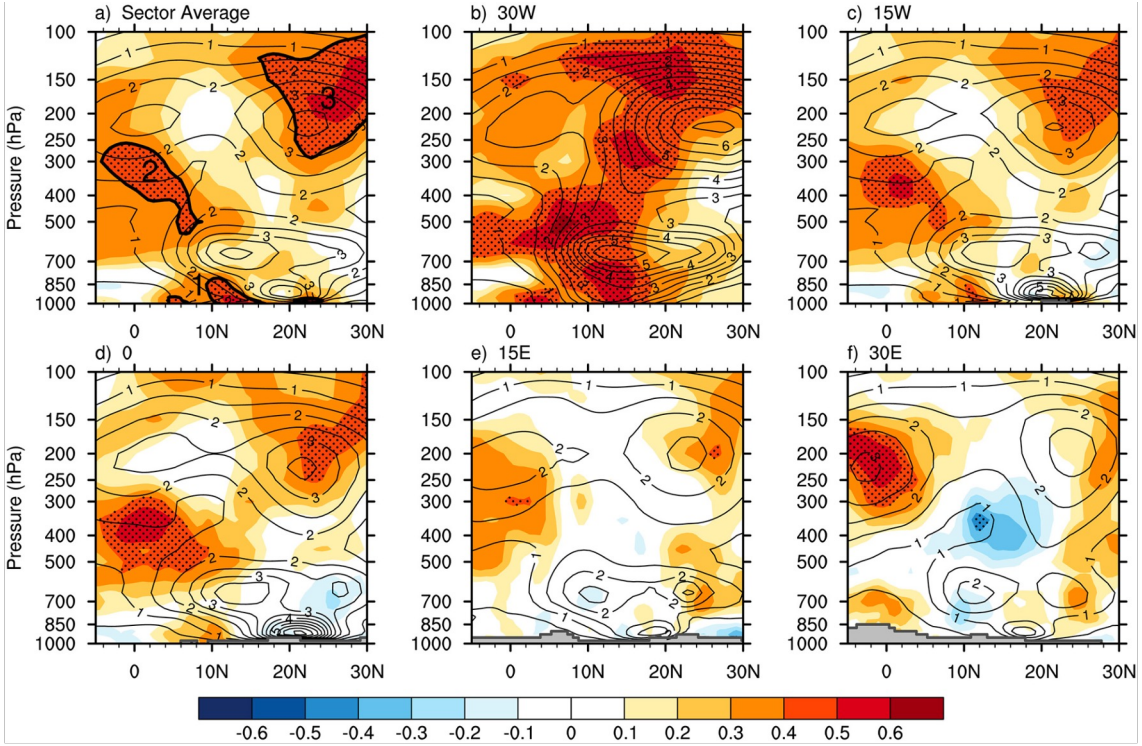
Correlations between TC Genesis Number and seasonal-mean EKE are not strong



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Relatively low correlations between TC Genesis Number and seasonal-mean EKE

&

~75% of N. Atlantic tropical cyclones have origins related to AEWs

???

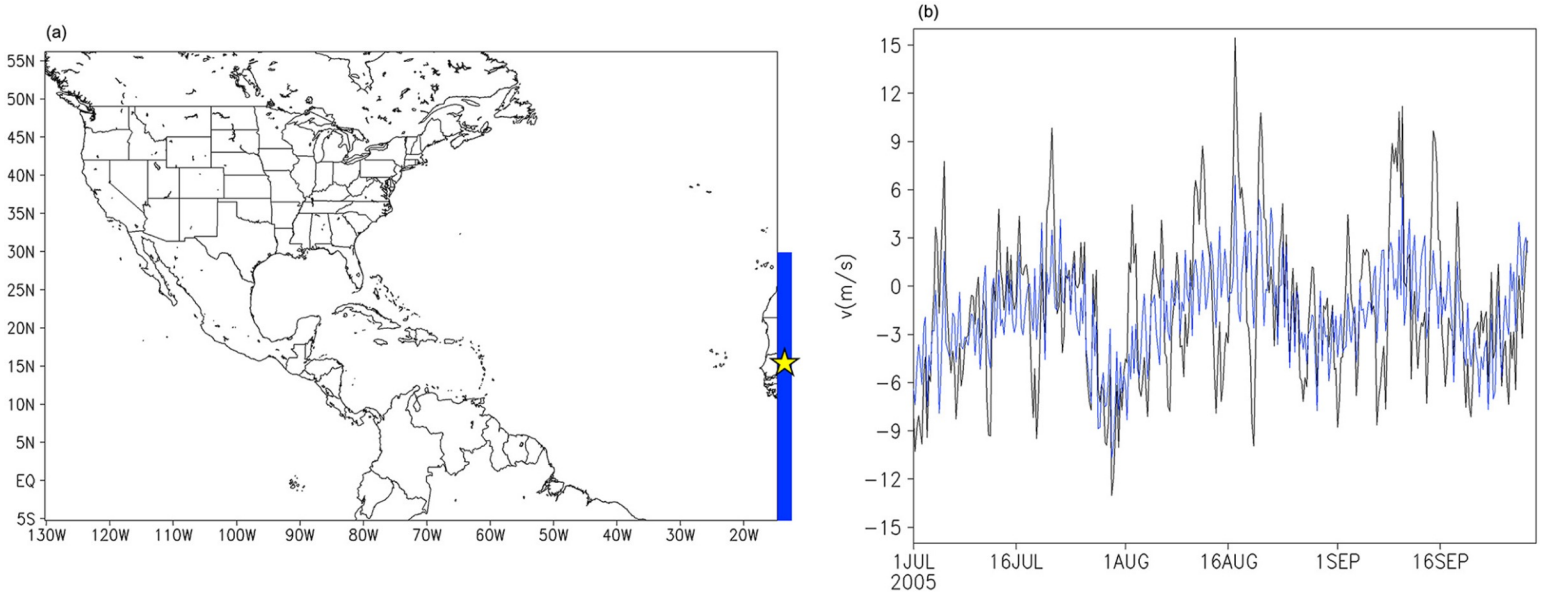
"These relatively low correlations indicate that TC genesis is governed by factors other than AEW activity such as ocean heat content, wind shear, and the large-scale circulation [*Gray*, 1984]." - From Russell et al. 2017

Recent modeling studies support the hypothesis that the global TC genesis is primarily controlled by the spatiotemporal distribution of favorable environmental conditions, not the number of precursor disturbances

Hoogewind, K. A., D. R. Chavas, B. A. Schenkel, and M. E. O'Neill, 2020: Exploring Controls on Tropical Cyclone Count through the Geography of Environmental Favorability. *J. Climate*, **33**, 1725–1745, https://doi.org/10.1175/JCLI-D-18-0862.1.

Emanuel, K., 2022: Tropical Cyclone Seeds, Transition Probabilities, and Genesis. *J. Climate*, **35**, 3557–3566, https://doi.org/10.1175/JCLI-D-21-0922.1.

What would happen in a N. Atlantic without AEWs?



- 27 km WRF simulations of 2005 hurricane season (10-member ensembles)
  - **Control: lateral boundary conditions prescribed by reanalysis**
  - AEW-suppressed: AEWs filtered out of boundary conditions

Patricola, C. M., Saravanan, R., & Chang, P. (2018). The response of Atlantic tropical cyclones to suppression of African easterly waves. *Geophysical Research Letters*, 45, 471– 479. https://doi.org/10.1002/2017GL076081

	Control	AEW suppressed	% change	*p* value
Number of TCs/season	19.5	20.2	+4%	0.64
Number of TC days/season	105	117	+11%	0.17
ACE (10^4 kt^2)	168	192	+15%	0.07

AEW-suppressed ensembles have more TCs, TC days, and Accumulated Cyclone Energy (ACE) than the control!

"This indicates that AEWs are not necessary to maintain climatological basin-wide TC frequency, even though TCs readily originate from these types of disturbances."

Patricola, C. M., Saravanan, R., & Chang, P. (2018). The response of Atlantic tropical cyclones to suppression of African easterly waves. *Geophysical Research Letters*, 45, 471– 479. https://doi.org/10.1002/2017GL076081

How else do the TCs form in these simulations?

- Patricola et al. 2018 suggests that **type** of pre-existing disturbance is unimportant for determining seasonal Atlantic TC counts
  - In absence of AEWs, TCs will generate from other low pressure disturbances
    - Likely just wavelike disturbances associated with the ITCZ

Caveats:
1) Only examined 1 active TC season. Would results be different for inactive season?
2) AEWs may be more important for TC genesis locations and landfall activity

Patricola, C. M., Saravanan, R., & Chang, P. (2018). The response of Atlantic tropical cyclones to suppression of African easterly waves. *Geophysical Research Letters*, 45, 471– 479. https://doi.org/10.1002/2017GL076081

TC-AEW Relationship in Climate Models

Annual Mean Counts of AEWs and TCs in Current and Future Simulations in 3 Climate Models with Resolutions of 25-50 km

	EC-Earth3p-HR		CMCC-CM2-VHR4		HadGEM3-GC31-HM	
	AEWs	TCs	AEWs	TCs	AEWs	TCs
Historical coupled	43	5	68	2	54	16
Future coupled	48	4	66	3	51	14
Percent change	12	–20	–3	50	–6	–13
p-value	0.001	0.01	0.3	0.2	0.1	0.07

- Observed Annual Mean AEW count varies between 20 and 50
- Observed annual mean TC count is about 9

- % change of AEWs and TCs in the future greatly depends on model

Bercos-Hickey, E., Patricola, C. M., Loring, B., & Collins, W. D. (2023). The relationship between African easterly waves and tropical cyclones in historical and future climates in the HighResMIP-PRIMAVERA simulations. *Journal of Geophysical Research: Atmospheres*, 128, e2022JD037471. https://doi.org/10.1029/2022JD037471

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Future coupled	48	4	66	3	51	14
Percent change	12	–20	–3	50	–6	–13
p-value	0.001	0.01	0.3	0.2	0.1	0.07
Historical uncoupled	39	5	61	11	57	19
Future uncoupled	40	5	55	9	62	19
Percent change	3	0	–10	–18	9	0
p-value	0.6	0.5	0.004	0.02	0.02	0.9

- Even more variable when you consider models that have a coupled ocean
- High uncertainty in projections of future TC/AEW numbers and their relationship

Bercos-Hickey, E., Patricola, C. M., Loring, B., & Collins, W. D. (2023). The relationship between African easterly waves and tropical cyclones in historical and future climates in the HighResMIP-PRIMAVERA simulations. *Journal of Geophysical Research: Atmospheres*, 128, e2022JD037471. https://doi.org/10.1029/2022JD037471

Future of TC Genesis Research

- As part of NOAA's next generation geostationary satellites project (GEO-XO), they will test out feasibility of microwave remote sensing from geostationary orbits
  - Challenge: needs extremely large antenna to get data at useful spatial resolutions
  - Would provide high spatial and temporal resolution measurements of TC genesis in the Gulf of Mexico and eastern Pacific
- Unmanned drone flights!

Iacovazzi, R., Q. ". Liu, and C. Cao, 2021: Future NOAA Satellites: Planning for Microwave Remote Sensing Readiness. *Bull. Amer. Meteor. Soc.*, **102**, E1123–E1125, https://doi.org/10.1175/BAMS-D-20-0291.1.

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Research Interests: tropical cyclones, extreme precipitation, climate change and variability, climate impacts and adaptation