UNOLS SCOAR Briefing

Air-Sea Transition Zone

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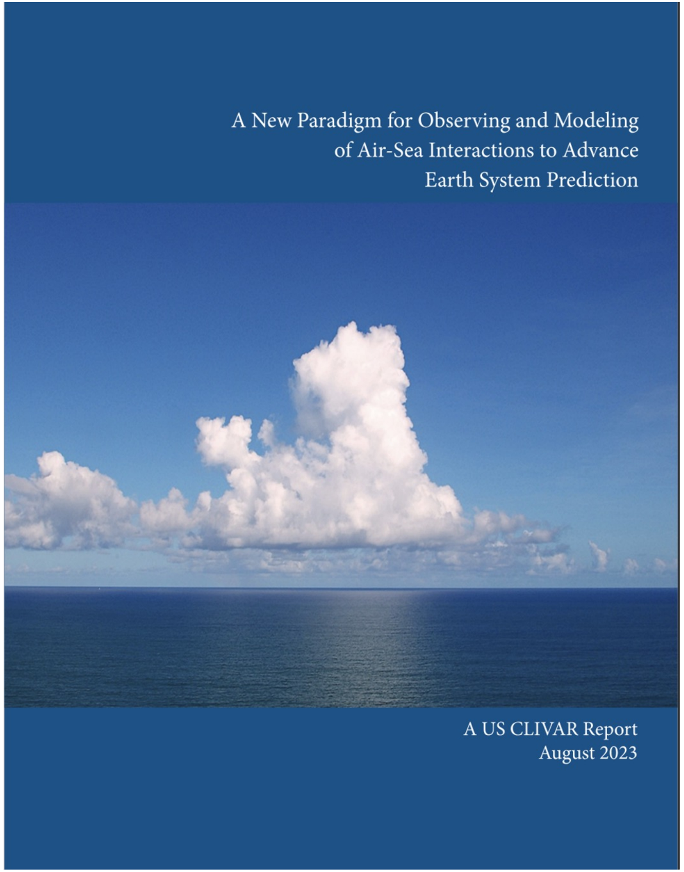
1 November 2023

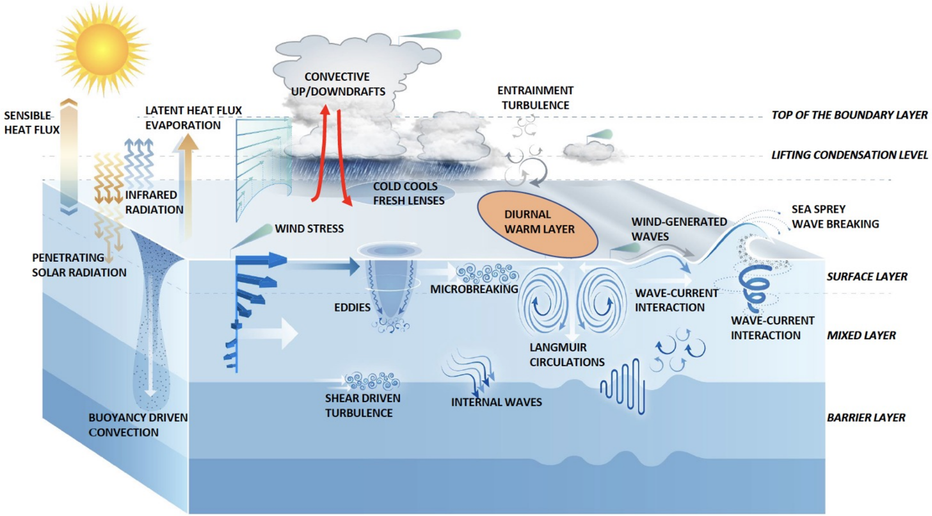


One-Year Study on the Roles of Air-Sea Interactions in the Earth System Predictability (ESP)

- Goal of the study: ***To develop a well-defined strategy to advance observing and modeling capabilities and understanding of air-sea interaction at all scales required for harnessing ESP***

- Background
    - Identified as a need by the community during workshops
    - An interagency committee's recommendation for a one-year study on advancing air-sea interaction observations
    - Sponsored by NASA, NOAA, NSF, and ONR

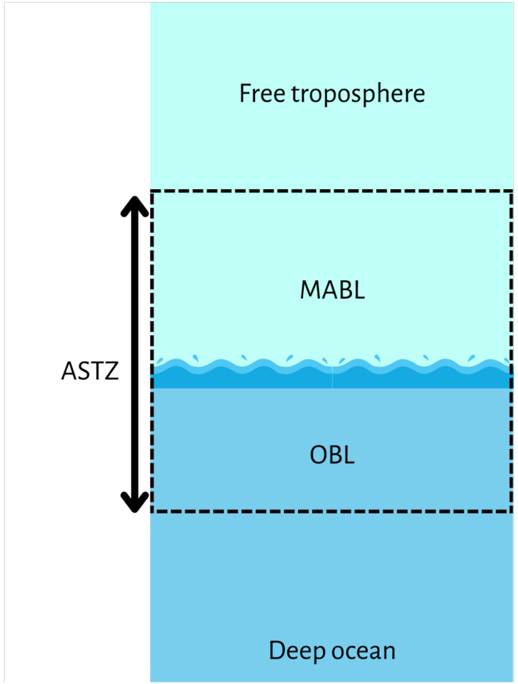
Air-Sea Transition



Adapted from Zhang et al. 2022

The Air-Sea Transition Zone

- The marine atmospheric boundary layer (MABL), the upper ocean mixed layer (OML), and their interface
- New paradigm: the ASTZ is a single entity that regulates the flow of energy and matter between ocean and atmosphere across scales
- Advancing Earth System Prediction on all scales can be accelerated through ASTZ observation, understanding, and modeling



Bringing together observing and modeling experts

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Climate Variability & Predictability

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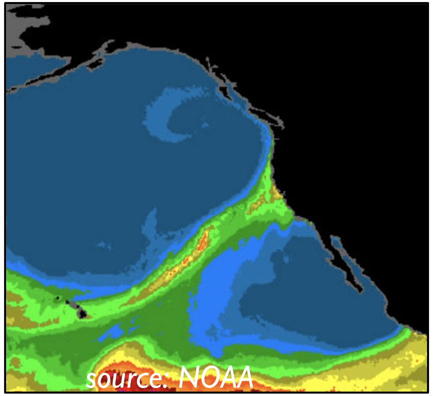
Societally-impactful weather and climate are affected by the ASTZ.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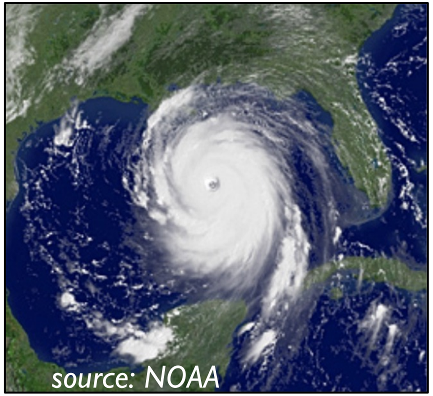
source: NOAA


credit: Analise Johnson


credit: Bob Nichols, USDA


credit: Rowan Romeyn

Why the ASTZ affects ESP

- OML–MABL communication on all scales affects weather and climate.
    - fast scales: surface fluxes regulate MABL potential energy and cloudiness, OML stratification
    - longer scales: ocean circulations alter patterns of SST, MABL convergence, and atmospheric circulations

- Current limits to observing the ASTZ hinder ESP.
    - Insufficient process understanding for parameterization development & improvement
    - Sparse observations: limited spatial sampling and limited duration hinder
        - coupled data assimilation development
        - satellite retrieval validation efforts
    - Data latency hinders initialization of coupled forecast models

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Scientific needs drive the system requirements

Aspects that define needs:

- Processes and Phenomena
- Space and Time Scales
- Regions

Processes and Phenomena Define Needs

Surface fluxes and sea state

- Quantify the role of the sea state in mediating air-sea fluxes and making remote sensing measurements

OBL and MABL turbulence and mixing

- Observations to evaluate turbulence theory under a range of conditions

Cloud processes

- Colocated observations of clouds, the MABL, OBL, and surface processes

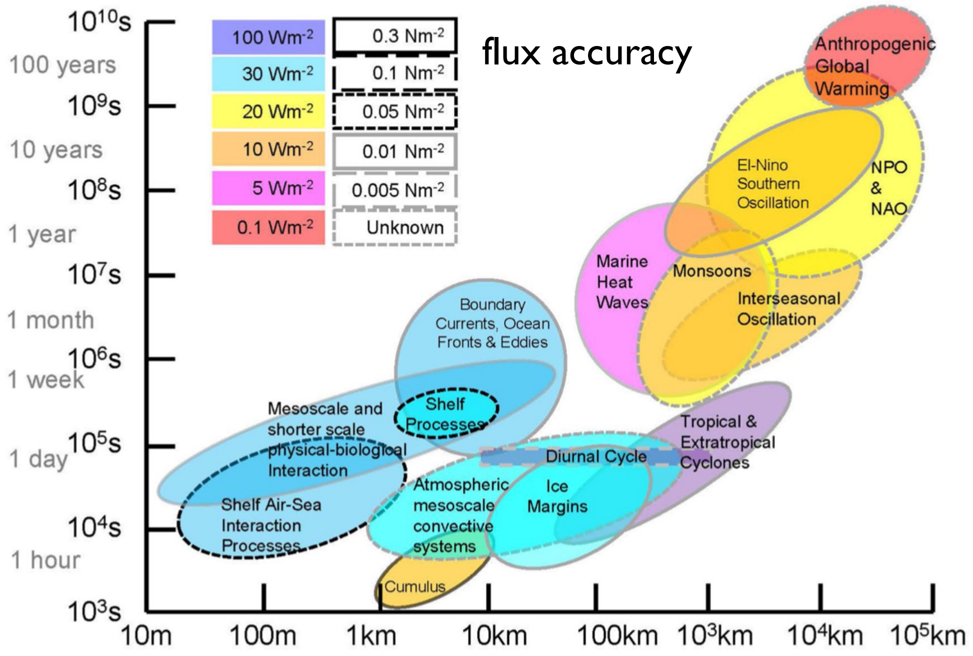
Extremes

- Observe in challenging regimes
- Improve prediction skill for extremes, e.g.,
  floods & droughts,
  tropical cyclones,
  marine heat waves,
  atmospheric rivers

Scales Define Needs

- Mesoscale and smaller
  in ocean and atmosphere
- Subseasonal to seasonal variability
- Interannual and longer scales

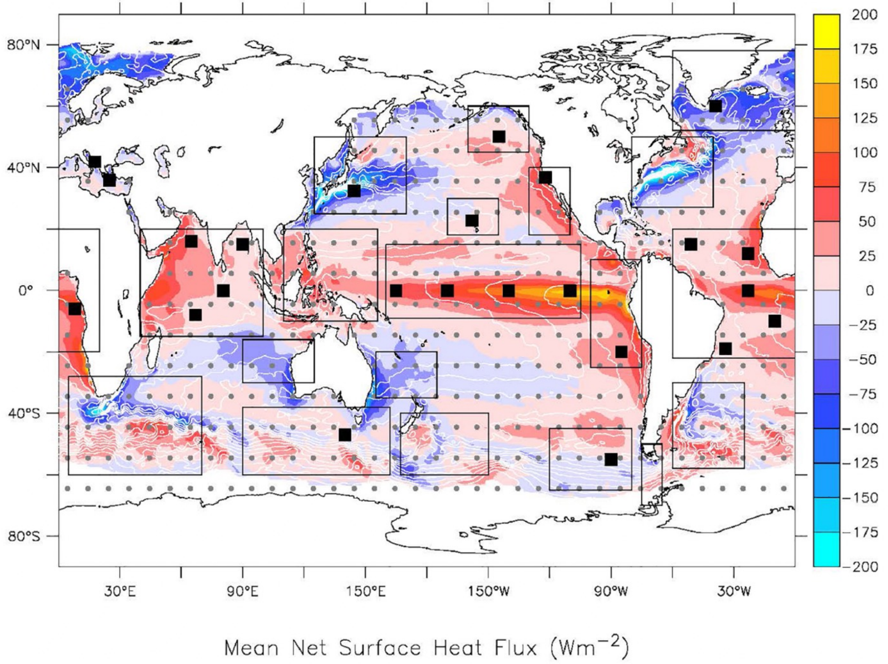
Scales of Processes



(Cronin et al., 2019)

Regions Define Needs

- High latitude
- Ice margins
- Shelf processes
- Eastern and Western Boundary Currents
- Tropical stratification and equatorial upwelling



(Cronin et al., 2019)

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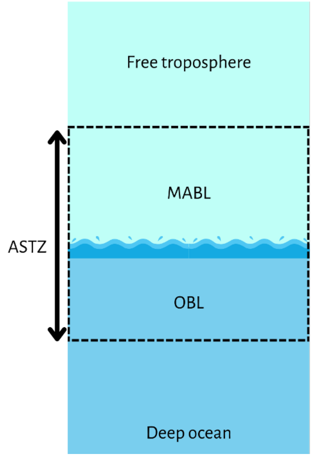
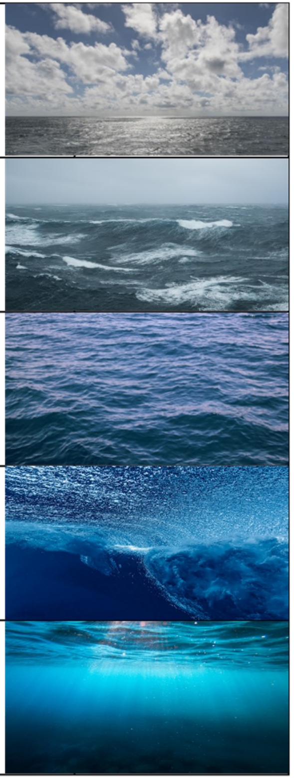
Some Common Scientific Needs that Emerge

1. 3D sampling of profiles of the ASTZ (thermodynamic, kinematic, fluxes)
2. Colocated coincident surface state variables
    a. air temperature and humidity, SST, winds, currents, precipitation
    b. globally, from satellites, & in situ platforms
3. ASTZ measurements during extreme events and in extreme environments
4. Modeling Needs
    a. ASTZ variables observed at appropriate resolution
    b. parameterization testing and development
    c. development of coupled data assimilation and observing system simulation experiments (OSSEs)



Need #1: 3D sampling of profiles of the ASTZ

MABL	
WASL	
Interface	
WOSL	
OBL	



- **MABL**: robust platforms & instruments for collecting T, q profiles; finer vertical resolution from satellites
- **WASL**: in situ observation of lowest few meters to compliment wave tank studies; UAVs with direct spray imaging systems
- **Interface**: directional wave spectra measurements concurrent with winds, currents, other ASTZ variables; SWOT, ODYSEA, Butterfly
- **WOSL**: fine vertical resolution of currents, turbulence, tracers for budget studies
- **OBL**: greater spatial and temporal resolution of routinely collected profiles; profile sampling across ocean fronts

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Need #2: Colocated, Coincident Surface State Variables Globally (e.g. T2m, q2m, SST, winds, currents, precipitation)

- **Scientific needs**
  - In situ measurements for cal/val of satellite surface flux products; coupled DA development; initialization of coupled forecast models
- **Current capabilities**
  - Surface-based: NOAA GDP and Argo arrays collect currents, SST, ocean mixed layer depth, but not air-side variables
  - Satellite: Non-collocated, non-coincident retrievals of turbulent flux variables; radiation, precipitation, stress are more available
- **Needs**
  - Surface-based: measurement of air-side variables along with ocean-side variables at sub-daily temporal resolution with spatial density similar to that of GDP/Argo arrays
  - Satellite: all needed variables for bulk flux algorithms from a single satellite at finest possible horizontal and temporal resolution, i.e., Butterfly; better characterization of radiation, precipitation quality over the ocean

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Need #2: Colocated, Coincident Surface State Variables Globally (e.g. T2m, q2m, SST, winds, currents, precipitation)

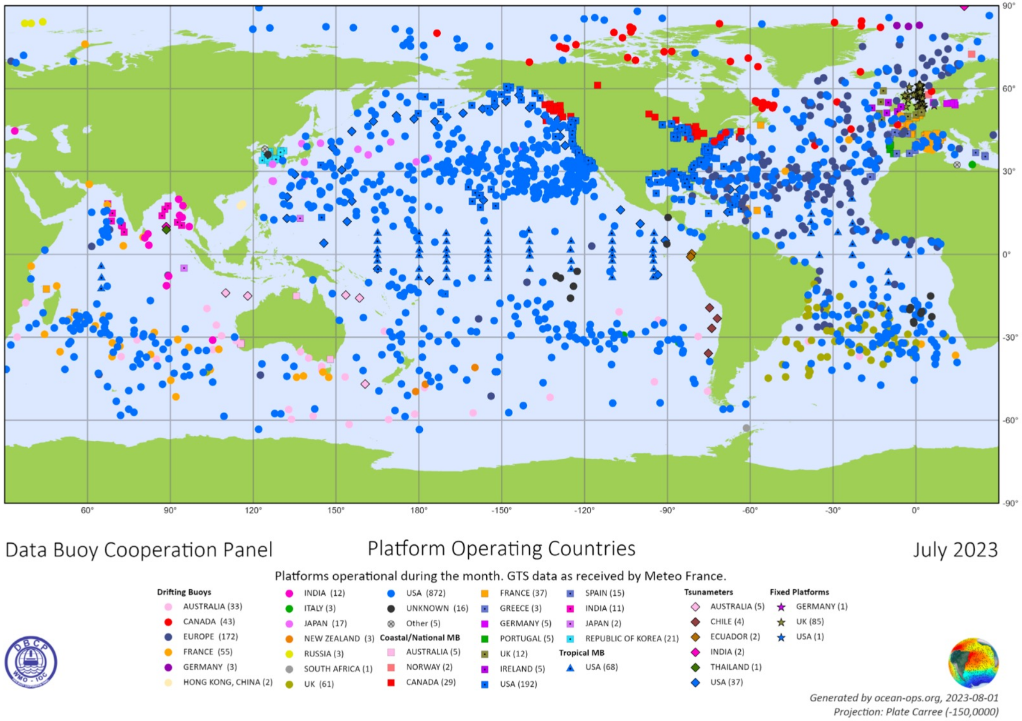
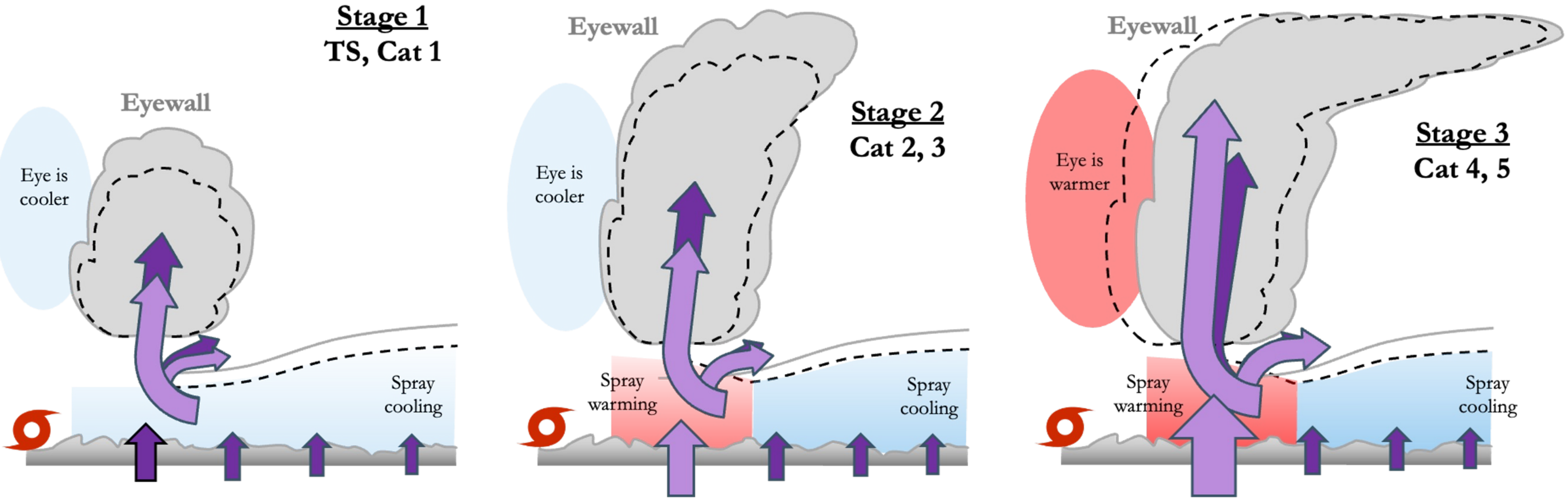


Figure 2. A map of in situ ocean and air-sea observing systems coordinated by the OceanOps program.

Need #3: Sampling of Extreme Events and in Extreme Environments

- **Scientific needs**
  - Extreme events are rare, short-lived, and destructive
  - Extreme environments play key roles in global energy and water cycles
- **Current capabilities**
  - Hurricane hunters, dropsondes, AXBTs, snapshots of opportunity
- **Needs**
  - durable platforms and ASTZ sensors that can be rapidly deployed and span the spatial & temporal scale of the event

Impacts of sea spray on hurricane development



Simply put, spray has two effects on heating and strengthening/weakening the hurricane:

The ocean is WARMER than the atmosphere, so the spray heats/strengthens

BUT: It takes heat from the atmosphere to evaporate the spray: so spray cools/weakens

Modeling results

Barr, Chen et al. 2023

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Implementation Strategies

1. Develop observational and modeling technology for coupled ocean-atmosphere prediction.

1. Observe the ASTZ in strategic regions.

1. Expand observations of extremes and challenging regimes.

1. Develop a global observing network to measure key air-sea coupling variables.

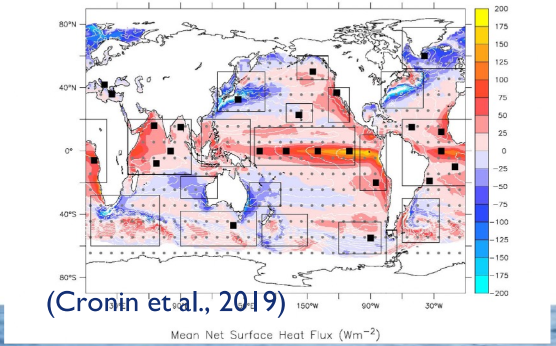
Strategy 1: Develop observational and modeling technology for coupled ocean-atmosphere prediction.

- Develop, test, and deploy sensors and platforms.
  - Requires a new paradigm of coordinated activity.
- Utilize model experiments to inform observing system design.
- Develop, test, and implement coupled data assimilation.
- Enable inclusive practices, including data sharing, e.g., FAIR guidelines and archiving best practices.

Strategy 2: Observe the ASTZ in strategic locations.

- Deploy suites of collocated observations at key sites.

- Observe the ASTZ across vertical and horizontal gradients.
    - Measure vertical profiles of scalars, turbulence, and fluxes.
    - Define required resolutions with theory and models.
    - Capture cross scale interactions and full parameter space with long time series.



(Cronin et. al., 2019)

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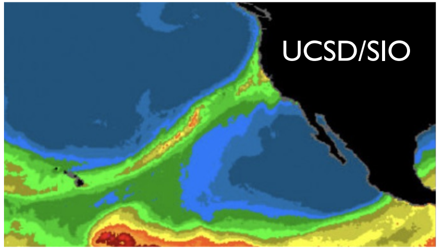
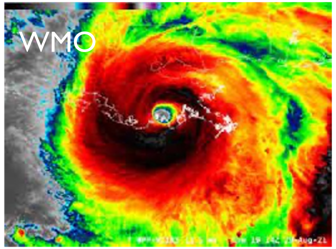
Strategy 3: Expand observations of extremes and challenging regimes.

- Rapidly deployed targeted, coordinated ASTZ observations of high-impact highly variable extremes, e.g.
  - Tropical/Extratropical Cyclones
  - Atmospheric Rivers
  - Marine Heat Waves
  - Marginal Ice Zones





- These require investment and technology demonstration programs.

Strategy 4: Develop a global observing network to measure key air-sea coupling variables.

- Support current and possible satellite and suborbital remote sensing missions
  - Diagnose budgets and flux parameters: waves, temperature, humidity, wind, currents, PBL height, precipitation, radiation
  - examples: SWOT, ODYSEA, Butterfly

- Build in-situ distributed network
  - Build upon existing global systems (eg NOAA GDP, Argo) especially for sub-surface parameters not possible from satellite (OML depth)
  - surface buoys in more diverse locations to provide key validation
  - continued development of low-cost drifters, autonomous vehicles

- Data assimilative models to tie together all of the observations and fill in where observations don't exist

Strategy 1 Roadmap:
Develop observational and modeling technology for coupled ocean-atmosphere prediction.

Short-term (0-2 years):

- Workshop to identify ASTZ measurements needed for coupled data assimilation (CDA) and process understanding, including the technology development (i.e., instrumentation and platforms) and data management neededs (i.e., reduced latency and dedicated observations) to support those measurements.
- Organize research to advance CDA capabilities.
- Organize CPTs for scale-aware parameterization development for atmospheric boundary layer convection, surface fluxes (including surface wave and ice margin effects), and ocean cross-isopycnal mixing.

Medium-term (3-5 years):

- Test newly developed scale-aware parameterizations in a hierarchy of model configurations.
- Assess the performance of new parameterizations and CDA strategies in S2S forecasts.

Long-term (>5 years):

- Incorporate new parameterizations and CDA methods into operational forecast models (i.e., R2O activities).

Strategy 2 Roadmap. Observe the ASTZ in strategic regions.

Short-term (0-2 y):

- Pair existing sustained platforms with existing technologies to enhance ASTZ sampling across regimes and scales with an emphasis on MABL height, near-surface air humidity and temperature, and ocean vector winds and waves.
- Initiate a program for technology development and testing with a focus on instrument size, battery weight reductions, and vehicle adaptations for long deployments (i.e., UUVs and UAVs).
- Create ASTZ testbed sites by leveraging existing, accessible near-coastal sites for technology testing (i.e., surface-piercing towers and autonomous vehicle docking).
- Initiate PPPs to identify available sites and adaptable technology for Super Site platforms for sustained Super Sites.

Medium-term (3-5 y):

- Test and refine ASTZ measuring instruments at coastal ASTZ testbed sites.
- Coordinate with planned field campaigns to test newly developed ASTZ measuring instruments.
- Leverage PPPs to expand locations, platforms, and vehicles for testing and collecting ASTZ measurements (i.e., aircraft, ships, and platforms affiliated with offshore energy production).

Long-term (>5 y):

- Develop open ocean ASTZ Super Sites, beginning with the tropics, then moving to more challenging locations.

Strategy 3 Roadmap.
Expand observations of extremes and other challenging regimes.

Short-term (0-2 y):

- Create ASTZ testbed sites by leveraging existing, accessible near-coastal sites for technology testing.
- Initiate a program to develop or enhance sensors and platforms for key variables in extreme conditions, such as polar locations.
- Initiate a program to develop additional instrumentation for air-deployed ocean surface and ocean profiling floats.
- Test range and capabilities of AUVs for these challenging regimes.
- Develop the modeling and assimilation communities for predictions, observations needed for improvements, and parameterization development.
- Coordinate with satellite observing and CDA communities to identify needs for satellite observations and assess their priorities and values.

Medium-term (3-5 y):

- Test sensors for key variables in extreme conditions at coastal ASTZ testbed sites and in field campaigns of opportunity.
- Test air-deployed ocean surface floats, autonomous vehicles, and other platforms as developed under this program.
- As measurements come online, assimilate them into CDA models and test improvements and changing needs.

Long-term (>5 y):

- Develop and maintain a suite of rapid-deployment vehicles and instruments to provide observations needed for CDA in regions where extreme events are thought to be imminent.
- Improve CDA capabilities to take advantage of new observations.
- Expand and enhance platforms, sensors, and models as observational and modeling needs are further developed. Continuous refreshment of the deployment needs is needed.

Strategy 4 Roadmap.
Develop a global observing network to monitor key air-sea coupling variables.

Short-term (0-2 y):

- Coordinate and maintain existing observational networks and strategies (i.e., Argo, global moored and drifting arrays, and TPON recommendations).
- Assimilate ASTZ data from existing satellite missions and moored arrays into operational models and reanalyses.
- Develop and improve the parameterization of fluxes from ASTZ state variables.
- Maintain coverage of satellite missions, buoy networks, and float networks observing key state variables for air-sea fluxes.
- Initiate programs to develop sensors to routinely measure coincident ASTZ state variables missing from global satellite and in situ observations (i.e., near-surface air temperature, humidity, and ocean currents).
- Inform the observational strategy with deficiencies in ASTZ reanalysis (i.e., accurate flux estimation, near-surface state variables, and conservation of heat and momentum across the interface).

Medium-term (3-5 y):

- Design remote sensing of key ASTZ state variables for fluxes. Determine wavelengths for passive and active remote sensing.
- Demonstrate sensors for atmospheric near-surface temperature and humidity.
- Test observing technology during process studies.
- Develop sensors for state variables for deployment on existing in situ and remote sensing platforms.
- Test adaptive and autonomous sampling techniques.
- Assess the effects of ASTZ variables on prediction. Demonstrate prediction with OSSEs.
- Initiate programs to develop sensors to measure MABL height and OML depth as well as surface wave directional spectra.

Long-term (> 5 y):

- Improve existing platforms and develop new platforms to better sample ASTZ variables, including capabilities to measure more ASTZ variables coincidently or throughout vertical profiles.
- Optimize, scale, and deploy newly engineered platforms or vehicles for collecting global operational observations.
- Launch satellite missions to measure ASTZ state and flux variables coincidently.
- Combine remote sensing observations, in situ observations, and models to estimate fluxes across the interface and throughout ASTZ vertical profiles.
- Demonstrate the ability of MABL height and OML depth sensors. Assess model representation of ASTZ responsiveness to fluxes and MABL height and OML depth measurements.
- Assess sampled and unsampled variability of ASTZ variables and quantify their impacts on weather, ocean, and climate models.

Conclusion:
Challenge for a new paradigm for the ASTZ

- Standard models for air-sea interaction have improved incrementally for decades.
- Further improvement requires modeling and observing interactions among more physical processes.
- *This report*
  - comprehensively outlines the science that drives ASTZ understanding, and
  - presents a roadmap for modeling and observing interactions in the ASTZ for the benefit of Earth system prediction.

Thank you!

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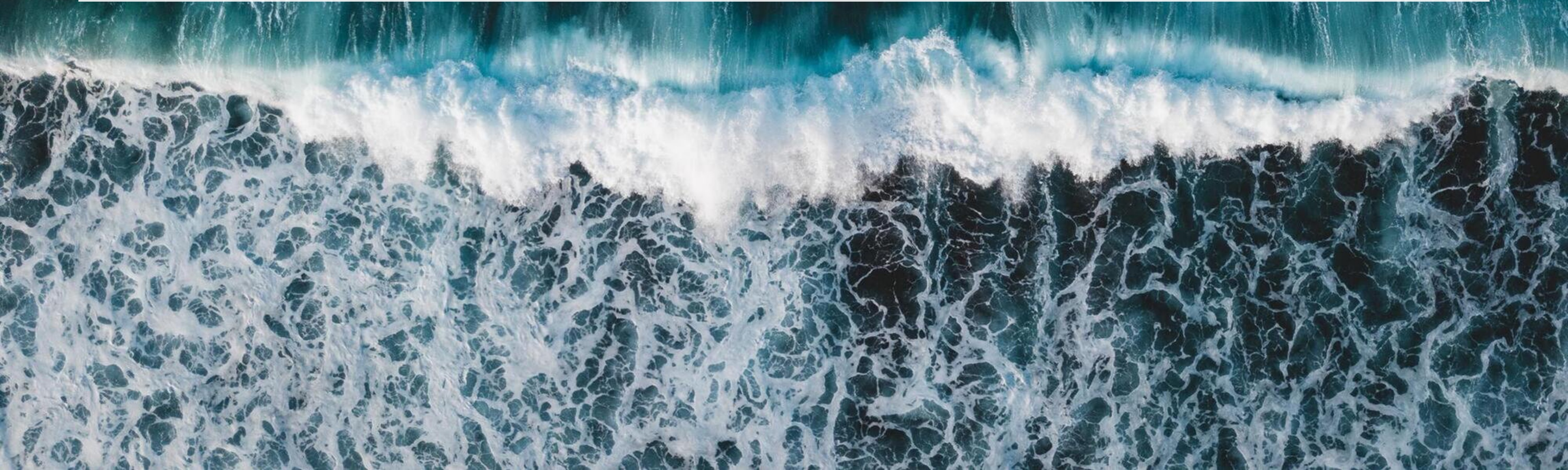

Purpose for Today

- To summarize the findings of the Air-Sea Transition Zone (ASTZ) study
- To introduce the ASTZ paradigm
- Field questions and discuss next steps

Need #4: Modeling Capabilities and Needs

- **Scientific needs**
  - Needed for parameterization development and testing; observing system design (OSSEs) and assessment (OSEs); state estimation; process understanding
- **Current capabilities**
  - DNS/LES: high-resolution for process understanding, parameterization development.
  - Scale-permitting or -resolving simulations: usually regional, some global
  - ESMs: global with many coupled components and parameterizations
- **Needs**
  - Observations to advance scale-aware parameterizations for "gray zone" simulations, including NWP
  - Observations to characterize temporal and spatial covariances of ASTZ variables for coupled DA
  - Higher-frequency ocean output from ESMs for ASTZ process assessment

Charge of the ASTZ Study Group

- **Identify current capabilities, key gaps**, lessons learned from the past, and best practices in data, technologies, understanding, and modeling requirements
- **Assess the relative importance to ESP to resolve various space and time scales**, interactions among different scale processes, and addressing model biases
- **Build upon recent and potential future advances in sensor/platform technology** to inform new satellite and in situ observing systems to resolve processes of ocean-atmosphere interaction, including estimates of turbulent air-sea fluxes of heat and moisture over the global oceans and their transport into the rest of the atmosphere through the marine boundary layer
- **Explore possibilities of using modern statistical and modeling tools and co-designing air-sea observing and data assimilation (DA) systems** to optimally use available data, fill observational blind spots, and minimize cost while harnessing predictability and providing broader societal benefits
- **Liaise and coordinate** with other relevant US and international activities (e.g., SCOR OASIS WG, US CLIVAR Air-Sea WG)
- **Produce strategy document** providing system recommendations to be shared with the Interagency Council for Advancing Meteorological Services (ICAMS)

3D Sampling of the ASTZ: MABL

- **Scientific needs**
  - Vertical profiles (10-100 m resolution) of T, q, u, v, w, turbulent fluxes, and their horizontal variability, especially across surface gradients; MABL and cloud base height
- **Current capabilities**
  - Surface-based: technology for measuring needed variables is mostly mature (direct measurement and remote sensors (e.g., Doppler LIDAR))
  - Satellite: MABL height (radio occultation)
- **Needs**
  - Surface or near-surface: robust, remote platforms for vertical, horizontal sampling; reductions in instrument weight, power needs
  - Airborne: robust remote sensors (DIAL, etc.)
  - Satellite: improved vertical resolution (T, q) and accuracy (q).

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3D Sampling of the ASTZ: WASL

- **Scientific needs**
  - Vertical profiles (~1 m resolution) of T, q, u, v, w, turbulent fluxes, and their horizontal variability, esp. as a function of wave state, since MOST doesn't apply here
  - Sea spray
- **Current capabilities**
  - <u>In situ</u>: sensors and platforms exist, but wave wash-over limits their deployment from buoys
  - <u>Laboratory</u>: wave tanks + direct spray imaging systems or light scattering techniques
  - <u>Modeling</u>: LES modeling
- **Needs**
  - <u>In situ</u>: platforms for vertical, horizontal sampling; reductions in instrument weight, power needs. *Example: T, q, w sensors and direct spray imaging systems on UAVs*
  - <u>Modeling</u>: in situ observations for validation

3D Sampling of the ASTZ: Interface

- **Scientific needs**
  - Direct measurement of surface fluxes (heat, momentum, freshwater, radiation)
  - Sea state measurements: SST, SSS, SSH, currents, directional wave spectra, rainfall
- **Current capabilities**
  - Surface-based: DCFS packages, radiometers from ships, buoys, aircraft; optical rain gauges; CTDs (SSS); ADCPs, GDP array, current meters; wave spectra buoys, LIDAR
  - Satellite: multiple platforms for SST, SSS, SSH, currents, significant wave height
- **Needs**
  - Surface-based: DCFS packages in poorly sampled/high uncertainty regimes; wave spectra in larger variety of conditions, including sea ice
  - Satellite: simultaneous measurements of wave spectra, winds, and currents, along with other ASTZ state variables, over many environmental and sea states: SWOT, ODYSEA, Butterly

3D Sampling of the ASTZ: WOSL

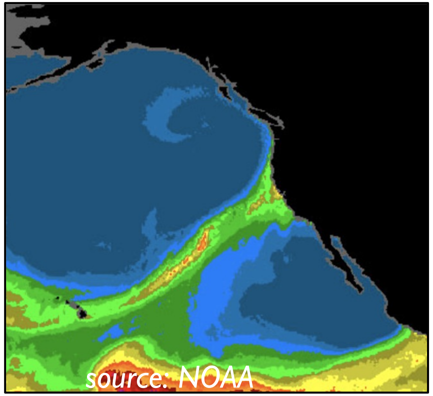
- **Scientific needs**
  - More understanding of momentum transport in high wind and complex wave states
  - Wave effects on Stokes drift-Langmuir circulation interactions
- **Current capabilities**
  - <u>Surface-based</u>: little capability in high-wind, complex-wave environments
  - <u>Modeling</u>: DNS/LES modeling; parameterizations being added to global models
- **Needs**
  - <u>Surface-based</u>: fine vertical resolution of currents, turbulence, tracers for budget studies
  - <u>Modeling</u>: observations to validate parameterizations

3D Sampling of the ASTZ: OBL

- **Scientific needs**
  - T, S, u, v profiles to initialize and validate coupled models (~5 m); ocean state estimation
  - T, S, u, v, profiles to measure vertical turbulent mixing (~1 m or less)
- **Current capabilities**
  - Surface-based: moorings, Argo array (1-10 m resolution below upper few m); UUVs, towed profiling instruments for finer vertical resolution, including near the surface
- **Needs**
  - Surface-based: greater spatial and temporal resolution of routinely collected profiles; profile sampling across ocean fronts
  - Modeling: observations to validate and refine mixing parameterizations

Why the ASTZ for ESP?

What societally-impactful weather and climate event predictions are impacted by the ASTZ?
What are the uncertainties in the ASTZ that impact these predictions?
How can improved observations and modeling address these uncertainties?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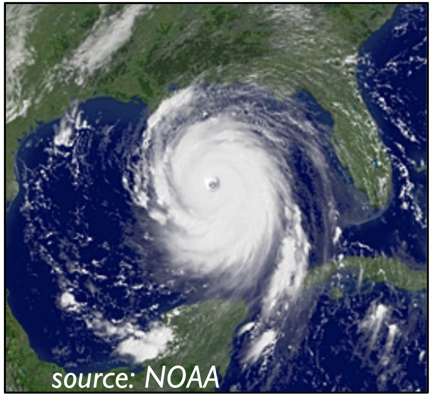
source: NOAA


credit: Analise Johnson


credit: Bob Nichols, USDA


credit: Rowan Romeyn

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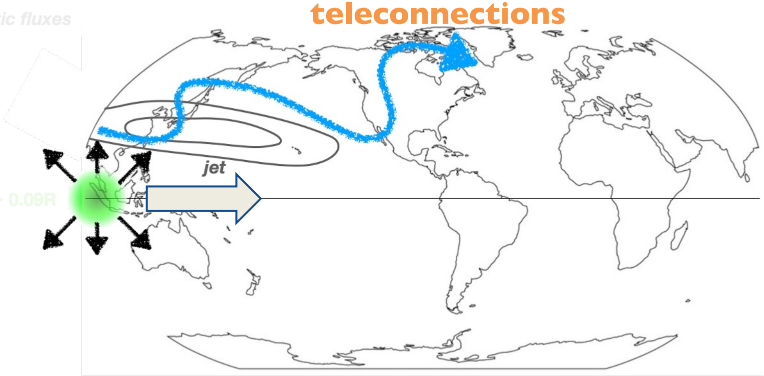
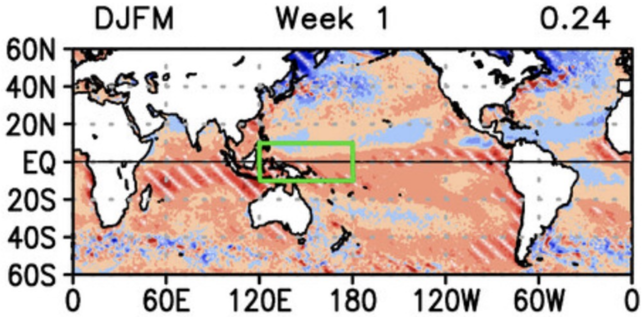
Example: WPac SST biases and S2S North American precipitation forecasts

MJO teleconnections

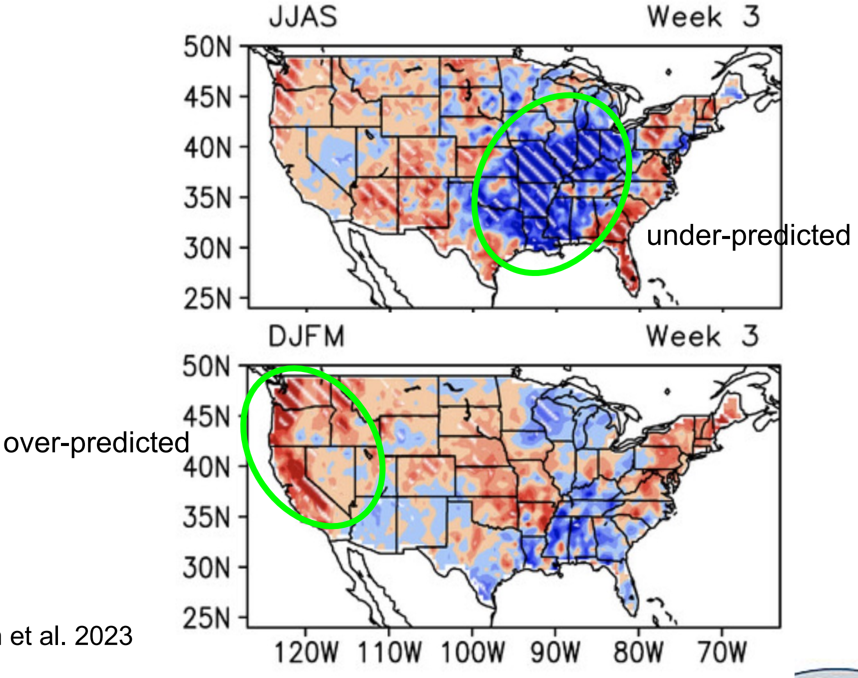


adapted from Henderson et al. 2017

UFS SST biases

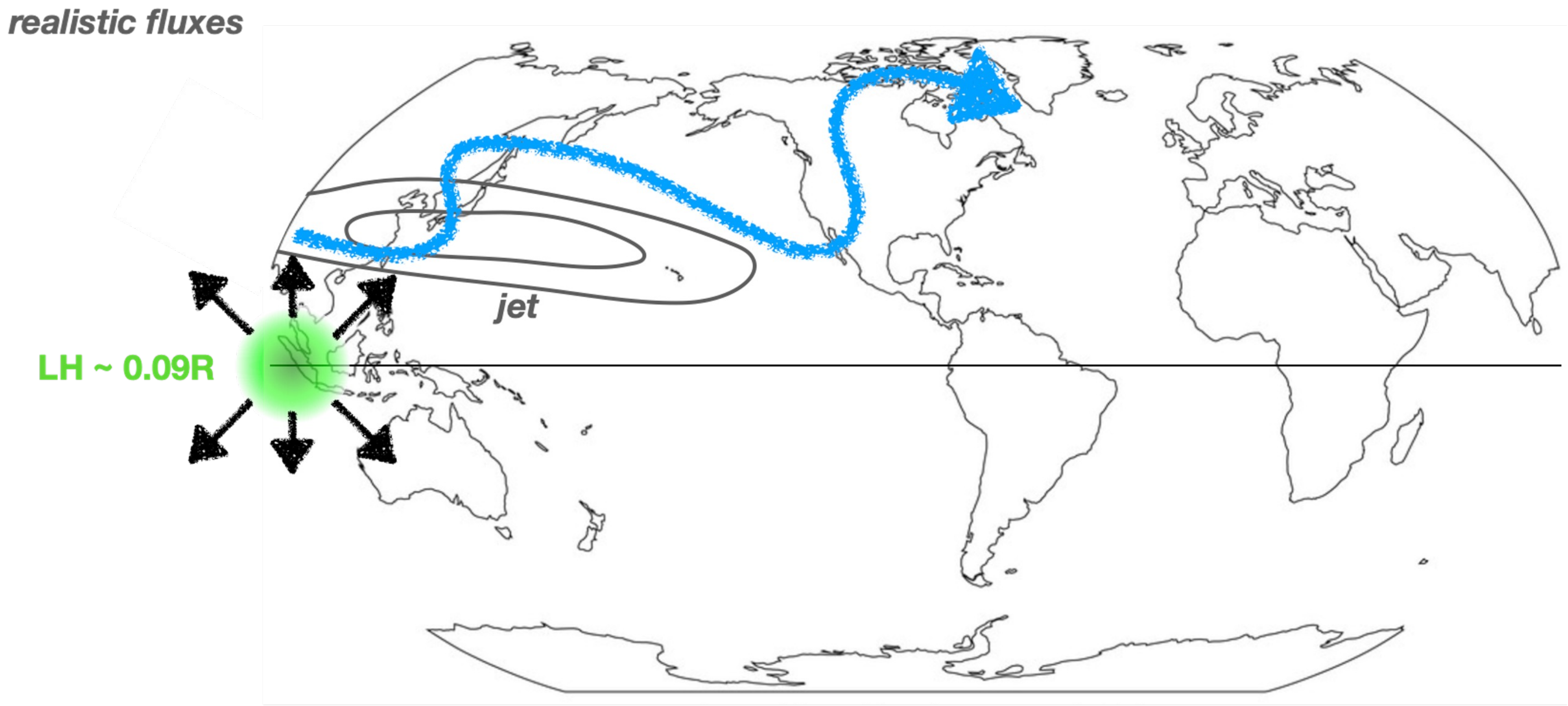


UFS precipitation biases per WPac SST bias



Stan et al. 2023

Example: surface fluxes and MJO teleconnections



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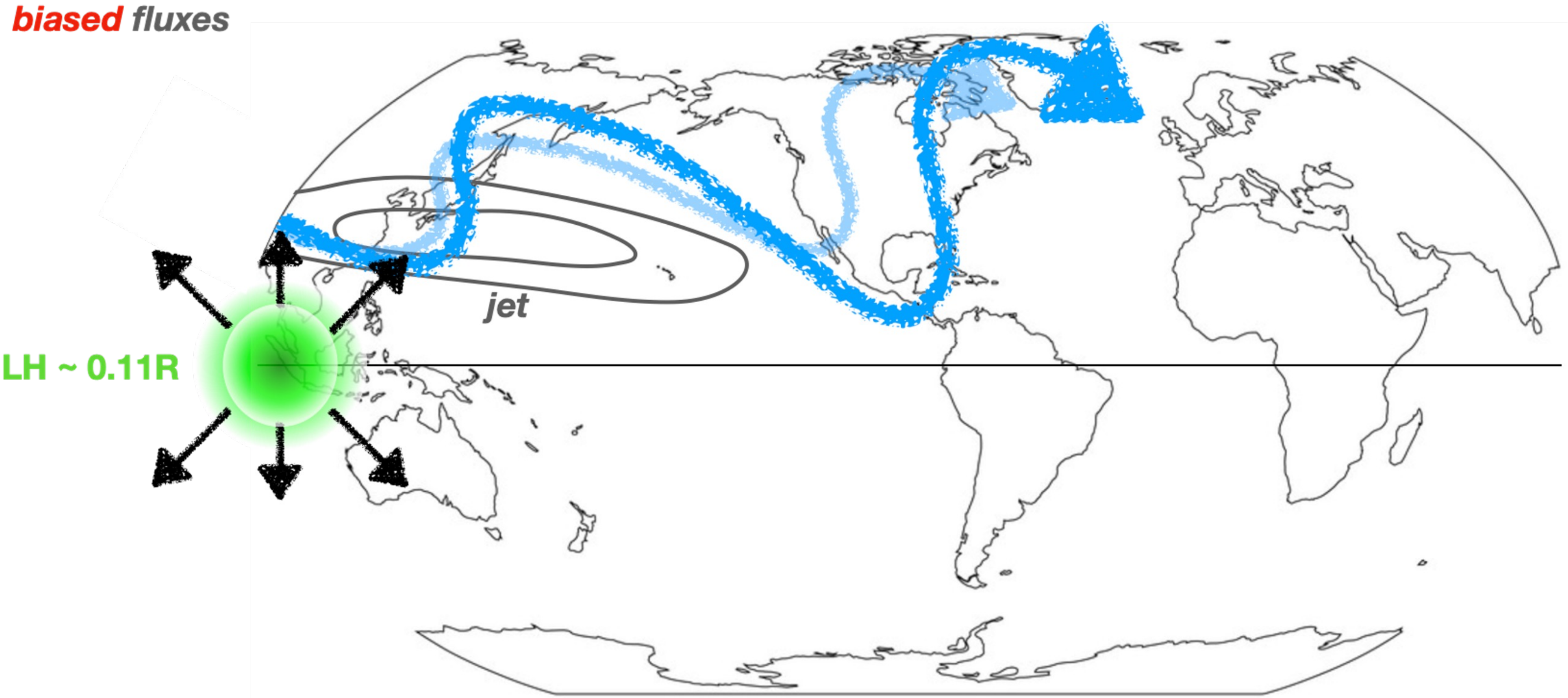
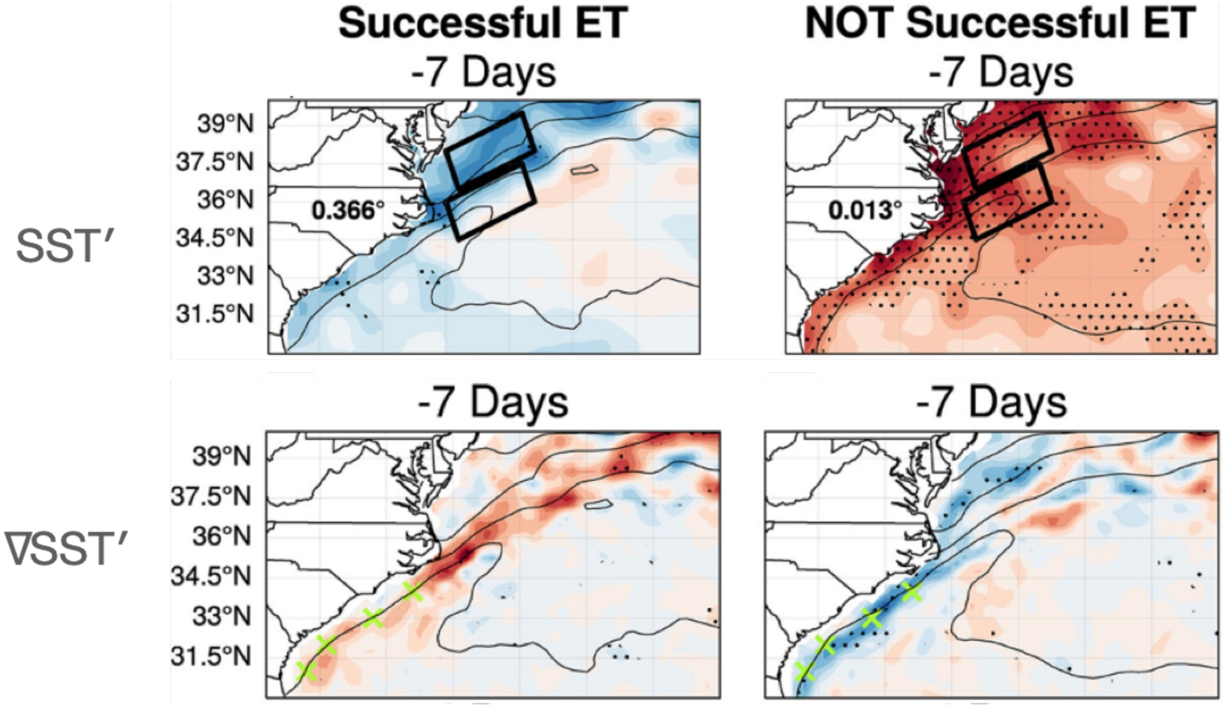
Example: surface fluxes and MJO teleconnections



adapted from Henderson et al. 2017

Example: WBCs and TC extratropical transition



Jones et al 2023 https://doi.org/10.1029/2023GL102904

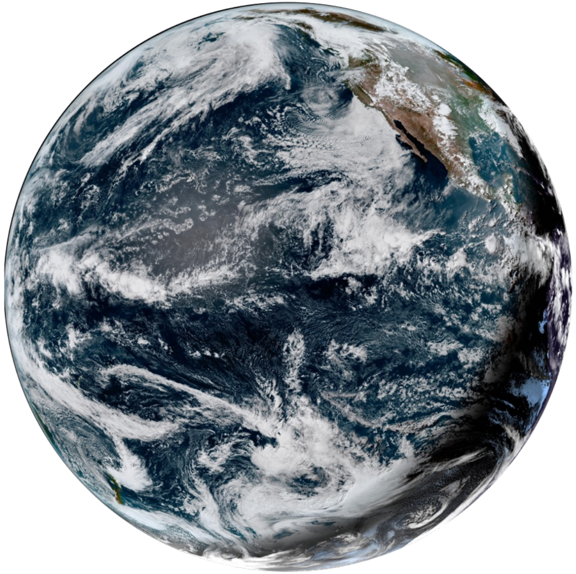
ET means:

- warm-core to cold-core system
- expansion of wind field and related hazards
- increased risks to midlatitude populations

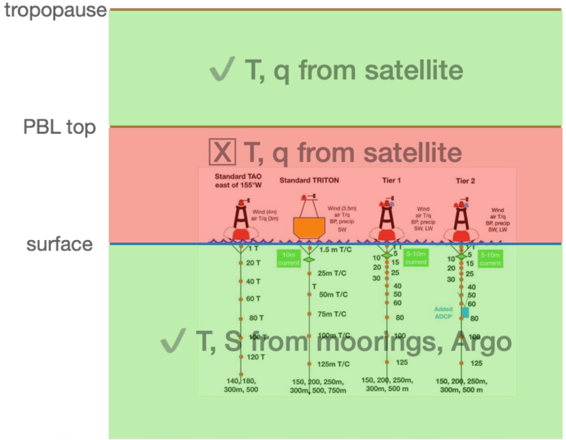
ET is favored when:

- SSTs are relatively cold
- fine-scale SST gradients are relatively large

MABL observations for ASTZ understanding across the globe



there is a lack of well-resolved PBL observations over the oceans



Need #3: Sampling of Extreme Events and in Extreme Environments

- **Scientific needs**
  - Extreme events are rare, short-lived, and destructive
  - Extreme environments play key roles in global energy and water cycles
- **Current capabilities**
  - Surface-based: AXBTs from aircraft; pre-positioned USVs; moorings in e.g., Southern Ocean
  - Satellite: Non-colocated, non-coincident retrievals of atmospheric, ocean surface variables (cloud and rain block observation of ocean surface); high temporal and spatial resolution of clouds, rainfall (e.g., GPM, IMERG early/late runs).
- **Needs**
  - Surface-based: durable platforms and ASTZ sensors (including those for subsurface ocean) that can be rapidly deployed and span the spatial & temporal scale of the event