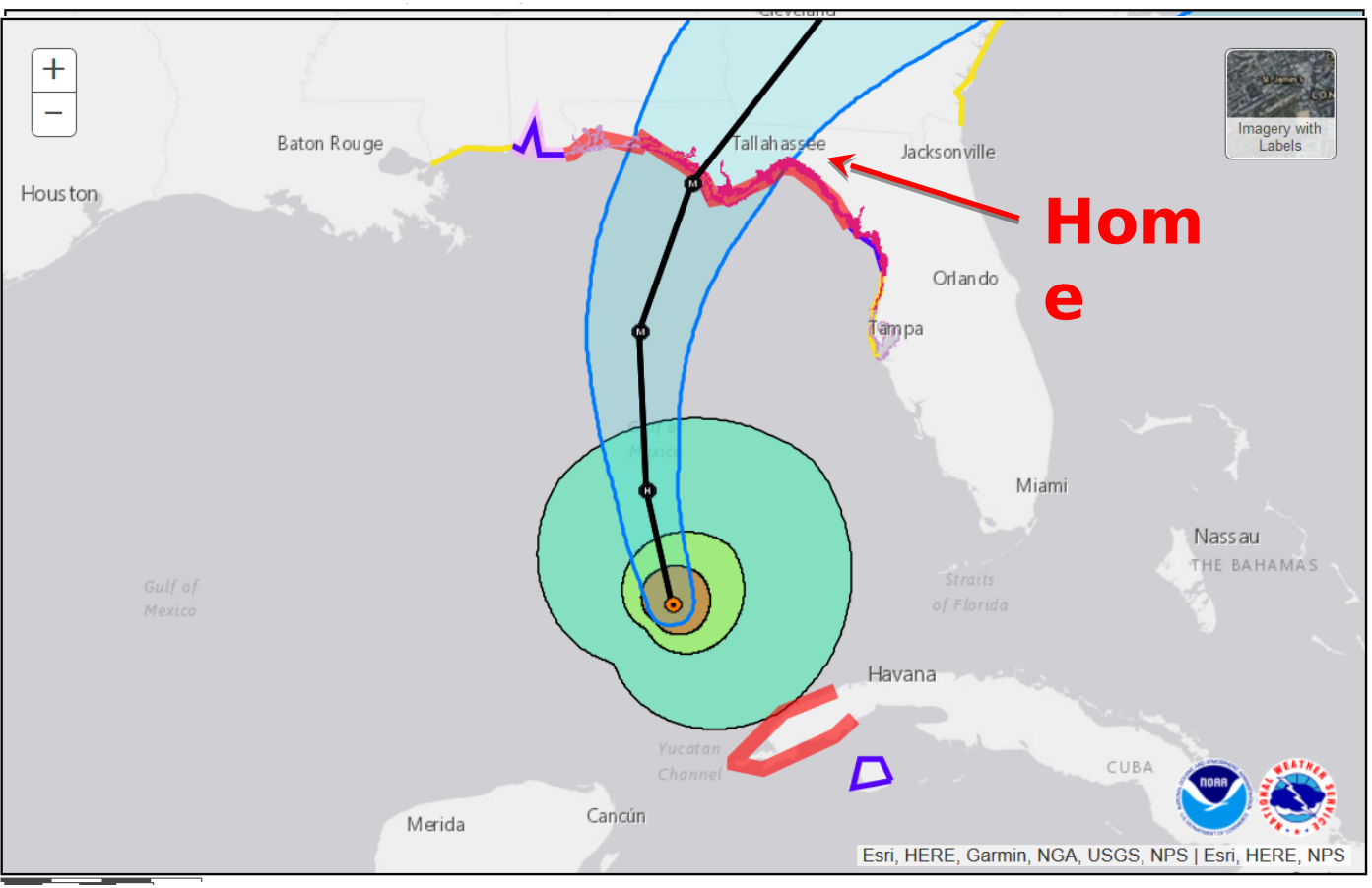
Three-Way Coupling of Surface Currents, Waves, and Wind Stress Over the Gulf Stream
Plus
Hurricane Related Motivation to Observe Currents

Mark A. Bourassa[1] and Qi Shi[1,2]

1. Center for Ocean-Atmospheric Prediction Studies and Department of Earth, Ocean and Atmospheric Science, Florida State University
2. Great Lakes Research Center

Hurricane-Related Motivation for Currents



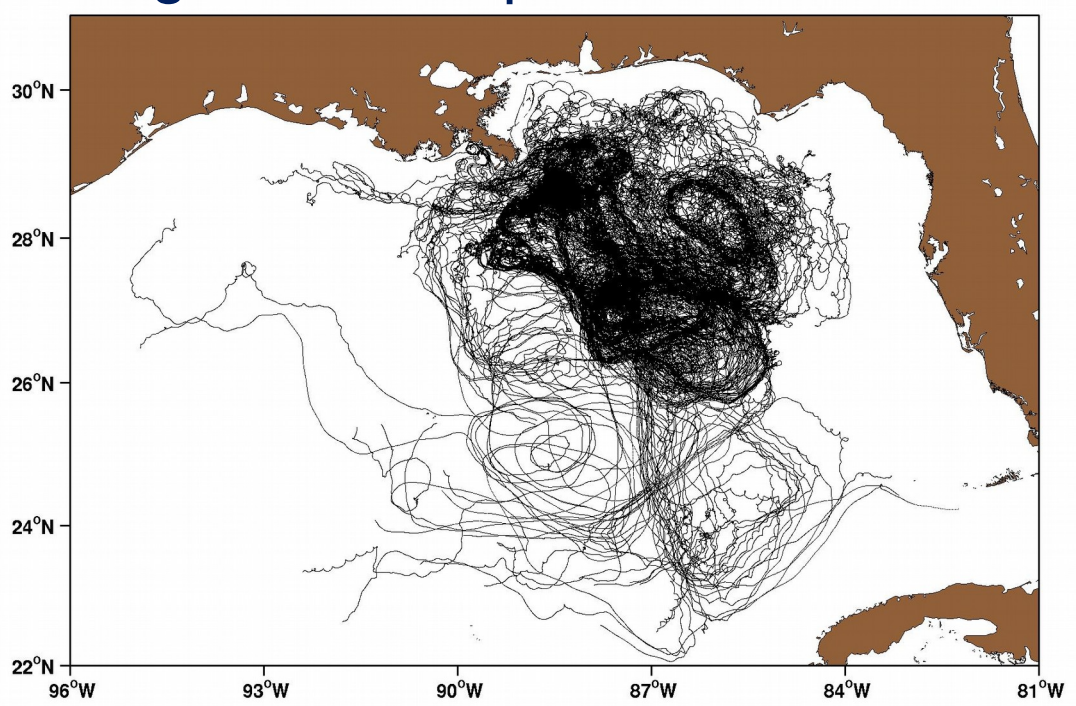
Hom
e

- Forecasts of tropical cyclone intensity have improve very little over the decades.
- In some cases, better knowledge of the location of warm and cold core ocean eddies is expected to improve forecasts

- An OSSE study using currents from gliders confirms that currents improve intensity forecasts (George Halliwell, personal communication, 2018)

Surface Velocity Observations

Grand LAgrangian Deployment (GLAD) trajectories August 1 to September 30, 2012

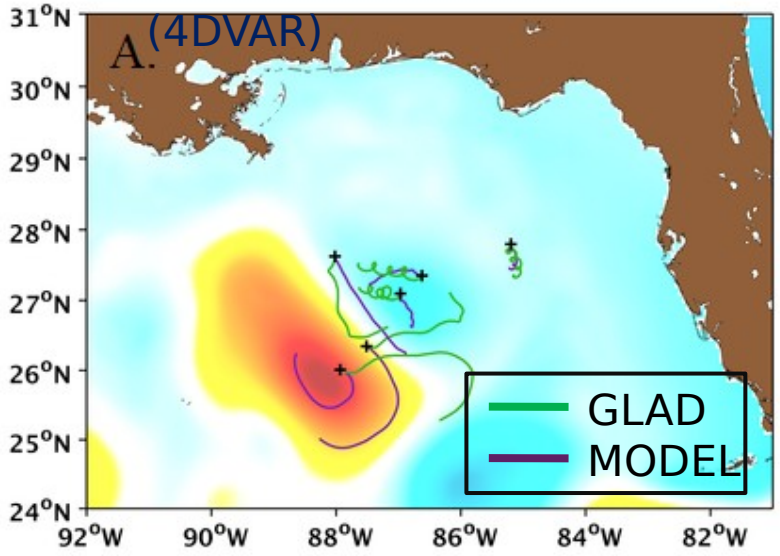


300 Drifters (positions reported every 5 min) used to **estimate Eulerian velocities** (these are assimilated in the Navy Coastal Ocean Model 4DVAR)

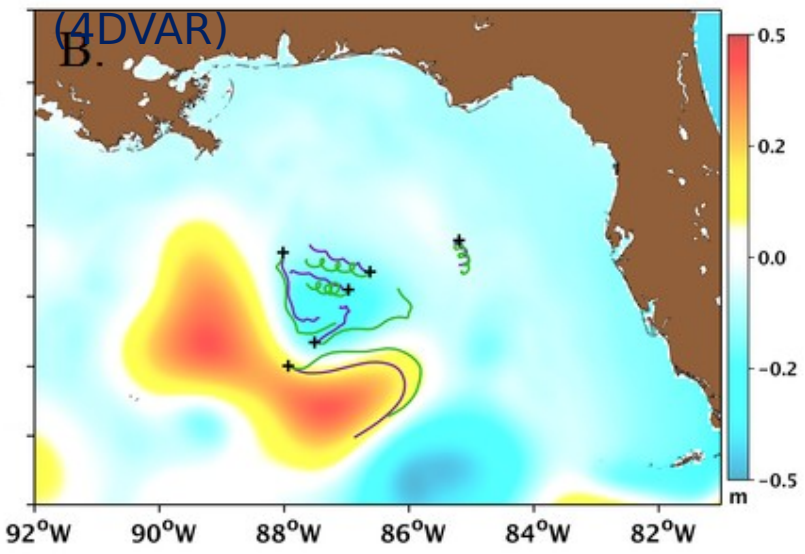
Results of Matthew Carrier, Gregg Jacobs, Hans Ngodock, Scott Smith, John Osborne, Innocent Souopgui, and Joseph D'Addezio

Impact of Velocity Assimilation on Ocean Model Forecast

SSH Observations (4DVAR)



VELOCITY Observations (4DVAR)



Including surface velocity observations in the assimilation procedure improves representation of mesoscale structure

Result is model forecast drifters that match closer to observations out to 96-hours

Results suggest that models benefit greatly from surface ocean velocity measurements

Observations about every 18 hours would be sufficient

Results of Matthew Carrier, Gregg Jacobs, Hans Ngodock, Scott Smith, John Osborne, Innocent Souopgui, and Joseph D'Addezio

Goals of Ocean/Wave/Atmosphere Coupling Study

- Our primary goal was to determine which of the following are important in a two-way coupled ocean-wave-atmosphere system
  - Boundary-layer stratification (as a modifier of stress)
  - Waves (as a modifier of stress)
  - Surface Currents (as a modifier of stress)
- Additional questions addressed:
  - Does the (modeled) atmosphere respond to small spatial scale ocean surface variability (stratification, waves and currents)?

    Yes – importantly
  - Does the ocean respond to these changes (if any) in the atmosphere?

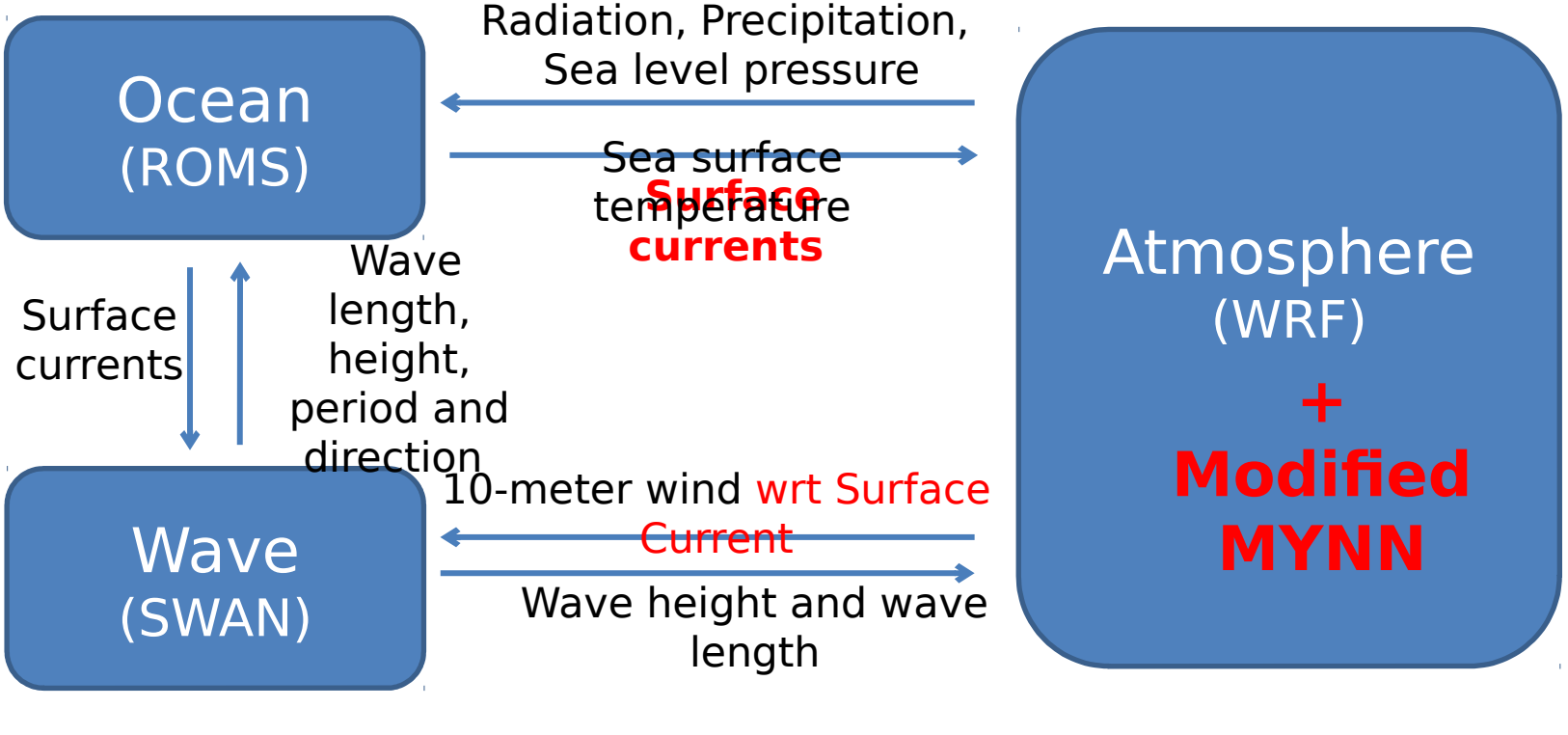
    Yes – quite substantially
  - Does resolution matter?

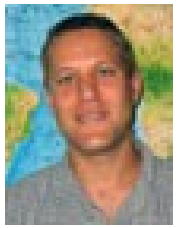
    Yes – it matters a lot!

Why Might We Want Two-Way Coupling?

- Ocean and atmospheric models are advancing to the resolutions where two-way coupling is arguably critical.
  - They are doing so to improve model accuracy.
  - Small scale processes greatly enhance the vertical transport of energy, materials in the ocean (salt, nutrients, gasses) and the atmosphere (water vapor)
  - These changes should impact
    - The global and regional energy and water cycles (weather)
    - Ocean mixed layer temperature and depth
    - CO_2 budgets of the ocean and atmosphere
    - Nutrient content for marine organisms
      - Impact fisheries

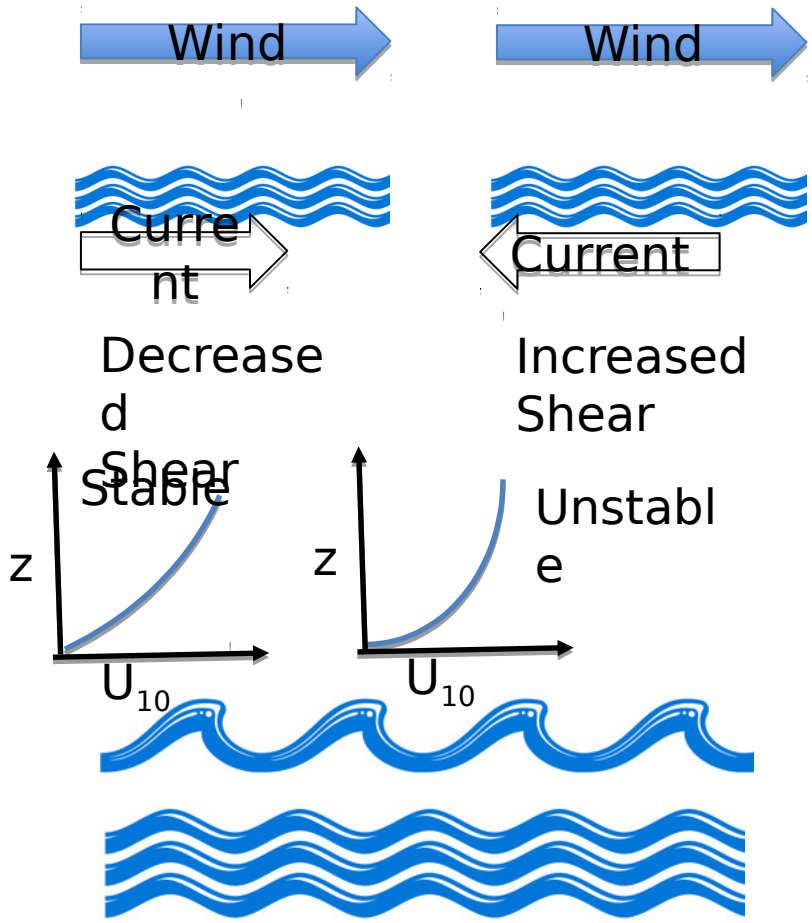
Ocean-Atmosphere-Wave Modeling





How Do Currents, Waves and Stability Modify Air-Sea Interaction?

- Currents change wind shear
  - $\Delta \mathbf{U} = \mathbf{U}(z) - \mathbf{U}_{sfc}$
  - Heat fluxes proportional to $\Delta \mathbf{U}$
  - Stress proportional to $|\Delta \mathbf{U}| \, \Delta \mathbf{U}$
- Reduced wind shear increases changes due to atmospheric stability
  - Stable: smaller U(z) and stress
  - Unstable: larger U(z) and stress
- Currents modify wave steepness
  - Increasing steepness increases stress
  - Decreasing steepness decreases stress
- Currents modify horizontal shear and Ekman motion



Wave graphics from https://www.vectorstock.com/royalty-free-vector/sea-water-waves-seamless-borders-set-vector-13969565

Experimental design

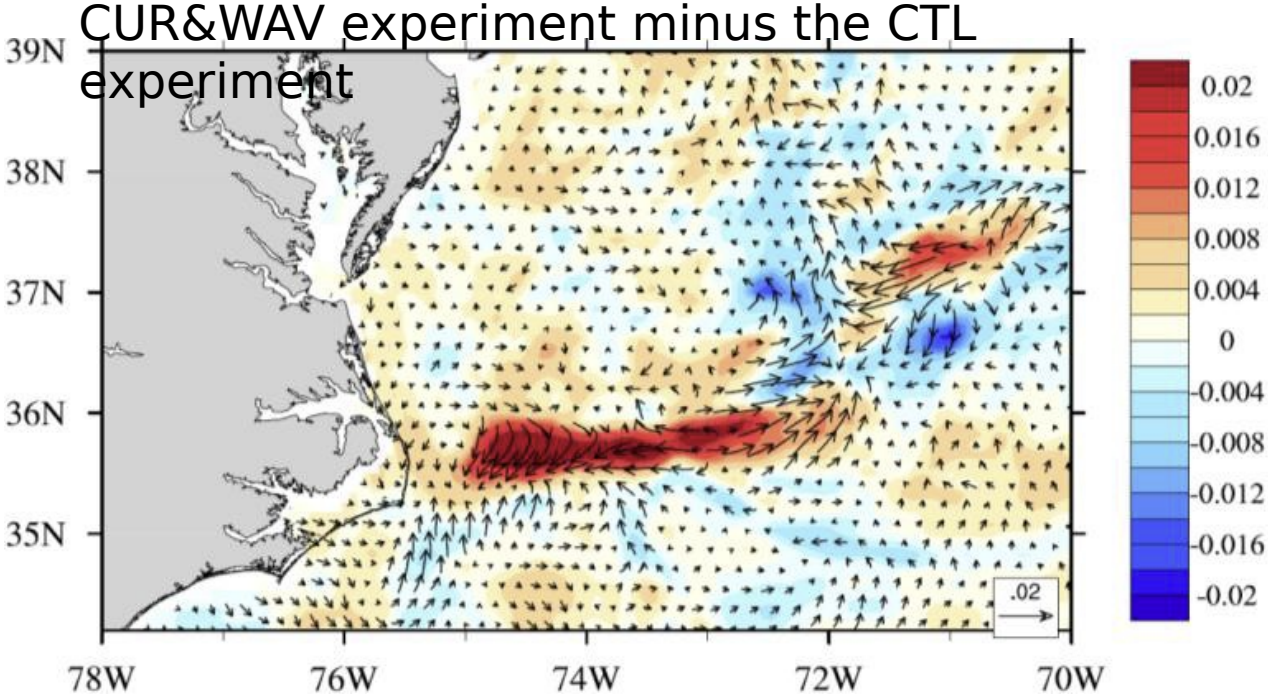
- These experiments were designed to separate the ocean currents' effect on the wind stress from the wave effect. The four experiments differ only in how wind stress is calculated in the bulk parameterization equation.

Experiments	Roughness length algorithm	Wind input for surface stress formulation	
CTL	COARE 3.0	$\vec{U}_{10}$	Stability only
CUR	COARE 3.0	$\vec{U}_{10} - \vec{U}_{CUR}$	+ currents
WAV	Taylor and Yelland	$\vec{U}_{10}$	+ waves
CUR-WAV	Taylor and Yelland	$\vec{U}_{10} - \vec{U}_{CUR}$	+ waves & currents

Ongoing work: Adding Stokes drift

Changes in October Wind Stress Magnitude

Relative to model with stress independent of waves and currents

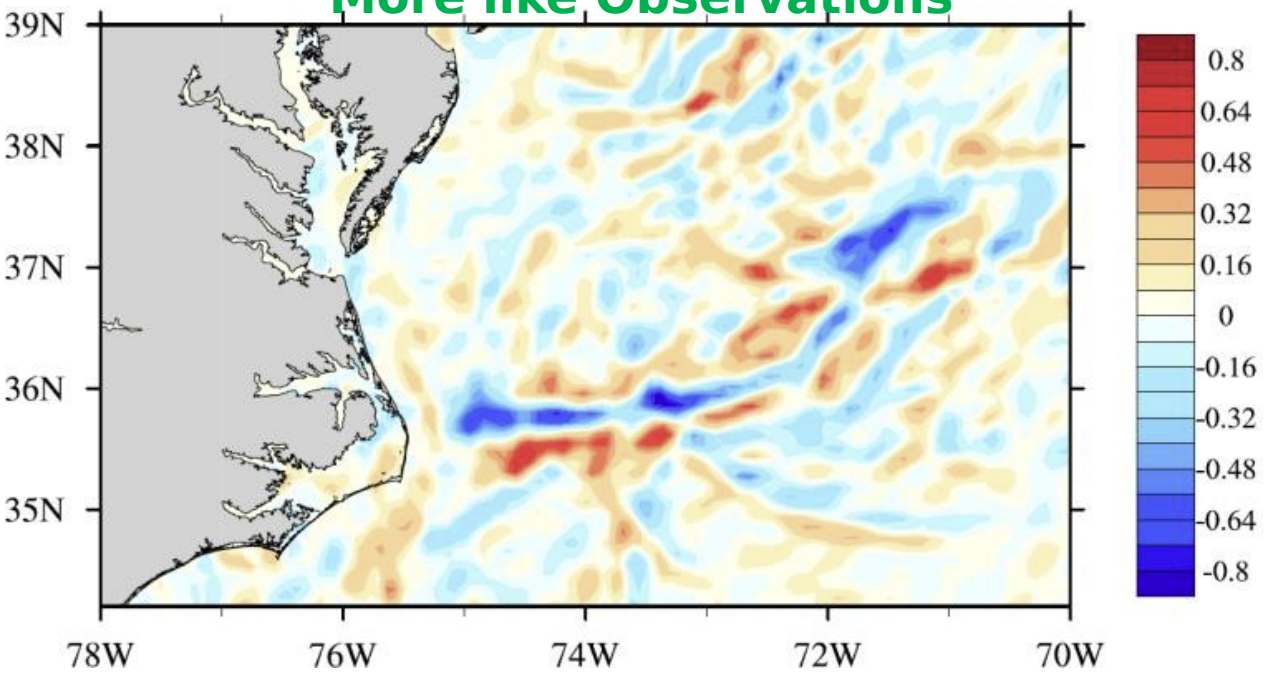


The decadal survey has a highly ranked goal by the weather panel, related to how spatial variability in the surface contribute to fluxes and the cycles of water and energy, as well as the transport of pollution. The influence of ocean currents were noted.

- The two-way coupled model has stronger stress gradients over the Gulf Stream
- Making the stress dependent on currents and sea state greatly strengthens these gradients, and currents are a much more important consideration
- These stress magnitudes seem to be more consistent with ASCAT observations

Changes in October Ocean Ekman Pumping

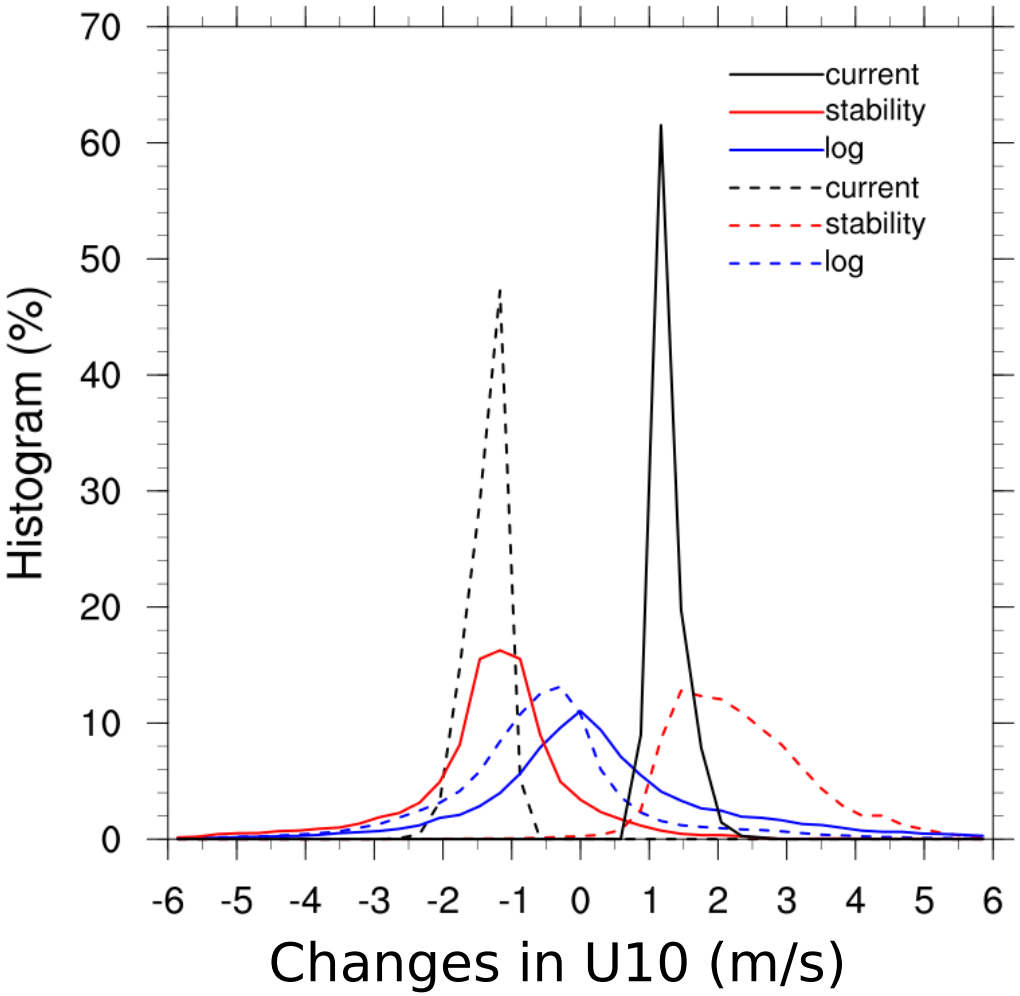
CUR&WAV- **More like Observations**



The influence of currents, in a two-way coupled model, were needed to greatly strengthen the positive and negative curl seen on the sides of a major current, resulting in much stronger Ekman pumping (+/-).

- When both waves and currents are considered, the Gulf Stream's heat budget is dominated by vertical motion and entrainment at the bottom of the mixed layer. Otherwise horizontal transport dominates
  - Curl of stress is greater (more like observations) over SST gradients and current gradients

Currents Are Very Important

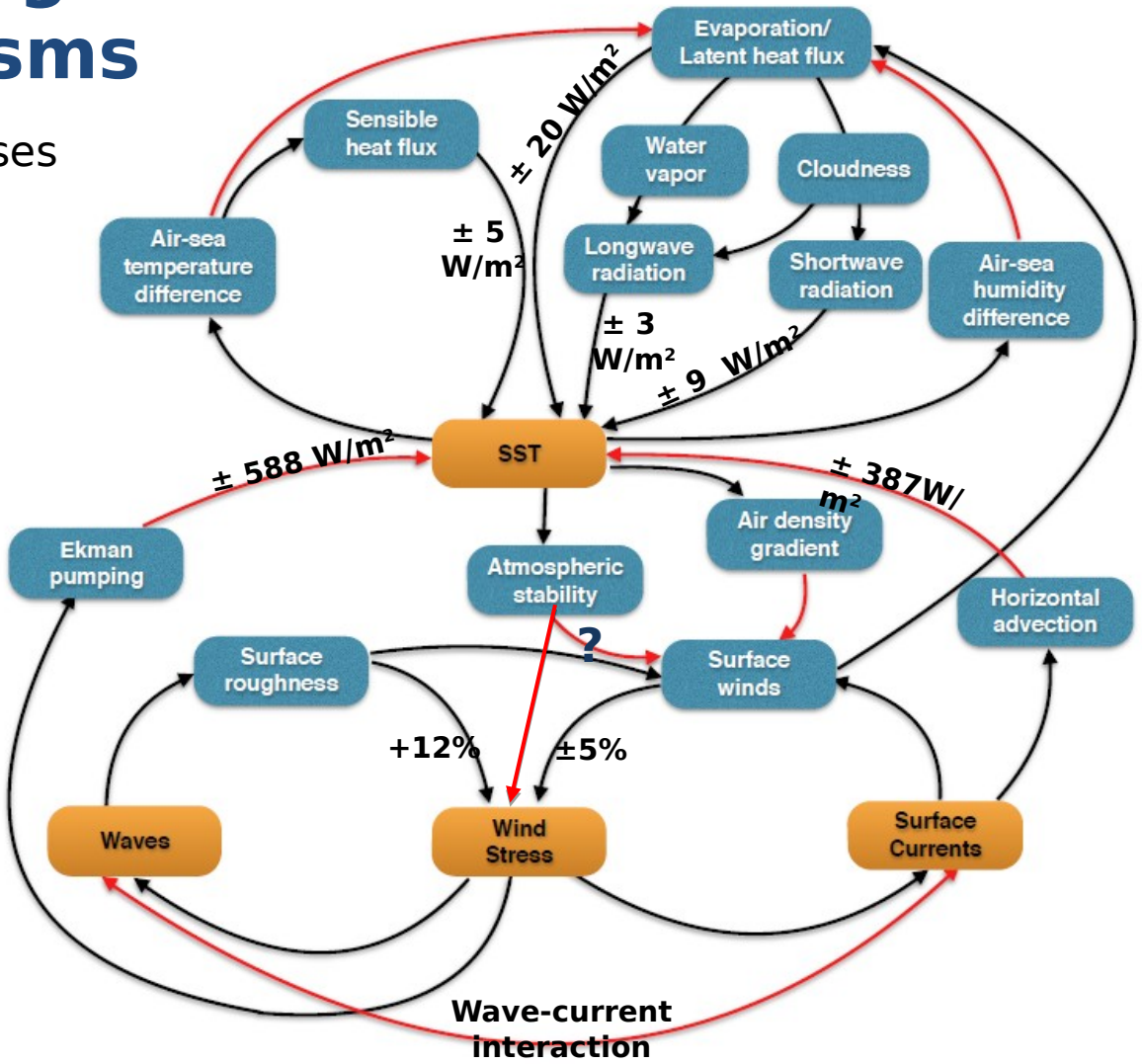


WAV-CUR model minus Control

- Histogram of six-hourly differences of current, stability and log terms in the log-wind equation between CUR_WAV and WAV experiments
- The statistics for strong-current (Us>1m/s) regions
- Wind changes associated with negative changes in current are indicated as solid lines.
- Wind changes associated with positive changes in current are indicated as solid lines.
- Currents and stability substantially counteract each other

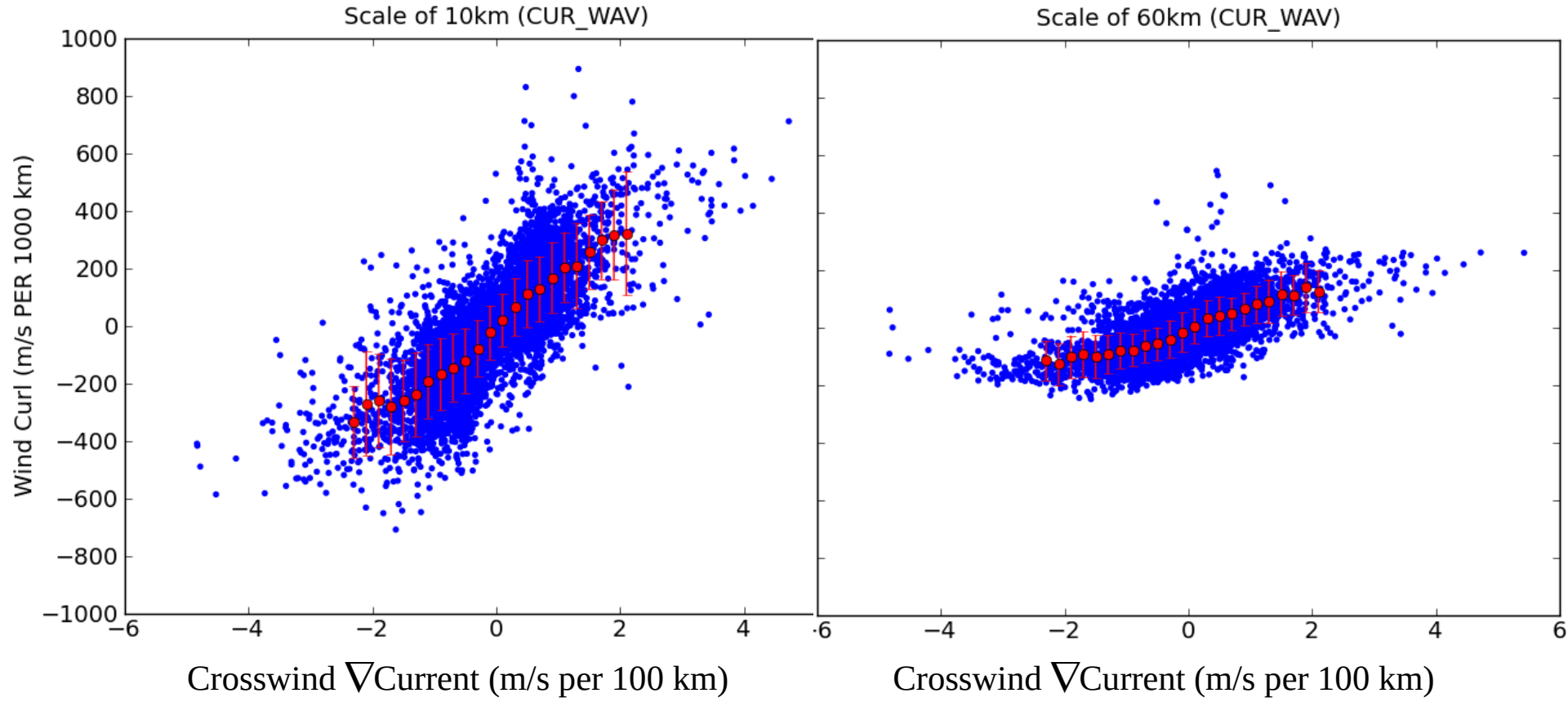
Coupling mechanisms

- Dominant processes



All numbers are median value of 30-day daily of the magnitude of differences between CUR+WAV and CTL over the Gulf Stream

Modeled Wind Curl vs Current Gradient (as a function of spatial scale)

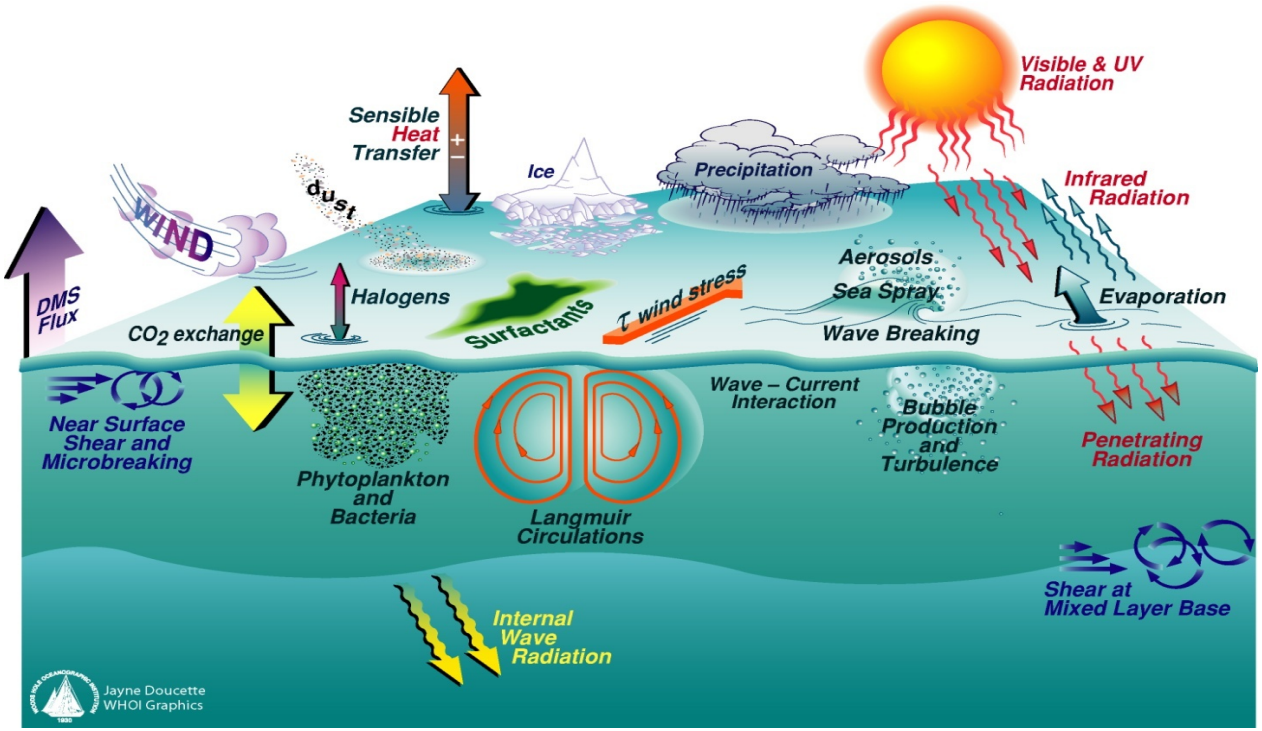


- Wind Curl (y) vs. Gradient of current perpendicular the wind vector (x)
- Current features are small in scale, so resolution matters in the coupled earth system

- Curls have much better signal to noise when calculated with a length scale of three times the spacing of wind vectors:
  - 10 km curl needs 3.3 km winds
  - 60 km curl needs 20 km winds

Summary

- The ocean and atmosphere are relatively strongly coupled on scales below about 70km
  - The strength of this coupling **depends on waves and currents**
  - The spatial derivatives of currents and directional wind (stress) show a strong coupling, and the strength is **very scale dependent**.
  - Coupled models will need to represent this coupling to properly describe the **energy and water budgets, as well as ocean forcing**



- The **atmosphere responds relatively quickly** to small scale ocean forcing
- Horizontal shear in surface stress, **due to currents**, is the a relatively big player
- The **ocean's response to this curl in stress can be very strong**.
  - Changing horizontal and vertical advection, SST, stratification, water vapor, and the radiation budget

Graphic created by WHOI

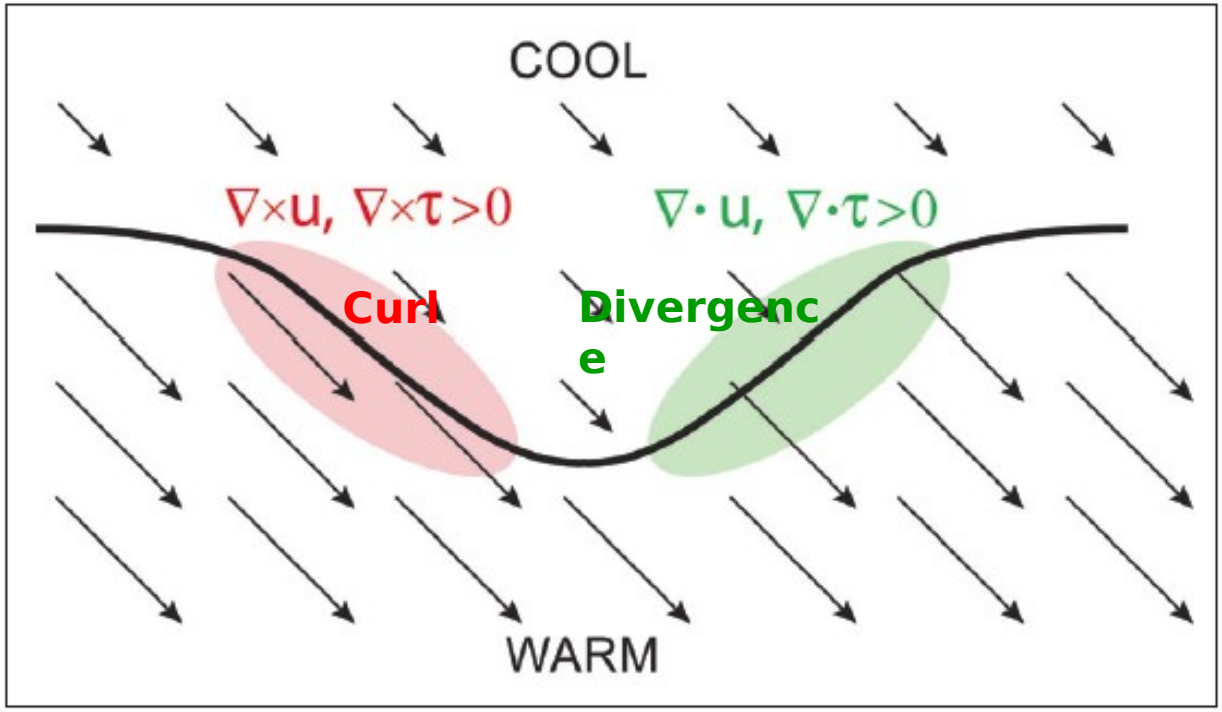
Three-Way Coupling of Surface Currents, Waves, and Wind Stress Over the Gulf Stream
Plus
Hurricane Related Motivation to Observe Currents

Mark A. Bourassa[1] and Qi Shi[1,2]

1. Center for Ocean-Atmospheric Prediction Studies and Department of Earth, Ocean and Atmospheric Science, Florida State University
2. Great Lakes Research Center

Backup Slides

Sensitivity of the wind stress curl to the crosswind SST gradient



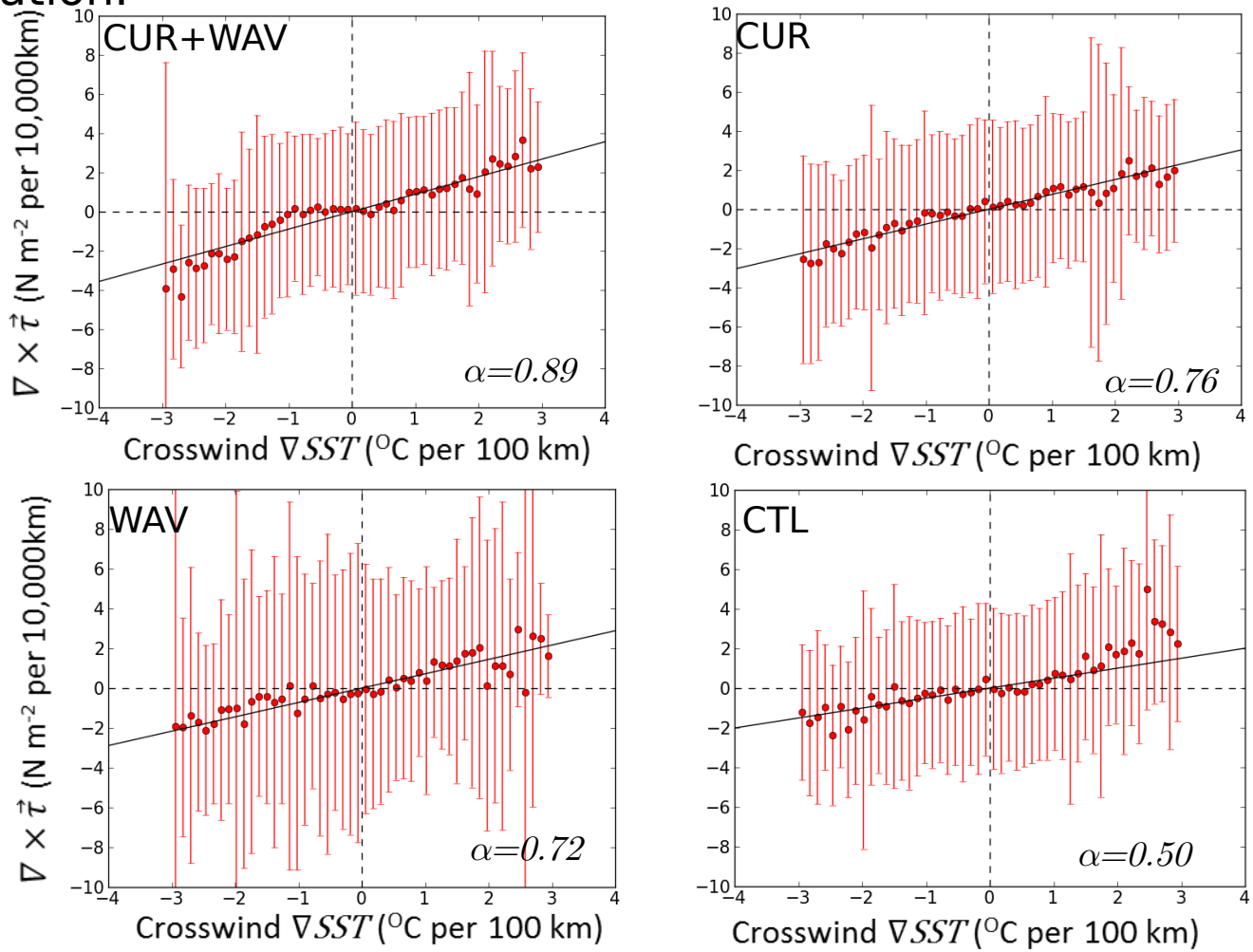
(*Chelton et al.*, 2007)

Coupling coefficient $\alpha = \dfrac{\nabla \times \vec{\tau}}{\nabla SST \times \dfrac{\vec{\tau}}{|\vec{\tau}|}}$

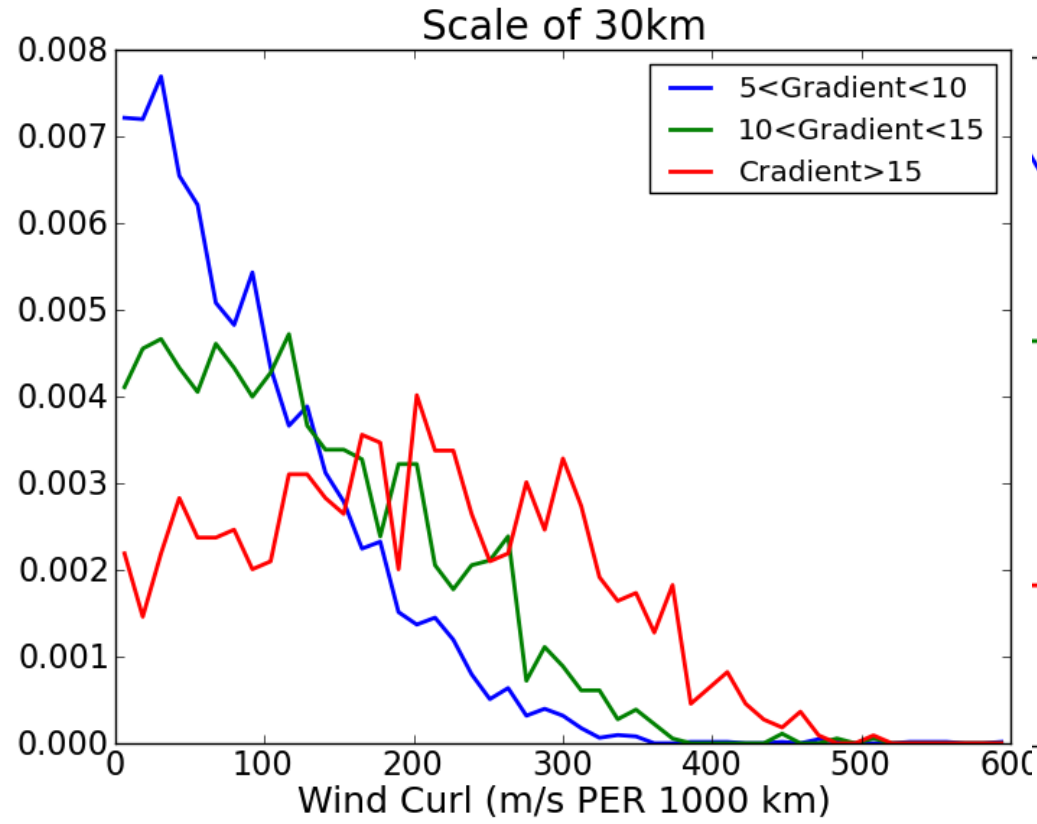
- Currents have already been shown to have a large impact on the pattern of stresses
- They also influence the pattern of SSTs (not shown in this version of the presentation)
- The coupling coefficient will be shown to be highly dependent on the physics considered in the parameterization of stress

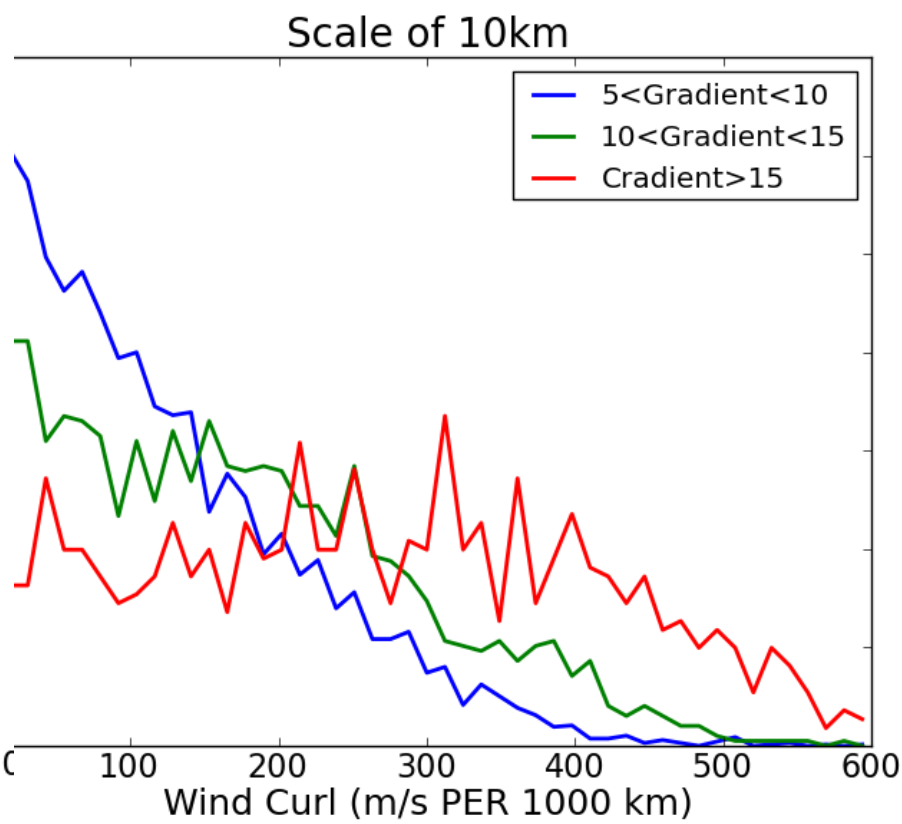
Coupling Coefficient

The coupling coefficient for model data is highly dependent on the stress parameterization.



Alternative Approach to Hypothesis





- The impact of strong current gradients is greatly diminished when curl is calculated on a 30km scale compared to calculations on a 10km scale.
- We could construct a hypothesis related to relative likelihood of occurrence.

Summary

- The curl of wind (stress) as a function of the gradient of surface current is a strong indicator of small scale (low end of mesoscale) coupling between the ocean and atmosphere
- We can diagnose this coupling with WaCM Geophysical variables
- This coupling appears to be relatively important for the regional and global energy and water cycles, as well as ocean forcing
- The signal is quite strong, but we must still complete an error analysis to show that we can resolve these differences with WaCM observations.

Science Goals Related to Air-Sea Interaction

Mark A. Bourassa[1] and Patrice Klein[2]

1. Center for Ocean-Atmospheric Prediction Studies and Department of Earth, Ocean and Atmospheric Science, Florida State University
2. JPL/Caltech, Pasadena, USA and LOPS/Ifremer/CNRS, France