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

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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)?

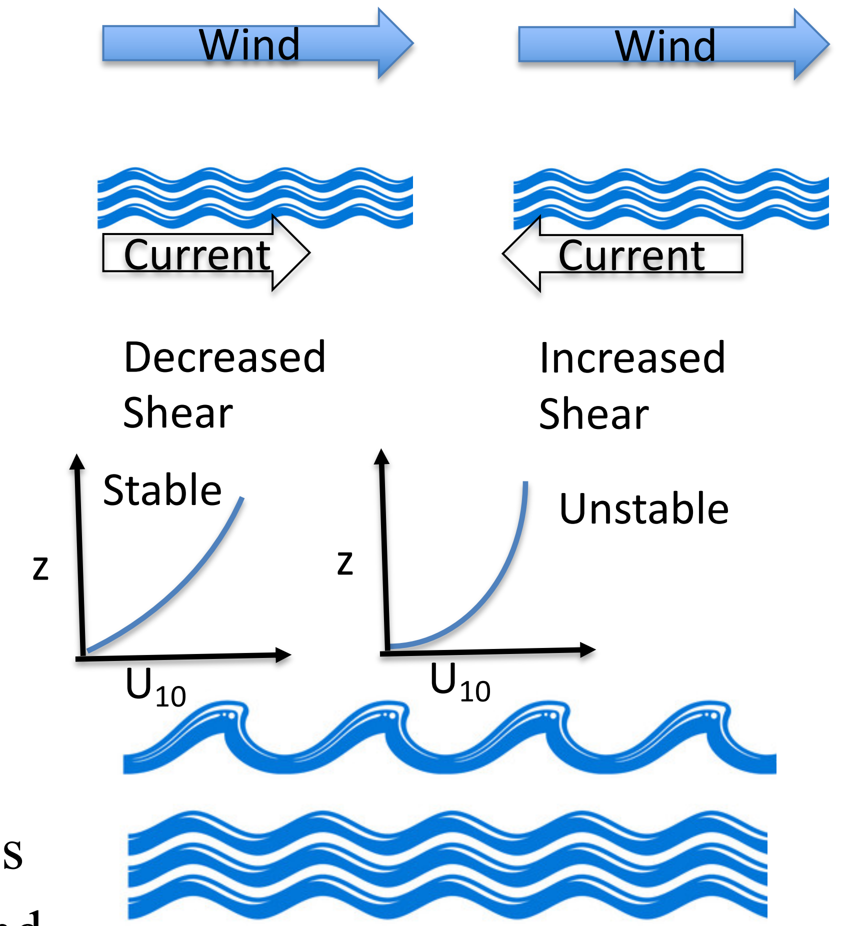
    Yes – importantly
  - Does the ocean respond to these changes (if any) in the atmosphere?

    Yes – quite substantially
  - Does resolution matter?

    Yes – it matters a lot!

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 ΔU
  - Stress proportional to |ΔU| ΔU
- Reduced wind shear results in increased 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 also 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.

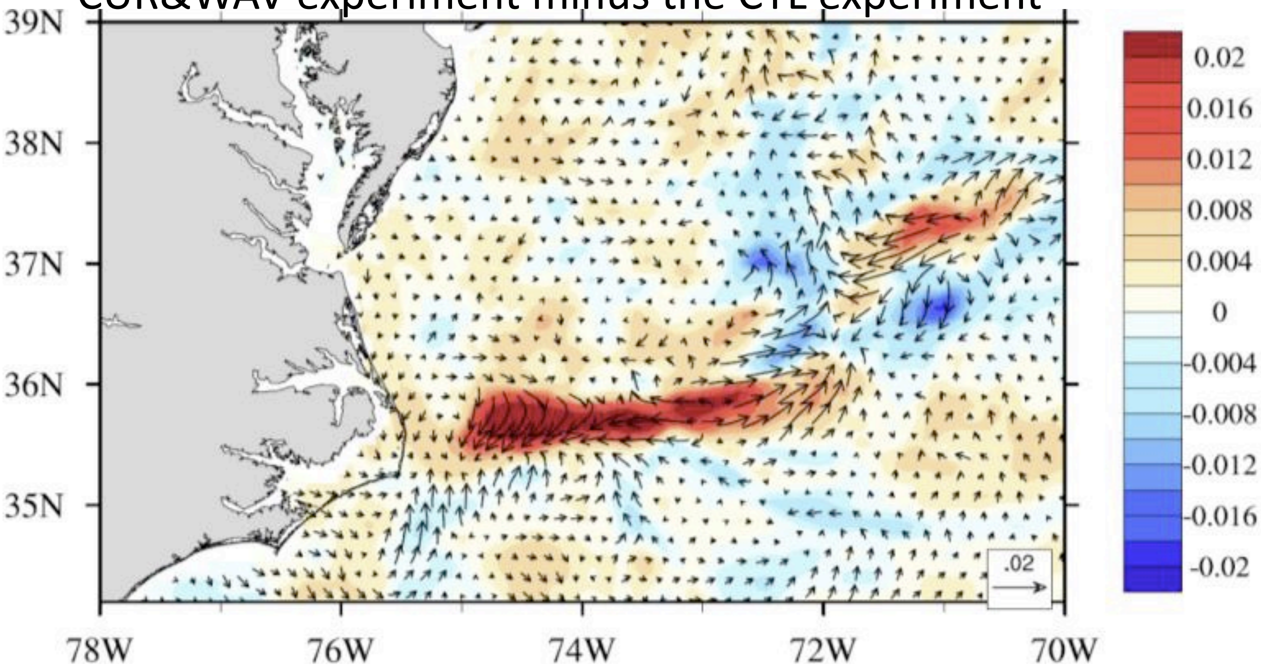
Experiments	Roughness length algorithm	Wind input for surface stress formulation	
CTL	COARE 3.0	$\vec{U}_{10}$	Stability only
CUR	COARE 3.0	$\vec{U}_{10} - \vec{U}_{CUR}$	+ currents
WAV	Taylor and Yelland	$\vec{U}_{10}$	+ waves
CUR-WAV	Taylor and Yelland	$\vec{U}_{10} - \vec{U}_{CUR}$	+ waves & currents

Ongoing work: Adding Stokes drift

Changes in October Wind Stress Magnitude

Relative to model with stress independent of waves and currents

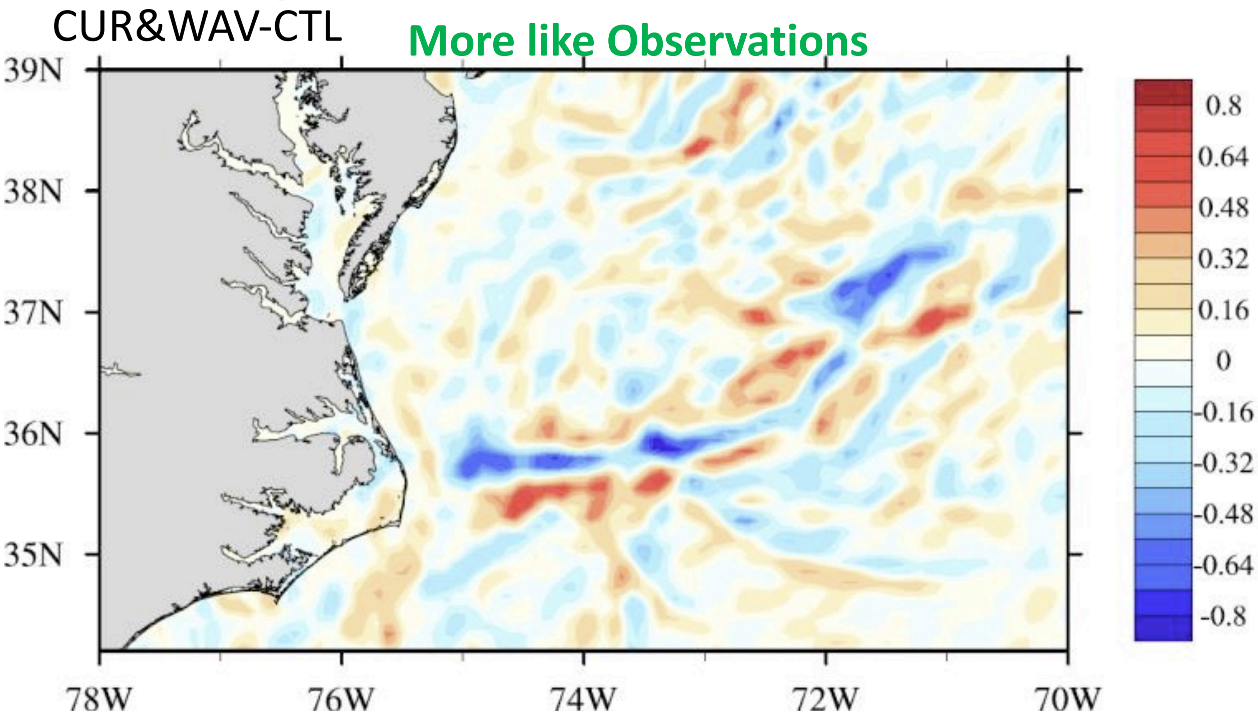
CUR&WAV experiment minus the CTL experiment



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

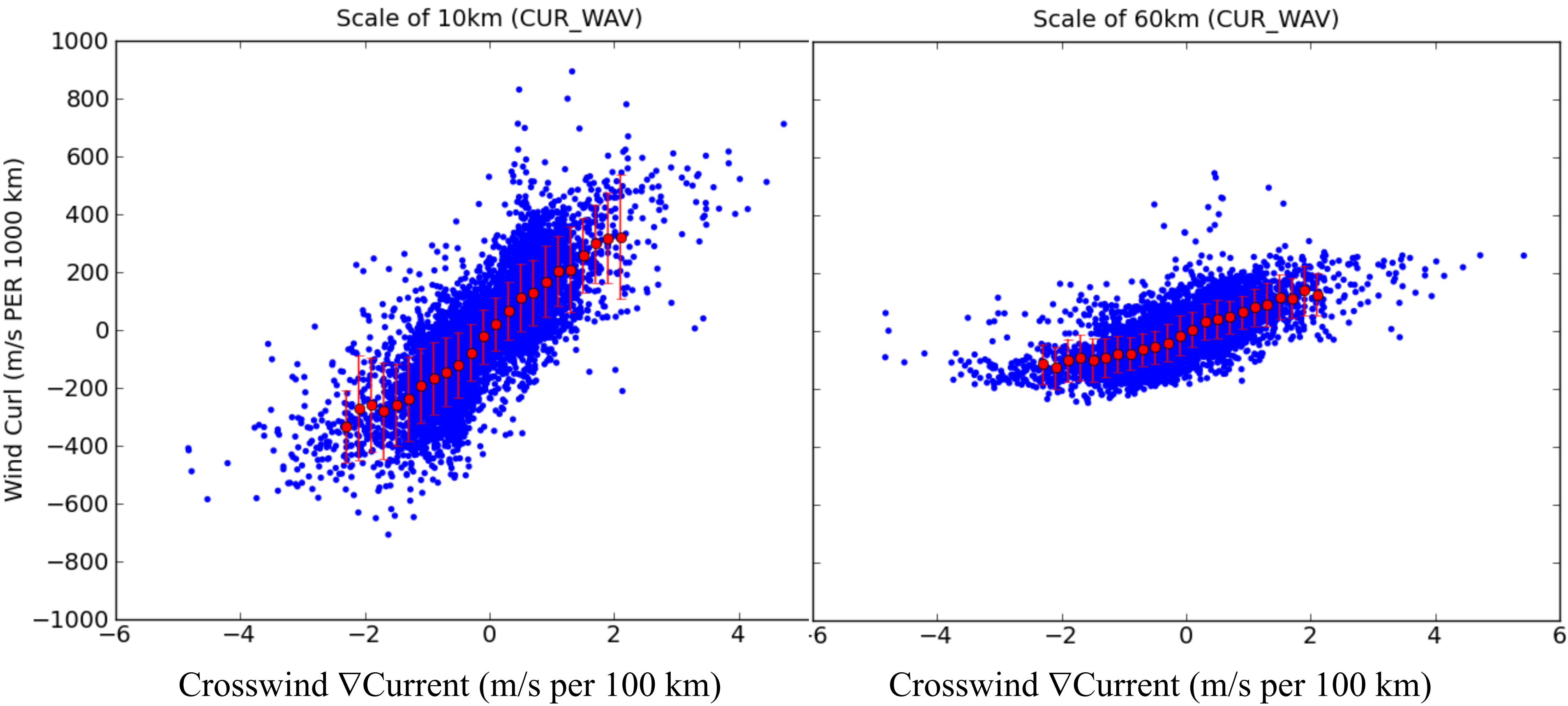
Changes in October Ocean Ekman Pumping



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 (m/s).

- 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

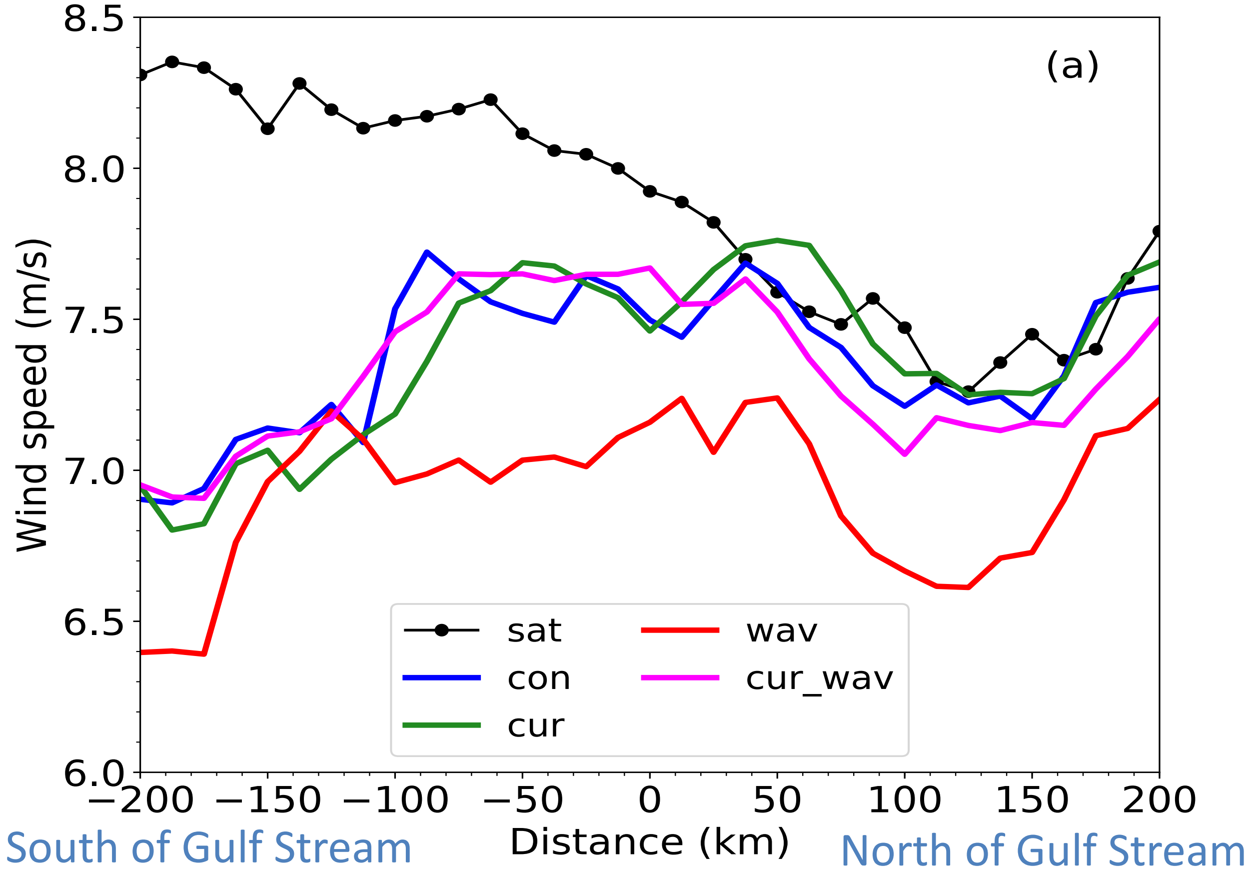
Modeled Wind Curl vs Current Gradient (as a function of spatial scale)



- 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

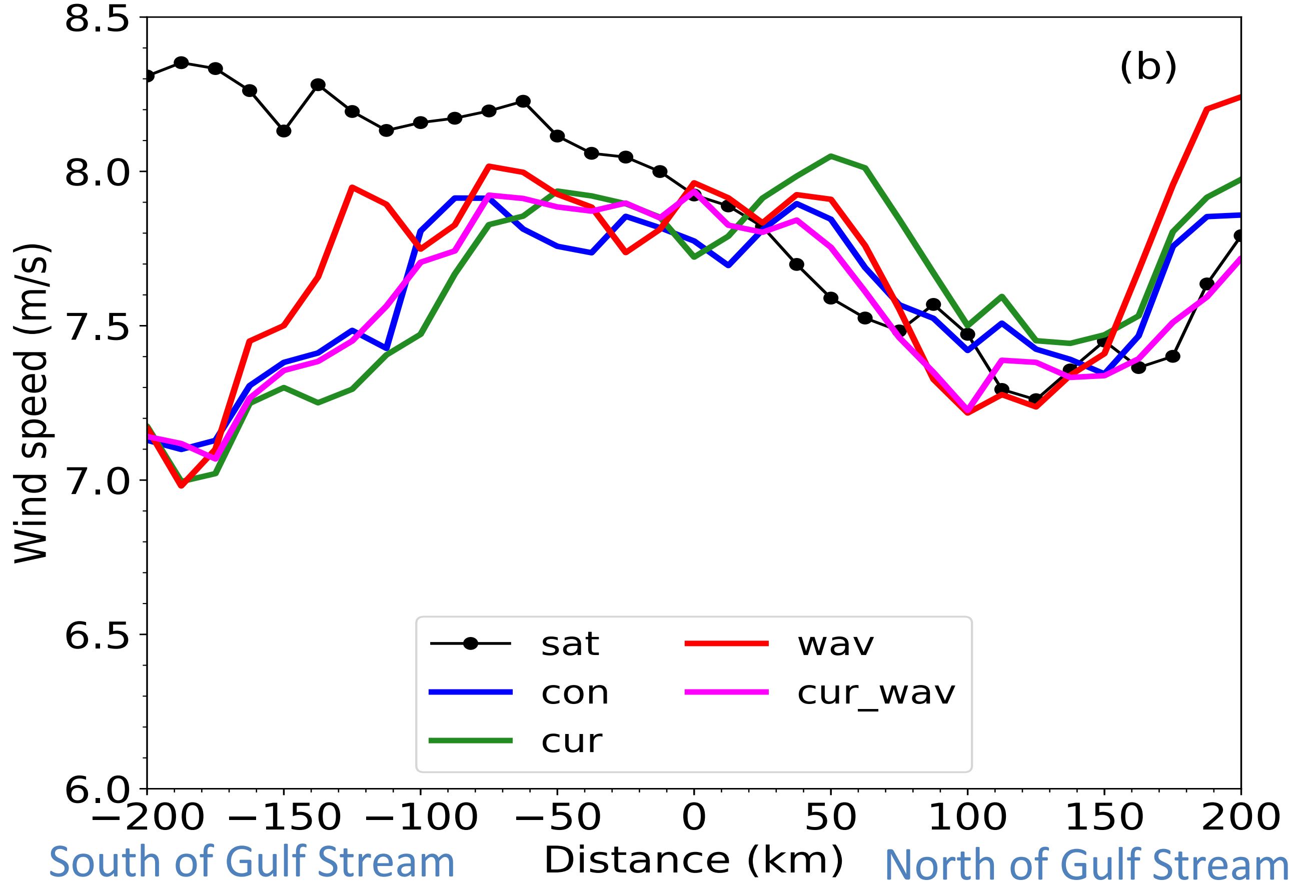
- Curls have much better signal to noise when calculated with a length scale of three times the spacing of wind vectors:
  - 10 km curl needs 3.3 km winds
  - 60 km curl needs 20 km winds

Comparison of Mean Modeled Wind to ASCAT



- Comparison of averaged ASCAT equivalent neutral winds (black dotted) to model winds (i.e., Winds vs equivalent neutral winds = bad)

Comparison of Mean Modeled Wind to ASCAT



- Comparison of averaged ASCAT wings to model winds converted to neutral winds using COARE 3.0 roughness length algorithm.
  - Stability and currents are important

Summary

- Model equivalent neutral winds are very sensitive to the stress parameterizations
  - Roughness length or neutral drag coefficient
  - Boundary-layer stratification adjustments in U_{10EN}
- These preliminary results show the importance of using the same roughness (or drag) parameterization for modeling and adjustment to U10EN.
- Monthly averages of instantaneous differences appear to provide some insight into tests for air-sea coupling
  - Particularly to boundary-layer stratification
    - Air/sea temperature differences
    - Wind stress
- Observations of air temperature could be used to greatly improve assessment

Graphic created by WHOI

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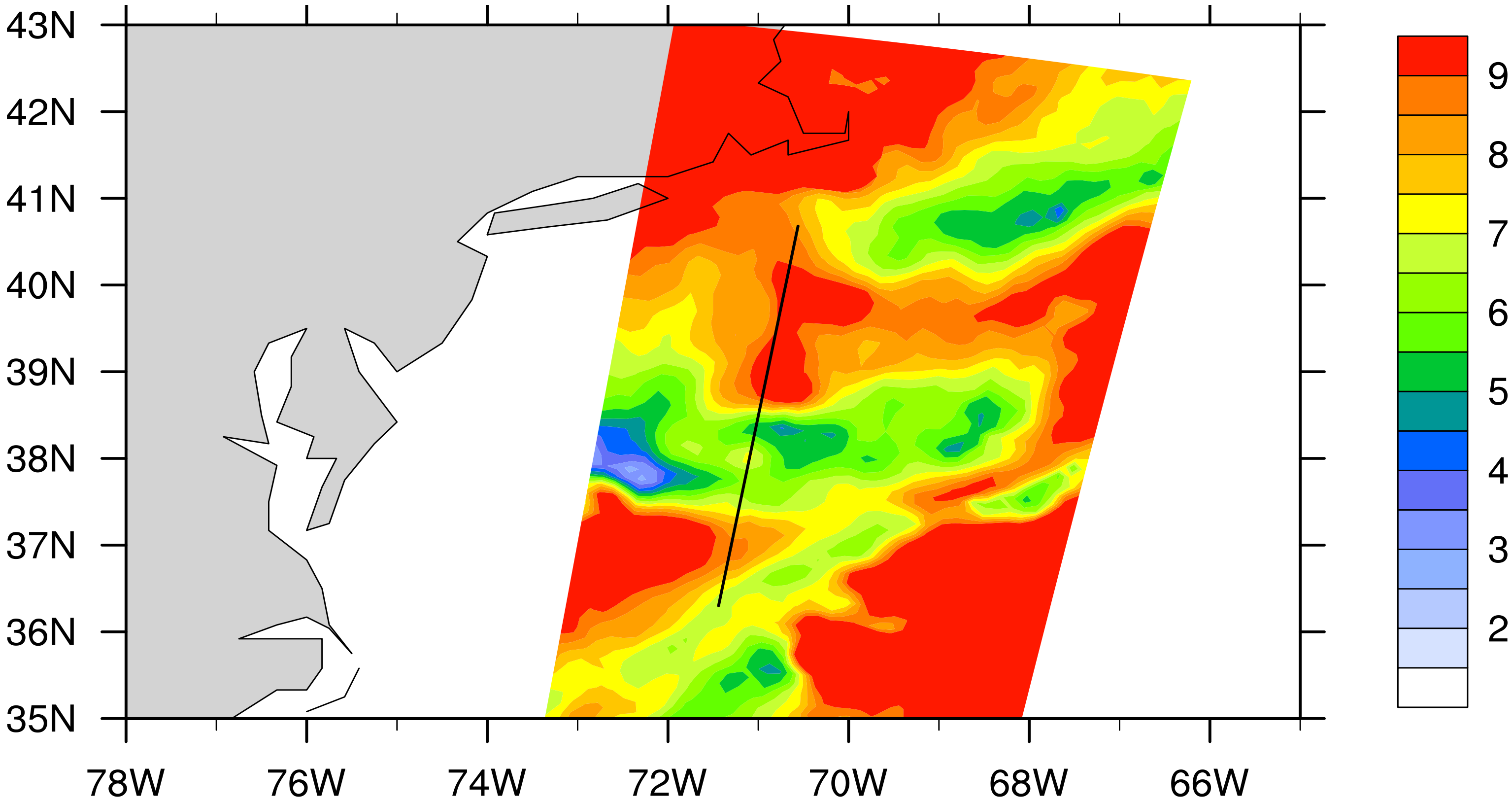
Backup Slides

Validation with ASCAT Winds



- ASCAT scatterometer observed wind speed (color shaded) near Gulf Stream region on October 15, 2012. The wind speed alone the backline is selected for comparison with modeled surface wind.

Ocean-Atmosphere-Wave Modeling

Ocean
(ROMS)

Wind stress, Surface heat fluxes
Radiation, Precipitation,
Sea level pressure

Sea surface temperature
Surface currents

Atmosphere
(WRF)
+
Modified
MYNN

Surface
currents

Wave length,
height, period
and direction

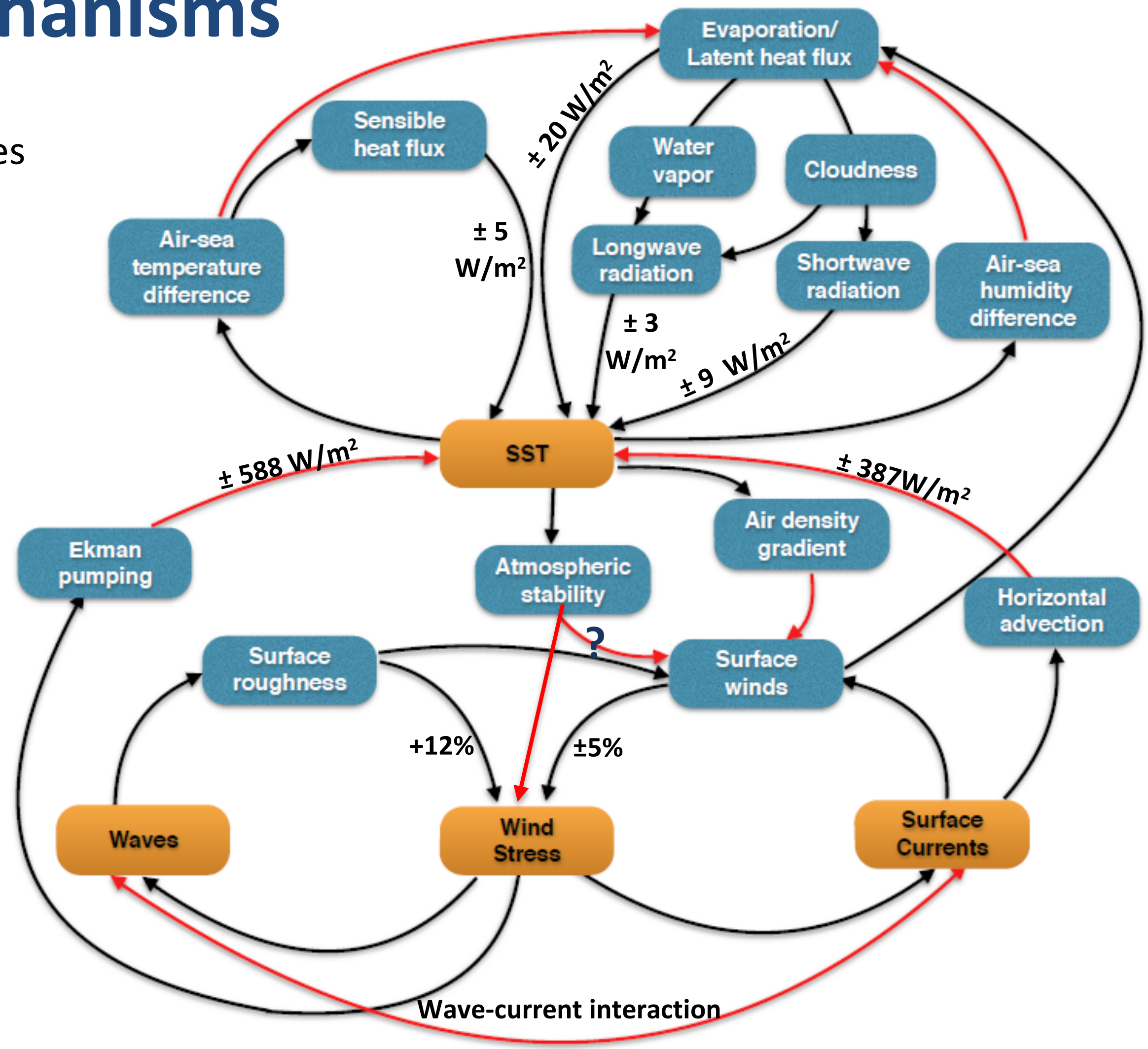
Wave
(SWAN)

10-meter wind wrt Surface Current

Wave height and wave length

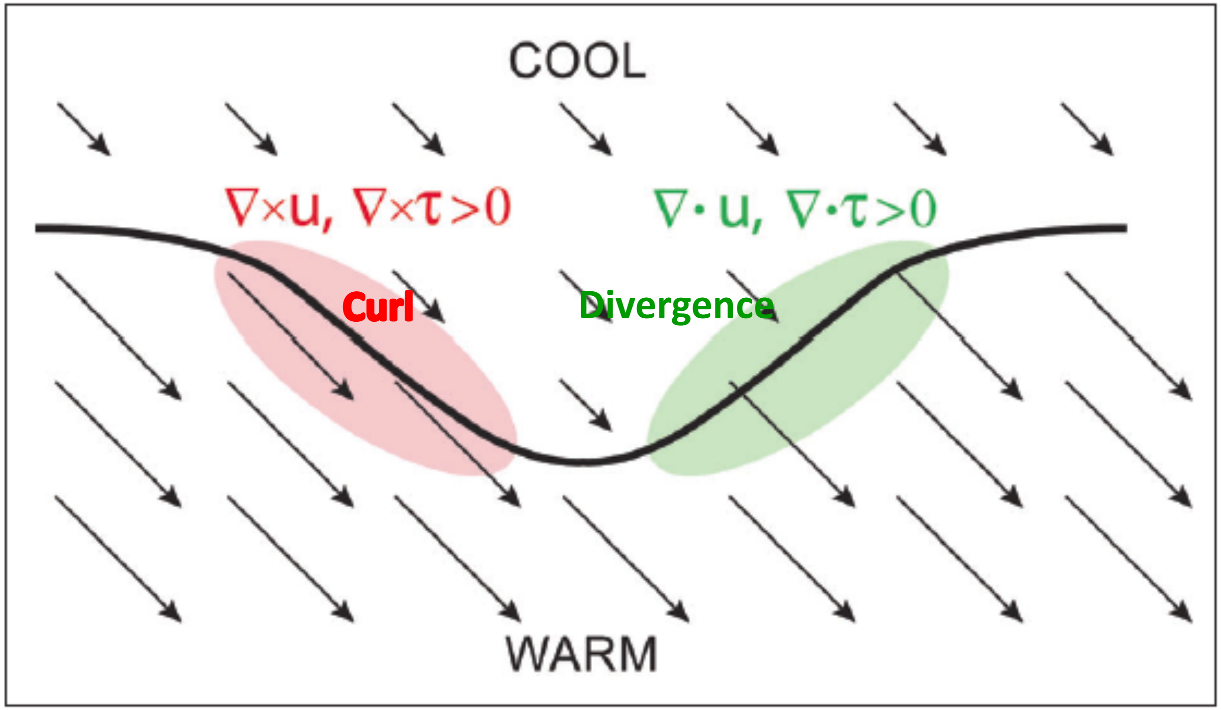
Coupling mechanisms

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

Sensitivity of the wind stress curl to the crosswind SST gradient



(*Chelton et al.*, 2007)

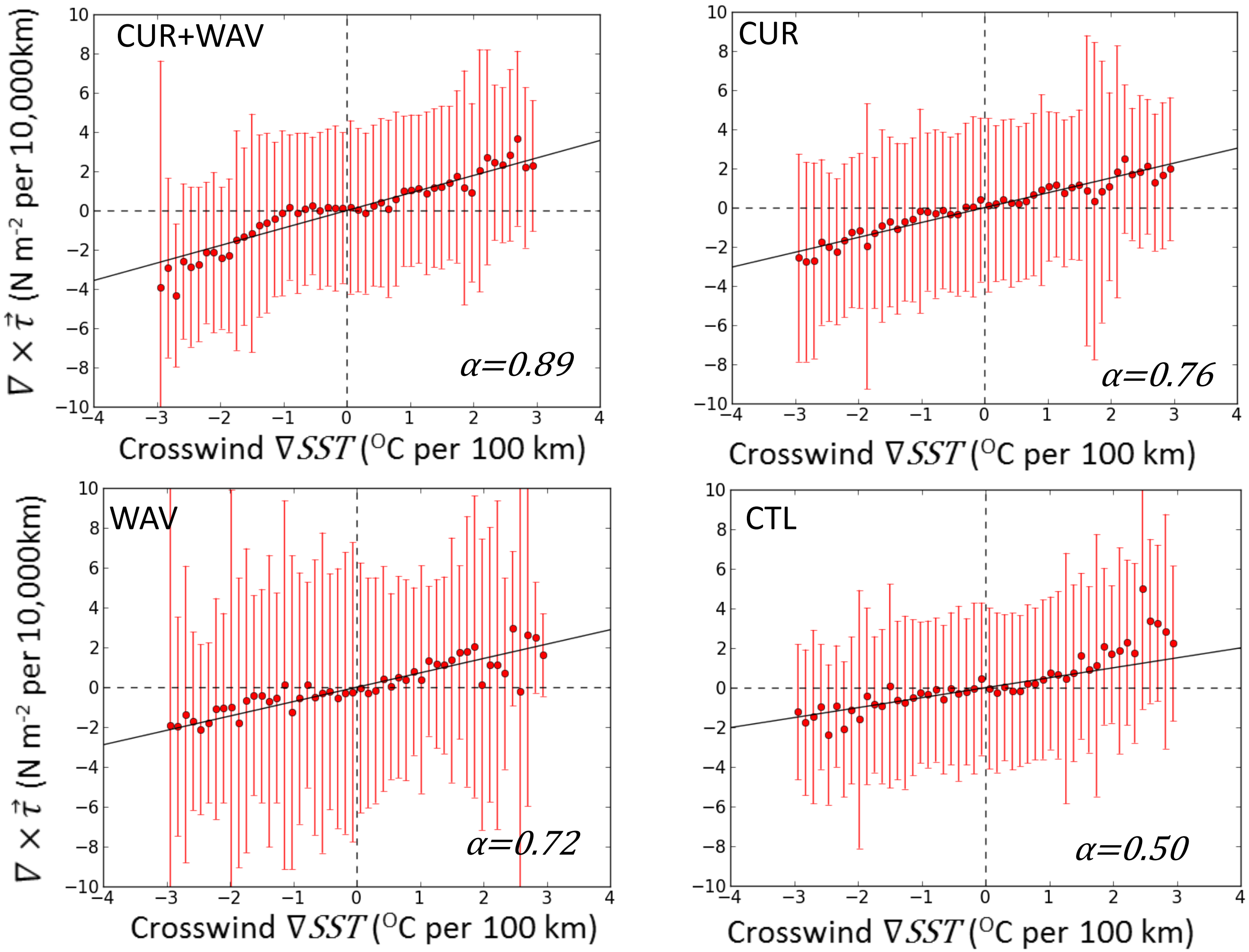
Coupling coefficient
$$\alpha = \frac{\nabla \times \vec{\tau}}{\nabla SST \times \frac{\vec{\tau}}{|\vec{\tau}|}}$$

- 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)

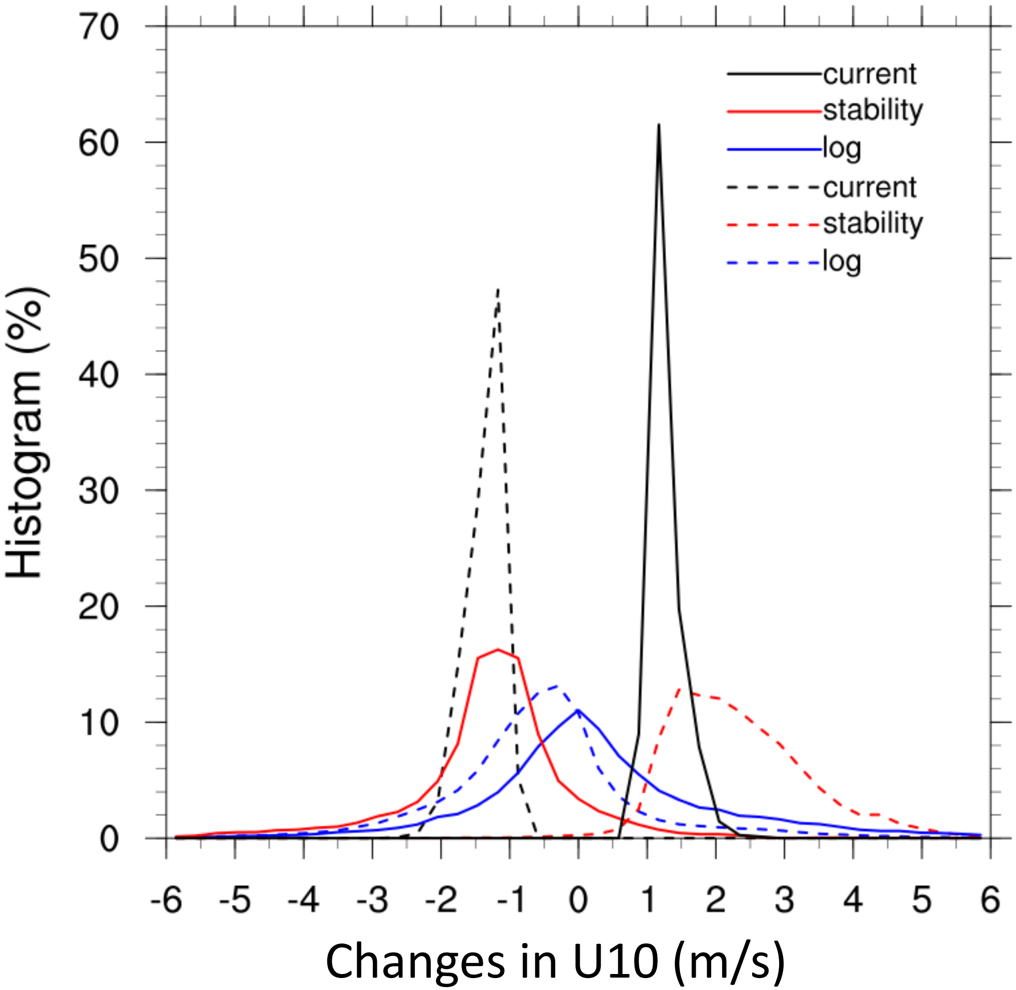
- The coupling coefficient will be shown to be highly dependent on the physics considered in the parameterization of stress.

Coupling Coefficient

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



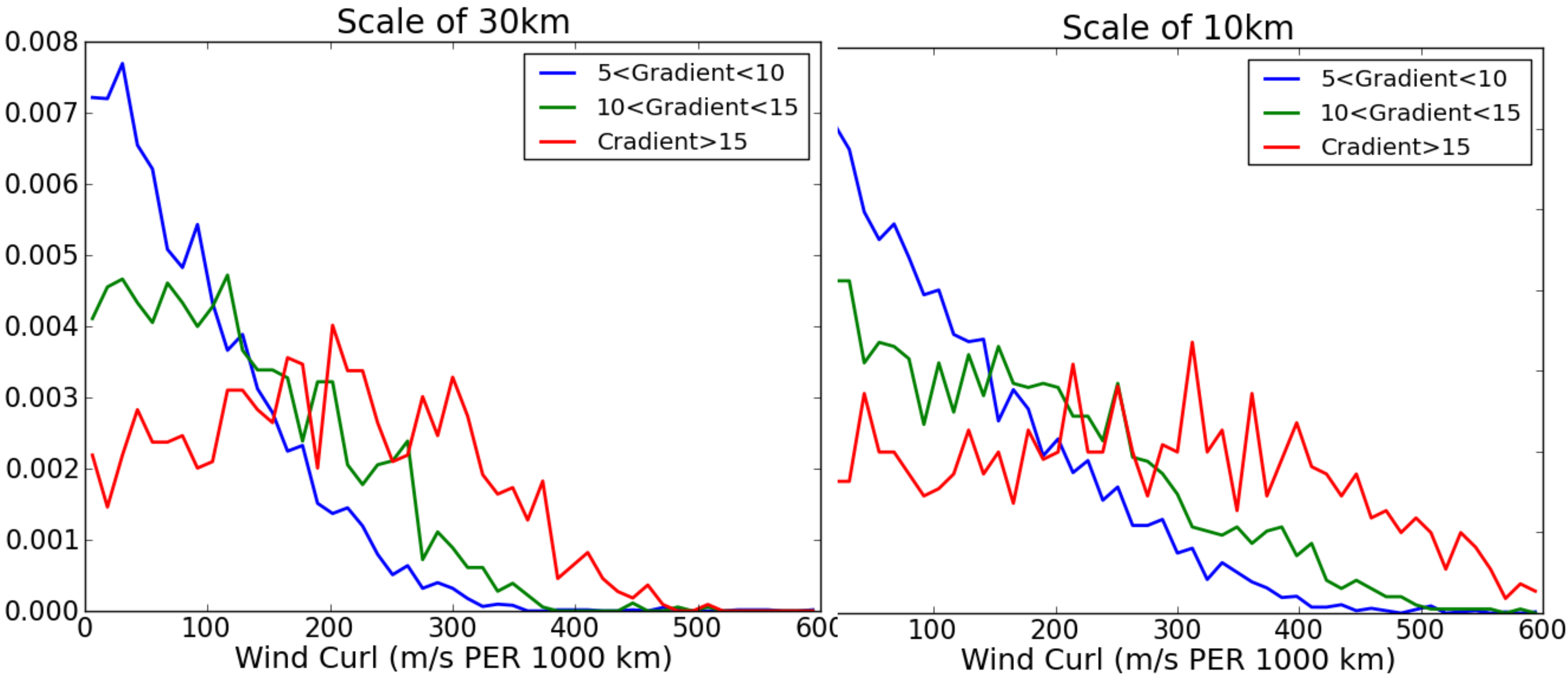
Currents Are Very Important



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

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

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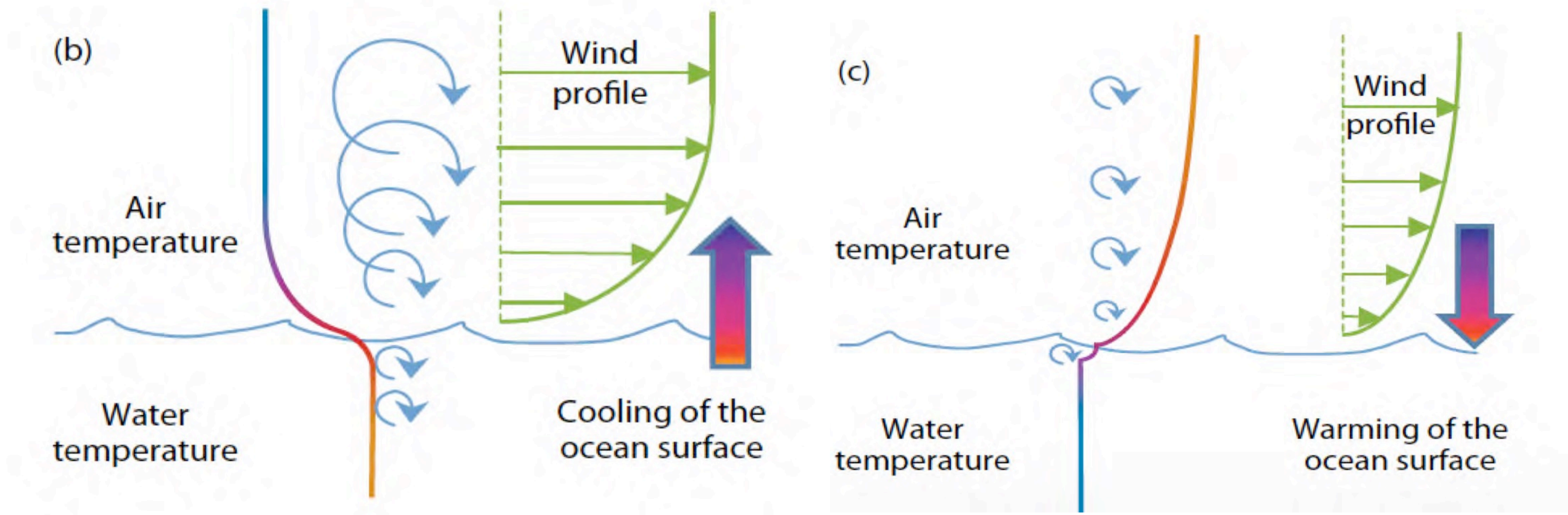
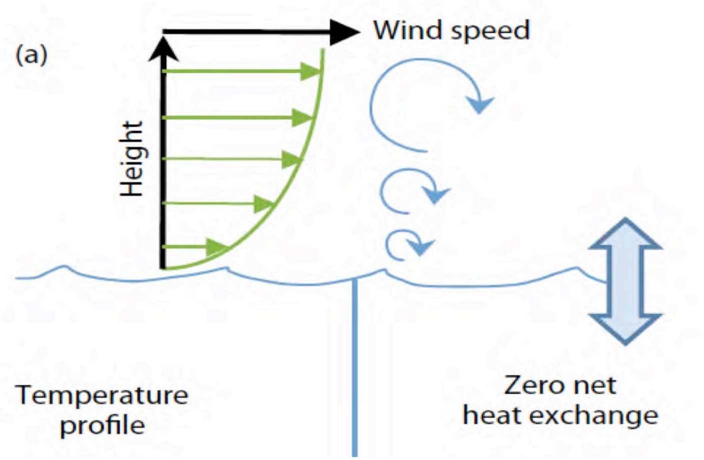
Density Stratification Influences Air-Sea Exchange

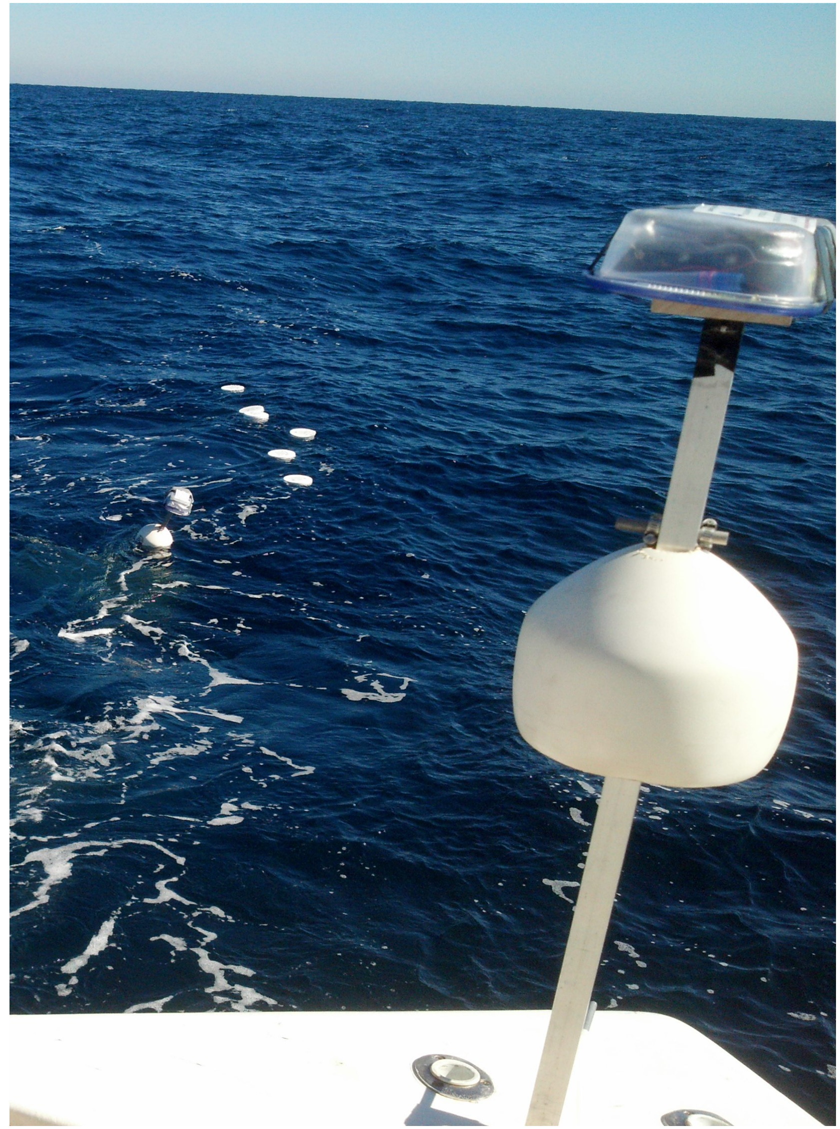




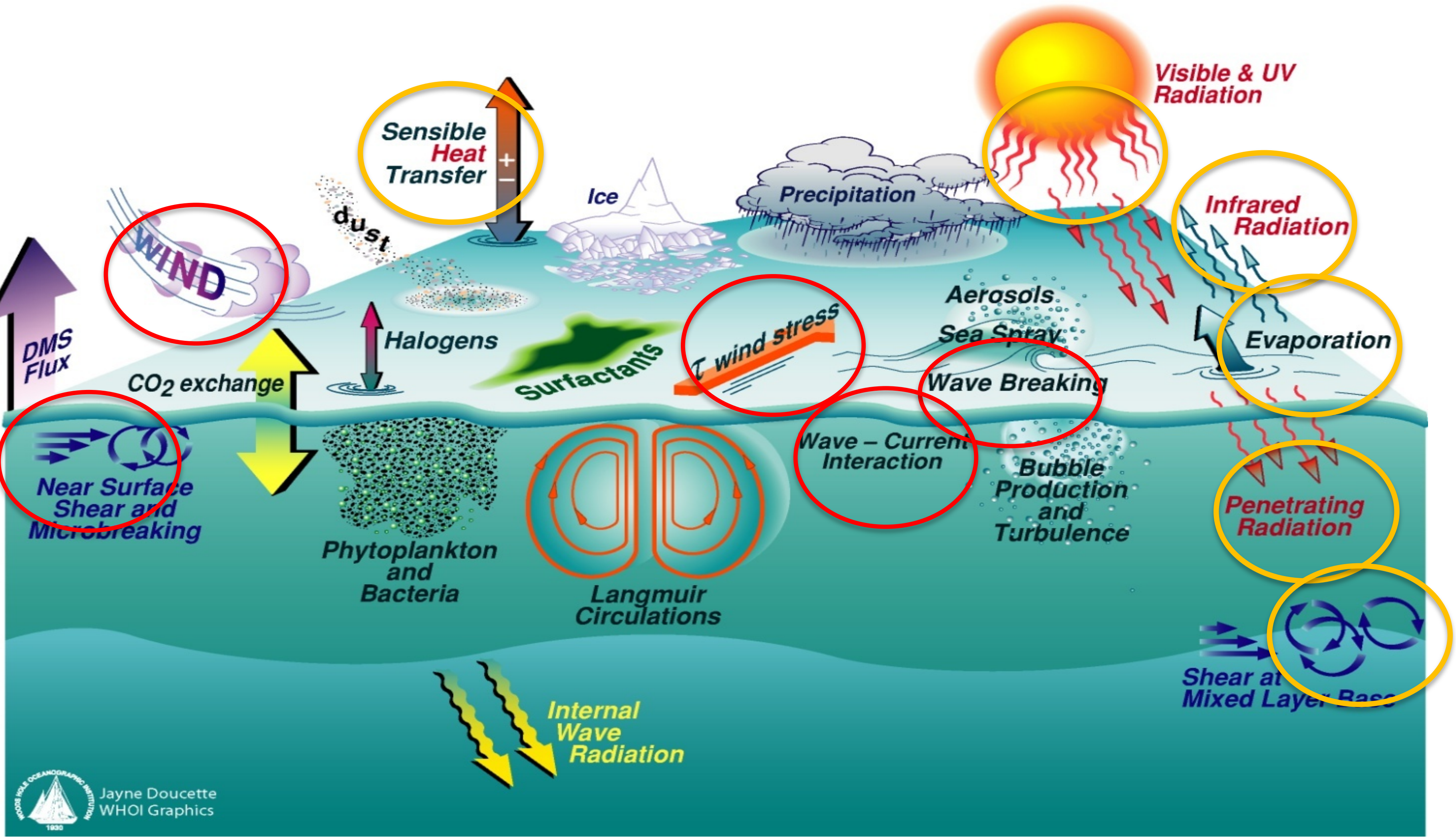
- Neutral Stability: (a) The air density is constant with height
- Unstable: (b) more dense over less dense. Ocean warms the air and the vertical flux of horizontal momentum (stress) is enhanced
- Stable: (c) Qualitatively opposite of unstable

Bourassa et al. Oceanography (2010)

We've Designed Drifters to Measure Surface Currents



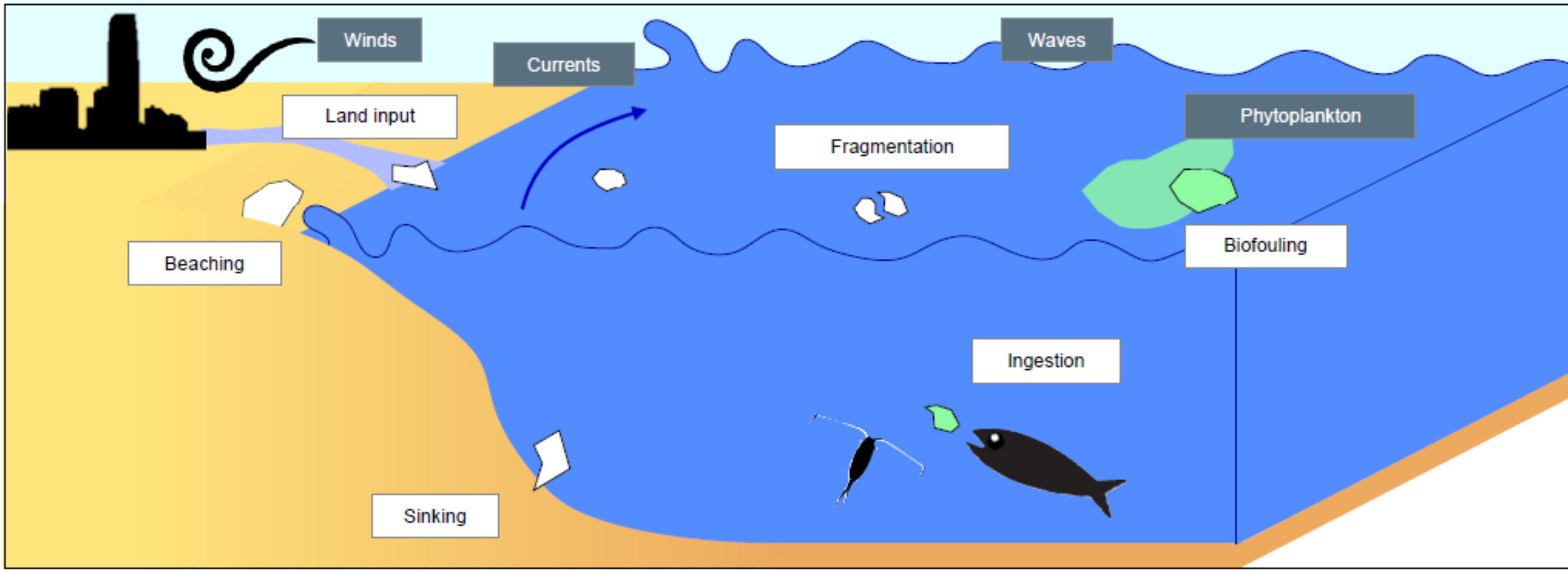
Processes & Items Influencing Air-Sea Interaction



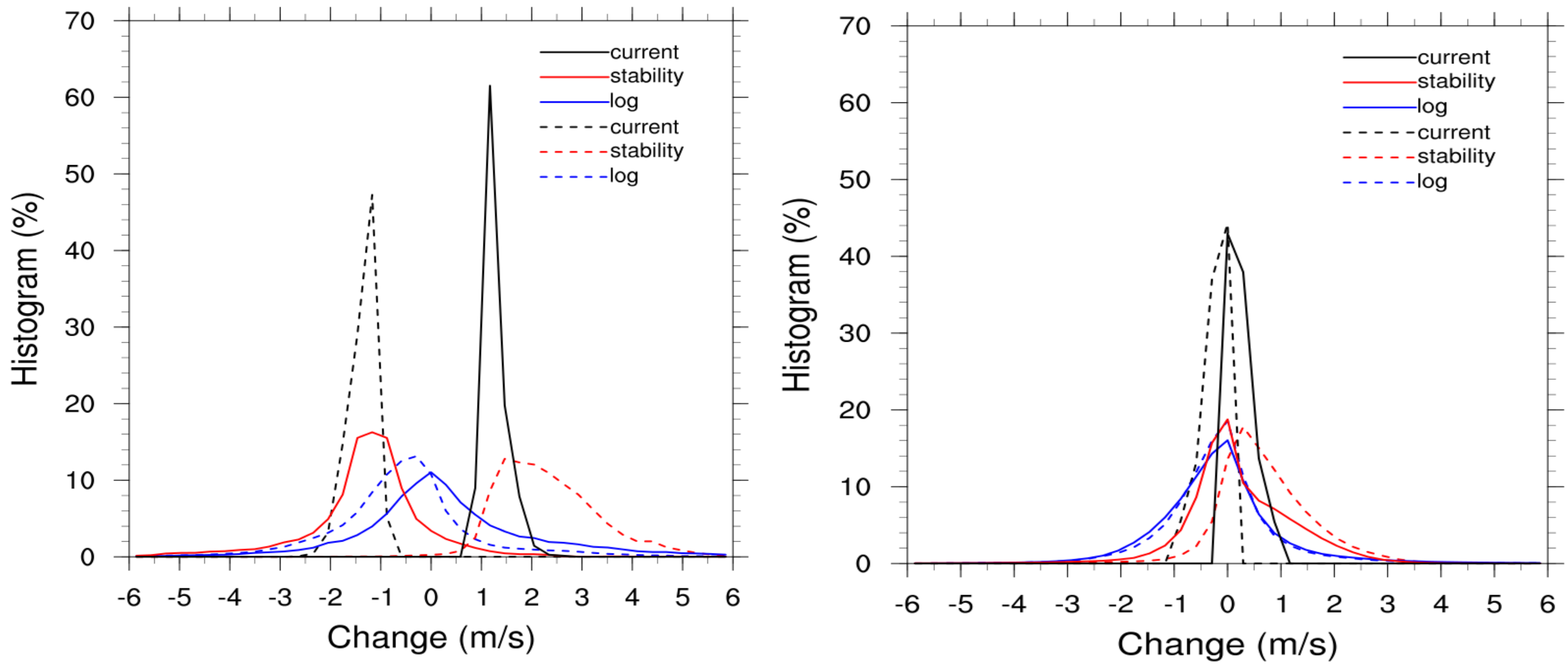
- Red: essential for wind coupling
- Orange: additional considerations essential for temperatures

Graphic created by WHOI

Air-Sea Interaction Influences Pollution and Debris Transport (Plastics)



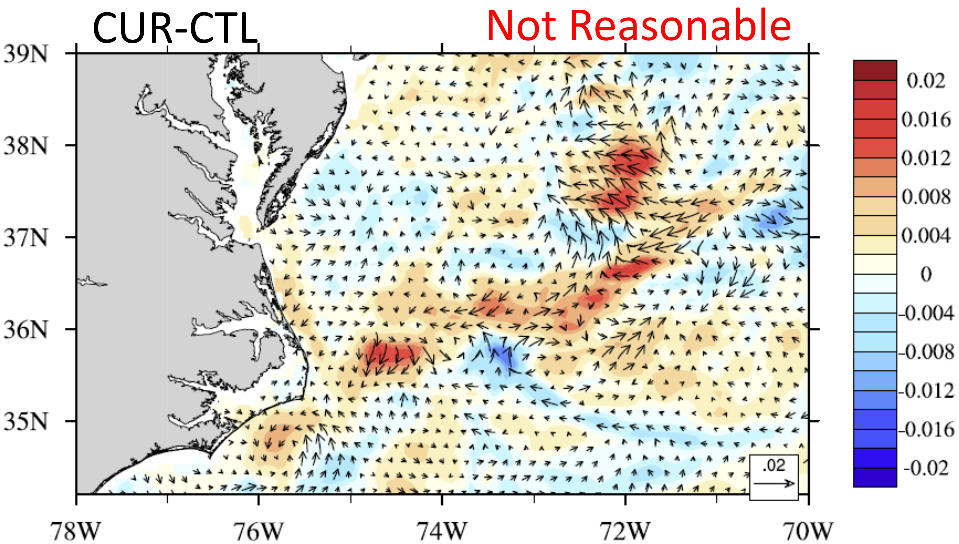
Surface Wind Response

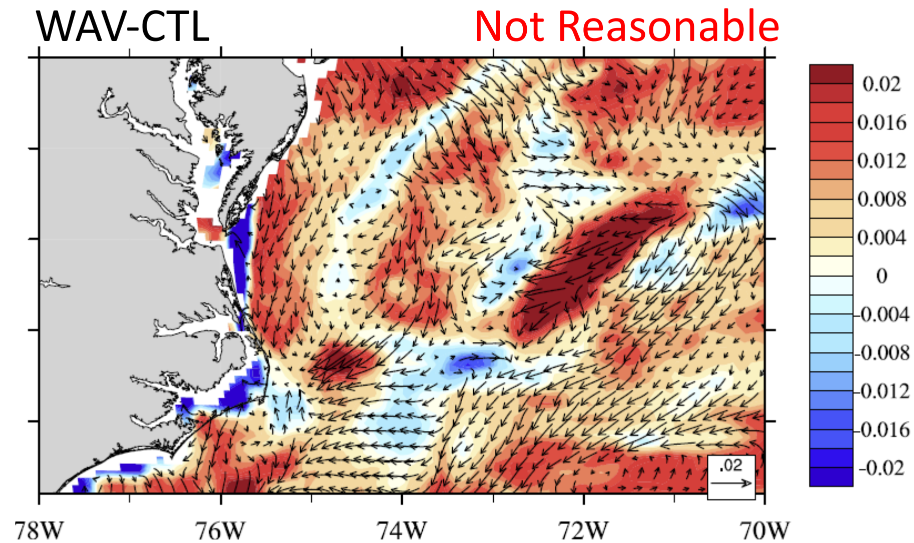


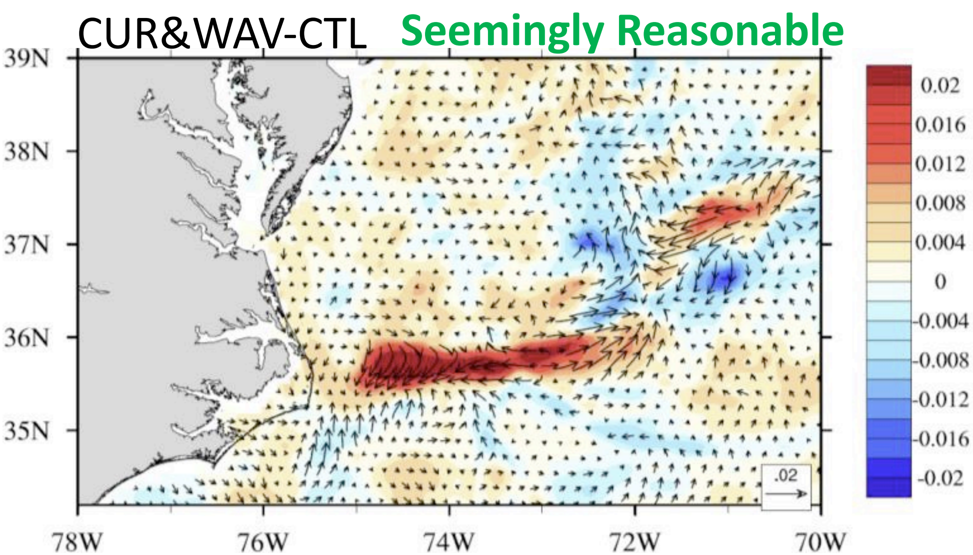
- Histograms of the difference of current, stability and log profile terms in the log-wind equation between CUR_WAV and WAVE experiments. The statistics are computed over strong-current (U_s>1m/s; left) and weak-current (U_s<1 m/s; right) regions. Dashed lines are associated with negative changes in currents.

Changes in October Wind Stress Magnitude

Relative to model with stress independent of waves and currents



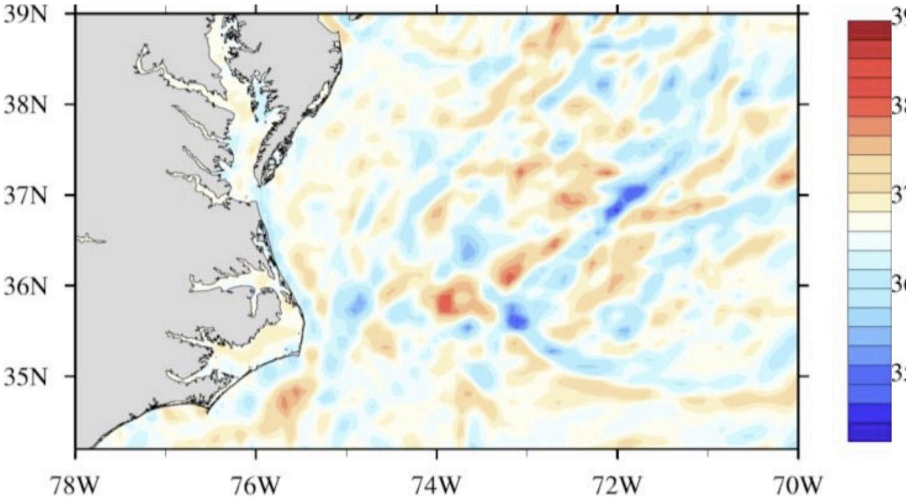




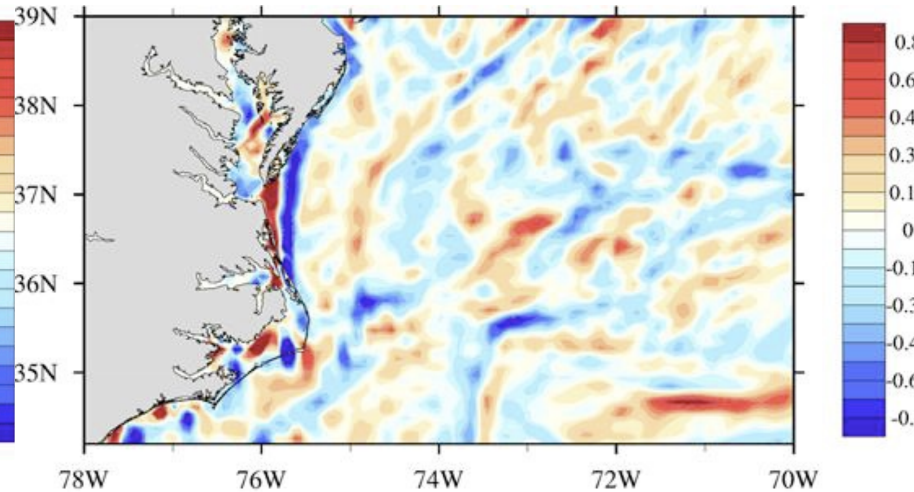
- Currents alone tend to reduce EKE production beyond reasonable values
- Waves alone tend to increase stress
  - But not as needed
- Waves together with currents are not a linear sum of the two
  - Good for ocean EKE
  - Surface currents are critically important

Changes in October Ocean Ekman Pumping

CUR-CTL

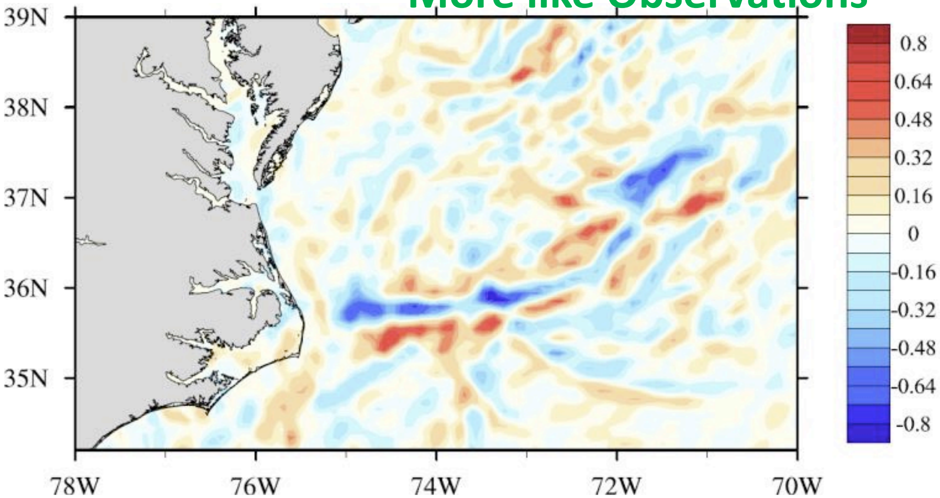


WAV-CTL



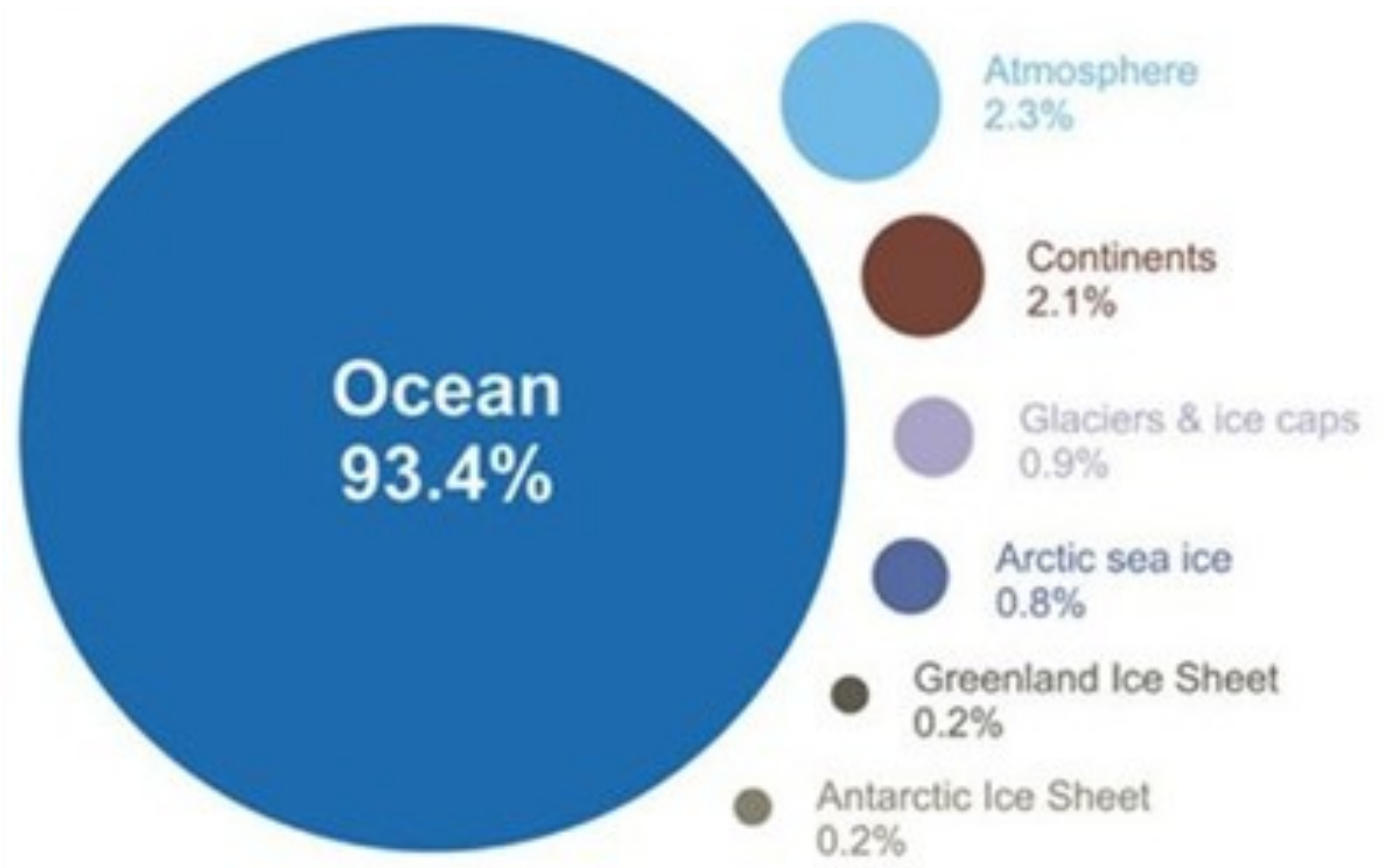
CUR&WAV-CTL

More like Observations



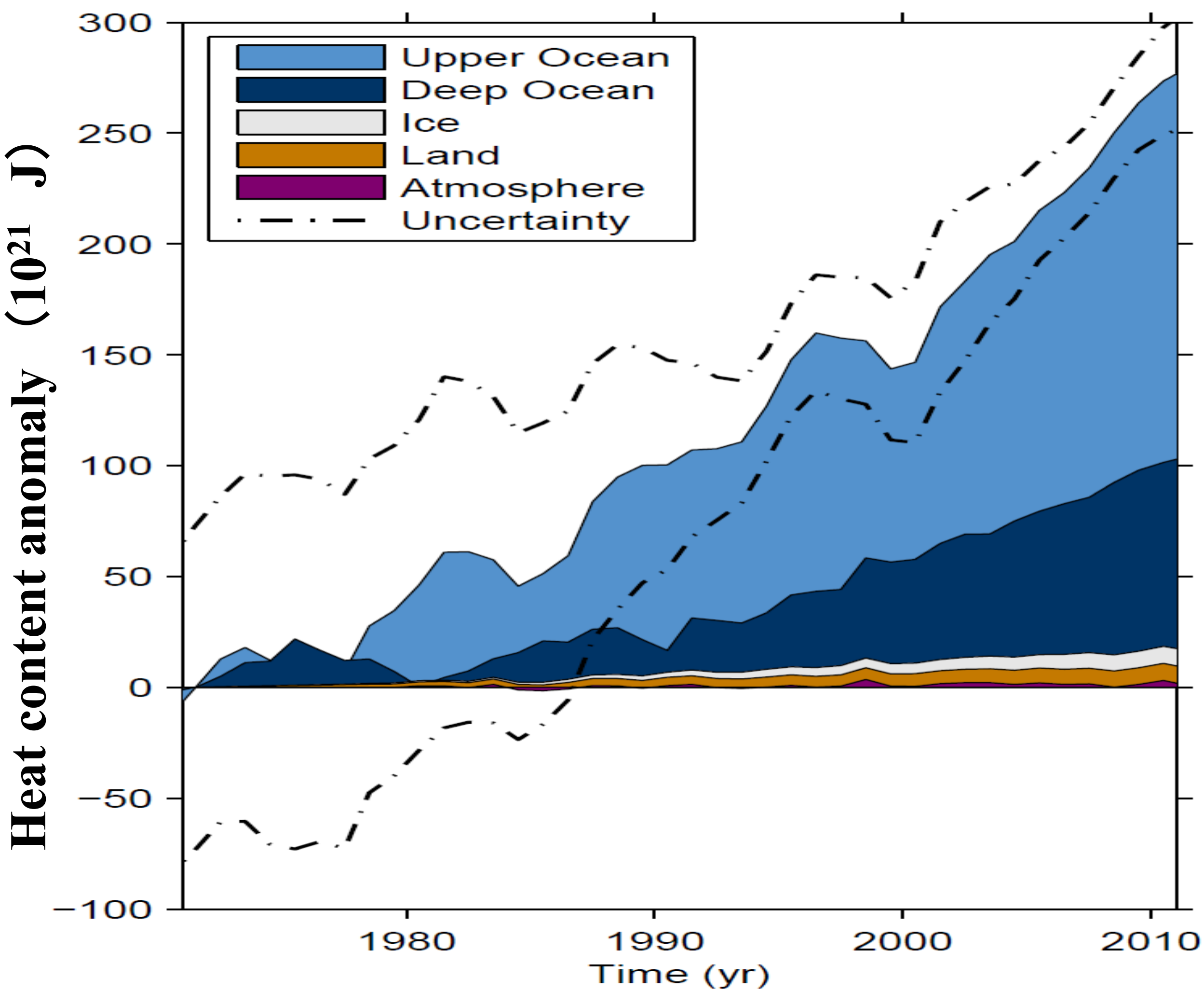
- In the upper two images the mixed layer heat budget is dominated by horizontal transport processes.
- In the bottom case, the heat budget is dominated by vertical motion
  - Curl of stress is greater over SST gradients (more like observations)

Where is the Warming-Related Energy Going?



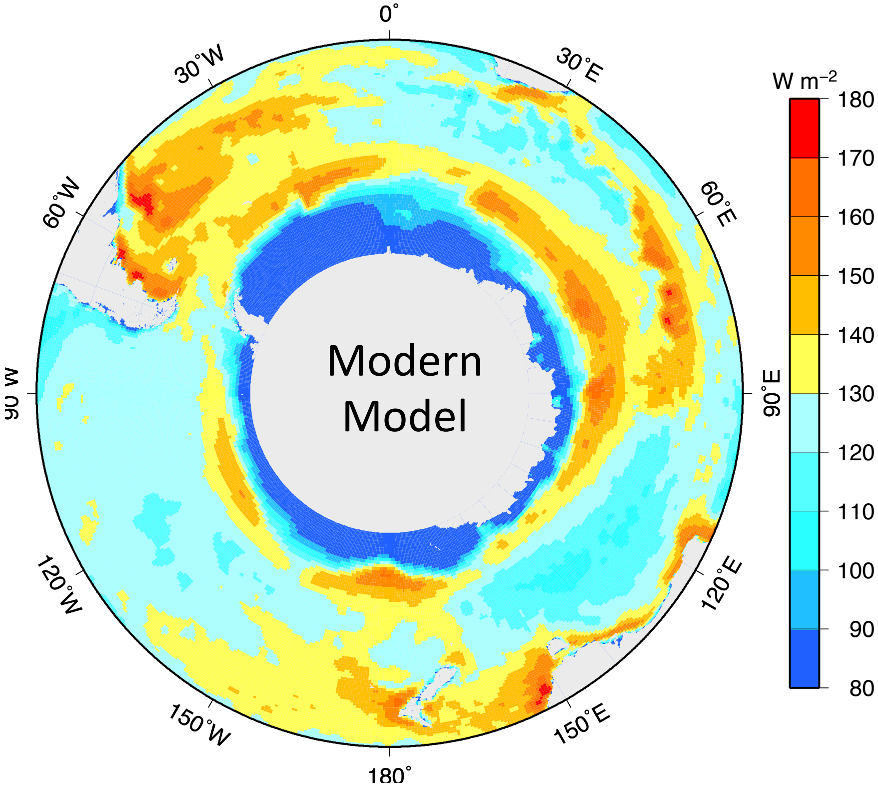
Links to Climate Change: Ocean Heat Content

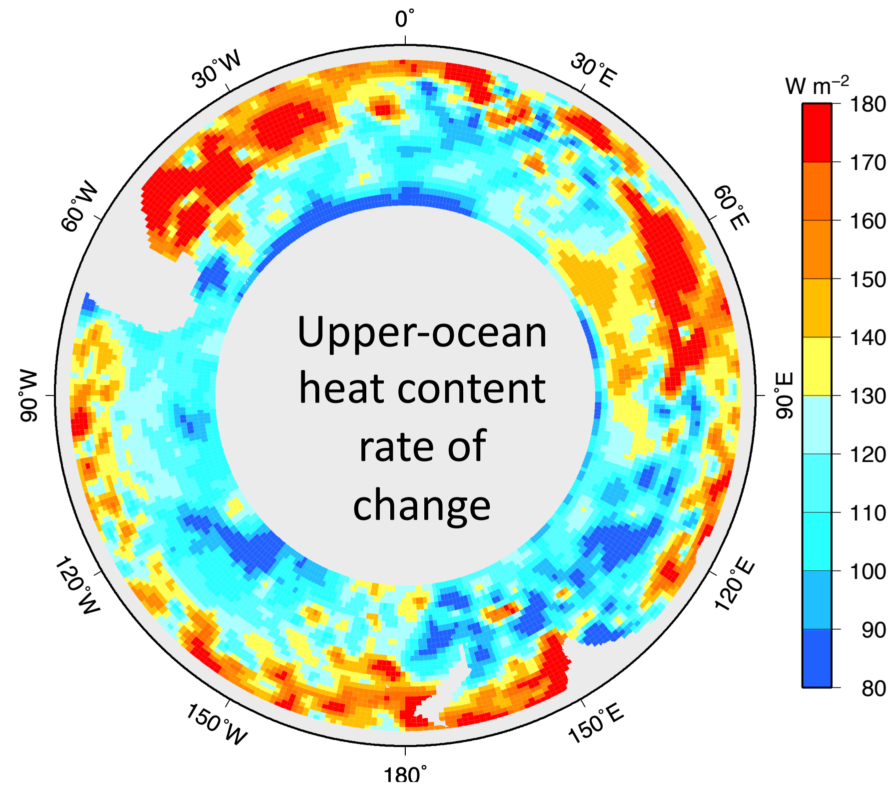
Where is global warming going?



IPCC AR5

Upper-Ocean Heat Content Rate of Change - Modern Model vs data - Seas Around Antarctica





Models (left) don't match observations (right)

- Except when averaged over the whole Southern Ocean
- If regional energy budgets are wrong, heating will occur in the wrong areas and air-sea exchange will be non-sense

Sarah Gille