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Atmospheric Response to Kinematic Coupling of Wind to Stress and Currents Over the Gulf Stream Region

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Motivation

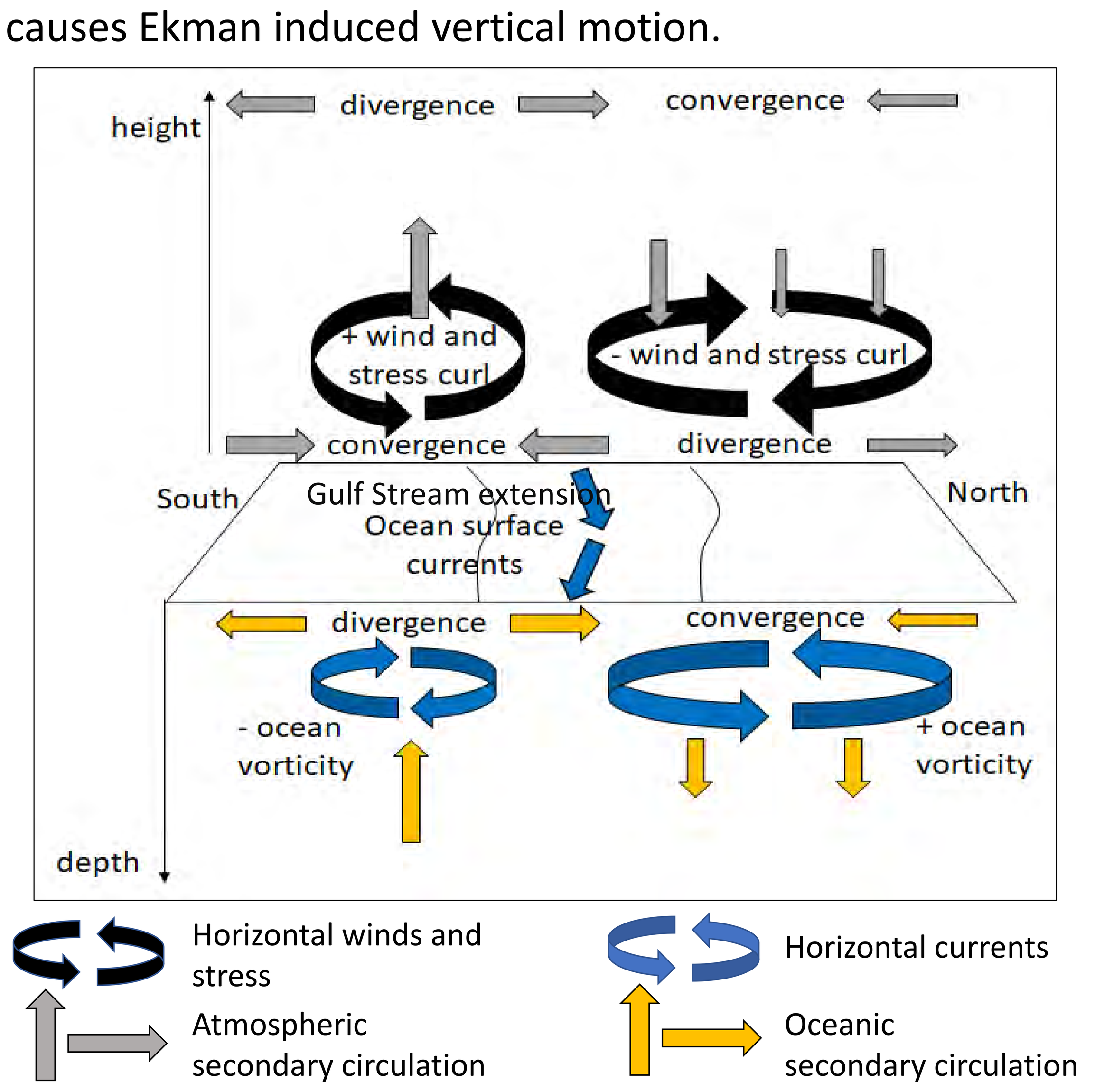
In coupled atmosphere/ocean and atmosphere/ocean/wave models, the kinematic coupling (between currents and winds), atmospheric horizontal resolution, and oceanic horizontal resolution each have a significant impact within the ocean mixed layer, as well as the atmosphere. The responses within atmosphere are examined here using two-way coupled atmospheric/ocean models. The first four coupled model simulations are completed with various combinations of 2km (submesoscale resolving) and 6km (submesoscale permitting) atmospheric and ocean grid spacing and without the kinematic coupling. The second four coupled model simulations use the same model resolutions defined in the first set of four simulations, but the kinematic coupling and feedback between the surface currents and wind stress is included.

Experiments	Simulation Name	Resolution	Wind Input for Surface Stress
Exp 1	a2o2	2 km ocn; 2 km atm	$\vec{U}_{10}$
Exp 2	a2o6	2 km ocn; 6 km atm	$\vec{U}_{10}$
Exp 3	a6o2	6 km ocn; 2 km atm	$\vec{U}_{10}$
Exp 4	a6o6	6 km ocn; 6 km atm	$\vec{U}_{10}$
Exp 5	a2o2-curr2	2 km ocn; 2 km atm	$\vec{U}_{10} - \vec{U}_{cur}$
Exp 6	a2o6-curr2	2 km ocn; 6 km atm	$\vec{U}_{10} - \vec{U}_{cur}$
Exp 7	a6o2-curr2	6 km ocn; 2 km atm	$\vec{U}_{10} - \vec{U}_{cur}$
Exp 8	a6o6-curr2	6 km ocn; 6 km atm	$\vec{U}_{10} - \vec{U}_{cur}$

Conceptual Diagram of Kinematic Coupling

This conceptual diagram depicts the vector wind and current perturbations that are strongest when the wind is moving parallel or antiparallel to the current. The ocean circulations will exist regardless of the feedback; however, the atmospheric circulations is determined by the inclusion of the kinematic coupling.

- To the right of the Gulf Stream extension: negative ocean relative vorticity is the current-induced horizontal circulation. This changes the vertical wind shear which causes a stress curl in the opposite direction as the current curl, which drives what we refer to as the ocean's secondary circulation. The ocean surface divergence acts to compress the Gulf Stream current and subsequently leads to stronger currents, gradients and curls.
- The current-induced surface wind circulation results from a tug of war between the current and the stress, with the stress usually winning, causing the current-gradient-induced wind circulation to be in the same direction as the stress, which extends well into the boundary-layer and causes Ekman induced vertical motion.

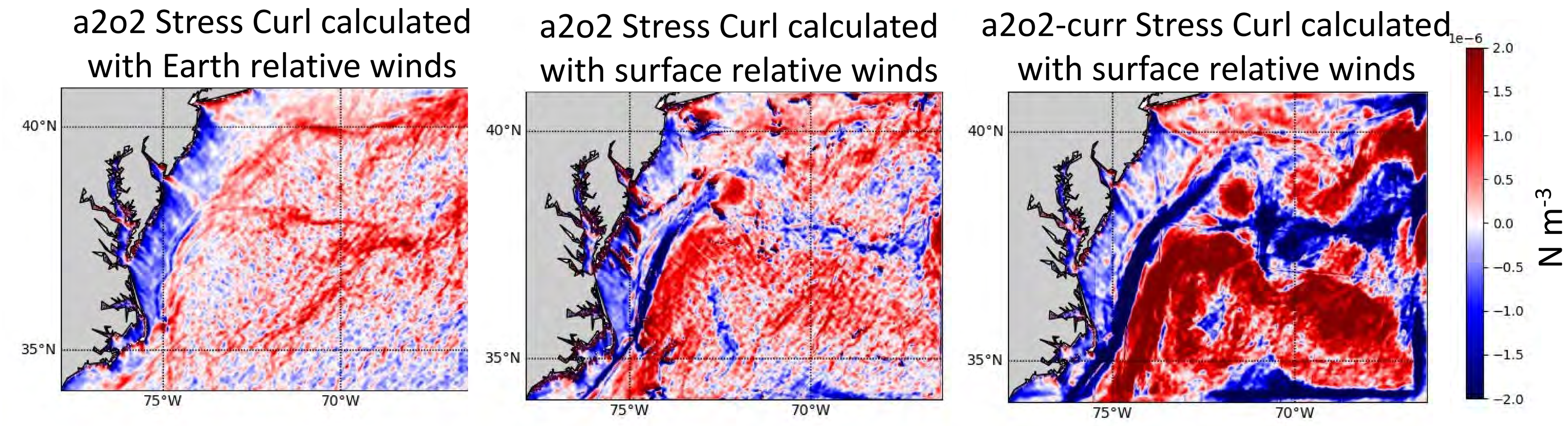


Acknowledgements

- Some of this work described here is built upon prior research by Zhan Su et al., Peter Gaube et al., Hyodae Seo et al., Lionel Renault et al., and much earlier work in the atmosphere and ocean related to Ekman transport.
- We thank ONR for largely funding this work, and support for MAB from NASA and NOAA.

Surface Stress

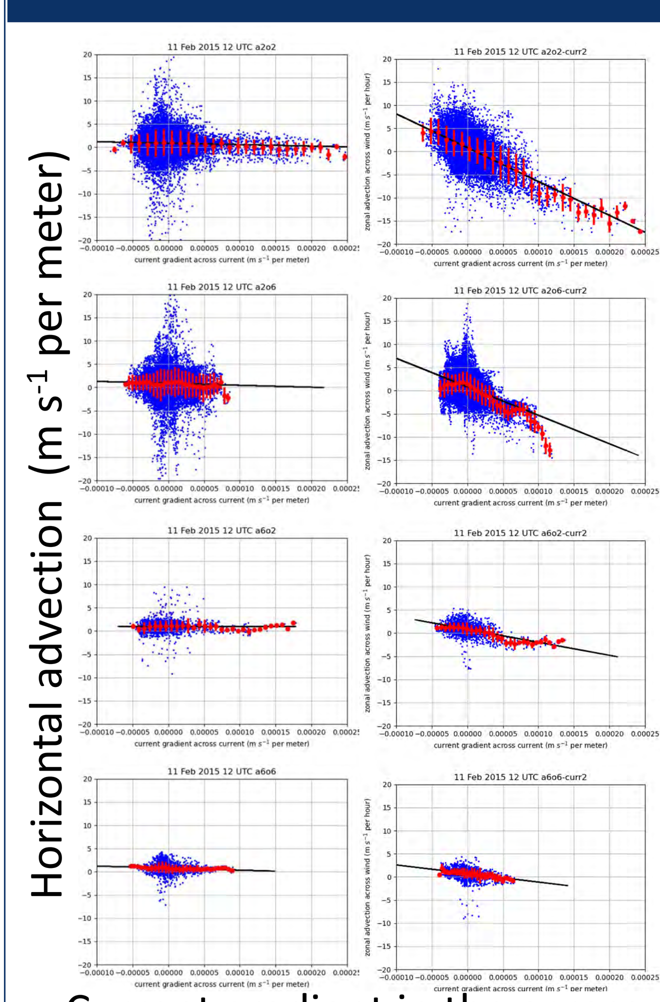
In a two-way coupled system that includes kinematic coupling, both fluids make large adjustments to each other and do so quickly. Without kinematic coupling, the adjustments are thermodynamic and related to boundary-layer stability.



The left image shows the surface stress pattern when surface currents are ignored in a kinematically uncoupled system. When stress is calculated using surface-relative winds without the current feedback (middle), the stress curl pattern changes considerably. Allowing two-way feedback between the wind and currents causes a much strong current-gradient-induced stress pattern, seen quite far from the current as seen in comparisons between ECMWF curl and scatterometer winds (Belmonte-Rivas and Stoffelen, 2019)

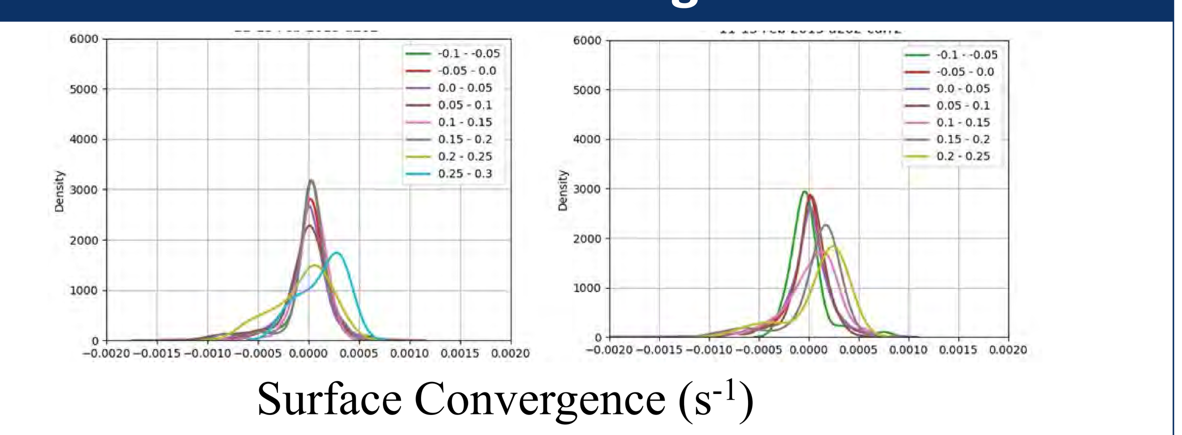
- Feedback between current, wind and stress is important and causes a strong change in the stress pattern.

Cross Current Surface Winds



In the uncoupled systems (left) the winds sort of align with the stress gradient, but in the coupled system (right) the winds align across the current. The current gradients (and the current) are stronger in the coupled system and highly dependent on resolution. To model these processes. we need high resolution and kinematic coupling!

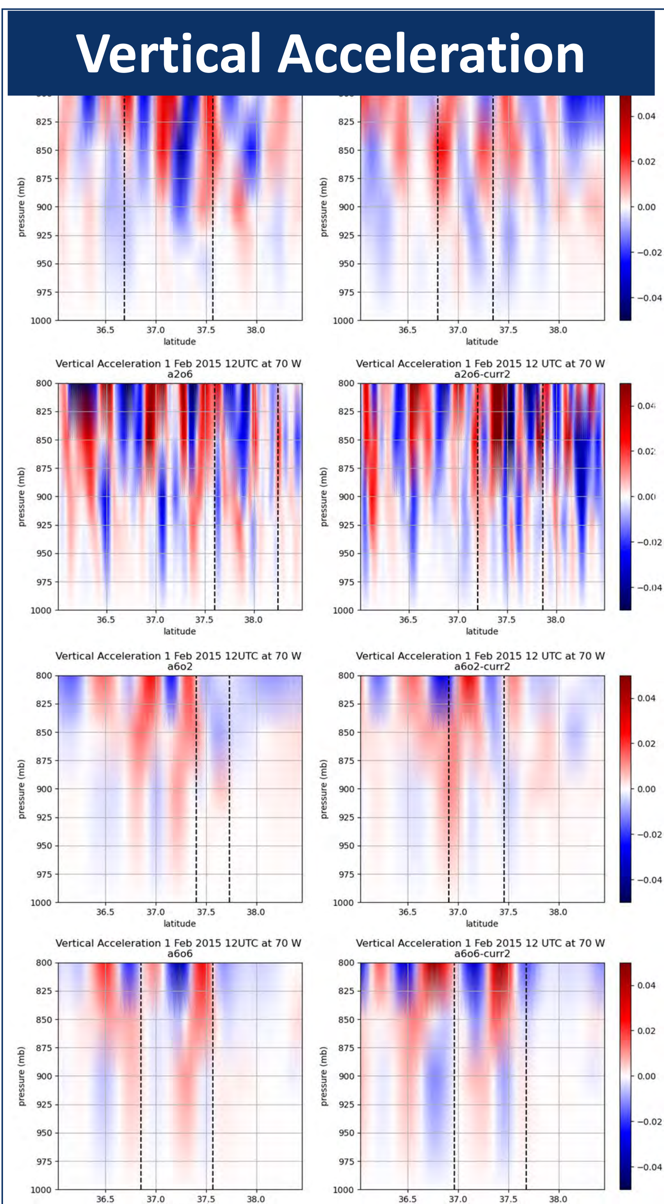
Surface Convergence



PDFs of surface convergence (s^{-1}) from the 2 km grid spaced model runs binned by current gradient across the current (CGAC, °C per meter) from 11-15 February 2015 for simulations with (right) and without (left) the kinematic coupling for an area including an atmospheric front between 35° to 38°N and 69° to 71°W.

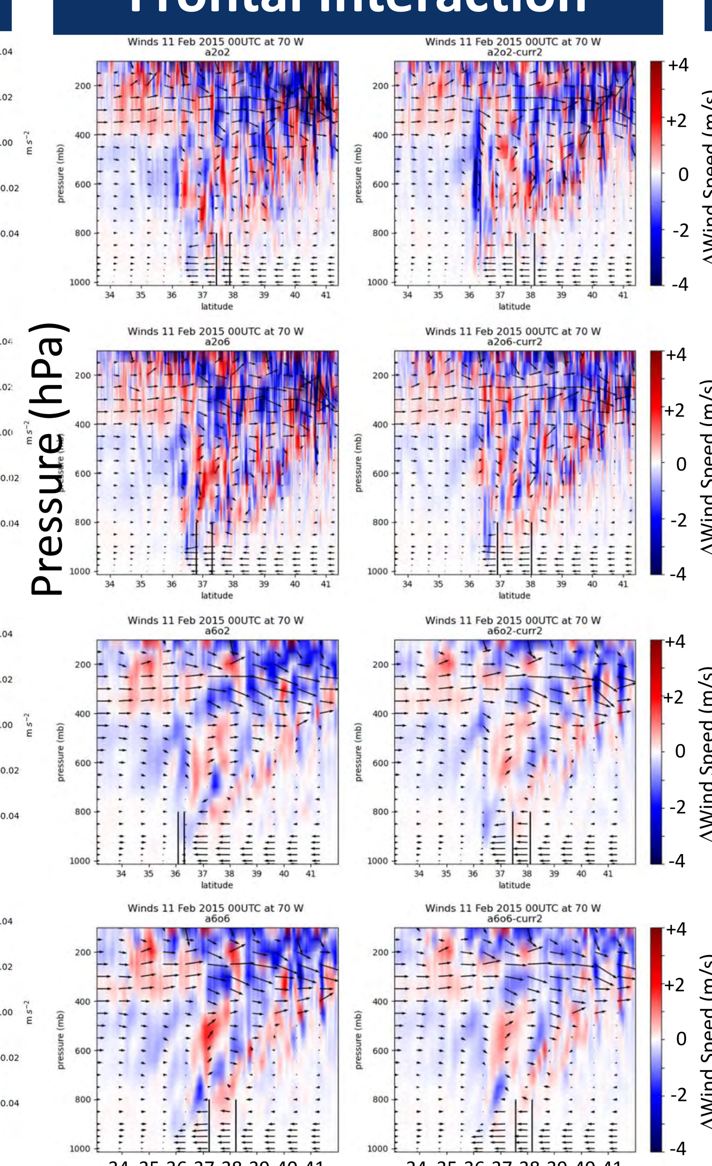
Identical pdfs would indicate no dependence on the CGAC, as is largely seen in the left image. The right image shows a nearly systematic and substantial shift in the PDFs, indicating that surface currents are dependent on the CGAC.

Vertical Acceleration



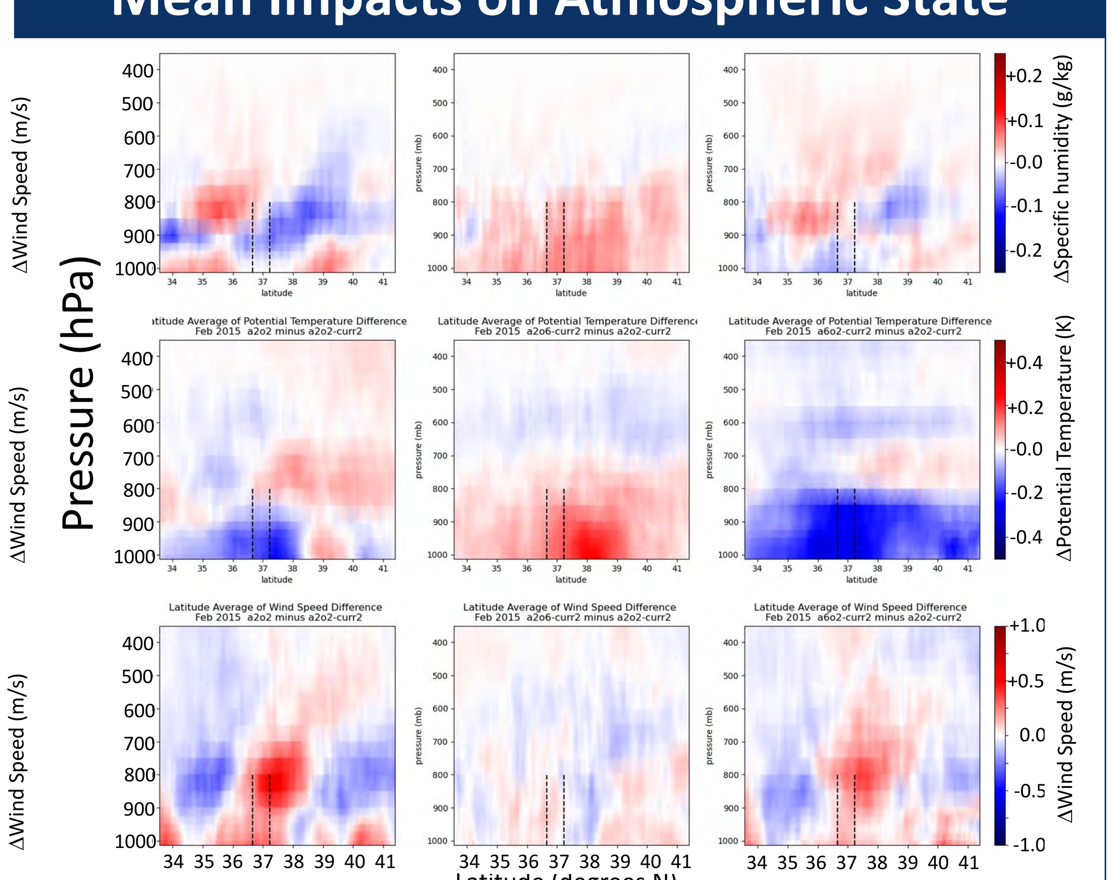
Vertical acceleration (m s^{-2}) along 70°W from 1 February 2015 at 12 UTC for the simulations without the dynamical coupling (left column) and simulations with the dynamical coupling (right column). The top row is the a2o2 simulation, the second row is the a2o6 simulation, the third row is the a6o2 simulation, and the bottom row is the a6o6 simulation. The dashed black lines indicate the Gulf Stream extension

Frontal Interaction



Vertical wind speed (m s^{-1}) with meridional and vertical wind vectors from 11 February 2015 at 00 UTC along 70ºW for the simulations without the dynamical coupling (left column) and including the dynamical coupling (right column). The top row is the a2o2 simulations, the second row is the a2o6 simulations, the third row is the a6o2 simulations, and the bottom row is the a6o6 simulations. The solid black lines indicate the Gulf Stream extension (surface currents > 1 m s^{-1}).

Mean Impacts on Atmospheric State



Monthly average (February 2015) specific humidity differences (g kg^{-1}, top row), potential temperature differences (K, middle row), and wind speed differences (m s^{-1}, bottom row) between the a2o2 and a2o2-curr2 simulations (left column) emphasizing the impacts of kinematic coupling, the a2o6-curr2 and a2o2-curr2 simulations (middle column) emphasizing the impacts of ocean model resolution, and the a6o2-curr2 and a2o2-curr2 simulations (right column) emphasizing the impacts of atmospheric resolution. The dashed black lines indicate the bounds of the Gulf Stream extension (surface currents > 1 m s^{-1}).

Short Summary

Current gradients induce changes to near surface convergence, curl and consequently changes vertical motion. This vertical acceleration peaks in the Ekman layer, integrating over the boundary-layer to cause a substantial change. These findings suggest that kinematic coupling should impact weather events and climate, particularly near strong gradients currents.