US CLIVAR Working Group Prospectus
Mesoscale and frontal-scale ocean-atmosphere interactions and influence on large-scale climate

1. Motivation

Processes at the air-sea interface are critical to understanding the circulation in the ocean and atmosphere. Decades of observational and modeling analysis have broadly identified two fundamental regimes of ocean-atmosphere coupling dependent upon spatial scale. At scales greater than about 1000 km outside the tropics, large-scale atmospheric variability associated with western boundary currents and ocean eddies drives an ocean thermal response through the mediation of surface turbulent heat fluxes and upper-ocean turbulent mixing (e.g., Cayan 1992; Alexander and Scott 1997). At smaller scales such as on mesoscales (i.e., 50-1000 km in the mid-latitudes and 1000 km in the tropics), however, ocean-forced variability of surface turbulent heat fluxes drives an atmospheric response in at least two forms, including a local atmospheric boundary layer response (e.g., Small et al. 2008) and a non-local response influencing the path and activity along the mid-latitude storm tracks (e.g., Chang et al. 2002; Brayshaw et al. 2011; Booth et al. 2012).

It is currently an open question how air-sea interactions mediated by ocean mesoscale variability impacts Earth's large-scale climate. This includes frontal-scale processes associated with western boundary currents in addition to distinct ocean eddies. While air-sea coupling is known to affect the local atmosphere through a boundary layer adjustment mechanism (Xie 2004; Minobe et al. 2008; Tokinaga et al. 2009; Frenger et al. 2013), others have also shown that the mesoscale and frontal-scale air-sea coupling modifies mid-latitude storm tracks (Nakamura et al. 2008; Booth et al. 2012; Small et al. 2014; Ma et al. 2015; O'Reilly et al. 2016a,b; Wills et al. 2016). To complicate matters, storms confined to the mid-latitude storm track, which overlies the western boundary currents and Southern Ocean fronts (e.g., Nakamura et al. 2004), strongly affect time-mean winds and pressure fields throughout the troposphere (O'Neill et al. 2015, 2017; Parfitt and Czaja 2016; Parfitt and Seo 2018). The colocation of the mid-latitude storm tracks with the strongest SST gradients confounds isolation of local air-sea interaction processes in time-mean satellite and model data (O'Neill et al. 2017, 2018; Parfitt and Seo 2018). A necessary path forward is to separate storm-related variability acting along SST frontal zones from the local SST-induced boundary layer response of interest here (Parfitt and Seo 2018). In the tropics, mesoscale coupled processes have been suggested to influence the organized convection (e.g., Li and Carbone 2012) and affect the Indian monsoon wind and rainfall (Seo 2017). Others have examined the effect of air-sea coupling on the energetics of the ocean circulation (e.g., Spall 2007; Hogg et al. 2009; Jin et al. 2009; Ma et al. 2016; Seo et al. 2007; 2016; Renault et al. 2016ab; 2017, 2018) and ocean biogeochemical processes (Chelton et al. 2011; Gaube et al. 2013; McGillicuddy 2016).

Mesoscale SST variability and large-scale SST fronts associated with western boundary currents strongly affect the distribution of precipitation in mid-latitudes (e.g., Minobe et al. 2008; Frenger et al. 2013; O'Neill et al. 2015; Ma et al. 2016; Pendergrass and Deser 2017). Understanding the nature of coupled air-sea processes driven by SST variability is thus important for understanding the hydrologic cycle, and for understanding how climate change will affect terrestrial freshwater distributions.

Essentially, current evidence suggests that the mean large-scale circulation of the atmosphere and ocean depends on accurate specification of air-sea coupling processes occurring on the oceanic mesoscales. It is thus important to resolve these interactions in weather and climate models and in satellite and in situ observations, and to more completely understand the physics governing the coupling.

Local mesoscale air-sea coupling is often diagnosed using a satellite-based empirical relation (Chelton et al. 2004; O'Neill et al. 2003, 2010a, 2012; Chelton and Xie 2010), which shows a linear proportionality between the spatial derivative of wind (curl and divergence) and that of SSTs. This has been a common and powerful metric to evaluate the air-sea coupling from numerical models (Small et al. 2008), although it includes contributions from broad scales that are represented in high-pass filtered inputs fields. An alternative diagnostic approach, such as that based on cross-spectral analysis (O'Neill et al. 2012; Bishop et al. 2017; Laurindo et al. 2018), could provide additional insights into understanding of air-sea interactions over a range of scales in satellite data, which then can be used to evaluate the numerical models.

One of the critical challenges that the community faces is a lack of detailed sustained *in situ* measurements that resolve the coupled boundary layer processes at small spatial/temporal scales. This has led the research community to rely heavily on numerical model simulations to infer the consequences of the mesoscale and frontal-scale air-sea coupling on the larger-scale atmospheric and oceanic circulation. However, due to the diverse nature of the complexity and hierarchy of the models ranging from idealized models (Spall 2007; Feliks et al. 2004; O'Neill et al. 2010b, 2017; Kilpatrick 2014, 2016; Schneider and Qiu 2015) to state-of-the-art coupled climate models (Roberts et al. 2009; Bryan et al. 2010), it is difficult to synthesize the existing results for robust conclusion on the effect of air-sea coupling across multiple scales.

The purpose of this Working Group (WG) is to establish, through community efforts, the dynamical and statistical diagnostic frameworks to interpret the coupled air-sea interactions over multiple spatial and temporal scales using satellite data and high-resolution numerical models. This WG is expected to play a central role in identifying where the community consensus lies on key uncertainties and directions forward.

The topic of the current WG proposal has been widely popular, attracting interests from a broad range of research communities. The ocean-atmosphere interaction over the western boundary currents (WBC) and its link to decadal and longer timescale predictability of the climate system has been first discussed in the WBC Workshop in Phoenix in 2009 (https://usclivar.org/working-groups/western-boundary-current/meetings), sponsored by the US CLIVAR WBC WG.

The community gathered again in Boulder in 2013 for a workshop entitled "Climate Implications of Frontal Scale Air-Sea Interaction" (http://www.cgd.ucar.edu/events/fsasi-workshop/), which brought together experts in physical oceanography and atmospheric sciences. Three key focus areas resulted from the deliberations, including: (1) describing the current state of research on the physics governing the boundary layer-SST coupling on oceanic mesoscales; (2) recognizing the importance of the feedback of the atmospheric response onto the ocean; and (3) the need to improve air-sea heat and momentum flux datasets. The community efforts since then have been fruitful, leading to a highly successful AMS Special Collection on these efforts (http://journals.ametsoc.org/topic/frontal_scale_air-sea).

The third workshop "Ocean Mesoscale Eddy Interactions with the Atmosphere" supported by the US CLIVAR was held in Portland in 2018 (https://usclivar.org/meetings/ocean-mesoscale-eddy-workshop), several action items were formulated such as to develop plans for a new coordinated analysis of satellite products and modeling experiments.

Our proposed WG will capitalize on the outcomes and action items from these previous workshops and serve as a primary means to efficiently provide continued momentum for coordinated studies on air-sea interaction across the multiple disciplines engaging major modeling centers and satellite and observational communities. The results from the WG effort will be used to guide *in situ* observational strategies and to foster coordinated process-modeling and high-resolution modeling efforts (e.g., Haarsma et al. 2016) and coherent analysis strategies to identify areas for challenges and requirements at the small spatial scales.

2. Objectives, Tasks, Timeline

(a) Objectives

The overarching mission/theme of the WG is to establish protocols for a diagnostic framework and coordinated modeling activity to study the air-sea interaction at multiple spatial scales. The main objectives of the WG are summarized as follows:

Objective #1: Identify available satellite and in situ observational datasets suitable to study air-sea interaction at spatial scales commensurate with the WG objectives, focusing on western boundary currents and mesoscale eddies. Provide guidance on diagnostic metrics, statistical methods, and dynamical frameworks to quantify the air-sea coupling over multiple space/time-scales, including possible separation of local effects from storm variability. Coordinate with data providers to obtain up-to-date datasets at the highest possible spatial and temporal scales available.

Objective #2: Coordinate the identification and collection of existing high-resolution climate model outputs from the national and international modeling centers and the planned simulations from HiRES-MIP, including PRIMAVERA for the WG and community. Compare the air-sea coupling between different model frameworks with observations using a standard set of robust metrics and diagnostics, particularly those which can be quantified from observations prepared in Objective #1. Provide results of this information to the modeling centers to guide improvements in modeling frameworks, including summary statistics.

Objective #3: Coordinate efforts to diagnose the feedbacks of the air-sea coupling onto ocean dynamics, the large-scale atmospheric circulation, and the hydrologic cycle (precipitation and evaporation).

Objective #4: Identify opportunities to advance understanding through future field experiments, coordinated modeling studies, in situ observational strategies, and satellite remote sensing. Where possible, we will endeavor to identify observational priorities and opportunities from a range of observing systems to improve understanding of air-sea coupling processes.

(b) Proposed specific tasks

1) Review the findings from existing studies and evaluate the robustness of the methodology and diagnostic metrics to identify uncertainties and gaps in our understanding.
2) Collect existing satellite data and high-resolution climate model outputs and make them available to the community in a convenient and uniform format (e.g., NetCDF). Provide documentation and metadata.
3) Construct the common metrics to diagnose air-sea coupling at multiple-scales along western boundary currents and ocean eddies to be applied to satellite data and existing model outputs.
4) Establish common modeling frameworks focusing on the western boundary current regions and the Southern Ocean.
5) Apply the metrics to models and conduct preliminary analysis, leveraging currently funded projects.
6) Identify observational priorities and observational system coverage suitable for evaluating and forcing model simulations, particularly the accuracy and resolution limitations of SST and air-sea flux observations.
7) Identify and compare current state-of-the-art flux parameterizations used in climate models and satellite-based surface flux analyses.
8) Examine the impacts of air-sea interaction on the predictability of large-scale weather patterns on subseasonal-to-seasonal (S2S) timescales.

(c) Timeline:

Year 1: WG team building, synthesize and review the current understanding and available datasets. Write a review paper (in J. Climate). Convene an AGU session that reviews current understanding of air-sea coupling at small-scales. Host a session at the CLIVAR Summit and WG annual meeting.

Year 2: Construct the common diagnostic, statistical, and theoretical metrics. Write a paper on the metrics (in BAMS). Establish a common modeling framework and conduct preliminary experiments applying the common metrics. Convene a session on this topic at AGU or Ocean Sciences Meeting.

Year 3: Complete the modeling runs and analyses and submit a second synthesis paper (J. Climate). Convene an AGU session on the mesoscale air-sea coupling. Host a community workshop synthesizing the results and plan for future focus. Prepare a final report of the WG activities and findings to US CLIVAR and its Panels.

3. Publications and Outreach

After each annual WG meeting, a review article will be published that documents the progress and remaining challenges. Various WG members will take the lead to write CLIVAR Exchange and US CLIVAR Variations articles regarding the progress of each of the sub-topics. A community workshop will be organized in Year 3.

4. Reporting Plan

The objectives and work plans of the proposed WG are highly relevant to the science goals of US CLIVAR. "High-resolution climate modeling and role of ocean eddies in ocean dynamics, air-sea interaction and BCG processes" is currently one of the long-term priorities for the US CLIVAR PSMI Panel. Similar aspects are relevant to other PPAI and POS Panel, in terms of coordinating the field campaigns and evaluating the impact on predictability, respectively. Several members of the PSMI Panel are supportive of the idea of our proposed WG, and we will coordinate closely with all three panels for the progress report and continuously seek for their feedback. The WG progress will be reported annually to inform the US CLIVAR Summit and other individual panel activities. Our WG will also work with others organizing the May 2019 Workshop on Atmospheric Convection and Air-Sea Interactions over the Tropical Oceans, the Width of Tropical Belt WG, and the US AMOC Science Team for possible coordination, as mesoscale and frontal-scale air-sea interaction are key processes in these activities.

5. Leadership and Confirmed Membership

Larry O'Neill (OSU) and Hyodae Seo (WHOI) will serve as co-chairs of the WG and will be responsible for development and coordination of the proposed efforts. The following WG members were chosen based on their relevant expertise, geographical distribution, gender, career stages, and diversity.

Domestic Membership

Member	Affiliation
(1) Hyodae Seo (Co-Chair)	WHOI
(2) Larry O'Neill (Co-Chair)	Oregon St. Univ.
(3) Angeline Pendergrass	NCAR
(4) Baylor Fox-Kemper	Brown Univ.
(5) Ben Kirtman	Univ. of Miami
(6) Jim Edson	WHOI
(7) Justin Small	NCAR
(8) Kyla Drushka	Univ. of Wash.-APL
(9) Mark Bourassa	Florida St. Univ.
(10) Niklas Schneider	Univ. of Hawaii
(11) Qing Wang	Naval Post. School
(12) Sarah Gille	SIO

International Membership

Member	Affiliation
(1) Arnaud Czaja	Imperial College, UK
(2) Ad Stoffelen	KNMI, Netherlands
(3) Ivy Frenger	GEOMAR, Germany
(4) Lionel Renault	IRD, France
(5) Malcolm Roberts	UK Met Office, UK
(6) Shoshiro Minobe	Hokkaido Univ., Japan

6. Resource Requirements

- Bi-monthly teleconference support
- Travel support: two annual WG meetings (one in conjunction with the 2020 Ocean Sciences meeting and the other before/after the AMS Conference on Air-sea Interaction)
- Page charges for three publications (review papers in BAMS, J. Climate)
- Organizational support for a 50-participant 1.5 day workshop during 2021, location TBD.

References

Alexander, M. A., and J. D. Scott, 1997: Surface flux variability over the North Pacific and North Atlantic Oceans. *J. Climate*, **10**, 2963-2978.

Booth, J. F., L. Thompson, J. Patoux, and K. A. Kelly, 2012: Sensitivity of midlatitude storm intensification to perturbations in the sea surface temperature near the Gulf Stream. *Mon. Wea. Rev.*, **140**, 1241-1256.

Brayshaw, D.J., B. Hoskins, and M. Blackburn, 2011: The Basic Ingredients of the North Atlantic Storm Track. Part II: Sea Surface Temperatures. *J. Atmos. Sci.*, **68**, 1784–1805.

Bryan, F.O., R. Tomas, J. M. Dennis, D. B. Chelton, N. G. Loeb, and J. L. McClean, 2010: Frontal Scale Air-Sea Interaction in High-Resolution Coupled Climate Models. *J. Climate*, **23**, 6277-6291

Cayan, D. R., 1992: Latent and Sensible Heat Flux Anomalies over the Northern Oceans: The Connection to Monthly Atmospheric Circulation. *J. Climate*, **5**, 354-369.

Chang, E.K., S. Lee, and K.L. Swanson, 2002: Storm Track Dynamics. *J. Climate*, **15**, 2163-2183.

Chelton, D. B., M. Schlax, M. H. Freilich, and R. F. Milliff, 2004: Satellite measurements reveal persistent small-scale features in ocean winds. *Science*, **303**, 978–983.

Chelton, D. B., and S.-P. Xie, 2010: Coupled ocean-atmosphere interaction at oceanic mesoscales. *Oceanogr*., **23**, 52-69.

Chelton, D., P. Gaube, M. Schlax, J. Early, and R. Samelson (2011b), The influence of nonlinear mesoscale eddies on near-surface oceanic chlorophyll, *Science*, **334**, 328–332.

Feliks, Y., M. Ghil, and E. Simonnet, 2004: Low-frequency variability in the midlatitude atmosphere induced by an oceanic thermal front. *J. Atmos. Sci*., **61**, 961–981

Frenger, I., N. Gruber, R. Knutti, and M. Münnich, 2013: Imprint of Southern Ocean eddies on winds, clouds and rainfall. *Nature Geosci*., **6**, 608–612.

Gaube, P., D. B. Chelton, P. G. Strutton, and M. J. Behrenfeld, 2013: Satellite observations of chlorophyll, phytoplankton biomass, and Ekman pumping in nonlinear mesoscale eddies. *J. Geophys. Res.*, **118**, 6349-6370.

Haarsma, R. J and co-authors, 2016: High Resolution Model Intercomparison Project (HighResMIP v1.0) for CMIP6, *Geosci. Model Dev*., **9**, 4185-4208.

Hogg, A. C. M., W. K. Dewar, P. Berloff, S. Kravtsov, and D. K. Hutchinson, 2009: The effects of mesoscale ocean–atmosphere coupling on the large-scale ocean circulation. *J. Climate*, **22**, 4066–4082.

Jin, X., C. Dong, J. Kurian, J. C. McWilliams, D. B. Chelton, and Z. Li, 2009: Wind–SST interaction in coastal upwelling: Oceanic simulation with empirical coupling. *J. Phys. Oceanogr*., **39**, 2957–2970.

Kilpatrick, T.J., N. Schneider, and B. Qiu, 2016: Atmospheric Response to a Midlatitude SST Front: Alongfront Winds. *J. Atmos. Sci*., **73**, 3489-3509

Kilpatrick, T.J., N. Schneider, and B. Qiu, 2014: Boundary layer convergence induced by strong winds across a midlatitude SST front. *J. Climate*, **27**, 1698-1718.

Laurindo, L. C., L. Siqueira, A J. Mariano, B. P. Kirtman, 2018: Cross-spectral analysis of the SST/10-m wind speed coupling resolved by satellite products and climate model simulations. Climate Dynamics. DOI: 10.1007/s00382-018-4434-6

Li, Y. and R. E. Carbone, 2012: Excitation of rainfall over the tropical western Pacific. *J. Atmos.*

Sci., **69**, 2983– 2994
Ma, X., P. Chang, R. Saravanan, R. Montuoro, J.-S. Hsieh, D. Wu, X. Lin, L. Wu, Z. Jing, 2015: Distant Influence of Kuroshio Eddies on North Pacific Weather Patterns? *Sci. Rep*., **5**, 17785
Ma, X., J. Zhao, P. Chang, X. Liu, R. Montuoro, R. J. Small, F. O. Bryan, R. J. Greatbatch, P. Brandt, D. Wu, X. Lin, and L. Wu, 2016: Western boundary currents regulated by interaction between ocean eddies and the atmosphere. *Nature*, **535**, 533–537.
McGillicuddy, D. J.: 2016. Mechanisms of physical-biological-biogeochemical interaction at the oceanic mesoscale. *Annual Review of Marine Science*, **8**, 125-159
Minobe, S., A. Kuwano-Yoshida, N. Komori, S.-P. Xie, and R. J. Small: 2008: Influence of the Gulf Stream on the troposphere. *Nature*, **452**, 206-209.
Nakamura, H., Sampe, T., Tanimoto, Y. and Shimpo, A., 2004: Observed Associations Among Storm Tracks, Jet Streams and Midlatitude Oceanic Fronts, in Earth's Climate: The Ocean-Atmosphere Interaction (eds C. Wang, S.-P. Xie and J. A. Carton), American Geophysical Union, Washington, D. C.. doi: 10.1029/147GM18.
Nakamura, H., T. Sampe, A. Goto, W. Ohfuchi, and S.-P. Xie, 2008: On the importance of midlatitude oceanic frontal zones for the mean state and dominant variability in the tropospheric circulation, *Geophys. Res. Lett.*, **35**, L15709, doi:10.1029/2008GL034010.
O'Neill, L. W. , T. Haack, D. B. Chelton, and E. Skyllingstad, 2017: The Gulf Stream Convergence Zone in the time-mean winds. *J. Atm. Sci.*, **74**, 2383-2412.
O'Neill, L. W., T. Haack, and T. Durland, 2015: Estimation of time-averaged surface divergence and vorticity from satellite ocean vector winds. *J. Climate*, **28**, 7596–7620.
O'Neill, L. W., D. B. Chelton, and S. K. Esbensen, 2012: Covariability of surface wind and stress responses to sea-surface temperature fronts. *J. Climate*, **25**, 5916–5942.
O'Neill, L. W., D. B. Chelton, and S. K. Esbensen, 2010a: The effects of SST-induced wind speed and direction gradients on mid-latitude surface vorticity and divergence. *J. Climate*, **23**, 255-281.
O'Neill, L. W., S. K. Esbensen, N. Thum, R. M. Samelson, and D. B. Chelton, 2010b: Dynamical analysis of the boundary layer and surface wind responses to mesoscale SST perturbations. *J. Climate*, **23**, 559-581.
O'Neill, L. W., D. B. Chelton, S. K. Esbensen, 2003: Observations of SST-induced perturbations of the wind stress fields over the Southern Ocean on seasonal time-scales. *J. Climate*, **16**, 2340-2354.
O'Reilly, C. H., S. Minobe, and A. Kuwano-Yoshida, 2016a: The influence of the Gulf Stream on wintertime European blocking. *Clim. Dyn*., **47**, 1545–1567.
O'Reilly, C. H., S. Minobe, A. Kuwano-Yoshida, and T. Woollings, 2016b: The Gulf Stream influence on wintertime North Atlantic jet variability. *Quart. J. Roy. Met. Soc*., **143**, 173–183.
Parfitt, R., and A. Czaja, 2016: On the contribution of synoptic transients to the mean atmospheric state in the Gulf Stream region. *Quart. J. Roy. Meteor. Soc*., **142**, 1554–1561.
Parfitt, R., and H. Seo, 2018: A New Framework for Near-Surface Wind Convergence over the Kuroshio Extension and Gulf Stream in Wintertime: The Role of Atmospheric Fronts. *Geophys*. *Res. Lett*., 45, https://doi.org/10.1029/2018GL080135.
Pendergrass, A.G. and C. Deser, 2017: Climatological Characteristics of Typical Daily Precipitation. *J. Climate*, **30**, 5985–6003.

Renault, L., M. J. Molemaker, J. C. McWilliams, A. F. Shchepetkin, F. Lemaré, D. Chelton, S. Illig, and A. Hall, 2016a: Modulation of wind work by oceanic current interaction with the atmosphere. *J. Phys. Oceanogr.*, **46**, 1685–1704.

Renault, L., M. J. Molemaker, J. Gula, S. Masson, and J. C. McWilliams 2016b: Control and Stabilization of the Gulf Stream by Oceanic Current Interaction with the Atmosphere. *J. Climate*, **46**, 3439-3453

Renault, L. J. C. McWilliams, , S. Masson, 2018: Satellite Observations of Imprint of Oceanic Current on Wind Stress by Air-Sea Coupling, *Sci. Rep.,* DOI:10.1038/s41598-017-17939-1

Roberts, M.J., and co-authors, 2009: Impact of resolution on the tropical Pacific circulation in a matrix of coupled models. *J. Climate*, **22**, 2541- 2556.

Schneider, N., and B. Qiu, 2015: The atmospheric response to weak sea surface temperature fronts. *J. Atmos. Sci*., **72**, 3356-3377

Seo, H., M. Jochum, R. Murtugudde, A. J. Miller, and J. O. Roads, 2007: Feedback of Tropical Instability Wave - induced Atmospheric Variability onto the Ocean. *J. Climate*, **20**, 5842-5855.

Seo, H., A. J. Miller, and J. R. Norris, 2016: Eddy-wind interaction in the California Current System: dynamics and impacts, *J. Phys. Oceanogr.*, **46**, 439-459

Seo, H., 2017: Distinct influence of air-sea interactions mediated by mesoscale sea surface temperature and surface current in the Arabian Sea. *J. Climate*, **30**, 8061-8079

Small, R. J., S. de Szoeke, S.-P. Xie, L. O'Neill, H. Seo, Q. Song, P. Cornillon, M. Spall, and S. Minobe, 2008: Air-Sea Interaction over Ocean Fronts and Eddies. *Dyn. Atmos. Oceans*, **45**, 274-319.

Small, R. J., R. A. Tomas, F. O. Bryan, 2014: Storm track response to ocean fronts in a global high-resolution climate model. *Clim. Dyn*., 43, 805-828.

Spall, M. A., 2007: Midlatitude wind stress-sea surface temperature coupling in the vicinity of oceanic fronts. *J. Climate*, **20**, 3785-3801.

Tokinaga, H., Y. Tanimoto, S.-P. Xie, T. Sampe, H. Tomita, and H. Ichikawa, 2009: Ocean frontal effects on the vertical development of clouds over the western North Pacific: In situ and satellite observations. *J. Climate*, **22**, 4241-4260.

Wills, S. M., D. W. J. Thompson, and L. M. Ciasto, 2016: On the Observed Relationships between Variability in Gulf Stream Sea Surface Temperatures and the Atmospheric Circulation over the North Atlantic. *J. Climate*, **29**, 3719-3730.

Xie, S.-P. 2004: Satellite observations of cool ocean–atmosphere interaction. *Bull. Amer. Meteor. Soc.*, 85, 195–209.