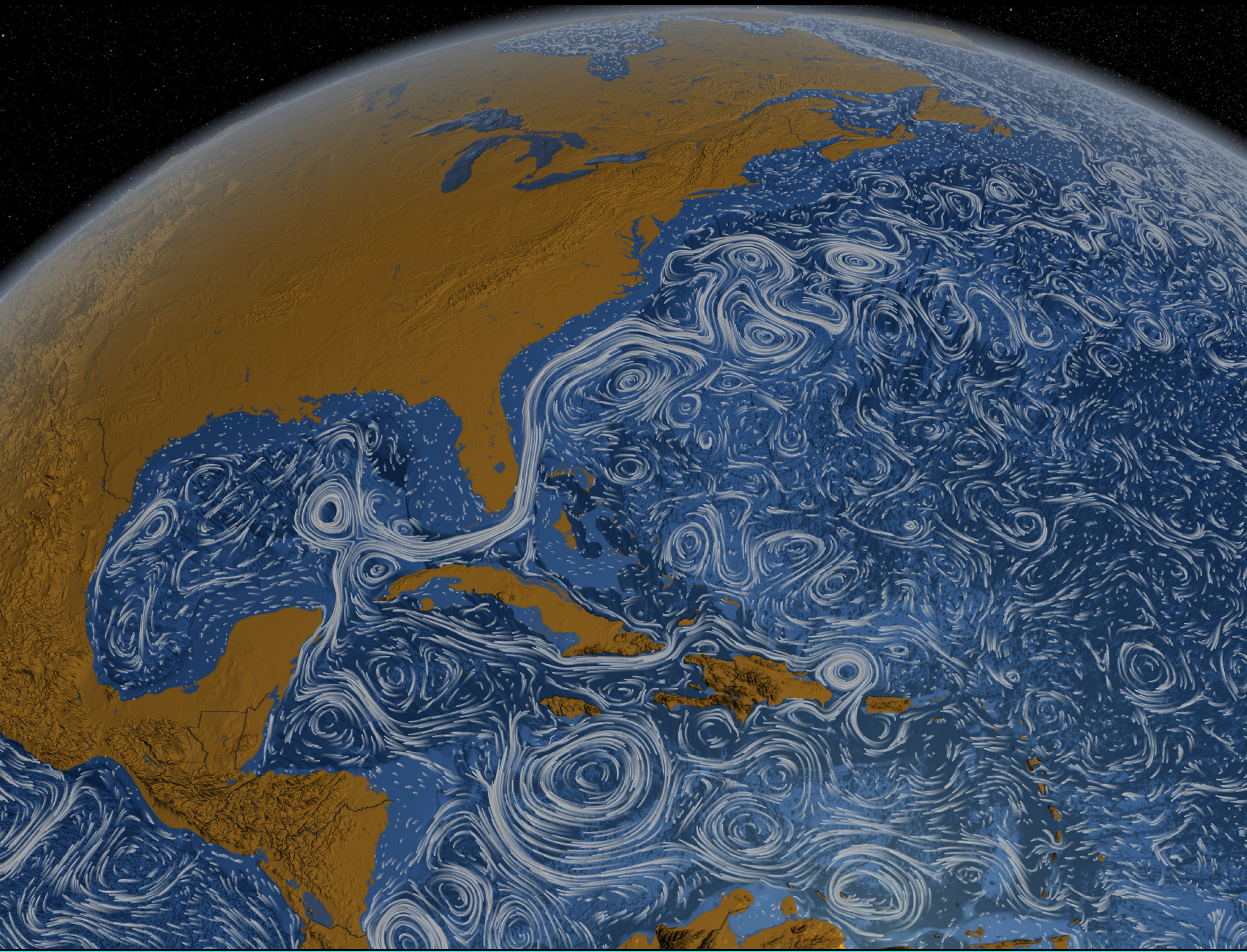

OCEAN MESOSCALE EDDY INTERACTIONS WITH THE ATMOSPHERE

February 17–18, 2018
Portland, Oregon

OCEAN MESOSCALE EDDY INTERACTIONS WITH THE ATMOSPHERE

Workshop Report

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FRONT COVER IMAGE

Views of our perpetual ocean (Credit: NASA)

BACK COVER IMAGES

Group photo of workshop participants (Credit: Kristan Uhlenbrock)

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1 EXECUTIVE SUMMARY

Mesoscale eddies, circling currents a few hundred kilometers across, are ubiquitous in the ocean. Ever improving observations – from satellites, moorings, and autonomous floats – show that eddies differ from their surroundings and can transport oceanic heat and composition over large distances. The imprint of eddies on sea surface temperatures (SST) affects the overlying atmosphere, and these interactions feedback to affect the eddies themselves. With rapid advances in numerical modeling, some numerical models, for the first time, have sufficient resolution to capture eddies and their interactions with the atmosphere.

As we learn more about the rich dynamics of these features, three questions emerge: How can we better assess, through direct measurements, eddy interactions with the atmosphere? How do such interactions affect ocean dynamics? Can eddies, despite their small sizes, influence weather and climate?

A US and International CLIVAR workshop, Ocean Mesoscale Eddy Interactions with the Atmosphere, held February 17-18, 2018, in Portland, Oregon, USA addressed these questions. More than 50 oceanographers and atmospheric scientists from ten nations (see list of participants) met to assess the state of knowledge about ocean eddy-atmosphere interactions and to plan research.

Presentations described observations showing that the eddy SST influences winds in the atmospheric boundary layer by modulating atmospheric pressures and vertical mixing. Winds, in turn, affect how hard the atmosphere pushes on the ocean surface, as do the currents themselves, with consequent effects on eddy energies and the ocean circulation.

We need a better understanding of how the wind stress and air-sea fluxes of heat and moisture are controlled – these are represented by empirical formulae containing uncertain parameters. When modeling the ocean independently, how should feedbacks from the atmosphere be represented? Finally, intriguing new model results suggest that the atmosphere, at weather scales or larger, responds to the cumulative effects of the much smaller ocean eddies. Such a response requires a “rectification” of local effects, which is not yet understood. Each set of issues was addressed by one of three breakout working groups. A consensus emerged from the workshop that eddy-atmosphere interactions are important for the ocean and the atmosphere at space and time scales much larger and longer than that of an individual eddy; we are on the cusp of new modeling and observational results that will show us how all this works.

Key recommendations from the workshop:

- To leverage upcoming field campaigns, some deploying exciting new observing technologies, to obtain observations of ocean-atmosphere interactions on the ocean-eddy scale
- To develop and evaluate new models of the atmospheric boundary layer for their use in providing an eddy-responsive upper boundary condition for ocean-sea ice only models
- To carry out a set of global model experiments, building on the CMIP6 HighResMIP initiative, using spatial filtering of the SST field to explicitly test the influence of ocean eddies on atmospheric weather and climate.

2 INTRODUCTION

Decades of observations have revealed the richness of the mesoscale eddy field in the oceans, especially in association with western boundary currents and in the Southern Ocean. These eddies have a strong and readily observable footprint on ocean surface properties that is conveyed to the overlying atmosphere. Air-sea fluxes are influenced on the eddy scale, and, at the same time, there is increasing evidence that the field of ocean eddies has a cumulative effect on air-sea fluxes and thus can significantly influence the climate of the atmosphere and of the ocean. The small spatial scale of ocean eddies, however, means they are not represented in the current generation of global coupled models used for climate prediction and projection (e.g., most CMIP6 simulations will be carried out with models that are not eddy permitting). Thus, we have a process – atmosphere-ocean interaction on the ocean eddy scale – that is beginning to be well observed and that is potentially significant for the dynamics and climate of both systems, yet is not captured by our "workhorse" modeling systems. This raises two related, challenges that motivated this workshop.

I: How to represent atmospheric feedbacks on ocean eddies in ocean-only models?

The development of ocean models, as well as their application to understanding the dynamics and biogeochemistry of the oceans, depends, at least for the foreseeable future, on simulations carried out using ocean-only models. These simulations are driven at the sea surface by fluxes of heat, water, and momentum, calculated using either idealized atmospheric states or atmospheric states determined from operational analyses or reanalyses. Typically, atmospheric information is unavailable on the spatial scale of ocean eddies. Even when such fine-scale information is available, the chaotic nature of dynamics in both media are such that a model is unlikely to preserve the spatial and temporal correspondence between the eddies and their atmospheric footprint found in nature. Therefore, it is a challenge to properly represent atmospheric feedbacks on ocean eddies in ocean-only models. Renault et al. (2016) have shown that the improper representation of these feedbacks leads to systematic biases in the mean state of the simulated ocean and in its variability.

II: How do atmospheric weather and climate respond to the ocean eddy field?

Recent modeling results show that the atmosphere responds not only to the large-scale distribution of sea-surface temperature (SST) and to the strength and location of ocean fronts, but to the variations of SST associated with the field of ocean eddies (Ma et al. 2017; Zhou et al. 2017). It is plausible that some observed associations between large-scale SST anomalies and the atmospheric circulation can be attributed to the variations in ocean eddy activity that typically follow shifts in the position of ocean fronts, and thus are correlated with large-scale variations in SST. Similarly, it is possible that the persistent inability of coupled models or atmospheric models driven by observed SST anomalies to capture the ocean influences on the atmosphere implied by observational analyses (e.g. Wills et al. 2016) may derive from the absence or misrepresentation of ocean eddies in these experiments.

Addressing both challenges requires improved observations and analyses of sea-surface fluxes and on developing and deploying models that are capable of representing the observed relationships between ocean eddies and fluxes at the sea surface.

The workshop built on these foundations, seeking to address the above two challenges in a coordinated way, such that results obtained from different models and modeling systems can be quantitatively compared and can be evaluated in comparison with observational analyses and coupled model outputs.

The overarching goal is to push the science beyond an exciting set of "one-off" results towards developing understanding of how ocean-atmosphere interactions at the ocean-eddy scale should be represented in climate models, so as to improve climate prediction and projection in both the atmosphere and ocean. This, in turn, requires the development of new observational analyses and computational and experimental approaches in ocean-sea ice only and in coupled models.

The one-and-a-half day workshop was held in Portland, Oregon, February 17-18, 2018, immediately following the 2018 Ocean Sciences Meeting. The first half-day was spent in plenary, with four review presentations that addressed:

- *In-situ* observations of air-sea interactions and feedbacks (Meghan Cronin, NOAA Pacific Marine Environment Laboratory)
- Satellite observations of air-sea interactions and feedbacks (Dudley Chelton, Oregon State University)
- The role of the current feedback to the atmosphere in determining the ocean dynamics (Lionel Renault, University of California Los Angeles)
- Covariability of mesoscale SST, surface heat fluxes, and surface convergence (Justin Small, National Center for Atmospheric Research)

Slides from the oral presentations as well as links to poster presentations are available via the online workshop agenda. Plenary discussion followed these presentations. Participants then split into three breakout working groups (WGs), each tasked with addressing a set of key questions.

WG1: Observational requirements for eddy-scale air-sea fluxes
- What is not known about air-sea fluxes on the ocean-eddy scale? What are the leading sources of error and uncertainty in these fluxes?
- What new analyses of existing observational data would address these gaps and uncertainties?
- What new observations or emerging observational technologies would address these gaps and uncertainties?

WG2: Representation of eddy-scale air-sea fluxes for ocean-only models
- What are the current methods for representing air-sea fluxes in ocean-only models on the ocean-eddy scale?
- What are the known errors or biases introduced by current methods?
- What new approaches are under development?

WG3: Impacts of the ocean eddy field and its variability on atmospheric weather & climate

- Are intraseasonal-interannual variations in ocean eddy activity a potential source of atmospheric predictability on these timescales?
- What are the resolution and physics requirements for atmospheric models to capture the influences of ocean eddy activity?

The working groups reported out in a plenary session the second morning of the workshop, followed by general discussion.

The remainder of this report provides syntheses of discussions within the WGs, followed by a brief overall summary that includes the recommendations and actions arising from the workshop.

Working Group 1: Observational requirements for eddy-scale air-sea fluxes

Turbulent and radiative exchanges of heat and momentum between the ocean and atmosphere influence weather and climate. Quantifying these air-sea fluxes is challenging. The ocean can affect the atmosphere circulation in two ways: by initiating deep and shallow convection and by enhancing the atmospheric baroclinicity through sensible heat fluxes near the surface and latent heat fluxes aloft. The ocean is affected by mixing, energy sources and sinks, and water mass formation and transformation. These impacts extend beyond physical parameters to ocean chemistry and ecosystems.

Recent evidence from observations and modeling studies suggest that the ocean mesoscale and sub-mesoscale create air-sea interaction patterns (see Fig. 1) that strongly influence key physical processes in the atmosphere affecting cloud formation and the general atmosphere circulation (Chelton et al. 2004; 2007; 2010; O'Neill et al. 2012; Frenger et al. 2013; Villa Boas et al. 2015). Modeling studies also suggest that the atmosphere affects the ocean mesoscale and sub-mesoscale through momentum fluxes (Renault et al. 2017; Renault et al., 2018; Meroni et al. 2018). Recent advances in understanding these processes have been obtained predominately from modeling efforts. Very few observational studies address the ocean mesoscale (and these are all located in the extra-tropics), and none address the ocean sub-mesoscale.

Reducing knowledge gaps and inaccuracies in air-sea fluxes and their phenomenology, especially at the ocean mesoscale, is important for improving short, medium, and long-term weather and climate prediction. Most of the uncertainties in the estimates of air-sea fluxes come from the lack of direct observations and, therefore, a lack of knowledge about the precise processes in play.

Current observational knowledge is based on ocean-atmosphere flux estimates, which rely on satellite observations, along with a very few *in situ* measurements from ships and buoys. Most of the observed quantities are indirect estimates.

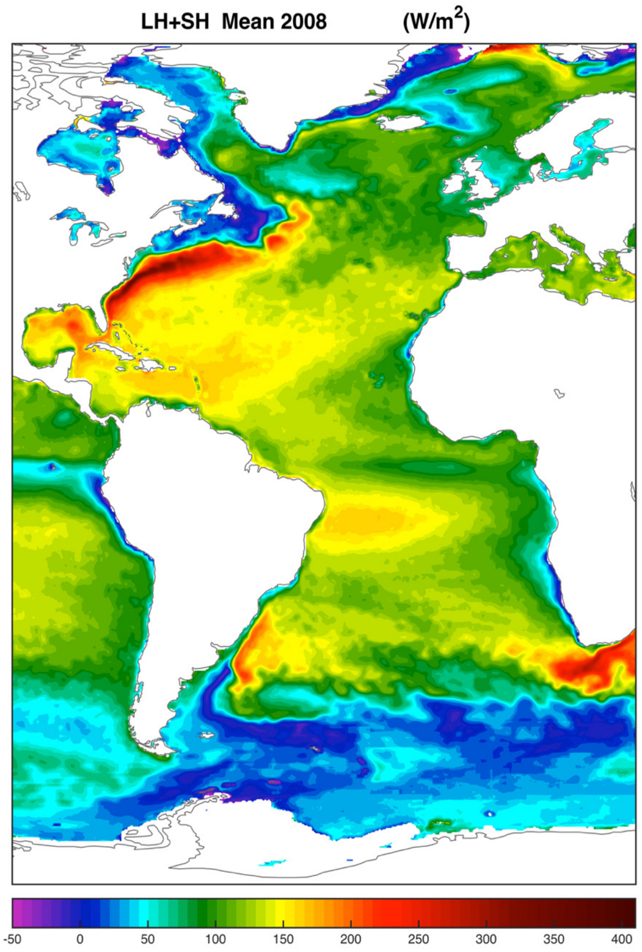

Figure 1. *Atlantic basin annual-mean latent and sensible turbulent fluxes showing a particular important amplitude in ocean mesoscale eddy rich regions (the Gulf Stream, the South Brazil Current and the Confluence, the Agulhas Retroflection and the Agulhas Ring pathway in and out of the Cape Basin). (Map from the HR OI-WHOI Fluxes Yu et al. 2019).*

Determining radiative and thermodynamic fluxes requires knowledge of shortwave and longwave incoming and outgoing radiation and turbulent latent and sensible heat fluxes. The latent and sensible heat fluxes are typically estimated from state variables, using a "bulk flux algorithm" (e.g., Fairall et al. 2003). The primary state variables for turbulent fluxes are surface winds relative to surface currents, skin temperature, surface air temperature, and surface humidity. Often these variables are unavailable, and parameterizations are needed to extrapolate them from observed variables. For example, skin temperature is derived from the *in situ* bulk sea surface temperature, usually observed at depths below the skin. Surface winds relative to surface currents are also indirectly estimated from other variables (10 m wind from scatterometers and ocean surface geostrophic velocity derived from altimetry). Cronin et al. (2019) provide a broader discussion of air-sea fluxes, current knowledge, and limitations.

Existing observations and modeling studies have not yet addressed (at least conclusively) the potential impacts of air-sea interactions on wind stress, on humidity biases (which might be important in the tropics), on precipitation (thought to be small), and on the diurnal cycle. Nor do assessments exist of the impact of the ocean latent heat flux, precipitation, and entrainment on ocean eddy-kinetic energy. Uncertainties in ocean-atmosphere interactions and air-sea fluxes estimates are therefore generally large, and this is true, in particular, at the ocean mesoscale and sub-mesoscale.

What new analyses of existing observational data would address these gaps and uncertainties?

Satellite observations provide, or will soon provide, vertical air profiles of air temperature, boundary layer temperature, and surface and vertical wind structure at horizontal resolutions of 100 km or better. They also will supply SST from infrared and microwave imagers with daily resolutions of 1/10° or higher, when various satellite SST observations are merged.

New coordinated analyses and comparisons of flux estimates from existing products could provide additional information on these quantities at scales closer to the ocean mesoscale. This would contribute to progress in our understanding of the processes that control air-sea exchanges and their impacts on the ocean and the atmosphere.

What new observations or emerging observational technologies would address these gaps and uncertainties?

Quantifying air-sea exchanges requires a variety of complementary observations targeted to improve our phenomenological understanding of air-sea exchanges and their relationships to ocean and atmosphere properties and to processes at the ocean mesoscale. More specifically, an increased capability in space, time and the accuracy of observations of ocean and climate variables (essential ocean variables – EOVs – and essential climate variables – ECVs), namely denser in space, more frequent, and extending to the whole world ocean, will enable the generation of improved flux estimates that include the ocean mesoscale. High-quality long time series in oceanic hot-spots for ocean mesoscale activity or regionally distributed measurements in eddy-rich zones are essential for progress in understanding ocean-atmosphere processes and for validating flux estimates obtained by remote sensing. These observations will also enable improvements in the bulk algorithms for air-sea fluxes.

Some new technologies are particularly appropriate for improving observations of the ocean-atmosphere exchanges at the ocean mesoscale. Among these are new satellite missions, currently under study, that will obtain direct observations of ocean currents, wind stress, and waves. Air drones can measure vertical profiles of humidity and wind in the lower atmosphere. Deployments of conventional airplanes could undertake direct covariance flux and infrared measurements. The use of LIDAR techniques from ships, planes, drones, and moorings could be a powerful means for acquiring profiles of the lower atmosphere and the upper ocean. Bulk algorithms could be improved using extensive observations with autonomous observing platforms: wave gliders, sail drones, and stations on buoys.

Two upcoming field projects offer promising opportunities for high-resolution observations of atmosphere-ocean interactions on the ocean-eddy scale, one in the tropics; the other in middle latitudes:

Tropics - EUREC^{4}A

Elucidating the Role of Clouds-Circulation Coupling in Climate (EUREC^{4}A), will take place January-February 2020 in the open ocean near Barbados. A project in this location will enable the sampling of varying atmospheric states over an ocean region rich in mesoscale and sub-mesoscale variability. This variability occurs beneath an atmosphere characterized by a rather steady trade wind regime. Eddies in this region have diameters of 200 to 300 km and lifetimes of several months up to years. In particular, anticyclonic and cyclonic eddies originating in the eastern basin and across the tropical North Atlantic move westward, reaching Barbados from the east, while energetic and long-lived anticyclonic North Brazil Current rings, which bring in fresh waters from the Orinoco and Amazon Rivers, reach Barbados from the south. The latter are key for the northward transport of properties from the South to the North Atlantic within the Atlantic Meridional Ocean Circulation. Preliminary studies based on satellite observations suggest they play a crucial role in air-sea interactions.

EUREC^{4}A-OA and the Atlantic Tradewind Ocean-Atmosphere Mesoscale Interaction Campaign (ATOMIC) are the dedicated ocean-atmosphere components of EUREC^{4}A that will take place in the context of the EUREC^{4}A airborne campaign (Fig. 2). This component will enhance the objectives and success of the whole program, by setting a local, oceanic constraint on the atmospheric evolution (as outlined in the overall EUREC^{4}A design, Bony et al. 2017). EUREC^{4}A-OA/ATOMIC comprises four oceanographic ships equipped with ocean-atmosphere high-resolution profiling, underwater gliders, and regular ocean drifters, as well as drifters sampling the air-sea interface, BioArgo floats, at least two air-drones, and a Saildrone, sampling the mesoscale and sub-mesoscale ocean and air-sea exchanges. These observations will enable the extended spatiotemporal sampling required to characterize ocean-atmosphere exchanges and their variability at ocean-eddy scales and will provide sufficient air-sea observations at different locations to accurately assess the relevant processes and their impacts.

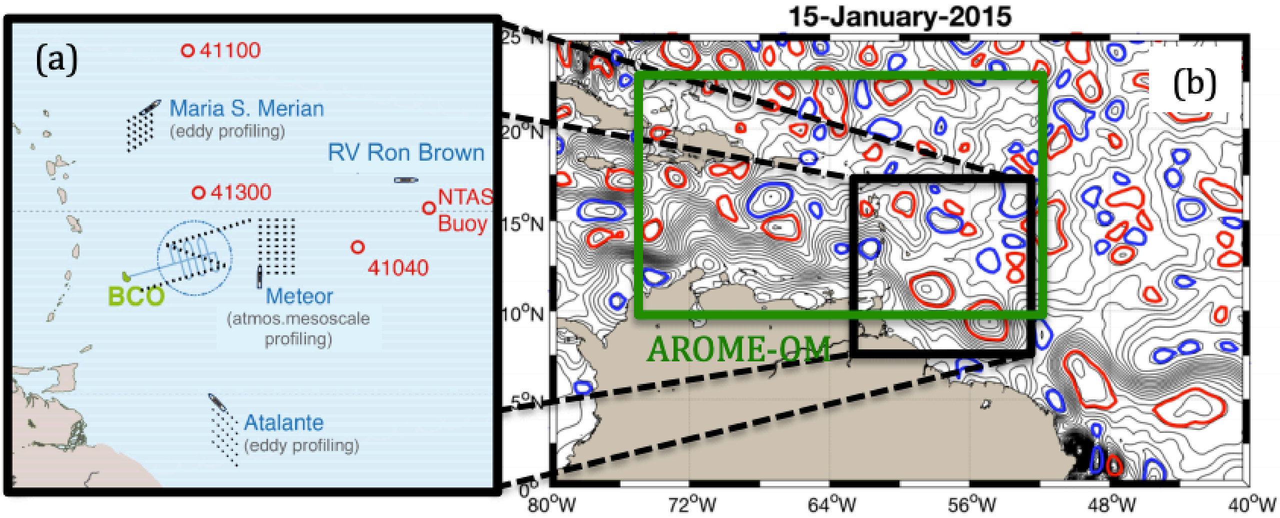

Figure 2. *Observation strategy for EUREC^{4}A core campaign (the 90km radius circle track of the Halo aircraft and the winding track of the ATR42 aircraft), EUREC^{4}A-OA (RVs Atalante, Meteor, and M. S. Merian), and ATOMIC campaign (RV Ron Brown and Northwest Tropical Atlantic Station (NTAS) buoy). BCO denotes the Barbados Cloud Observatory. (b) Sea surface height (contours) and anticyclonic (red) and cyclonic (blue) contours of ocean mesoscale eddies derived by applying the novel automatic eddy-tracking method of Laxenaire et al. (2018) for the 15 of January 2015. The black box shows the EUREC^{4}A-ATOMIC region. The green box shows the French modeling domain for the Météo France operational numerical prediction system for the region (AROME Outre-Mer). (From the* EUREC4A-OA component plan*)*

Midlatitudes – Surface Water and Ocean Topography (SWOT) fast-track CalVal mission

Conceived as a major new tool for climate studies, the SWOT satellite mission will launch in 2021 to observe the dynamics of the ocean upper layer at an unprecedented horizontal resolution of a few kilometers. During part of 2022 the coverage will be reduced, and the temporal resolution enhanced. This is an ideal opportunity – unique for many years to come – for coordinating *in situ* experiments capable of complementing model studies with much needed empirical evidence of fine scale global variability and its integrated role in the Earth system. Key questions to be addressed in the year to come are the role of the fine scales on the ocean energy budget (McWilliams 2016) and fine scale air-sea interactions (Lehahn et al. 2018; Renault et al. 2018; Sasaki et al. 2014).

The primary objective of the fast-sampling phase is calibration and validation (CalVal). During this period, orbit crossovers will open scientific opportunities in a variety of ocean regions, offering twice-daily synoptic images of the fine-scale ocean circulation. The SWOT nominal period for the fast-sampling phase is January-March 2022. Acknowledging the risk of postponement due to technical delays, the SWOT Science Team has encouraged the international community to coordinate fine-scale campaigns, so that a large number of SWOT crossovers will be accompanied by *in situ* studies during this fast-sampling phase.

In addition to the CalVal site in the California Current System (Wang et al. 2018), some of the planned activities will take place in the eddy-rich Cape Basin southeast of Africa, in the Southern Ocean south of New Zealand, and in the western Mediterranean Sea. These activities represent excellent opportunities for very high-resolution studies of air-sea exchanges. More information on these planned *in situ* experiments can be found in d'Ovidio et al. (2019).

WG2: Representation of eddy-scale air-sea fluxes for ocean-sea ice only models

Forced ocean-sea ice models are not truly representative of the coupled ocean-atmosphere-ice system, but they have their uses, and they will be around as long as coupled models have significant biases. Furthermore, coupled models are computationally expensive, and their atmospheres cannot be linked to present-day conditions without using data assimilation. Regional coupled models that include the feedback of surface oceanic currents on the atmosphere, however, have shown that ocean-interactions on eddy scales provide an unambiguous energy sink mechanism called eddy killing (Renault et al. 2016). When included in models, eddy killing can correct long-standing biases in the representation of western boundary currents. Eddy killing reduces the eddy-mean flow interaction (both the forward and inverse cascades) and leads to more realistic solutions. Further continued improvements in ocean models will require that they fully account for air-sea interactions, either with a responsive atmosphere (coupled planetary boundary layer) or with additional parameterizations.

There are two main methods for representing air-sea fluxes on the ocean eddy scale with a prescribed atmosphere. The first uses bulk formulae, despite uncertainties as large as 20% (Brodeau et al. 2017). Until recently the computation of the wind stress used in forced ocean-sea ice models did not take into account the ocean current velocity (absolute wind). The CORE protocol (Coordinated Ocean-Ice Reference Experiments, Griffies et al. 2009) uses relative winds ($U_A - U_O$) in bulk formulae, but this does not take into account that the stress is modulated by the current-stress interactions on ocean eddy scales. Renault et al. (2016) proposed, instead, to use $U_A - (1-S_{tau})U_O$, where S_{tau} is on the order of 0.3. This is based on regional high-resolution coupled numerical simulations and has not been tested globally. The second method uses atmospheric boundary layer models. They are costlier computationally and are not the norm. Deremble et al. (2013) derived a cheaper alternative (CheapAML), but it allows only for SST impact, while the winds remain prescribed.

There are several challenges to computing S_{tau} using observations, as observations typically already include a current-stress effect. Forcing fields should not contain the imprint of the ocean mesoscale field. For example, scatterometers actually measure the surface stress, not the wind velocity. This means that scatterometer-derived winds contain current signatures on eddy scales that will be different from those in the forced model. There is, therefore, a need for new observations using Doppler scatterometry to simultaneously measure collocated winds and currents (SST and waves would be good too), in order to be able to derive absolute winds that can be used to compute relative winds in the numerical model. Atmospheric reanalyses based on prescribed SST and no ocean currents do provide absolute winds, but their coarse resolutions (when compared to ocean eddy scales) do not allow for a proper representation of eddy fluxes. One should also note that Quikscat winds are often used to correct the winds in atmospheric reanalyses, and it is, therefore, unclear if they truly provide absolute winds.

S_{tau} can be derived from high-resolution coupled models (Renault et al. 2016), but the results will depend strongly on the choice and configuration of the model, especially the parameterizations of boundary-layer vertical mixing in the atmosphere and the ocean. One recommendation from the working group is to further develop planetary boundary layer models that are computationally cheap and comprehensively inclusive of relevant variables. Several approaches exist using geostrophic winds, air temperature, and humidity vertical mixing or a slab atmospheric boundary layer with shear (Schneider and Qiu 2015), but they need to be evaluated. Another suggested approach is to use coupled models with data assimilation in the atmosphere to constrain it to current conditions.

WG3: Impacts of the ocean eddy field and its variability on atmospheric weather & climate

Large-scale SST variations and the associated upper ocean heat content variations in the tropics have long been recognized to be fundamental in influencing global atmospheric circulations, providing an important source of climate predictability at seasonal or longer time scales. In contrast, extratropical large-scale SST variability is driven by atmospheric variability, and its influence on midlatitude atmospheric circulations, including jet streams and storm tracks, is commonly considered weak (cf. Kushnir et al. 2002). This by no means suggests, however, that midlatitude ocean circulations that feature strong oceanic fronts and energetic eddies have no impact on weather and climate. Instead, studies in the past decade have revealed that the influence of midlatitude SSTs on the atmosphere is not through their large-scale patterns, but through their frontal signatures along energetic current systems, such as the Gulf Stream and Kuroshio, as well as the Antarctic Circumpolar Current (ACC) in the Southern Ocean. The strong SST gradients associated with oceanic fronts is shown to have an influence on the baroclinicity in the lower atmosphere, “anchoring” storm tracks. Tangible evidence has been presented to link observed variability of western boundary currents with storm track variability. Locally, over the warm flank of the front, deep convection intensifies, leading to a locally strengthened storm track at low levels and more explosive cyclogenesis. Remotely, a large-scale downstream response, albeit weak in terms of eddy-driven jet position or weather regimes, is also observed. Recent new investigations, however, call for more detailed understanding of causal relationship between the mean climate and local storm activity.

While progress is being made in understanding the connection between oceanic fronts and storm track dynamics, the advent of high-resolution satellite observations in the past decade has provided ample evidence that mesoscale SSTs associated with energetic ocean eddies along oceanic fronts can have a strong impact on the atmospheric boundary layer, including well-defined responses of winds, rainfall, clouds, and other related atmospheric variables to eddy-induced SST anomalies. Two different mechanisms have been proposed to explain the influence of mesoscale-scale SST features. Atmospheric pressure gradients in the boundary layer adjust to the SST gradients, driving surface wind convergence in regions with warmer SST. This so-called "pressure adjustment mechanism" (PAM) can explain the occurrence of the precipitation band along the warmer flank of the Gulf Stream front. An alternative mechanism is often referred to as the vertical mixing mechanism (VMM), in which a warmer SST leads to a more unstable boundary with deeper vertical mixing. This causes momentum associated with the stronger winds in the free troposphere to be brought down to the surface. Figure 3 gives schematic summary of the impacts of ocean eddies on the atmospheric boundary layer.

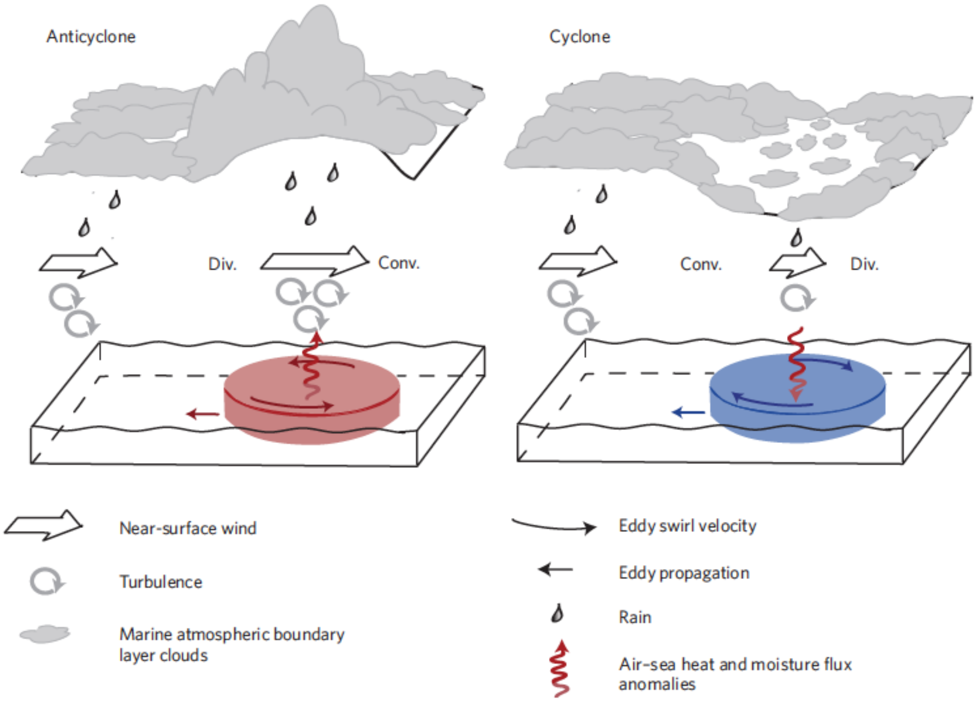

Figure 3. *Schematic summary of the impact of ocean eddies on atmospheric boundary layer for a Southern Hemispheric warm-core anticyclone (red, left) and a cold-core cyclone (blue, right). Div., wind divergence; conv., wind convergence. (After Frenger et al. 2013)*

Although the impact of ocean mesoscale eddies on the atmospheric boundary layer has been well established, a more important question that remains largely unanswered is whether and how eddies can affect large-scale atmospheric circulations and storm tracks. Given the mismatch in scales between ocean mesoscale eddies (~100 km) and the atmospheric Rossby radius of deformation (~1,000 km), effects of ocean eddies on the free atmosphere can be explained only by invoking nonlinear mechanisms. Recent studies using high-resolution atmospheric models indicate asymmetric responses to warm versus cold ocean eddies, with considerably larger amplitudes of response to warm than cold eddies. This asymmetry results in a rectified vertical flux of moisture into the atmospheric boundary layer that acts to amplify the genesis and growth of storms through the effects of moisture on baroclinic instability, in turn leading to a local strengthening of the atmospheric eddy variance in the lower to middle troposphere. The asymmetric atmospheric response to ocean eddies is supported by satellite-based analysis of observed rainfall that shows considerably stronger warm-eddy-induced rainfall response than cold-eddy-induced response (Fig. 4). High-resolution atmospheric model simulations further reveal a remote atmospheric response downstream of eddy active regions, which can lead to a north-south shift of the jet stream and storm track.

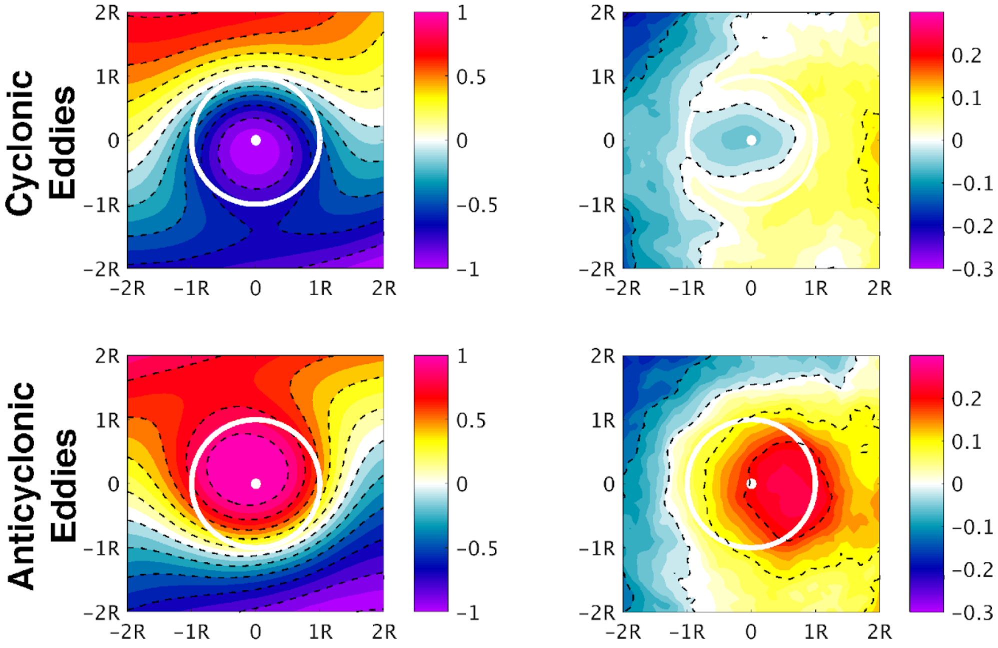

Figure 4. *Composite of SST anomalies (°C, left) and IMERG (Integrated Multi-satellite Retrievals for Global Precipitation Mission) satellite measured rain anomalies (mmd-^{1}, right) for cold-core cyclonic eddies (upper panel) and warm-core anticyclonic eddies (lower panel). (After Liu et al. 2018)*

These recent studies motivate us to revisit the role of extratropical SSTs in climate variability and predictability, by focusing on the effect of mesoscale SST variability associated with oceanic fronts and eddies on extratropical extremes, such as explosive cyclones and atmospheric rivers, jet streams, and storm tracks. Three sets of scientific questions were formulated during the workshop discussion:

- How do mesoscale SST variations associated with oceanic fronts and eddies influence the atmosphere on meso, synoptic, and climate scales and what are the underlying mechanisms? What is the causal relationship between extreme synoptic events and the mean climate? How is explosive cyclogenesis influenced by mesoscale SST forcing? What is the relative role of SST gradient versus eddy-induced SSTs in forcing the atmosphere? What are the underlying dynamical processes responsible for the asymmetric atmospheric response to ocean eddies?
- Are intraseasonal-to-decadal variations in ocean eddy activity a potential source of atmospheric predictability on these timescales? In particular, can the persistence of ocean mesoscale eddies provide a source of predictability for extratropical extremes, such as atmospheric rivers, on subseasonal scales?
- What are the resolution and physics requirements for atmospheric models to capture the influences of mesoscale SST forcing? Is it sufficient to just increase the horizontal resolutions of atmospheric models?

Because ocean eddies evolve very slowly and atmospheric weather noise dominates in midlatitudes, addressing the above questions using only observational analyses will be extremely difficult. Numerical modeling offers an attractive alternative, because the effects of mesoscale SST forcing can be readily isolated by conducting simulations with and without the presence of mesoscale SST anomalies. To this end, we propose a coordinated multi-model experiment and analysis effort to systematically assess the impact of mesoscale SST variability on weather and climate. One major challenge for this multi-model effort is the requirement for high horizontal resolutions (~20 km–25 km) for the participating atmospheric models, in order to fully resolve the effect of mesoscale SSTs on the atmosphere; this can be computationally demanding. To address this challenge, we propose to coordinate this multi-model effort with the ongoing High-Resolution Model Intercomparison Project (HighResMIP), as a part of the Coupled Model Intercomparison Project 6 (CMIP6). Specifically, the proposed multi-model experiment will be an expansion of the existing historical forced atmosphere (ForcedAtmos) runs for the period 1950–2014. The new set of runs will be identical to the historical ForcedAtmos runs coordinated by HighResMIP, except that the participating high-resolution atmospheric models will be forced by a lowpass filtered daily 0.25° HadISST2-based SST north (south) of 25°N (25°S), so that mesoscale SST anomalies will be removed from the SST forcing. Considerable discussion addressed how to identify the best filtering strategy for removing mesoscale SST anomalies. A well-coordinated analysis effort is planned to compare this new set of multi-model simulations with the HighResMIP historical ForcedAtmos runs to address the set of questions above.

3 CONCLUSION AND ACTION ITEMS

The overall conclusion from this short workshop is that the science addressing how the ocean mesoscale interacts with the atmosphere is far from mature; rather we are at the cusp of new discoveries as observational systems and computational models, for the first time, become capable of providing comprehensive information on these previously unobserved and unmodeled spatial scales. Looming in the background are unexplained persistent biases in coupled models and the puzzle of explaining why the real coupled system appears to be more predictable on seasonal timescales than our best coupled seasonal forecasting systems (the "signal to noise paradox" in climate prediction, cf. Scaife & Smith 2018), leading to the suggestion that both may be resolved by models that fully capture ocean-atmosphere interactions on the ocean mesoscale. Perhaps more intimidating, for both modelers and observationalists, while also intriguing, is the possibility that even smaller scales in the ocean – the sub-mesoscale – are, through the violations of geostrophy and resulting vertical transports of heat, of fundamental importance to the coupled climate system (cf. McWilliams 2018).

Action items from the workshop include communicating its outcomes, contributing to the development of research programs, engaging with planning for observational campaigns, and developing new modeling experiments and observational analyses.

Communication:

- A report on the workshop appeared in Eos (Robinson et al. 2018)
- Workshop participants are contributors to a major OceanObs'19 community white paper (Cronin et al. 2019).
- Workshop outcomes have been reported to the CLIVAR Ocean Model Development Panel at its 5th Session, March 2019.

Programmatic:

- Workshop outcomes informed the proposal for a Japanese project "Hotspots under a changing climate" in the spring of 2018. While this proposal was declined, a resubmitted proposal is pending.
- The workshop informed a successful proposal from the CLIVAR Atlantic Regional Panel to conduct a CLIVAR-FIO (First Institute of Oceanography) 2020 Summer School in Qingdao on the topic: Ocean Macroturbulence and Its Role in Earth's Climate.
- The workshop results provide support for the development of satellite Doppler scatterometry, capable of simultaneously measuring ocean surface winds and currents.

Observational:

- In addition to EURECA4 and the SWOT CalVal opportunities described above, efforts will be made to include a focus on ocean-eddy atmosphere interactions in the upcoming Year of the Labrador Sea project.
- Develop plans for a new coordinated analysis of satellite products, together with reanalysis products, focused on air-sea fluxes and their impacts on the ocean.

Modeling:

- Develop analysis protocols and diagnoses for high-resolution coupled model experiments.
- Design filters to remove ocean-eddy SSTs to be applied in atmosphere-only model experiments forced by observed SSTs.

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Appendix A: Organizers

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Walter Robinson (Chair)	North Carolina State University
Ping Chang	Texas A&M University
Eric Chassignet	Florida State University
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Appendix C: Agenda

Saturday, February 17, 2018

Time		***Presenter***
08:30	Welcome/Objectives	Walter Robinson, North Carolina State U.
08:45	*In situ* observations of air-sea interactions and feedbacks	Meghan Cronin, NOAA PMEL
09:15	Discussion	
09:30	Satellite observations of air-sea interactions and feedbacks	Bertrand Chapron, IFREMER
10:00	Discussion	
10:15	Break	
10:30	Role of the current feedback to the atmosphere in determining the ocean dynamics	Lionel Renault, U. California Los Angeles
11:00	Discussion	
11:15	A review of covariability of mesoscale SST, surface heat fluxes, and surface convergence	Justin Small, NCAR
11:45	Discussion	
12:00	Working lunch	
12:30	Poster session	
13:30	Panel discussion with speakers	Walter Robinson, North Carolina State U. (moderator)
14:15	Breakout groups: • WG1: Observational requirements for eddy-scale air-sea fluxes • WG2: Representation of eddy-scale air-sea fluxes for ocean-only models • WG3: Atmospheric weather & climate impacts of the ocean eddy field & its variability	WG1: Sabrina Speich, Ecole Normale Supérieure WG2: Eric Chassignet, Florida State U. WG3: Ping Chang, Texas A&M U.
15:30	Break	
16:00	Breakouts resume	
17:30	Adjourn	

Sunday, February 18, 2018

Time		***Presenter***
08:30	Recap from day 1	Walter Robinson, North Carolina State U.
08:45	Breakout reports	
08:45	WG1: Observational requirements for eddy-scale air-sea fluxes	Sabrina Speich, Ecole Normale Supérieure
09:00	Discussion	
09:15	WG2: Representation of eddy-scale air-sea fluxes for ocean-only models	Eric Chassignet, Florida State U.
09:30	Discussion	
09:45	WG3: Atmospheric weather & climate impacts of the ocean eddy field & its variability	Ping Chang, Texas A&M U.
10:00	Discussion	
10:15	Break	
10:45	Synthesis discussion	
11:45	Closing/Next steps	Walter Robinson, North Carolina State U.
12:00	Adjourn	
	Working lunch of Organizing Committee and facilitators.	

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