An international initiative for the tropical Ocean-Atmosphere interactions at the ocean mesoscale

The US (ATOMIC) and European (EUREC^{4}A-OA) components

ATOMIC ***Atlantic Tradewind Ocean-Atmosphere Mesoscale Interaction Campaign***
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1. Introduction

The atmosphere and ocean drive processes in one another through air-sea interaction mechanisms – primarily mixing in turbulent boundary layers. Above most of the oceans, liquid clouds of a few thousand meters or less mix the lower atmosphere in a process called shallow convection. The warm cloud types dominate coverage of the ocean and may strongly influence weather on seasonal to sub-seasonal time scales. Indeed, deep and shallow convection are intricately linked, with shallow convection acting to humidify the lower troposphere and create conditions in which deep convection can arise. Shallow convection exerts an important influence on sea surface temperatures (SSTs) and salinity by moderating the air-sea exchanges of energy and moisture. For global prediction models in the foreseeable future, shallow convection is a “grey-zone” problem in which the circulations are too small to be represented explicitly, but too large and too few to be represented with the equilibrium statistical approaches required for parameterization. The issue stems not from the scale of individual clouds but rather of the mesoscale circulations that organize the shallow convection, producing a large range of cloud morphologies that affect radiative fluxes and possibly precipitation at the surface.

The interaction between shallow convection and the ocean’s surface layers is a two-way street: though shallow convection influences SSTs, shallow convection is itself controlled to a large extent by SST and air-sea fluxes, which are mediated by processes within the ocean, especially Oceanic Barrier Layers (OBL) and mesoscale ocean eddies. OBL are near-surface layers created by low salinity waters and embedded in the ocean mixed layer. OBLs tend to decouple the ocean mixed layer from momentum fluxes but also may drive subsurface warming through facilitating the penetration of short wave radiation to the base of the OBL. In doing so, the OBL can influence weather and climate patterns. The OBL in the tropical northwest Atlantic are some of the thickest in the world (Mignot et al. 2007); unlike other OBL in central regions of the tropical oceans, they are also persistent over most of the year and are accompanied by warm anomalies below the OBL that are still within the ocean mixed layer. This subsurface reservoir of heat can have a strong effect on hurricane intensification (Balaguru et al., 2012 *PNAS*), whereby wind stirring causes the upper ocean to warm up, as opposed to the cold oceanic wakes that usually accompany hurricanes. On the other hand, if the subsurface heat anomaly associated with OBL is not re-exposed to the atmosphere, then the question arises as to the effect of a net heat export into the ocean interior, and its relevance to climate.

Ocean mesoscale eddies are another mechanism that strongly affect the ocean surface budget and therefore SST. They are ubiquitous in the ocean (Chelton et al., 2011 *Progr. Oceanogr.*). There is increasing evidence, mostly from observations in the extra-tropics, that dynamical processes associated with mesoscale ocean eddies drive SST anomalies which in turn impact the air-sea exchanges and the overlying atmosphere (wind, clouds, rainfall, Frenger et al. 2013 *Nat. Geosci.*; Villa Boas et al. 2015 *Geophys. Res. Lett., Ma et al. 2016, Nature, DOI 10.1038/nature18640.*). Preliminary results suggest it is also the case in the tropics (MS Thesis of Léa Olivier, LMD-ENS). This topic is gathering high interest in the scientific community; air-sea interactions at the scale of ocean eddies were the theme of a recently organized

CLIVAR workshop co-chaired by S. Speich (www.clivar.org/events/ocean-mesoscale-eddy-interactions-atmosphere-workshop). Preliminary results from satellite and in-situ data show that in the Tropical Northwest Atlantic, ocean eddies are massive heat reservoirs that capture the fresh waters of the Amazon and Orinoco rivers. These regional OBL hotspots are efficient heat and humidity sources for the atmosphere. However, the exact genesis, properties and fate of the regional mesoscale ocean eddies, as well as their precise influence on Tropical Northwest Atlantic air-sea interactions, surface energy budgets, and atmosphere shallow convection is still poorly known.

Better understanding of the coupling the ocean and atmosphere offers the opportunity to improve seasonal to inter-seasonal predictions by alleviating errors in modeling the coupled ocean-atmosphere system. Those errors might arise one of four sources: 1) inaccurate representation of the transfer of moisture, energy, and momentum from the atmospheric boundary layer to the free atmosphere; 2) errors in representing the coupling of the atmospheric boundary layer to the ocean surface layer; 3) neglecting the meso-scale circulations which organize shallow convective circulations in the atmosphere and influence the distribution of cloud properties, and 4) errors in representing ocean properties, such as OBLs, which strongly influence SSTs.

The **Atlantic Tradewind Ocean-Atmosphere Mesoscale Interaction Campaign** (**ATOMIC, US)** and the **Ocean-Atmosphere** component of **EUREC⁴A** (**EUREC⁴A-OA, Europe)** initiatives will take advantage of the complementary existing international EUREC⁴A intensive atmospheric field campaigns taking place during 6 weeks in January-February 2020 **to address the Northwest Tropical Atlantic Ocean-atmosphere interactions at the mesoscale and their relation to the regional OBL, air-sea interactions and atmospheric shallow-convection.**

2. The ATOMIC and EUREC⁴A-OA components

The international field campaign named EUREC⁴A (Elucidating the role of clouds-circulation coupling in climate) will take place from 20 Jan to 20 Feb 2020 over the Northwest Tropical Atlantic, near Barbados (Bony et al. 2017 *Surv. Geophys.*, www.eurec4a.eu). EUREC⁴A, which has been endorsed by the World

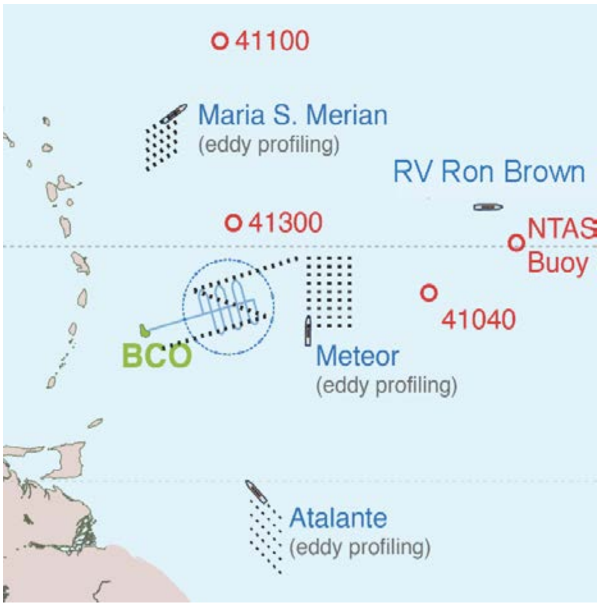

Figure 1. Observation strategy for the EUREC⁴A core campaign. BCO denotes the Barbados Cloud Observatory. EUREC4A aircraft operations (race track and circle traces) will be conducted from Barbados. Red number denote NOAA buoys. Ship locations are approximate. Rawinsondes will be launched from the ships and BCO.

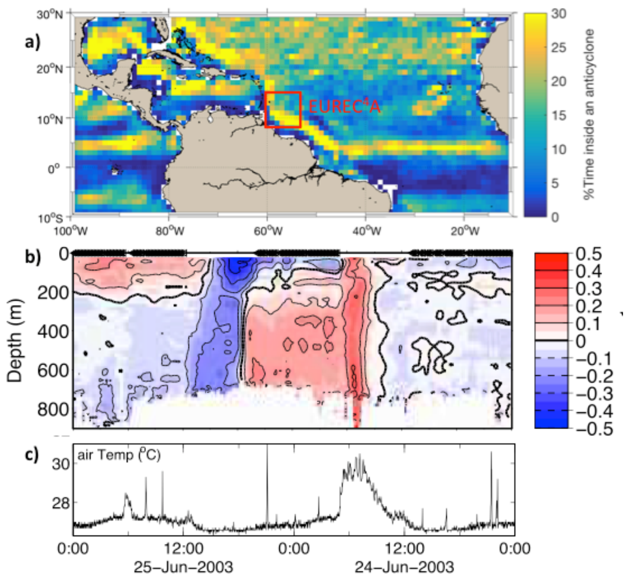

Figure 2. (a) Percentage of presence of ocean mesoscale anticyclonic eddies (Laxenaire et al. 2018, JGR) derived from satellite altimetry. The red box shows the EUREC⁴A region, (b) meridional current profiles (black segments at 0m when the ship is not moving) and (c) air temperature taken during a survey through an anticyclonic eddy west of Barbados (Southern Ocean 172 campaign). The eddy was associated with air temperature perturbation >2°C, (for clarity time axis is reversed as the ship was cruising to the west).

Climate Research Program (WCRP) is designed to test critical hypotheses related to the interplay between clouds, (atmospheric) convection and circulations, and their role in climate sensitivity. It will in particular focus on the shallow marine cumulus prevalent over the world's trade-wind belts and tropical oceans. Cloud sensitivity to changing environmental conditions has the potential to strongly influence the evolution of future climate warming. EUREC^{4}A's core measurements come from two well-equipped research aircrafts (the French ATR-42 and German HALO, Fig. 1), includes a dense network of atmospheric soundings from HALO dropsondes, and land-based instrumentation from the Barbados Cloud Observatory. The plan for intensive atmospheric observations during EUREC^{4}A, and the international momentum and cooperation associated with it, are opportunities for complementary investigations to better understand air-sea interactions, and interactions between the atmosphere and ocean boundary layers, shallow cumulus clouds, tropospheric water vapor in the North Tropical Atlantic.

The **ATOMIC & EUREC^{4}A-OA** teams propose to take advantage of EUREC^{4}A to address complementary aspects albeit key for the complete understanding of shallow-convection processes in the Tropical Atlantic. The **ATOMIC & EUREC^{4}A-OA** projects will complement EUREC^{4}A by focusing on the air-sea exchange and connecting it to the processes above and below the material surface of the ocean. The atmospheric work will focus on the processes associated with shallow convection – vertical mixing by clouds and turbulence, cloud-radiative coupling, the role of precipitation how shallow convective transport of scalars and momentum affect the local and regional structure of the marine boundary layer and how the shallow cumuli affect the oceanic surface energy budget. The oceanic work will focus on the role of eddies, barrier layers, and surface forcing on oceanic boundary-layer mixing. The oceanic work will benefit from and require the unprecedented surface forcing information provided by the large scale atmospheric array and from direct flux observations from ships.

The **ATOMIC & EUREC^{4}A-OA** program will feature a two-month field observation period combined with extensive process-level modeling with linkages to operational Numerical Weather Predictions (NWP) centers and climate model centers. Indeed, EUREC^{4}A's construction, based on two research aircraft, one hosting remote sensing instrumentation at high-altitude, launching dropsondes from a circular flight path towards determining the atmospheric vertical velocity profile, with a second aircraft making low-altitude surface flux and microphysical measurements (Fig. 1). The aircraft dropsonde and ship upsonde data will be assimilated to provide re-analysis field of large scale and mesoscale forcing. The **ATOMIC & EUREC^{4}A-OA** will add airborne and shipborne observing systems that complement EUREC^{4}A. The shipborne observations will focus on continuous time series profiling in contrast to the airborne spatial snapshots planned by EUREC^{4}A.

In particular, **ATOMIC & EUREC^{4}A-OA** will focus on **(A) tropical ocean-atmosphere interactions at the ocean mesoscale (10-500 km), and assess the impact of the air-sea coupling on both the ocean and atmosphere at this spatial scale**, and **(B) the multi-scale modeling of the atmosphere and of ocean-atmosphere coupling**. For this purpose, **ATOMIC & EUREC^{4}A-OA** teams propose:

- **(A)** To lead oceanographic and ship-based atmospheric measurements and deploy innovative automated devices (gliders and drones) towards characterizing the variability of oceanic and atmospheric properties at the mesoscale, and to deploy a ship-based network of radiosondes to characterize the atmosphere variability on the diurnal time scale and on a spatial scale larger than the area of aircraft operations;
- **(B)** To promote a coordinated global analysis of EUREC^{4}A and **ATOMIC & EUREC^{4}A-OA** observations and modeling that will advance the understanding of cloud-circulation and morphology and how the ocean-atmosphere couplings produce transitions of the boundary layer structure across the edge of the mesoscale eddies, and make use of these observations to improve the weather and climate models.

The US and European Programs to Study Tropical Atlantic ocean-atmosphere interactions at the mesoscale (ATOMIC & EUREC^{4}A-OA) will offer the unique and unprecedented opportunity to extensively observe such interaction in the Tropics with in situ measurements. Indeed, the EUREC^{4}A region is one pathway of numerous mesoscale eddies originating from the near-equatorial Atlantic Ocean and along the Brazilian coast (Fig. 2a). This region is also characterized by fresh surface water influenced by South-American river run-off that leads to the frequent formation of OBL. The interplay between eddies and this particular vertical structure results in complex mesoscale variability at the ocean surface that has a strong signature in sea surface temperature (SST), surface salinity (visible satellite), and air temperature fields (Fig. 2bc). The eddies will impact the atmosphere through their surface fluxes, which in turn can affect the shallow cloud fields and their organization, but the strength of this connection is not yet known. Only a synergy between intense and comprehensive ocean-atmosphere observations and modeling can help advance this knowledge.

Moreover, the exchange of carbon dioxide (CO_2) between the atmosphere and the ocean is driven by their CO2 concentration or partial pressure difference at the interface. Globally, this difference is mainly driven by the ocean side with the ocean circulation playing a major role in the exchange of mass between the spheres. While the large-scale effect of circulation and mixing on the exchange of CO_2 between the ocean and the atmosphere is well understood, much less is known at smaller scales. Locally, studies have shown that ocean eddies strongly contribute to the vertical transfer of surface properties, yet the resulting effect on the exchange of CO_2 has not been fully quantified. Here, we propose to investigate the exchange of CO_2 between the atmosphere and the ocean in an ocean eddy environment. In the proposed experiment, we will monitor both the ocean and atmospheric CO_2 partial pressure as well as environmental variables such as SST, sea surface salinity, surface wind, current structure, and surface air pressure, while systematically navigating through mesoscale ocean eddies of different origins and surface signature. The study aims to provide a better understanding to what extend eddy driven transport and mixing of oceanic water masses enhances the local air-sea exchange of CO_2.

These are the objectives of the combined and coordinated US-European **ATOMIC & EUREC^{4}A-OA**.

(A) Observing the tropical ocean-atmosphere interactions at the ocean mesoscale

The strategy chosen for the **ATOMIC** & **EUREC^{4}A-OA** campaigns is a 1.5/2-month cruises with different ships (the German R/Vs *Meteor* and SA *Merian*, the French *Atalante*, and the US-NOAA R/V *Ronald H. Brown*), the request for an additional equipped aircraft (the US-NOAA G-4 and P-3 aircraft) and the deployment of different additional observing equipment such as the Boreal drone, Saildrones, and Oculus gliders complementing the intensive atmospheric and oceanic measurements of the core EUREC^{4}A campaign. The ship cruise will involve both station observation to monitor the large-scale environment periods and surveys of selected eddies.

- The Boreal drone will help to understand how the ocean and the atmosphere interact at the mesoscale and to unravel the physical mechanisms controlling the mesoscale organization of the atmospheric boundary layer. The Boreal drone (endurance of 10h/1000 km, Robert et al. 2017 *La Météorologie*) will be launched from Barbados island and during the ATR42/HALO flights to map SST, sea state and the surface energy and aerosol fluxes, and meteorological parameters near the ocean surface and to quantify ocean-atmosphere interactions on scales of several hundred km within the EURAC^{4}A study region.
- The international fleet of ships will survey intensely different mesoscale ocean structures whose position will be known precisely via an automated remote sensing eddy detection developed at LMD and applied on near-real time. The US-NOAA ship R/V *Ronald H. Brown* will be positioned near the NTAS permanent station (Fig. 1). The German ship *Meteor* will be positioned in the northern side of the region. The French ship will be positioned south of Barbados, along the southern pathway of mesoscale eddies. Another European ship will very likely complement the ship constellation and spatial repartition to fully cover the EUREC^{4}A domain. These surveys will be carried out using autonomous gliders (independent from ships) in addition to ship based high-resolution CTD, RapidCAST, XBTs, ADCP current profiles, and underway observations of atmospheric and oceanic parameters including current.
- Saildrones will measure air-sea fluxes of latent and sensible heat and radiation, surface and upper ocean temperature and salinity to fill the gaps between stationary ships. Saildrones can stay in water for six months to provide a seasonal context for the field campaign.
- Station locations will be set in accordance with other EUREC^{4}A oceanographic campaigns to form a radiosonde network (with up to four soundings per day) in a region encompassing the core experiment area. This network will be used to derive a continuous temporal evolution (resolving the diurnal cycle) of the large-scale synoptic circulation and of the apparent heat source and moisture sink around the periods of the core experiment flights. This will also result in better meteorological analysis in the region by the real-time assimilation of EUREC^{4}A-OA observation by operational centers.

(B) Multi-scale modeling the tropical Atlantic ocean-atmosphere coupled system
EUREC^{4}A and **ATOMIC** & **EUREC^{4}A-OA** will provide an unprecedented dense network of co-localized observations of the atmosphere and of the ocean in the trade-wind regime that will benefit the modeling community. At the international level (GEWEX GASS), EUREC^{4}A has been proposed as an opportunity for the second phase of the intercomparison of models on the grey zone (resolutions between 100 m to 10 km where boundary layer and convective processes are partially resolved and parameterized). These joint modeling activities involve a hierarchy of models from Large Eddy Simulation (LES) to NWP regional (operational like AROME *Outre-Mer* or research models like Meso-NH and WRF-ARW) and global (e.g. LMDz, ARPEGE, IFS, and FV3) models. **ATOMIC** & **EUREC^{4}A-OA** modeling activities will aim at improving our understanding not only of the impact of the ocean mesoscale eddies on air-sea coupling and the atmospheric boundary layer but more generally of shallow convection and clouds in the trade-wind regimes and the underlying mechanisms and radiative impact of the mesoscale atmospheric organization. They ultimately aim at improving the physical parameterizations of NWP and climate models, and to facilitate development of coupled ocean-atmosphere cloud and eddy-resolving models.

3. Duration

The field program will be approximately two months in the January-March 2020 time frame. The project will be 4 years beginning in 2019.

4. Relevance to CLIVAR's present activities

EUREC^{4}A has been endorsed by the World Climate Research Program (WCRP). It is of major relevance for WCRP related activities (including CLIVAR). **ATOMIC** & **EUREC^{4}A-OA** are directly and/or indirectly related to numerous CLIVAR goals and activities, including CLIVAR's regional panels (e.g., Atlantic, Northern and Southern Ocean Implementation Panels), all the CLIVAR's global panels (Global Synthesis and Observations Panel – GSOP, Ocean Model Development Panel – OMDP, the Climate Dynamics Panel – CDP, and the CLIVAR/GEWEX Monsoons Panel), several Research Foci (Decadal climate variability and predictability – DCVP, Consistency between planetary energy balance and ocean heat storage– CONCEPT-HEAT, Understanding and predicting weather and climate extremes, ENSO in a changing Climate), and several endorsed projects (e.g., TACE, PIRATA, IASCLIP, CLIVAR Repeat Hydrography), and major activities (e.g., Atlantic Meridional Overturning Circulation – AMOC, including RAPID-MOCHA and SAMOC). CLIVAR has just started to explore possibilities for an initiative on mesoscale oceanic eddies (www.clivar.org/events/ocean-mesoscale-eddy-interactions-atmosphere-workshop). Data collected in **ATOMIC** & **EUREC^{4}A-OA** will help in the understanding of processes responsible of the ocean mass and meridional heat transport and property fluxes for the CLIVAR Repeat Hydrography program, as well as air-sea heat exchange calculations needed to meet the western hemisphere warm pool prediction goals of IASCLIP. Clearly **ATOMIC** & **EUREC^{4}A-OA** will be an important element to consider the future Tropical Atlantic Observing System (TAOS).

5. Broader impacts and benefits of the proposed activity

The **ATOMIC** & **EUREC^{4}A-OA** measurements set the context for a yet more ambitious effort to build on the EUREC^{4}A measurements and by so doing to provide a benchmark data set for constraining a new generation of coupled models capable of resolving convective heat transport in the atmosphere, and meso- to sub-mesoscale variability in the ocean. This large internationally coordinated project will also advance our understanding of the coupled system at the ocean mesoscale, and mesoscale oceanography in its own right, including also ocean biogeochemical and biological processes. Improved knowledge and model representations of the interaction of cumulus clouds with the atmospheric and oceanic boundary layers resulting from ATOMIC and EUREC4A-OA, have the potential to tap unrealized predictability in the climate system and thereby improve seasonal to subseasonal weather and climate prediction. Improved representation of the cumulus cloud ensemble constrains regional and global cloud and tropospheric water vapor climate feedbacks, which in turn constrains projections of both global climate, and the hydrological response of rainfall, its spatial distribution, and its extremes in a changed climate.

Moreover, each of the ships will be equipped with active remote sensing (e.g. Radar and Lidar - similar to instruments at the Barbados Cloud Observatory site and on the HALO and ATR-42 aircraft). This also makes this campaign very attractive for space-agencies (e.g. ESA: ADM-Aeolus, EarthCARE, Sentinel; NASA:

MODIS, VIIRS) for reference data to evaluate and improve their retrieval models (e.g. in support of the EarthCARE mission, the German EarthCARE office is at the MPI-M).

6. The International Consortium

❖ International collaborations

- EUREC^{4}A is originally a French-German initiative (led by S. Bony and B. Stevens, Bony et al. 2017). It currently involves several French institutions (LMD, LATMOS, LSCE, LAMP, SAFIRE) and many other institutions in Europe (MPI, DLR, GEOMAR, ECMWF, U. of Leeds, KNMI, U. of Delft) and in the US (NOAA, MIT, WHOI, NASA). EUREC^{4}A, which has become a capstone field experiment in support of the WCRP Grand Challenge on *Clouds, Circulation and Climate Sensitivity* (Bony et al., *Nature Geosci.*, 2015), is discussed every year at the WCRP JSC, and connects to several WCRP core projects: GEWEX (several white papers for joint modeling activities related to EUREC^{4}A have been discussed at the last GEWEX Pan-GASS conference in Australia in Feb 2018) and CLIVAR (EUREC^{4}A has been discussed at the CLIVAR Atlantic Regional Panel, at the kickoff workshop for the tropical Atlantic Observing System review and at the Ocean mesoscale eddies and air-sea interactions workshop in Portland, USA, Feb 2018).
- In Germany, MPI, GEOMAR and the University of Hamburg have submitted a proposal for the deployment of 2 Research Vessels (*Meteor* and *Merian*) during EUREC^{4}A; the deployment of one of them (*Meteor*) has already been accepted (Mar 2018), and a recommendation to submit a new proposal for the second one has been issued.
- In the US, the deployment of the NOAA ship *Ronald H. Brown* and NOAA aircraft P-3 and G-4 is pending (Atlantic Trade-Wind Ocean-Atmosphere Mesoscale Interaction Campaign -ATOMIC- proposal, C. Fairall). At NASA (D. Winker), a proposal for the deployment of the P3 aircraft (with wind and water vapor lidars on board) is pending. University-based researchers will coordinate on proposals to NSF to support participation and analysis.
- In the UK, a proposal (EUREC^{4}A-UK) has been submitted by the U. of Leeds (led by Alan Blyth) to deploy the FAAM aircraft and support the national Paracon project on convection.

❖ Participants (PIs)

France: S. Speich, H. Bellanger, S. Bony, B. Deremble, J.-L. Dufresne, F. Hourdin, I. Musat, C. Muller, R. Vogel (*Laboratoire de Météorologie Dynamique – LMD – IPSL*); G. Reverdin (*Laboratoire d'Océanographie et du Climat : Expérimentations et Approches Numériques – LOCEAN – IPSL*); F. Beucher, D. Bouniol, F. Burnet, G. Canut, F. Couvreux, C. Denjean, G. Faure, H. Giordani, R. Honnert, C. Lac, G. Roberts, R. Roehrig (*Centre National de la Météorologie – CNRM – MétéoFrance*).

Germany: J. Karstensen (*GEOMAR*); S. Kinne, B. Stevens (*Max-Planck-Institut for Meteorology*), W. Mohr (*Max-Planck-Institut for Marine Microbiology*)

USA: C.W. Fairall (NOAA PSD), P. Zuidema (RSMAS U. Miami), K. Emanuel (EAPS MIT), M. Zhao (NOAA GFDL), R. C. Perez (NOAA AOML), S. Bigorre (Physical Oceanography WHOI), Chidong Zhang (NOAA PMEL), J. Thomson (APL/U Washington), R. Pincus (NOAA PSD), J. Olson (NOAA GSD), G. Feingold (NOAA CSD), C-A Clayson (WHOI), S. de Szoeke (Oregon State University), Jerome Schmidt (NRL).

❖ Financial Implications

- ***US Cost Estimates***

The US team is pursuing an initiative within NOAA to participate in the project. If fully successful, NOAA would provide the R/V *Ronald H. Brown* (30 days, 850* USk$), the G-4 aircraft (120 hrs, 350 dropsondes, 850* USk$), and the P-3 aircraft (120 hrs, 50 dropsondes, 850* USk$). NOAA's Climate Variability (CVP) program and NOAA's Office of Weather and Air Quality (OWAQ) have been approached to offer a request for proposals for NOAA and non-NOAA scientists to participate in ATOMIC. We anticipate that university investigators would also propose to NSF to be involved in the field program or the modeling efforts. To fully utilize the US platforms would require on the order of 3-5 m$/yr for three years of joint NOAA/NSF funding plus 1-2 m$/yr in NOAA's research laboratory funds (including about 0.7 m$ for two month deployment of Saildrones and Oculus gliders).

- ***French Cost Estimates***

The French EUREC^{4}A team is funded through a European Research Council grant. It has submitted a pre-request of the R/V *Thalassa* or *Atalante* whose availability is still pending. National grant proposals have been and will be submitted in the coming months to INSU-CNRS and ANR to complement the costs for the cruises, additional equipment, data processing and analyses as well as modeling experiments and parameterization studies. The French funding is in the order of 3 m$.

- ***German Cost Estimates***

The German have already obtained the ship time and costs coverage for at least one ship (R/V *Meteor*). The availability of the R/V *Merian* is still pending. The cost of data validation, calibration and analyses will be covered by in-kind sources (GEOMAR and Max-Plank Institute of Meteorology) and additional external funding.