The ocean-mesoscale component in the EUREC4A++ program
A ship proposal linked to granted ship time GPF 18-1_69, EUREC4A++

1. General Information

We request ship time for a dedicated field study of ocean/atmosphere interaction across mesoscale eddies in the tropical Northwest Atlantic. The proposed experiment is embedded in a concerted observing campaign executed in the framework of the "Elucidating the role of Cloud-Circulation Coupling in Climate" (EUREC^{4}A) program, a German-French led capstone field study in support of the World Climate Research Programme's Grand Science Challenge on *Clouds, Circulation and Climate Sensitivity*. The field/observational campaign of EUREC^{4}A (EUREC^{4}A++) takes advantage of new methods to use dropsondes to measure profiles of vertical motion on the mesoscale; doing so allows it to constrain large-scale budgets of mass, momentum and enthalpy, simultaneously with measurements of surface energy exchange and the distribution of cloudiness Its measurements are designed to test hypotheses related to the interplay between clouds, (atmospheric) convection and circulation and ultimately their role in climate change and provide an opportunity to measure and characterize interactions with the ocean mixed layer in ways that previously were not possible. Operations will focus on an area east and south of Barbados for an entire month, between 20 January and 20 February 2020, to complement scheduled aircraft operations. The period will overlap with the ADM-Aeolus mission and provide preparatory measurements for the EarthCARE mission, two flagship satellite platforms of the European Space Agency Living Planet Programme.

In addition to the observational EUREC4A++ campaign, an exciting component of EUREC^{4}A is the high resolution modeling that will be performed in support of field operations. Following the approach taken during the NARVAL2 campaign a 2.5 km cloud resolving simulations will be performed over the entire tropical Atlantic but with nesting higher resolution simulations. During EUREC^{4}A the high resolution nest with 150 m resolution will be solved over the entire domain. This modelling will be performed in cooperation with the DWD Hans Ertel Research Center, and is also being coordinated internationally, opening the possibility for benchmark measurements to test an emerging new generation of coupled (ocean eddy and atmosphere convection resolving) models)

At this stage the GPF granted ship time for one ship to operate in the EUREC^{4}A++ framework (GPF 18-1_69, EUREC4A++; called from now on "**Ship 1**"). **Ship 1** has its clear focus in support for sampling the **atmospheric mesoscale and its link to cloud formation**. Crucially it will anchor the area of aircraft operations to provide surface based estimates of cloud and boundary layer properties, importantly including surface fluxes. The **Ship 1** observing campaign is thus to be executed in a coordinated way with airborne sampling (German HALO [funded by the Max-Planck-Society] and the French ATR-42 research aircraft [funded by an ERC Advanced ERC grant]) and land based sampling (at MPI-M's Barbados Cloud Observatory (BCO) site at the east coast of the island) components. The focus of this concerted experiment is in quantifying how cloud amount in shallow (1-3 km) cumulus layers responds to changes in the large-scale environment (as measured by the aircraft), how shallow clouds contribute to convective aggregation, and test retrievals of cloud and atmospheric properties. The ocean sampling during the **Ship 1** expeditions include a survey of the local oceanic state (CTD and turbulence sampling and ship based currents) with the area of sampling guided by the atmospheric sampling requirements. Ship 1 will also contribute airborne sondes and drifter measurements to supplement the upper air measurements and better constrain operational analyses during EUREC^{4}A++.

The need for a second ship

Ocean mesoscale eddies creates specific air-sea interaction pattern that can have an integral effect on the large scale atmosphere (and ocean) dynamics. Recent advances in state of the art knowledge were predominately obtained from modeling efforts, but a few observational studies exists. Adding **a dedicated ocean mesoscale eddy air-sea interaction experiment** to the EUREC^{4}A++ campaign would be of great benefit for the whole program as it poses a local, oceanic constrain to the atmospheric evolution (as been outlined in the overall EUREC^{4}A design; Bony et al. 2017). Temporal variability over a fixed mesoscale (200-300 km) study area allows for sampling varying atmospheric states, on the time-scales of the EUREC^{4}A++ field study, spatial sampling at different locations within the area is required to characterize ocean variability.

The western tropical Atlantic is, as it turns out, an ideal laboratory for the proposed study. It hosts a rich mesoscale variability under an atmosphere that is characterized by a rather steady trade wind regime. Eddies in the study region have a diameters of 200 to 300 km and lifetimes of several months up to years. In particular south of Barbados, very energetic and long lived anticyclonic North Brazil Current (NBC) rings are commonly found. Similar the well know Agulhas Rings in the South Atlantic, the NBC rings are important transport agents of water masses from the southern into the northern Atlantic Ocean and thereby contribute to the upper limp of the Atlantic's meridional overturning circulation.

A dedicated ship based experiment that targets high resolution ocean/atmosphere observations in mesoscale eddies requires flexibility in selecting the appropriate survey area. Hence there are three fundamental reasons to request here a second ship: (i) Because **Ship 1** will serve the observing needs for the atmospheric mesoscale experiment and will coordinate the sampling with the airplanes and the BCO site, **Ship 2** is required for the oceanic mesoscale eddy experiment; (ii) The ability to dedicate **Ship 2** to survey different oceanic conditions but in the same large-scale atmospheric environment allows to compare the influence of oceanic versus atmospheric variability; (iii) **Ship 2** will extend the upper air measurements so as to better constrain the large-scale state and better benchmark modelling studies.

Synergistic effects from a parallel operation of the two ships

The parallel execution of both ship-based experiments is crucial to maximizing the EUREC^{4}A++ experiment success. The sampling of atmospheric and oceanic data in parallel will allow characterization the atmospheric state, including boundary layer clouds, precipitation and the turbulent structure of the atmospheric, but likewise the oceanic boundary layers, in high resolution and thereby complementing the EUREC^{4}A modeling efforts. Making use of two ships leaving (or entering) Bridgetown at the same time, the cloud-evolution shall be investigated by parallel atmosphere/ocean observations in an upwind position to the BCO site reference station at the east coast of Barbados Island and combined with the aircraft campaigns. We will capture the boundary condition statistics and air mass movement in a very detailed way, but also assess the extent to which the structure of the upper ocean structure imprints itself on the atmosphere and vice-versa. From the ocean parallel observations of turbulence using microstructure probes in the upper 200m and hydrography and currents, the spatial variability of mixed layer instabilities (e.g. near inertial currents) will be investigated. The two ships will continue to operate in a concerted strategy – but with **Ship 1** focusing on the atmospheric mesoscale, in a strictly coordinated way with BCO and the aircraft campaigns, and **Ship 2** (this proposal) focusing on the mesoscale eddy realm, most likely to the south of the **Ship 1** operations area.

However, consequently the ship time requested here (**Ship 2**) requires being concurrent to **Ship 1** and the aircrafts operations, and in the period January 20th to February 20th, 2020. The length of the EUREC^{4}A++ field study is chosen with respect to the time-scale of synoptic variability (several days) so as to ensure sufficient sampling of different synoptic conditions and thereby allow the characterization in varying weather regimes, i.e., high-wind speed versus low wind speed, strong stability versus low stability, and most importantly, variability in the large-scale motion field that may or may-not be imprinted on the atmospheric and ocean state. It is one of the key objectives of the EUREC^{4}A++ field study to overcome the typical time/space sampling restrictions that had hampered previous campaigns, so as to assess the response of clouds to different large-scale conditions. Investigating the cloud response to vertical mixing, and recording benchmark data for a new generation of satellite sensing and coupled convection and ocean-eddy resolving models, makes EUREC^{4}A an opportunity that presents itself only once every few decades. This is true for the atmospheric mesoscale as well as for the oceanic mesoscale part of the experiment.

Implications of this proposal for granted ship time GPF 18-1_69, EUREC4A++ (Ship 1)

Based on the reviewers comments in GPF18-1_69 (Ship 1) their clear support for sampling the atmospheric mesoscale justified the approval of the proposal. The mesoscale ocean aspect was not well distinct in the last proposal. With the current proposal for a second ship (**Ship 2**) and a focus on the ocean mesoscale we are confident that the synergy but also the unique work on each of the two ships is now much clearer. For completeness we also mention here the implications of the current proposal for executing GPF18-1_69, EUREC4A++ (**Ship 1**). Namely, the chief scientist will be sole Stefan Kinne (MPI Meteorology Hamburg) and Johannes Karstensen (GEOMAR Kiel) will be chief scientists for the proposed cruise. Moreover, the physical oceanography observations on Ship 1 will be done by Jacek Piskozub (IOPAN, Sopot, Poland).

1.1 Applicants/Antragsteller

1.2 Topic / Thema

Air-sea interaction experiment across mesoscale ocean eddies in the western tropical Atlantic in the in context with the EUREC4A++ campaign

1.3 Label / Kennwort

The ocean mesoscale component in the EUREC4A++ field study

1.4 Discipline / Fachgebiet und Arbeitsrichtung

Discipline/Fachgebiet: Physical Oceanography, Meteorology, Biogeochemistry
Focus/Arbeitsrichtung: Mesoscale eddies, air-sea interaction, cloud formation and evolution, surface radiation budget, aerosols, physical and biogeochemical processes.

1.5 Period and equipment / Fahrtzeitraum und Großgeräte

- Working days and transit between stations: 32 days (synchronized with GPF 18-1_69)
- Mandatory timeframe: 20 January to 20 February 2020 (set by international EUREC4A++ experiment incl. research airplanes)
- Working area: 10°N-17°N, 54°-60°W
- Departure and arrival harbor: Bridgetown (Barbados); for logistics and experimental reasons to be coordinated with GPF 18-1_69; Point-a-Pitre (Guadeloupe) could be an alternative

- Large gear: ADCP, TSG, (underway)CTD, gliders, towed instruments, atmospheric profiling (leveled cloud radar, Raman-Lidar, ceilometer, wind lidar), atmospheric column properties via passive remote sensing (microwave radiometer, cloud cameras, sun-photometer), cloud in-situ sampling (cloud kites, radiosondes)

1.6 Summary / Zusammenfassung

Die beantragte Reise wird, als Teil der EUREC^{4}A++ Kampagne, einen Fokus auf die Ozean/Atmosphäre-Kopplung über mesoskaligen Ozeanwirbeln haben. Dazu sollen sowohl ozeanische wie atmosphärische Profilmessungen durchgeführt werden die Untersuchungen der Mechanismen der Wechselwirkung ermöglichen. Die lokale zeitliche Entwicklung der atmosphärischen wie ozeanischen Grenzschicht und deren Kopplung ist von vorrangigem Interesse. Das Experiment wird konzertiert mit einer bereits geförderten Kampagne (CPF 18-1_69; Flugzeuge und Landstation BCO) durchgeführt um eine quasi 4-D Abtastung der Atmosphäre zur Untersuchung von Wolken-Entwicklungen auf verschiedenen Raum- und Zeitskalen zu ermöglichen. Die ozeanische Mesoskala wird zeitlich und räumlich hochauflösend vom Schiff, aber parallel auch mit autonomen Glidern, vermessen. Die räumliche und zeitliche Entwicklung des oberen Ozeans, daran geknüpfte dynamische, bio-geochemische Prozesse und deren Wechselwirkung mit der Atmosphäre steht im Fokus der Untersuchungen. Die EUREC^{4}A^{++} Kampagnen stellen einen Datensatz in Aussicht, an dem die Modellentwicklung in der Passatwindregion vorangetrieben werden kann, sowohl zur Modellierung von Ozeanwirbeln als auch zur Modellierung atmosphärischer Konvektion. Die geplanten Schiffsmessungen sollten so Randbedingungen für die Modellierung schaffen. Das EUREC4A knüpft an die einflussreichen Ozean/Atmosphäre Schiffskampagnen ATEX und BOMBEX (beide 1969 unter Nutzung von 5 Schiffen) an - aber mit modernen Messmethoden (inkl. satellitengestützer Sensoren).

The requested ship time, which contributes to the EUREC4A++ campaign, will focus on the ocean / atmosphere coupling across mesoscale ocean vortices. For this purpose, both ocean and atmosphere profile measurements will be carried out, which allow investigating mechanisms of interaction between the two. The local temporal evolution of the atmospheric and oceanic boundary layer and their coupling is of primary interest. The experiment will be carried out in concert with an already funded campaign (CPF 18-1_69, airplanes and land station BCO) and a quasi 4-D sampling of the atmosphere is achieved. The data will provide the base for investigating cloud evolution over a full life-cycle. The oceanic mesoscale is measured in time and space with high resolution from the ship, but in parallel with autonomous gliders. The spatial and temporal development of the upper ocean is linked to dynamic, biogeochemical processes and their interaction with the atmosphere. The EUREC4A++ campaigns are promising a dataset to advance model development in the trade winds region, both for modeling ocean vortices and for modeling atmospheric convection. The planned ship measurements should thus create boundary conditions for the modeling. The EUREC4A builds on the influential ocean / atmosphere ship campaigns ATEX and BOMBEX (both in 1969 using 5 vessels) - but with modern measurement methods (including satellite-based sensors).

2. Scientific background, previous work/Stand der Forschung, eigene Vorarbeiten

2.1 Scientific background / Stand der Forschung

The atmosphere and ocean drive processes in one another through air-sea interaction mechanisms – primarily mixing in turbulent boundary layers. On the atmospheric side liquid clouds of a few thousand meters or less in depth mix the lower atmosphere (shallow convection). The warm cloud types dominate coverage of the ocean strongly influence weather on seasonal to sub-seasonal time scales, and are crucial in determining the response of climate models to warming, and hence quantities such as the equilibrium climate sensitivity. 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 atmospheric circulations that organize the shallow convection, producing a large range of cloud morphologies that affect radiative fluxes and possibly precipitation at the surface.

Through its ability to link patterns of cloudiness to the large-scale and ocean-mesoscale environment EUREC4A++ promises to be the most significant field study of the trades ever. The EUREC4A experiment (Bony, Stevens and Co-authors 2017) has been conceived to test the leading hypothesis for a strong cloud feedback on radiative forcing. The cloud-base cloud fraction is closely coupled to vertical mixing, both by large-scale motions and through convective mass transport. A yet more ambitious effort to build on the EUREC4A measurements, through what we call EUREC4A^{++}, will 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. EUREC4A^{++} will also advance our understanding of the ocean, including ocean biogeochemical and biological processes, in its own right.

Clouds & radiation budget

The availability of complementary and also redundant data will advance our understanding of important processes for clouds and should improve to representation of clouds in modeling. One of the challenging questions is: Under what conditions occurs the breakup of strato-culmulus (Sc) decks? Stratocumulus cloud decks are quite frequent in the trade wind region (Wood 2012). They form over the colder water near the west-African coast and transported by the trade winds westwards over warmer ocean-waters and after a few days start to break up. Certainly the change in sea-surface temperature is an influential factor but also others factors including aerosol may be important (Stevens and Feingold 2009). In particular in spring the cloud character is dominated by short-lived trade-wind cumulus clouds. The clouds and their environment have been observed at the MPI-Met station BCO at the east coast of Barbados uses active remote sensing (by radar and lidar) to probe (arriving) atmospheric structures (e.g. cloud, precipitation, aerosol and water vapor) (Stevens et al. 2016). However, concurrent ship based observational campaigns that complement the BCO observations over the life-cycle of clouds have never been acquired but are a focus of this proposal.

The combination of surface radiation budget and atmospheric condition measurements is performed in a nearly operational manner for more than 17 years in the *Atmospheric Radiation Measurement* (ARM) Programme (e.g. Ackerman and Stokes 2003). The radiation data are organized in the *Baseline Surface Radiation Network* (BSRN). All ARM stations are land-based with few island-stations assumed to be representative for the marine atmospheric character. Over the vast ocean areas little information exists concerning the state of the cloudy atmosphere and the resulting energy budget at the surface. The technological development in remote sensing allows for passive microwave radiometry and active lidar remote sensing under marine conditions. Weather proved sky imagers enable the continuous observation of cloud cover and cloud type and have been proven very valuable for the interpretation of specific radiation scenarios. These modern observing assets will be used concurrently on the ships and accompanying platforms (BCO; aircrafts).

The cloud evolution/life-cycle and the ocean mesoscale experiments will complement the more atmosphere oriented measurements of Ship 1 and will allow to quantify the state of and processes within the upper ocean, the effects of ocean spatial variability, and the role of ocean eddies on air-sea interaction. Trivially, but crucially, it increases the sampling of important aspects of the lower atmosphere, including air-sea sensible and latent heat fluxes, precipitation, cloud base height and boundary layer properties (Vial et al. 2017). It doubles the microphysical sampling of clouds so as to better constrain aerosol-cloud interactions in a well-constrained large-scale area. Less trivially, by maintaining adequate separation from Ship 1 and the BCO it also greatly expands the upper air measurements, which will be crucial for obtaining the best possible analyses, also on the convective scale, thus enabling coordination and better links with meteorological and hydrological services (strong connections between EUREC^{4}A and the ECMWF and DWD are already established).

Ocean Mixed and Barrier layer

The oceanic mixed layer (ML) is the turbulent boundary layer of the ocean, but the variety of instabilities arising from the ocean meso and submeso-scale makes it a rich source of phenomena that interact with the atmospheric boundary layer. Shallow atmospheric convection influences SSTs, but this process is strongly influenced by SST itself. Air-sea heat-, freshwater-, and momentum-fluxes are mediated by processes within the ML. Likewise, spatial gradients in ocean properties are important drivers of motion in the atmosphere (Lindzen and Nigam, 1987, Naumann et al., 2017). Oceanic processes on short timescales (e.g. diurnal cycle, near-inertial waves) can immediately influence the lower atmosphere but likewise (and much more known) impact the atmosphere on longer - seasonal to interannual - time scales.

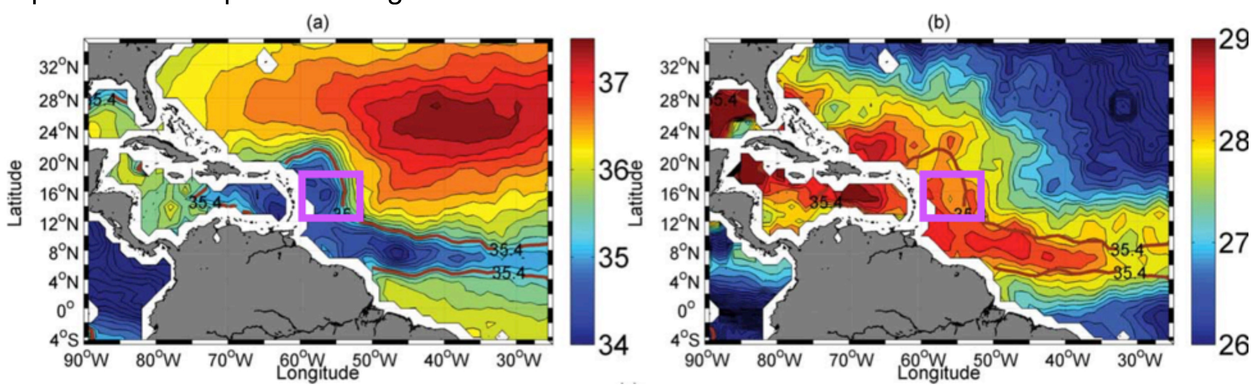

***Figure 1** Mean sea surface salinity (a) and sea-surface temperature (b) in the western tropical North Atlantic. The thick contour delineating the Amazon River plume extend (merged with the low salinity waters from the ITCZ towards the east) as defined by Reul et al. (2014). The magenta square indicates the region of the EUREC4A++ experiment.*

In the western tropical Atlantic (including the EUREC4A^{++} region) the discharge from the Amazon and Orinoco Rivers is easily identified in surface salinity pattern (Figure 1). These two rivers account for ~18% of all riverine input to the oceans. The freshwater influence extends far from the coast and can reach the French West Indies (Coles et al. 2013). In regions of high fresh water input where the uniform density mixed layer becomes shallower than the uniform temperature, the region between the base of the mixed layer and the base of the isothermal layer is defined as the ocean barrier layer (OBL) as it acts as a “barrier” to entrainment cooling and vertical mixing (e.g. Sprintall and Tomczak, 1992).. OBLs also decouple the ocean mixed layer from momentum fluxes and drive subsurface warming through facilitating the penetration of short wave radiation to the base of the OBL and inhibiting cooling from below. In fact, Foltz and McPhaden (2009) found that seasonal variations in OBL thickness in the central tropical North Atlantic exert a considerable influence on SSTs through the modulation of vertical heat flux at the base of the mixed layer. 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 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), 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.

Mesoscale eddies

Mesoscale features, such as eddies and fronts, can create local hot spots of anomalous air-sea interaction (e.g. Villas Bôas et al. 2015; Frenger et al. 2013). Eddies are ubiquitous in the ocean (Chelton et al., 2011). 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; Villa Boas et al. 2015, Ma et al. 2016).

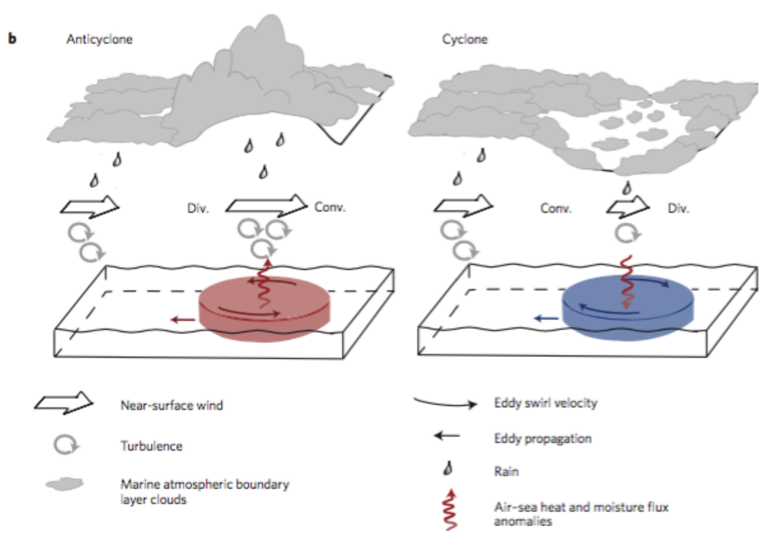

Figure 2: *Schematic summarizing the impact of oceanic eddies on the lower atmosphere for a Southern Hemispheric warm-core anticyclone (red, left) and a cold-core cyclone (blue, right). Div., wind divergence; conv., wind convergence. (From Frenger et al. 2013)*

While mesoscale eddies are often associated with SST anomalies, the regional OBL hotspots in the working area proposed here are efficient heat and humidity sources for the atmosphere, but also drive anomalous winds and patterns of shallow circulation which are thought to influence cloudiness and the preconditioning of the atmosphere for deeper convection. 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, for instance in dissipating or amplifying eddy properties, is still poorly known and the proposed experiment will provide valuable data needed to understand and describe the feedback mechanisms.

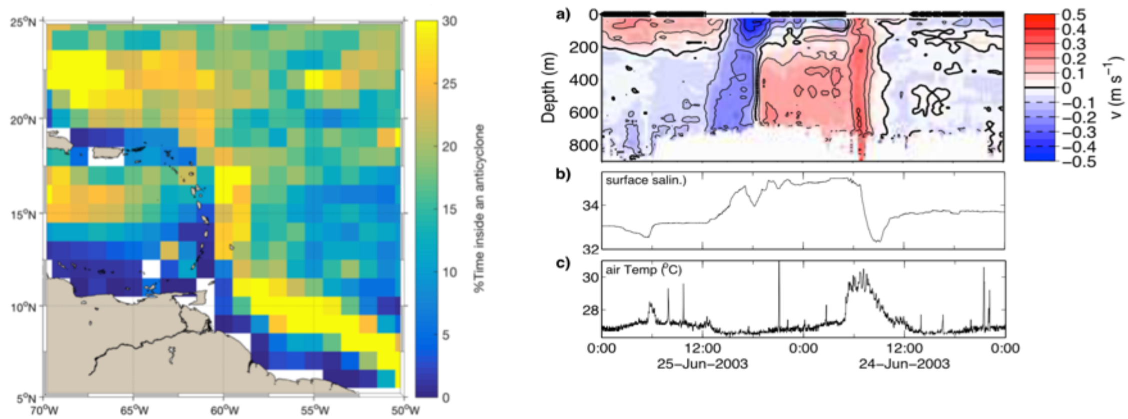

Figure 3: *(left) Long term mean anticyclonic eddy occurrence (1993-2016) in the EUREC4A++ region based on satellite sea-level anomaly data analysis (after Laxenaire et al. submitted). (right) Two days RV SONNE (SO172) ship survey through a North Brazil Current Ring west of Barbados (ship was going east to west, time axis is reversed for clarity). a) Meridional current section (triangles at 0 m denote ship was stationary), (b) sea surface salinity (psu), and c) air temperature (Boney et al. 2017).*

In the tropical Atlantic, a wide range of different eddies occur (Chelton et al. 2009; Laxenaire et al. submitted). In the proposed survey region in particular the North Brazil Rings are most frequently observed (Johns, 2003; Dengler et al., 2004; Laxenaire et al. submitted Fig. 3, left). Individual ship surveys (Figure 3, right panel) revealed that SSS anomalies in these eddies are aligned (in timing) with air (and sea-surface, not shown) temperature anomalies. The coupling of the atmosphere to the ocean under such varying SST (and SSS) conditions likely influences cloud cover and cloud properties (following the scheme Fig. 2). Moreover, the rather abrupt change in SST can lead to abrupt changes in surface coupling by influencing near surface stability. This leads to large changes in surface fluxes, and also momentum transport, and has been hypothesized to influence atmospheric convergence, cloudiness, and perhaps also trigger precipitation

From dedicated ship and glider studies in the eastern tropical Atlantic we could show that also in the tropical ocean mesoscale eddies often preserve sea surface temperature (SST) and salinity (SSS) anomalies over extended periods of time (months, e.g. Schütte et al. 2016). This is possibly related to submesocale processes, in particular near-inertial internal waves, which are part of the eddies' dynamical regime (Karstensen et al. 2017; Pietri & Karstensen 2018).

Biogeochemistry

Dinitrogen (N_2) fixation is globally the largest source of 'new' nitrogen (N) to the ocean and controls ocean productivity on time scales of ocean circulation, and therefore is crucial to the strength of the biological carbon pump, i.e. the sequestration of CO_2 into the ocean. While not limited by N, N_2 fixation itself can be limited by the availability of phosphorus (P) and/or iron (Fe). These nutrients (P and Fe) are delivered to the ocean by various routes including riverine input. The riverine input by the Amazon & Orinoco discharge harbor specific groups of N_2-fixing microorganisms (diazotrophs), namely the diatom-diazotroph associations (DDAs) (Subramaniam et al. 2008, Foster et al. 2007) and the unicellular cyanobacterium group A (UCYN-A) (Martínez-Pérez et al. 2016) into the ocean. Both groups, DDAs and UCYN-A, are symbiotic associations of cyanobacteria with a eukaryotic, phototrophic host. Both symbiotic associations have been observed in several oceanic regions but seem at particularly high abundance in the waters with riverine origin.

However, whether the mesohaline waters (or any of its characteristic nutrients) are a specific factor determining the distribution and/or activity of DDAs and UCYN-A, both major N_2 fixers in the ocean, is currently not known. This is partially due to a lack in spatial and temporal resolution of measurements done until today, particularly across mesoscale features. The Western tropical North Atlantic is also a region of relatively high primary production considering the oligotrophy of the water masses. This productivity is likely the result of i) the riverine influence and ii) a high turnover of the newly produced material, *i.e.* remineralization. During remineralization, organic nitrogen and ammonium are released into the water column. The released N can either be taken up directly or be nitrified to nitrite and subsequently to nitrate by specialized organisms. The extent of nitrification in these waters could in part determine what kind of organisms can grow and interact with each other since (nearly) all organisms can use ammonium but not all organisms can use nitrite or nitrate as an N source. However, the intensity and importance of nitrification in the oligotrophic, tropical surface waters is currently not well understood.

The exchange of carbon dioxide between the atmosphere and the ocean is driven by their CO_2 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. In the high latitude ocean, e.g., mixing of poleward flowing warm water masses with cool and nutrient rich subpolar waters enhances both the solubility effect and biological drawdown of CO_2, leading to a negative CO_2 gradient between the ocean and the atmosphere resulting in a strong air-to-sea CO_2 flux. In contrast in the oceanic upwelling zones carbon rich subsurface water reaches the ocean surface resulting in a positive CO2 gradient between the spheres and a carbon flux from the ocean to the atmosphere.

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 transport of water masses, 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 sea surface temperature, sea surface salinity, surface net productivity (biological CO_2 drawdown), surface wind and surface air pressure, while systematically navigating through a mesoscale ocean eddy.

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. The results will present a leap forward in our understanding regarding the processes driving the air-sea CO_2 flux variability regionally, resulting in improved regional carbon budgets. Furthermore, the results and the obtained process understanding will be highly valuable for future generations of Earth System Models that aim to resolve mesoscale processes.

2.2 Previous work / Eigene Vorarbeiten

Drs. J. Karstensen and M. Dengler are Physical Oceanographers with a focus on experimental work using autonomous and ship based observations.

Dr. J. Karstensen was a lead PI on the "Eddy Hunt Project" in 2014, an interdisciplinary study partly financed by the Cluster of Excellence "The Future Ocean" in Kiel. The exciting results of this study revealed both unexpected and partly spectacular results and led to many publications (e.g., *Biogeosciences* special issue, www.biogeosciences.net/special_issue213.html) and the development of the REEBUS project idea. Examples of highlights of the study of this particular eddy are (Fiedler et al. 2016, Fischer et al. 2016, Grundle et al. 2017; Hauss et al. 2016, Karstensen et al. 2015, 2017, Löscher et al. 2016, Romero et al. 2016, Schütte et al. 2016).
The research of Dr. M. Dengler focused on investigating physical processes related to mixing in the ocean and their implication for biogeochemical processes (e.g. Dengler and Quadfasel, 2002; Schafstall et al. 2010; Kock et al. 2012; Hummels et al. 2013; Sandel et al., 2015; Thomsen et al., 2016; Rovelli et al., 2016). He is an expert on measuring ocean turbulence from shipboard and autonomous platforms using microstructure sensors and fine-scale observations. He was or is a PI in SOPRAN, SFB 754 and EU-PREFACE focusing on the interaction of physical and biogeochemical processes and their impact on climate variability
Drs. Karstensen and Dengler are PIs on the BMBF funded project REEBUS, an experimental study on mesoscale eddies physics and coupling with biogeochemical processes, which will be carries out in Winter 2019/2020 in the eastern tropical Atlantic.

The EUREC4A campaign builds on the US lead RICO (Rain in Cumulus over the Ocean) campaign [https://www.eol.ucar.edu/field_projects/rico] the end of 2004 in the Caribic, where Bjorn Stevens (then at UCLA) already participated as PI. The campaign produced many reference data-sets for subsequent LES-simulations of atmospheric convection. This representation of convection in climate modeling is still a limiting element and the major research of the atmospheric department at the Max Planck Institute for Meteorology. Eurec4a with more advanced and capable instrumentation on airplanes as well as on ground (in particular via observations from ship and via new satellite remote sensing capabilities from space is expected to complement the modeling efforts with needed observational constrains.

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2.3 national and international cooperation / Nationale und Internationale Einbindung

The ship request is for participation in EUREC4A, a major multi-national campaign in the western Atlantic. EUREC4A, which is described extensively by Bony, Stevens and Co-Authors (2017), is a flagship field study of the World Climate Research Programme's Grand Science Challenge on *Clouds, Circulation and Climate*. It is co-led by B. Stevens of the MPI for Meteorology in Hamburg and has strong participation from the German atmospheric research community, with groups from the Universities in Hamburg, Leipzig, Cologne and Munich all involved. Additionally extra-university research institutes, including four Max Planck Institutes (Hamburg, Bremen, Göttingen and Mainz), as well as DWD DLR, GEOMAR and TROPOS and international (French, Dutch, US, UK and Polish) partners will contribute to taking observations (by contributing with instruments and staff) as well as performing coordinated modeling (by providing near-real-time modeling [i.e. in the framework of $HD(CP)^2$ modeling] or by applying and analyzing the measurements in studies to improve processes understanding and sub-grid parameterizations in modeling [i.e. DWD sponsored HErZ cooperation with MPI-M]).

EUREC4A^{++} field program will be centered around a month of flight operations by the German HALO and the French ATR-42 aircraft, whose flight-hours have been secured (via German MPG funds and a French ERC Advanced Grant) for a pre-determined time period (20 January to 20 February, 2020), so that the timing of this ship request is essential. HALO aircraft can reach higher altitudes and will to survey the lower stratusphere with its remote sensing package and extensive dropsonde releases. The ATR-42 aircraft will fly in the lower troposphere, mostly just above cloud base, and complement the HALO measurements with in-situ and active remote sensor (lidar and radar) sampling in and near lower altitude (trade-wind) clouds. The requested ships are planned to be part of a small flotilla that is planned to include one to four additional ships (even only for different subsets of the aircraft sampling time-period) from other nations (ship proposals are pending in France, Holland, Spain and the US). The here proposed coordinated measurements with the R.V. Maria S. Merian (Ship 2) and R.V. Meteor (Ship 1; GPF 18-1_69) will establish a strong German contribution to EUREC4A++ by forming the nucleus, with the Barbados Cloud Observatory (BCO), of the surface based measurement network. Each of the two 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). The satellite data offer also necessary information as to spatial context, thus a strong involvement not only by modeling but also by satellite retrieval capabilities will be sought during (for day-to-day planning) and after (for subsequent data-analysis) the campaign. Additional aircraft proposals that want ot join the experienmt has been send out (FAAM aircraft via Unveristy Leeds in a EUREC4A-UK context) and the P3 aircraft (with wind and water vapor lidars on board) to NASA (US).

3. Goals and Schedule / Ziele und Arbeitsprogramm

3.1 Goals

Three overarching goals are defined for the proposed cruise: (1) observing the life-cycle of clouds (a concerted effort with Ship 1, BCO, aircrafts); (2) observing the evolution of the lower atmospheric, considering the ocean underneath; (3) local observations of atmosphere and ocean on the oceanic mesoscale. All three are contributions to the scientific goal of the whole EUREC^{4}A^{++} campaign which is to assemble quality atmospheric and associated oceanic data, to capture statistics and relationships among different atmospheric properties as well as between atmospheric and oceanic properties on time scales of hours (diurnal cycle) to weeks and spatial scales of 100s' meters to the atmospheric mesoscale. The data is used to develop a much better process understanding of cloud formation and evolution (life-cycle) and air-sea interaction processes – including secondary coupling to air-sea gas exchange and marine particle (e.g. amines). The data will also be used to primarily to constrain and evaluate modeling efforts operating at very high resolution.

Atmospheric dynamics, in particular the stability of the boundary layer, are key processes in this context. From the ocean side, SST anomalies are important control parameters for interaction with the atmosphere. The origin of SST anomalies could be local warming (e.g. associated with OBL, downwelling, or advection of heat anomalies) or cooling (e.g. by upwelling of subsurface waters). In particular oceanic mesoscale features such as eddies and fronts, can cause local up- or downwelling and thus SST anomalies. Ocean eddies provide a kind of laboratory to study how ocean variability influences mesoscale processes in the atmosphere, and differences among eddies in similar atmospheric conditions may serve as proxies for atmosphere ocean interactions over deeper versus shallower mixed layers.

Sustaining and creating SST (and to a certain degree also SSS) anomalies in mesoscale eddies is linked to sub-mesoscale dynamics. Mixed layer instabilities, entrainment fluxes across the mixed layer base, and entrainment and vertical fluxes at the eddy rim (transition between eddy and surrounding waters). Near-inertial waves (NIW) play a crucial role in this context and a set of goals of the proposed expedition are linked to NIW generation and propagation. With the two ships operating in parallel but embedded in the EUREC4A modeling efforts, the spatial scales of wind variability can be determined and the oceans response measured, including the decay time of near-inertial currents. The NIW period in the region ranges from from 46h at 15°N to 69h at 10°N, while and the damping time scales of NIW currents are thought to be about 5 to 7 days. At least two full NIW events should be surveyed in the open ocean (in concert with **Ship 1**). In addition NIW/NI currents interaction with mesoscale eddies are another survey goal. The potential role of the material surface that is rotating and wind stress fluctuation will also be considered in the experiment.

Less directly, the ocean also influences the atmosphere through particulate emissions and its role in mediating the transfer of trace gases. On long time scales the role of biology in influencing air-sea gas exchange influences the ability of the ocean to take up atmospheric carbon-dioxide, the behavior of micro-organisms is key to understanding the Nitrogen isotopic record. Mesoscale eddies in the region, for instance North Brazil Current Rings, often carry signals from the Amazon/Orinoco river which in turn impact nutrient and carbon chemistry. Analysis of oxygen isotopes (δ^{18}O) will be used to quantify the riverine water contribution.

Key atmospheric measurements of **Ship 1** will also be sampled on **Ship 2**. Continuous atmospheric profiling will be done with active remote sensing (radar and ceilometer) and passive remote sensing (microwave, rain radar, sun-photometer) to capture the statistics (variability and average) of the structure and microphysical properties of clouds and their environment (temperature, aerosol, water, rain) to investigate how cloud properties are influenced by the environment, including the properties of ocean and ocean surface. The atmospheric monitoring is supplemented by regular scheduled radiosondes launches and a novel setup to more frequently profile detail in the atmospheric boundary layer and in lower altitude clouds with a tethered balloon (a cloudkite). The main objective of Cloudkite measurements is to better understand the role of turbulence in formation and evolution of clouds. To achieve this, the instrument box onboard the

Cloudkite includes a verity of sensor and instruments that are able to measure both cloud microphysics (e.g. droplet size distribution) and turbulence. The main strength of the Cloudkite design is that the instruments are aligned/oriented such that their probing volumes have maximum overlapping. This makes it possible to fully resolve the coupling between cloud microphysics and turbulence. In addition, Cloudkite measurements can shed light on the impact of turbulence on spatial distribution of drops (e.g. existence of clustering, local drop concentrations), which is central to understanding of rain initiation, cloud evolution and radiative features. In order to establish statistically sound process understanding and data testbeds for atmospheric and oceanic properties sufficiently long sampling periods (weeks) are needed.

Specifically the proposed expedition addresses:

- Provide spatially and temporally resolved measurements of the upper ocean (upper 1000m) covering the diurnal cycle up to several days (inertial) periods.
- Investigate ocean-atmoshere coupling due to meso- and submesoscale SST and SSS variability in ocean eddies including diapycnal mixing processes and the roll of ocean barrier layers.
- Characterize the influence of ocean mesoscale eddies on air-sea gas exchange, and the atmospheric state (cloudiness, momentum transport)
- Study ocean biological processes that influence biogeochemical trace-gas exchanges
- Study the temporal evolution of ocean mesoscale eddies
- Document the role of sub-mesoscale processes in the evolution of the ocean mixed layer in situations with varying winds (strength, direction)
- Capture the structure and lifetime of low altitude (trade-wind cumulus) clouds and influences of the environment are these properties
- Capture the statistics of clouds and environment, including lower boundaries such as ocean properties, atmospheric state, vertical velocities and aerosol (to serve as cloud nuclei)
- Study spatial and temporal variability of N_2 fixation and the responsible organisms at the oceanic mesoscale
- Measure primary production and nitrification rates as proxies for the overall productivity and N turnover, which are crucial parameters in the biological carbon pump, *i.e.* the in-ocean CO_2 flux but on the oceanic mesoscale
- Determine net productivity of surface waters to constrain net uptake of CO_2 by biological processes in relation to eddy-driven nutrient availability
- Determine the dilution of Amazon & Orinoco catchment precipitation via oxygen isotope ($\delta^{18}O$)

3.2 Work Program

3.2.1 Working Area and details work plan

The working area of Ship 2 is in the region from 10°N-14°N/54°-60°W (Figure 4). The region has been chosen as a pristine marine background to probe trade-wind cumulus clouds and their environment but likewise to probe an environment prone to the occurrence of ocean mesoscale structure, in particular eddies. The proposed cruise is separated in two experimental parts (cloud evolution & mesoscale eddy experiment, Figure 4) and the respective work plan is outlined in detail below. The ocean/atmosphere processes that are investigated set the time and space scales for the experiments and the way the ships (along with other observing infrastructure) is used.

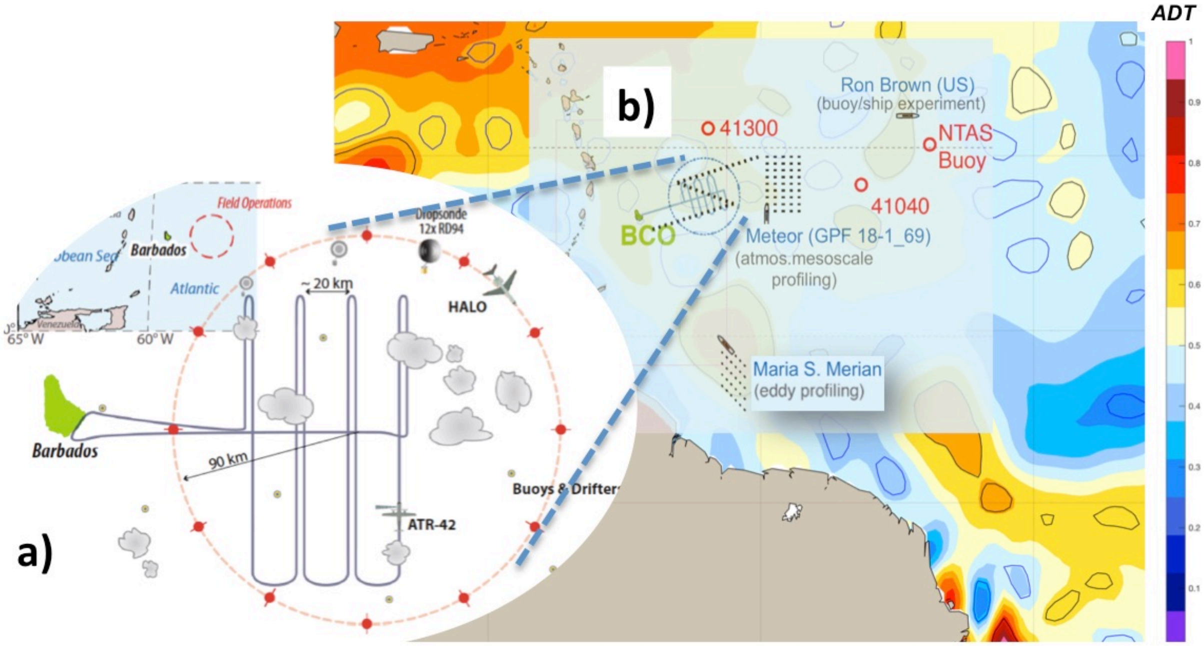

__Figure 4:__ Overview of proposed ship operations in the western Atlantic, east of Barbados in connection with EUREC4A (Boney at al. 2017). __a) Cloud evolution experiment__ where Meteor (Ship 1) and Maria S. Merian (Ship 2) will record at different distances in the circle that shows the planned aircraft surveys. __b)__ Absolute Dynamic Topography (ADT; 31. Jan. 2015) with eddy signatures (NBC Rings; indicated by red circular structures in the southern part of the region). The __Mesoscale eddy experime__nt across selected NBC Rings (shown for reference only) by Maria S Merian is indicated. Operation area of US ship (proposed) near NTAS mooring is shown for completeness.

Work plan "Cloud evolution/life-time stages experiment":

This two-ship coordinated experiment will be an important component of the EUREC4A++ experimental part on cloud dynamics/life-cycle studies. As such different time/space scales sampling are needed and can only be achieved operating two ships in a concerted way which is also aligned with the aircraft sampling. For intermediate (atmospheric) scales the two German research vessels will align at different distances in the wind-direction to survey the cloud lifetime cycle and cloud processing. CloudKites (one on each ship) and all other atmosphere measurements will be operated. In order to achieve statistically significant results, the two ship concerted observing effort is executed over a period of one week (synoptic scale in the region; see ATEX/BOMBEX design). This design includes also the surface sampling at Barbados (BCO) and the aircrafts – for a nested survey on large/regional atmospheric scales. The aircraft sample a circular arrangement around BCO in order to capture the boundary conditions and mass transport within the circle, while the ships provide a local focus/small scale experimental design. During the two-ship experiment we will also perform oceanic in-situ sampling. One is a near-inertial current experiment. On both ships we will record synchronized microstructure measurements to measure ocean turbulence in the upper 200m, record upper-ocean velocities using the ship-board ADCPs (75kHz and 38kHz) for vertical shear determination, and observe with XBTs (Deep Blue; 700m) on Ship 1 (GPF 18-1_69) and with an underway CTD system on Ship 2 (this proposal) the evolution of the upper layer over selected diurnal cycles. The observations will be aligned to possible wind stress variability events that may initiate near-inertial currents/waves. Later analysis of air-craft sampling will reveal the existence and possibly the evolution of associated SST anomalies and subsequent air-sea flux feedbacks.

It is assumed that both ships will start from the same port (Bridgetown) and steam out east, against the wind – thus sampling the low-level wind air trajectories towards BCO. An inter-calibration of instruments installed on both ships (e.g. atmospheric profiling and in-situ sampling) will be done. After approaching the operational area for Ship 1 (13-15°N / 54-56°W; GPF 18-1_69) the cloud evolution experiments is initiated. Both ships will steam in different directions allowing estimating decorrelations scales of the atmospheric profiles. Subsequently both ship are aligned along the wind-direction for simultaneous sampling at different distances (possible positioned such that also sampling by BCO and/or aircraft) occurs in the same direction.

Work plan "Oceanic Mesoscale experiment":

The proposed second experiment aims to carry out a detailed high-resolution, multi-parameter study of individual eddies and their signatures in the ocean and the overlying atmosphere. This experiment has multidisciplinary components. The ambitious eddy study follows an approach demonstrated most successfully during the 2014 "Eddy Hunt Project" and also applied in the BMBF REEBUS campaigns in the eastern tropical Atlantic (most likely RV Meteor). Using refined and proven automated detection methods employing remote sensing products (sea level anomaly, microwave sea surface temperature, ocean color) an early detection of eddies will be possible during the months preceding the proposed cruise.

Eddies will be sampled by shipboard observations and by autonomous gliders. In all eddies it is expected that the largest gradients of the mesoscale eddy are located just beneath the mixed layer at a depth of approx. 100 m, while intense sub-mesoscale activity is expected in the surface layer and underneath the eddy core (approx. 1000 m). Special attention will be given to the rim of the eddy where strong vertical sub-mesoscale motion may be concentrated in sharp fronts at the surface connecting matter exchange with the mesoscale top cap and core. Elucidating these contrasting roles by connecting the large range of relevant scales is a major and novel aim of the study.

The general concept of the study of an individual eddy will start with a detailed survey of mesoscale properties of the eddy with a horizontal scale of approx. 200 km. This includes the current field in the upper 1200 m as well as physical and a suite of biogeochemical properties at the surface and in the upper 1200 m of the water column. On the basis of this survey and with the aid of remote sensing information of temperature, currents and ocean color information from an airplane, the exact locations of the sub-mesoscale studies will be determined. We plan two focus areas for these studies: (i) Eddy centre with sub-surface core, and (ii) frontal zone at rim of the eddy. Both sub-mesoscale studies will feature a large range of observational techniques, which will be deployed in a concerted way. We will here applied ship will sample an eddy over at least two full local inertial periods, which are in the range of 46h (at 15°N) and 69h (at 10°N).

Cloud evolution/life time survey:

- Concerted atmospheric observations with Ship 1, BCO and airplanes:
  - Cloudkite measurements is to better understand the role of turbulence in formation and evolution of clouds

- Concerted ocean observations with Ship1
  - Underway vessel-mounted ADCP (VMADCP) survey of currents;
  - Underway surface seawater sampling for continuous analysis of hydrographic properties (T, S);

  - Hydrographic CTD and discrete water sampling for chemical and biological parameters;
  - Survey of microstructure and turbulence with free-falling microstructure profiler

Ocean Mesoscale experiment:

- Underway vessel-mounted ADCP (VMADCP) mapping of eddy currents;
- Underway surface seawater sampling for continuous analysis of hydrographic properties (T, S);
- Hydrographic (CTD-O_2) and discrete water sampling for chemical and biological parameters;
- Deployment of Slocum gliders with T,S, optical sensors and microstructure (submesoscale resolution) in eddy core and at eddy rim.
- Survey of microstructure and turbulence using free-falling microstructure profiler from ship;

In the following, we provide a brief description of the scientific contributions and observational approaches of the partners and their working groups involved in this study:

CTD-O_2 water sampling rosette (CTD/RO): The mesoscale CTD/RO hydrographic survey will be carried out along two x-shaped transects. Profiling and water sampling will be performed using a Seabird 911+ system mounted to a rosette with 24 bottles. The CTD-O_2 has a double sensor configuration and in addition a fluorescence and PAR sensor. A backup system will be on board during the cruise.

Underway-CTD: An Oceanscience Underway CTD will be used to acquire research grade CTD profiles while underway at full cruising speed. The freefall profiler offers vertical profiles from a moving platform. Its deployment winch and re-spooling mechanism allows the probe to be recovered and re-launched time after time without needing to stop or slow down the vessel. CTD section can thus be acquired in a time-efficient manner and at excellent spatial resolution.

Velocity observations: Shipboard observations of current velocity will be carried out continuously throughout the cruise by shipboard Acoustic Doppler Current Profiler (ADCP). R/V Meteor is equipped with 38 kHz and 75 kHz Ocean Surveyors that allow measurement of current velocity in the upper 1200 m of the water column.

Shipboard microstructure observations: **A** ship-board microstructure measurement system (MSS) will be used to quantify turbulence in the water column during the mesoscale eddy survey and during the submesoscale process studies. The profiler samples microstructure shear and temperature, oxygen (response time of 0.3s) and turbidity, and is equipped with standard CTD sensors. Two to five microstructure profiles will be collected prior to or following CTD/RO stations to determine diapycnal fluxes of oxygen, nutrients, trace gases and other chemical and biological parameters.

Glider observations: To survey sub-mesoscale features, Slocum gliders capable of autonomously measuring temperature, salinity, depth, oxygen, chlorophyll, and turbidity will be employed. The gliders will each have additional sensors mounted on the gliders top. One glider will be equipped with a nitrate sensor (SUNA – submersible ultraviolet nitrate analyzer, Satlantic) while the second glider will be equipped with a microstructure probe (MicroRider, Rockland Scientific) featuring two shear sensors and two fast temperature sensors. Glider-based turbulence measurements have the distinct advantage that they are capable of quantifying near-surface mixed layer turbulence, opposed to the traditional vertical profilers that are deployed from the vessel. One of the deep gliders will also be equipped with an ADCP for quantifying currents, and vertical current shear. This glider will conduct large-scale surveys to identify mixing mechanisms within the eddies. The gliders will also be tasked with measuring chlorophyll concentrations and optical backscatter.

Discrete water sampling: On all CTD-O_2 stations, water samples from the upper 1200 m will be analysed for nutrient content (NO_3^-, NO_2^-, NH_4^+, PO_4^{3-}) employ proven wet-chemistry methods. Salinity and oxygen analysis will be used to calibrate the CTD sensors. The CTD-O_2 transects across the eddy will be extended well beyond the frontal zone to allow eddy waters to be contrasted with the background situation outside the eddy.

pumpCTD: The pumpCTD system will be used to obtain high-resolution nutrient profiles in the upper ~250 m and net productivity measurements (O_2/Ar ratios) using a continuous flow membrane inlet mass spectrometer (Kaiser et al. 2005) coupled to the pumpCTD. Nutrient concentrations will be assessed as described above. Nutrient concentrations and O_2/Ar ratios can then be used in combination with the physical structure to obtain nutrient fluxes and net O_2/CO_2 fluxes, based on biological productivity, across mesoscale features.

Biological measurements: N_2 fixation, nitrification and primary production measurements complementary to measurements on ship 1 to cover larger spatial variability and across mesoscale/eddy features for smaller-scale variability. Measurements are complementary to net productivity and nutrient measurements from the pumpCTD.

Cloudkite: Cloudkite is a tethered 250 m^3 helium-filled balloon-kite combination aerostat (i.e. Helikite: 15 m long, 10 m wide/high) for atmospheric instruments with a net payload of 50 kg when operating at an altitude of 1 km above the ship. It is designed for simultaneous acquisition of cloud-microphysics and cloud/atmospheric turbulence. In particular, the payload for the propsoed campaign includes instruments to detect cloud particle size, shape, and spatial distributions; quantify aerosol concentrations, especially CCN; and the atmospheric state (turbulence, temperature, and humidity). The data acquisition per launch includes less than an hour for imaging instruments and a few hours for non-imaging instruments. It will be used to sample the atmospheric boundary layer and the lowest layers of trade wind cumulus clouds.

cloud radar / microwave / ceilometer / cloud camera: The combination of these instruments provide detailed information of clouds (above). A 94 GHz cloud radar provides cloud structural information (e.g. vertical dimension, density, freezing level), a microwave determines the water content, the ceilometer offers a more accurate cloudbase altitude estimate and a thermal cloud camera extends spatial coverage. Cloud detail statistics is complement by similar measurements on other ships and at the BCO site.

Radiosondes: frequent radiosondes complement cloud-kite data on atmospheric state with higher altitude data (up into the stratosphere). Radiosonde launches on this ship are complemented by radiosondes launches on other ships and at the BCO site as well as dropsondes (from the air-planes) so that larger scale vertical movements of atmospheric can be derived.

Distrometer / rain gages: these instruments measure the precipitation that reaches the ground. As precipitation is extremely sparse many samples, much more than can be sampled during

EUREC4A++, are needed for reliable statistics. Still events with precipitation in terms of clouds and environmental properties are of interest.

Sun-photometer: sun-photometer measure the atmospheric solar attenuation at well chosen solar spectral wavelengths to provide information on water vapor, on aerosol column amount and on typical aerosol size. These direct measurements are highly accurate and used to calibrate satellite retrievals and aerosol properties in global models, which in turn offer regional context.

Broadband Radiation Downwelling broadband solar and infrared measurements, which provide combined information on atmospheric properties, are already part of the standard equipment onboard and certainly will be used in the data-analysis

Atmospheric state data: the standard ship instrumentation monitors air and ocean temperature, humidity and wind, which will be included in the data-analysis

3.2.2 National operation / Arbeiten in Hoheitsgebieten anderer Nationen

Operations may take place inside the EEZ (outside 12nm) of Barbados and eventually Trinidad & Tobago and Guyana. Maybe one country will send an observer on board the ship

3.2.3 Deployment of heavy equipment/Einsatz von Geräten

CTD rosette for water sampling (24 bottles) and at station profiling (temperature, salinity, oxygen), a winch with at least 2000m single-core cable are requested. A multibeam echo sounder is requested. Vessel mounted ADCP (hull 75kHz and moon pool 38kHz) is essential for underway and on-station current measurements. Incubation experiments will be done on deck. The ships own CTD will be used as a backup system. An uCTD/RapidCast system will be installed at the aft-deck for underway profiling. The CloudKite requires an own winch to be installed on the aft deck and space to fill the balloon with helium.

3.2.4 Special requests/Besondere Anforderungen

- Continuous operation of 75 kHz VMADCP,
- Installation of 38 kHz VMADCP and submersible pump system in moon pool,
- Backup CTD system
- Continuous operation of thermosalinograph,
- Deck pool for glider ballasting and dive test,
- Fast Rescue Boat or zodiac for deployment/retrieval of gliders,
- MilliQ de-ionized water system,
- -80°C freezer,
- Liquid N_2-generator,
- Additional radios sounding will be performed under specific atmospheric conditions.
- Underway measurements of meteorological parameters, of temperature/salinity with thermosalinograph.
- Deck space for continuous seawater flow-through incubators (3 x 1 m^2) preferably not shaded
- Deck space for CloudKite

3.2.5 Schedule/Arbeitstage

The ship's schedule is based on a ship speed of 10 kn. The station time has been estimated based on typical lowering and hoisting speeds for winched instruments as well as our experience gained on previous cruises with the deployment and recovery of autonomous equipment. The planned eddy studies represent an ambitious and complex sequence and interplay of a large suite of instrumentation. This will require some degree of flexibility to accommodate weather- or instrument-related delays or rescheduling needs. The exact sequence of the deployment and recovery of the various observation and sampling instruments will be worked out in a specific pre-cruise workshop of all participating working groups. The following is a draft schedule that is based on the expected duration and replications of the different components of the study (i.e., planned number of CloudKite flights, uCTD surveys, deployments of gliders, MicroStructure probing etc.).

Start Harbor: Bridgetown (Barbados)

1st Cloud evolution/life-cycle experiment (Concerted activity with Ship 1 and aircraft surveys)

Transit to survey area about 100 nm off Barbados (intercalibration) *10 h*
Atmospheric and ocean sampling over local synoptic time scale (7 days): 168 h

- Sequence of CloudKite launches (both ships)
- Radiation / sunphotometer / cloud camera
- Microstructure obs. (every 1h)
- CTD casts (every 4h upper 1000m)
- sADCP/uCTD surveys
- NIW experiments
- Regional/local air-sea exchange surveys

Mesoscale eddy experiment

Transit to survey area about 240 nm south, where NBC Rings occur frequently *24 h*
1st Atmospheric and ocean sampling over mesoscale (see details above) 270 h

- x-shaped VMADCP/CTD/MSS survey of eddy (upper 1200m; 35 stat.) 164 h
- 1st intensive eddy centre sampling/observation campaign 24 h
- NIW experiments 24 h
- Transit to eddy rim 10 h
- 1st intensive eddy rim sampling/observation campaign 24 h
- 2nd intensive eddy rim sampling/observation campaign 24 h

2nd Atmospheric and ocean sampling over mesoscale (see details above) 270 h

- x-shaped VMADCP/CTD/MSS survey of eddy (upper 1200m; 35 stat.) 164 h
- 1st intensive eddy centre sampling/observation campaign 24 h
- NIW experiments 24 h
- Transit to eddy rim 10 h
- 1st intensive eddy rim sampling/observation campaign 24 h
- 2nd intensive eddy rim sampling/observation campaign 24 h

Transit Barbados (260nm) *26 h*

3.2.6. Travel/An- und Abreise

Bridgetown, Barbados / Bridgetown, Barbados

3.2.7 Measures for liable marine research / Maßnahmen zur verantwortungsvollen Meeresforschung

We will follow the DFG regulations summarized in the „Erklärung zu einer verantwortungsvollen Meeresforschung“ and the (OSPAR) Code „Code of Conduct for Responsible Marine Research in the Deep Seas and High Seas of the OSPAR Maritime Area” to avoid unnecessary environmental and ecosystem disturbances.

4. Funding / Mittel für die Durchführung der Reise

The proposed cruise has no specific project funding. Instruments and consumables for instruments will be provided by in-kind contributions of the respective institutions (MPI Meteorology, MPI for Marine Microbiology, MPI for Dynamics and Self-Organization, GEOMAR).

4.1 Travel and accommodation

Funding for flights, transport from the airport to the hotel and accommodation for the 19 German participants is requested:

Flights to embark the research vessel from Hamburg to Barbados and return for German participants (19 x 2000 EUR per person)	38.000 Euro
Transfer from hometown to airport (19 x 100 Euro per person)	1.900 Euro
Hotel accommodation equipment setup crew (9 Pers.) in Barbados before cruises (9 x 3 days x 100 Euro per person and night):	2700 Euro
Daily allowance for 3 days before the cruise (9 x 3 days x 45 Euro per day and person)	1215 Euro
Total	**43.815 Euro**

4.2 Container transports

The German groups will ship in total 6x20” containers and 7 “big boxes”:

- *University of Cologne:* transport of the radar and the microwave requires 1x20” container (radar) and 2 big boxes (microwave).
- *MPI-DS Göttingen*: cloud-kite equipment require 2x20” containers (balloon, winch) and 3 big boxes (equipment and helium)
- *MPI-MM Bremen*: 1x20” container (equipment on 8 pallets, separate pallet with gas); transportation of frozen samples on the return leg (estimated at 5000 Euro).
- *University of Hamburg and MPI-M:* shipping 2 big boxes (radiosondes and equipment)
- *GEOMAR:* 2x20” containers (CTD rosette, Glider, Salinometer, uCTD and other instruments and consumables)
  (Note If the cruise is scheduled following the cruises by Körtzinger/Baschek (RV Meteor) and an exchange between the ships can be made in Barbados, only one container would need to be shipped from Kiel to Barbados.)

Price estimate: The calculations below are based on "typical" costs for container (20") and box shipping Hamburg – Barbados as been done frequently by the MPI-Met for the BCO site and amount to 4500 Euro for a container (one way) and at 2000 Euro from a big box (one way).

MPI-DS: 2x20" containers from Göttingen/Cologne to Barbados & back	18.000€
MPI-DS: 3xbig boxes Göttingen/Barbados return	12.000€
MPI-MM:1x20" container Bremen/Barbados return	9.000€
MPI-MM: frozen samples Barbados/Bremen (one way only)	5.000€
GEOMAR: 2x20" containers Kiel/Barbados return	18.000€
Uni HH: 2xbig boxes HH/Barbados return	8.000€
Uni Cologne: 1x20" containers from Cologne/Barbados return	9.000€
Uni Cologne: 2xbig boxes Cologne/Barbados return	8.000€
Total	**87.000€**

5. Working group/Fahrteilnehmer

Name	Task	Institute
1. J. Karstensen	Fahrtleiter / Chiefscientist	GEOMAR
2. A. Bendinger	Glider respons.; CTD watch lead	GEOMAR
3. C. Begler	Ocean instrum. Techn.	GEOMAR
4. M. Hundsdorfer	MSS.; CTD watch lead	GEOMAR
5. A. Bendinger	lADCP respons.; CTD watch lead	GEOMAR
6. NN	CTD respons.; CTD watch lead	GEOMAR
7. G. Demange	delta ^{18}O; 0.5 CTD watch	LOCEAN
8. NN	uCTD respon; CTD watch	GEOMAR
9. J. Ribbe	Salinometer respons.,	UQ
10. NN	ADCP respons. & CTD watch	ENS
11. G. Bagheri	Cloudkite II / sunphotometer	MPI-DS
12. NN	Cloudkite II	MPI-DS
13. NN	Cloudkite II	MPI-DS
14. NN	Cloudkite II	MPI-DS
15. W. Mohr	Incubation/Primary Productivity	MPI-MM
16. NN	Incubation/nutrients /O_2/Ar	MPI-MM
17. NN	Pump CTD/Ar/O_2	MPI-MM
18. NN	Pump CTD/ Nano Nutrient	MPI-MM
19. NN	cloud radar / microwave	Uni Koeln
20. NN	ceilometer / cloud camera	MPI-Met
21. NN	radiosondes	Uni HH
22. C. Klepp	rain radar / distro / sunphotometer	Uni HH
23. tbd	Doctor (mandatory)	Briese

Institutions:
GEOMAR: Helmholtz Zentrum für Ozeanforschung Kiel, Kiel, Germany
Uni HH: Universität Hamburg, Hamburg, Germany
ENS: Ecole Normale Superior, Paris, France
MPI-MM: Max-Planck-Institut für Marine Microbiologie, Bremen, Germany
MPI-DS: Max Planck Institute for Dynamics & Self-Organization, Göttingen, Germany
MPI-Met: Max-Planck Institute for Meteorologie, Hamburg, Germany
Uni Köln: Universität zu Köln, Cologne Germany
LMD: Laboratoire de Météorologie Dynamique, Paris, France
UQ: University of Queensland, Towomboo, Australia

6. Data / Daten-/Probensicherung und -verfügbarkeit

The Kiel Data Management Team (KDMT) maintains the Ocean Science Information System (OSIS) as a central information and research data sharing utility for marine research projects at GEOMAR and Kiel University. It is publicly accessible and can be utilized by all cruise participants, including national and international collaborators. OSIS merges information on expeditions, experiments and numerical models with peer review publications and available research data. The view of all information in OSIS is open to the public while access to actual data in ongoing research projects may be restricted for definable periods of time (moratorium). Alternatively the submission status of data files including the responsible investigator as contact person is visible to the public and may foster collaborations with interested researchers.

Members of the KDMT are active PANGAEA data curators and can assist researchers during preparation of their sample archival and data publication procedures in a World Data Center (e.g. PANGAEA) which will then warrant long-term archival and access to the research data. This data publication process will be based on available files in OSIS and is therefore transparent to all reviewers and other researchers. Cooperation with a world data center and the union for application of International Geo Sample Numbers (IGSN) will make data and samples globally trackable and increase their scientific value and usability. Links to data publishers or principle investigators provide contact information for external scientists.

The chief scientist and all principal investigators involved in this cruise's research will comply with the time schedule below regulating the availability of all information and all research data and where applicable also of physical samples resulting from this cruise. Following the cruise the KDMT will support and assist researchers in their data management activities.

Availability of metadata in OSIS (https://portal.geomar.de/osis): 2 weeks after completion of the cruise and related experiments Availability of data in OSIS (https://portal.geomar.de/osis): 6 months after completion of the cruise and related experiments. Availability of data in a WDC/PANGAEA (http://www.pangaea.de or as compilation at http://www.pangaea.de/search?q=campaign:CRUISENAME): 3 years after completion of the cruise and related experiments.

7. Declaration / Erklärungen

Die Unterzeichner verpflichten sich, die geplanten Forschungsaktivitäten im Rahmen der „Erklärung zu einer verantwortungsvollen Meeresforschung“ (Anlage 1 und 2) durchzuführen.

8. Signatures/Unterschriften