<u>Final Report for FORMOSA from 23. November 2023</u>

Project title: "FOur dimensional Research applying Modelling and Observations for the Sea and Atmosphere" (FORMOSA)

Project number: K227/2019

Executive Summary

Despite various restrictions due to COVID-19 we have been able to reach major goals of the project and to achieve scientific/technological progress on numerous topics. This concerns, e. g., the conduction of field operations with radars and lidars, which in part became possible only because of major achievements in remotely controlling these complex instruments. On the other hand, some field operations with newly developed instruments were postponed or had to be cancelled. The communication and interaction between the project partners were also hampered by COVID-19 restrictions, and group meetings took place in hybrid format.

Furthermore, some oceanographic expeditions had to be postponed or canceled. Still, the tasks in FORMOSA work packages WP5.1-WP5.3 have now be successfully finished. Only WP5.4, focusing on the North Sea, was not completed since we were not allowed to carry out the required measurements. Research cruises in the Kattegat and the South Atlantic region were substantially delayed but were also finally carried out. Some promising results regarding FORMOSA were achieved and will be published in the near future. The numerical model setup and validation in WP6.1 has been completed, but the planned model-data comparison for the North Sea (WP6.3) could not be carried out (see above). The main part of these analyses has now been shifted to the Kattegat region. These investigations (WP6.2 and modified WP6.3) are still ongoing.

Many technological and scientific results have been achieved during FORMOSA, most of which are published in peer review journals (see below).

1. Achievement of objectives and milestones

The first VAHCOLI lidar prototype developed for FORMOSA was finished in 2019 and a first field campaign was successfully completed (Lübken & Höffner,2021). Two improved proto-types were constructed by November 2022. An extensive field campaign is performed since December 2022 (still ongoing). The novel prototype includes a multi-field of view upgrade for sounding in five directions. The field campaign allowed for the first time wind measurements up to 25 km (Mense et al., 2023). The improved performance triggered for the first time the direct investigation of turbulence by measuring the spectral width (Munk et al., 2021). Since then, the optimization of VAHCOLI has led to an increase in laser power by a factor of 2.5 and a decrease of the spectral width (Munk et al., 2023). The experiences gained in FORMOSA led to new projects funded by EU (EULIAA) and BMBF (LidarCUBE).

The MMARIA concept has been expanded and exploited as indicated in the proposal with our new concept called SIMONe. These systems have been successfully installed in Southern Argentina, Peru, northern Germany, and northern Norway. Procedures exploiting 4D mesoscale features at both first- and second-order statistics have been developed. Radar imaging by MAARSY was successfully implemented and tested. It is currently being applied to selected kilometer-scale mesospheric events, like Kelvin Helmholtz instabilities and bores. Due to COVID-19, major delays have been experienced with the bi-static implementation of MAARSY-3D. We expect the installation to be finished in summer 2024. Therefore, some activities related to WP 2.2, 2.3, and 2.4 were not conducted as originally planned. Instead, direct numerical simulations and MAARSY statistics of kilometer-scale dynamics features have been investigated.

Observations performed in the framework of WP 2 triggered comparison with simulations performed at IAP. The meteor radar system SIMONe in Argentina provides frequency spectra of two horizontal velocity components. We performed KMCM simulations (MS 4.1) and analyzed frequency spectra simulated in the observational volume of the SIMONe/Argentina system in MS 4.2 (Avsarkisov et al., 2023). We also determined the corresponding structure functions in collaboration with the radar department (Poblet et al. 2023). An analysis of vertical wavenumber spectrua was done using balloon-borne measurements from the lidar department (Faber et al., 2023, and BSc thesis of N. Dusch).

Due to COVID-19 restrictions it was not possible to operate our lidar facility at ALOMAR in Northern Norway by students or scientists. Therefore, special maintenance procedures and field campaigns dedicated to LITOS and VAHCOLI could not be realized. Still, the installation of new diode lasers and the implementation of a sophisticated instrument control allowed to perform regular observations and to collect a significant database for further scientific analysis. At IAP, a new lidar with wind measurement capabilities is currently being installed which allows comparing with local observations, mainly weather balloons and VAHCOLI.

At IAP, a new balloon borne turbulence instrument (LITOS) was developed and employed several times in field campaigns. Fortunately, one of the latest flights entered a tropopause fold event and allowed for the first time to study the impact of turbulence on such a phenomenon (Söder et al., 2021). We showed that eddy heat flux can significantly modify the potential vorticity distribution across tropopause folds.

In addition, the oceanographic fieldwork was severely affected by COVID-19 restrictions, leading to cancellations of experiments and a shift in regional focus. Despite these limitations, a total of three successful research cruises, dedicated to FOROMSA, were conducted in the Baltic Sea and Kattegat region. Additionally, acoustic turbulence data for FORMOSA were obtained during research cruises in the South Atlantic Ocean, on the Chilean shelf, and inside a Patagonian fjord. All essential tasks in WP5.1-WP5.3 are therefore fully completed, as documented by the available data sets and three project publications in peer-reviewed journals. Additional analyses and publication work, focusing especially on the most recent data sets from the Kattegat and the South Atlantic, are currently carried out at IOW. Work package WP5.4 (North Sea study area) could not be completed as the COVID-19 regulations did not allow us to perform the required measurements during cruise EMB265. Modelling work in WP6.1 has been completed. Similar to WP5.4 also the numerical analyses in WP6.3 could not be carried out as the experimental data for the planned model-data comparison could not be obtained (see above). Our focus will now be on the comparison of model results with data from the successfully completed ship expedition EMB265 (Kattegat/Skagerrak). More details about our activities and results are described below.

2. Activities and obstacles

Regarding VAHCOLI, the first measurement campaign at the beginning of 2020 successfully completed the commissioning phase of a prototype in agreement with the original plan. Thereafter work was massively hampered by COVID-19 (delayed delivery, travel restrictions etc.). We therefore concentrated on the development of VAHCOLI at IAP and ILT. Major improvements were implemented. Two improved systems are now available, where one of them (which includes the five fields of view upgrade) has proven to work for more than 1000 hours. The new capabilities led to unexpected findings regarding atmospheric dynamics, e.g. an under-estimation of vertical winds in ECMWF. Doppler Mie wind measurements were also used for validation of AEOLUS satellite wind measurements (Mense et al., 2023).

Prof. Juha Vierinen participated in the deployment of SIMONe in Norway, as well as in the implementation of wind field analysis. In addition, he collaborated in the development and implementation of MIMO, as well as in the geophysical interpretation of the observations. Related to FORMOSA, Prof. Vierinen has also simulated the implementation of MIMO imaging in the upcoming EISCAT 3D project. We have co-authored in total 11 publications related to FORMOSA. As indicated above, some activities related to WP 2.2, 2.3, and 2.4 were not completed, due to delays related to COVID-19. However, the 4D exploration of mesoscale structures with MMARIA/SIMONe systems is running smoothly.

Regarding modelling, excellent communication with the project partners allowed us to fulfill all milestones of WP 4. We have developed two new velocity-filtering techniques for observational and simulated velocity fields and a new approach for the analysis of kinetic energy and helicity spectra. Various velocity decomposition techniques, such as Helmholtz and helical decompositions were tested and implemented.

The FORMOSA team at IOW conducted two successful research cruises in the northern Baltic Sea, jointly with our partners from Stockholm University. FORMOSA expedition EMB265 with the R/V Elisabeth Mann Borgese finally took place in May 2021, but with only half the scientific crew and abandoning the planned working area in the North Sea, which affected WP5.4 and WP6.3. Despite these limitations, an excellent data set was obtained in the Kattegat area and in the western Baltic Sea. Also the planned South Atlantic expedition M180 with R/V Meteor had to be postponed several times, but finally took place in February-April 2022, providing important data for WP5.3. Most recently, together with partners from Chile, we explored the use of acoustic turbulence measurements inside a Patagonian fjord (cruise SO296 with R/V Sonne, Jan/Feb 2023), contributing to WP5.2 and WP5.3.

Delayed field work and a shift in the regional focus due to COVID-19 also affected the modeling tasks in WP6.1-6.3. A new and high-resolution model grid for the GETM ocean circulation model has now been implemented for the entire Baltic Sea, integrated into a coarser-resolution model for the entire North Sea/Baltic Sea. This new model has already been validated. The originally planned application to the North Sea area (WP6.3) was canceled due to the lack of experimental data-. The main part of the analysis has now been shifted to the Kattegat region. These investigations are still ongoing.

3. Results and successes

A list of publications achieved within FORMOSA is provided in the attachment.

Regarding VAHCOLI several papers where published in peer review journals. In Lübken & Höffner (2021), the concept of VAHCOLI is introduced, successfully demonstrating the application of sophisticated laser spectroscopy to derive winds and temperatures even under daylight conditions. The compact design of VAHCOLI and its capability for autonomous operation are presented and used to study the impact on geophysical observations (Munk et al., 2021). The performance of the Alexandrite ring laser, developed in cooperation between IAP and ILT, is presented in Munk et al. (2023). Höffner et al. (2021) propose a space-borne lidar, based on techniques developed for VAHCOLI. In November 2021, Jan Froh finished his PhD on the application of laser spectroscopy in VAHCOLI (Froh et al., 2022). Mense et al. (2023) recently published first lidar observations of atmospheric dynamics, including wind measurements along five fields of view. Strotkamp et al., (2019) studied the application of VAHOLI technique from space, Höffner et al. (2021) published a performance study for contemporary Alexandrite satellite lidars using iron resonance fluorescence. Technology transfer to the industry was successfully initiated by participation in the funding program "Zentrales Innovationsprogramm Mittelstand", in the course of which the production of the VAHCOLI housing was performed in the industry (project “MoLiCu”). This initial project was extended through the BMBF RUBIN (Regionale unternehmerische Bündnisse für Innovation) programme in the project LidarCUBE. Further development of the spectroscopic applications in VAHCOLI is funded through the EU project EULIAA. A satellite based iron lidar has been proposed to ESA by IAP and ILT. A next generation UV laser for ground-based and space-borne lidars is demonstrated in the laboratory (Scheuer et al., 2023).

As part of FORMOSA, four-dimensional exploration of mesoscale mesospheric structures observed by radar has started. During this period new multi-static systems (SIMONe) have been installed (e.g., Chau et al., 2021, Conte et al., 2021), and 4D techniques have been improved (e.g., Chau et al., 2019, Chau and Clahsen, 2019, Urco et al., 2019b, Vierinen et al., 2019). Preliminary results from first-order (e.g., Chau et al, 2021, Vargas et al, 2021, Volz et al., 2021, Conte et al., 2022, Charuvil et al., 2022a, Poblet et al., 2023b) and second-order statistics (Vierinen et al., 2019, Charuvil et al., 2022b, Conte et al., 2022, Poblet et al., 2022, Poblet et al., 2023a) have been achieved. Similarly, the exploration of 4D kilometer-scale mesospheric structures has been achieved (e.g., Urco et al., 2019a, Chau et al., 2020, Chau et al., 2021, Ramachandran et al., 2023). Our 4D efforts in Norway have been extended to studies of radar aurora events (Huyghebaert et al., 2022, Huyghebaert et al., 2023).

A major theoretical result within WP4 is the realization that the cold summer mesopause region is controlled by stratified turbulence at horizontal scales smaller than 250km. This result is essential for understanding the formation of the cold summer mesopause region. The analysis of vertical spectra of energy and helicity (MS 4.3) obtained from balloon-borne measurements revealed that both cascades are dominated by eddy turnover time. A dual-cascade scenario was observed in a strongly stratified case.

At IOW, a first FORMOSA study focusing on the methods for acoustic turbulence measurements (WP5.1) has now been published (Muchowski et al., 2022). We showed that the acoustic method is suitable for high-resolution estimates of turbulence in the upper ocean (WP5.1). The technique is applied to investigate turbulence generated by lee waves in the vicinity of a narrow sill (WP5.2). In a follow-up study we used data from a second joint cruise in the same area and a combination of in-situ and acoustic turbulence measurements to study sub-mesoscale turbulence behind topographic obstacles (WP5.3) (Muchowski et al., 2023). Finally, we summarized new insights gained with the acoustic approach in WP5.1-WP5.3 of FORMOSA in an overview paper by Muchowski et al. (2022).

We are currently analyzing an excellent dataset regarding turbulence measurements in the Kattegat region from FORMOSA project expedition EMB265. The focus of this work is on near-surface mixing and the role of sub-mesoscale dynamics (WP5.3). Additional turbulence data have been collected during cruise M180 (Feb/Mar 2022, South Atlantic Ocean), focusing on near-surface sub-mesoscale dynamics (WP5.3). These data are currently being analyzed in the framework of a MSc thesis, supervised by PI Umlauf. The numerical modeling work package WP6.1 is now completed but WP6.3 had to be abandoned due to the lack of observations. Instead, we shifted the regional focus to the Kattegat region, where observations were made during cruise EMB265.

4. Equal opportunities and internationalisation

Internationalization has been a key characteristic of FORMOSA. Basically all experimental and theoretical developments took place in cooperation with international partners.

5. Structures and collaboration

SIMONe implementation and analysis have resulted from an international collaboration with colleagues from MIT Haystack Observatory and UiT Arctic University of Norway. Collaboration with MIT Haystack Observatory was not directly part of FORMOSA, but FORMOSA has benefited from it.

Prof. Dr. Becker has left IAP and is now working at CORA (Boulder, US). He is the main developer of the KMCM code. Fulfillment of milestones 4.1 and 4.2 are performed in close collaboration with him. A newly established collaboration with Prof. Hoyas helped us to analyze the frequency spectrum. .

The oceanographic part of FORMOSA at IOW benefits from the close collaboration with Stockholm University (Prof. Christian Stranne). Several joint expeditions have been carried out, three joint papers have been published, and more manuscripts are in preparation.

6. Quality assurance

Basically all manuscripts within FORMOSA are published in peer-review journals with open access. Data used in the publications are stored in a repository (with an associated DOI) and are publically available. All oceanographic measurement data obtained in the project are stored and made available in the IOW data management system after careful quality control in accordance with the institute's data policy. IOW has an accredited calibration laboratory and thus guarantees measurement accuracies at the highest international level. The DFG Code of Good Scientific Practice adopted in 2019 was implemented by the Leibniz Association. This was later approved by all institutions in 2021. Animal experiments were not carried out within the framework of this project.

7. Additional resources

IAP has tremendously supported this project in various ways, for example, by making major investments in the lidar and radar infrastructure (new building for VAHCOLI, new power lasers, new transmitters, new electronics and optics etc.), using high performance computing facilities, engaging scientists and technicians (not funded by FORMOSA) for technical support and scientific analysis, etc. etc.

At IOW the project was supported by the purchase of an EK80 special echo sounder from Kongsberg (Sweden) with a value of about EUR 40,000. This device has already been used for data acquisition on the project expeditions EMB265 (May 2021), M180 (Feb/Mar 2022), and SO296 (Jan/Feb 2023).

8. Outlook

The VAHCOLI lidars built in FORMOSA are currently used for extended observations. The results are evaluated and published. Some outstanding findings are currently being compiled for the PhD thesis of Thorben Mense, to be submitted in January 2024. New projects regarding commercial applications of VAHCOLI have been acquired.

In the future, the radar systems, techniques, and expertise gained as part of FORMOSA will be used to characterize the 4D first and second-order mesoscale dynamics at MLT altitudes at different latitudes and seasons (e.g., over Argentina, Peru, Germany, and Norway), and to improve mesoscale parameterization of global circulation models.

On the oceanographic side, the following activities are ongoing at the moment or anticipated:

- Publication of acoustic turbulence measurements obtained during FORMOSA expedition EMB265 in the Kattegat region (WP5.2, WP5.3)
- Completion of a MSc thesis and publication on turbulence measurement during expedition M180 with R/V Meteor (24.02-14.04 2022) in the South Atlantic (WP5.3).
- Publication of model results obtained in WP6.2 and WP6.3.

Furthermore, FORMOSA inspired a new collaborative research project in Germany, Sweden and Norway called “SkaMix”.