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ILWAO – Phase 2:
International Leibniz Graduate School
for Waves and Turbulence
in the Atmosphere and Ocean

Leibniz-Institute: Leibniz-Institute of Atmospheric Physics, Kühlungsborn (IAP)
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Contents

1 Executive Summary

The project ILWAO (International Leibniz Graduate School for Waves and Turbulence in the Atmosphere and Ocean) is a common science cooperation and a graduate school with participation from the following institutions:

- Leibniz-Institute of Atmospheric Physics in Kühlungsborn (IAP)
- Leibniz-Institute for Baltic Sea Research in Warnemünde (IOW)
- Institute of Fluid Mechanic of the University Rostock (LSM)

This project was a continuation of a very successful graduate school being active since 2008. The main aim of ILWAO is the investigation of internal waves (in particular gravity waves) and turbulence and their importance in the atmosphere and ocean.

Some unique facilities (lidar, radar, in-situ soundings etc.) were employed to perform unprecedented observations in the middle atmosphere, in the ocean, and also in laboratory experiments. Theoretical investigations and simulations supported the interpretation of experimental results. As can be seen in appendix 11.1 an impressive collection of scientific results was achieved and published in international science journals (155 papers in the period 2012-2017), and also in bachelor's, master's, and PhD theses. Some examples of research activities and results are highlighted in section 4.

In summary, ILWAO was a very fruitful cooperation between three different institutes (two from the Leibniz society, and one from the Rostock University) regarding the importance of dynamical processes in the atmosphere and ocean, supported by laboratory experiments. We intend to continue ILWAO with separate funding beyond the period of this core project.

2 Original questions and aim of the project

The main aim of ILWAO-2 was to study dynamical phenomena such as gravity waves, tides, and turbulence, from different perspectives being relevant for the atmosphere and ocean, supported by laboratory investigations. Apart from addressing common science topics an important aspect of ILWAO-2 was the education of students in a graduate school. As is described in more detail in section 4.1 the seminars were very successful and we decided to continue this seminar beyond the funding period of ILWAO.

The prime science aims of ILWAO pursued at IAP concentrated on developing new instrumental techniques to observe gravity waves, tides and turbulence in the middle atmosphere, i. e. from approximately 10 to 100 km. This basically concerns lidars[1], radars, and balloon borne detectors for turbulence measurements up to the middle stratosphere. In this context, some unprecedented observational capabilities were developed. Examples are: i) the DoRIS[2] detector to measure winds (and temperatures) by RMR[3] lidar in the entire middle atmosphere, ii) the three-dimensional coverage of winds by meteor radars in MMARIA configuration[4], and iii) the detection of ultra-fine structures (down to milli-meter scale) by the balloon-borne instrument LITOS[5]. Apart from exploiting new instrumental methods, many hours of lidar and radar observations were performed, primarily at our sites in Kühlungsborn (54°N) and at ALOMAR[6] in Northern Norway (69°N), but also during a field campaign in Davis, Antarctica (68°S). The observations were accompanied by theoretical studies and model calculations based on the model KMCM[7]. This is one of the very few models worldwide which allows to study the fine structure of gravity waves and their impact on global scales.

It should be noted that the technical, financial and personal efforts to perform these sophisticated observations and simulations were far beyond the possibilities of ILWAO and were heavily supported by internal funding of IAP. In total, the results achieved during ILWAO were significantly beyond what has been planned in the original proposal. This concerns new experimental and theoretical achievements and publications in peer reviewed journals (see below for more details).

To achieve the goals of ILWAO, IOW concentrated on the development of its research infrastructure for field observations and numerical modelling. For in-situ observations of turbulent quantities new micro-structure profilers have been acquired, as well as high-frequency Acoustic Doppler Current Profilers (ADCP). One important platform for autonomous profiling in the Bornholm Basin and the Eastern Gotland basin is GODESS (Gotland Deep Environmental Sampling Station, see https://www.io-warnemuende.de/GODESS.html) which provides high-resolution profiles of temperature, salinity, oxygen and several other parameters. It is also equipped with a turbulence device, such that profiles of turbulent mixing can be observed even during harsh weather conditions. Also numerical models were improved. Here, foci relevant for ILWAO research were the quantification of numerical dissipation and mixing and strategies for reducing these numerical artefacts by means of optimizing vertically adaptive coordinates. The infrastructure at IOW is augmented by the research vessel Elisabeth Mann Borgese owned by IOW and by larger research vessels from the German ship pool, as well as supercomputers at the HLRN (Norddeutscher Verbund für Hoch- und Höchstleistungsrechnen). Supported by this infrastructure, ILWAO-related field campaigns were carried out mainly in the Baltic Sea (see sections 4.3.2 and 4.3.3). High-resolution model simulations have been carried out by means

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[1] LIDAR: laser induced detection and ranging

[2] DoRIS: Doppler Rayleigh Iodine System

[3] RMR: Rayleigh-Mie-Raman

[4] MMARIA: Multi-static, Multi-crequency Agile Radar for Investigation of the Atmosphere

[5] LITOS: Leibniz-Institute Turbulence Observations in the Stratosphere.

[6] ALOMAR: Arctic Lidar Observatory of Middle Atmosphere Research

[7] KMCM: Kühlungsborn Mechanistic general Circulation Model

of the General Estuarine Transport Model (GETM) for several regions on the North Sea and the Baltic Sea. For example, based on existing observations from earlier campaigns, basin-wide mixing in the Central Baltic Sea was quantified by using a numerical model (section 4.3.1). Total mixing (including numerical mixing) of salinity and temperature has been estimated for a model application to the Western Baltic Sea (section 4.3.4).

At the Chair of Fluid Mechanics, ILWAO-2 aimed at further improving the experimental setup for the investigation of stratified flows. With this unique facility, it was possible to generate density and velocity fields in stratified flows and measure these fields simultaneously with high resolution. The study of the transition of internal waves to turbulence above various topographic elements is important in order to understand the wave-turbulence coupling which is relevant for various oceanographic and atmospheric scenarios. Some examples of scientific results regarding internal waves in stratified flows are presented in section 4.4.1. The experimental setup further allowed for detailed investigations of the effect of unidirectional turbulent incident flows as well as surface waves on the seabed. Due to the complex nature of the processes which govern the interaction between turbulent flows and sediment transport, numerical simulations of the flow and sediment transport were also performed. The combination of both experimental and numerical investigations thus enabled a detailed understanding of the governing processes which lead to sediment transport at the bottom of the ocean and also to the burial of objects on the seabed (see sections 4.4.2 and 4.4.3).

3 Overall development of project plan

The experimental and theoretical investigations performed at IAP during ILWAO are in agreement with the original plans. Some adjustments regarding the experimental and theoretical tasks took place during the project phase to account for new instrumental capabilities and new insights in relevant processes. For example, our new technique to observe winds by lidar (DoRIS) allowed for the first time to measure gravity waves in temperatures and winds in the middle atmosphere. Furthermore, secondary gravity waves are now considered to be important which significantly modifies model simulations. Some results are presented in section 4.2.

As originally planned, IOW concentrated on understanding effects of internal waves and turbulence in the coastal ocean by means of dedicated field observations. Specifically, the extension of the autonomous GODDESS profiling station was a great success. For the numerical modeling, the goal of developing a new parametrization for internal mixing was not further persued, since model simulations for the Central Baltic Sea revealed that effective vertical mixing is dominated by boundary mixing (see section 4.3 for details).

As planned, the laboratory experiments regarding internal waves were extended to include an analysis of the transition of internal waves to turbulence on a tilted surface. Furthermore, a considerable amount of research went into the analysis of the interaction between turbulent flows and (buried) objects at the bottom of the ocean. The latter topic was the driving force of multiple laboratory experiments, which also focused on waves and sediment transport phenomena. Additionally, two PhD theses were conducted which focused on the numerical simulation of sediment transport and turbulent flows around objects at the bottom of the ocean.

4 Achievements

4.1 Graduate School

An important part of ILWAO-2 was the education of students in the frame of a graduate school. Several students presented and discussed their work which in most cases was part of their master or PhD theses. In the time period from 2012 to 2017 a total of 11 seminars with 55 presentations took place at the three institutes involved. A detailed list of presentations in the ILWAO graduate school is provided in Appendix 11.2. The following table summarizes the dates and locations of the seminars.

Date	Location	Semester	No. of Presentations
1. June 2012	IAP Kühlungsborn	SS 2012	6
14. December 2012	Univ. Rostock	WS 2012/2013	4
3. May 2013	IOW Warnemünde	SS 2013	6
8. January 2014	IAP Kühlungsborn	WS 2013/2014	4
20. June 2014	LSM, Univ. Rostock	SS 2014	3
21. November 2014	Insel Vilm	WS 2014/2015	13
10. July 2015	IAP Kühlungsborn	SS 2015	6
8. January 2016	LSM, Univ. Rostock	WS 2015/2016	4
17. June 2016	IOW Warnemünde	SS 2016	3
20. January 2017	IAP Kühlungsborn	WS 2016/2017	3
15. September 2017	LSM, Univ. Rostock	WS 2017/2018	3

We also invited specialists (senior scientists) in the field of atmospheric/oceanographic dynamics to present overviews and/or deeper insights into science topics related to ILWAO. Apart from educational and networking aspects the ILWAO seminars turned out to be very exciting and stimulating. Several cross-disciplinary science initiatives were generated on the basis of these seminars. To mention two examples: i) the concept of wave mixing being rather common in ocean science was for the first time applied to the impact of gravity wave transport on trace gases in the middle atmosphere; ii) the experience with laboratory flow chambers being available at LSM was used to test, optimize and calibrate the LITOS turbulence sensor which has been flown on several balloon flights in recent years.

Please note that in the following we do not give citations since a) all citations from ILWAO are listed in the reference list (see Appendix 11.1), and b) we only report on some highlights from ILWAO and do not aim at presenting a comprehensive review of the research topics involved.

4.2 Science Results from IAP

In the following we present some examples of science results from IAP concentrating on developing new instrumental techniques to observe gravity waves, tides and turbulence in the middle atmosphere, i. e. from approximately 10 to 100 km. This basically concerns lidars, radars, and balloon borne detectors for turbulence measurements up to the middle stratosphere. We also present result from modeling with KMCM.

4.2.1 Lidar observations of waves and balloon borne measurements of turbulence

During the project phase of ILWAO-2 a new technique called DoRIS was developed to measure winds quasi-continuously by lidar in the middle atmosphere, where no other technique is available. DoRIS was successfully validated by co-located and simultaneous rocket-borne techniques measuring winds in-situ. For the first time, gravity waves were observed both in temperatures and winds in the middle atmosphere which allowed to deduce unique wave parameters. For example, kinetic and potential energies were derived which showed that they are rather different. Furthermore, spectra of velocity and temperature fluctuations were deduced,

Figure 1: Students and scientists from IAP, IOW, and LSM, participating in a seminar within the ILWAO graduate school performed at IAP in January 2014.

which are important for comparison with various theories regarding cascading processes in the atmosphere.

The longest time series of lidar temperature measurements in the middle atmosphere were achieved at IAP in Kühlungsborn in May 2016 (total of 230 hours). This allowed for the first time to detect the temporal evolution of gravity waves and tides and their mutual interaction (see Fig. 2).

The existence of secondary gravity waves has been considered for some years. However, their importance for atmospheric dynamics has only recently been assessed. It turned out that several features of the wind field in the middle atmosphere as measured by radars can best be explained assuming the existence of secondary gravity waves. Furthermore, secondary gravity waves were recently detected by lidar. It should be mentioned, however, that the unequivocal detection of secondary waves by ground based instrument requires to measure background winds since these instruments measure Doppler-shifted waves which are substantially different from in-situ wave parameters if the wind is comparable in magnitude to the phase velocity.

During ILWAO a new technique to measure turbulence on balloons in the tropo- und stratosphere was developed: LITOS (Leibniz-Institute Turbulence Observations in the Stratosphere). This instrument detects turbulent fluctuations with a resolution of a few millimeters which is much better compared to alternative methods. We have performed several flights in Kühlungsborn and also at ALOMAR and are currently publishing the results. At the same time we are continuously improving the operational and technical performance of LITOS.

4.2.2 Radar techniques

During ILWAO-2 we focused on the studies of polar mesospheric summer echoes (PMSE) and associated gravity waves and turbulence measurements. These echoes occur between approximately 80 to 90 km altitude and between May and August (see figure 3). At polar

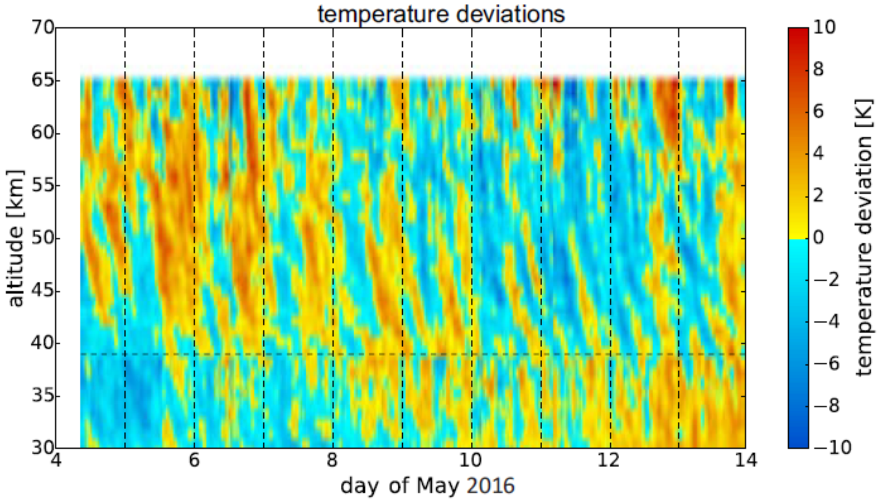

Figure 2: The longest time series world-wide of lidar temperature observations in the middle atmosphere. A total of 230 hours of measurements were achieved in May 2016. This plot shows temperature deviations due to gravity waves and tides. The variations change with time which points to a mutual interaction between various waves. This figure is taken from Baumgarten et al. (2017).

latitudes, the occurrence rate is $>$ 95%. The physical mechanism behind these echoes is basically understood and involves the existence of charged ice particles, turbulence, and free electrons. We investigated the structure of PMSE using the Middle Atmosphere Alomar Radar System (MAARSY). MAARSY allows multi beam, spaced antenna, narrow and wide beam as well as imaging experiments. We associated the apparent PMSE fluctuation on high-resolution observations (2 ms sampling) to statistical fluctuations of a random process. The findings were validated by using Monte Carlo simulations of the scattering process as well as considering instrumental effects.

Using MAARSY multi-beam capabilities, we investigated the angular dependence of PMSE and found that PMSE scattering is in general isotropic, while previous findings of an apparent high aspect sensitivity could be reproduced and explained by localized isotropic scattering, that in turn could be produced by kilometer-scale atmospheric gravity waves. Furthermore, using atmospheric radar imaging and a combination of narrow and wide beam observations, it was found that PMSE scattering is mainly patchy with size varying between and 1 km and 5 km. Finally, we also showed that turbulence and wind measurements using PMSE as tracers can be significantly improved if the spatial and temporal ambiguities are carefully considered.

4.2.3 Parameterization of orographic gravity waves

During the second phase of ILWAO, we finalized a new parametrization of orographic gravity waves (OGW). Such a parametrization is inevitable in every climate model with moderate resolution in order to simulate the correct strength of the polar night. Note that the summer-to-winter-pole circulation in the upper mesosphere is driven by non-orographic gravity waves. The new OGW scheme is an extension of the classical scheme of McFarlane. Our extensions include 1) the general dispersion relation for medium-frequency GWs in order to allow for very long vertical wavelengths which occur in the case of a strong polar night jet, 2) the full energy deposition, 3) the damping of the parameterized OGW by the turbulent vertical diffusion pro-

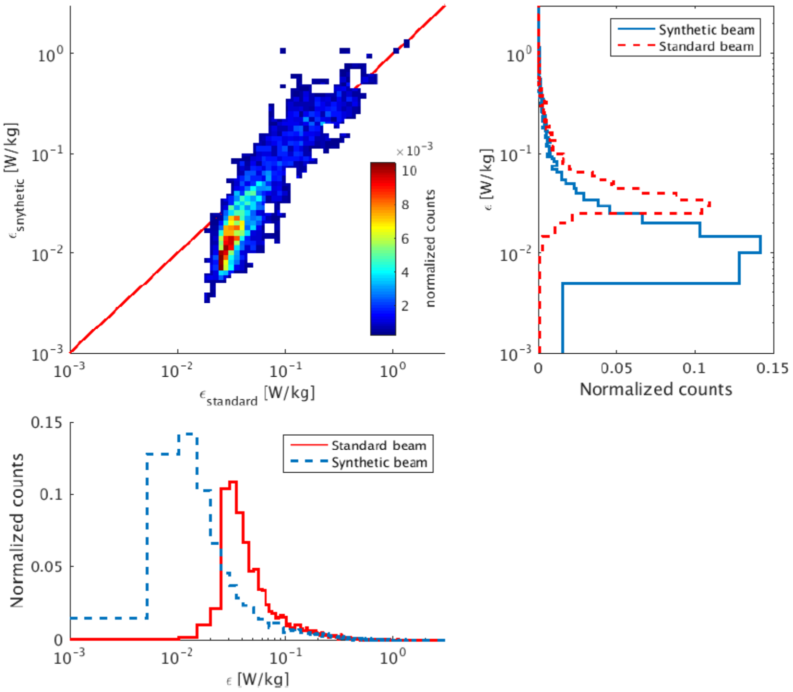

Figure 3: Histogram for energy dissipation rates (ϵ) derived by the narrow beam and the synthetic narrow beam. Top left: 2-D correlation in ϵ between the standard narrow beam and the synthetic narrow beam. The red line indicates x = y. A deviation can be seen especially for small ϵ. The cumulative histograms along x and y direction are shown in the top right and lower panels, respectively. The red line shows the cumulative histogram for the standard narrow beam and the blue line for the synthetic narrow beam. This figure is taken from Sommer and Chau (2016).

duced by the boundary-layer scheme, and 4) the effects of the OGW-induced turbulent vertical diffusion on the resolved flow.

The new parameterization was used in several studies based on the new version of the Kühlungsborn Mechanistic general Circulation Model (KMCM) which includes explicit computations of radiation, the moisture cycle, simple thermospheric processes, and the full surface energy budget via a slap-ocean model. In the following we illustrate the importance of OGW in the simulation of sudden stratospheric warming events (SSWs) in the northern winter hemisphere.

Figure 4 shows the zonal-mean zonal wind at 64°N during an arbitrary winter season simulated with KMCM (from October to April). In panel 4a (with OGW), the strength of the polar night jet is moderate in early winter. Two consecutive SSWs occur in late January and early February, which is followed by a stable situation. The spring transition occurs in April. Such a behavior is typical for the northern hemisphere. When OGW are neglected (panel b), the polar night is unrealistically strong until January, and an unrealistically long SSW occurs in February.

Even though SSWs are induced by tropospheric forcing of quasi-stationary Rossby waves, the conditioning of the polar night jet by the OGW is essential for a realistic simulation of the dynamics in the northern winter middle atmosphere. We also note that neglecting OGW leads to an unrealistically strong polar night in the southern hemisphere (from May to October). Furthermore, OGW contribute to Interhemispheric Coupling, which is global mode of internal variability in the mesosphere and essential to understand hemispheric differences of the summer polar mesopause region.

Recently, a GW-resolving version of KMCM was developed which explicitly simulates realistic effects of OGW in the winter middle atmosphere. We found that the intermittency of the body forces from OGW leads to the generation of so-called secondary gravity waves in the stratopause region. These secondary waves can propagate to higher altitudes and affect the circulation in the winter upper mesosphere and lower thermosphere. This newly discovered vertical coupling mechanism cannot be covered when gravity waves are parameterized.

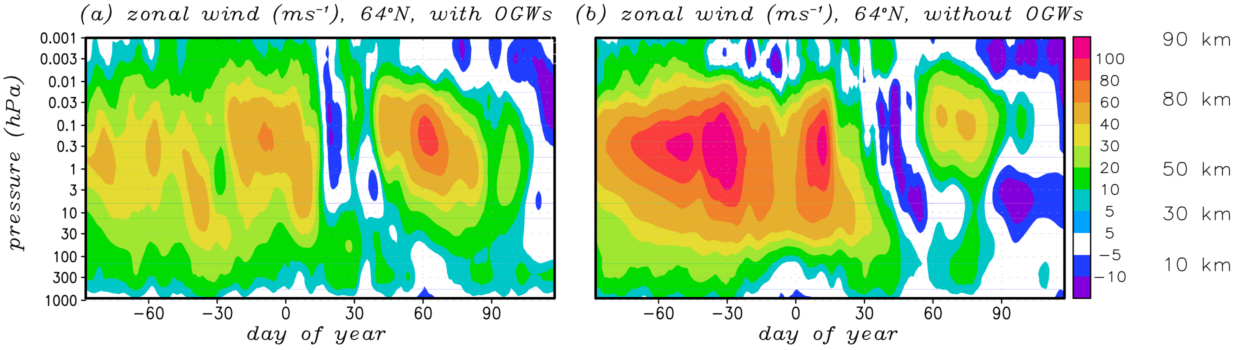

Figure 4: Temporal evolution of the zonal-mean zonal wind at 64°N during wintertime as simulated with KMCM. (a) Simulation with the standard model configuration. (b) Simulations ignoring orographic gravity waves. Day 0 is December 31.

4.3 Science Results from IOW

4.3.1 Effective mixing in a non-tidal stratified basin

Recent results from a tracer release experiment have shown that, similar to many lakes and ocean basins, deep-water mixing in the Baltic Sea is largely determined by mixing processes occurring in the energetic near-bottom region. Due to the complexity and small vertical extent of this region, however, previous modeling studies of the Baltic Sea have so far not been able to provide a numerically and physically sound representation of boundary mixing. In a study we discuss first results from a nested high-resolution simulation of the central Baltic Sea that aims at a realistic description of the turbulent bottom boundary layer with the help of new numerical techniques (adaptive coordinates) and state-of-the-art turbulence modeling. Using a comprehensive data set from the Baltic Sea Tracer Release Experiment, we show that the model is able to reproduce the key dynamical processes (near-inertial waves, topographic waves, and a rim current) with excellent accuracy. Boundary mixing triggered by these processes was found to result in simulated basin-scale mixing rates in close agreement with observations, including a seasonal variability that has been emphasized in previous studies. With the different mixing processes modeled correctly the tracer release experiment was successfully represented in the model (see Fig. 5). These results may be relevant also for the description of mixing in large lakes and other stratified basins.

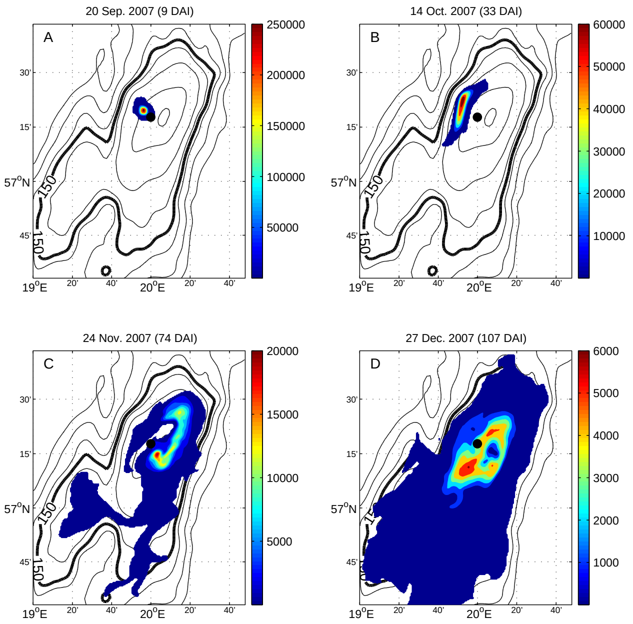

Figure 5: Vertically integrated tracer concentrations of the numerical tracer release experiment (in pmol/m^2). Black lines show isobaths at 20-m intervals; the black dot indicates the injection location. DAI denotes "day after injection" on 11 September 2007. This figure is taken from Holtermann et al. (2014).

4.3.2 Near-inertial waves in a non-tidal basin

Previous investigations from the first phase of ILWAO have shown that internal waves near the inertial frequency (near-inertial waves) contain a large fraction of the overall kinetic energy in the Baltic Sea, and provide the most important contribution to mixing in deep interior layers. However, observed interior mixing rates were generally found to be too small to explain the observed long-term changes in deep-water properties, pointing to the importance of mixing processes in the vicinity of the lateral slopes of the basin. The large contribution of boundary mixing to net vertical mixing suggested by the tracer experiment described above also seemed to be in agreement with the relevance of boundary mixing. However, the spatial and temporal variability of these boundary mixing processes, their physical mechanisms, and their energy sources were unclear at the beginning of ILWAO-2.

The focus of ILWAO-2 was therefore on the dynamics of the energetic slope regions, and their effect on diapycnal mixing. Some of the main results from these investigations are summarized in fig. 6, illustrating the typical cross-slope variability of stratification and energy dissipation based on ship-based turbulence microstructure observations in the Bornholm Basin (southern Baltic Sea) during summer conditions. Striking is in particular the strongly turbulent bottom boundary layer (regions II and IV in Fig. 6b) that could be identified in all other cross-slope transects as well. Our measurements also showed that, similar to the less turbulent interior region of the basin, boundary mixing is fueled by near-inertial wave motions. However, according to the general notion of boundary mixing, the high turbulence levels in the near-bottom region do not automatically imply strong mixing rates because fluid near the bottom is often well-mixed already. Surprisingly, however, our data revealed that regions of strong near-bottom turbulence and near-bottom stratification are often collocated (see region II in fig. 6), suggesting that boundary mixing may be effective in mixing waters with different densities. Based on some theoretical ideas of boundary mixing near sloping topography developed during the project, it was shown that the mixing efficiency, which quantities this effect, reaches values as high as those in the strongly stratified interior. This implies that boundary mixing may be more efficient than previously thought — with relevant consequences also for other ocean basins.

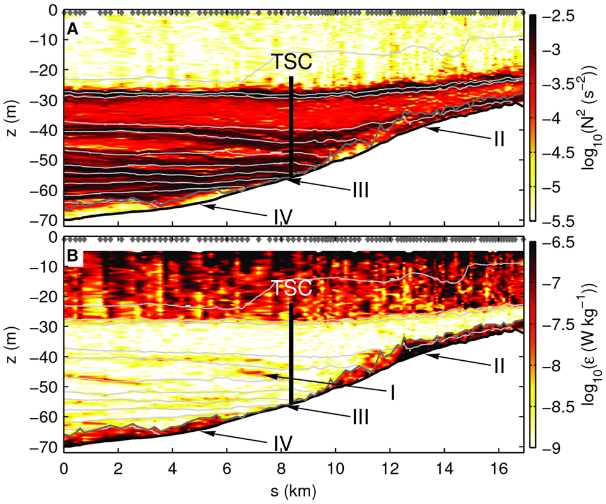

Figure 6: Variability of (a) stratification and (b) turbulence dissipation rate along an approximately 16 km long transect on the south-western slope of the Bornholm Basin (southern Baltic Sea). Grey contour lines indicate the density structure (isopycnals). Arrows mark different mixing regimes discussed in the main text. This figure is taken from Lappe & Umlauf (2016).

4.3.3 Salinity inversions under upwelling-favorable winds

In an observational and theoretical study we discuss and explain the phenomenon of salinity inversions in the thermocline offshore from an upwelling region during upwelling favorable winds. Using the non-tidal central Baltic Sea as an easily accessible natural laboratory, high-resolution transect and station observations taken during a two-ship campaign in July 2012 in the upper layers are analyzed. The data show local salinity minima in the strongly stratified seasonal thermocline during summer conditions under the influence of upwelling favorable wind, see fig. 7. A simple analytical box model using parameters (including variation by means of a Monte Carlo method) estimated from a hindcast model for the Baltic Sea is constructed to explain the observations. As a result, upwelled water with high salinity and low temperature is warmed up due to downward surface heat fluxes while it is transported offshore by the Ekman transport. The warming of upwelled surface water allows maintenance of stable stratification despite the destabilizing salinity stratification, such that local salinity minima in the thermocline can be generated. Such salinity minima in the Baltic Sea have been observed and published before, however, without further explanation. Inspection of published observations from the Benguela, Peruvian, and eastern tropical North Atlantic upwelling systems shows that also there salinity inversions occur in the thermocline, but in these cases thermocline salinity shows local maxima, since upwelled water has a lower salinity than the surface water. It is hypothesized that thermocline salinity inversions should generally occur offshore from upwelling regions whenever winds are steady enough and surface warming is sufficiently strong. The Baltic Sea observations (Fig. 7) show that thermocline salinity has high spatial and temporal variability. Determination of the decay rate of this variability could help to estimate efficiency of diapycnal mixing (e.g., due to breaking of internal waves) and isopycnal mixing (e.g., due to submesoscale eddies).

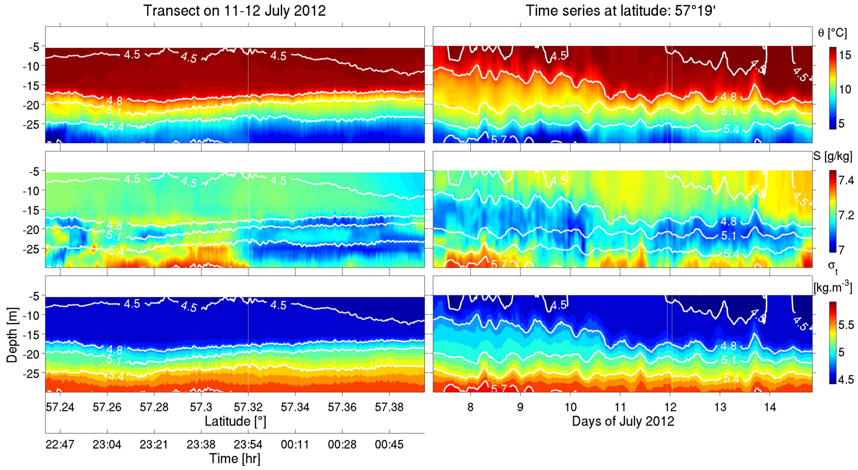

Figure 7: Observations in the upper ocean during a two-ship campaign in the Central Baltic Sea in July 2012. Spatial (left panels) and temporal (right panels) change of potential temperature (top), absolute salinity (middle), and potential density anomaly (bottom). The bold white lines in all panels show the isopycnals. This figure is taken from Burchard et al. (2017).

4.3.4 Quantification of numerical dissipation and mixing

It is well known that in numerical models the advective transport relative to fixed or moving grids needs to be discretized with sufficient accuracy to minimize the spurious decay of tracer variance (spurious mixing). In a study a general analysis of discrete variance decay (DVD) caused by advective and diffusive fluxes is established. Lacking a general closed derivation for the local DVD rate, two non-invasive methods to estimate local DVD during model runtime are discussed. Whereas the first was presented recently, the second is a newly proposed alternative. This alternative analysis method is argued to have a more consistent foundation. In particular, it recovers a physically sound definition of discrete variance in a Finite-Volume cell. The diagnosed DVD can be separated into physical and numerical (spurious) contributions, with the latter originating from discretization errors. Based on the DVD analysis, a 3D dissipation analysis is developed to quantify the physically and numerically induced loss of kinetic energy. This dissipation analysis provides a missing piece of information to assess the discrete energy conservation of an ocean model. Analyses are performed and evaluated for three test cases, with complexities ranging from idealized 1D advection to a realistic ocean modelling application to the Western Baltic Sea (fig. 8). In all test cases the proposed alternative DVD analysis method is demonstrated to provide a reliable diagnostic tool for the local quantification of physically and numerically induced dissipation and mixing. This new method has been used for the assessment of numerical mixing and dissipation in different other studies.

4.4 Science Results from LSM

4.4.1 Laboratory investigations of internal waves

The experimental setup of the water channel for stratified flows allowed for detailed simultaneous measurements of both density and velocity fields. Additionally, it was possible to generate

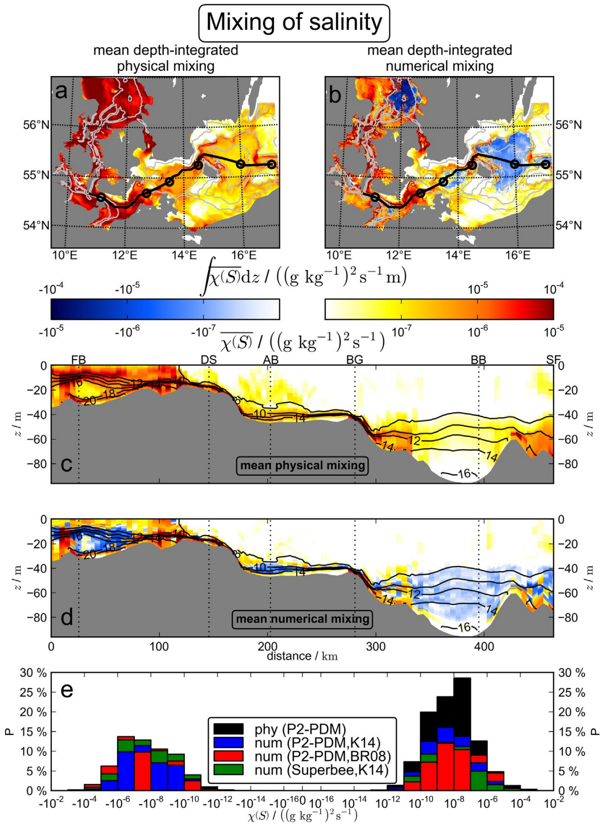

Figure 8: Analysis of a realistic Western Baltic Sea model: mixing of salinity. Depth-integrated and depth-resolved mixing rates averaged over the period 19–28 September 2008 are shown in (a)–(d), respectively. Based on hourly data along the transect, the statistical distribution of the physical and the numerical mixing rates is shown in panel (e) diagnosed by the different analysis methods (Burchard and Rennau, 2008; Klingbeil et al., 2014). This figure is taken from Klingbeil et al. (2014).

internal waves via an appropriate wave generator and the setup was further extended to include a tilted surface. Several such surfaces of varying inclination angles were used in the experiments. With the prescribed setup, it was possible to evaluate the breaking of internal waves due to these tilted surfaces (Fig. 9), which eventually also leads to mixing and the generation of turbulence. Furthermore, by considering only the relevant mass flow of the system, it was possible to determine a mixing efficiency between 0.06 and 0.6, depending on the inclination of the tilted surface.

4.4.2 Laboratory investigations of the flow and scour around objects on the seabed

Further research at the Chair of Fluid Mechanics at the University of Rostock dealt with the effect of turbulent flows and waves on objects at the bottom of the ocean. The scour and burial of objects on the seafloor is of major interest within the offshore construction industry. Unexploded ordnance (UXO) from WW1 and WW2 may cause significant damage to persons and machinery. Thus, extensive cost-intensive surveys have to be undertaken in order to find and recover or even destroy these objects. Knowledge of the state of the burial of such objects as well as of their characteristic scour patterns is needed in order to accurately identify them. In this context,

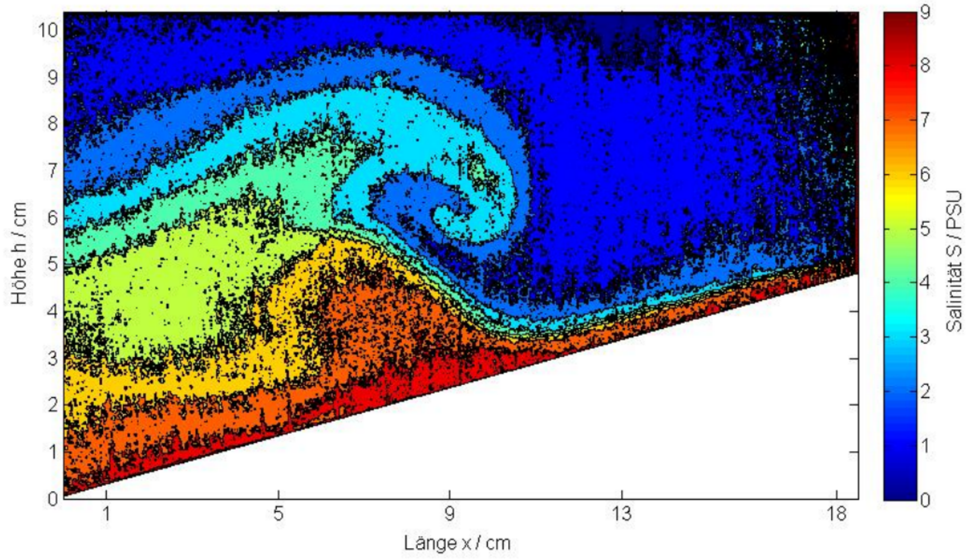

Figure 9: Breaking internal wave on a 15˙ tilted surface. This figure is taken from Büttner et al. (2012).

a good understanding of the different mechanisms which lead to sediment transport in turbulent flows and thus to the scour and burial of objects is necessary.

Numerous laboratory experiments were conducted in this respect which mainly aimed at understanding the flow around horizontally bedded finite cylinders. For this, such a cylinder was placed on a flat surface in an open wind tunnel in order to characterize the flow at Reynolds numbers comparable to those at the bottom of the ocean. Furthermore, several experiments were also conducted in the water channel, where the cylinder was placed on a sediment bed. The focus of these experiments was thus the development of the sand bed around the cylinder due to unidirectional turbulent incident flow. Additional experiments without a mean incident flow but with surface waves were also performed in order to investigate the influence of surface waves on the sediment on the seafloor. These experiments ultimately provided essential validation for numerical simulations and thus opened up the possibility of understanding the fundamental mechanisms for bed load transport and suspended transport in order to predict the scour pattern around the objects, caused by the objects themselves.

4.4.3 Numerical simulations of the flow and scour around objects on the seabed

Numerical simulations of the turbulent flow and sediment transport around such objects were conducted with both 'traditional' CFD, using the open-source solver openFOAM, as well as with the lattice Boltzmann method, using the open-source solver Palabos. The simulations with openFOAM concentrated primarily on simulating the characteristic flow structures around horizontally bedded finite cylinders and their interaction with the sediment on the seabed. It was found that the characteristic flow structures around the cylinder due to a unidirectional incident flow are independent of the considered Reynolds number regime, which was between $10^4 < \mathrm{Re} < 10^5$. A strong horseshoe vortex is developed upstream of the cylinder, which leads to a significant erosion of the sand bed in this area. The cylinder then gradually rolls upstream into the eroded hole until a quasi-stationary state of the sand bed is reached. At this point, the sediment which is eroded tends to be moved uphill, where it then moves directly downhill again due to avalanching effects, thus preventing further erosion of the scour hole. Downstream of

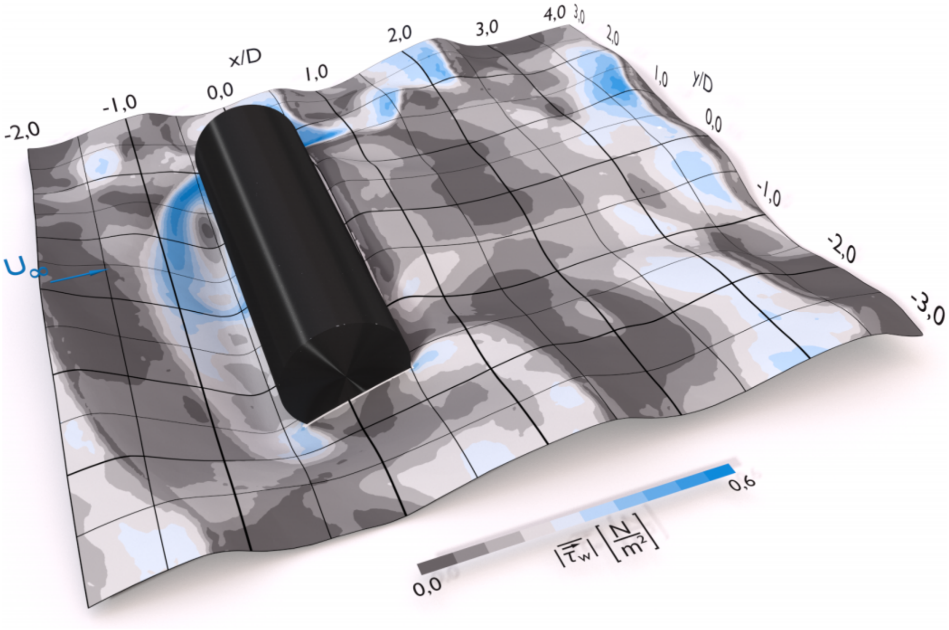

Figure 10: Quasi-stationary state of the sediment bed around a horizontally bedded finite cylinder, color-coded with the temporal average of the wall shear stress $|\tau_w|$ in N/m^2 obtained via a simulation with openFOAM at a Reynolds number of Re = 1.7 $\times$ 10^4. This figure is taken from Tim Rückborn's PhD thesis (2017).

the cylinder on the other hand, the detachment of the flow leads to a recirculation zone, within which the flow velocities are so small that sediment is accumulated. Figure 10 shows the quasi-stationary state of the sediment bed around the cylinder, together with the averaged wall shear stress, which is the main driving factor behind sediment transport.

Furthermore, the open-source solver openFOAM was extended to include a coupling of the flow simulation to the simulation of bed load transport. In order to also be able to deal with the erosion around curved geometries, iterative mesh updates were included, which ultimately involve continuous recalculations of the mesh. Although this method is thus fairly time-consuming, it has been shown to provide an accurate prediction of the initial development of the sediment bed, even around more complex geometries such as a horizontally bedded finite cylinder.

In an attempt to avoid the constant (re-)generation of meshes and due to its flexibility, the lattice Boltzmann method was considered as an alternative simulation approach. Due to the fact, that this method is a relatively new approach to CFD and that the open-source code Palabos is still very much under development, the main aim here was primarily to enable simulations of turbulent flows around arbitrarily complex and potentially moving objects. This involved extensive additions to the Palabos code, namely regarding the incorporation of arbitrarily shaped objects in the sense of off-lattice boundaries, local three-dimensional grid refinement as well as an appropriate collision model, which can effectively be understood as the flow model of the lattice Boltzmann method. Special attention was given to the fact that all implementations should guarantee numerically stable but nonetheless also accurate simulations, even at relatively low resolution. The final combination of all implementations was shown to provide satisfactory results of the flow around both a wall-mounted finite cylinder as well as the considered case of a horizontally bedded finite cylinder. Furthermore, the Palabos code was extended to also include the coupling of the flow simulation to a simulation of suspended sediment transport under turbulent flow conditions. Although the initial simulations only considered the aspects of erosion and sedimentation and thus neglected avalanching effects and bed load transport, it was possible to simulate the evolution of the scour hole upstream of the cylinder as well as the deposition of sediment in the wake of the cylinder within the recirculation zone (Fig. 11).

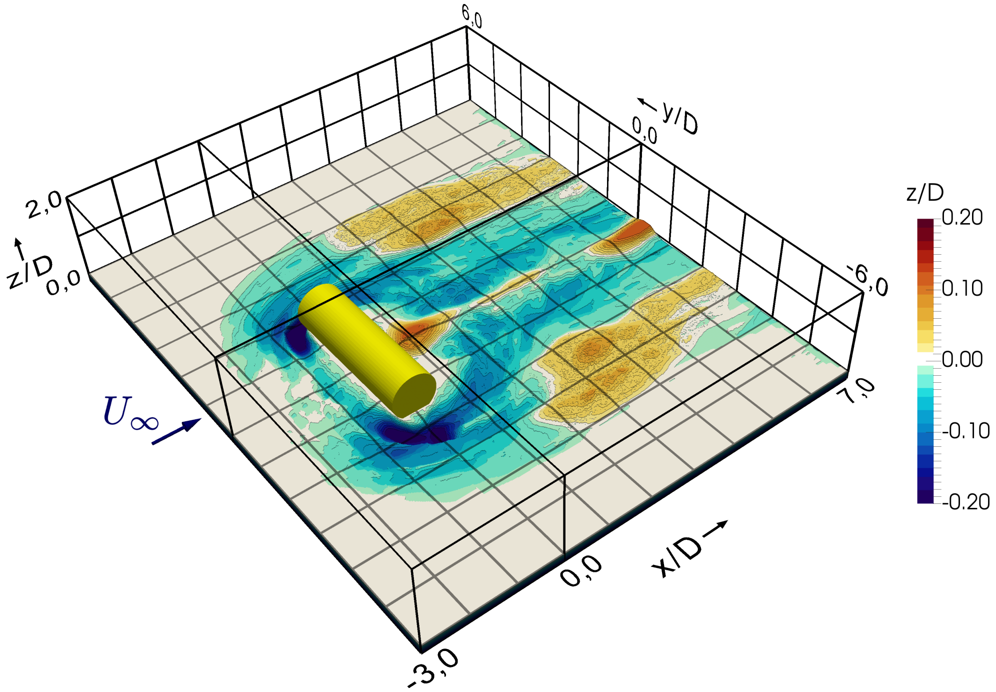

Figure 11: Scour and sedimentation in the vicinity of a horizontally bedded finite cylinder at Re = 1.7 × 10^4, as obtained from a lattice Boltzmann simulation of both the flow and sediment transport. This figure is taken from Helen Morrison's PhD thesis (2017).

5 Economic exploitation

The understanding of turbulent flows and their effects on sediment transport around various objects at the bottom of the ocean is particularly relevant for the offshore construction and marine industry, especially when it comes to improving their abilities of finding unexploded ordnance. The erosion and subsequent scouring around objects may also be relevant for offshore industries when it comes to improving the lifetime of their own developed structures, such as offshore wind farms. Within ILWAO-2, however, no attempt for such an commercial use of the obtained results was undertaken.

6 Contributions from cooperation partners

(see above)

7 Bachelor-, Master- and PhD-Theses

Note that all theses are closely related to the ILWAO graduate school (e. g., with presentations etc.) but not all of them were funded from the ILWAO project.

Bachelor's/Master's/PhD theses at IAP

[1] J. Bahnsen. Simulation von Schwerewellen - Anwendung des Raytracing-Programms GROGRAT. Bachelor's Thesis, Universität Rostock, 2014.

[2] S. Brune. *Analysis of the Global Spectrum of the Atmospheric Horizontal Kinetic Energy from the Boundary Layer to the Mesopause*. PhD thesis, Universität Rostock, 2012.

[3] K.-G. Eller. Lidarmessungen von Schwerewellen während stratosphärischer Erwärmungen in mittleren Breiten. Diplom, Universität Rostock, 2013.

[4] J. Hildebrand. *Wind and temperature measurements by Doppler Lidar in the Arctic middle atmosphere*. PhD thesis, Universität Rostock, 2014.

[5] C. Jürss. Untersuchung von Schwerewellen über Andenes im Januar 2016. Bachelor's Thesis, Universität Rostock, 2017.

[6] B. Kaifler. *Thermal structure and gravity waves in the Antarctic middle atmosphere observed by lidar*. PhD thesis, Universität Rostock, 2014.

[7] M. Kopp. *Ein neues tageslichtbasiertes RMR-Lidar: technischer Aufbau sowie geophysikalische Analyse von Temperaturgezeiten und NLC über Kühlungsborn ($54°$N, $12°$O)*. PhD thesis, Universität Rostock, 2017.

[8] V. Matthias. *The role of planetary waves in coupling processes of the middle atmosphere*. PhD thesis, Universität Rostock, 2014.

[9] M. Placke. *Gravity waves and momentum fluxes in the mesosphere and lower thermosphere region*. PhD thesis, Universität Rostock, 2014.

[10] Ch. Ridder. Relationship of gravity waves and small scale variations in noctilucent clouds. Master's thesis, Universität Rostock, 2014.

[11] M. Schlutow. A Positive Definite Scheme for Mass Conserving Spectral Tracer Transport in Global Climate Models. Diplom, Universität Rostock, 2012.

[12] A. Schneider. *In-situ turbulence observations in the stratospheric wind and temperature field*. PhD thesis, Universität Rostock, 2015.

[13] H. Schneider. Seasonal variation and short-term variability during SSWs of the gravity wave momentum flux. Master's thesis, Universität Rostock, 2016.

[14] F. Senf. *On the interaction between thermal tides and gravity waves in the middle atmosphere*. PhD thesis, Universität Frankfurt, 2012.

[15] J. Soeder. Development of a small-scale LITOS payload for turbulence measurements in the stratosphere. Master's thesis, Universität Rostock, 2014.

[16] S. Sommer. *Resolving the horizontal structure of mesospheric echoes applying modern radar approaches*. PhD thesis, Universität Rostock, 2016.

[17] B. Sommerfeld. Parameterisation of momentum transport due to cumulus-convection. Master's thesis, Universität Rostock, 2016.

[18] M. Stanev. Analysis of simultaneous wind measurements in the mesosphere using doppler-wind lidar and rocketsondes. Diplom, Universität Rostock, 2014.

[19] E. Sy. Windmessungen in der Mesosphäre - Kalibrierung der Jod-Spektrometer des ALOMAR RMR-Lidar. Bachelor's Thesis, Universität Rostock, 2013.

[20] A. Szewczyk. *Mesospheric turbulence: The role in the creation of mesospheric inversion layers and statistical results*. PhD thesis, Universität Rostock, 2015.

[21] A. Theuerkauf. *Stratospheric turbulence observations with the new balloon-borne instrument LITOS*. PhD thesis, Universität Rostock, 2013.

[22] H. Wilms. Einfluss von Schwerewellen auf mesosphärische Eisschichten. Master's thesis, Universität Rostock, 2012.

[23] B. Wolf. Parametrisierung orographischer Schwerewellen. Diplom, Universität Rostock, 2013.

[24] F. Zaage. Statistische Analyse vertikaler Kopplungsprozesse während stratosphärischer Erwärmungen. Master's thesis, Universität Rostock, 2012.

Bachelor's/Master's/PhD theses at IOW

[25] J. Becherer. *Estuarine Circulation in well-mixed tidal inlets*. PhD thesis, Universität Rostock, 2014.

[26] T. Boelke. Prozessierung und Analyse von marinen Temperaturmikrostrukturdaten. Master's thesis, Universität Rostock, 2012.

[27] R. Heyn. Effects of vertical shear on high-frequency internal motions in the Baltic Sea. Master's thesis, Universität Rostock, 2012.

[28] R. Kemsies. Observation and analysis of boundary-mixing induced by near-inertial waves in the Bornholm Basin. Master's thesis, Universität Rostock, 2013.

[29] K. Klingbeil. *Approaches for the improvement of physical transport processes in numerical models of the coastal ocean*. PhD thesis, Universität Rostock, 2014.

[30] X. Lange. Numerical simulations of estuarine circulation in a non-tidal estuary. Master's thesis, Universität Rostock, 2015.

[31] L. Lappe. *Boundary mixing in non-tidal basins: Observations from the Baltic Sea*. PhD thesis, Universität Rostock, 2017.

[32] M. Lorenz. Numerical study of the overturning circulation in the Persian Gulf. Master's thesis, Universität Rostock, 2017.

[33] M. Mohammadi-Aragh. *Impact of physically relevant and numerically induced diapycnal mixing and meso-scale dissipation on meridional mass and tracer transports in the Southern Ocean*. PhD thesis, Universität Hamburg, 2014.

[34] K. Purkiani. *Numerical analysis of stratification and destratification processes in tidally energetic inlets*. PhD thesis, Universität Rostock, 2015.

[35] E. Schulz. *Residual circulation in tidally energetic estuaries: contributions and dependencies*. PhD thesis, Universität Rostock, 2014.

[36] K. Schulz. *Suspended sediment transport near sloping topography*. PhD thesis, Universität Rostock, 2017.

[37] E. van der Lee. *Observation of internal waves in the Baltic Sea: Motions near the inertial and buoyancy frequencies*. PhD thesis, Universität Rostock, 2012.

Bachelor's/Master's/PhD theses at LSM

[38] M. Behrend. Ermittlung des Geschwindigkeitsprofils einer offenen Gerinneströmung auf verfestigtem Sandboden mittels LDA für numerische Simulationen. Bachelor's Thesis, Universität Rostock, 2015.

[39] K. Belovodski. Vergleich von Ergebnissen aus Labormessungen und numerischen Simulationen mit Messungen im Naturmaßstab. Bachelor's Thesis, Universität Rostock, 2014.

[40] T. Bestier. Charakterisierung einer Versuchsanlage zur Erzeugung von Oberflächenwellen. Bachelor's Thesis, Universität Rostock, 2015.

[41] S. Eilek. Turbulenzmodellierung mit dem Lattice Boltzmann Code „palabos“. Master's thesis, Universität Rostock, 2014.

[42] M. Focke. Numerische Simulationen des Verhaltens interner Wellen an einer geneigten Ebene. Bachelor's Thesis, Universität Rostock, 2011.

[43] J. C. Graumann. Untersuchung der Versandung zylindrischer und kegelstumpfförmiger Objekte im Wasserkanal. Bachelor's Thesis, Universität Rostock, 2014.

[44] M. Heimbuch. Auslegung, Fertigung und Erprobung eines Wellengenerators. Bachelor's Thesis, Universität Rostock, 2014.

[45] N. Karow. Strömungs- und Strukturmessungen mittels Volumetric Light Field Velocimetry. Master's thesis, Universität Rostock, 2015.

[46] H. Kaufmann. Aufbau einer Anlage zur Erzeugung und Absorption von Oberflächenwellen. Bachelor's Thesis, Universität Rostock, 2015.

[47] W. Knorr. Time–Resolved Stereo–PIV–Messungen im Nachlauf eines quer zur Strömung auf einer Endscheibe lagernden Zylinders. Bachelor's Thesis, Universität Rostock, 2013.

[48] N. Kurth. Time–Resolved Stereo–PIV–Messungen seitlich und vor einem quer zur Strömung auf einer Endscheibe. Bachelor's Thesis, Universität Rostock, 2013.

[49] E. Labs. Untersuchung der Umströmung eines Kegelstumpfes und eines versandeten Zylindersmittels TR–Stereo–PIV im Windkanal. Bachelor's Thesis, Universität Rostock, 2014.

[50] S. Michelis. Optimierung der Einlassbedingungen im Wasserkanal mittels optischer Strömungsmesstechnik. Bachelor's Thesis, Universität Rostock, 2012.

[51] H. Morrison. *Lattice Boltzmann Simulationen zur Umströmung von Objekten am Meeresboden*. PhD thesis, Universität Rostock, 2017.

[52] R. Nimz. Untersuchung der Versandung von Objekten am Meeresboden unter Einfluss von Oberflächenwellen. Bachelor's Thesis, Universität Rostock, 2015.

[53] T. Rückborn. *Numerische Simulation von Sedimenttransport im Umfeld versandeter Zylinder*. PhD thesis, Universität Rostock, 2017.

[54] G. Schlettwein. Numerische Simulationen mittels der Lattice–Boltzmann–Methode. Bachelor's Thesis, Universität Rostock, 2012.

[55] M. Schmudlach. LDA–Messungen im Wasserkanal. Bachelor's Thesis, Universität Rostock, 2012.

[56] L. Schnellhammer. Time–Resolved Stereo–PIV–Messungen an einem quer zur Strömung auf einer Endscheibe lagernden Zylinder. Bachelor's Thesis, Universität Rostock, 2012.

[57] C. Schütt. Versandungsmessung mittels eines Laserabstandssensors. Bachelor's Thesis, Universität Rostock, 2015.

[58] T. Schwerdtfeger. Untersuchung der Umströmung eines versandeten Zylinders mittels TR–Stereo–PIV im Windkanal. Bachelor's Thesis, Universität Rostock, 2015.

[59] H. S. Tran. Vermessung der zeitlich veränderbaren Strömungsgeschwindigkeit und Bodenstruktur mit einer Lichtfeldkamera. Master's thesis, Universität Rostock, 2015.

[60] S. Welker. Untersuchungen zur Versandung von Objekten im Wasserkanal mit laseroptischer Messtechnik. Bachelor's Thesis, Universität Rostock, 2013.

8 References

A complete list of publications from ILWAO-2 is presented in appendix 11.2.

9 Backup and availability of research data

The original research data are safely stored at the individual institutes. Several measures are installed (e.g. backups on file servers) to guarantee that these data are available for future applications. Data being published in peer review journals are frequently stored separately, following demands from the publishing companies.

10 Press releases and reports in media

We published a press release when starting ILWAO in 2008 which triggered substantial coverage in various news papers and public media (e.g. internet). Furthermore, several activities within ILWAO were reported in a local newspaper ('Ostseezeitung') and also by 'Leibniz-Nordost', which is a newsletter of the five Leibniz-Institutes in Mecklenburg-Vorpommern.

11 Appendices

11.1 Publication list

Publication list of ILWAO-2 for the period 2012 - 2017, sorted according to institutes and in alphabetical order. **Note that all publications are closely related to the ILWAO graduate school (e. g., with presentations in the seminars etc.) but only a fraction was actually funded directly from the ILWAO project.**

Publications in journals from IAP

[1] R. A. Akmaev, J. M. Forbes, F.-J. Lübken, D. J. Murphy, and J. Höffner. Tides in the mesopause region over Antarctica: Comparison of Whole Atmosphere Model simulations with ground-based observations. *J. Geophys. Res.*, 121:1156–1169, 2016.

[2] G. Baumgarten, J. Fiedler, J. Hildebrand, and F.-J. Lübken. Inertia gravity wave in the stratosphere and mesosphere observed by Doppler wind and temperature lidar. *Geophys. Res. Lett.*, 42:10,929–10,936, 2015.

[3] G. Baumgarten and D. C. Fritts. Quantifying Kelvin-Helmholtz instability dynamics observed in Noctilucent Clouds: 1. methods and observations. *J. Geophys. Res.*, 119:9324–9337, 2014.

[4] K. Baumgarten, M. Gerding, G. Baumgarten, and F.-J. Lübken. Temporal variability of tidal and gravity waves during a record long 10 day continuous lidar sounding. *Atmos. Chem. Phys.*, 2017. submitted.

[5] K. Baumgarten, M. Gerding, and F.-J. Lübken. Seasonal variation of gravity wave parameters using different filter methods with daylight lidar measurements at mid-latitudes. *J. Geophys. Res.*, 122:2683–2695, 2017.

[6] E. Becker. Dynamical control of the middle atmosphere. *Space Sci. Rev.*, 2012.

[7] E. Becker. Mean-flow effects of thermal tides in the mesosphere and lower thermosphere. *J. Atmos. Sci.*, 74:2043–2063, 2017.

[8] E. Becker and S. Brune. Reply to “Comments on ‘Indications of stratified turbulence in a mechanistic GCM’ ”. *J. Atmos. Sci.*, 71:858–862, 2014.

[9] E. Becker, R. Knöpfel, and F.-J. Lübken. Dynamically induced hemispheric differences in the seasonal cycle of the summer polar mesopause. *J. Atmos. Solar-Terr. Phys.*, 129:128–141, 2015.

[10] E. Becker and S. L. Vadas. Secondary gravity waves in the winter mesosphere: Results from a high-resolution global circulation model. *J. Geophys. Res.*, 2017. submitted.

[11] O. Bothe, J. H. Jungclaus, and D. Zanchettin. Consistency of the multi-model CMIP5/PMIP3-past1000 ensemble. *Climate of the Past*, 9(6):2471–2487, 2013.

[12] S. Brune and E. Becker. Indications of stratified turbulence in a mechanistic GCM. *J. Atmos. Sci.*, pages 231–247, 2013.

[13] R. Büttner, M. Brede, F.-J. Lübken, and A. Leder. Experimentelle Untersuchungen zur Ausbreitung und Transition interner Wellen. In *Fachtagung 'Lasermethoden in der Strömungsmesstechnik', 4. - 6. September 2012, Rostock*, 2012.

[14] L. C. Chang, W. E. Ward, S. E. Palo, J. Du, D.-Y. Wang, H.-L. Liu, M. E. Hagan, Y. Portnyagin, J. Oberheide, L. P. Goncharenko, T. Nakamura, P. Hoffmann, W. Singer, P. Batista, B. Clemesha, A. H. Manson, D. M. Riggin, C.-Y. She, T. Tsuda, and T. Yuan. Comparison of diurnal tide in models and ground-based observations during the 2005 equinox CAWSES tidal campaign. *J. Atmos. Solar-Terr. Phys.*, 78–79:19–30, 2012.

[15] J. L. Chau, P. Hoffmann, N. M. Pedatella, V. Matthias, and G. Stober. Upper mesospheric lunar tides over middle and high latitudes during sudden stratospheric warming events. *J. Geophys. Res.*, 120:3084–3096, 2015.

[16] J. L. Chau, G. Stober, C. M. Hall, M. Tsutsumi, F. I. Laskar, and P. Hoffmann. Polar mesospheric horizontal divergence and relative vorticity measurements using multiple specular meteor radars. *Radio Sci.*, 52:811–828, 2017.

[17] J. F. Conte, J. L. Chau, G. Stober, N. Pedatella, A. Maute, P. Hoffmann, D. Janches, D. Fritts, and D. Murphy. Climatology of semidiurnal lunar and solar tides at middle and high latitudes: Interhemispheric comparison. *J. Geophys. Res.*, 122, 2017.

[18] D. Demirhan-Bari, A. Gabriel, H. Körnich, and D. H. W. Peters. The effect of zonal asymmetries in the Brewer-Dobson circulation on ozone and water vapor distributions in the northern middle atmosphere. *J. Geophys. Res.*, 118:3447–3466, 2013.

[19] T. D. Demissie, P. J. Espy, N. H. Kleinknecht, M. Halten, N. Kaifler, and G. Baumgarten. Characteristics and sources of gravity waves observed in noctilucent cloud over Norway. *Atmos. Chem. Phys.*, 14:12133–12142, 2014.

[20] D. C. Fritts, G. Baumgarten, K. Wan, J. Werne, and T. Lund. Quantifying Kelvin-Helmholtz instability dynamics observed in Noctilucent Clouds: 2. modeling and interpretation of observations. *J. Geophys. Res.*, 119:9359–9375, 2014.

[21] D. C. Fritts, H. Iimura, R. Lieberman, D. Janches, and W. Singer. A conjugate study of mean winds and planetary waves employing enhanced meteor radars at Rio Grande, Argentina (53.8°S) and Juliusruh, Germany (54.6°N). *J. Geophys. Res.*, 117, 2012.

[22] D. C. Fritts, P.-D. Pautet, K. Bossert, M. J. Taylor, B. P. Williams, H. Iimura, T. Yuan, N. J. Mitchell, and G. Stober. Quantifying gravity wave momentum fluxes with mesosphere temperature mappers and correlative instrumentation. *J. Geophys. Res.*, 119:13583–13603, 2014.

[23] D. C. Fritts, L. Wang, G. Baumgarten, A. D. Miller, M. A. Geller, G. Jones, M. Limon, D. Chapman, J. Didier, C. B. Kjellstrand, D. Araujo, S. Hillbrand, A. Korotkov, G. Tucker, and J. Vinokurov. High-resolution observations and modeling of turbulence sources, structures, and intensities in the upper mesosphere. *J. Atmos. Solar-Terr. Phys.*, 162:57–78, 2017.

[24] A. Gabriel. Long-term changes in the northern mid-winter middle atmosphere in relation to the quasibiennal oscillation. *J. Geophys. Res.*, 2017. submitted.

[25] A. Gaßmann. A global hexagonal C-grid non-hydrostatic dynamical core (ICON-IAP) designed for energetic consistency. *Quart. J. R. Met. Soc.*, 139:152–175, 2012.

[26] A. Gaßmann. Entropy production due to subgrid-scale thermal fluxes with application to breaking gravity waves. *Quart. J. R. Met. Soc.*, 2017. submitted.

[27] A. Gaßmann and H.-J. Herzog. How is local material entropy production represented in a numerical model? *Quart. J. R. Met. Soc.*, 2014.

[28] M. Grygalashvyly, E. Becker, and G. R. Sonnemann. Gravity wave mixing and effective diffusivity for minor chemical constituents in the mesosphere/lower thermosphere. *Space Sci. Rev.*, 168:333–362, 2012.

[29] A. Haack, M. Gerding, and F.-J. Lübken. Characteristics of stratospheric turbulent layers measured by LITOS and their relation to the Richardson number. *J. Geophys. Res.*, 119:10605–10618, 2014.

[30] M. He, J. L. Chau, G. Stober, C. M. Hall, M. Tsutsumi, and P. Hoffmann. Application of Manley-Rowe relation in analyzing nonlinear interactions between planetary waves and the solar semidiurnal tide during 2009 sudden stratospheric warming event. *J. Geophys. Res.*, 2017. submitted.

[31] S. Hien, J. Rolland, S. Borchert, L. Schoon, C. Zülicke, and U. Achatz. Spontaneous gravity wave emission in the diff erentially heated rotating annulus experiment. *J. Fluid Mech.*, 2017. submitted.

[32] J. Hildebrand, G. Baumgarten, J. Fiedler, U.-P. Hoppe, B. Kaifler, F.-J. Lübken, and B. P. Williams. Combined wind measurements by two different lidar instruments in the Arctic middle atmosphere. *Atmos. Meas. Tech.*, 5:2433–2445, 2012.

[33] J. Hildebrand, G. Baumgarten, J. Fiedler, and F.-J. Lübken. Winds and temperatures of the Arctic middle atmosphere during January measured by Doppler lidar. *Atmos. Chem. Phys.*, 17(21):13345–13359, 2017.

[34] D. L. Hysell, D. C. Fritts, B. Laughman, and J. L. Chau. Gravity wave-induced ionospheric irregularities in the postsunset equatorial valley region. *J. Geophys. Res.*, 122, 2017. accepted.

[35] C. Jacobi, N. Samtleben, and G. Stober. Meteor radar observations of mesopause region long-period temperature oscillations. *Adv. Radio Sci.*, 14:169–174, 2016.

[36] B. Kaifler, F.-J. Lübken, J. Höffner, R. J. Morris, and T. P. Viehl. Lidar observations of gravity wave activity in the middle atmosphere over Davis (69°S, 78°E), Antarctica. *J. Geophys. Res.*, pages 4506–4521, 2015.

[37] N. Kaifler, G. Baumgarten, J. Fiedler, and F.-J. Lübken. Quantification of waves in lidar observations of noctilucent clouds at scales from seconds to minutes. *Atmos. Chem. Phys.*, 13:11757–11768, 2013.

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[42] G. Kishore Kumar, W. Singer, J. Oberheide, N. Grieger, P. P. Batista, D. M. Riggin, H. Schmidt, and B. R. Clemesha. Diurnal tides at low latitudes: Radar, satellite, and model results. *J. Atmos. Solar-Terr. Phys.*, 118:96–105, 2014.

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[46] Q. Li, M. Rapp, A. Schroen, A. Schneider, and G. Stober. Derivation of turbulent energy dissipation rate with the Middle Atmosphere Alomar Radar SYstem MAARSY and radiosondes at Andøya, Norway. *Ann. Geophys.*, 34:1209–1229, 2016.

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