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

Proposal in the frame of the „Pakt für Forschung“
to the „Senatsausschuss Wettbewerb (SAW) der WGL“
from a network of the following institutions:

Leibniz-Institute of Atmospheric Physics
Kühlungsborn
Prof. Dr. Franz-Josef Lübken
(applicant and speaker)
Prof. Dr. Markus Rapp
Prof. Dr. Erich Becker

Leibniz-Institute for Baltic Sea Research (IOW)
Warnemünde
Prof. Dr. Hans Burchard

Laboratory of Fluid Mechanics (LSM)
Rostock University
Prof. Dr. Alfred Leder

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1. Introduction

An international Leibniz Graduate School called ILWAO was founded in summer 2008 as part of the „SAW-Verfahren“. ILWAO-1 involved PhD students, University professors and other scientists from two Leibniz-Institutes (IAP and IOW), and from the Rostock University. As will be explained in more detail in section 3 this graduate school turned out to be very successful in terms of scientific cooperation and education for students. During a closing meeting in October 2010 there was overwhelming consensus that such a successful cooperation should be continued. Since this cooperation concentrates on specific aspects of atmospheric physics and oceanography, it is not planned as a long-term commitment and should therefore not be part of the WGL institutional funding. The latter would also effectively exclude the participation of the University institute in ILWAO (note that PhD students at LSM during ILWAO-1 were funded through this project).

We decided to apply for a second phase of ILWAO for a number of reasons. Probably most important, this strengthens a very successful scientific cooperation between institutes studying similar phenomena from different perspectives (atmosphere, ocean, laboratory studies). Several new scientific topics of common interest were identified during the first phase of ILWAO which should be studied in the future. PhD students involved in ILWAO broaden their view on experimental and theoretical aspects of fluid mechanics in a wide range of applications. Most students currently involved in ILWAO have started their theses after ILWAO began, i. e., they are not yet finished with their work. A second phase of ILWAO would allow them to finish their theses in a stimulating environment. The bachelor/master program has started only recently at the Rostock University. Professors from IAP and IOW lecture specific courses within the physics master program, namely „Physics of the Atmosphere and Ocean“. This is the only program of this kind in Germany. We can expect to attract even more students in the future. Last not least, ILWAO has been an advertisement for WGL, in particular regarding cooperation between Leibniz institutes and the University. Terminating ILWAO would significantly handicap future common activities.

It should be noted that the Science Advisory Board of IAP (Wissenschaftlicher Beirat) in its report from the latest meeting on 20/21 October 2010 explicitly support a second phase of ILWAO[a)]. The funding requested in this proposal is basically for PhD students at the three institutes. It should be noted that this is the only proposal of IAP in the SAW application procedure for 2012, i. e., we do not try to get extra funding on top of a regular SAW proposal. In the following we describe in more detail the scientific background, the achievements from ILWAO-1, and the scientific goals for the second phase of ILWAO.

2. Scientific Background

Gravity waves (GW) and turbulence play a crucial role for atmospheric physics and oceanography since they significantly influence the energy and momentum budget as well as the transport of trace gases and other solutes. Since gravity waves propagate over large horizontal and vertical distances they act as an important coupling mechanism in the atmosphere and

[a)] Quotation from the report: „Dies ist besonders wichtig, da sich die Anzahl der Doktoranden und Diplomanden in den letzten Jahren sehr erfreulich entwickelt hat. In diesem Zusammenhang spielt auch die internationale Leibniz Graduiertennschule für Schwerewellen und Turbulenz in der Atmosphäre und im Ozean (ILWAO) eine bedeutende Rolle. ILWAO stärkt die Kooperation des IAP mit anderen hochkarätigen Einrichtungen in Mecklenburg-Vorpommern und ist eine hervorragende Einrichtung zur gemeinsamen Ausbildung von Doktoranden. Es wäre sehr bedauerlich, wenn eine solch erfolgreiche Graduiertenschule nach einer relativ kurzen Anlaufzeit beendet werden müsste. Der Beirat unterstützt daher eine geeignete Fortführung von ILWAO uneingeschränkt.

in the ocean. Two Leibniz institutes in Mecklenburg-Vorpommern study the atmosphere and ocean, respectively, and are therefore concerned with gravity waves and turbulence. Various experimental and theoretical techniques are applied, some of which are unique world wide. Waves and turbulence phenomena are also studied in laboratory experiments at the Rostock University. In several workshops and seminars during ILWAO-1 the common scientific interest in waves and turbulence was highlighted and collaborative studies were initiated.

3. Achievements in the first phase of ILWAO

Several PhD theses were promoted within ILWAO and a significant number of manuscripts have been published (see list in the Appendix). Common seminars and workshops with participants from all three institutes were organized in each semester. Several national and international experts were invited to stimulate the discussion. The workshops and seminars were also an important part of the education of PhD students and gave them a chance to present their results. In the following only few scientific highlights are described. More details are given in the references listed in the Appendix.

Gravity waves, tides, and winds from lidar: Only since a few years quasi-continuous temperature measurements are available from the ground to the MLT[b]. This capability was used to derive a first morphology of gravity waves at 54°N and 69°N, including seasonal variation of amplitudes, wavelengths, dissipation etc. A tentative comparison with local wind fields in the stratosphere did not show a significant correlation between GW activity and winds. Therefore, ray tracing model simulations shall be used to identify more closely potential sources and sinks of gravity waves. The lidar technique was developed further to allow for daylight measurements which is obviously essential for applications at summer polar latitudes. First measurements of thermal tides at 69°N showed surprisingly large amplitudes, much larger than expected from models. The phase of these tides is in nice agreement with mesospheric ice layers being modulated with local time. A comprehensive comparison with radar wind tides and an explanation why tides are so large in the polar summer MLT region is pending. A new lidar technique to measure winds in the stratosphere and mesosphere called DORIS[c] was recently developed at IAP. This method allows to measure winds quasi continuously in a height range where no other technique is available (apart from sporadic rocket launchings). Comparison with radar and balloon data shows good agreement where measurements overlap. Even gravity waves were detected in the wind field which opens a new range of capabilities for scientific studies.

Gravity waves and winds from radars: Radar scattering from meteor trails was used to derive short period gravity wave amplitudes and momentum fluxes in the MLT region at middle and polar latitudes. Gravity wave activity shows a maximum in summer and a secondary weaker maximum in winter with stronger magnitudes at high latitudes. For the first time the experimental results were compared with a new model called KMCM[d] which simulates gravity waves in the MLT region with high spatial resolution. Measurements and models show similarities in terms of wind variances and momentum flux. The seasonal and latitudinal variation of gravity wave activity in the MLT region is to a certain extent explained by wave filtering and breaking in the stratosphere and lower mesosphere.

Combining lidars and radars: For the first time a combined analysis of mesospheric gravity waves from simultaneous wind (from radar) and temperature (from lidar) measurements was

[b] MLT=mesosphere/lower thermosphere (50-120 km)
[c] DORIS=Doppler Rayleigh Iodine System
[d] KMCM=Kühlungsborn Mechanistic general Circulation Model

performed. This allows, for example, to study the predictions of linear wave theory, such as the polarization relation. The synergy of both techniques comes from the combination of quasi continuous wind data (but in a limited height range) with temperatures in the entire height range from 10 to 120 km (but with interruptions due to bad weather). In this context, a new lidar technique for day time measurements was established. In a case study, similar dominant wave modes with periods between 6 and 11 h were found in meridional wind and temperature fluctuations with a phase shift of 180°. The main characteristics of these waves were reproduced by KMCM which describes the generation, propagation, and dissipation of waves.

Turbulence from balloons: A new balloon-borne instrument called LITOS[e)] was developed for the detection of small scale turbulent fluctuations of winds and temperatures in the lower stratosphere. The aim is to quantify turbulent processes which are important for damping of gravity waves and for transporting trace gases from lower to higher altitudes. Several flights took place from Kühlungsborn and from Kiruna (68°N, Sweden). The spatial resolution of LITOS is a few millimeters only, which permits to derive turbulence parameters in unprecedented quality. Layers with large turbulent energy dissipation rates were identified. A detailed comparison with numerical model simulations is pending.

Explicit simulation of gravity waves in the atmosphere: The KMCM model was used to study mesoscale motions in the troposphere which are important for climate dynamics because they transform kinetic energy generated by large-scale weather systems to three-dimensional small-scale turbulence. However, basically all GCMs cannot simulate the transition from a -3 to a -5/3 spectral slope in the horizontal energy spectrum. We analyzed the horizontal kinetic energy spectrum with KMCM. The model employs an advanced parametrization of subgrid-scale turbulent diffusion. Indeed, the model is capable of reproducing the transition from the synoptic -3 to the mesoscale -5/3 spectral slope of the kinetic energy spectrum at $\sim$ 10 km height. Analysis of the spectral energy budget reveals a horizontal energy cascade which is indicative of stratified macroturbulence. The high-resolution version of KMCM was extended up to the lower thermosphere. For the first time, wave driving of the residual circulation in the upper mesosphere was modeled explicitly in a self-consistent way.

Simulations of wave transport in the atmosphere: The dynamical data of KMCM were used to force the IAP mesospheric chemistry transport model MECTM[f)]. This allowed for the first time to consider the effects of GWs on the photo-chemistry in the MLT region on a global scale. A sensitivity experiment reveals that GWs have profound vertical mixing effects on all relevant long-living minor constituents in the MLT, inducing feedbacks on short-living compounds. It is well known in oceanography that vertical mixing due to GWs occurs on top of GW-induced turbulence. To the best of our knowledge this concept was for the first time applied in middle atmosphere physics. This application was developed within ILWAO which demonstrates the potential synergy effects of scientific cooperations.

Observations of near-inertial waves in the Bornholm Sea: High-resolution observations of near-inertial wave motions have been carried out for the Bornholm Basin (Baltic Sea) for summer and winter stratification during several research cruises from 2008 to 2010. These motions were shown to be associated with persistent narrow shear-bands, strongly correlated with bands of enhanced dissipation rates which are the major source of mixing inside the permanent halocline. In spite of strongly varying stratification and different atmospheric forcing conditions, the observed mixing rates were found to scale with local shear and stratification

[e)] LITOS=Leibniz Institute Turbulence Observations in the Stratosphere

[f)] MECTM=Mesospheric Chemistry Climate Model

in a nearly identical way. This scaling is largely consistent with a proposal recently developed for internal-wave mixing on the continental shelf. Our high-resolution data also showed the presence of high-frequency internal wave modes near the buoyancy period (around 5 min), suggesting that the interaction of these waves with the near-inertial shear bands is tightly connected to the enhanced dissipation rates. This interaction of high- and low-frequency motions is crucial for most fine-scale parameterizations and will therefore be one of the focal points in the future. Apart from mixing processes in the interior, densely spaced microstructure turbulence measurements have revealed the importance of boundary mixing driven by near-inertial currents. These boundary mixing processes may provide an important or even dominant contribution to mixing on the basin scale.
Non-hydrostatic extension of a coastal ocean model: Non-hydrostatic pressure gradients have been implemented into a regional ocean model (GETM[g)]) which is a prerequisite for quantifying the effect of high-frequency internal waves on turbulence and mixing in stratified oceanic basins. A new approach was applied, namely to directly include the vertical velocity equation into the non-hydrostatic pressure gradient formulation. This allows for a flexible extension towards better resolving non-hydrostatic pressure gradients. The model extension has been validated for a large ensemble of idealized test cases, including generation of internal waves at the entrance to a fjord.
Internal wave studies in the laboratory: A standard experiment for a controlled generation of internal waves was defined and set up using a wave generator inside the flow tank for stratified shear flow. Internal waves were successfully excited and propagated depending on the underlying stratification. The wave propagation was modeled using a new improved 3 layer model. The turbulence field was determined in addition to the density field. The qualification of the experimental facility was completed within the timeframe of ILWAO 1. Ongoing research covers the measurement of turbulence parameters with respect to internal wave generation.

4. Plans for second phase of ILWAO

Gravity wave and background observations with lidar, radar, balloons, and rockets: We intend to continue and expand our observations of gravity waves, tides, turbulence, and background parameters such as temperatures and winds. Apart from the experimental techniques mentioned above, several new tools will be available. For example, routine wind measurements by DORIS are now available in the mesosphere which (in combination with radar winds) allows for the first time to detect gravity waves and their filtering by winds from the troposphere to the MLT region. IAP has built one of the largest VHF radar worldwide at polar latitudes (69°N) called MAARSY[h)] which allows unprecedented detection of horizontal structures of turbulence. The interaction between GWs and turbulence will be investigated in the tropo-/stratosphere, and during summer also in the mesosphere. Information about horizontal structures also comes from OH airglow observations and from lidar tomography. Momentum fluxes derived from meteor radar measurements shall be compared and validated with similar measurements from sophisticated MF radar Doppler winds at middle and polar latitudes. Such narrow-beam Doppler MF radars are only available at IAP.

Since November 2010 IAP is running a Fe lidar at Antarctic latitudes (Davis, 69°S) which has already produced unexpected results. Together with the observations of our Australian partners this promises to give new insight in interhemispheric differences of GW morphology.
Influence of GWs on mesopheric ice clouds: Ice clouds in the summer mesosphere at middle

[g)] GETM=General Estuarine Transport Model
[h)] MAARSY=Middle Atmosphere Alomar Radar SYstem

and polar latitudes show spectacular GW features. There are hints for an anti-correlation of short period GWs and the occurrence of mesospheric ice clouds observed as noctilucent clouds (NLC) by lidar and as polar mesosphere summer echoes (PMSE) by VHF radars. We intend to compare NLC/PMSE activity with simultaneous observations of background conditions and gravity waves in winds and temperatures.
WADIS campaign: Within the sounding rocket project WADIS[i)] (funded by DLR) two campaigns will take place at the Andoya Rocket Range (69°N) in 2012 and 2013 with an unprecedented setup of experimental techniques. Rocket-borne turbulence sensors will detect horizontal structures of turbulence. Radars, lidars, and other groundbased instruments (airglow, imaging temperature mapper, etc.) will provide detailed information about the background atmosphere and waves. Turbulence in the troposphere/lower stratosphere is detected by radars and by our balloon borne sensor LITOS. The aim of WADIS is to measure the entire chain of GW generation, propagation, filtering, and dissipation from the troposphere to the MLT region.

The observations mentioned above shall be further analyzed applying modeling. The goal is to better understand the physical processes behind gravity waves, and potential implications for the energy and momentum budget, as well as transport of trace gases in global models.
Progress in atmospheric modeling: It has been criticized that a turbulence model with a prescribed mixing length is not compatible with the scale-invariance of turbulent stress in the inertia range. We intend to continue our theoretical studies to design a new, scale-invariant diffusion scheme for application in KMCM and other models. First simulations indicate that this new scheme successfully simulates the macroturbulence spectrum without the need for an artificial hyperdiffusion. We plan to apply these ideas also to the mesosphere. A new method for mass-conserving tracer transport was developed which allows to couple MECTM directly to KMCM and to study vertical and horizonal mixing by gravity waves with a consistent representation of resolved and parameterized scales. A new radiative-transfer scheme was developed for KMCM and will be used to study the effects of GWs on radiation under non-LTE [j)] conditions. The question is how the interactions of GWs and radiative transfer feed back on GW-mixing of minor constituents. We also plan to adopt the new community model ICON[k)] and to implement the theoretical results mentioned above, in particular regarding macroturbulence and the role of non-hydrostatic GWs in the mesosphere.
Resolving shear-instabilities and their drivers in Baltic Sea basins: The observations during ILWAO-1 allowed us to associate shear-bands with regions of enhanced mixing as described above. But the vertical resolution was too low to study the breaking process in detail. We plan to base new observations in the Bornholm Basin on a nested instrumental approach using various short-term deployments: the water column of approximately 90 m depth will be sampled simultaneously with different moored Acoustic Current Profilers (ADCPs) and moored Conductivity-Temperature-Depth (CTD) loggers, each covering different temporal and spatial resolution. Apart from this bottom-mounted instrumentation, we plan to locate an instrument platform directly inside the shear-bands mentioned above. Mixing parameters will be provided from (a) simultaneous microstructure ship observations, and (b) from the „structure function approach“ to infer dissipation rates from high-resolution velocity profiles. With this, we will be able to resolve individual shear-instabilities, and relate them to the large-scale internal-wave field and local changes in mixing. We plan to test some of the closure

[i)] WADIS=Wellenausbreitung und Dissipation in der mittleren Atmosphäre: Energiebudget und Spurenstoffverteilung

[j)] LTE=Local Thermodynamic Equilibrium

[k)] ICON=ICOsahedral Non-hydroststatic general circulation model assumptions in the internal-wave parametrization described above. Our second study site will be the Gotland Basin, the largest of the deep basins of the central Baltic Sea, where IOW has recently established an autonomous profiling station. We plan to extend this profiler platform with instrumentation to infer internal-wave parameters and mixing rates at the vertical scale of individual shear-instabilities. Shear data at sufficiently high resolution will be provided by an acoustic current meter, and high-resolution stratification will be measured by the existing CTD system. Mixing rates will be inferred from temperature and conductivity microsensors.

The numerical modelling during ILWAO-2 will follow two major tasks: The internal mixing parameterisation for shelf seas suggested some years ago in the literature (supported by results from ILWAO-1) will be refined using data from ILWAO-1 and ILWAO-2. Since this parameterisation depends on both vertical shear and stratification, the new high-resolution shear data from ILWAO-2 will give new insights into the dependence of mixing on these parameters. Existing internal mixing parameterisations in GOTM[1)] will be supplemented by this new parameterization and will be tested against observational data for various scenarios in stratified basins. Finally, the turbulence parameterisation will be implemented into the 3D model GETM to quantitatively reproduce observed inertial motions in the Bornholm Sea and other basins of the Baltic Sea. While the large hydrostatic scales will be resolved by the model, it is the aim to consistently parameterize the smaller non-hydrostatic scales and their feedback to the larger scales.

Laboratory investigations of internal waves: Focus of laboratory experiments for the second phase of ILWAO will be the interaction between topography and stratified flow. The experimental setup has proven to be a unique facility to generate density and velocity fields in a stratified flow and to measure these fields simultaneously with high time resolution. Using this setup it is planned to determine the generation of internal waves above topographic elevations and to measure the subsequent transition to turbulence. This experiment will clarify the wave-turbulence coupling for several configurations relevant for oceanographic and atmospheric research, for example, clear-air turbulence near mountains and turbulence generation on ocean ridges and sills. Further advances are expected from the evaluation of these cases in numerical simulations in cooperation with the IAP and the IOW.

5. Time schedule for the second phase of ILWAO

2011	2012	2013	2014	2015
termination of PhD theses detailed planning of 2nd phase: science topics, seminars etc. definition of topics for future PhD theses				
	project start			
	organising seminars and workshops, invite national and international scientists			
	lectures with special emphasis on ILWAO related topics ; supervising PhD theses			
	period for the next group of PhD theses			
			internal evaluation	final report
				project end

1) GOTM=General Ocean Turbulence Model, www.gotm.net

6. Appendix: Publications

In the following we list papers only which are prepared in the framework of ILWAO and with major participation from PhD students from ILWAO. Other publications closely related to ILWAO are listed separately. Several presentations were given during international symposia (not listed here).

Publications within first phase of ILWAO

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Placke, M., P. Hoffmann, E. Becker, C. Jacobi, W. Singer, and M. Rapp (2011a), Gravity wave momentum fluxes in the MLT–Part II: Meteor Radar investigations at high and mid latitudes in comparison with modeling studies, *J. Atmos. Solar-Terr. Phys.*, doi: 10.1016/j.jastp.2010.05.007, in press.

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Senf, F., and U. Achatz (2011), On the impact of middle-atmosphere thermal tides on the propagation and dissipation of gravity waves, *J. Geophys. Res.*, submitted.

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PhD thesis from ILWAO

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Klingbeil, K. (2009-2013), Numerical modelling of internal wave dynamics in stratified basins, Ph.D. thesis, Rostock University.

Knöpfel, R. (2011), Einheitliche Berechnung des Strahlungstransfers von der Oberfläche bis zur unteren Thermosphäre, Ph.D. thesis, Rostock University.

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Placke, M. (2012), Schwerewellenmessungen in Winden und Temperaturen mit Radar- und Lidargeräten, Ph.D. thesis, Rostock University.

Renkwitz, T. (2013), Horizontal aufgelöste Beobachtungen in der Mesopausenregion: Methodik und Ergebnisse, Ph.D. thesis, Rostock University.

Schneider, A. (2013), Turbulenzmessungen mit Ballons in der Stratosphäre, Ph.D. thesis, Rostock University.

Senf, F. (2011), Wechselwirkung von Schwerewellen und thermischen Gezeiten, Ph.D. thesis, Rostock University.

Theuerkauf, A. (2011), Hochaufgelöste Temperatur- und Geschwindigkeitsmessungen zum Nachweis von Turbulenz in der Stratosphäre, Ph.D. thesis, Rostock University.

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