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Gerrit Lohmann · Helge Meggers
Vikram Unnithan · Dieter Wolf-Gladrow
Justus Notholt · Astrid Bracher *Editors*

Towards an Interdisciplinary Approach in Earth System Science

Advances of a Helmholtz Graduate Research School

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Introduction

Earth System Science—Past Experiences and Future Trends

Vikram Unnithan, Astrid Bracher, Klaus Grosfeld, Annette Ladstätter-Weißenmayer, Gerrit Lohmann, Helge Meggers, Justus Notholt and Dieter Wolf-Gladrow

Abstract Earth System Science has developed over the last two decades from an interesting concept in Earth sciences education to a fully integrative science focussed on understanding the complex system Earth. This evolution is partially due to the radical and far reaching anthropogenic changes and the general feeling of helplessness with regards to the possible consequences and future impacts on the Earth System. This paper proposes that a paradigm shift in undergraduate and graduate education is needed to further develop Earth System Science. Graduate programs such as the Earth System Science Research School (ESSReS), which are intrinsically trans- and interdisciplinary will help to change rigid subject specific mind-set among faculty and students. The health and sustainability of our planet is at stake.

1 Introduction

Astronomers have been looking for habitable planets for many decades (Fritz et al. 2014). It could be argued that the primary motivation was not to find other life forms but to find a suitable alternative for Earth. If some of the doom and gloom scenarios (Elliott and Hanson 2003) are to be believed, we would need this alternative soon, perhaps even within this century. What is clear and a fact is that the future of Earth is in our hands and it is in our interest as a species to keep it going/habitable.

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The understanding that the Earth is a complex system with many interwoven feedback mechanisms is not new—Jacques-Joseph Ébelmen who in 1845 correctly identified fundamental process and factors affecting global biogeochemical cycles (Berner 2012), Vladimir Vernadsky's noosphere or the science of science (Winkler 2014), GAIA theory (Lovelock 1972), or 'Goldilocks' planet[1] to name a few. At any time, natural processes have determined the Earth's climatic history. For example various processes that have historically altered the Earth's view, such as the Milankovitch cycles in the Earth's movements around the sun, various shifts in Earth tectonic plates occurring over thousands of years, asteroid impacts on Earth or volcanic eruptions have had strong natural effects on different time-scales on Earth. Until the middle or later part of the 20th century scientists (natural/social) were getting to grips with the details and methods in their own specialized fields. However, in the past decades, with increasing anthropogenic impact, there has been a growing need to understand the interconnections and tele-connections between the various parts of the Earth system. This is even more urgent since we are slowly but steadily changing/influencing aspects of this system without fully understanding the impacts and consequences. Dramatic increase in CO_2 and methane emissions, excessive bio-geo resource exploitation, manifold increase in population, decreasing biodiversity, changing land-use practices to name just a few changes.

Earth System Science (ESS) has been varying described as the "the whole in the sum of its parts" (Victor Smetacek, per. comms) or "an integrative super-discipline that accepts that biophysical sciences and social sciences are equally important in any attempts to understand the state, and future of the Earth System" (Pitman 2005) or "seeks to integrate various fields of academic study to understand the Earth as a system and considers interaction between the various elements of the Earth System".[2] The aim is to take a step back, not to focus on the details of the particular part or subject or nuance but to understand the workings of the system as a whole. For most scientists this is difficult since this implies an intrinsic degree of uncertainty or not understanding a particular aspect or part of the system. For educators, this is complicated since it is impossible to provide comprehensive ESS education when there are large uncertainties in our understanding. Nevertheless, ESS programs at undergraduate levels were designed and started in the 90s (Love et al. 1993; Miall 1995; Ireton et al. 1996). Good examples of visionary programs are those of Stanford or ETH, Zurich. In the early to mid 2000, graduate (MSc) and PhD programs we being offered under the umbrella of ESS. ESSReS (Grosfeld et al. 2013) was one of the few PhD schools, funded by the Helmholtz Association, to embark on this holistic journey.

[1] Goldilocks planet may be just right for life—space—25 April 2007—New Scientist. http://www.newscientist.com/article/dn11710#.U-sd04CSwRo.

[2] Earth System Science. http://en.wikipedia.org/wiki/Earth_system_science.

2 Review

The last 15 years have seen a significant increase in awareness of global climate change and sustainability issues. Slowly but steadily scientists, engineers, economists, politicians are all beginning to accept that there is a problem which transcends political boundaries. The 2001 Amsterdam Global Change Conference (Canadell and Noble 2001) highlighted this acceptance and put forward a plea to governments, public-private institutions and people of the world to agree on ethical framework for global stewardship and strategies for Earth system management, and importantly for the development of a new international system for global environmental science that draws from existing expertise, integrates natural and social sciences, and creates bridges between environmental and developmental issues. These sentiments have been reiterated over the years by the IGBP program (William et al. 2010), various IPCC reports[3] and countless global forums and scientific conferences such as the ESS 2010 (Downy and Cornell 2011) or Bonn Climate Change Conference 2014.[4]

What has changed significantly in the last decade (Ignaciuk et al. 2012) is the advancement in terms of sensors and observational systems, especially satellite remote sensing-based. Enhanced tools to store and digest this data coupled by significant advances in computation have led to the development of more sophisticated models which can describe biophysical processes in greater details. This in turn provides a better handle on model uncertainties and predictions for future Earth scenarios. In addition, the plea to setup educational programs that focus more on the integrative aspects has not fallen on deaf ears. Earth and Environmental Sciences or Earth System Sciences are currently the most important keywords used in most biogeoscience undergraduate and graduate programs.[5] Neither is ESS a concept of the western world (Walker 1999), it has established itself as an important educational concept which is accepted globally (Dong et al. 2009).

The ESSReS PhD program (Grosfeld et al. 2013; Meggers et al. 2014) was designed to address this aspect of collaborative science across the bio, geo-physics to computing sciences. In its second term, ESSReS brought together 23 outstanding PhD students from 12 countries to conduct their research in various disciplines, ranging from climate sciences, bio-geosciences, geo-information sciences to computer modelling and remote sensing of the atmosphere (Meggers et al. this volume). From these numbers it is clear that the program has been successful in its primary aim of educating the next batch of academics. The ESSReS program also highlighted aspects that could be improved. For example, it is not sufficient to broaden the horizon for the students. Faculty, and especially supervising faculty need to

[3] IPCC—Intergovernmental Panel on Climate Change. http://www.ipcc.ch/.

[4] Bonn climate change conference—June (2014). http://unfccc.int/meetings/bonn_jun_2014/meeting/8031.php.

[5] Earth System Science Courses. http://serc.carleton.edu/introgeo/earthsystem/nutshell/courses.html.

understand the benefits of such trans-disciplinary education as opposed to the more traditional roles in graduate, highly specialised education. Additional opportunities and incentives are needed to help faculty in this aspect. Perhaps, it would be beneficial if funding agencies and educational institutions are not stuck in their traditional roles to support individual sciences but open and expand their support to inter- and trans-disciplinary sciences.

3 Future Trends

Optimisms is one of the human traits that according to Walker (1999) might be the key factor determining the future of mankind. The optimistic bias inclines us to believe that natural disasters will not happen to us and that human advancement and ingenuity would release mankind from a dependence on nature. Social scientists might argue what "us" means in this context. It is clear that our capacity to understand the environment and the complex feedback mechanisms at variable spatial and temporal scales has dramatically improved. However, our capacity to predict and control the environment is still in its infancy. The link between science, technology on the one hand and human behavioural evolution on the other will determine the future of the Earth system.

Elliott and Hanson (2003) argues that the future of the geosciences is going to look very different to that of today. The revolution in education will see the bringing down of the wall between the natural and social sciences. This shift will be accompanied by process-driven, technology biased and (energy) resource focussed earth system science. The danger of such a process is the possibility of syndication (Elliott and Hanson 2003), in which resources form the basis for economic and social divides. A holistic education, at graduate and undergraduate levels, is probably the only way to continue the change in mind-set from the grassroots upwards. Other challenges for the future are institutional (Lawton 2001) and rely on international bodies and governments accepting joint responsibility and stewardship of our planet.

4 Conclusion

Earth System Science remains in a state of infancy albeit a distinct growth spurt in the last decades. Encouragement comes from various fields of social, natural and engineering sciences where the realisation starts to form that the future of the planet is in our own hands.

For higher education, especially graduate and PhD studies, there is a clear need to further foster inter- and trans-disciplinary and holistic sciences by including students and faculty from a variety of fields and different institutions. The ESSReS PhD program has been exceptionally successful in this aspect. In addition, there is

an urgent need to change the mind-set within faculty, science administrators and students to accept and promote such system science approaches. ESSReS has only been partially successful in breaking these barriers and mind-set between scientific fields. For example the computer scientist needs to understand that not only computer algorithms are of interest but also processes, processes interactions and relationships between parameters are critical for climate science.

It is clear that ESS is the way forward and ESSReS was one of the first steps, especially in higher education landscape in Germany. It is necessary to continue this initiative, as it is the way forward towards a sustainable and health planet.

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The Educational Program of the Earth System Science Research School (ESSReS)

Helge Meggers, Matthias Buschmann, Klaus Grosfeld and Stefanie Klebe

Abstract The Earth System Science Research School (ESSReS) is an international and interdisciplinary research school for 23 PhD students at the Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research (AWI) and their partner universities: University of Bremen and Jacobs University Bremen. ESSReS combines observations, modelling, and data analysis in order to decipher the Earth's complex climate system. Structured training, international exchange and supervision support interdisciplinary research at an early stage of the scientific career.

Keywords Post-graduate education · Earth System Science · Research school · Progress assessment

1 Introduction

Post-graduate education in Germany has changed a lot over the past decades. Formerly, PhD students generally did not have the option to attend formal classes and lectures and were expected to conduct their independent research, including occasionally teaching courses for students. Since the introduction of bachelor and masters studies with the Bologna Process in the late 90th, the higher education in Europe has been harmonized, leading to more structured and focused studies at the expense of a broad and universal disciplinary education. At this same time, special fields such as Earth System Science became more interdisciplinary. In consequence, universities and research institutes have established so-called research schools and/or graduate schools, offering specific courses and training alongside the doctorate.

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The Helmholtz "*Earth System Science Research School*" (ESSReS) is a small unit of PhD students co-organized by three educational and research institutions in the city state Bremen: University of Bremen (Institute for Environmental Physics, IUP), Jacobs University (School of Engineering and Science, JU), and Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research in Bremerhaven (AWI).

The principal concept of ESSReS and its management structure has already been introduced by Grosfeld et al. (2013). For the educational program the existing research infrastructure at the host institutes offered a unique research environment to study past, present and future changes of the Earth System (compare to Meggers et al. 2014). In its second term ESSReS brought together 23 PhD students from 12 countries to conduct their research in various disciplines, ranging from climate sciences, bio-geosciences, geo-information sciences to computer modeling and remote sensing of the atmosphere. After successful completion of the first ESSReS group (Grosfeld et al. 2013), the second generation of PhD students within ESSReS have been trained and prepared in this interdisciplinary environment since October 2011. This book in the Springer Briefs on Climate Change series provides an overview of the various PhD students' research projects. We present the structure of the accompanying academic program of ESSReS including seminars and courses, and illustrate how the courses were conceived and carried out.

2 The Educational Program

ESSReS aims to exchange and cooperate with other graduate programs that have related topics, since this cooperation produces synergy and added value. The associated Helmholtz Graduate School for Polar and Marine Research (POLMAR) at the AWI offers an educational training program, which is also open for interested ESSReS PhD students. Thus, the PhD students have access to a huge range of research facilities, course offers, and to a larger scientific community. This helps building their individual scientific network. Larger events like self-organized PhD conferences, career symposia or cost-intensive training courses were more easily tackled by joining resources of different research schools. In the following, we present a number of selected activities.

2.1 Introductory Courses

Throughout the duration of the ESSReS program a series of courses were conducted, covering most of the scientific fields within the research school participating institutes. In the first year, a set of lectures was organized to address the basics of the respective fields in order to provide an overview of the various methodologies. The aim was to create a common scientific language by bridging the various field-specific approaches to a common understanding of how to address

Fig. 1 One of the ESSReS excursions included a trip on-board RV Heincke (*left*) to get hand-on experience in sea floor mapping in the German Bight near Helgoland, another excursion was carried out with the RC Uthörn (*right*) to the Weser Mouth *photos* Dimitar Misev (ESSReS PhD student) [The RV Heincke cruise 2012 has been effective and interesting for both, the ESSReS PhD students and the shipboard system operator. An ESSReS computer scientist, who had never been on-board of a research vessel before, worked within the bathymetry group to learn the mapping of the North Sea seafloor nearby Helgoland. The ESSReS PhD student learned a lot about the multi-beam echo-sounder system, but recognized that the data processing on-board was inefficient. He wrote a few scripts to automate the manual work and to enhance the shipboard workflow, which is now helpful for all shipboard scientists in the future]

scientific questions in Earth System Science. Introductory lectures were given by senior scientists from the participating institutes, covering topics such as remote sensing of the atmosphere, the climate system and its components, and an overview of the complex system within the living ocean. Two cruises with research vessels (RC Uthörn, RV Heincke) were offered with practical courses, providing an introduction to ship-borne marine bio-geoscience research methods and to gain first-hand experience in applied oceanography, biology, geology and geophysics (Fig. 1). Next to these scientific topics, marine navigation and positioning systems were introduced to the PhD students. After participating in these short trips to Helgoland (RV Heincke) or to the Weser Mouth (RC Uthörn) some PhD students were highly motivated to join longer research trips to the northern and southern polar region (e.g. on board RV Polarstern).

2.2 Expert Courses

The expert courses from the second academic year onwards were designed to give a more detailed insight into the research fields of the participating institutes. The content is focused on their respective expertise in Climate Sciences, Physics, Geology, Geophysics and Biology.

In addition to a series of lectures, the physics/geophysics course "*Remote Sensing of the Atmosphere and Cryosphere*" offered visits to Bremen companies to illustrate

current alternatives to a scientific career. The geology course "*Paleoclimate: From proxies to climate data*" introduced the PhD students geological records like sediment cores and the age determination of sediments. Paleoceanographic changes were explained on different time scales. The biology course "*Bioarchives, a source of climate reconstructions*" was held by biologists from AWI to illustrate work on carbonate bio-archives (mainly bivalves) for the reconstruction of past climate and environmental variability. Both courses had an efficient practical part, working with sediment cores (Geology) and molluscs (Biology).

2.3 Seminar Series

The ESSReS student group gathered for monthly seminars, which alternately took place at one of the participating institutes. Main goal of these student/coordinator-organized meetings was a regular informal exchange of the PhD students, providing a familiar atmosphere and an open working environment. This set-up not only strengthened the social network of the group, but also enabled scientific exchange and student-to-student learning. Usually, up to three presentations per event were given by the students, fostering motivation and the bottom-up approach, team building effects and conflict management.

In the beginning, the student talks covered the personal background, i.e. master thesis or earlier work, which later evolved into regular updates on their current research work. Some students also used the familiar and interdisciplinary audience to practice talks later to be held at a conference or summer school. The informal atmosphere was a perfect setting to get comfortable presenting to a bigger, more specialized audience. It was of great benefit that most of the audience were not from the same scientific field, which fostered a clear presentation and bottom-up explanation of background processes and pre-requisites. Consequently, some specific experiences of PhD students were used to tutor the group in special skills like, e.g., "*Python*" or "*Rasdaman*" (see Sect. 2.5).

2.4 Computational Skills Courses

In the first and second year of the program, a series of courses were offered to teach several computational skills needed for a productive work flow. These courses included an introduction to Unix/Linux operating systems, to scripting languages (*Bash*, *Python*) and to a series of specialized tools for plotting and data analysis (*GMT*, *GIS*). In addition to the three main courses, a workshop in Earth System Modeling (organized together with POLMAR) provided practical hands-on learning in Earth System Modeling, giving the chance to explore the dynamics of the Earth's climate system as well as of global carbon cycling and the biogeochemical

impacts of fossil fuel CO_2 emissions. The ESSReS students were trained in advanced computer skills and gained experience with high-level data visualisation packages.

2.5 Transferable Skill Courses

Beyond an excellent scientific education, social skills are of great importance in today's professional business. Therefore, additionally to the scientific work a set of mandatory transferable skills courses were developed and offered in cooperation with the Imperial College London. The courses were designed to prepare PhD students for their future career and reflect on personal characteristics like presentation and communication skills, personal development, leadership and time management.

The first course for PhD students in their first academic year entitled "*Research skills development*" focused on personal and research effectiveness including team working, networking and communication skills. The second course "*Presentation and communication skills*" concentrated on the presentation of own results in front of a group including feedback. It included learning to prepare a presentation, to eliminate excitement, to prepare a structured scientific text or talk and to understand the review process. In the third academic year, the last course "*Career and leadership*" aimed at career planning (in and outside of science) and the development of an understanding of leadership. Further topics were team working in a heterogeneous group, planning the own career and "*real life*" training exercises.

The feedback on these courses from ESSReS participants was very positive and the course contents were regarded as helpful for their daily work. The mixed group, including PhD students from different Helmholtz research schools in each of the courses was considered an asset. Additionally, it was appreciated that the venue was far away from daily life, enabling a focused and effective course environment.

2.6 Academic Writing Courses

A cooperation with the Centre for Foreign Languages at the University of Bremen was established for individual English language training sessions. Besides workshops and individual coaching sessions, a seminar on "*How to manage writing processes efficiently*" was held and the students' feedback was very positive. During individual coaching sessions, students were asked to bring own manuscripts or research papers soon to be published. Individual challenges were discussed and strategies for a better-written language developed. This approach to work with current texts was perceived as very effective and useful.

2.7 Excursions

Various excursions within ESSReS were offered to the PhD students as on-site training, practical application and social event. While the visit of RV Polarstern and the participation on cruises with RV Heincke and RC Uthörn also focused on scientific topics (see Sect. 2.1) and the preparation for the participation of a longer expedition, additional social gatherings were organized to foster networking opportunities. An excursion to the Harz mountain range and the meteorological observatory on the "Brocken" peak gave the opportunity to become acquainted with the history and the geology of the northern part of Germany. After visiting northern Germany's highest elevation, another excursion went to the national park Waddensea near Cuxhaven including a hike through the tidal flats from the mainland to the island of Neuwerk.

2.8 Annual Retreat

An annual retreat in autumn of each year was held to ensure a regular exchange between the PhD students and the supervisors/senior scientists of the three institutions (Fig. 2). The supervisors and other scientists from the working fields of each PhD student were invited to participate in the retreat, where oral and poster

Fig. 2 ESSReS students and supervisors at the second ESSReS retreat at the Botanika Conference Centre in Bremen (November 2013)

presentations of all PhD students as well as invited talks were given. All PhD students had to give at least one talk and present two posters in total during the three retreats. An evaluation sheet for both, talk- and poster presentation was prepared and all supervisors and guest scientists of the retreat were asked to evaluate the student contributions. The best poster and the best talk were awarded with a present and an ESSReS certificate.

3 International Exchange

ESSReS maintains cooperation with foreign institutions and offered an international exchange for all PhD students. ESSReS recruited PhD students originating from 12 countries (Austria, Brazil, China, Ecuador, Germany, Iran, Italy, Japan, Macedonia, The Netherlands, Poland and Russia). Thus, a high level of intercultural exchange was guaranteed.

A dedicated ESSReS website (http://earth-system-science.org/) was created to inform the PhD students and the international public about the scientific work and the students' personal developments (see Grosfeld et al. 2013).

3.1 International and National Meetings

The students within ESSReS had the possibility to apply for travel grants for workshops, meetings, conferences and stays at external institutes (see Sect. 3.2). In order to receive a grant, a proposal had to be submitted to the Academic Council. All PhD students used this possibility and students travelled to meetings all over the globe (see map in Fig. 3). Additionally, the students had the possibility to participate in semi-annual AWI/IUP seminars with special topics like "*Advances in Earth System Modeling*" or "*Climate Variability*".

3.2 Visit in a Foreign Lab

Apart from various visits of conferences or seminars ESSReS offered its students support for a three-month stay abroad to enhance collaboration with specialists of the respective research field. Within their first two years, three PhD students of group II took advantage of this possibility and visited Copenhagen (Denmark), Paris (France) and Toronto (Canada). All these visits to foreign labs had specific outcomes and contributed to papers of the PhD students.

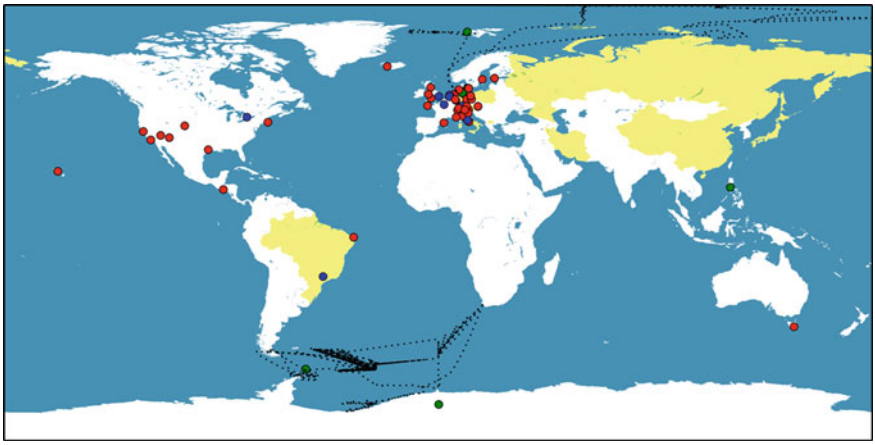

Fig. 3 Overview of the travel destinations (both ESSReS and third party funded) of ESSReS group II students including conferences, meetings or summer schools (*red*), fieldwork (*green*), RV Polarstern tracks/Polar aircraft routes (*black*) or research visits to a foreign lab (*blue*). The home countries of the students were marked in *yellow*

3.3 Invited Guest Scientists

Both ESSReS PhD students and supervisors had the opportunity to invite external experts from academia or industry to the research school. One of the guests was an expert in risk management modeling who gave a valuable insight into the field of "*Catastrophe Modeling*" and the students got insights into how their work may be implemented outside academia. Another guest of ESSReS gave a series of scientific lectures on "*Spectral methods for time series analysis*" and was available for consultation by the PhD students, which was used frequently. Finally, ESSReS has invited a senior editor of the scientific journal *Nature* to inform the PhD students about the internal and external challenges in science publishing. Exclusively for the PhD students the every-day work of an editor and possible future career options at a scientific publisher were presented.

4 Progress Assessments

ESSReS developed and established a Progress Assessment Form for both, PhD students and supervisors. This was done to evaluate the individual progress of the PhD students' projects. The form was filled-out independently by PhD students and supervisors in order to identify different perceptions of progress and the PhD timeline. Apart from this intermediate assessment, the PhD students were asked to set up bi-annual PhD committee meetings on a regular basis, during which the PhD students were asked to present a progress report of the last months and the goals for the upcoming months, discuss

problems and planned publications, conference attendance or expeditions. An assessment of potential risks within the work plan, methodological approaches or external factors was required to anticipate delays in the completion of the PhD.

Anonymous feedback was given to the PhD students during the monthly seminar and a discussion was encouraged where the students reflected on their individual progress compared to the overall results of the assessment survey.

5 Conclusions

Climate change and its regional to global impact on the Earth system is one of the crucial questions in Earth and Climate System Sciences. Hence, PhD education in Earth System Science in present times is focusing on a highly interdisciplinary and herewith also on inter-institutional education programs. With this approach we prepare young experts for scientific or industrial/economy careers or work in the public sector. The integration of both, climate observation and climate modeling in a research school entailed collaboration and networks of PhD students and experts (supervisors) in a spectrum of subjects and timescales. Earth System Science includes various disciplines and methods. The education program at the three institutes/universities, cooperating within ESSReS is built on the connection of scientists from the field of Climate System Science.

ESSReS aims at the integration of research at the interface of Geology, Biology, Physics, Geophysics, Mathematics and Informatics. It is therefore multi- and interdisciplinary in every aspect. The training, curriculum, and PhD research subjects are closely located at the interfaces between the participating disciplines. This is guaranteed by interdisciplinary supervision of the PhD project, documented by the members of the so-called "*PhD committee*" (advisory team; Grosfeld et al. 2013). The long-term goal is not only to enhance exchange and interaction between these disciplines, but to enforce a newly integrated concept, where separation between disciplines becomes more and more obsolete. Consequently, ESSReS provide a solid base for a new generation of excellent scientists in Earth and Environmental Sciences.

References

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