Report of the

International Weddell Gyre Workshop

at the Hanse Wissenschaftskolleg
(Hanse Institute for Advanced Study),
Delmenhorst, Germany
at 17 – 19 September 2012

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1. Background and aim

Large gyre systems are most prominent features of the Southern Ocean, and the Weddell Gyre, together with the Ross Sea Gyre, is the largest one of these. It forms an elongated cyclonic feature extending along the entire length of the Weddell and Enderby basins. Circumpolar Deep Water from the Antarctic Circumpolar Current to the north is introduced into the Weddell Gyre mainly near its eastern edge, and constitutes the large intermediate water mass of the gyre at depths <1500 m. This water mass, locally known as Warm Deep Water (WDW) is characterized by a temperature maximum. Virtually all other water masses in the Weddell Gyre derive from the WDW. It mixes with shelf and surface waters to produce the densest waters in the world's oceans, i.e., Weddell Sea Bottom Water. Such formation sequences at the shelves also generate Weddell Sea Deep Water, the latter of which is also formed from large-scale mixing within the gyre. The Weddell Sea Deep Water occupies a depth range which allows it to abandon the gyre circulation, thus it is the main ingredient of the Antarctic Bottom Water, which is found at abyssal depths of all world oceans, not only in the Southern Hemisphere. The processes that lead to the deep and bottom waters involve surface waters which in this way contribute to the ventilation of abyssal waters and through these of the world oceans. Besides ventilation (i.e., providing oxygen), these processes also sequester gases, like (anthropogenic and natural) CO_2 and man-made gases, such as chlorofluorocarbons.

One of the main aims of marine geology in the Weddell Gyre is to understand how these properties have varied in the past. The Weddell Gyre, as maybe the most prominent ocean region connecting the deep ocean with the surface and eventually the atmosphere, has a high potential to influence global climate by controlling gas exchange and direct heat flow, modulated through sea ice. At the same time, the geological record in the Weddell Gyre is particularly complex, with predominant downslope transport of sediments in many regions. Both geology and oceanography of the region, as well as biology, are severely influenced by the occurrence of ice, which has effects on the interactions of ocean, atmosphere and solid Earth. Sea ice and icebergs are important transport mechanisms, with a potential to respond drastically to climatic changes. Biological productivity in the Weddell Gyre can be very high, but spatially and temporally very variable. The actual controlling factors of this variability, which determine species composition and abundance, are poorly understood. The sensitivity of the heat balance in the Weddell Gyre, as well as the potentially global effects of relatively small changes in this area, make it a key area for understanding the implications of global change. Continuous observation of the Weddell Sea is mandatory if we want to ensure that we do not miss essential changes in the Earth system.

The aim of the workshop was therefore to bring together scientists investigating different aspects of the science and functioning of the Weddell Gyre. Due to the global nature of the issue, scientists from all parts of the world were invited to participate, in particular oceanographers, marine (geo)chemists, -biologists, -biogeochemists and -geologists. The number of participants during the 3 days of the workshop was 33. We formally called it a workshop, as its final aim is to prepare for a book with the tentative title "The Weddell Gyre, a pre-eminent region of the Southern Ocean - A multi-disciplinary perspective -" to be finished by the end of 2013. However, the meeting is also a mini-symposium as the participants were invited to present their latest research from the Weddell Gyre.

2. Introduction

Doris Meyerdierks of the HWK welcomed all participants to the workshop.

Hanse-Wissenschaftskolleg (HWK) – Doris Meyerdierks

The Hanse-Wissenschaftskolleg (HWK) is a non-profit foundation under civil law of the federal states of Bremen and Lower Saxony, and the city of Delmenhorst. As an independent *Institute for Advanced Study*, the HWK offers outstanding scientists and scholars from around the world the opportunity to concentrate on research projects without the distraction of everyday routines in academia and to gain insights from other disciplines and from a variety of scientific traditions. Based on a strong reviewing process and recommendations by the HWK Scientific Advisory Board, the rector appoints especially qualified scientists at all career levels as "Fellows", from postdocs to emeriti. With its Fellowships, the HWK supports inter- and trans-disciplinary collaboration with cooperation partners at neighboring research institutions. The HWK focuses thereby on the four research areas Energy Research, Marine and Climate Research, Neurosciences and Cognitive Sciences, and Social Sciences. Focusing on these, the HWK strengthens and interconnects nationally and internationally recognized research and excellence clusters including those of regional universities and research institutes.
In addition to the Fellowship program, the HWK organizes and supports study groups, workshops and conferences. Through its conference programs and public lecture series, the HWK also serves as a place of intellectual debate. These conferences and workshops are distinguished by their international orientation and the interdisciplinary composition of the participants. For more information please visit www.h-w-k.de

Introduction to the workshop – Mario Hoppema

All participants were welcomed to the workshop and the great venue offered by the Hanse Institute for Advanced Study HWK. Many people from all kinds of scientific disciplines have worked in the Weddell Gyre. For example, for the Alfred Wegener Institute, where I work, it is one of the main regions of investigation (as also seen from all ship tracks of FS Polarstern in the Southern Ocean). But much important scientific work has also been done by other nations, e.g., the U.K., U.S.A. and South American countries. In Delmenhorst we are particularly glad to see many scientists from the U.K., and are specifically happy to welcome two scientists from the U.S.A.

The idea for the workshop came up after the "International Symposium on Antarctic Earth Sciences" in Edinburgh, U.K. in 2011, where a session on "Polar gyre systems in the Southern Ocean" was proposed. Also a textbook was envisaged at that time, as initiated by co-organizer Walter Geibert. From all polar gyres, we focused our attention on the Weddell Gyre, the region the organizers know best and visited frequently and which in itself has great importance within the Southern Ocean.

The interest in the Weddell Gyre and Weddell Sea is of old times; sometimes the gyre was in the spotlights unintentionally – e.g., the Endurance Expedition of Ernest Shackleton in 1914. A very important characteristic of the gyre is the seasonal ice cover; in the winter it is completely ice-covered while in the summer only the western part carries perennial ice. The sea ice is a matrix

for many different processes, and a lid on the surface water. When the Weddell Gyre is mentioned in public, the great Weddell Polynya, which existed in 3 consecutive winters in the 1970s, is often mentioned as well; it is an unprecedented natural phenomenon and this in itself has produced much research in the region. Nowadays the science in the gyre is not only based on ships, but also on Argo floats and gliders, as well as on satellite imagery. Moorings and sediments traps provide year-round ground truthing. Specific sub-regions of the Weddell Gyre, with their own processes and signatures are Maud Rise, the Weddell-Scotia Confluence, the eastern Weddell Gyre for exchange with the Antarctic Circumpolar Current, ice shelves and cavities, and the Antarctic Peninsula.

Introduction to the workshop: Motivation and aims – Walter Geibert

The personal experience that led me to supporting this workshop is based on apparently contradictory findings from different disciplines in the Weddell Gyre. I found that apparently high productivity at the sea surface, as found with biogeochemical approaches, is not at all reflected in marine sediments, or in the satellite data that were available at the time. There was also no obvious iron source to support the observed high productivity.

A resulting interdisciplinary collaboration, designed to resolve these conflicting observations, led to new insights into productivity in the Weddell Gyre. It delivered the reasons for satellites underestimating productivity in sea-ice covered areas, and it showed the role of wind-drifted sea-ice for productivity in an iron-limited area. Some facts (like the sedimentary record) still remain unexplained.

However, based on this experience, I believe that a lot of progress can be made by collaborating across disciplines in the Weddell Gyre. Therefore, the aim of the workshop is mainly to create a network across different disciplines, countries and career stages, focused on the Weddell Gyre. We also aim at giving the research subject more weight by focusing attention to it, and creating a lasting structure to facilitate international collaboration on the topic. Eventually, we will prepare the outline of a book that addresses the WG from different angles, serving as an introduction to the whole WG community.

3. Recommendations for future research

Rapporteur: Judith Hauck
The below text is based on the notes taken by the rapporteur.

At the end the second day of the workshop, a discussion was held. The guidelines for this discussion were formulated by the organizers as follows:
A. Which recommendations with respect to future research can we make for the Weddell Gyre?
B. Which actions can we take towards solving existing problems, or implement recommendations?
C. How can we organize ourselves to achieve more cooperation between disciplines, i.e., tackle problems/projects over disciplinary boundaries? – The outcome of this question is described in the next section.

Scientific problems/challenges that are considered important were identified. These include:

- What is important with respect to the forcing mechanism of the Weddell Gyre? Brine formation, wind, and sea-ice coverage; how important are these individual forcing mechanisms for dynamics of the Weddell Gyre?
- Understanding scales of variability (spatial, temporal); long-term observations or gliders do that for the shelf front current; something similar is needed for bottom (CFCs?).
- Current flow meters in the outflow regions – about 10 moorings from Lamont, BAS in South Orkney; recovery next year). Is that enough? This depends on the question.
- Diversity of science: future research should aim to become more interdisciplinary. More crossing of disciplines needed.
- About 100 years ago nearly all predators were removed – is there still a measurable impact and what are the time lines? Is the Weddell Gyre small enough to figure out this impact? Can we find a signal of NPP in the sediments as a consequence of changes due to whales?
- Scales of variability (polynya), huge range of scales (space and time), how to address extreme variability?
- Dissolution issue of silica. Anomaly of particle remineralization – there is no satisfying explanation at the moment. We need to understand that for trace metals, proxies for productivity etc.
- Age of Dissolved Organic Matter, trace metals (?); signals in water column are not well understood.

As to the **modelling** of the Weddell Gyre; the question posed was whether we know enough of the Weddell Gyre to construct a reliable model of it. This might, however, be the wrong question: "Just start modelling and see what is missing". It was regretted that the modelling community was not represented at all at the workshop.
Some models of the Weddell Gyre are available, mentioned were those at AWI, MIT and Scripps (interesting representation of seasonal cycle in Weddell Gyre; model-data-assimilation; Matt Mazloff is interested in collaboration).

For biological processes, modeling small-scale turbulence would be helpful for the interpretation. It was remarked that models do not have predictive capability to say a shelf will collapse in xxx years; but as a qualitative statement, if they collapse, changes will be huge and rapid and we can investigate what the impacts on climate would be. As to carbon: there is a

spectrum of opinions whether there is C piling up in the deep Weddell Sea or not – modelling should help with that, as a priority. As to the ice shelves – how does the Weddell Gyre communicate with the ACC? How does WDW enter the gyre? The gyre is not well constrained, there is no defined eastern boundary – these are issues that modelling should address.

Although there are certainly **differences between the Weddell and Ross Sea gyres**, these were previously (i.e., before the workshop) not considered to be great. The keynote talk by Michael Weber somewhat changed this insight, namely where he referred to the iceberg alley where icebergs from all around the Antarctic continent find their way out to the north through the Weddell Sea along the eastern side of the Antarctic Peninsula. Enhanced iceberg melting in the Weddell Gyre introduces trace metals, which support phytoplankton primary production. Differences in these two gyres are certainly also related to water masses, where upwelling may be more important in the Weddell Gyre.

How can we **enhance our knowledge** of the gyre?
- As most data have been collected in summer, we need winter data. We need new tools: e.g., autonomous floats may be suited for getting data in winter.
- Long-term data series would be good, both pelagic and the benthic sea-floor, coupling water column and benthos, also with moorings.
- Make data comparable! Intercalibration, methods comparison, needs a group of people to be feasible.
- Different communities must be willing to work together, need to work together on cruises.
- Cables from e.g. Neumayer into deep Weddell Sea that measure autonomously.

Recommendation: Satellite data of the gyre is missing by the phasing out of ENVISAT. Sentinel will replace ENVISAT. Now would be a good time to express interest in that. Define interesting questions for next generation of satellites, maybe specific locations can be requested. Subscribe at ESA as PI and ask for satellite time.

Recommendation: Pick out one place as a reference point or station. This should be a place where every research vessel that is present in the region should visit for performing measurements. Ideally, this is a station that is close to regular ship tracks to research stations.

Since the Weddell Gyre is a source region of many worldwide cycles, small-scale or local processes may have impact on a global scale.
- The water outflow at depth is well confined in the Orkney Passage.
- Buttressing and speed-up of glaciers as local processes were also mentioned in this regard.
- We need to understand small scales and details first before going to large scales. For example, we want to know precursors to WSBW formation under the shelf and details of water mass transformation. Storing of water masses, how much is exported from the system to communicate with the world's ocean – production/export of AABW.
- Concentration gradient from north to south along isopycnals! Isopycnal exchange rate across the ACC is not known now, but may be known in 5-10 years.

Actions to be taken were not discussed in detail, but seem to follow from the recommendations and identification of research issues as described above. Because some vital disciplines were missing at the workshop this was not further addressed.

4. Future cooperation in Weddell Gyre research

The workshop has been very useful, which was confirmed by many participants. Should we plan for a repeat workshop in 2-3 years time from now? More in general, how can we solidify the Weddell Gyre community? Is this with a larger symposium, where we would aim for much more attendants than at the present workshop? We could opt for a SCOR working group, which would also provide financial support for meetings. But then a proposal needs to be written. Or should we just have an email list or web site /wiki? A group within the social media for scientists, ResearchGate, is a possibility as well.

Mentioned was the "Southern Ocean Observing System" (SOOS) with a multidisciplinary implementation plan in its infancy (SCOR/SCAR initiative). SOOS should bring communities together that would otherwise not talk to each other. We could try and establish a Weddell Gyre node in SOOS. Within SOOS, comparison and coherency with the remaining of the Southern Ocean is covered as well.

Action: Mike Meredith being involved in SOOS will look into the possibilities at SOOS.

There was a general consensus that as a Weddell Gyre community, being organized is useful.

A repeat meeting in 2-3 years was agreed upon. This could be at HWK again (this is certainly a compliment for HWK), as proposed, but rotating the venue would bring more people from another country where it will then take place.
A more "interactive program" could be planned, so people will know before registering what will be expected from them and what they can expect.
Walter would possibly volunteer with a meeting in Scotland.

Another suggestion was a workshop linked to SCAR Open Science Conference in Auckland, New Zealand, which would combine as people might go anyway. On the other hand, this is far away for many people being interested in a workshop.

Action:
Resulting from this workshop is a **report** (this report).

However, it was also decided to aim for a **review paper** in the refereed literature which should describe the challenges in the future research in the Weddell Gyre. Mike Meredith mentioned a similar exercise for a paper in Reviews in Geophysics. Maria Vernet will take the lead for this effort, where she would be happy with somewhat more intensive support by 2-3 people. Solicited is one page of writings, possibly including one figure. Contributions are welcome. Maria will prepare the outline of such a review paper soon after the workshop.

5. Preparation of textbook on the Weddell Gyre

On day three, a subgroup of the participants discussed the preparation of an introductory textbook on the Weddell Gyre. The aim of the book is to provide an overview of the Weddell Gyre from the viewpoint of different disciplines. This can serve as an introduction to scientists new to the area, to complete their knowledge about neighbouring science aspects, and to give an overview about relevant literature and developments.
The session, based on a tentative outline of the book, was structured into (1) identifying subjects that should be covered, (2) ordering the subjects, and (3) discuss potential authorships and reviewer roles.

The book will be edited by Walter Geibert and Mario Hoppema. Authors for the chapters will be leading experts in their field, recruited from the field of workshop participants and beyond. Author teams composed of participants from more than one country are particularly welcome, in order to provide views that are not biased by national research programmes. However, author teams for a chapter need to have one lead author.

The discussion on day 3 was recorded in an online document, using the prezi software, and the resulting outline is accessible at

http://prezi.com/ifwf2y9gtnkq/textbookweddell/?auth_key=272beb001f2f2a069065ee066ccded29ae896131 .

The outline, as well as expressions of interest to author or review individual chapters, will serve as a starting point for the editors to begin the production of the book. Submission of the chapters is planned for May 2013.

6. Abstracts of talks

Keynote talk

Antarctic deglaciation since the Last Glacial Maximum – implications for the Weddell Gyre development

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To understand the last sea-level rise is a key to understand current and future climate change. Here, the role of the Antarctic ice sheets is poorly understood, yet crucial because ice-sheet collapse in a warming world could cause rapid sea-level rise. We developed a chronology for the Weddell Sea sector of the East Antarctic ice sheet (EAIS) that, combined with ages from other Antarctic ice-sheets, indicates that the advance to (at 29 –28 ka) and retreat from their maximum extent (at 19 ka, and again, at 16 ka) was nearly synchronous with Northern Hemisphere ice sheets (Weber, M.E., Clark, P. U., Ricken, W., Mitrovica, J.X., Hostetler, S.W. and Kuhn, G. (2011): Interhemispheric ice-sheet synchronicity during the Last Glacial Maximum. Science 334, 1265-1269, doi: 10.1126:science.1209299).

Using an atmospheric general circulation model, we conclude that surface climate forcing of Antarctic ice mass balance would likely cause an opposite response, whereby a warming climate would increase accumulation but not surface melting. Furthermore, our new data support teleconnections involving a sea-level fingerprint forced from Northern Hemisphere ice sheets as indicated by gravitational modeling. Also, changes in North Atlantic Deep Water formation and attendant heat flux to Antarctic grounding lines may have contributed to synchronizing the hemispheric ice sheets.

Well-dated deep-sea sites from the Scotia Sea (Weber, M.E., Kuhn, G., Sprenk, D., Rolf, C., Ohlwein, C. and Wicken, W. (2012): Dust transport from Patagonia to Antarctica – a new stratigraphic approach from the Scotia Sea and its implications for the last glacial cycle. Quaternary Science Reviews 36, 177-188, doi: 10.1016/j.quascirev.2012.01.016) confirm ice-sheet retreat at 19 and ca. 16 ka, as inferred from the flux rate of ice-rafted detritus (IRD) that was transported along the “iceberg alley”. There is also a major IRD pulse at ca. 15 – 14 ka, indicative for a substantial contribution of the Antarctic ice sheets to meltwater pulse 1a.

The new data from both the Weddell Sea and the Scotia Sea challenge previous reconstructions of a late and monotonous ice-sheet retreat between 12 ka and 7 and call for a principal revision of the Antarctic deglacial history, with previously unrecognized, highly dynamic ice sheets and clear responses to all meltwater pulses, suggesting a substantially higher contribution to the last sea-level rise.

The Weddell Gyre history from marine sedimentary records

Gerhard Kuhn[1] and Claus-Dieter Hillenbrand[2]

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The Weddell Gyre (WG) history is closely related to the formation of the Antarctic Circumpolar Current (ACC), which may have developed after the opening of the Tasman Gateway and Drake Passage between Antarctica and the adjoining continents in the upper Eocene (Huber et al., 2004; Francis et al., 2008). We have only very limited information from a couple of deep-sea drill sites about proto Weddell Gyre conditions, but the available data and models indicate that its establishment was associated with oceanic cooling (Mackensen & Ehrmann, 1992; Cristini et al., 2012).

Studies on sediment cores from the Atlantic sector of the Southern Ocean and from the Weddell Sea provide information on the history and glacial/interglacial variability of the ACC and the WG since the early Oligocene. How does ACC flow speed interact with WG dynamics? Is the WG circulation independent from the ACC or is it related to seasonal and/or continuous sea ice coverage? Is its circulation related to brine formation in polynyas and subsequent supercooling of these brines below floating ice shelves, i.e., to the formation of Weddell Sea Bottom Water (WSBW) and Antarctic Bottom Water (AABW)? Was there a brine formation without floating ice shelves during glacials? Is the configuration of deep outflow of WSBW relevant for WG dynamics? Very little information has been provided to these questions up to now.

The initiation of circumpolar circulation in the upper Eocene changed the oceanography and the sedimentary record drastically. In addition to an increase in the supply of ice-berg rafted debris (IBRD) to the Southern Ocean, the supply of the clay minerals chlorite and illite, which are mainly formed by physical weathering, increased on the expense of smectite, which is produced under humid and warm climatic conditions (Ehrmann & Mackensen, 1992). Decreasing atmospheric pCO_2, changes in Southern Ocean deep water ventilation, and primary productivity have been recorded in several marine sediment proxies. After the middle Miocene Climatic Optimum, the Antarctic ice sheet build-up intensified and clear glacial/interglacial cycles during the Pliocene have been described from Gunnerus Ridge in the southeastern part of the WG (Hillenbrand and Ehrmann, 2003).

After ~3.6 Ma, coinciding with the onset of widespread glaciation on the Northern Hemisphere, the composition of sediments deposited in the Weddell Sea changed significantly. High biogenic opal contents in the older sediments point to a favorably productive environment with sea ice coverage possibly only during winter (Hillenbrand and Ehrmann, 2005). Interglacials and even extreme warm interglacials, during which the West Antarctic Ice Sheet (WAIS) may have collapsed (Naish et al., 2009), have dominated the deposition under the WG during this time. The Antarctic glaciers may have been warm based and may have flowed faster, while little or no ice shelves surrounded the Weddell Sea. This should have reduced the formation of brines and thus WSBW/AABW production. The late Pliocene and lower Pleistocene sediments recorded cold conditions with low primary productivity, but with partially (mainly on seamounts) high carbonate contents from planktic foraminifera. Brine formation took place as it does today, mainly during interglacials. The East and West Antarctic ice sheets covered most of the shelf areas during glacial periods. Therefore, the brine and bottom water production was reduced as it is indicated by a decrease of grain-size in glacial-time sediments recovered from the AABW outflow area in the deep western Weddell Sea (Brehme, 1992; Fütterer et al., 1988; Grünig,

1991; Pudsey 1992). Alkalinity of Weddell Sea waters increased from interglacial to glacial periods, deepening the carbonate compensation depth during glacials (Rickaby et al., 2010). Oxygen and carbon isotopes from planktonic and calcareous benthic foraminifera, geochemical and clay mineral composition and other environmental proxies in sediment records from the continental margin in the Weddell Sea vary with the Pleistocene glacial-interglacial cycles and provide good archives for past changes in climate and ice sheet dynamics (Grobe & Mackensen, 1992; Anderson & Andrews, 1999; Diekmann et al., 2003; Smith et al., 2010; Weber et al., 2011; Hillenbrand et al., 2012; Stolldorf et al., 2012).
We will present and discuss environmental conditions and sedimentological processes in the Weddell Sea for climatic conditions similar to present, warmer than today, and colder than today.

Why are the deep-sea sediments of the Weddell Gyre virtually free of biogenic remains? A biogeochemical perspective

Walter Geibert

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With the availability of deep-sea sediment cores from the Weddell Gyre (WG) and the Antarctic Circumpolar Current (ACC), it became evident that the two regions differ significantly in their sediment inventory. Whereas the abundance of biogenic siliceous sediments underlying the ACC has given the whole region the name “opal belt”, the deep-sea sediments of the WG are virtually free of biogenic remains. At the time, the best explanation seemed to be a much lower productivity in the WG, attributed to the lower availability of light, and abundant sea-ice cover. These findings seemed to be confirmed by results from open ocean sediment traps, which recorded virtually no biogenic fluxes through the deep water column of the WG. Early satellite data were considered with doubt because of the extreme patchiness of the chlorophyll distribution, together with a poor coverage of the polar region. Consequently, the lack of biogenic sediments in the WG was attributed to low surface primary production. This explanation did not hold as more data on productivity from the WG became available.

In fact, various recent studies, using in-situ productivity estimates based on nutrient depletion, inverse modelling, or the improved satellite coverage, show the WG as an exceptionally productive region. This implies that particle preservation in the WG is anomalously low, but no valid explanation for this exceptional feature has been offered so far.

What remains, is a surprising mismatch between very high surface productivity in the WG, temporarily matching ACC levels, and sediments that do not mirror any of the overlying biology. Here, I investigate potential explanations for the poor preservation of siliceous particles, including the availability of certain trace elements, deep upwelling affecting the settling velocity, low productivity, and other biogeochemical or physical factors that might contribute to the unusual sedimentation pattern. Results of preliminary experiments point to a potential role of the presence of the winter mixed layer, at sub-zero degrees, in the poor preservation of biogenic particles in the Weddell Gyre, through inhibiting particle aggregation.

Keynote talk

Control volume estimates of buoyancy fluxes from the Orkney Passage and South Scotia Sea

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Changes in the outflow of dense waters from the Weddell Sea

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The outflow of dense water from the Weddell Sea toward the Atlantic is one of the most significant renewals of abyssal waters in the world ocean. These waters are warming strongly in the South Atlantic, prompting questions concerning the temporal stability of their supply, and climatic changes in their formation. Here, an overview of recent studies into the controls on export of dense waters from the Weddell Sea into the Scotia Sea is presented. Original concepts related changing variability in export to changing cyclonicity of the Weddell Gyre, whereby more intense atmospheric forcing led to changes in the slopes of density and temperature surfaces where they intersect the South Scotia Ridge. Recent results from repeat hydrography and moored time series of temperature have added significantly to our understanding of the key processes, and suggest that local changes in barotropic circulation at the South Scotia Ridge, combined with ageostrophic processes in the near-bottom layers, can change both the temperature and speed of the dense water outflow on rapid timescales (order of just a few months). New results suggest that the overflow can be strongly episodic in nature, with dense waters pooling and creating bottom layers with strong abyssal gradients in temperature, salinity and density. These layers can persist for significant periods of time before being flushed by new overflows of water of similar density, or denser. Ongoing and planned work is outlined, including the array of 6 current meter moorings in Orkney Passage, which will capture for the first time the time-varying fluxes associated with the outflow

Scales of variability and long term trends in the north-western Weddell Sea

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The Weddell Sea Warm Deep Water (WDW) is fed by Circumpolar Deep Water (CDW) from the Antarctic Circumpolar Current (ACC). Several studies in the last decade looked at the multi-year trend of the WDW and showed significant changes in the heat content on different time scales. We readdress these analyses by determining local high-resolution temporal and spatial scales of variability from Seaglider data collected in January-March 2012 during the GENTOO project. Shelf surface Weddell Gyre waters as well as WDW mix along the Antarctic shelf front

current, creating a highly variable regime, with variable potential temperature (θ) maximum properties in the water column. We find that off-shelf the 2500m isobaths, the θ maximum of the WDW is stable to a degree that it can be used for longer term analysis. Using the high-resolution analysis to quality control historic data from many sources, we look at multi-year variability and trends in the θ maximum of the WDW core, around the Weddell Gyre. Little variability of the θ maximum is found since the mid-1980s and no statistically significant trend. Only in the late 1970s and early 1980s, during which the great Weddell Sea polynya has been observed for the last time, the θ maximum was significantly colder in the southern and north-western part of the gyre. There seems to be no significant trend in the core of the WDW at the inflow region into the Weddell Gyre.

Freshwater fluxes in the Weddell Gyre: Results from $\delta^{18}O$

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The Weddell Gyre is regarded as the primary location of deep and bottom water formation and sequestration of carbon, nutrients and atmospheric gases in the Southern Ocean. Major quantities of dense, cold waters generated near and on the Antarctic continental shelf spill down the slopes entraining surrounding water masses as they descend. The waters travel northwards hugging the western boundary before being exported into the mid-latitude Southern Ocean and spreading globally at depth. These processes are critically reliant on the freshwater balance of the region, as at low temperatures density, and by extension stratification, circulation and deep water formation, depend almost entirely upon salinity.

We investigate the freshwater composition of water masses entering and exiting the Weddell Sea through comprehensive measurements of the stable isotopes of oxygen ($\delta^{18}O$). At high latitudes, $\delta^{18}O$ combined with salinity data enables the partitioning and quantification of freshwater from meteoric (glacial ice melt, precipitation), and sea-ice melt sources. As each component will vary on seasonal, inter-annual and decadal timescales, it is important to understand their nature and impact on the freshwater budget of the Weddell Gyre. In this region, the $\delta^{18}O$ pure source glacial and non-glacial freshwater endmembers are sufficiently well-constrained to enable quantification of their exports to be carried out by this method.

Two full-depth hydrographic research cruises conducted as part of the UK ANDREX (Antarctic Deep Water Rates of EXport) project (JC30 - Jan 2009, JR239 - Mar-Apr 2010) combined with the US-led I6S cruise (2008) allowed the formation of a 'box' around the Weddell Gyre, extending from the Antarctic Peninsula, along the South Scotia Ridge and the edge of the Weddell Basin to 30°E, before heading south to the Antarctic Continent. Individual box import and export of the different forms of freshwater and from the Gyre into the global oceanic thermohaline circulation (THC) were quantified by solving the three-component mass balance for each water sample and combining with calculated velocity fields.

Meteoric water is found to be the dominant freshwater source in the near-surface waters, accompanied by a maximum in sea-ice melt. Distributions are observed to track the circulation of Antarctic Bottom Water; relative maxima for meteoric water at depth suggest the presence of sizable contributions of shelf waters during water mass formation, whilst negative sea-ice fractions suggest its formation as part of the same process. Large quantities of freshwater are

observed to enter the Weddell Gyre from the east as part of the Antarctic Slope Front. Combined with transient tracer data (CFC, SF_6, nobles gases), water mass ages and source location fractions are determined, enabling the assessment of freshwater fluxes within the Weddell Gyre. The context of these results with regard to implications for controls on ocean circulation and climate against a background of a changing hydrological cycle are discussed.

Exchanges between the Weddell Sea and the rest of the Southern Ocean

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Bottom water formation in the Southern Ocean plays an important role in the lower cell of the Meridional Overturning Circulation and in marine biogeochemical cycling, by ventilating and cooling the ocean abyss and sequestering carbon and nutrients there. The lack of adequate observations has to date hindered the quantification of exchanges of mass and physical and biogeochemical tracers between the Weddell gyre and the global ocean. The Antarctic Deep Water Rate of Export (ANDREX) project seeks to determine these exchanges through analysis of the first systematic hydrographic and tracer survey along the gyre's outer rim. These measurements (including temperature, salinity, nutrients, carbon system parameters, chlorofluorocarbons, sulphur hexafluoride, oxygen isotopes and noble gases) are combined with velocity observations in an inverse model to obtain a self-consistent estimate of the physical and biogeochemical transports across the edge of the Weddell Gyre and of the rate at which the deep ocean is ventilated from the region. Of particular interest to the analysis are the quantification of bottom water formation and the density profile of ventilation in the gyre, as well as an assessment of the region's role in biogeochemical cycling and anthropogenic carbon sequestration. In this presentation, we will discuss the initial results of the box inverse model, focusing on the physical circulation and bottom water formation rates in the Weddell Gyre.

On the variability of Antarctic Bottom Water in the Weddell Sea

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On the Antarctic continental shelf, the intricate interplay between the ocean, the atmosphere and the cryosphere, leading to the formation of Antarctic Bottom Water (AABW), makes it potentially very sensitive to the significant climatic changes observed in Antarctica. The recent observations of a rapid freshening of the AABW in the Indian and Pacific sectors of the Southern Ocean and a widespread warming in the Atlantic highlight this sensitivity. The driving mechanisms of this variability are still an open question.

Here, we report the first observational evidence of a recent decadal freshening of the AABW exported from the Weddell Sea, based on the analysis of 16 occupations (1993-2010) of the

SR1b hydrographic section in eastern Drake Passage. We present evidence suggesting that the breaking of the Larsen B ice shelf and changes in the atmospheric conditions near the Antarctic Peninsula linked to the Southern Annular Mode are the most likely causes of the observed freshening. Recent decadal changes in the SAM have been linked to greenhouse gas emissions and ozone depletion, raising the possibility of a partially anthropogenic cause for the observed AABW freshening.

AABW entering the Weddell Sea from the Indian Ocean is also poorly known due to the lack of observations in the eastern Weddell Gyre. Using 4 repeats (1993, 1996, 2006 and 2008) of the I6S line along 30°E, we observe significant changes in the properties of the AABW entering the Weddell Sea. We found a decrease in the density of the AABW during the 2000s (with respect to the 1990s) caused by a warming of the water. We track back the origin of this warming to the entrainment of warmer ACC water, caused by a southward migration of the fronts, as the dense shelf water cascades down the continental slope near the Amery Ice Shelf.

Slowing down of deep and bottom water ventilation and anthropogenic carbon storage in the Weddell Sea

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We used a 27-year long time series of repeated transient tracer observations to investigate the evolution of the ventilation time scales and the related content of anthropogenic carbon (C_{ant}) in deep and bottom water in the Weddell Sea. This time series consists of chlorofluorocarbon (CFC) observations from 1984-2008 together with first combined CFC and sulphur hexafluoride (SF_6) measurements from 2011 along the Prime Meridian in the Antarctic Ocean and across the Weddell Sea.

Applying the Transit Time Distribution (TTD) method, we find that all deep water masses in the Weddell Sea have been continually growing older and getting less ventilated during the last 27 years. The ventilation rate decline of Weddell Sea Deep and Bottom Water of 18-23% seems to be mainly caused by mixing with Warm Deep Water, which aged much faster by 35%. Increasing entrainment of Warm Deep Water or a slowing down of the Weddell Gyre circulation may also play a role. As a consequence of the aging, the C_{ant} increase in the deep and bottom water formed in the Weddell Sea is lower by 14-22% over the period of observations than in a hypothetic steady state scenario. Caution is recommended if using non-synoptic transient tracer data simultaneously in a TTD approach from that region.

U-Th series nuclides in the Weddell Sea

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The natural U-Th decay series provides well-soluble tracers that have traditionally been used to study water mixing and ventilation rates, as well as particle-reactive nuclides suitable to study the transport of particles.

Radium isotopes are often used to show the distribution of terrestrial signals in the open ocean. Concentrations in coastal and surface waters of the Weddell Sea are relatively low because of the absence of wide and shallow shelf seas and of submarine groundwater discharge. ^{228}Ra and ^{227}Ac activities increase with depth due to release from the deep sea floor. ^{224}Ra has in some instances been used to trace terrestrial inputs around the Peninsula and around icebergs.

The deposition rate of the particle-reactive nuclides ^{210}Pb, ^{230}Th and ^{231}Pa in the central Weddell Sea is only 13, 40 and 50%, respectively, of their net production rate in the water column, indicating a very low scavenging efficiency. This agrees with the very low particle fluxes observed in a deep sediment trap.

The short-lived ^{234}Th shows the recent (several weeks) history of the particle flux from the surface layer. The highly variable export flux in the Weddell Sea, and corresponding export fluxes of carbon and trace metals, can in some instances be related to growth events of the weeks before as recorded by satellite. The contrast between the sometimes appreciable export flux and the extremely low burial fluxes of the longer lived nuclides is explained by a very shallow mineralization, as has been demonstrated with ^{234}Th profiles.

Dissolved concentrations of particle-reactive nuclides are traditionally explained by reversible scavenging, a process that in a 1-D ocean would predict a linear increase of dissolved and particulate concentrations with depth. The Weddell Sea was the first ocean area where the ^{230}Th distribution was shown to deviate strongly from this model, and the accumulation of this isotope at mid-depths in the Weddell Sea by upwelling and low scavenging remains unique. Dissolved ^{210}Pb and ^{231}Pa reach their maximum concentrations at shallower depths. The distribution of all three nuclides can be explained in a model including the upwelling of Lower Circumpolar Deep Water and Upper Circumpolar Deep Water, a scavenging sink in the upper MOC circulation cell, and a mineralization that is shallowest for ^{210}Pb. It is suggested that ^{231}Pa is removed from Weddell Sea Deep Water when this passes on its way north the opal-rich bottom nepheloid layers of the Antarctic Circumpolar Current.

Keynote talk

LARISSA, the LARsen Ice Shelf System: integrating biology, geology and glaciology to understand abrupt environmental changes in coastal Antarctica

Maria Vernet

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A profound transformation in ecosystem structure and function is occurring in coastal waters of the western Weddell Sea. This transformation is yielding a redistribution of energy flow between chemical-based and light-based biological production, and causing the rapid demise of the extraordinary deep ecosystem discovered beneath the ice shelf (cold seep). An integrated, multi-disciplinary program is addressing these rapid and fundamental changes occurring in the Antarctic Peninsula region as a consequence of the abrupt collapse of the Larsen B Ice Shelf in the fall of 2002: the LARISSA project. Results to date show that previously dark, oligotrophic waters of the Larsen embayments now support a thriving light-based phytoplankton community, with production rates and phytoplankton composition similar to other productive areas of the Weddell Sea. This production is sinking and accumulates in sediments, providing food for the

establishment of new benthic communities. The development of a new paleoproductivity index in marine sediments links ocean productivity measured as DMSP (dimethylsulfoniopropionate) and MSA (methylsulfonic acid) measured in ice cores, within time scales of thousands of years. The interdisciplinary research has provided a rich environment to develop new techniques and a more comprehensive way of establishing energy flow in coastal Antarctic environments.

Combined effects of ocean acidification and iron availability on Southern Ocean phytoplankton communities

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Accounting for about 20% of the global annual phytoplankton production, the Southern Ocean (SO) exerts a disproportional control on the global carbon cycle and contributes to a large proportion to the oceanic sequestration of anthropogenic CO_2. Primary production in that area is mainly controlled by iron and light availability as well as by grazing, but also carbonate chemistry was shown to have significant effects. While combined effects of iron and light have received a lot attention, knowledge on combined effects with ocean acidification is sparse. We present results of shipboard incubation experiments conducted with a phytoplankton community from the Weddell Sea testing the combined effects of pCO_2 and iron availability. Phytoplankton communities were exposed to three different pCO_2 levels (180, 380 and 800 µatm) under iron-deplete and -replete conditions. Species composition, primary production and photophysiology were found to strongly differ in response to ocean acidification. Responses were further modulated by iron availability. Our study confirms that primary production and species composition of SO phytoplankton communities are sensitive to increased pCO_2. Under iron-limitation, however, the CO_2-sensitivity of primary production is strongly reduced. With respect to species composition, pronounced shifts in species composition at intermediate and high pCO_2 levels were observed, resulting in either Pseudo-nitzschia- or Chaetoceros-dominated communities. Effects of iron availability were also modulated by pCO_2, as stimulating effects by iron only occurred under elevated pCO_2 levels. These interactive responses have the potential to influence the biological carbon pump and thus the predictions for the CO_2 drawdown in the SO.

Marine benthos under the Weddell Gyre

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The seafloor area under the Weddell Gyre spans over and influences several Antarctic biogeographic regions in the Antarctic as defined by Linse et al. (2006), such as the Weddell Sea, East Antarctic Dronning Maud Land, the eastern Antarctic Peninsula, South Orkney, South Sandwich and Bouvet islands. This wide geographic coverage means that host is an influential component the Antarctic benthic biodiversity. In 2004, Gutt et al. estimated the total number of macrozoobenthic species for the Antarctic shelf as 11000 – 17000 based on the data from the Weddell Sea shelf alone. Since Brandt et al. (2007), we know that the Antarctic deep sea has similar if not higher benthic species diversity than the Antarctic shelf. In several marine invertebrate groups the endemism in the Antarctic is high with 50-80%, with endemic species

showing circum-Antarctic as well as regional or local distributions. The recent biodiversity assessment done under the Census of Antarctic Marine Life showed that some areas under the Weddell Gyre, especially its western part have been partially sampled while several areas of the deep sea and eastern part are unknown (Griffiths, 2010). Analysing the biogeographic relationships within the Southern Ocean of 9 benthic invertebrate classes, including over 10 000 species from over 6000 sites, showed a strong clockwise connectivity between species/taxon connectivity and the Circumpolar Current, with decreasing similarity from South America to the Amundsen/Bellingshausen seas (Giffiths et al., 2009). Within the Polar Front, a distinct Antarctic large-scale pattern was observed. Research on the benthos directly underlying the Weddell Gyre has shown that despite being under the same water masses, local benthic assemblage compositions as well as biomass differ between and within shelf and deep sea habitats (Linse et al., 2007). The circulation of the water masses and their oceanographic phenomenon like upwelling influence the distribution of species, for example, the trochoid gastropod *Calliotropis (Solaricida) antarctica* was discovered near the Shackleton Fracture Zone in 2800 m depth, later recorded in 2000 m east of the Antarctic Peninsula, in 750 – 2200 m in the South Sandwich Trench and in 250 – 500 m on the Bouvet shelf. Connectivity has also been found between vent species from the East Scotia Ridge vents and from the Dragon vent field at the Southwest Indian Ridge. Analysing molecular relationships in the Antarctic bivalve species *Limopsis marionensis* and *Lissarca notorcadensis* showed evidence for horizontal gene flow in these species over wide geographic distances, most likely caused by the dispersal of larvae and juveniles with demersal currents (Linse et al., 2007, unpublished).

In summary: the benthic biogeographic patterns are influenced by climate change and oceanography (past and present), molecular genes and their relationships can give valuable information on the evolutionary history of a taxon and its population connectivity. The taxon's reproductive mode (brooding or free spawning) is important for the species dispersal and connectivity. With knowledge about this, the distribution and genetic information taken from benthic species can also be used as a proxy for modelling past and present oceanography.

Acoustic detection of krill in the Weddell Sea from an underwater Seaglider

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The GENTOO project aims to investigate the potential for gliders to make high resolution temporal and spatial biological and physical observations of ocean currents and krill distribution at the east Antarctic Peninsula. A newly developed stand alone echosounder Imagenex ES853 120 kHz was integrated into a Seaglider to collect mean volume backscatter measurements of Antarctic krill during a two week expedition to the Weddell Sea. We show the first results from this cruise, including calibration of the echosounder using a tungsten carbide sphere. The ES853 was also mounted on a Rectangular Midwater Trawl (RMT8) to collect samples of krill from the swarms identified in the acoustic data, thus validating target identification methods using the single beam data. Finally, we show data from two short deployments of the echosounder integrated into the glider and introduce some of the challenges associated with acoustic measurements made from a moving platform such as a glider.

Molecular transformation and degradation of refractory dissolved organic matter and role of the Weddell Sea for global carbon cycling

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Dissolved organic matter (DOM) in the deep sea and in most pelagic surface ocean waters is of refractory nature with mean residence times of 4 000–6 000 years. This fraction comprises almost 75% of the global ocean organic carbon inventory and is a long-term buffer in the global carbon cycle. Here, we compiled the so far most comprehensive molecular data set of 197 Fourier transform ion cyclotron resonance mass spectrometry analyses from solid-phase extracted marine DOM covering two major oceans, the Atlantic sector of the Southern Ocean and the East Atlantic Ocean. Molecular trends and $\Delta^{14}C$ dating of 34 DOM samples, ranging from -229 to -495‰, were combined to model an integrated degradation rate for bulk dissolved organic carbon (DOC) resulting in a predicted age of >24 ka for the most persistent DOM fraction. Individual first order kinetic degradation rates for 1557 mass peaks indicate that numerous DOM molecules cycle on timescales much longer than the turnover of the bulk DOC pool resulting in estimated residence times of more than 75 ka. With gradual ageing, DOM molecules encompass only a narrow range of elemental ratios H/C (1.17 ± 0.13), and O/C (0.52 ± 0.10) and molecular mass (360 ± 28 and 497 ± 51 Da) reflecting the most stable composition in the oceanic environment which we term “island of stability”. Further, we could identify 339 mass peaks likely contributing to an increased DOC abundance in the Southern Ocean which potentially reflect an enhanced sequestration of refractory DOC.

Keynote talk

Eavesdropping on the Weddell Sea – Remote observation of marine mammals through a basin-wide acoustic array

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Marine mammals and birds as top predators consume a significant part of the primary production of the oceans. Harvesting organic material from the water column and breathing at the surface they constitute a carbon pump, transferring CO_2 from the ocean into the atmosphere. However, by redistributing nutrients into the upper water layers they can also enhance the productivity, leading to an increased carbon absorption and sedimentation. Both effects are species dependent and calculating quantitative assertions requires the knowledge of the spatio-temporal distribution of the animals. But for many marine mammal species the uncertainty in population size still

reaches the order of a magnitude. Traditional ways of counting animals visually during ship transects often suffer from low encounter rates, and especially the ice covered areas of the Southern Ocean are rarely surveyed during polar winter. Typically, on a transect across the Weddell Sea at most two or three blue whales are sighted, making it very hard to determine population trends. On the other hand, a hydrophone in the water picks up blue whale sounds almost continuously throughout the year. While visibility is limited to surfacing animals a few kilometers around the ship, their sounds travel several hundred kilometers through the water thus increasing the area survey-able by a hydrophone more than thousand fold, providing much better statistics. Moreover, as acoustic recorders can be deployed for several years in oceanographic moorings, polar winter conditions and heavy ice cover do not hinder permanent data acquisition. A network of about 20 recorders currently deployed by the Alfred Wegener Institute in the Weddell Sea and the acoustic observatory PALAOA at the ice shelf continuously record the acoustic environment. Advanced spectrogram visualisation tools allow graphing these multi-year long acoustic recordings into easily readable images and reveal detailed distribution and migration data for several species. So far, blue, fin, humpback, sperm, killer and possibly minke whales as well as Weddell, Ross, crabeater, and leopard seals have been detected and are easily distinguishable through their species specific vocalisations.

Carbon uptake in the Weddell Gyre, where 'old' (deep water) and 'new' (fossil fuel CO_2) meet in icy surface waters

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The presentation discusses recent advances in and key questions for Weddell Gyre research on the marine carbon cycle. These questions are:

- What is the long-term Weddell Gyre carbon uptake of atmospheric carbon dioxide (CO_2)?
- What is the air(-ice)-ocean CO_2 transfer in seasonally ice covered waters? How will it change?
- Does ikaite significantly affect Weddell Gyre carbonate chemistry?
- Which other calcium carbonate dissolution and precipitation processes affect the Weddell Gyre carbon cycle?
- Are seasonally ice covered waters a strong pump for atmospheric carbon dioxide as recently suggested?
- What is the current and future CO_2 uptake by Antarctic Bottom Water?
- What is the saturation of gases (carbon dioxide, chlorofluorocarbons, oxygen) in newly formed bottom water in the Weddell Gyre?
- How will ocean acidification affect marine carbon cycling?

Strategic measurements and synthesis activities for addressing these questions are identified. These include the Surface Ocean CO_2 Atlas (SOCAT, www.socat.info), deep ocean carbon synthesis products, such as GLODAP and CARINA, time series measurements, repeat hydrographic sections and process studies on the role of sea ice in ocean-atmosphere gas transfer, of calcium carbonate processes and of ocean acidification in the Weddell Gyre carbon cycle and uptake of atmospheric CO_2.

Observations of increasing DIC in the deep waters of the Weddell Gyre

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The world ocean takes up a large portion of the anthropogenic CO_2 (C_{ant}) emitted into the atmosphere. Determining the resulting increase in dissolved inorganic carbon (DIC) is challenging, particularly in the sub-surface and deep Southern Ocean where the time rate of change of DIC is expected to be low. Moreover, equating the increase in DIC to the increase in C_{ant} requires the assumption of steady-state biogeochemistry and hydrography, which is not necessarily appropriate in the dynamic Southern Ocean. Nonetheless, we use this approach, like other methods do, in order to gain an estimate of the rate of storage of Cant in the deep Weddell Gyre, for which earlier estimates ranged widely.

Using 11 cruises, spanning the era from 1973 to 2011, we investigate the time rate of change of DIC in the Weddell Gyre along (i) a meridional section along the Prime Meridian, (ii) along the continental slope at the western end of a near-zonal section between Kapp Norvegia and the tip of the Antarctic Peninsula and (iii) over the bottom of the Weddell Sea. Data coverage for (i) is better than for (ii) and (iii), at 11, 6 and 6 datasets, respectively.

In the Weddell Sea Bottom Water at the Prime Meridian, we observe a time rate of increase of DIC of 0.12±0.04 µmol kg^{-1} $decade^{-1}$. The spatial distribution (i.e., over depth and latitude) of the increase in DIC bears a remarkable resemblance to that of CFCs, suggesting that the changes in C_{ant} are propagated from the surface, rather than reflecting variability in deep-ocean processes (e.g., remineralization of organic matter). Near the tip of the Antarctic Peninsula, it may be expected that the coldest, most recently ventilated waters, flowing closely against the continental slope, will exhibit an increasing DIC over time. Due to the relative scarcity of data there, we opt to determine the DIC at -1.25ºC by linear regression of DIC against potential temperature for all samples below 2000 m depth and within 400 m from the seafloor. The inferred DIC at -1.25ºC over the years of data availability (1993 to 2011) shows a rate of 0.13 ± 0.10 µmol kg^{-1} $decade^{-1}$.

At the bottom of the Weddell Sea, here defined as all samples located within 250 m from the sea floor and between 20ºW and 40ºW, no relationship is found between DIC and potential temperature. The mean values of DIC in these near-bottom waters are observed to have remained constant at 2248.5±0.5 µmol kg^{-1} over the years of observations, suggesting that no significant, recent ventilation of these waters has taken place. This finding is in line with the observed near-absence of CFCs at this location.

Although we show the gradual increase in DIC over the period of observations, we lastly question the validity of the assumption of steady-state conditions. Concomitant with the increase in DIC, we tentatively observe increases in dissolved nitrate (NO_3), phosphate (PO_4) and silicate (Si); and decreases in dissolved oxygen (DO). The ratios between the slopes of these trends (dPO_4/dt:dNO_3/dt:dDIC/dt:dDO/dt = 1:12:82:-76) resemble the Redfield remineralization ratios (1:16:106:-132), suggesting that the observed increase in DIC may be partly attributed to enhanced remineralization at depth or to increased entrainment of ‘old’ (i.e., nutrient-rich) waters during the formation of bottom waters. The latter alternative is compatible with the observed

increase in the temperature of the bottom waters, pointing to the increasing presence of warm, nutrient-rich Circumpolar Deep Water in the WSBW.

How well do we know anthropogenic carbon in the (deep) Weddell Sea? A preliminary assessment

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Thacker (2012, doi:10.1016/j.marchem.2012.02.004) introduced a new method to estimate anthropogenic carbon, the so-called *local two-regression method.* We revisit anthropogenic carbon estimates on the Prime Meridian in the Weddell Sea, following Thacker's guidelines. Checking the relationship between all possible variables and dissolved inorganic carbon (DIC) suggests that salinity, apparent oxygen utilization (AOU) and alkalinity are linearly related to DIC and possibly the best regressors in a multi-linear regression of DIC.

Our analysis, which includes a better constraint on the uncertainty as compared to previous estimates, indicates that anthropogenic carbon accumulation between 1992 and 2008 is not significantly different from zero in Weddell Sea Deep Water (WSDW) and Weddell Sea Bottom Water (WSBW) and not distinguishable between the two water masses.

An independent test of the method, where additional carbon is artificially and virtually added to the data sets at rates of 0.1 to 2 µmol kg^{-1} yr^{-1}, however, suggests that the method is not able to capture this fictive carbon increase. The local two-regression method might therefore lead to erroneous estimates of anthropogenic carbon in the deep Weddell Sea, calling for further investigation.

Dissolved barium in the Weddell Gyre

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Two full depth sections across the Weddell Gyre were sampled by the icebreaker FS Polarstern in February and March 2005. The total amount of dissolved barium (Ba_d) data in the Southern Ocean, which is still not very large, has been augmented significantly. Ba_d is relatively high in the surface layer and also in the whole water column, as compared to the adjacent waters north (Antarctic Circumpolar Current) and east (Antarctic Zone of the Indian sector). The Weddell Gyre seems to by atypical with respect to the Ba_d distribution within the Southern Ocean. The deep gyre is characterized by a significant Ba_d enrichment as compared to the inflowing water into the Weddell Gyre. Significant depletion of Ba_d in the surface layer is likely to be associated with biogeochemical processes, as found previously. However, we speculate that also sea-ice formation plays a role, i.e., by barite ($BaSO_4$) precipitation in supersaturated brines. Particulate Ba, either formed in the surface layer or just below that, rains down the water column, redissolution occurring in deeper waters where undersaturation of barite is prevalent. In the bottom layer, strong enrichment of Ba_d was found, exhibited as a Ba_d maximum, which is likely caused by Ba efflux from the sediments. In very recently formed Weddell Sea Bottom Water at the slope of the Antarctic Peninsula, though, a Ba_d minimum is observed. This can be explained

by the shelf water component during the formation of bottom water, the former having a relatively low Ba_d concentration. Throughout the water column, a strong correlation exists between Ba_d and dissolved silicate, although the relationship is different from that in the Antarctic regions to the east. The Southern Ocean, in turn, has a relationship different from other oceans. A tentative Ba_d budget was constructed using known concentrations and water mass rates. The deep water is mainly supplied with Ba_d by the surface layer, but also to a lesser extent by the bottom layer. Weddell Sea Deep Water, enriched in Ba_d, is transported out of the Weddell Gyre into the ACC as Antarctic Bottom Water, the gyre thus being a source of Ba_d to the world oceans.

7. Abstracts of posters

Biological and physical contributions to N_2, O_2, CO_2 and DMS disequilibria in Southern Ocean surface waters

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We present high spatial resolution measurements of pCO_2, dO_2/Ar, O_2, N_2 and dimethylsulfide (DMS) concentrations in Southern Ocean surface waters during austral summer of 2010 – 2011 (R/V Polarstern ANT-XXVII/2) and describe the biological and physical controls on gas distributions.

Our cruise track encompassed a variety of distinct hydrographic domains, including the sub-Antarctic and Antarctic pelagic regions (Atlantic sector), the marginal ice zone of the Weddell Sea and the West Antarctic Peninsula. In the pelagic waters of the sub-Antarctic and Antarctic regions, pCO_2 and dO_2/Ar were close to atmospheric equilibrium while DMS concentrations were typically low (< 5 nM). In the marginal ice zone, greatest variability in gases and Chl a was observed. Strong gas disequilibria of dO_2/Ar, pCO_2 and DMS were associated with ice edge blooms. In the West Antarctic Peninsula region, largest pCO_2 and dO_2/Ar excursions were observed (min. 100 µatm for pCO_2, max. +50 % for dO_2/Ar), while DMS variability was more limited. During our observations, the surface waters were a net sink of CO_2 and a net source for DMS.

Comparison of gases across the different regions shows contrasting regulating factors. In the pelagic realm north of the marginal ice zone, physical control (i.e., atmospheric forcing and mixing at hydrographic frontal zones) exerts a discernible effect on gas distributions. In the other regions, sea ice dynamics seem to be the most important driving force stimulating the biological gas cycling.

Natural and anthropogenic carbon in Antarctic Bottom Water: sequestration, accumulation and export from the Weddell Gyre to the global ocean

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In the Southern Ocean, the Weddell Gyre is regarded as the primary location for the formation of deep and bottom waters and is potentially a significant area for the sequestration of carbon, nutrients and atmospheric gases. Major quantities of dense, cold waters generated near and on the Antarctic continental shelf spill down the slopes entraining surrounding water masses as they descend. Circulating northwards, the waters are subsequently exported into the mid-latitude Southern Ocean, spreading globally at depth as an integral component of the southern closure of the meridional overturning circulation. Measurements of CFCs, SF_6 and the inorganic carbon system from two cruises - extending from the Antarctic Peninsula, along the South Scotia Ridge and the edge of the Weddell Basin to 30°E - conducted as part of the UK ANDREX (Antarctic Deep water Rates of EXport) project in 2009-2010 are used to investigate this process. Estimates of anthropogenic carbon in Antarctic Bottom Water are combined with velocity field outputs from an inverse model to derive quantitative information on the production within and export from the gyre, and to understand the key processes involved. Historical comparisons with GLODAP-based estimates enable the assessment of changing carbon inventories, fluxes and water mass formation rates within the region.
Initial results confirm the slow accumulation of anthropogenic carbon occurring in the deepest waters of the Weddell Gyre. Increases in northward export through the South Scotia Ridge over the last twenty years highlight the role of the region in injecting human-derived carbon into the global abyss.

Southern Ocean Transient Tracers - Preliminary results of SF_6 and CFC-12 measurements

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The transient tracers SF_6 and CFC-12 where measured during the Polarstern-Expedition ANT-XXVIII/3 as part of the Southern Ocean Eddy Pump Project. The transient tracers are used to constrain Transit Time Distribution (TTD) models to calculate the mean age of water masses. Based on these results it is possible to estimate column inventories of anthropogenic carbon (C_{ANT}). Together with further obtained parameters (e.g., DIC, TA, oxygen, nutrients), it should provide more information about transport processes and the role of CO_2 uptake by the ocean in high latitudes. The preliminary results show section plots of partial pressure and mean age (Δ/Γ=1.0) of the tracers as well as the corresponding salinity and potential temperature. The sections are divided into three areas of interest – a transect along 10°E, a bloom area with a high chlorophyll-a concentration and an eddy-like structure north of South Georgia.

Towards a nutrient budget of the Weddell Gyre

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Bottom water formation in the Southern Ocean plays an important role in the lower branch of the Meridional Overturning Circulation and in the global biogeochemical cycles, by ventilating and cooling the deepest layer of the world's ocean and sequestering carbon. Within the framework of

the Antarctic and Deep Water Rates of Export (ANDREX) project, we aim to evaluate the role of the Weddell Gyre in global biogeochemical cycling through the first systematic hydrographic and tracer measurements along the gyre's outer rim. In this work, dissolved inorganic nutrient fields are combined with velocity measurements in a box inverse model to obtain a self consistent estimate of nutrient transports across the rim of the Weddell Gyre. Our preliminary nutrient budget suggests a slight negative imbalance (i.e., exports) of nitrate (-0.9 kmol s^{-1}), but significant imbalances of phosphate (-2.6 kmol s^{-1}) and silicate (-67.3 kmol s^{-1}). Largest exports of nutrients are mainly associated with WSDW and WSBW. Further work will be done in order to determine the robustness of these results to then evaluate the importance of the gyre in the transport of nutrients to the global ocean.

Northwestern Weddell Sea data sets

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APPENDIX A – Program of the workshop

Day 1 – Monday, 17 September

9:00-9:10	Welcome at HWK
9:10-9:20	Short introduction - all participants
9:20-9:35	Mario Hoppema- Introduction to the workshop
9:35-9:50	Walter Geibert: Motivation and aims of the workshop. Information about the book project
9:50-10:30	Keynote: Michael Weber- Antarctic Deglaciation Since the Last Glacial Maximum – Implications for the Weddell Gyre Development
10:30-11:00	*Coffee*
11:00-11:25	Gerhard Kuhn: The Weddell Gyre in the past: speculations about its history and glacial/interglacial variability from geological records
11:25-11:50	Walter Geibert -Why are Weddell Gyre sediments virtually free of biogenic remains?
11:50-12:30	Keynote: Kurt Polzin- Control volume estimates of buoyancy fluxes from the Orkney Passage and South Scotia Sea.
12:30-13:50	*Lunch and break*
13:50-14:15	Mike Meredith- Changes in the outflow of dense waters from the Weddell Sea
14:15-14:40	Sunke Schmidtko - Scales of variability and long term trends in the north-western Weddell Sea
14:40-15:05	Mike Meredith (Pete Brown) - Freshwater fluxes in the Weddell Gyre: results from delta-18O
15:05-15:30	Loic Jullion- Exchanges between the Weddell Gyre and the rest of the Southern Ocean: Preliminary results from the ANDREX project
15:30-16:00	*Coffee*
16:00-16:25	Loic Jullion (A. Naveira Garabato)- On the variability of Antartic Bottom Water in the Weddell Sea
16:25-16:50	Oliver Huhn - Slowing down of deep and bottom water ventilation and anthropogenic carbon storage in the Weddell Sea
16:50-17:15	Michiel Rutgers van der Loeff - U-Th series nuclides in the Weddell Sea
17:15-17:30	Short break
17:30-18:30	Poster session
18:30	Dinner

Day 2- Tuesday 18 September

9:00-9:40	Keynote: Maria Vernet - Extensive subsurface phytoplankton biomass in the Larsen A embayment in April 2012
9:40-10:05	Clara Hoppe - Combined effects of ocean acidification and iron availability on Southern Ocean phytoplankton communities
10:05-10:30	Katrin Linse - Marine benthos under the Weddell Gyre – species distributions and connectivity
10:30-11:00	*Coffee*
11:00-11:25	Sophie Fielding - Acoustic detection of krill in the Weddell Sea from an undersea glider
11:25-11:50	Oliver Lechtenfeld - Molecular transformation and degradation of refractory dissolved organic matter and implications for the Weddell Sea carbon budget
11:50-12:30	Keynote Bio: Lars Kindermann: Eavesdropping on the Weddell Sea – Remote observation of marine mammals through a basin-wide acoustic array
12:30-13:50	*Lunch and break*
13:50-14:15	Dorothee Bakker - Carbon uptake in the Weddell Gyre, where 'old' (deep water) and 'new' (fossil fuel CO2) meet in icy surface waters
14:15-14:40	Steven van Heuven - Observations of increasing DIC in the deep waters of the Weddell Gyre
14:40-15:05	Judith Hauck - How well do we know anthropogenic carbon in the (deep) Weddell Sea? A preliminary assessment
15:05-15:30	Mario Hoppema - Dissolved barium in the Weddell Sea
15:30-16:00	*Coffee*
16:00-18:30	Plenary Discussion (with short break)
18:30	*Dinner*

Day 3:
Preparation of textbook

APPENDIX B – List of participants

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