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Towards data assimilation in ice-dynamic models: the (geo)physical basis

1 Introduction

This Habilitation considers the application of active electromagnetic reflection techniques – radar for short – to answer questions as they are raised in cryospheric sciences. The basic objective is: How can we derive physical properties from the interior on a natural ice mass by performing measurements at its surface?

The large ice masses play a key role in the planet's global hdrological cycle. They store vast amounts of water in solid form and thus influence the global sea level. Because of this property, the large ice sheets came into the focus of research and public attention during the last decades because of the changes in mass the ice sheets might experience under a chaning climate. The flow of large ice masses is controlled by processes occurring at their surface, at their base and by the spatial variation of rheological properties within the ice. The internal structure of the ice masses represents an integrated memory of the interaction of these processes and properties, knowledge of which has key implications for unraveling their history and predicting their future behaviour.

Over the last seven years my research engaged in the detection of macro-scale internal layer architecture with active electromagnetic methods. These active methods are also known as radio-echo sounding (RES), ground-penetrating radar (GPR), snow radar or alike, depending on the type of system, frequency and observational range. In general, laterally imaging the layer architecture of radar reflections yields complementary information to the direct evidence of physical properties otherwise solely provided by ice cores, which are however limited to single points.

Three main objectives were treated:

(i) understanding of physical properties on the micro-scale which cause coherent layered reflections or incoherent backscatter;

(ii) exploiting the layer architecture and related information acquired during data acquisition to deduce and understand ice kinematics and dynamic behaviour (flow);

(iii) using the lateral variation in layer depth of shallow reflections to deduce the spatio-temporal variation of specific surface mass balance, an important proxy for ground-truthing satellite-derived values of accumulation, especially in Antarctica and Greenland, and understand relevant physical processes.

Most recently, measurements from ice masses were extended to measurements of snow stratigraphy in a seasonal snow cover and changes thereof over the course of one winter season. One ultimate goal of my reasearch is to move forward the field of applied geophysics in croyspheric sciences to enable the transition from simply characterising the static components of systems towards the characterisation of transient processes to provide forecasts for near-future behaviour. A main purpose would be to advance the application of four-dimensional data assimilation techniques (4D-Var) in geophysical applications. In this context, the research presented in this Habilitation provides the physical basis for understanding what causes the reflections of electromagnetic waves in the radio frequency range in ice and how the observed features can be scientifically exploited.

2 Research synopsis: the bottom line

Before data assimilation for improving ice-dynamic models of ice sheets, shelves or glaciers can be tackled, the inherent properties of the subsystems contributing to the overall system behaviour have to be understood. The main subsystems considered in this Habilitation are:

- physical properties and characteristics of ice and snow from geophysical data
- ice dynamics and kinematics
- processes in the atmospheric boundary layer and effects on spatio-temporal distribution of accumulation

In this section I want to present a short summary of the main results. In the third section, the relevant publications are thematically grouped into these categories, followed by a compilation of the actual publications.

2.1 Physical properties and characteristics of ice and snow from geophysical data

Application of radar for imaging the snow, firn and ice column usually utilizes a transmitter and receiver moved at a certain distance from each other across the surface along the survey profile. The device is either towed by hand, a snowmobile or tractor, or carried on-board an airplane or helicopter. At defined intervals, either at equal temporal or spatial increments, the transmitter emits an electromagnetic pulse into the snow column. Distances between consecutive measurements vary, depending on the system performance, between about 0.1 and 10 m. The pulse penetrates into the snow column and is partly reflected where the complex dielectric permittivity changes. The reflected signals travel back to the receiving antenna at the surface. The complete signal is recorded as a function of traveltime of the transmitted radar pulse.

Three factors are known to change the dielectric constant in firn and ice: gradients in the real part, the permittivity, are mostly related to density; they dominate reflections in the upper 100s of meters. Variations in the imaginary part are proportional to conductivity, related to acidity, and depend on frequency. They are the governing reflection cause in deeper ice. A third mechanism involves dielectric anisotropy of the crystal fabric of ice, but it becomes significant only at the deeper levels ($>$500–1000 m) of the ice sheet, where changes in anisotropic crystal fabrics could develop. Other radar techniques are based on frequency-modulated continuous wave (FMCW) transmissions or stepped-frequency radars. Although the technical details on data acquisition and processing are different, the results are the same – an image of subsurface reflections along a profile.

One tool employed in several of the publications listed in subsection 3.1 is a finite-difference numerical code of the Maxwell equations. Based on the complex dielectric permittivity measured along an ice core by means of dielectric profiling, the code calculates the estimated response signal received at the surface for a given electromagnetic pulse emitted at the surface into the ice. By means of comparison of synthetic radargrams with measured radargrams and sensitivity studies, it became possible to attribute the physical change observed in the ice-core data to an observed continuous internal reflection horizon. This method proved very efficient for improving the depth estimate of internal reflections caused by changes in conductivity, mostly related to aerosol deposition from volcanic eruptions (e.g. Eisen et al., J.Glac., 2006). The method was later complemented by including data on the crystal orientation fabric (COF) measured along the same ice core. However, as COF data was spatially too sparse in terms of depth resolution, it has not yet been incorporated in the forward model. Nevertheless, it was possible by Eisen et al. (TC, 2007) for the first time ever to identify a continuous internal reflection horizon which is caused by a transition in COF (from elongated girdle to single maximum texture). This is especially important for establishing realistic models of rheological properties for ice-dynamic flow, as for an anisotropic ice crystal the effective viscosity differs by up to two orders of magnitude compared to an isotropic distribution of ice. An extension of this study by Drews et al. (TC, 2009) led to the possibility to relate observed macro-scale basal zonations in radargrams obtained in ice sheets (the so-called echo-free zone, on the order of several hundreds meter thick) to layer disturbances on the micro-scale (on the order of milli- to centimeters). Apart from another set of constraints for ice-dynamic models, this is important for the selection of sites for deep ice-core drilling, as the echo-free zone hints to potential disturbances in the layer sequence – and thus age – of the ice, which could result in unusable information in an ice core.

Another field of study lead to the characterization of the thermal structure of a large Alpine glacier (Eisen et al., Ann.Glac., 2009). As the liquid water content of ice depends exponentially on its temperature below the pressure melting point, it was possible by radar methods to characterize those parts of the glacier, which were significantly below the freezing point. This study sets a starting point for future observations of the evolution of the glacier's thermal structure under changing climate conditions, but moreover implies different rheological and hydraulic behaviour for the different regimes, important to separate in envisaged modelling studies.

A third subject treated in the context of physical properties of ice and snow is the temporal characterisation of seasonal snow-pack evolution (Heilig et al., CRST 2009, Heilig et al., Hyd.Proc., 2009). With the development of an upward-looking GPR application it became possible to monitor the evolution of a seasonal snow cover from underneath. This enabled us to establish relations between the observed reflection signatures, physical properties and the underlying processes and temporal evolution. The findings are the basis to assimilate the GPR data in snowpack models for improved evaluation of snow metamorphosis, melt processes and ultimately snow-pack stability for forecasting avalanche danger.

2.2 Ice dynamics and kinematics

Ideally, an ice-dynamic model would be able to reproduce and evolve the true stress and strain distributions and correct rheological respective fabric properties from given initial and boundary conditions. However, current ice-dynamic models are still far from achieving this in three dimensions, simply for the reason of limited computing power. In order to pursue a one-dimensional approach, studies like Wesche et al. (J.Glac., 2007) provide local topography, velocities and strain fields at the surface, which can then either be incorporated into dynamic models or be used for validation purposes.

However, as especially geophysical radar surveys yield regional-scale data sets of internal layer architecture in ice sheets, and thus relative three-dimensional age distributions, direct exploitation of these data sets could allow for improved three-dimensional deduction of velocity, strain or stress fields. As an initial step, Eisen (J.Glac., 2008) investigated a kinematic approach to determine two-dimensional velocity distributions from a given age field by means of an inverse method using singular value decomposition. The age field is taken from internal radar layer architecture and is treated as a tracer field. As the system of equations is generally underdetermined, it is necessary to provide further boundary conditions at the surface, as e.g. established by Wesche et al. (J.Glac., 2007), or spatial distributions of surface accumulation, which can likewise be deduced from radar data, as discussed next. Based on these results, further developments should aim in the long run at directly assimilating layer architecture (i.e. isochrones) into ice-dynamic models to improve model quality and reliablility.

2.3 Processes in the atmospheric boundary layer and effects on spatio-temporal distribution of accumulation

The spatial distribution of accumulation has been investigated by means of ground-penetrating radar in specific areas of the dry-snow zone of Antarctica, the dry-snow zone and percolation zone of Greenland and a temperate glacier in the Swiss Alps. The underlying physical principle of utilizing GPR for accumulation studies is the layered persistence of changes in physical properties over time, from which radar waves are reflected. Several processes cause simultaneous changes of physical properties of an ice mass. For instance, density is mainly altered by seasonal temperature or radiation changes or storm events with heavy precipitation, coherently on the scale of ten to more then hundred kilometers. Another important factor, especially in the dry snow zones of the large ice sheets, is the deposition of volcanic aerosols at the surface, which lead to peaks in electric conductivity. Once a layer is formed at the surface, further accumulation on top leads to layer submergence. As such a layer forms at the surface at basically the same time, it can be considered an isochrone, i.e. a layer of equal age. By performing GPR surveys one can image the depth of these layers along the profile. The depth of a layer or the distance between layers is an indicator for the amount of ice that has been accumulated within the respective time period (i.e. age difference) between the layers. Mapping layer architecture along single profiles or over larger areas in the form of grids or alike provides a 2D or 3D view of layer architecture. From this, averaged mass balance can be deduced. This measurement principle has been applied in numerous papers and is laid out in detail in the comprehensive review paper by Eisen et al. (Rev. Geophys., 2008), together with a presentation and overall discussion of other methods to determine specific surface mass balances on ice sheets.

The fundamental result of my research in this respect is that accumulation (i.e. the positive contribution to mass balance) is much more variable than previously assumed. In Dronning Maud Land (DML), Antarctica, a point measurement of accumulation has been found to be representative only within a distance of several kilometers. However, covariance seems to appear over a much larger area, up to several hundred kilometers. This finding is of great importance for the interpretation of accumulation from ice-core records, which usually have separations of several hundred to even thousand kilometers, and for determining the overall state of mass balance of ice sheets within the assessment of global climate change and sea-level rise. As for DML, winter accumulation was likewise found to vary significantly on a glacier in the Swiss Alps. Before this result, researchers assumed that the overall precipitation determined from weather stations over a certain period and region is a good proxy for integral accumulation on a glacier, given a calibration has been established before. However, it turned out that accumulation on a glacier can likewise vary significantly enough to cause errornous results when modelling glacier mass balance. The main reason for the observed variability of accumulation is the same in Alpine regions as well as on the Antarctic plateau: redistribution of snow by small variations in wind speed. Whereas it is obvious that the overall topography of mountains influences accumulation, it has been less clear to which extent small-scale variations in surface slope (on the order of degrees) influence the wind redistribution. Thus, it has been surprising that a topographic high in surface elevation of only one meter over a hundred meter distance is large enough to cause a signficant redistribution on the order of ten percent.

On the ice sheets, in general, these small-scale variation overlay the large-scale trend in accumulation caused by tropospheric conditions. A first-order estimate of accumulation at a point can be obtained from the distance to the coast and mean temperature. An extreme case for small-scale variations in accumulation has been investigated in Anschütz et al. (GRL, 2006). Our interpretation is that oscillations in the atmospheric surface boundary layer are initiated by a break in surface slope, where the polar plateau in DML enters an outlet glacier through a mountain range. On an undisturbed surface, these oscillation cause a variation in wind speed and thus a variation in accumulation. Once this system has been stable for a long enough time, unulations in surface elevation develop from the variation in accumulation. This, in turn, again influences wind speed and thus accumulation. The result is the development of dunes with a dominant wavelength of 5 km and undulations of $\sim$10 m. Overall, this process causes quasi-harmonic oscillations of surface undulations, surface slope and accumulation, with a clear anticorrelation of accumulation and slope at zero lag.

The significance of these findings lies in their application to other methods for determining mass balance, like numerical atmospheric modelling or satellite remote sensing, e.g. by mapping passive microwave radiation or altimetric surveys. As regional-scale atmospheric models operate on grids $>$10 km increment and satellite sensors typically have footprints in size on the order of 10–100 km^2, both methods can presently not resolve smaller-scale features or variations, but only provide grid-cell or footprint-averaged information. If processes occuring on the sub-footprint-scale are unknown or wrong processes taken into account, data analysis can lead to errorenous results, which might turn out, in the worst case, to be unusable.

3 Relevant publications in thematic order

Several publications inclcuded in this cumulative Habilitation resulted from studies in the framework of dissertation and diploma theses, for which I acted as the main advisor on the scientific and/or technical level:
Dissertations: H. Anschütz (Uni. Bremen), H. Machguth (Uni. Zürich), C. Wesche (Uni. Bremen), G. Rotschky (Uni. Bremen), A. Heilig (Uni. Heidelberg), R. Drews (Uni. Bremen);
Diploma thesis: T. Dunse (Uni. Bremen).
In these publications the doctoral or diploma candidate acted as the first author, according to the DFG ”Regeln der guten wissenschaftlichen Praxis”. In the following I first provide a list of publications in thematic order, according to the categories laid out above. This is complemented by the actual publications, which are usually available in the form of electronic reprints reproduced here.

3.1 Physical properties and characteristics of ice and snow from geophysical data

Drews, R., **Eisen, O.**, Hamann, I., Kipfstuhl, S., Lambrecht, A., Steinhage, D., Wilhelms, F., Miller, H. Layer disturbances and the radio-echo free zone in ice sheets, The Cryosphere, 3, 195–203, http://www.the-cryosphere.net/3/195/2009/, 2009.

Eisen, O., Hamann, I., Kipfstuhl, S., Steinhage, D., Wilhelms, F. Direct evidence for continuous radar reflector originating from changes in crystal-orientation fabric, The Cryosphere, 1, 1–10, http://www.the-cryosphere.net/1/1/2007/tc-1-1-2007.html, 2007.

Eisen, O., Bauder, A., Riesen, P., Funk, M. Deducing the thermal structure in the tongue of Gornergletscher, Switzerland, from radar surveys and borehole measurements, Annals of Glaciology, 50, 51, 63–70, 2009.

Eisen, O., Wilhelms, F., Steinhage, D., Schwander, J. Improved method to determine RES-reflector depths from ice-core profiles of permittivity and conductivity, Journal of Glaciology, 52, 177, 299–310, 2006.

Heilig, A., Schneebeli, M., **Eisen, O.** Upward-looking Ground-Penetrating Radar for monitoring snow-pack stratigraphy, Cold Regions Science and Technology, 59, 2–3, 152–162, doi:10.1016/j.coldregions.2009.07.008, 2009.

Heilig, A., **Eisen, O.**, Schneebeli, M. Temporal Observations of a Seasonal Snowpack using Upward-Looking GPR, in revision with Hydrological Processes, 2009.

3.2 Ice dynamics and kinematics

Eisen, O. Inference of velocity pattern from isochronous layers in firn, using an inverse method, Journal of Glaciology, 54, 187, 613–630, 2008.

Wesche, C., **Eisen, O.**, Oerter, H., Schulte, D., Steinhage, D. Surface topography and ice flow in the vicinity of the EDML deep-drilling site, Antarctica, Journal of Glaciology, 53, 182, 442–448, 2007.

3.3 Spatio-temporal distribution of accumulation

Eisen, O., Frezzotti, M., Genthon, C., Isaksson, E., Magand, O., van den Broeke, M., Dixon, D. A., Ekaykin, A., Holmlund, P., Kameda, T., Karlöf, L., Kaspari, S., Lipenkov, V., Oerter, H., Takahashi, S., Vaughan, D. Snow accumulation in East Antarctica, Reviews of Geophysics, 46, RG2001, doi:10.1029/2006RG000218, 2008.

Anschütz, H., Steinhage, D., **Eisen, O.**, Oerter, H., Horwarth, M. Small-scale spatio-temporal characteristics of accumulation rates in western Dronning Maud Land, Antarctica, Journal of Glaciology, 54, 185, 315–323, 2008.

Dunse, T., **Eisen, O.**, Helm, V., Rack, W., Steinhage, D., Parry, V. Characteristics and small-scale variability of GPR signals and their relation to snow accumulation in Greenland's percolation zone, Journal of Glaciology, 54, 185, 333–342, 2008.

Anschütz, H., **Eisen, O.**, Steinhage, D., Oerter, H., Scheinert, M. Investigating small-scale variations of the recent accumulation rate in Coastal Dronning Maud Land, East Antarctica, Annals of Glaciology 46, 14–21, 2007.

Machguth, H., **Eisen, O.**, Paul, F., Hoelzle, M. Strong spatial variability of accumulation observed with helicopter-borne GPR on two adjacent Alpine glaciers, Geophysical Research Letters, 33, L13503, doi:10.1029/2006GL026576, 2006.

Anschütz, H., **Eisen, O.**, Rack, W., Scheinert, M. Periodic Surface Features in Coastal East Antarctica, Geophysical Research Letters, 33, L22501, doi:10.1029/2006GL027871, 2006.

Eisen, O., Rack, W., Nixdorf, U., Wilhelms, F. Characteristics of accumulation in the vicinity of the EPICA deep-drilling site in Dronning Maud Land, Antarctica, Annals of Glaciology, 41, 41–46, 2005.

Steinhage, D., **Eisen, O.**, Clausen, H. B. Regional and temporal variation of accumulation around North-GRIP derived from ground based ice-penetrating radar, Annals of Glaciology, 42, 326–330, 2005.

Rotschky, G., **Eisen, O.**, Wilhelms, F., Nixdorf, U., Oerter, H. Spatial characteristics of accumulation patterns derived from combined data sets in Dronning Maud Land, Antarctica, Annals of Glaciology, 39, 265–270, 2004.