Bridging the gap: from terrestrial to icy moons cryospheres

ISSI Proposal (Call for International Teams 2023)

Part A

Abstract

Ice is omnipresent in our Solar System; on Earth, on planetary bodies, and on moons in the outer Solar System. In the past, terrestrial and extraterrestrial cryosphere science mostly developed as independent research fields whereas synergies may shed light on both fields. This ISSI Team brings together scientists working on terrestrial and extra-terrestrial cryospheres. The main goal is to make knowledge hidden in the vast amounts of existing data from different research groups accessible by consolidating it into a comprehensive meta-data enriched compilation of ice properties. This extends to relevant physical regimes on both Earth, and icy moons including data from field campaign measurements, laboratory experiments, and planetary missions.

Information on thermal, physical, and chemical ice properties will be used to derive parametrizations[1]. These can be easily implemented as initial and boundary conditions or sub-scale material parameters in numerical models, thereby significantly enhancing the data's simulation readiness. At the end of the project, the database, the accompanying parametrizations, and potential simulation results will be made publicly available. This approach will provide us with the unique opportunity to transfer and extrapolate the information from the Earth to the outer Solar System bodies. Our ISSI Team is an important step forward to bring together the Earth cryosphere community and the icy moons community to explore cryo-environments at different scales. With the launch of the JUICE mission this year and Europa Clipper mission in 2024, this research is timely and will lay the foundation for joint analyses between terrestrial and extra-terrestrial cryosphere communities to address future mission data from the outer Solar System.

1 Scientific rationale

Ice and icy materials are present in many places in the Solar System and form the main constituents of polar caps, terrestrial ice sheets, ice masses covering regions in permanent shadow, and the outer layers of icy moons. Main research areas that aim to better understand these icy regions include:

- **Polar research** studies the terrestrial cryosphere as one key indicator of Earth's global climate system (Notz, 2009). As one of the main drivers, the cryosphere plays a pivotal role. Consequently, monitoring, characterizing and determining projections of eustatic sea level change depends on an in-depth understanding of terrestrial bodies of ice (Fyke et al., 2018), and in particular, of oceanogenic ice – the ice formed from ocean water.
- **Planetary research** focuses on studying the outer ice crust of Ocean Worlds in the outer Solar System (e.g., Coustenis and Encrenaz, 2013). While the Cassini mission provided a wealth of data on Enceladus and Titan (Sotin et al., 2021), future measurements of the Europa Clipper (Howell and Pappalardo, 2020) and JUICE (Grasset et al., 2013; Hussmann et al., 2017) missions will allow us to study the interior structure, formation and evolution of Europa and Ganymede, and in particular to characterize the structure and composition of their cryosphere.

A better understanding of the structure and evolution of terrestrial and planetary ices requires information about their thermal, physical, and chemical properties at a variety of scales (Fig. 1). Data at the level of individual ice crystals that affect the ice micro-structure (Llorens et al., 2016), is mostly available from terrestrial field campaigns and laboratory measurements (Montagnat

[1] interpolations to express the dependence of properties on e.g., temperature, pressure or depth, and chemical composition

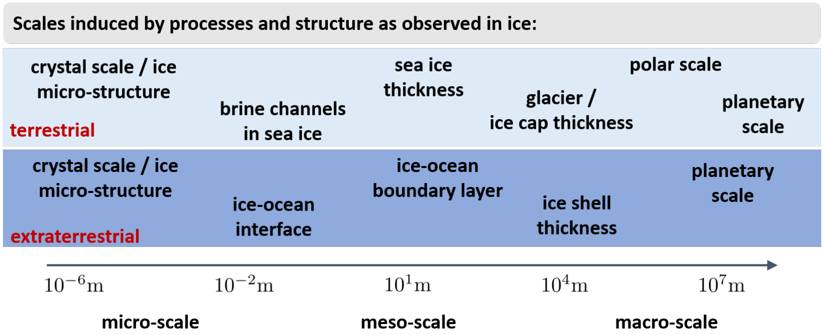

Figure 1: Icy bodies in our Solar System comprise different scales of interest, ranging from the crystal scale, boundary layer scales, typical ice thickness scales for glaciers, ice caps or ice shells to global scales (polar or planetary scale).

et al., 2014; Kerch et al., 2018). Mushy layers and brine channels in sea ice and ice-ocean interfaces lie at the boundary between micro- and meso-scales. The latter include length scales of meters to tens of meters and cover terrestrial sea ice thickness and the ice-ocean boundary layer on icy ocean worlds. Macro-scales, in turn cover structures that reach from tens to hundred of kilometers. These scales are typically met in planetary data sets and can be used to infer large-scale dynamics, as well as global-scale heterogeneities. Information, such as thermal and electrical conductivity, salinity, internal structure (layering), porosity, grain size, and rheological properties, is available mostly for terrestrial and in some cases for planetary environments at different levels of detail. While some of the data is available from direct measurements, other information is extrapolated to relevant conditions using numerical modeling. However, this information is scattered among literature studies, reports from field campaigns and experiments, and terrestrial and planetary data bases. Moreover, various formats are used for the data sets and associated meta-data information, which makes the comparison difficult.

In this project, we aim to collect a comprehensive set of information about thermo-physical and chemical properties of terrestrial and planetary ice, from field measurements, laboratory experiments, and numerical models. Starting with an extensive literature review, we will include this information into a searchable (meta-)database following a harmonized structure for various - potentially heterogeneous data sets from different sources. Together with associated comparative analyses that will result from the work effort of our ISSI Team this constitutes a data hub (here: Ice Data Hub). The Ice Data Hub comprises the potentially enriched meta-data along with a functional layer facilitating data access. It will be made available to the wider scientific community.

The objectives of this project are:

1. **Ice data sets:** Collect data sets (along with their meta data) that describe the thermal, physical, and chemical properties of terrestrial and planetary ices, as well as internal structure of icy bodies:
   - Thermal properties: thermal conductivity, heat capacity, thermal expansivity, etc.
   - Physical properties: porosity, grain size, rheological properties, density, etc.
   - Chemical properties: salinity, chemical composition, clathrate-hydrates, etc.
   - Internal structure of the ice that provides information on the temperature, pressure, and potentially chemical conditions
2. **Comparative analyses of ice data:** Conduct descriptive comparative analyses; derive parametrizations and apply these in state-of-the-art numerical models that investigate physical processes on different scales:
   - Provide scripts and code snippets to compare terrestrial data sets at various locations
   - Derive parametrizations based on integrated data sets resulting from terrestrial observations and/or lab data and extrapolate to other physical regimes or scales
   - Utilize parametrizations of thermo-physical, rheological, and chemical properties in numerical simulation codes for planetary ice shells and/or ice-ocean boundary models

1.1 Ice data sets

To accomplish **Objective 1** we will collect available data sets from both terrestrial and planetary ice. To our knowledge, no collection containing both terrestrial and planetary data exists and no comprehensive comparison between terrestrial and planetary ice data is available to date to relate or contrast ice material properties (thermal conductivity, viscosity, elasticity, density) and cryo-structural features (chemical heterogeneities and layering).

Terrestrial data sets cover the Greenland and Antarctic ice sheets (MacGregor et al., 2015), sea ice (Weeks and Ackley, 1986), saline lake ice (Buffo et al., 2022; Doran et al., 2003; Yoda et al., 2021), and laboratory grown ices (Weeks and Cox, 1974; Kuehn et al., 1990). A wealth of data on various ice properties is available at various spatial scales for terrestrial analog ices. For icy moons, less is known about the structure and chemistry of their icy shells. However, first order constraints on their thicknesses, chemistries, and thermal structures have been devised from remote sensing observations and numerical models (Schubert et al., 2004, 2010; Trumbo et al., 2019; Waite et al., 2006), providing characteristic scales and properties that can be compared/contrasted against those of terrestrial ice systems to extend our understanding of ice thermophysical and geochemical processes across planetary relevant spatiotemporal scales and environmental conditions.

Within the ISSI Team we will discuss existing ice data sets and decide what information is the most relevant to characterize the ice structure from micro- over meso- to macro-scale. We will collect data and associated meta-data information relevant to the ice structure and dynamics indicative of layering and heterogeneities, and thermo-physical and chemical properties from a variety of sources that include peer-reviewed publications (e.g., Fukusako, 1990; Arenson et al., 2021; Liley, 2005), reports (e.g., Yen, 1981; Angelopoulos et al., 2022), and data bases (e.g., PANGAEA, Polar Data Catalog, Planetary Data System). The information will be compiled into a searchable Ice Data Hub that will also include details about data provenance (i.e., measurements, models) with appropriate referencing to the original publications. The Ice Data Hub will be one of main outputs of our ISSI Team and will be made publicly available at the end of the project.

1.2 Comparative analyses of ice data

The **2nd Objective** will use data corresponding to the meta-data integrated into the Ice Data Hub (output of Objective 1) to investigate correlations between the data sets collected for different terrestrial regimes as well as representative icy moons environments. For tabulated data sets we will derive parametrizations by fitting experimental measurements and data sets that can then be easily used in numerical simulation codes. Additionally, we will investigate the extrapolation of terrestrial data to icy moons conditions by including our parametrizations in numerical models of ice dynamics (e.g., Elmer/Ice Licciulli et al., 2020; GAIA, Plesa et al., 2020; SOFTBALL, Buffo et al., 2021). Both models of the mushy layer interface that naturally occurs at the base of sea and saline lake ice (Thomas, 2017) and potentially at the ice-ocean interface of icy moons (Buffo et al., 2020), and global-scale models that investigate the dynamics in the ice shells of icy moons (Tobie et al., 2003; Kalousová et al., 2016; Allu Peddinti and McNamara, 2015; Plesa et al., 2020; Rückriemen-Bez et al., 2022) rely on such parametrizations to investigate the evolution of icy bodies. For example, data on thermal conductivity can be used to parameterize its temperature dependence. In turn, this parametrization can be used in numerical simulations to determine how it affects the thermal state and dynamics in the ice shells of icy satellites (e.g., Rückriemen-Bez et al., 2022; Carnahan et al., 2021). By testing our parametrizations with available state-of-the-art numerical models of ice shells, we will demonstrate the advantages of the Ice Data Hub in providing information for future investigations in a comfortable, user-friendly manner.

The forthcoming JUICE (Grasset et al., 2013) and Europa Clipper (Howell and Pappalardo, 2020) missions will provide unprecedented information about the icy moons of Jupiter, in particular Europa and Ganymede. With geophysical, remote-sensing instruments (e.g., Culha et al., 2020; Schroeder et al., 2016) these missions will investigate the structure and associated thermo-physical and chemical properties of ice in the outer Solar System and the results obtained in this objective have the potential to inform these future measurements of icy bodies.

Our data collection and the analyses will provide a "go-to" resource for future work that will bring together terrestrial and planetary ice communities.

2 Work plan and schedule

Over the duration of the project (two years) we plan to have two one-week in-person meetings in Bern, with the possibility for remote participation of team members that may not be able to travel. Additionally, we will organize an online meeting towards the end of the project to wrap up our results and discuss the final outcome of our team. Over the entire duration of the project, monthly online meetings will take place to discuss our progress. The preliminary schedule is the following:

- **1st meeting (late 2023 / beginning 2024):** review and categorize data from polar/sea-ice and planetary ice; agree on uniform representation of data of the same category; decide what information on thermo-physical and chemical properties to include in the Ice Data Hub.
- **2nd meeting (late 2024 / beginning 2025):** evaluate the data collected in the Ice Data Hub; add expressions when data is available as function of some parameter (e.g., thermal conductivity measured for different temperatures at constant pressure); perform extrapolations from terrestrial to planetary environments and test these extrapolations with numerical models.

3 Scientific output

The proposed ISSI Team will bring together, for the first time, researchers from the polar/sea-ice and planetary research communities to work on both terrestrial and extra-terrestrial ice. The scientific output of this ISSI Team includes:

- **A searchable meta database** that will contain information about the thermo-physical, rheological, and chemical properties from terrestrial field campaigns, laboratory measurements, planetary data, and models.
- **A set of tools in form of python scripts, jupyter notebook, or similar** to derive parametrizations of data sets where necessary and to analyze data from the Ice Data Hub.
- **Team publication on a terrestrial cryosphere data compilation to inform future research on (exploration of) icy moons.** The publication will have a review character and provides reference to the individual ice data repositories, as well as harmonized metadata for a comparative analysis. Additional publications might result from data collection in Objective 1 and data analyses in Objective 2 (e.g., a paper on comparison of ice properties at different terrestrial locations and a paper comparing parametrizations and their effect on results from numerical models).

We will adhere to open access formats as best scientific practice and commit to make the publications, data, scripts, and codes that will be developed by our ISSI Team openly available whenever possible. Links to data repositories and publications resulting from our ISSI Team will be listed on the ISSI Team website. In addition to journal publications, we also plan to present project updates at international conferences in order to increase the visibility of our work.

4 Financial support requested from ISSI

We request financial support from ISSI that will cover living expenses during the in-person meetings in Bern. We also request team coordinator travel support. For the hybrid meetings, we request a room equipped with WiFi access, a Zoom license, and technical devices that will allow for interaction between the in-person participants and the online attendees. We intend to use the online collaboration tools provided by ISSI, such as Overleaf, for preparing the publications, and a project website at ISSI with internal and public areas.

A. References

Allu Peddinti, D. and McNamara, A. K. (2015). Material transport across Europa's ice shell. *Geophysical Research Letters*, 42(11):4288–4293.

Angelopoulos, M., Damm, E., Simões Pereira, P., Abrahamsson, K., Bauch, D., Bowman, J., Castellani, G., Creamean, J., Divine, D. V., Dumitrascu, A., et al. (2022). Deciphering the properties of different Arctic ice types during the growth phase of MOSAiC: Implications for future studies on gas pathways. *Frontiers in Earth Science*, 10:Art–Nr.

Arenson, L., Colgan, W., and Marshall, H. P. (2021). Physical, thermal, and mechanical properties of snow, ice, and permafrost. In *Snow and ice-related hazards, risks, and disasters*, pages 35–71. Elsevier.

Buffo, J., Brown, E. K., Pontefract, A., Schmidt, B. E., Klempay, B. E., Lawrence, J., Bowman, J., glass, J., Plattner, T., Chivers, C. J., and Team, t. O. (2022). The bioburden and ionic composition of hypersaline lake ices: Novel habitats on earth and their astrobiological implications. *Astrobiology*.

Buffo, J., Schmidt, B., Huber, C., and Walker, C. (2020). Entrainment and dynamics of ocean-derived impurities within europa's ice shell. *JGR: Planets*.

Buffo, J. J., Meyer, C. R., and Parkinson, J. R. G. (2021). Dynamics of a solidifying icy satellite shell. *Journal of Geophysical Research: Planets*, 126(5):e2020JE006741. e2020JE006741 2020JE006741.

Carnahan, E., Wolfenbarger, N. S., Jordan, J. S., and Hesse, M. A. (2021). New insights into temperature-dependent ice properties and their effect on ice shell convection for icy ocean worlds. *Earth and Planetary Science Letters*, 563:116886.

Coustenis, A. and Encrenaz, T. (2013). *Life beyond Earth: The search for habitable worlds in the universe*. Cambridge University Press.

Culha, C., Schroeder, D. M., Jordan, T. M., and Haynes, M. S. (2020). Assessing the detectability of europa's eutectic zone using radar sounding. *Icarus*, 339:113578.

Doran, P. T., Fritsen, C. H., McKay, C. P., Priscu, J. C., and Adams, E. E. (2003). Formation and character of an ancient 19-m ice cover and underlying trapped brine in an "ice-sealed" east antarctic lake. *Proc Natl Acad Sci U S A*, 100(1):26–31.

Fukusako, S. (1990). Thermophysical properties of ice, snow, and sea ice. *International Journal of Thermophysics*, 11(2):353–372.

Fyke, J., Sergienko, O., Löfverström, M., Price, S., and Lenaerts, J. T. (2018). An overview of interactions and feedbacks between ice sheets and the Earth system. *Reviews of Geophysics*, 56(2):361–408.

Grasset, O., Dougherty, M., Coustenis, A., Bunce, E., Erd, C., Titov, D., Blanc, M., Coates, A., Drossart, P., Fletcher, L., et al. (2013). Jupiter icy moons explorer (juice): An esa mission to orbit ganymede and to characterise the jupiter system. *Planetary and Space Science*, 78:1–21.

Howell, S. M. and Pappalardo, R. T. (2020). NASA's Europa Clipper—a mission to a potentially habitable ocean world. *Nature Communications*, 11(1):1–4.

Hussmann, H., Lingenauber, K., Oberst, J., Enya, K., Kobayashi, M., Namiki, N., Kimura, J., Thomas, N., Lara, L., Steinbrügge, G., et al. (2017). The Ganymede Laser Altimeter (GALA). In *European Planetary Science Congress*, volume 11.

Kalousová, K., Souček, O., Tobie, G., Choblet, G., and Čadek, O. (2016). Water generation and transport below Europa's strike-slip faults. *Journal of Geophysical Research: Planets*, 121(12):2444–2462.

Kerch, J., Diez, A., Weikusat, I., and Eisen, O. (2018). Deriving micro- to macro-scale seismic velocities from ice-core c axis orientations. *The Cryosphere*, 12(5):1715–1734.

Kuehn, G., Lee, R., Nixon, W., and Schulson, E. (1990). The structure and tensile behavior of first-year sea ice and laboratory-grown saline ice.

Licciulli, C., Bohleber, P., Lier, J., Gagliardini, O., Hoelzle, M., and Eisen, O. (2020). A full stokes ice-flow model to assist the interpretation of millennial-scale ice cores at the high-alpine drilling site colle gnifetti, swiss/italian alps. *Journal of Glaciology*, 66(255):35–48.

Liley, P. (2005). Thermophysical properties of ice/water/steam from- 20 C to 50 C. *International Journal of Mechanical Engineering Education*, 33(1):45–50.

Llorens, M.-G., Griera, A., Bons, P. D., Lebensohn, R. A., Evans, L. A., Jansen, D., and Weikusat, I. (2016). Full-field predictions of ice dynamic recrystallisation under simple shear conditions. *Earth and Planetary Science Letters*, 450:233–242.

MacGregor, J. A., Fahnestock, M. A., Catania, G. A., Paden, J. D., Gogineni, S. P., Young, S. K., Rybarski, S. C., Mabrey, A. N., Wagman, B. M., and Morlighem, M. (2015). Radiostratigraphy and age structure of the Greenland Ice Sheet. *Journal of Geophysical Research: Earth Surface*, 120(2):212–241.

Montagnat, M., Azuma, N., Dahl-Jensen, D., Eichler, J., Fujita, S., Gillet-Chaulet, F., Kipfstuhl, S., Samyn, D., Svensson, A., and Weikusat, I. (2014). Fabric measurement along the NEEM ice core, greenland, and comparison with GRIP and NGRIP ice cores. *The Cryosphere*, 8(4):1129–1138.

Notz, D. (2009). The future of ice sheets and sea ice: Between reversible retreat and unstoppable loss. *Proceedings of the National Academy of Sciences*, 106(49):20590–20595.

Plesa, A.-C., Kowalski, J., and Rückriemen-Bez, T. (2020). Compositional convection in Europa's ice shell: a scale-coupled approach. In *EPSC*, pages EPSC2020–1038, Virtual meeting.

Rückriemen-Bez, T., Plesa, A.-C., Kowalski, J., and Terschanski, B. (2022). Large-scale dynamics and the fate of salts in europa's icy shell. In *EPSC*, pages EPSC2022–689, Granada, Spain.

Schroeder, D. M., Romero-Wolf, A., Carrer, L., Grima, C., Campbell, B. A., Kofman, W., Bruzzone, L., and Blankenship, D. D. (2016). Assessing the potential for passive radio sounding of europa and ganymede with rime and reason. *Planetary and Space Science*, 134:52–60.

Schubert, G., Anderson, J., Spohn, T., and McKinnon, W. (2004). Interior composition, structure and dynamics of the galilean satellites. *Jupiter: The planet, satellites and magnetosphere*, 1:281–306.

Schubert, G., Hussmann, H., Lainey, V., Matson, D. L., McKinnon, W. B., Sohl, F., Sotin, C., Tobie, G., Turrini, D., and Van Hoolst, T. (2010). Evolution of icy satellites. *Space Science Reviews*, 153(1-4):447–484.

Sotin, C., Kalousová, K., and Tobie, G. (2021). Titan's Interior Structure and Dynamics After the Cassini-Huygens Mission. *Annual Review of Earth and Planetary Sciences*, 49:579–607.

Thomas, D. N. (2017). *Sea ice*. John Wiley & Sons.

Tobie, G., Choblet, G., and Sotin, C. (2003). Tidally heated convection: Constraints on Europa's ice shell thickness. *Journal of Geophysical Research: Planets*, 108(E11).

Trumbo, S. K., Brown, M. E., and Hand, K. P. (2019). Sodium chloride on the surface of Europa. *Science advances*, 5(6):eaaw7123.

Waite, J. H., J., Combi, M. R., Ip, W. H., Cravens, T. E., McNutt, R. L., J., Kasprzak, W., Yelle, R., Luhmann, J., Niemann, H., Gell, D., Magee, B., Fletcher, G., Lunine, J., and Tseng, W. L. (2006). Cassini ion and neutral mass spectrometer: Enceladus plume composition and structure. *Science*, 311(5766):1419–22.

Weeks, W. and Cox, G. F. (1974). Laboratory preparation of artificial sea and salt ice.

Weeks, W. F. and Ackley, S. F. (1986). *The growth, structure, and properties of sea ice*, pages 9–164. Springer.

Yen, Y.-C. (1981). *Review of thermal properties of snow, ice, and sea ice*, volume 81. US Army, Corps of Engineers, Cold Regions Research and Engineering Laboratory.

Yoda, M., Sekine, Y., Fukushi, K., Kitajima, T., Gankhurel, B., Davaasuren, D., Gerelmaa, T., Ganbat, S., Shoji, D., and Zolotov, M. Y. (2021). Field investigations of chemical partitioning and aqueous chemistry of freezing closed-basin lakes in mongolia as analogs of subsurface brines on icy bodies. *Journal of Geophysical Research: Planets*, 126(11):e2021JE006972.