CSQ-20 Summary

Question	Knowledge Advancement Objectives	Geophysical Observables	Measurement Requirements	Tools & Models	Policies / Benefits
What is the mass balance of the cryosphere and how is it changing over time?	Measure the change in the mass balance of all components of the cryosphere system, including ice sheets and ice shelves, glaciers and ice caps, sea ice, permafrost and snow cover.	• Glacier area change and volume change • Ice sheet mass balance • Ice shelf mass balance • Sea ice thickness and extent • Permafrost volume change • Snow mass on land	Global record of mass loss across all parts of the cryosphere. Continuous record of change required throughout the full 30-40-year satellite record. Monthly or finer temporal resolution measurement frequency for all observational components. Medium (1 km) spatial resolution for all components. Multi measurement type observational capability.	EO satellite datasets. Auxiliary data including bed topography under all land ice, and regional climate model data estimating surface mass balance component.	Climate change adaptation and mitigation policy. Delivering on Paris agreement and IPCC monitoring. Improve future projections of ice mass loss, which remain the greatest uncertainty in future sea level rise projections.
	Measure the regional pattern of variability in ice mass loss.	As above.	High (100 m) spatial resolution measurements required, at the	As above.	

			glacier or basin scale.		
	Provide near real time monitoring of ice mass change	As above.	NRT raw satellite data access and automated processing chains. Online portal to deliver service through. Weekly measurements of all components.	As above.	

CSQ-20 Narrative

Fluctuations in Earths ice mass have occurred in almost all regions of the cryosphere, in response to change in environmental forcing mechanisms and as a longer-term response to climate change. Satellite observations have shown that the mass balance of the Antarctic and Greenland Ice Sheets has changed dramatically over the last 40-years, with ice loss increasing by six times over this period, increasing global sea levels by 17.8 mm (The IMBIE team, 2018). While in Greenland surface melt driven lubrication drives the majority of ice mass loss, in Antarctica the dominant process is warm ocean water driven melt, demonstrating that the dominant physical process is different in the North and South Hemispheres. While the ice sheets contribute one third of the total sea level rise budget, ice loss is also occurring on mountain glaciers and ice caps. Observations have shown that glacier mass loss has increased from -120 Gt per year in the 1970 to -327 Gt per year between 2010 and 2019. In mountain glacier regions the dominant cause of ice loss is increasing air temperatures (Slater et al., 2021). While Arctic sea ice cover has been decreasing for the last 40-years, Antarctic sea ice extent remained stable through to the 2020's. In recent years we have seen a dramatic reduction in Antarctic sea ice extent, impacting the energy balance of the region and causing devastating impacts on emperor penguin breeding cycles who are reliant on sea ice floes. Overall, the rate of ice loss on earth has increased by 57 % since the 1990's, increasing the cryosphere's contribution to global sea level rise. As yet, snow on land and permafrost volume are not included in global cryosphere mass budget assessments, however this will be possible in the future. Studies should quantify the regional variability in the change in ice mass of different elements of the cryosphere, and understand the physical mechanisms driving this change.

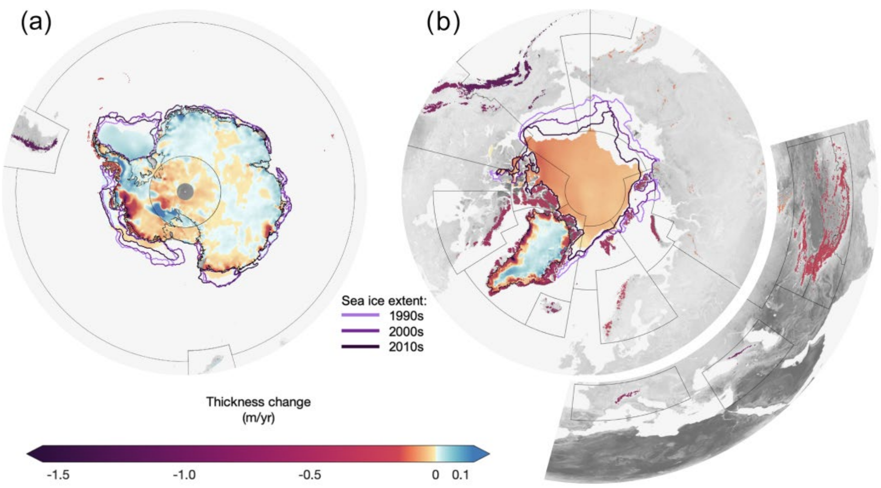

Fig. 1: Average rate of ice thickness change in the (a) Southern Hemisphere and (b) Northern Hemisphere. Changes in Antarctic (1992– 2017) and Greenland ice sheet (1992–2018) thickness were estimated using repeat satellite altimetry following the methods of Shepherd et al. (2019). Sea ice thickness trends between 1990 and 2019 are determined from numerical sea ice and ocean modelling (Zhang and Rothrock, 2003), as well as the average minimum of sea ice extent in February (Antarctic) and September (Arctic) (purple lines) for each decade during the same period. Glacier thickness change between 1992 and 2018 for glacier regions defined in the Randolph Glacier Inventory (RGI Consortium, 2017) (black boundaries) are from mass change estimates (Braun et al., 2019; Foresta et al., 2016; Jakob et al., 2020; Tepes et al., 2021; Wouters et al., 2019; Zemp et al., 2019b) which have been converted to a thickness change assuming an ice density of 850 kg m−3. From Slater et al., 2021.

References

- Wallis, B.J., Hogg, A.E., van Wessem, J.M. *et al.* Widespread seasonal speed-up of west Antarctic Peninsula glaciers from 2014 to 2021. *Nat. Geosci.* (2023). https://doi.org/10.1038/s41561-023-01131-4
- The IMBIE Team,. (2019) Mass balance of the Greenland Ice Sheet from 1992 to 2018. Nature https://doi.org/ 10.1038/s41586-019-1855-2.
- Landy JC, Dawson GJ, Tsamados M, Bushuk M, Stroeve JC, Howell SEL, Krumpen T, Babb DG, Komarov AS, Heorton HDBS, Belter HJ, Aksenov Y. (2022) A year-round satellite sea-ice thickness record from CryoSat-2. *Nature*. 609(7927):517-522. doi: 10.1038/s41586-022-05058-5.
- Baumhoer, C. A., Dietz, A. J., Kneisel, C., and Kuenzer, C., (2019) Automated Extraction of Antarctic Glacier and Ice Shelf Fronts from Sentinel-1 Imagery Using Deep Learning, *Remote Sens.11*(21), 2529; https://doi.org/10.3390/rs11212529
- Mottram R., Hansen, N., Kittel, C., J. van Wessem, M., Agosta, C., Amory, C., Boberg, F., van de Berg, W. J., Fettweis, X., Gossart, A., van Lipzig, N. P. M. van Meijgaard, E., Orr, A., Phillips, T., Webster, S., Simonsen, S. B., and Souverijns, N. (2021) What is the surface mass balance of Antarctica? An intercomparison of regional climate model estimates, *The Cryosphere*, 15, 3751–3784, doi.org/10.5194/tc-15-3751-2021.
- Slater, T., Lawrence, I. R., Otosaka, I. N., Shepherd, A., Gourmelen, N., Jakob, L., Tepes, P., Gilbert, L., and Nienow, P. (2021) Review article: Earth's ice imbalance, *The Cryosphere*, 15, 233–246, https://doi.org/10.5194/tc-15-233-2021.
- Surawy-Stepney, T., Hogg, A.E., Cornford, S.L. *et al.* Episodic dynamic change linked to damage on the Thwaites Glacier Ice Tongue. *Nat. Geosci.* **16**, 37–43 (2023). https://doi.org/10.1038/s41561-022-01097-9
- P. R. Holland, G. K. O'Connor, T. J. Bracegirdle, P. Dutrieux, K. A. Naughten, E. J. Steig, D. P. Schneider, A. Jenkins, and J. A. Smith, (2022) Anthropogenic and internal drivers of wind changes over the Amundsen Sea, West Antarctica, during the 20th and 21st centuries, The Cryosphere, 16, 5085–5105, doi.org/10.5194/tc-16-5085-2022.
- Maclennan, M. L., Lenaerts, J. T. M., Shields, C., & Wille, J. D. (2022). Contribution of atmospheric rivers to Antarctic precipitation. Geophysical Research Letters, 49, e2022GL100585. https://doi.org/10.1029/2022GL100585
- Nilsson, J., et al. (2015), Green- land 2012 melt event effects on CryoSat-2 radar altimetry, *Geo-phys. Res. Lett.*, *42*, 3919–3926, doi:10.1002/2015GL063296.
- Fretwell, P. T., and Trathan, P. N., (2021) Discovery of new colonies by Sentinel2 reveals good and bad news for emperor penguins, Remote Sensing in Ecology and Conservation, https://doi.org/10.1002/rse2.176