

Thank you to the reviewers for their positive and constructive reviews of our manuscript. We have revised the manuscript in order to address the comments raised by each reviewer. In summary, the main changes are:

- We have revised the introduction to make clear why we do not consider snow on land, permafrost and river and lake ice (please see our responses to reviewer comments below for more details) and we have added example summaries of their changes over time.
- We have expanded upon details of the observational techniques used to measure glacier mass balance. At the request of Etienne Berthier (LEGOS), who got in touch with us privately, we have included two more estimates of glacier mass changes derived from optical stereo images to expand upon the amount of observational data used in our glacier estimate. These have had a minimal impact on our glacier (4 Gt/yr, 2%) and global ice loss (< 1%) estimates during the common period 1994-2017.
- Redesigns of Figures 2 and 3 for readability, and 4 to include cumulative errors.
- We have expanded on the computation of our uncertainty estimates across the manuscript.
- Several changes and additions to the text with improvements suggested in the reviewers' comments.

We have responded to the comments of each individual reviewer in full below. Reviewer comments are in *black italic*, and our responses are in [blue](#). We have included a tracked changes version of the manuscript after our responses, so it is clear where changes have been made. We believe these changes have substantially improved the manuscript; thank you to both of the reviewers for their comments.

Anonymous Referee #1

This manuscript uses a variety of satellite observation and numerical models in order to quantify mass change of the Earth's glaciers and ice caps, the ice sheets, sea ice and Antarctic ice shelves. Overall, the manuscript is clear, well written and clearly addresses the stated objectives. Generally, the methods utilized here have been well utilized in past studies and are appropriate for this work. Given this, I only have minor comments listed below for the authors to address and consider for a revised version of this manuscript. Specific items are provided below.

[Thank you for your review of our manuscript – we have addressed each of your specific comments below.](#)

L41 – “...impacts on their marine ecosystem...” suggest change to “...impacts the marine ecosystem...”

[Done.](#)

L43 – I think it would be worthwhile to note that although in situ records may have been obtained as early as the 1890s, that this would have been limited to only a very few locations.

Thanks, we have amended the sentence to reflect this.

L50-51 – I would revise this last line. I think it is fine to note that trends in permafrost, terrestrial snow and lake/river ice are beyond the scope of this study. However, I would advise removing “which are small in comparison”. This might be true, but that should not necessarily diminish the importance of the changes in these elements of the cryosphere

We do not intend to diminish the importance of these elements of the cryosphere, so we have revised this part of the text to (1) better explain why they are beyond the scope of this study and (2) provide more information to the reader on recent changes in these elements.

L58 – “within local mass concentration units” can you describe this more fully? Doesn’t this just mean “within a region”? Remember this is a review article and the terminology/description needs to be understandable by a wide readership.”

Mass concentration units are gravity field basis functions to which GRACE observations are fitted. We agree this is not accessible for a wide readership, so we have removed this to avoid confusion for the reader – providing a detailed technical background on the techniques used to derive glaciers mass changes falls outside the scope of this review paper, and adds a layer of complexity that is not necessary for a wider readership to appreciate the results presented. For the interested readers, additional information can be found in the studies we have cited.

L60-63 – Can you provide more detail here on CryoSat-2 and diff SAR InSAR methods? In particular, can you comment on whether variable penetration of the radar energy into glacier/ice surface impacts the uncertainty in the elevation differencing? Related to CryoSat-2, are there any issues in terms of using CryoSat-2 to measure changes in glaciated regions with significant topography? If these are not issues, please state why they are not. Related to CryoSat-2 data, can you mention the product level used? Was this an ESA distributed product or a custom derived product created by the authors? Related to DInSAR, can you mention the sensors utilized (broadly) to create the DEM products?

We have added more details on the swath altimetry and DInSAR methods. Also at the request of Etienne Berthier (LEGOS), who got in touch with us privately, we have included two more estimates of glacier mass changes derived from optical stereo images to expand upon the amount of observational data used in our glacier estimate: one for the Southern Andes and for the High Mountain Asia region. These have had a minimal impact on our glacier (4 Gt/yr, 2%) and global ice loss (< 1%) estimates during our common period.

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L114-180 – I know that this section is focused on Antarctic Ice Shelf changes, but you may also want to mention here (or elsewhere if more appropriate) recent changes to Arctic Ice Shelves as well. You do not necessarily need

to quantify these changes but they should at least get a mention if this is a review paper of the changes of Earth's ice

Thanks for bringing this to our attention – as this section focuses on Antarctic ice shelf change we feel it is more appropriate to include this in the introduction, where we have added a sentence about recent changes in Arctic ice shelves.

L170-175 Somewhere here you may want to quickly discuss where the major declines in Arctic sea ice occur spatially. And how does this match with other studies?

Thanks – we have added this to the text.

Anonymous Referee #2

This manuscript (MS) gives a nice review of the ice imbalance on the Earth and a direct measure of global climate change, when it in the last part of the MS relates to the energy needed to melt the ice. The MS is generally well written and gives an overview of the methodology used in assessing each of the components.

Thank you for your review of our manuscript – please find responses to each of your general and specific comments below.

However, the level of references is kept to a minimum and mostly citing work directly related to numbers derived in this MS. Relying only on a limited number of studies makes the error propagation hard to assess.

We have expanded on the computation of our uncertainty estimates, where requested in your specific comments, in the hope that this is now more clear.

The title of the paper may also lead the reader to think it is a review of earth ice balance estimates. I would suggest the title to be more specific such as “Budget of the Earth meteoric ice masses”. In the view of a budget-study, I only have minor comments to the manuscript.

Thank you for this suggestion, but we prefer our original title as it is an accurate and understandable description of the topic (Earth's ice).

- The term “meteoric” refers to ice of meteorological origin; it is not appropriate here because ice shelves and sea ice derive significant parts of their mass from the ocean as well (“oceanic”).

- We feel that “ice imbalance” is clearer to a wider audience than “Budget of the ...masses”.

L16 – Suggest removing “from”

Done.

L19 – It is not clear from the title nor abstract that you only consider meteoric ice.

I suggest adding “not accounting for changes in permafrost,...”. The melting permafrost will also require energy from the “energy imbalance.”, and therefore adding to the error estimate of the derived numbers in the MS

As we mentioned in response to your earlier comment, “meteoric” refers to ice of meteorological origin; ice shelves and sea ice derive significant parts of their mass from the ocean as well, so it is therefore not appropriate for us to say we only consider meteoric ice. The term “permafrost” is also not appropriate as it refers to frozen ground, not ice. We have, however, amended the introduction to clarify that we are considering both meteoric and oceanic ice.

We have also amended the introduction to explain that we do not consider elements of the cryosphere that are not ice (i.e. snow on land and permafrost) or river and lake ice, and we have added example summaries of their changes over time. We have also clarified in the abstract and main text that our assessment of the global energy imbalance pertains to the elements of the cryosphere we have considered.

L24 – Suggesting rephrasing: Meteoric ice is stored in the Earth’s cryosphere land components; Ice sheets, Ice caps and glaciers, and its ocean components; ice shelves and sea ice (fig 1)

Thank you for this suggestion - however we would prefer to stick with our original wording as we feel the suggested sentence implies sea ice and ice shelves are solely meteoric in origin, which is not the case (they are partly oceanic).

L29 – subglacial melt and evaporation are missing

Thanks, we have added these to the sentence.

L31 – As the manuscript is relevant for a broader audience, please use a few more words on the Weertman reference

We have amended this clause to make this clearer to a broader audience.

L32 – are there 343 ice shelves or more than 340?

We have amended to read “over 300” (the database evolves and this was the value reported in Shepherd et al., 2018).

L35 – remove “on”

Done.

L42 – Missing a couple of lines about the change in Earth albedo with the loss of sea ice

Thanks, we have added this to the text.

L50 – The smaller components will add to the imbalance, please give numbers on the approximate magnitude of these components

This sentence was also flagged by reviewer 1: we have amended this sentence to explain that we do not consider elements of the cryosphere that are not ice (i.e. snow on land and permafrost) or river and lake ice, and we have added example summaries of their changes over time.

L53 – “6”-> “six”

Done.

L60 – The accumulation area is limited, but assuming fixed ice-density in the volume to mass conversion of the glaciers is an overestimate, this should be included in the uncertainty.

Here we are reporting a published mass balance estimate and its associated uncertainty as derived by the authors of the study – we feel it is beyond the scope of a review paper to amend single mass balance estimates and uncertainties which have already been published in the literature. However, we have added some text here to provide more information on the different techniques and their limitations to the reader.

L64 – please list the observational sources which are the only estimate available

Only the Zemp et al. studies provide estimates for the ice sheet peripheral glaciers – we have added this in the text to make this clearer.

L67 – How is the uncertainty propagated in time? This is a more general question as it is general hard to grasp from the MS how uncertainty is propagated, both for the individual estimates and the total imbalance. Please add information in the relevant sections of the manuscript

We accumulate the uncertainty over time as the root sum square of the annual uncertainties – we do mention this in this sentence but we appreciate it might not be clear, so we have amended our wording slightly.

As we mentioned previously, we have also expanded on the computation of our uncertainty estimates, where requested in your specific comments, in the hope that this is now more clear.

Fig2 – please change the colors so the studies can be separated

We have modified the colours used and increased the line thickness on Figure 2b so they are more easily separated.

L72 – What is a close agreement? Please report the magnitude of 1 standard deviation, it is not readable from the figure. Maybe add a table (maybe in supp.)

Thank you for your suggestion – our preference is not to create a supplementary section and to have all the information in the main text so it is readily available. With this in mind we have added the standard deviation in all regions included in our inter-comparison in the text.

L77 – 10,130pm1713 Gt -> -10,130pm1,713 or -10130pm1713. This is a general comment and should follow the same convention throughout the MS. You also give Tt in some cases please consider the number of significant digits.

Done.

L96 – Much of the uncertainty in the ice thickness is in the areas where it is modeled. “measured”-> “estimated”.

Done.

L117 – this statement with the reference to fig 3 is hard to follow as figure 3 only shows the peninsula. Please be specific as to which ice shelves are included in the study.

We have amended the text to clarify that the ice shelves in question are at the Antarctic Peninsula. We have redrawn Figure 3 which more clearly labels the ice sheets included.

Figure 3 – the color bar for time is not readable

We have redrawn this figure so it is more readable

L120 – Again, how is figure 3 informing on calving? Please add information in the caption to help the reader to better understand the figure

We have amended the caption to explain that “Iceberg calving is calculated as the difference in area between successive barrier positions.”

L127 – A polynomial-fit to elevation data is not trivial, which parameters are included in this, please elaborate on this equation and give references

We have rewritten the text to clarify that the ice shelf thickness change data were sourced from Adusumilli et al. (2020) and computed following the method of Paolo et al., (2015). We have summarised their method, and added a note to say that “Full details of the methods used in this calculation can be found in Paolo et al. (2015).”

L130 – The altimetry is adjusted for firn air, guess this is from RACMO, but not mentioned in the text. Additional information about the firn would be of high relevance.

As the data and method are published, we do include citations to support each stage of the processing. We do however summarise the approach and refer the reader to Paolo et al., (2015) for further details, where the firn model is described in full.

L150 – The reference guidelines <https://www.the-cryosphere.net/submission.html#references> states “Informal or so-called ‘grey’ literature may only be referred to if there is no alternative from the formal literature”. Please give an argument for not having other references and therefore need to use “personal comm”. This appears multiple places in the MS. Then I will leave it with the editor to see if this is justified.

There are two instances of “personal comm” which corroborate the PIOMAS and GIOMAS ice density being equal to 917 kg/m^3 . Axel Schweiger and Jinlun Zhang both confirmed via email that 917 kg/m^3 was the fixed ice density used in PIOMAS and GIOMAS, however we could not find this value in any publications. We double-checked this with Schweiger and Zhang, asking whether any such publication exists, and they confirmed that there are none. We are therefore unable to reference the 917 kg/m^3 value for ice density without grey literature.

The final instance of “personal comm” followed the statement “We assumed an error on monthly PIOMAS/GIOMAS volume of 1,800 km³” This sentence has now been expanded in order to also address comment 2.25, and no longer includes the grey reference.

The sea ice section more generally: For the density of sea-ice “glacier-ice” density is chosen for PIOMAS and GIOMAS, which is normally associated with first-year ice. Timco and Frederking (1996) report “in situ density of first-year sea ice range from 0.84 to 0.91 Mg m⁻³ for the ice above the waterline, and 0.90 to 0.94 Mg m⁻³ for the ice below the waterline.” Please comment on the volume conversion and the effects on the uncertainty conversion. The neglect of multi-year ice densities in the model estimates (multi-year is included in Tilling’s CS2 estimate) seems to overestimate the mass derived from the models. This should at least be included in the uncertainty.

The value of 917kg/m³ was chosen because this is the (fixed) density used in the PIOMAS / GIOMAS models to attribute a volume to the simulated ice growth. Schweiger et al. (2011) estimate the monthly error on PIOMAS volume by a range of methods including comparison to in-situ. The error they derive will therefore inherently account for errors in ice density (if the wrong ice density was used then the volume will not compare well with the in-situ data). Therefore using a different ice density other than that programmed into the model to convert from volume to mass would be inappropriate. We have amended the text so that this is made clear to the reader.

L165 – how is this uncertainty derived?

The errors on PIOMAS volume for October and March are 1,350 and 2,250 km³, estimated in Schweiger et al., (2011) using a range of methods including comparison to in-situ data and model sensitivity analyses. We take the average of these (1,800 km³) as the uncertainty for all months, and in the absence of a formal uncertainty budget for GIOMAS we assign it the same monthly uncertainty, which seems a reasonable inference given that the PIOMAS uncertainties are themselves uncertain (Schweiger et al., 2011). We have added this explanation to the text.

L186 – The text states 1.2pm0.3 and the table states 1.2pm0.9, which is the right number?

Thanks for spotting this, the text is a typo: the correct number is in the table (please note the table is 1196 + 90 Gt/yr which is not 1.2 ± 0.9 Tt/yr). We have fixed this.

Table 1 – As the periods are not the same it would be informative if the numbers could be given both as rates and totals in this table.

Thank you for this suggestion - however we feel adding totals would almost double the amount of information in this table (which is already large), mix mass rates and cumulative mass change, and make it unwieldy and potentially confusing for the reader. The total mass change for each component is already presented separately to the reader, both in the text and in Figure 4, so we feel it is not necessary to add here.

L220 – Is the temperature of -20 used for all ice bodies? E.g. -20 seem cold for sea-ice with snow on top and water below

The energy required to melt Earth's ice is primarily associated with phase transition (333,000 J/kg), with only a small contribution due to warming to the melting point (2108 J/kg °C). The fractional energy required for warming is therefore 0.68 % per °C. For ice at -30, -20 and -10 °C, the fractional energy is 19 %, 12 % and 6 %, respectively. In the absence of reliable temperature data, we choose -20 °C as a mean value for ice shelves and sea ice. However, you're correct to raise this as an uncertainty, so we have included an uncertainty of 10 °C in our energy budget calculation. We have amended the text to describe the fractional energy sensitivity and the temperature uncertainty.

L222 – What is the uncertainty on this number?

As per our response to your previous comment, we have added uncertainties, now including an estimated uncertainty in temperature.

Figure 4 – Figure 4 please add the cumulative uncertainty.

We have added the mass change and estimated cumulative uncertainty for each individual ice component, and their sum, at the end of the study period as shaded bars.

Review Article: Earth's ice imbalance

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Abstract. We combine satellite observations and numerical models to show that Earth lost 28 trillion tonnes of ice between
10 1994 and 2017. Arctic sea ice (7.6 trillion tonnes), Antarctic ice shelves (6.5 trillion tonnes), mountain glaciers (6.12 trillion
tonnes), the Greenland ice sheet (3.8 trillion tonnes), the Antarctic ice sheet (2.5 trillion tonnes), and Southern Ocean sea ice
(0.9 trillion tonnes) have all decreased in mass. Just over half (5860 %) of the ice loss was from the northern hemisphere,
and the remainder (420 %) was from the southern hemisphere. The rate of ice loss has risen by 57 % since the 1990s – from
15 0.8 to 1.2 trillion tonnes per year – owing to increased losses from mountain glaciers, Antarctica, Greenland, and from
Antarctic ice shelves. During the same period, the loss of grounded ice from the Antarctic and Greenland ice sheets and
mountain glaciers raised the global sea level by $34.65.0 \pm 3.12$ mm. The majority of all ice losses ~~from~~ were driven by
atmospheric melting (68 % from Arctic sea ice, mountain glaciers ice shelf calving and ice sheet surface mass balance), with
the remaining losses (32 % from ice sheet discharge and ice shelf thinning) being driven by oceanic melting. Altogether,
these elements of the cryosphere have ves taken up 3.2 % of the global energy imbalance.

20 1 Introduction

Fluctuations in Earth's ice cover have been driven by changes in the planetary radiative forcing (Vaughan et al., 2013),
affecting global sea-level (The IMBIE Team, 2018, 2020; Zemp et al., 2019), oceanic conditions (Rahmstorf et al., 2015),
atmospheric circulation (Francis and Vavrus, 2012; Vellinga and Wood, 2002) and freshwater resources (Huss and Hock,
2018; Immerzeel et al., 2020). Earth's cryosphere is created as meteoric ice in Antarctica, Greenland, and in mountain
25 glaciers, and as frozen sea water in the Arctic and Southern oceans (Fig. 1). The polar ice -sheets store more than 99 % (30
million km³) of Earth's freshwater ice on land (Fretwell et al., 2013; Morlighem et al., 2017), and even modest losses raise
the global sea level (The IMBIE Team, 2018, 2020), increase coastal flooding (Vitousek et al., 2017) and disturb oceanic
currents (Golledge et al., 2019). Ice sheet mass balance is the net balance between mass losses associated with ice flow,
melting at the ice-ocean interface, subglacial melt and the surface mass balance (the net difference between precipitation,
30 sublimation, evaporation, wind erosion and meltwater runoff). Ice shelves are a major source of ocean fresh water (Jacobs et
al., 1992), provide mechanical support for impart resistive forces on grounded ice upstream (buttressing), which would speed
up in its absence (Weertman, 1974), and have been a persistent element of the climate system throughout the Holocene

period (Domack et al., 2005). There are over ~~30043~~ documented ice shelves (the vast majority of Earth's inventory) around Antarctica (SCAR, 2020; Shepherd et al., 2018) containing an estimated 380 thousand km³ of ice (Fretwell et al., 2013), and
35 fluctuations in their volume occur as a result of changes in their extent (Cook and Vaughan, 2010) and thickness (Adusumilli et al., 2020). Although ice shelves are much smaller and sparsely distributed across the Arctic, ice shelves fringing the northern coast of Ellesmere Island in Canada (Mortimer et al., 2012) and the Russian Arctic islands (Willis et al., 2015) have collapsed in recent decades. Mountain glacier ice moderates global sea-level and regional hydrology (Huss and Hock, 2018), impacting ~~on~~-local communities who rely on it as a source of freshwater (Immerzeel et al., 2020). There are over 215
40 thousand glaciers worldwide (RGI Consortium, 2017) containing 160 thousand km³ of ice (Farinotti et al., 2019), and their retreat has accounted for 21 % of global sea-level rise between 1993 and 2017 (WCRP Global Sea Level Budget Group, 2018). Typically 15 to 25 million km² of the global ocean surface is covered in sea ice at any one time of year, though its thickness and extent vary seasonally and due to long-term changes in Earth's climate (Maksym, 2019). Sea ice plays a key role in the freshwater and energy budgets of the polar regions and impacts ~~the on their~~ marine ecosystem (Stroeve and Notz,
45 2018), as well as regulating the absorption of solar radiation in summer (Pistone et al., 2014). Furthermore, sea ice and its loss could influence oceanic and atmospheric circulation and affect weather patterns in the mid-latitudes (Maksym, 2019; Vihma, 2014).

Although sparse in situ records of glacier mass balance date back to the 1890's (Zemp et al., 2015), substantial records of change for other components of the cryosphere did not begin until the advent of satellite observations in the 1970's. Ice shelf
50 extent has been recorded episodically in satellite imagery since the 1940's (Cook and Vaughan, 2010), sea ice extent has been monitored by satellites since the late 1970's (Cavalieri et al., 1999), and ice sheet, ice shelf, sea ice, and glacier thickness changes have been recorded systematically in satellite altimetry since the 1990s (Gardner et al., 2013; Laxon et al., 2013; Shepherd et al., 2010; The IMBIE Team, 2018, 2020). Here, we combine satellite observations of changing ice sheet, ice shelf, glacier, and Arctic sea ice mass, with in situ and model-based estimates of glacier and Southern Ocean sea ice
55 mass, to quantify trends in Earth's meteoric and oceanic ice. We do not ~~include consider trends in other~~ elements of the cryosphere that are not ice which are small in comparison (i.e. snow on land and permafrost), or where knowledge of their global extent and change is limited (river and lake ice). However, these elements of the cryosphere have also experienced considerable change over recent decades: for example, it is estimated that the quantity of snow on land has decreased by 49 ± 49 gigatonnes per decade in the northern hemisphere since 1980 (Pulliainen et al., 2020); that permafrost (perennially frozen ground) has warmed globally by 0.29 ± 0.12 °C during the past decade (Biskaborn et al., 2019); and that the duration of river and lake ice cover has shortened by 12 days per century in the northern hemisphere over the last 200 years (Magnuson et al., 2000), ~~such as permafrost, snow on land, and river and lake ice.~~

2 Mountain Glaciers

We combined ~~eight~~⁶ estimates of mass change from an extrapolation of local glaciological and geodetic measurements (Zemp et al., 2019, 2020), satellite gravimetry (Wouters et al., 2019), satellite swath altimetry (Foresta et al., 2016; Jakob et al., 2020; Tepes et al., 2020) ~~and~~ satellite synthetic differential aperture radar interferometry (DInSAR) (Braun et al., 2019), ~~and satellite optical stereo images~~ (Dussaillant et al., 2019; Shean et al., 2020), to produce a reconciled estimate of global glacier mass changes between 1962 and 2019 and over 19 glacier regions defined in the Randolph Glacier Inventory (RGI Consortium, 2017) (Fig. 2). Satellite gravimetry directly measures glacier mass change from fluctuations in Earth's gravitational ~~field~~ field within local mass concentration units at monthly intervals, and as a result does not require knowledge of the density of the material lost or gained (Wouters et al., 2019). ~~However, satellite gravimetry provides measurements at a spatial resolution on the order of hundreds of kilometres, which limits the interpretation of the spatial distribution of ice loss within individual glaciers.~~ Satellite swath altimetry, ~~and DInSAR~~ SAR interferometry and optical stereo imagery ~~both~~ measure surface elevation change, which is converted to mass by assuming a fixed density of ice with an associated uncertainty of 60 kg/m³ (Huss, 2013). ~~Satellite swath altimetry the former~~ uses the swath interferometric mode of CryoSat-2 ~~to which provides obtain~~ a dense grid of repeated elevation measurements (Foresta et al., 2016). CryoSat-2 swath altimetry provides up to two orders of magnitude more data than conventional altimetry processing, and homogeneous spatial coverage necessary to derive mass changes over relatively small glaciers with highly variable topography (Gourmelen et al., 2018; Jakob et al., 2020). The included DInSAR estimate measures surface elevation changes by while the latter applies differential SAR interferometry to convert each radar scene into a digital elevation model (DEM) and differences it to a reference DEM differencing digital elevation models (DEMs) generated from the SRTM and TanDEM-X synthetic aperture radar missions (Braun et al., 2019). It is important to note that, for both satellite radar altimetry and DInSAR, the radar signal can penetrate beyond the glacier surface into snow and firn (Braun et al., 2019; Jakob et al., 2020); the impact of radar penetration on elevation measurements is difficult to quantify as it depends on spatiotemporal variations in snow and firn characteristics, and is an area of ongoing research. We also include estimates of glacier mass balance derived from satellite optical stereo imagery, which generates time series of high resolution DEMs from ASTER, Worldview-1/-2/-3 and GeoEye-1 satellite imagery (Dussaillant et al., 2019; Shean et al., 2020). In glacier regions where these estimates are available (High Mountain Asia, Southern Andes), they offer almost complete coverage of glaciated areas at high (metre-scale) resolution which can resolve changes within individual glaciers. However, optical imagery is weather-dependent and cloud cover can limit coverage in glacier regions. For each region we aggregated annual mass change rates determined from the techniques available: each region includes between 2 and 4 estimates except for glaciers peripheral to Antarctica and Greenland, where only ~~one~~ is ~~estimates derived from the extrapolation of in-situ and geodetic data are~~ available. For studies in which time-varying mass change rates are not available, we assume the mass change rate to be linear over the period considered and scale the uncertainty by the square root of the number of years. We computed the cumulative mass change as the integral of the aggregated mass change rates and accumulate the associated uncertainty over time as the root sum square of the annual

errors. We summed the regional estimates to derive the global glacier mass change and the overall uncertainty as the root-mean square of the regional errors.

We assessed the consistency of the in situ and satellite gravimetry, ~~and~~ altimetry and stereo imagery estimates between 2010 and 2015 in 7 regions (Arctic Canada North and South, Russian Arctic, Iceland, Svalbard and Jan Mayen, High Mountain Asia and Southern Andes) where measurements from all techniques overlap (Fig. 2). We record the largest difference (26 Gt yr⁻¹) and standard deviation (14 Gt yr⁻¹) between mass balance estimates in Arctic Canada North – the largest region included in our inter-comparison. The standard deviations of the mass change estimates are 9 Gt yr⁻¹, 8 Gt yr⁻¹, 6 Gt yr⁻¹, 5 Gt yr⁻¹, 2 Gt yr⁻¹ and 2 Gt yr⁻¹ for the Southern Andes, Russian Arctic, High Mountain Asia, Arctic Canada South, Iceland and Svalbard and Jan Mayen regions, respectively. In general, there is close agreement between estimates determined using each
technique and they agree to within 1 standard deviation of their mean between 2010 and 2015 with the exception of Iceland – where the altimeter estimates only provide a constant rate of mass change during the overlap period and reduce the variability. We find the greatest difference between estimates in High Mountain Asia, with a standard deviation of 214 Gt between the three techniques and those determined from altimetry being the most negative. Based on our reconciled estimate, glaciers have collectively lost ~~-9,975±10,130~~ ± 1,667±713 Gt of ice between 1962 and 2019, raising the global mean sea-level by ~~27.78±1~~ ± 4.68 mm during this period. Glaciers peripheral to Greenland and in Alaska and the Southern Andes have experienced the largest losses (Fig. 2) – ~~5,6947~~ ± 63548 Gt between 1962 and 2019 – and account for more than half (~~576~~ %) of the global glacier mass loss over this period. Globally, the rate of glacier mass loss has increased from ~~-120 ± 70±~~ Gt yr⁻¹ in the 1970s to ~~-32746 ± 657~~ Gt yr⁻¹ between 2010 and 2019, peaking at ~~-50636 ± 1928~~ Gt yr⁻¹ in 2018. Glacier mass loss is linked to increasing air temperatures; approximately 70 % of the global glacier mass loss has been attributed to anthropogenic forcing, and the remainder is due to natural climate variability (Marzeion et al., 2014).

3 Ice sheets

Ice sheets lose mass when ice discharge and melting at the surface and ice-ocean interface combined exceed snowfall. We use estimates of ice sheet mass balance and their uncertainty – derived from an ensemble of satellite altimetry, satellite gravimetry and input-output datasets which span the period 1992-2018. For the Antarctic (24 datasets) (The IMBIE Team, 2018) and Greenland (26 datasets) (The IMBIE Team, 2020) ice sheets, independently derived estimates of mass change from the three satellite geodetic techniques were combined into a single estimate of ice sheet mass balance. Estimates of ice sheet mass balance derived from these methods at the continental scale are similar and can be collated to reduce uncertainty (The IMBIE Team, 2018, 2020): satellite altimetry directly measures changes in ice sheet height (Otosaka et al., 2019; Sandberg Sørensen et al., 2018) converted into mass by assigning a specific density to the volume change (Shepherd et al., 2019) or by explicitly accounting for snowfall fluctuations through firn modelling (Sørensen et al., 2011). Satellite gravimetry measures temporal variations in Earth's gravity field using spherical harmonic solutions (Velicogna et al., 2020)

or through local mass concentration analysis (Luthcke et al., 2006). The input-output method removes ice discharge into the oceans (output), estimated from satellite observations of ice velocity and ~~measurements-estimates~~ of ice thickness, from the net snow accumulation (input) (Mouginot et al., 2019; Rignot et al., 2019) determined from regional climate modelling (Noël et al., 2018; van Wessem et al., 2018).

These satellite surveys (e.g. Fig. 1) show the Antarctic ice sheet lost $2,603 \pm 563$ Gt of ice between 1992 and 2017, and the Greenland ice sheet lost $3,902 \pm 342$ Gt of ice between 1992 and 2018. Since 2012, the rate of ice loss from Antarctica has tripled when compared to the previous two decades, owing to widespread glacier speedup (Mouginot et al., 2014) and thinning (Shepherd et al., 2019) in the Amundsen and Bellingshausen Sea sectors in response to the circulation of warm water under the region's ice shelves (Jacobs et al., 2011). Ice shelf collapse (Cook and Vaughan, 2010) (Fig. 3) and thinning at the Antarctic Peninsula has triggered speedup of glaciers upstream (Hogg et al., 2017) as a consequence of reduced ice shelf buttressing. Unlike in Antarctica, where almost all of the ice loss is associated with ice dynamical imbalance, just over half of Greenland's mass loss during this period arose due to increases in meltwater runoff (Enderlin et al., 2014) enhanced by atmospheric circulation during several warm summers (Bevis et al., 2019). The remaining ice loss was due to increased glacier discharge, primarily at Jakobshavn Isbræ (Holland et al., 2008) and at outlet glaciers in the southeast (Howat et al., 2008) and northwest (Moon et al., 2012). Both ice dynamic and surface processes in Greenland have led to widespread thinning at the ice sheet margins and within individual glacier catchments (McMillan et al., 2016) (Fig. 1). Altogether, ice losses from Antarctica and Greenland have caused global sea levels to rise by 17.8 ± 1.8 mm between 1992 and 2017 (The IMBIE Team, 2018, 2020).

145 4 Antarctic ice shelves

To compute trends in the volume of Antarctic ice shelves associated with changes in their extent, we combined satellite-based records of their thickness (Fretwell et al., 2013) and area change (Cook and Vaughan, 2010) over time, adjusted for changes in thickness where they have been recorded (Adusumilli et al., 2020). We restrict this calculation to ice shelves at the Antarctic Peninsula, where a record of progressive retreat has been well-established (Fig. 3). Although area changes have been mapped since the late 1940's, comprehensive estimates of their thickness only began in the early 1990's. To estimate the thickness of icebergs calved prior to this period, we combined in situ, airborne, and satellite-derived measurements of ice thickness recorded prior to when the ice shelf calving took place (Fig. 3). Uncertainties in volume change associated with ice shelf retreat were computed as the product of errors in ice thickness, determined from the variance of the thickness data, and extent, determined from the precision of the satellite imagery (Cook and Vaughan, 2010). We then used ~~multi-mission~~ satellite ~~radar~~-altimetry to ~~compute trends in the volume~~determine the volume changes of Antarctic ice shelves ~~due-owing~~ to changes in their thickness, and their associated uncertainty, ~~between 1994 and 2020~~ (Adusumilli et al., 2020). For this calculation, we use time series of ice thickness change and their estimated uncertainty derived by Adusumilli et al. (2020)

from ERS-1, ERS-2, Envisat and CryoSat-2 satellite radar altimetry between 1994 and 2020, following the method of Paolo et al. (2015). Adusumilli et al. (2020) applied the following processing steps: (i) ice shelf surface elevation was computed by adjusting the altimeter range measurements ~~were first adjusted~~ for changes in ocean surface height, including contributions due to the geoid, mean dynamic topography, ocean tide, ocean load tide, atmospheric pressure, and sea-level rise; (ii) time series of ice shelf elevation change were produced by grouping the elevation measurements within regularly spaced 10 km grid cells, applying a space-time polynomial fit to data from each mission; (iii) time series of ice shelf thickness change were calculated by adjusting the elevation change for fluctuations in firn air content and using a hydrostatic buoyancy relationship, assuming values of 917 and 1,028 kg/m³ for the densities of ice and ocean water, respectively; and (iv) time series of ice shelf volume change were computed from the thickness changes and using the minimum (fixed) area for each ice shelf. Full details of the methods used in this calculation can be found in Paolo et al. (2015). The total change in ice shelf volume is computed as the sum of changes due to thinning and retreat, and the uncertainty is estimated as the root sum square of the respective uncertainties. ~~We constructed separate time series of elevation change for each mission using a space time polynomial fit to data falling within regularly spaced 10 km grid cells. The individual elevation change time series were then merged by ensuring that rates of height change during overlapping time periods were equal to the average of rates from each mission. We calculated changes in ice shelf thickness, and the associated changes in volume, by adjusting the height changes for changes in firn air content and using a hydrostatic buoyancy relationship, assuming values of 917 and 1,028 kg/m³ for the densities of ice and ocean water, respectively.~~

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175 Antarctic ice shelves have lost $8,667 \pm 1240$ Gt of their mass ~~since between~~ 1994 and 2020, 54 % of which has been due to reductions in their extent and the remainder due to changes in their thickness. Although episodic iceberg calving is part of the natural cycle of ice mass transport through the continent, there has been a 39,717 km² loss of ice shelf area at the Antarctic Peninsula (e.g. (Cook and Vaughan, 2010)), where air temperatures have risen several times faster than the global trend (Vaughan et al., 2003). Warmer air leads to increased surface melting, which can promote iceberg calving through hydraulic fracture of crevasses (Scambos et al., 2013). At the same time, ocean-driven melting has caused some ice shelves to thin at their base, particularly in the Amundsen and Bellingshausen Seas (Paolo et al., 2015; Shepherd et al., 2010) where warm circumpolar deep water is present (Jacobs et al., 1996), but also at the Antarctic Peninsula (Shepherd et al., 2003). Ice shelf thinning can promote instability by weakening their lateral margins (VielI et al., 2007). Both processes – calving front retreat and basal melting – have triggered speedup of inland ice (Rignot et al., 2004; Scambos et al., 2004; Shepherd et al., 2004) due to the associated reduction in buttressing (Joughin et al., 2012), leading to global sea-level rise (The IMBIE Team, 2018) even though ice shelves themselves are not a direct source of ocean mass. The ice shelf losses combined amount to 3 % of their present volume, while those in the Amundsen and Bellingshausen Seas are now 10 to 18 % thinner (Paolo et al., 2015) and those at the Antarctic Peninsula are 18 % smaller in extent (Cook and Vaughan, 2010).

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5 Sea ice

190 We estimated trends in the mass of Arctic sea ice using a combination of sea-ice ocean modelling and satellite measurements of thickness change: between 1980 and 2011 we used the Pan-Arctic Ice-Ocean Modelling and Assimilation System (PIOMAS), a coupled sea ice-ocean model forced with atmospheric reanalyses (Zhang and Rothrock, 2003); from 2011, we used CryoSat-2 satellite radar altimetry measurements of sea ice volume (Tilling et al., 2018). We converted PIOMAS volume estimates to mass assuming a fixed density of 917 kg/m^3 : this is the density used in the PIOMAS model to attribute a
195 volume to the simulated sea ice growth (Schweiger, personal comm), therefore it is appropriate to convert PIOMAS volume estimates back to mass using this same density, as opposed to one that varies according to season or ice type. We divided CryoSat-2 monthly volume estimates into regions of multi-year and first-year ice and multiplied by densities of 882 kg/m^3 and 916.7 kg/m^3 , respectively, to convert to mass (Tilling et al., 2018). The presence of melt ponds on the Arctic sea ice surface from May to September make it difficult to discriminate between radar returns from leads and sea ice floes,
200 preventing the retrieval of summer sea ice thickness and volume from radar altimetry (Tilling et al., 2018). As a result, we computed the winter-mean (October to April) mass trend across the Arctic for both CryoSat-2 and PIOMAS estimates to maintain consistency: the difference between winter (October-April) and annual (January-December) PIOMAS mass trends during 1980-2011 is 19 Gt yr^{-1} (6 %); smaller (6%) when compared to the magnitude of the overall 12-month trend (-324 Gt yr^{-1}). Since the annual trend is slightly larger, we consider our winter-average mass trend to be a conservative estimate of the
205 actual Arctic sea ice mass loss. In the absence of an available satellite-derived Antarctic sea ice volume product, we used the Global Ice-Ocean Modelling and Assimilation System (GIOMAS) (Zhang and Rothrock, 2003), the global equivalent to PIOMAS, to estimate the trend. We gridded GIOMAS sea ice thickness data onto 0.2×0.5 degree grids, multiplied by cell area to retrieve total volume and used a density of 917 kg/m^3 to convert to mass (as in PIOMAS, this is the density used to attribute a volume to the simulated sea ice growth in GIOMAS (Zhang, personal comm)). Antarctic sea ice trends were
210 computed as annual averages between January and December. The uncertainties on PIOMAS volume for October and March are $1,350$ and $2,250 \text{ km}^3$, respectively, estimated in Schweiger et al. (2011) using a range of methods, including comparison to in situ data and model sensitivity analyses. We take the average of these ($1,800 \text{ km}^3$) as the uncertainty for all months and, in the absence of a formal error budget, we assign the same uncertainty to monthly GIOMAS estimates. We convert this monthly volume error of $1,800 \text{ km}^3$ to a mass error using the fixed assumed an error on monthly-PIOMAS/GIOMAS density
215 volume of 1800 km^3 (Schweiger et al., 2011; Schweiger & Zhang, personal comm), and converted to a mass error using a density of 917 kg/m^3 . We estimated the uncertainty on monthly Arctic sea ice volume and mass from CryoSat-2 as a percentage ~~error~~uncertainty, which varies from 14.5 % volume in October to 13 % volume in April (Tilling et al., 2018). The uncertainty on the winter-average (Arctic) and annual-average (Antarctic) mass was propagated from the monthly ~~errors~~uncertainties. Finally, we estimated the uncertainty associated with a rate of mass change over a given time period by
220 dividing the total error by the number of years.

Between the winters of 1980 (October 1979 to April 1980) and 2019 (October 2018 to April 2019), Arctic sea ice mass reduced by $230 \pm 27 \text{ Gt yr}^{-1}$, predominantly due to a decline in the lateral extent of the ice cover (Fig. 1), which accounts for 93 % of the variance in volume over the entire PIOMAS record. The entire summer ice pack has thinned, largely attributable to the loss of the oldest and thickest ice, and sea ice cover has receded in the Beaufort, Chukchi and East Siberian seas (Stroeve and Notz, 2018). Arctic sea ice loss has been attributed to atmospheric warming driven by anthropogenic CO₂ emissions (Meredith et al., 2019; Stroeve and Notz, 2018), which has been enhanced in the Arctic when compared to the mid-latitudes likely due to sea ice loss itself (Dai et al., 2019; Screen and Simmonds, 2010). Between 1980 and 2019, GIOMAS volume estimates, which incorporate observations of sea ice extent, show an increase in Antarctic sea ice of $+43 \pm 17 \text{ Gt yr}^{-1}$. No consensus has been reached on whether trends in Antarctic sea ice cover are anthropogenically driven, for example e.g. via the depletion of the Ozone layer (Ferreira et al., 2015), or the result of natural climate variability (Meehl et al., 2016; Zhang et al., 2019). Given the vastness of the continent it surrounds, regional analyses of Southern Ocean sea ice are essential to understand the processes driving it. The overall trend is a combination of sea ice gains in the western Ross Sea and losses in the Amundsen and Bellingshausen seas, with small increases elsewhere thickening in the Weddell Sea and thinning in the Amundsen Sea (Fig. 1), accompanied by increases and reductions of the extent in each region, respectively (Parkinson, 2019). In general, global climate models predict a shrinking southern ice cap in response to climate change; projections from the latest coupled climate models suggest that Antarctic sea ice will decline during the 21st century (Roach et al., 2020).

6 Earth's ice imbalance

To determine the global ice imbalance, we summed the mass change of each ice component computed at annual intervals and estimated the combined uncertainty as the root sum square of the individual errors uncertainty estimates. Between 1994 and 2017, the Earth lost $27.57 \pm 2.10 \text{ Tt}$ of ice (Fig. 4) – at an average rate of $1.2 \pm 0.13 \text{ Tt per year}$ (Table 1). Ice losses have been larger in the northern hemisphere, primarily owing to declining Arctic sea ice ($-7559 \pm 1021 \text{ Gt}$) followed by glacier retreat ($-5,148,247 \pm 564,617 \text{ Gt}$) and Greenland ice sheet melt ($-3,821 \pm 323 \text{ Gt}$). Ice in the southern hemisphere from the ice shelves ($-6,543,32 \pm 1221 \text{ Gt}$), the Antarctic ice sheet ($-2,545 \pm 554 \text{ Gt}$), glaciers ($-965,72 \pm 729,35 \text{ Gt}$), and sea ice in the Southern Ocean ($-924 \pm 674 \text{ Gt}$) has been lost at a total rate of $-477,8 \pm 146 \text{ Gt yr}^{-1}$ – 34 % slower than in the northern hemisphere ($-719,23 \pm 207 \text{ Gt yr}^{-1}$). Earth's ice can be categorised into its floating and on-land components; grounded ice loss from ice sheets and glaciers raises the global sea-level (The IMBIE Team, 2018, 2020; Zemp et al., 2019), influences oceanic circulation through freshwater input (Rahmstorf et al., 2015) and glacier retreat impacts local communities who rely on glaciers as a freshwater resource (Immerzeel et al., 2020). Grounded ice losses have raised the global mean sea-level by $245.92 \pm 1.89 \text{ mm}$ and $9.78 \pm 2.56 \text{ mm}$ in the northern and southern hemispheres respectively, totalling $345.60 \pm 3.12 \text{ mm}$ over the 24-year period. Although the loss of floating sea ice and ice shelves does not contribute to global sea-level rise, sea

ice decline increases habitat loss (Rode et al., 2014), coastal erosion (Overeem et al., 2011) and ocean circulation (Armitage et al., 2020), and may affect mid-latitude weather and climate (Blackport et al., 2019; Overland et al., 2016).

255 There is now widespread evidence that climate change has caused reductions in Earth's ice. On average, the planetary surface temperature has risen by 0.85 °C since 1880, and this signal has been amplified in the polar regions (Hartmann et al., 2013). Although this warming has led to higher snowfall in winter, it has also driven larger increases in summertime surface melting (Huss and Hock, 2018). The global oceans have warmed too (Hartmann et al., 2013), with significant impacts on tidewater glaciers (Hogg et al., 2017; Holland et al., 2008), on floating ice shelves (Shepherd et al., 2010), and on the ice streams which have relied on their buttressing (Rignot et al., 2004). Atmospheric warming – anthropogenic or otherwise – is
260 responsible for the recent and long-term reductions in mountain glacier ice (Marzeion et al., 2014), and ocean-driven melting of outlet glaciers has caused the vast majority of the observed ice losses from Antarctica (The IMBIE Team, 2018). Elsewhere, the picture is more complicated. In Greenland, for example, roughly half of all ice losses are associated with trends in surface mass balance, and the remainder is due to accelerated ice flow triggered by ocean melting at glacier termini (The IMBIE Team, 2020). Although the retreat and collapse of ice shelves at the Antarctic Peninsula has occurred in tandem
265 with a rapid regional atmospheric warming (Vaughan et al., 2003), warm circumpolar deep water has melted the base of ice shelves in the Amundsen and Bellingshausen Seas (Jacobs et al., 2011) and this now amounts to over half of their net loss. While the progressive retreat of Arctic sea ice has been driven by radiative forcing, this has been mediated in part by the increasing presence of open water (Perovich and Richter-Menge, 2009), and broader changes in oceanic conditions are expected to play an increasingly important role (Carmack et al., 2016). Finally, although the extent of Southern Ocean sea
270 ice has shown little overall change, there have been considerable regional variations owing to changes in both atmospheric and oceanic forcing (Hobbs et al., 2016). Attributing Arctic sea ice decline and ice shelf calving to increased radiative forcing, approximately 68 % of the recent global ice imbalance is due to atmospheric warming, and the remainder is due to ocean-driven melting. We determine the energy required to melt the total ice loss as:

$$E = M(L + c_p \Delta T) , \quad (1)$$

275 where M is the mass of ice, ΔT is the rise in temperature required (we assume an initial ice temperature of -20 ± 10 °C), L is the latent heat of fusion for water ($333 \text{ J g}^{-1}/\text{g}$), and c_p is the specific heat capacity of water ($2108 \text{ J Kg}^{-1} \text{ °C}^{-1}$). Although the initial temperature is poorly constrained, the fractional energy required for warming is a small (0.7 % °C^{-1}) percentage of the total energy imbalance. Altogether, the ice sheet, glacier, ice shelf and sea ice loss amounts to an $8.9 \pm 0.9 \times 10^{21}$ J sink of energy, or $3.2 \pm 0.3 \text{ %}$ of the global imbalance over the same period (Schuckmann et al., 2020).

Even though Earth's cryosphere has absorbed only a small fraction of the global energy imbalance, it has lost a staggering 28 trillion tonnes of ice between 1994 and 2017. The loss of grounded ice during this period has caused sea-levels to rise by 345.60 ± 3.12 mm, and the loss of floating ice has caused reductions in the planetary albedo (Thackeray and Hall, 2019), reductions in the buttressing of grounded ice (Rignot et al., 2004), ocean freshening (Jacobs et al., 1996), and ocean cooling (Bintanja et al., 2013). Our assessment is based primarily on observations; we use satellite measurements to determine Antarctic and Greenland ice sheet mass balance and to determine changes in the mass of Antarctic ice shelves associated with retreat and thinning, we use a combination of satellite observations and *in situ* measurements to determine changes in the mass of mountain glaciers, and we use a combination of numerical models and satellite observations to determine changes in the mass of sea ice. There is generally good agreement in mass trends derived from observations and models, where both are available. Only our estimate of Southern Ocean sea ice mass imbalance depends on modelling alone (Zhang and Rothrock, 2003), though satellite observations of changes in its extent (Parkinson, 2019) and *in situ* observations of changes in its thickness (Worby et al., 2008) suggest that little change has occurred in Antarctic sea ice cover. The overall rate of ice loss has increased by 5749 % over the past 24 years compared to the 1990s, and *in situ* measurements of changes in glacier mass (Zemp et al., 2019) and satellite records of ice shelf extent (Cook and Vaughan, 2010) which pre-date the complete survey confirm this trend. Although a small fraction of mountain glacier losses are associated with retreat since the little ice age (Marzeion et al., 2014), there can be little doubt that the vast majority of Earth's ice loss is a direct consequence of climate warming.

Data availability

Mountain glacier mass change data from glaciological and geodetic observations are freely available at (<https://doi.org/10.5281/zenodo.1492141>). ~~and~~ Elevation change fields from DInSAR are available via the World Data Center (<https://doi.org/10.1594/PANGAEA.893612>). Glacier digital elevation models and elevation change maps derived from satellite optical stereo imagery are available at (<https://nsidc.org/data/highmountainasia>) and (<https://doi.pangaea.de/10.1594/PANGAEA.903618>), respectively. Mass change data for the Antarctic and Greenland ice sheets are provided by the ice sheet mass balance intercomparison exercise (IMBIE) and are available at (<http://imbie.org/data-downloads/>). Changes in ice shelf extent can be downloaded from the Scientific Committee on Antarctic Research digital database (<https://www.add.scar.org/>). Changes in ice shelf thickness from Adusumilli et al. (2020) are freely available at (<https://doi.org/10.6075/J04Q7SHT>). PIOMAS/GIOMAS data are freely available from the University of Washington Polar Science Data Center (<http://psc.apl.uw.edu/data/>).

Author contributions

- 310 TS, IRL, INO and AS designed the study, performed the data analysis and wrote the manuscript. NG, LJ and PT prepared mountain glacier mass change estimates from CryoSat-2 satellite radar altimetry. LG prepared the ice sheet thickness change datasets from multi-mission satellite radar altimetry used in Fig. 1.

Competing interests

The authors declare that they have no conflict of interest.

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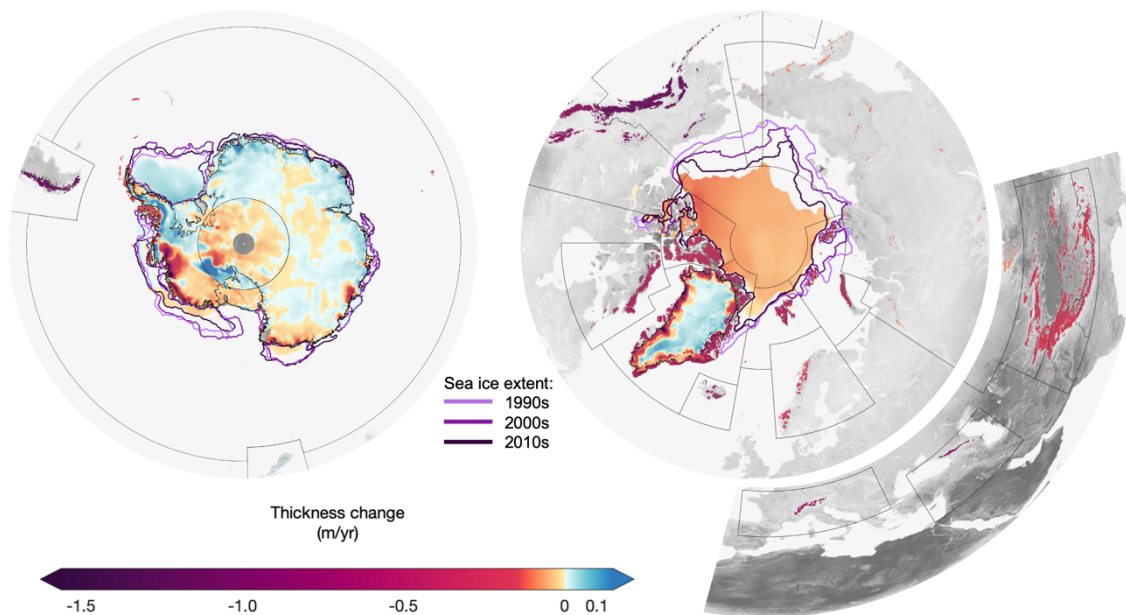
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	1980s	1990s*	2000s	2010s**	1994-2017
Arctic Sea Ice	-156 ± 88	-298 ± 88	-360 ± 88	-94 ± 119	-329 ± 44
Antarctic Sea Ice	+196 ± 67	-27 ± 67	+71 ± 67	-83 ± 75	-40 ± 29
Ice Shelves Calving	-140 ± 15	-125 ± 25	-176 ± 57	-250 ± 68	-155 ± 36
Ice Shelves Thinning	-	-19 ± 52	-233 ± 57	-53 ± 71	-129 ± 39
<i>Total Floating Ice</i>	-	-469 ± 125	-698 ± 137	-480 ± 172	-653 ± 75
Antarctic	-	-55 ± 38	-78 ± 37	-206 ± 47	-111 ± 24
Greenland	-	-34 ± 24	-166 ± 21	-247 ± 23	-166 ± 14
Glaciers	-62 ± 668	-206 ± 634	-2520 ± 604	-32746 ± 657	-26670 ± 412
<i>Total Grounded Ice</i>	-	-296 ± 779	-4954 ± 747	-77998 ± 835	-5437 ± 4950
Total	-	-764 ± 147	-11931 ± 1567	-125978 ± 1912	-1196200 ± 90

*1990s: the decade is not entirely surveyed but starts from 1994 for Ice Shelves Thinning, and from 1993 for Antarctica and from 1992 for Greenland

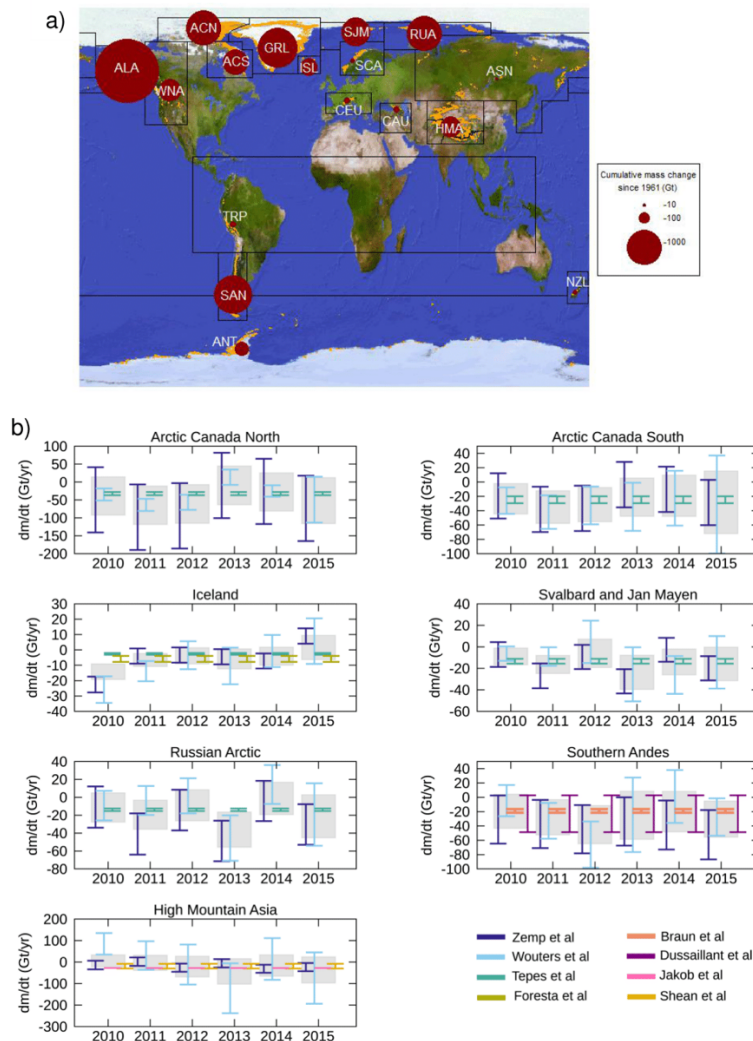
**2010s: the decade is not entirely surveyed but covers up to 2016 for the Antarctic ice sheet, up to 2017 for Greenland, and up to 2019 for sea ice, glaciers and ice shelf calving.

Table 1 Average mass change rates (Gt yr⁻¹) of the different global ice components, total floating ice, total grounded ice and global total per decade and over the common period 1994-2017.

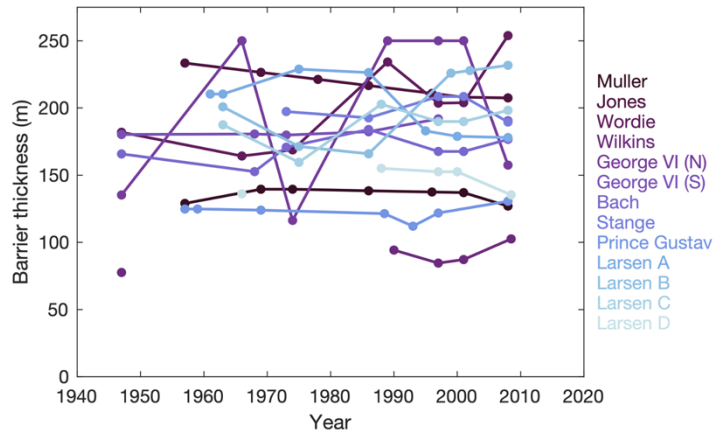
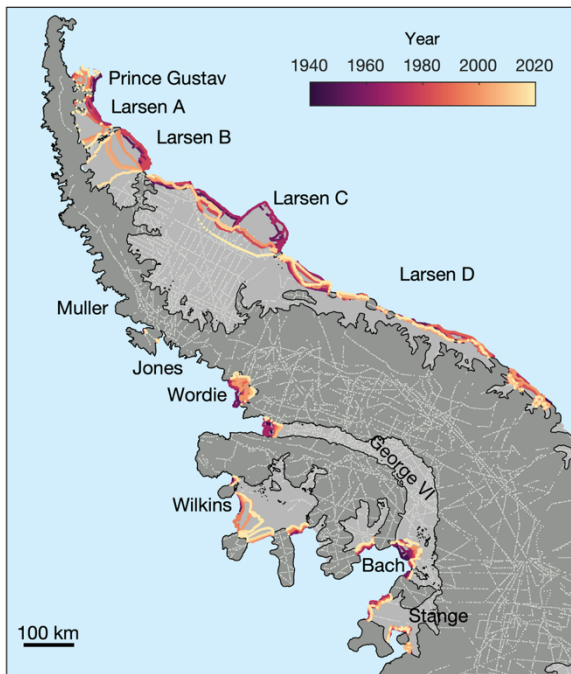


605 **Figure 1 Average rate of ice thickness change in the (left) southern and (right) northern hemispheres. Changes in Antarctic (1992-2017) and Greenland ice sheet (1992-2018) thickness were estimated using repeat satellite altimetry following the methods of (Shepherd et al., 2019). Sea ice thickness 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., 2020; Wouters et al., 2019; Zemp et al., 2019) which have been converted to a thickness change assuming an ice density of 850 kg/m³. The black circle at the south pole indicates the southern limit of the orbit of ERS and ENVISAT satellite altimeters, which were in operation between 1992 and 2010. The area between 81.5° and 88° S has been covered by CryoSat-2, which launched in 2010.**

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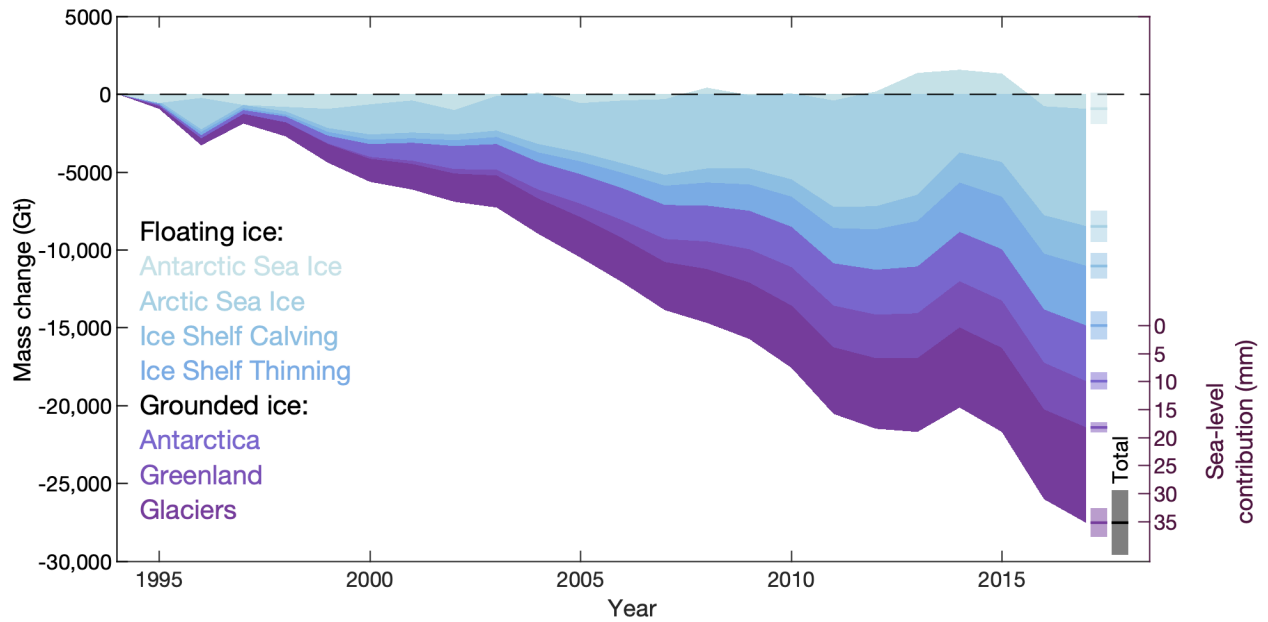


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 Figure 2 (a) Cumulative mass change for glacier regions (Gt) between 1962 and 2019. Outlines of the glacier regions (RGI 6.0) are marked by black lines and glacierized areas are indicated in orange: ACN, Arctic Canada North (area 105,110 km²); ACS, Arctic Canada South (40,888 km²); ALA, Alaska (86,725 km²); ANT, Antarctic and Subantarctic (132,867 km²); CAU, Caucasus and Middle East (1,307 km²); CEU, Central Europe (2,092 km²); GRL, Greenland (89,717 km²); HMA, High Mountain Asia (97,606 km²); ISL, Iceland (11,059 km²); NZL, New Zealand (1,161 km²); RUA, Russian Arctic (51,591 km²); SAN, Southern Andes (29,429 km²); SCA, Scandinavia (2,949 km²); SJM, Svalbard and Jan Mayen (33,958 km²); TRP, Low Latitudes (2,341 km²); WNA, Western Canada and USA (14,524 km²). (b) Glacier rate of mass change (Gt yr⁻¹) in regions where estimates from different techniques are available, including satellite altimetry (Foresta et al., 2016; Jakob et al., 2020; Tepes et al., 2020), extrapolation of in-situ glaciological and geodetic data (Zemp et al., 2019, 2020), satellite gravimetry (Wouters et al., 2019), and satellite InSAR (Braun et al., 2019), and satellite stereo imagery (Dussaillant et al., 2019; Shean et al., 2020) over the period 2010–2015. The reconciled estimate (calculated as the average of the estimates available in a given region and year) is shown in grey.



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Figure 3 Change in Antarctic ice shelf barrier position (left) and thickness (right) over time. Barrier positions are derived from episodic satellite imagery (Cook and Vaughan, 2010), and barrier thicknesses are derived from airborne ice penetrating radar (light grey lines) and satellite radar altimetry (Fretwell et al., 2013). Iceberg calving is calculated as the difference in area between successive barrier positions.



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Figure 4 Global ice mass change between 1994 and 2017 partitioned into the different floating (blues) and grounded (purples) components. Shaded bars indicate the cumulative mass change and estimated uncertainty for each individual ice component (blues, purples) and their sum (black). The equivalent sea-level contribution due to the loss of grounded ice from Antarctica, Greenland and mountain glaciers is shown in the y-axis on the right hand side.