Use case: Monitoring Greenland ice mass changes in the 21st century for usage in the context of Earth System modeling

Quality assessment question: "Are the Greenland ice mass change data of sufficient accuracy and spatial/temporal resolution to be used in glaciological, climatological, and/or hydrological modeling efforts, such as for the calibration or validation of an ice sheet model?"

Ice sheets are a major contributor to current (and potentially future) global sea-level rise and can serve as clear indicators of ongoing climatic changes. Their changes furthermore play a key role in affecting (polar as well as global) ecosystems and several (feedback) mechanisms within the atmosphere, ocean and cryosphere. A proper assessment of ice sheet mass changes due to warming climatic conditions therefore plays a crucial role in dealing with these issues. In that regard, the 'Gravimetric mass balance data for the Antarctic and Greenland ice sheets from 2003 to 2022 derived from satellite observations' dataset provides key information with respect to ice sheet mass change data for both the Greenland and Antarctic ice sheets. The dataset on the Climate Data Store (CDS) is based on satellite gravimetry, which enable mass changes to be measured regularly and consistently over the entire ice sheets. Remote sensing devices, such as used by the GRACE and GRACE-FO missions, are namely able to inspect directly and repeatedly large areas of ice. More particularly, the GRACE(-FO) mission is able to detect changes within the Earth’s gravitational field (resembling a redistribution of mass), and further processing of these data transforms this raw information into mass balance and grounded mass change data (Forsberg et al., 2017; Groh et al., 2019). Remote sensing techniques that use satellite data are therefore considered the only feasible manner to derive accurate mass change data of the remote ice sheets on a regular basis. This notebook investigates how well the resulting ice sheet mass change data can be used to monitor Greenland ice mass changes in the 21st century. This will be evaluated within the context of, for example, using the mass change data for the calibration or validation of an ice sheet model. More specifically, the notebook investigates whether the dataset is of sufficient maturity and quality for that purpose in terms of its accuracy and its spatial/temporal resolution.

Quality assessment statement

- Mass change detection by GRACE(-FO) is a useful tool to quantify the total grounded ice mass change of the Greenland Ice Sheet but, however, it also has its limitations of which the user should take note before using the product. What GRACE(-FO) actually detects are patterns of mass redistribution, indicating that a material should be redistributed (e.g. by liquid discharge) in order for GRACE(-FO) to be able to detect the mass changes over certain locations. In that sense, an amount of melted ice being replaced by its mass-equivalent amount of meltwater at the same location would result in zero mass change. Only grounded ice mass changes are considered in the dataset, mass changes of floating ice are not considered (which is, however, relatively limited for the GrIS). GRACE(-FO) data are therefore considered to be the sum of mass changes driven by changing rates of solid ice discharge (i.e. ice dynamics) and mass changes driven by changing rates of runoff and accumulation (basal, internal and surface conditions) over grounded ice.

- A large problem with the dataset is that no pixel-by-pixel mass change and error products are included for the ice sheets. However, time series data for various basins are available from the data files. A spatial resolution at the basin-level is, however, clearly too coarse with respect to GCOS requirements (GCOS, 2022). As most ice sheet models work with gridded data, a similar spatial structure of the dataset would be of higher quality than the current data structure. Another issue with the data is the occurrence of (occasionally very) high error values. In some cases for the GrIS, monthly error estimates even exhibit values larger than 400 Gt. The main reason for these high uncertainty values is a combination of various factors that can impact the precision and accuracy of GRACE(-FO) measurements. These include errors related to measurement noise (e.g. due to leakge of the signal outside the region of interest due to the coarse resolution of GRACE(-FO) data acquisition), uncertainties related to the Earth's gravitational field (e.g. due to the shift of the Earth's center of mass, or due to the influence of the atmosphere and oceans on the Earth's gravity field), uncertainties related to signals overlapping with ice mass changes, particularly Glacial Isostatic Adjustment (GIA), etc. Users should also note that peripheral glaciers and ice caps are included in the GrIS mass change product. Data gaps are also present (e.g. during the transition period between GRACE and GRACE-FO in 2017-2018 CE). These are not filled up and not flagged, users need to identify them themselves.
- Concerning the specific use case and user question, using GRACE(-FO) mass change data in an ice sheet modeling framework for Greenland offers some advantages, such as the ability to calibrate/validate large-scale mass changes, as well as a high temporal resolution which allows for detailed analysis. However, it also has limitations, including a coarse spatial resolution (at the ice sheet-wide or basin-scale), an ungridded data structure (only a time series of cumulative mass changes are available), the presence of (occasionally very) high uncertainties, and some notable temporal gaps in the time series. To mitigate these limitations, mass changes with high uncertainties can, for example, be excluded or weighted according to their respective uncertainties to improve the accuracy of the model calibration (data assimilation) or validation procedures.

▯ Methodology

Short description

The mass balance of an ice sheet is the difference between mass gained (from snow accumulation) and mass lost (by runoff or ice discharge through the grounding line), which is the same as the net mass change of the ice sheet. Remote sensing techniques, such as the use of satellites, are an important feature to derive and study the mass changes of the ice sheets. The 'Gravimetric mass balance data for the Antarctic and Greenland ice sheets from 2003 to 2020 derived from satellite observations' dataset provides monthly gravimetric mass balance (GMB) values and their uncertainty for the Greenland (GrIS) and Antarctic Ice Sheet (AIS). The data represent a time series of the cumulative mass changes of the grounded ice of the ice sheets and their basins that are derived using satellite gravimetry data from the GRACE(-FO) missions. Data are available for the whole ice sheet as well as at the basin level, but no gridded data are provided. Data are available since 2002 with units in Gt (Gigatonnes). For a more detailed description of the data acquisition and processing methods, we refer to the documentation on the CDS and the ECMWF Confluence Wiki.

Structure and (sub)sections

In this notebook, the applicability of ice sheet mass change data to be used in an ice sheet-modeling framework will be assessed. We will check whether the data for Greenland are of sufficient adequacy in terms of its accuracy and its spatial/temporal resolution to be used for this purpose. This will be realized by analyzing the spatial and temporal characteristics of ice sheet mass change data and their uncertainty, by assessing the spatial and temporal resolution of the dataset, by discussing other potential limitations and error sources of the dataset, and by evaluating the implications for the usage of the data in terms of the specific use case and question (i.e. monitoring Greenland and Antarctic ice sheet mass changes to be used for the calibration or validation of an ice sheet model). The structure is as follows:

- **Data preparation and processing**: This section loads packages, defines requests for download from the CDS, downloads the actual data and inspects the data to reveal its structure. Also the functions that are used in this notebook are defined in this section.
- **Quantifying Greenland Ice Sheet mass changes in space and time**: This section derives (cumulative) ice sheet mass changes for Greenland since 2002 from GRACE-(FO) and expresses it as a time series for the entire ice sheet and its basins separately.
- **Ice sheet mass changes uncertainty estimates in space and time**: This section analyses the uncertainty term of the mass change change product for Greenland and assesses its characteristics in both space and time. We also express the uncertainty as a time series for the entire ice sheet and its basins.
- **Analysis of spatio-temporal resolution and coverage of the GRACE(-FO) GrIS mass change estimates**: This section further discusses the temporal and spatial coverage of the data in the ice sheet mass change product, and quantifies the amount of data gaps present.
- **Implications for use of GRACE(-FO) mass change data in an ice sheet modelling framework**: The final section uses all information derived above to assess the suitability of the ice sheet mass change dataset (with respect to its accuracy and spatial/temporal coverage and resolution) to use the product as a data calibration (i.e. data assimilation) or validation tool in the context of an ice sheet model for Greenland.

? Analysis and results

? Data preparation and processing

First we load the packages:

In [413…

```
import fsspec
import matplotlib as mpl
import matplotlib.pyplot as plt
import matplotlib.colors as mcolors
import matplotlib.ticker as mticker
import numpy as np
import xarray as xr
from scipy.stats import linregress
from matplotlib.gridspec import GridSpec
import re
from math import ceil
import pandas as pd
import calendar
import os
os.environ["CDSAPI_RC"] = os.path.expanduser("~/verhaegen_yoni/.cdsapirc")
from c3s_eqc_automatic_quality_control import download

plt.style.use("seaborn-v0_8-notebook")
```

Then we define the parameters, i.e. for which ice sheet (or which basins of these ice sheets) we want the mass change data to be extracted:

In [414…

```
variables = ["GrIS_total", "GrIS_1", "GrIS_2", "GrIS_3", "GrIS_4", "GrIS_5", "GrIS_6", "
```

Then we define requests for download from the CDS and download and transform the glacier mass change data.

In [415…

```
collection_id = "satellite-ice-sheet-mass-balance"
request = {
    "variable": "all",
    "format": "zip",
}
ds = download.download_and_transform(collection_id, request)
ds_err = ds[[f"{var}_er" for var in variables]].compute()
ds = ds[variables].compute()
ds = xr.combine_by_coords([ds, ds_err])
print("Downloading done.")
```

```
100%|██████████| 1/1 [00:00<00:00,  6.91it/s]
Downloading done.
```

Let us inspect the data:

In [416…

```
ds
```

Out[416]:

xarray.Dataset

▸ Dimensions: (**time**: 216)

▾ Coordinates:

time	(time)	datetime64[ns]	2002-04-16T20:23:54.375000 ... 2...

▸ Data variables: (18)

▸ Indexes: (1)

▸ Attributes: (12)

It is a dataset that consists out of several time series data, containing cumulative values of the total ice sheet mass change of, in this case, the entire Greenland Ice Sheet (`GrIS_total`) or its basins (`GrIS_{basin_number}`), as well as their uncertainty (`GrIS_{basin_number}_er`) since 2002. Mass changes and their uncertainty are expressed in units of Gt and the time period between two measurements is variable. Note that no gridded data are given in this dataset, and hence no spatial resolution can be derived. For basin definitions and delineation, see Zwally et al. (2012).

Let us perform some data handling before getting started with the analysis:

In [417…

```
variables_to_drop = [var for var in ds.data_vars if '_er' in var]
ds = ds.drop_vars(variables_to_drop)

year_to_ns = 1.0e9 * 60 * 60 * 24 * 365
with xr.set_options(keep_attrs=True):
    ds = ds - ds.isel(time=0)
for var, da in ds.data_vars.items():
    da.attrs["region"] = da.attrs["long_name"].split("_", 1)[0].title()
    da.attrs["long_name"] = "Cumulative mass change"
for var_name, da in ds.data_vars.items():
    # Check if the variable name contains a number
```

```
    match = re.search(r'_(\d+)', var_name)
    if match:
        basin_number = match.group(1)
        da.attrs["region"] = f"Greenland basin {basin_number}"
    else:
        da.attrs["region"] = f"Cumulative mass change of the Greenland Ice Sheet from GR

for var, da in ds_err.data_vars.items():
    da.attrs["region"] = da.attrs["long_name"].split("_", 1)[0].title()
    da.attrs["long_name"] = "Mass change error"
for var_name, da in ds_err.data_vars.items():
    # Check if the variable name contains a number
    match = re.search(r'_(\d+)', var_name)
    if match:
        basin_number = match.group(1)
        da.attrs["region"] = f"Greenland basin {basin_number}"
    else:
        da.attrs["region"] = f"Mass change error of the Greenland Ice Sheet from GRACE(-

with xr.set_options(keep_attrs=True):
    ds_diff = ds.diff("time") / ds["time"].diff("time").astype(int)
    ds_diff *= year_to_ns / 12
for var_name, da in ds_diff.data_vars.items():
    # Check if the variable name contains a number
    match = re.search(r'_(\d+)', var_name)
    if match:
        basin_number = match.group(1)
        da.attrs["region"] = f"Greenland basin {basin_number}"
    else:
        da.attrs["region"] = f"Non-cumulative mass change of the Greenland Ice Sheet fro
    da.attrs["long_name"] = "Mass change"
```

We also define a plotting function to visualize the time series:

In [418…

```
def plot_timeseries(ds):
    variables = list(ds.data_vars.values())
    num_vars = len(variables)

    # Create a GridSpec layout with enough rows
    num_rows = (num_vars + 1) // 2  # Integer division, ensuring enough rows

    fig = plt.figure(figsize=(8, 3 * num_rows))
    gs = GridSpec(num_rows, 2, figure=fig)

    # Plot the first variable, spanning the first row
    ax = fig.add_subplot(gs[0, :])
    variables[0].plot(ax=ax, color='k')
    ax.set_title(f"{variables[0].attrs.get('region', '')}")
    ax.set_xlim(np.min(ds["time"]), np.max(ds["time"]))
    ax.grid(color='#95a5a6',linestyle='-',alpha=0.25)

    # Plot the remaining variables, two per row
    for i, da in enumerate(variables[1:], start=1):
        row = (i + 1) // 2
        col = (i + 1) % 2
        ax = fig.add_subplot(gs[row, col])
        da.plot(ax=ax, color='b',linewidth=1)
        ax.set_title(f"{da.attrs.get('region', '')}")
        ax.set_xlim(np.min(ds["time"]), np.max(ds["time"]))
        ax.grid(color='#95a5a6',linestyle='-',alpha=0.25)
        ax.tick_params(axis='x', rotation=45)

    plt.tight_layout()
    return fig, gs
```

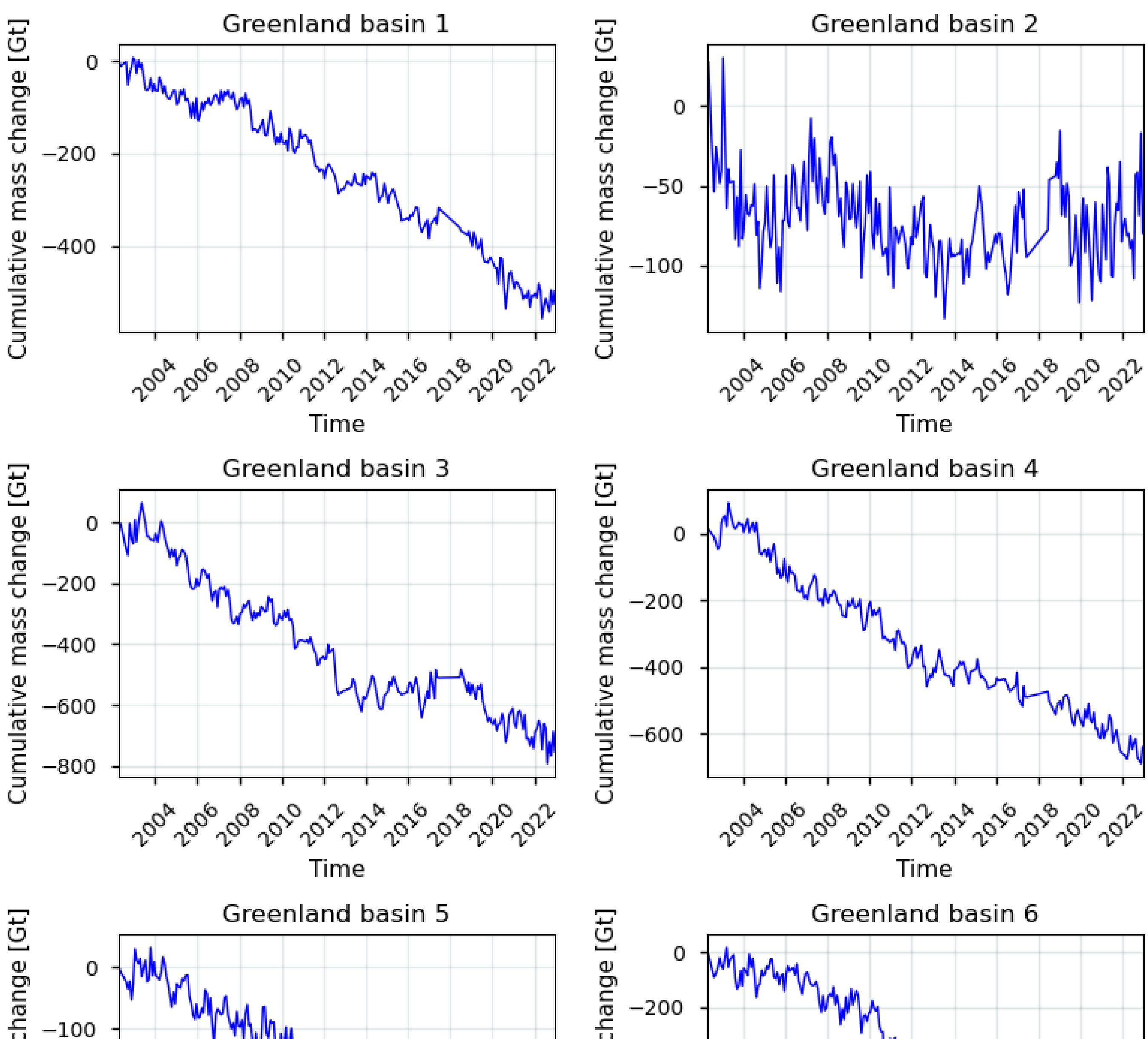
With everything ready, let us now start with the analysis:

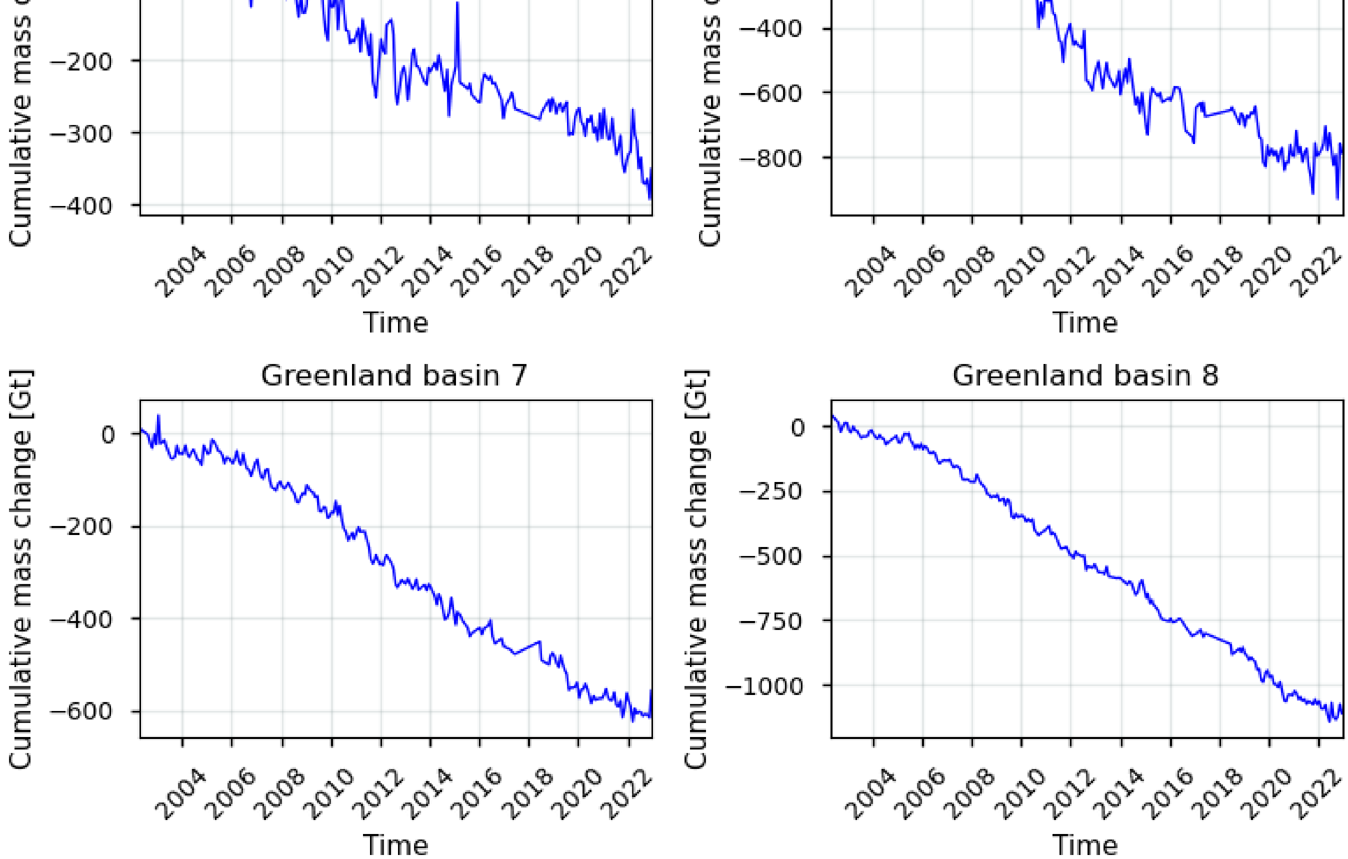
? Quantifying Greenland Ice Sheet mass changes in space and time

We begin by plotting the Greenland Ice Sheet cumulative mass change ΔM_{GRACE} between the begin and end period with the defined plotting function:

In [419…

```
fig, gs = plot_timeseries(ds)
```





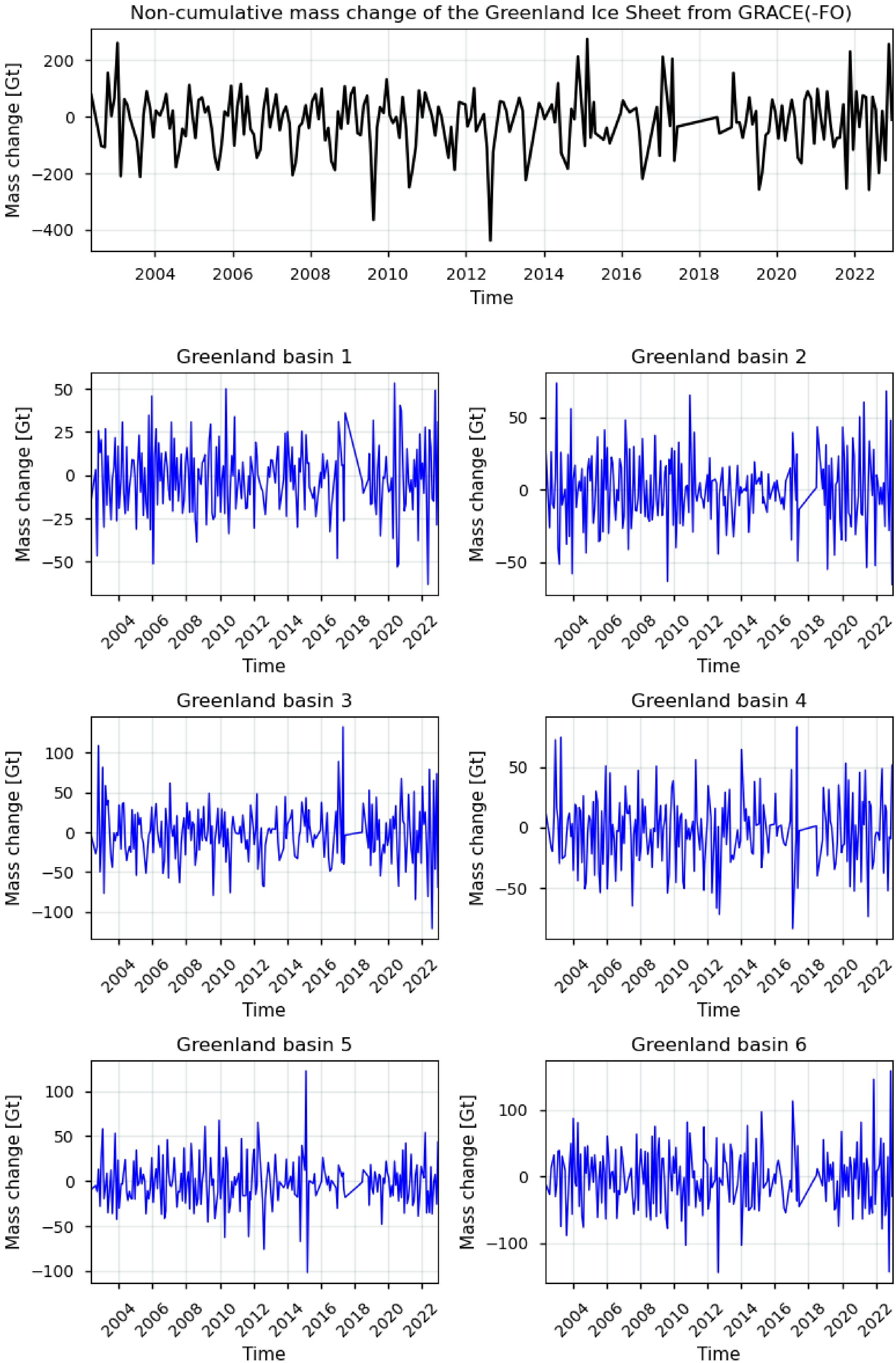
The mass changes and their errors derived from GRACE(-FO) are expressed in Gt (Gigatonnes). Since the Gt is a unit of mass, one Gt of ice weighs exactly the same as a Gt of water. It can also be translated into a volume, for example one Gt of water (density 1000 kg/m^3) is exactly one km^3, while one Gt of ice (density 917 kg/m^3) in volume becomes 1.091 km^3 of ice. GRACE(-FO) data are in fact considered to be the sum of mass changes driven by changing rates of solid ice discharge (i.e. by ice dynamics) and mass changes driven by changing rates of runoff and accumulation (basal, internal, as well as climatic conditions at the surface). What GRACE(-FO) actually detects are patterns of mass redistribution, indicating that a material should be redistributed (e.g. by liquid discharge) in order for GRACE(-FO) to be able to detect gravity anomalies and the corresponding mass changes over certain locations. In that sense, an amount of melted ice being replaced by its mass-equivalent amount of meltwater at the same location would result in zero mass change. Only grounded ice mass changes are considered in the dataset, mass changes of floating ice are not considered (which is, however, relatively limited for the GrIS).

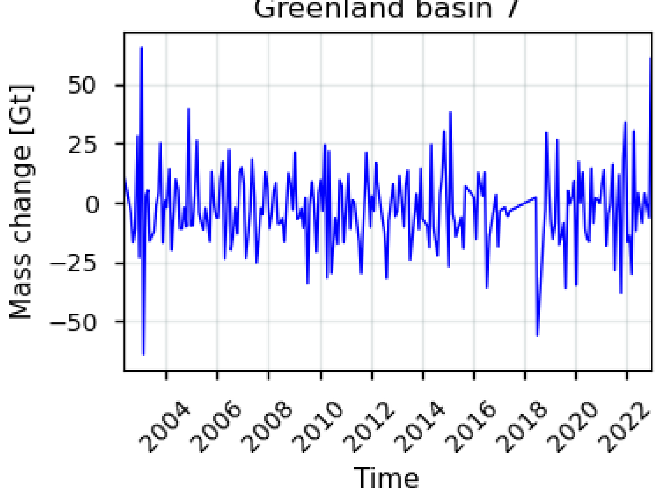
The provided graphs illustrate the cumulative mass change of the Greenland Ice Sheet from GRACE(-FO) data, highlighting a consistent decline in ice mass from 2002 onwards. The overall trend across all basins shows significant ice loss, indicating the profound impact of climate change. The first graph on top represents the cumulative mass change of the entire Greenland Ice Sheet. It shows a steady decline, underscoring the extensive ice loss over the last several decades (e.g. Sasgen et al., 2020). The subsequent graphs below detail the mass change in individual basins. Overall, these graphs highlight the significant and widespread loss of ice mass across the Greenland Ice Sheet, with different basins showing varying rates and patterns of ice loss. This variability could be due to regional climatic conditions, glacial dynamics (i.e. solid discharge), and other environmental factors. The findings underscore the critical state of the Greenland Ice Sheet, serving as a clear indicator of the impacts of climate change (Groh et al., 2019; Otosaka et al., 2023).

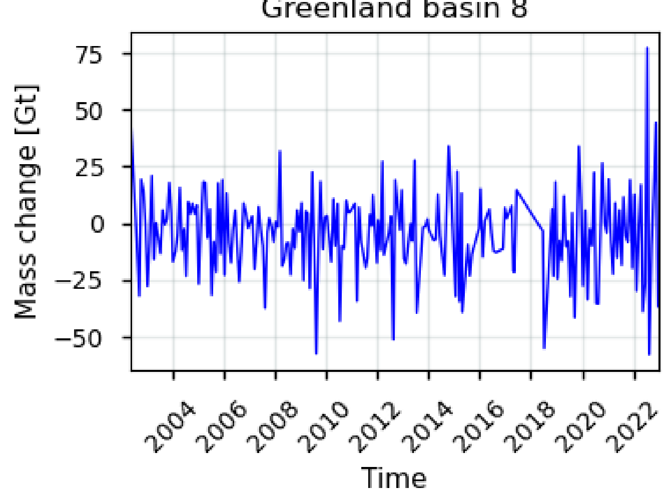
Let us now plot the data in a non-cumulative way (i.e. at variable-spaced time intervals):

In [420…

```
fig, axs = plot_timeseries(ds_diff)
```


Non-cumulative mass change of the Greenland Ice Sheet from GRACE(-FO)
Mass change [Gt]
Time
Greenland basin 1
Greenland basin 2
Greenland basin 3
Greenland basin 4
Greenland basin 5
Greenland basin 6

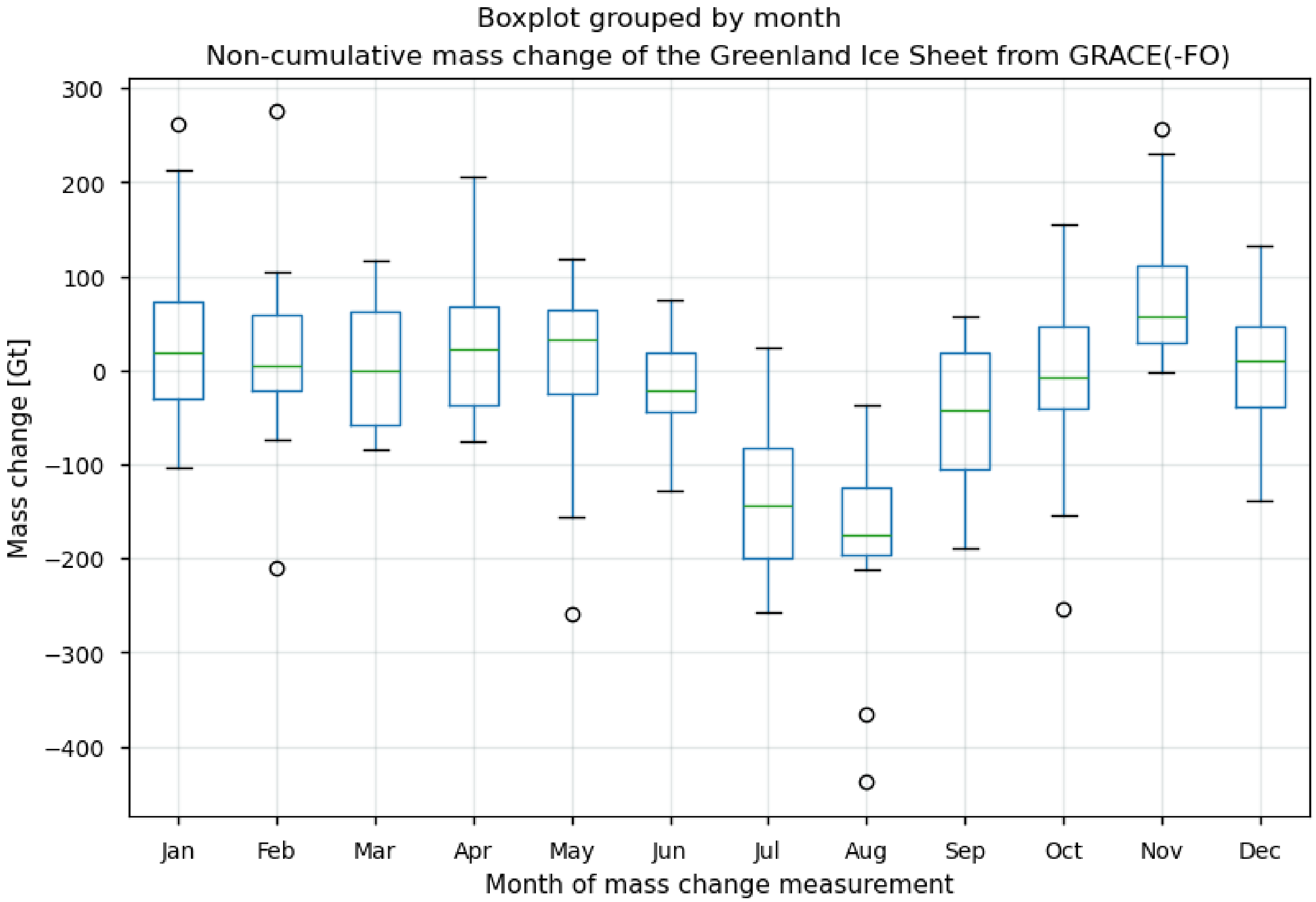




Perhaps the pattern above becomes clearer if we group the mass changes of the entire ice sheet for each month during which a GRACE-(FO) mass change measurement took place. Therefore, a boxplot is created for each month to inspect the mass changes that occur within each distinct month:

In [421…

```
# Create the figure and axes for the plot
fig, ax = plt.subplots(layout="constrained")
# Get the first variable from ds_diff
first_var = next(iter(ds_diff.data_vars.values()))
# Convert the data array to a dataframe
df = first_var.to_dataframe()
# Add the month information
df["month"] = df.index.month
# Create the boxplot
df.boxplot(
    by="month",
    ax=ax,
    ylabel=f"{first_var.attrs['long_name']} [{first_var.attrs['units']}]",
    xlabel="Month of mass change measurement",
)
# Set the title and x-tick labels
ax.set_title(f"{first_var.attrs['region']}")
ax.set_xticklabels([calendar.month_abbr[m] for m in ax.get_xticks()])
ax.grid(color='#95a5a6', linestyle='-', alpha=0.25)
plt.show()
```



The data may be biased, however, by the fact that the time period between two GRACE(-FO) measurements is variable in time (see later). Nevertheless, the data suggests a clear seasonal pattern, with summer months showing more variability and larger negative changes due to higher melting rates, while winter months exhibit a tighter boxplot range, reflecting more stable conditions with slightly positive mass changes on average. These patterns are likely influenced by seasonal climatic factors, with warmer summer temperatures leading to increased melting and larger negative mass changes. The presence of outliers indicates occasional extreme events significantly affecting the ice sheet's mass, such as unusually warm periods or significant precipitation events.

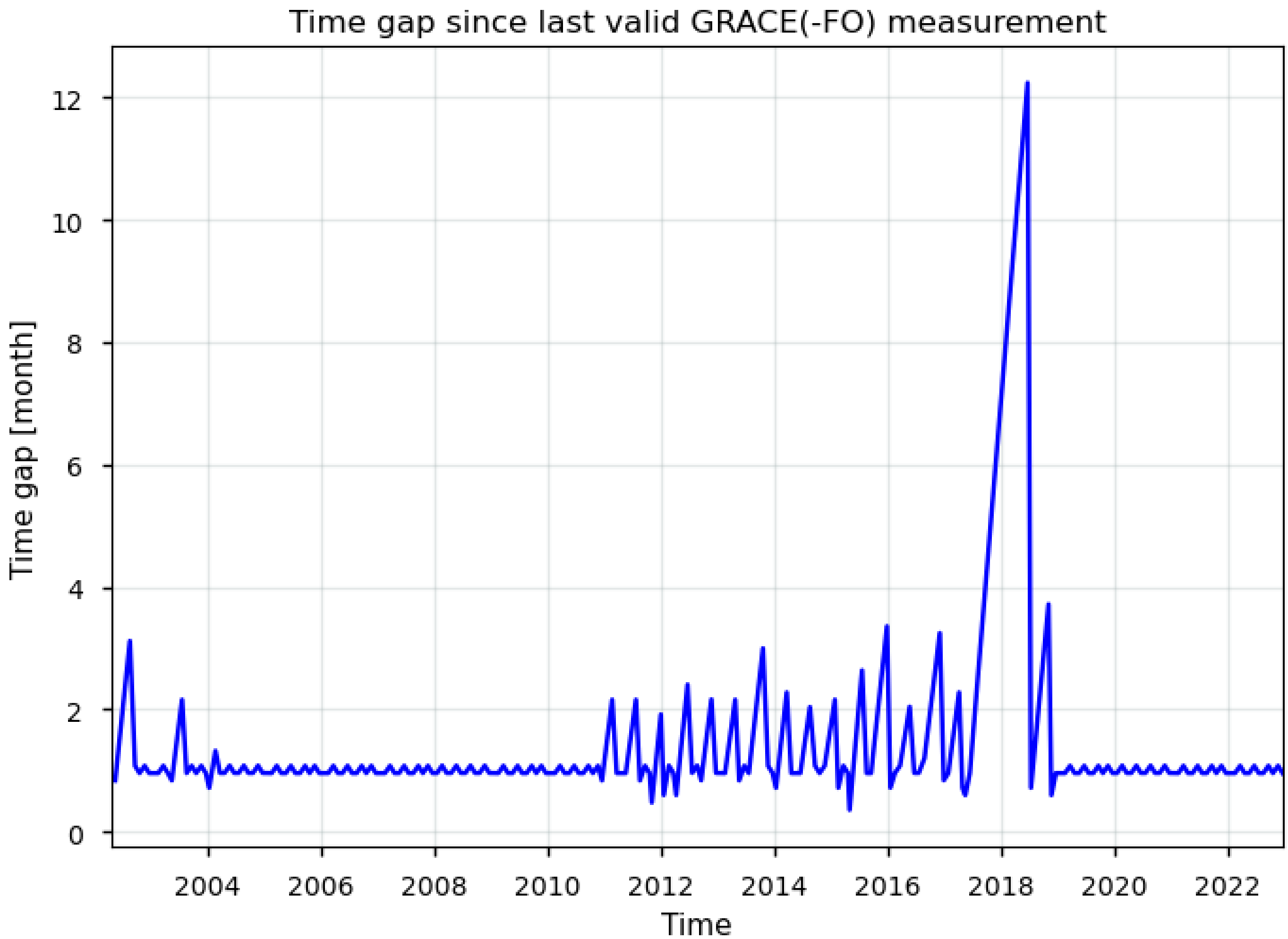
Let us now explore the error of the product:

▯ Analysis of spatio-temporal resolution and coverage of the GRACE(-FO) GrIS mass change estimates

Now that we have visualized the spatial and temporal patterns of mass changes, we can investigate the spatio-temporal resolution and extent of the GrIS mass changes to get an idea of the dataset’s maturity. Let us begin by identifying temporal data gaps (coverage) and the temporal resolution in the time series:

In [422…

```
time_gap_months = 12 * ds["time"].diff("time").astype(int) / year_to_ns

# Create the plot
fig, ax = plt.subplots()
time_gap_months.plot(ax=ax, color='b')
ax.set_ylabel("Time gap [month]")
ax.grid(color='#95a5a6', linestyle='-', alpha=0.25)
ax.set_xlim(np.min(ds["time"]), np.max(ds["time"]))
ax.set_title("Time gap since last valid GRACE(-FO) measurement")
plt.show()
```



The plot above visualizes the time gaps in the GRACE(-FO) data collection, highlighting periods of consistent monthly data acquisition, increased variability in the measurements, and significant data gaps due to the GRACE-(FO) mission transition. The most prominent feature in the plot is namely the large spike in the time gap around 2017-2018, where the gap reaches up to 12 months. This significant gap corresponds to the end of the original GRACE mission and the transition period before the launch of the GRACE Follow-On (GRACE-FO) mission in May 2018. During this period, there was a hiatus in the data collection, as the original GRACE satellites were decommissioned and the new GRACE-FO satellites were not yet operational. Generally speaking, a temporal resolution of ca. 1 month (which is mostly the case) is noted, which is in agreement with the optimum requirement proposed by GCOS (2022).

Let us have this quantified:

In [423…

```
start, end = ds["time"].isel(time=[0, -1]).dt.strftime("%d/%m/%Y").values.tolist()

for string, date in zip(("start", "end"), (start, end)):
    print(f"The {string:^5} date of the time series is", date)

expected = len(pd.date_range(start, end, freq="ME", inclusive="both"))
actual = len(set(ds["time"].dt.strftime("%Y%m").values))
for string, date in zip(("expected", "present"), (expected, actual)):
    print(f"The amount of months with mass change measurements that is {string} between

missing = 100 * abs(expected - actual) / expected
print(f"For a consistent monthly temporal resolution, the amount of months with missing
```

```
The start date of the time series is 16/04/2002
The  end  date of the time series is 17/12/2022
The amount of months with mass change measurements that is expected between these two da
tes is 248
```

```
The amount of months with mass change measurements that is present between these two dat
es is 213
For a consistent monthly temporal resolution, the amount of months with missing data is
14.11%.
```

With respect to the spatial coverage, a major issue for the GrIS is whether to include or exclude the outlying peripheral glaciers and ice caps (which is for example not the case for the surface elevation change dataset on the Climate Data Store). The GRACE(-FO) GMB data, however, do account for the mass changes of all ice caps and glaciers over entire Greenland. This is due to the nature of GMB data acquisition, which cannot separate close ice mass bodies because of its coarse spatial resolution (several hundred kilometers) during the data acquisition. The contribution of Greenland's peripheral glaciers and ice caps is approximately 30-35 Gt/year (Otosaka et al., 2023). To exclude these areas from the GRACE(-FO) time series, a scaling factor of 0.84 is often used (Bolch et al., 2013; Colgan et al., 2015). The spatial resolution is complicated by the fact that no gridded data are available for download, although they exist through other sources (e.g. the TU Dresden website). However, data are only available as a time series at the ice sheet-wide and basin-scale, which is clearly too coarse with respect to GCOS requirements, and also complicates the use of the data in ice sheet models that often require gridded data. This information can nevertheless be important, as the mass changes in Greenland are clearly seen to be associated with relatively narrow marginal ice zones, especially in west and southeastern Greenland, and major outlet glaciers such as Jakobshavn and Helheim glaciers (Forsberg et al., 2017).

Additionally, GRACE(-FO) data has a relatively coarse spatial resolution during data acquisition, which can blur the boundaries between different basins and make it challenging to attribute mass changes to specific basins accurately (i.e. due to leakage errors), for example due to the nearby presence of Canadian ice caps.

Ice sheet mass changes uncertainty estimates in space and time

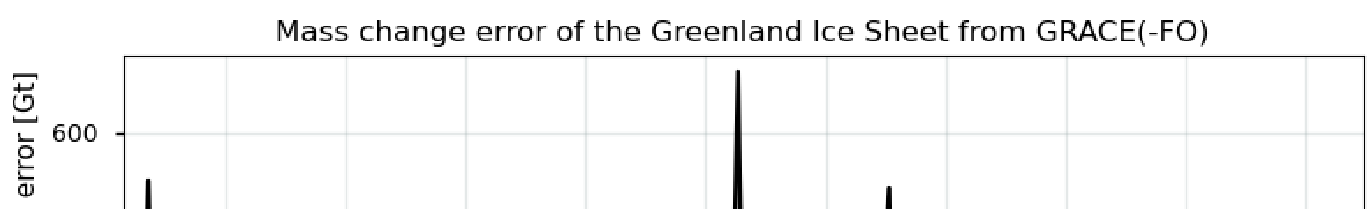
The total error of a monthly ice sheet mass change estimate for Greenland is given by the sum of the precision (random) and the accuracy (systematic) error:

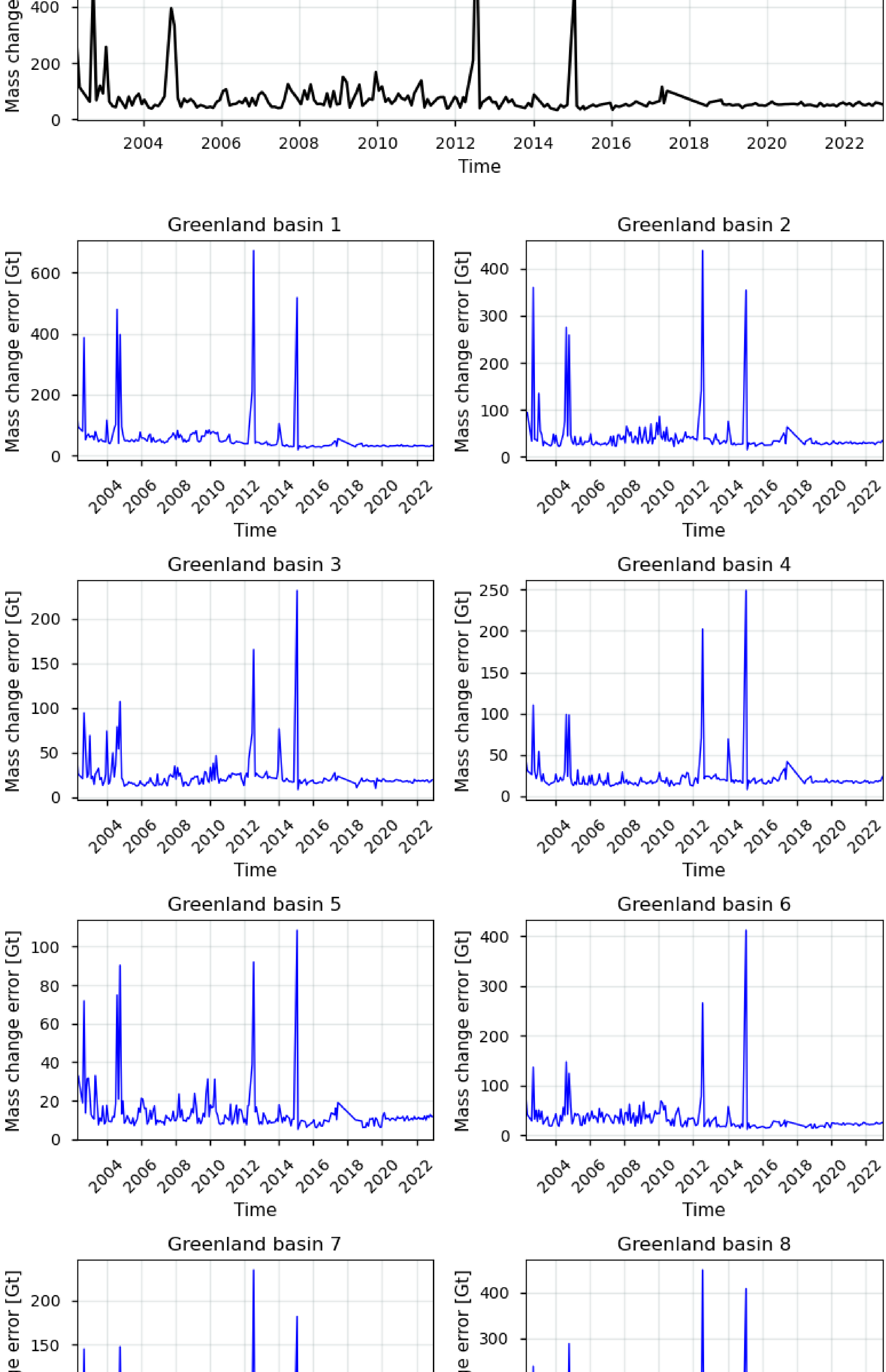
$\varepsilon = 1.96 * \sigma + \delta$ where σ is the standard deviation (random error) and δ the accuracy error.

For the GrIS, the product deals with both precision and accuracy errors in its final results. The precision error accounts for the statistically distributed random error around one average value. The accuracy error accounts for how much the expected value deviates from the "true" value. For the precision error, the 95% confidence interval (1.96 sigma) propagated from the data, is provided. Therefore, in the case for the GrIS, the total uncertainty of the data is given by ε. Hence, in the C3S products the most complete error estimate that was evaluated by Barletta et al. (2013) was given. The study reports that roughly half (ca. 50%) of the total error is attributed to the precision error, the other half is the accuracy error in the monthly error estimate. In the following section below, we will thus consider the uncertainty of the dataset as being $\varepsilon_{\Delta M_{GRACE}}$.

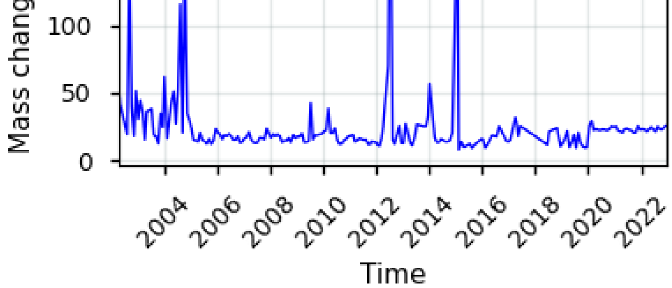
Let us plot a time series of the errors:

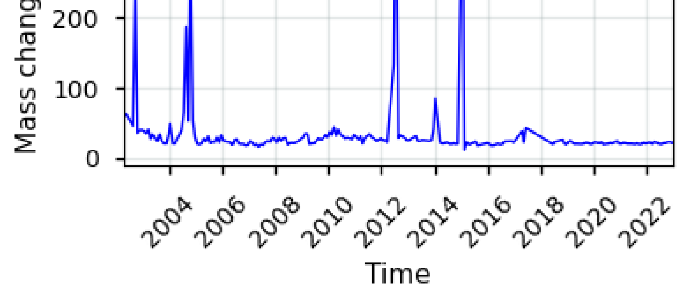
In [424…
```
fig, axs = plot_timeseries(ds_err)
```





Mass change
Time
Greenland basin 1
Greenland basin 2
Greenland basin 3
Greenland basin 4
Greenland basin 5
Greenland basin 6
Greenland basin 7
Greenland basin 8
Mass change error [Gt]





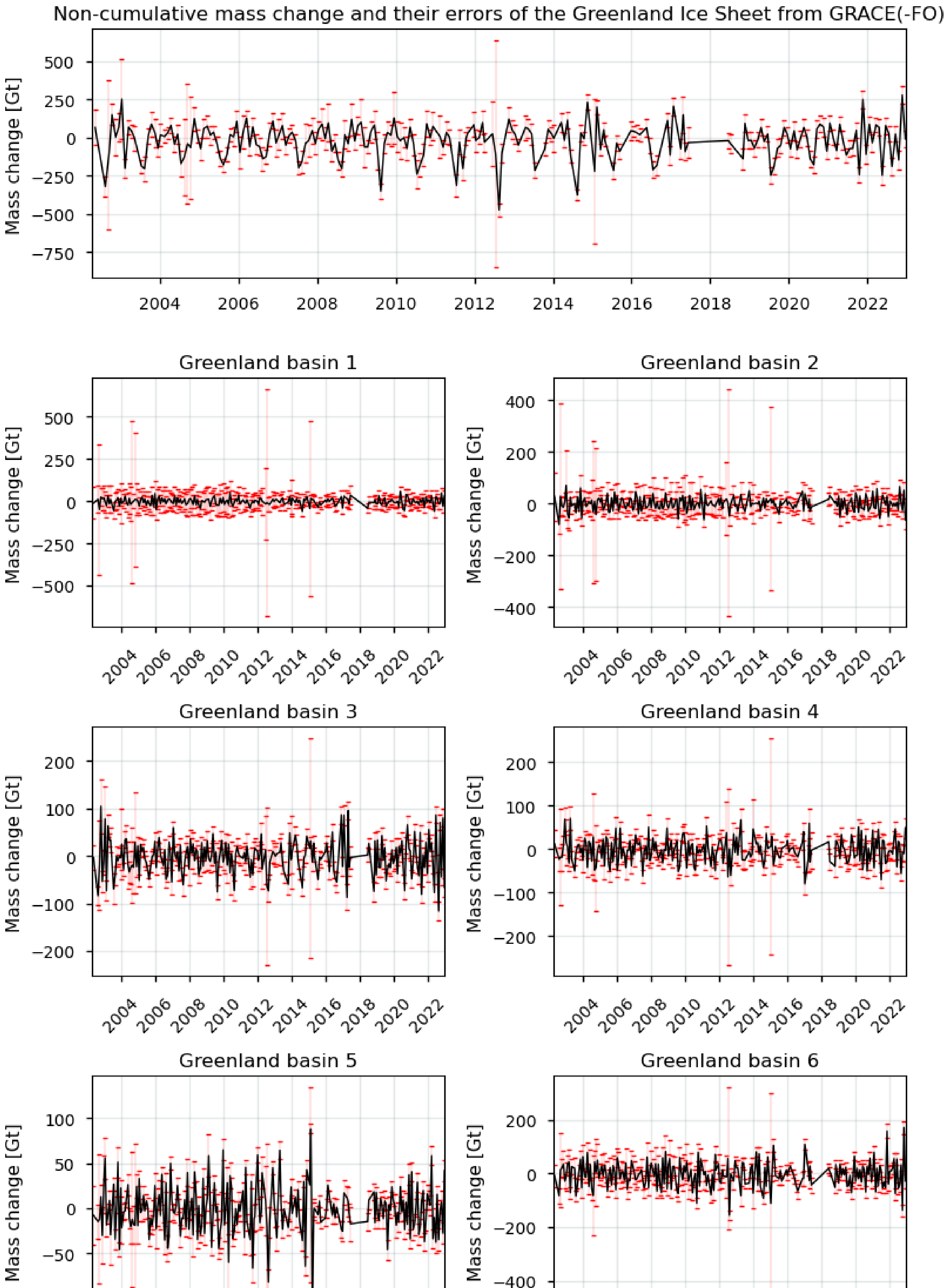
Note that these values are not normalized to a certain time period, as the time gap between two measurements is variable. Uncertainties in GRACE ice mass change estimates are occasionally very high and arise from various sources. These include, amongst others, errors related to measurement noise (e.g. due to leakge of the signal outside the region of interest, such as the Canadian ice caps, due to the coarse resolution of GRACE(-FO) data acquisition), uncertainties related to the Earth's gravitational field (e.g. due to the shift of the Earth's center of mass, or due to the influence of the atmosphere and oceans on the Earth's gravity field), uncertainties related to signals overlapping with ice mass changes, particularly Glacial Isostatic Adjustment (GIA), etc.

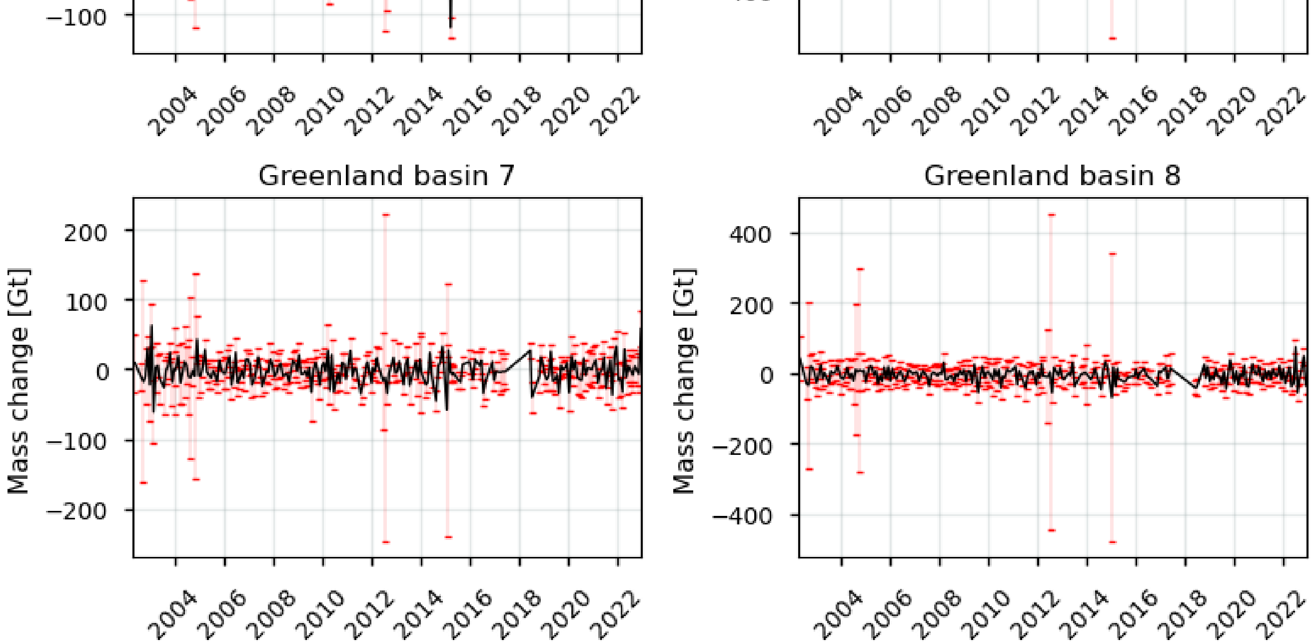
Let us plot mass change time series with error bars:

In [425…

```
# Assuming ds and ds_err

variables = list(ds.data_vars.values())
num_vars = len(variables)

# Create a GridSpec layout with enough rows
num_rows = (num_vars + 1) // 2  # Integer division, ensuring enough rows

fig = plt.figure(figsize=(8, 3 * num_rows))
gs = GridSpec(num_rows, 2, figure=fig)

# Plot the first variable with error bars, spanning the first row
ax = fig.add_subplot(gs[0, :])
# Calculate monthly mass change from cumulative data
monthly_mass_change = np.diff(variables[0].values, prepend=0)
yerr = ds_err[f"{variables[0].name}_er"]

# We assume time is in the same length as cumulative series, except for the first value
time = variables[0]["time"].values[1:]

ax.errorbar(time, monthly_mass_change[1:], yerr=yerr[1:],
            fmt='-', color='k', ecolor='r', linewidth=1, elinewidth=0.15, capsize=1.5, c
ax.set_title(f"Non-cumulative mass change and their errors of the Greenland Ice Sheet fr
ax.set_xlim(np.min(ds["time"]), np.max(ds["time"]))
ax.grid(color='#95a5a6', linestyle='-', alpha=0.25)
ax.set_ylabel("Mass change [Gt]")

# Plot the remaining variables, two per row
for i, da in enumerate(variables[1:], start=1):
    row = (i + 1) // 2
    col = (i + 1) % 2
    ax = fig.add_subplot(gs[row, col])
    # Calculate monthly mass change from cumulative data
    monthly_mass_change = np.diff(da.values, prepend=0)
    yerr = ds_err[f"{da.name}_er"]
    time = da["time"].values[1:]

    ax.errorbar(time, monthly_mass_change[1:], yerr=yerr[1:],
                fmt='-', color='k', ecolor='r', linewidth=1, elinewidth=0.15, capsize=1.
    ax.set_title(f"{da.attrs.get('region', '')}")
```

```
    ax.set_xlim(np.min(ds["time"]), np.max(ds["time"]))
    ax.grid(color='#95a5a6', linestyle='-', alpha=0.25)
    ax.tick_params(axis='x', rotation=45)
    ax.set_ylabel("Mass change [Gt]")

plt.tight_layout()
plt.show()
```





We can furthermore calculate the average values (arithmetic means over time):

In [426…

```
da = ds_err
variables = list(da.data_vars.values())
variables[0].attrs["region"] = f"in total"
for i, da in enumerate(variables, start=1):
    print(f"The arithmetic mean mass change error of the GrIS {da.attrs.get('region', ''
```

```
The arithmetic mean mass change error of the GrIS in total is 76.72 Gt with a maximum of
740.25 Gt.
The arithmetic mean mass change error of the GrIS basin 1 is 58.71 Gt with a maximum of
671.28 Gt.
The arithmetic mean mass change error of the GrIS basin 2 is 42.94 Gt with a maximum of
438.62 Gt.
The arithmetic mean mass change error of the GrIS basin 3 is 23.66 Gt with a maximum of
231.57 Gt.
The arithmetic mean mass change error of the GrIS basin 4 is 22.24 Gt with a maximum of
249.10 Gt.
The arithmetic mean mass change error of the GrIS basin 5 is 13.86 Gt with a maximum of
108.55 Gt.
The arithmetic mean mass change error of the GrIS basin 6 is 33.96 Gt with a maximum of
412.35 Gt.
The arithmetic mean mass change error of the GrIS basin 7 is 24.06 Gt with a maximum of
234.92 Gt.
The arithmetic mean mass change error of the GrIS basin 8 is 33.13 Gt with a maximum of
450.22 Gt.
```

For the entire ice sheet, error values mostly range between 0 and 50 gigatonnes (Gt), with occasional spikes reaching around 400 Gt or more. When comparing the errors to the respective monthly mass change magnitudes, it can be noted that for the majority of the time series, the errors are relative large when compared to the actual changes in mass. This suggests that the data should be handled with care for most periods. Periods with high error bars, indicate times when the data are even less reliable. For some months, these error values are very high, indicating that these periods should also be treated with caution. The user can decide to leave this months out if desired.

It is difficult to compare these errors to GCOS requirements (GCOS, 2022) because (a) the GCOS does not propose thresholds for mass change explicitely, but solely for ice sheet volume changes, (b) the GCOS reformulates error requirements in the form of precision errors (2σ), while the error in the GrIS mass change product contains an error product that combines precision and accuracy errors, and (c) the time difference between two GRACE measurements varies over time, and the time series also exhibits time gaps (which complicates normalizing the errors to a common timeframe). Moreover, since no independent datasets are available for gravity-derived ice sheet mass changes, validation procedues are difficult to conduct.

Let us normalize the errors to Gt/month by using the time period between two measurements as calculated above:

In [427…

```
# Here `ds_err` is an xarray Dataset
da = ds_err
variables = list(da.data_vars.values())
variables[0].attrs["region"] = "in total"
time_gap_months_aligned = xr.DataArray(np.insert(time_gap_months, 0, 1), dims=["time"],

for var in variables:
    var.data = np.sqrt((var.data / (time_gap_months_aligned))**2)

# Iterate and print the results
for i, var in enumerate(variables, start=1):
    print(f"The arithmetic mean mass change error of the GrIS {var.attrs.get('region', '
```

```
The arithmetic mean mass change error of the GrIS in total is 74.61 Gt/month with a maxi
mum of 768.99 Gt/month.
The arithmetic mean mass change error of the GrIS basin 1 is 56.76 Gt/month with a maxim
um of 697.34 Gt/month.
The arithmetic mean mass change error of the GrIS basin 2 is 41.56 Gt/month with a maxim
um of 455.65 Gt/month.
The arithmetic mean mass change error of the GrIS basin 3 is 22.96 Gt/month with a maxim
um of 171.61 Gt/month.
The arithmetic mean mass change error of the GrIS basin 4 is 21.34 Gt/month with a maxim
um of 210.17 Gt/month.
The arithmetic mean mass change error of the GrIS basin 5 is 13.52 Gt/month with a maxim
um of 95.61 Gt/month.
The arithmetic mean mass change error of the GrIS basin 6 is 32.57 Gt/month with a maxim
um of 276.07 Gt/month.
The arithmetic mean mass change error of the GrIS basin 7 is 23.34 Gt/month with a maxim
um of 244.04 Gt/month.
The arithmetic mean mass change error of the GrIS basin 8 is 31.75 Gt/month with a maxim
um of 467.70 Gt/month.
```

□ Implications for use of GRACE(-FO) mass change data in an ice sheet modelling framework

In the following section, we integrate all information derived above to assess the suitability of the ice sheet mass change dataset (with respect to the spatial/temporal characteristics of the error and its coverage/resolution) to use the product as a data calibration (i.e. data assimilation) or validation tool in the context of an ice sheet model for Greenland.

At the heart of an ice sheet model is the solution of the time-dependent continuity equation for ice thickness H:

$$\frac{\partial H}{\partial t} = -\nabla \cdot (\vec{v} H) + M$$

where H is the ice thickness, $\vec{v}$ is the vertically averaged horizontal velocity vector and M is the total mass balance. All terms have units of m/yr of ice equivalents. The latter term quantifies the mass gained or lost due to surface, internal and basal processes (i.e. liquid discharge in the case M is negative), as well as the mass of ice being lost to the ocean due to ice dynamics (i.e. by solid ice discharge):

$$M = SMB - D$$

where:

- M is the mass balance of the ice mass loss or gain,
- SMB is surface mass balance (often also supplemented by the basal and internal mass balance),
- D is the solid ice discharge (zero for land-terminating glaciers/ice sheets)

The GRACE(-FO) satellites provide measurements of mass changes over large spatial scales, capturing the entire Greenland Ice Sheet and surrounding ice caps. It furthermore provides monthly estimates of mass change, which are essential for detecting seasonal variations and short-term trends. In that regard, their data could serve as input for the mass balance term M in ice sheet models. However, data would need to be converted from actual mass changes (in Gt) to mass balances (in in m/yr ice equivalents), using the density of ice and the surface area:

$$M = \frac{\frac{\Delta M_{GRACE}}{\Delta t}}{A \cdot \rho_{ice}}$$

with:

- ΔM_{GRACE} is the mass change in gigatonnes during a certain time interval (kg)
- A is the surface area (m²)
- ρ_{ice} is the density of ice (typically 917 kg/m³)
- Δt is the time interval (years).

A calibration or data assimilation procedure then involves adjusting several unknown parameters in the mass balance equations (e.g. related to the intensity of melt/runoff or solid ice discharge). This allows the modelled mass changes to match the observed ones. For instance, in a least-squares fitting procedure, the sum of squared residuals can be minimized:

$$\text{minimize} \quad \sum_i (y_i - f(x_i))^2$$

where:

- y_i is the observed data (i.e. here the GRACE(-FO) mass changes from the dataset)
- $f(x_i)$ is the model prediction for the ith data point in the time series

The quality of the input data, however, plays an important role when using observed mass changes in an ice sheet modelling framework.

In that regard, some important limitations for using GRACE(-FO) mass change data in ice sheet models arise. The most important limitation is that no gridded data are available for download from the Climate Data Store. This gridded data structure is needed to be able to incorporate the data into ice sheet models. GRACE(-FO) data thus have a spatial resolution that is too coarse (data are presented as time series at the ice sheet-wide or basin-scale), and its presented data structure is not adequate, which limits its ability to resolve small-scale variations and mass changes in individual glaciers or regions within Greenland, as well as the integration into an ice sheet modelling framework. As such, the GMB products can only be usefully compared with an ice sheet model on an ice-sheet wide or basin-to-basin scale.

Leakage of signals from adjacent regions (e.g. the Canadian ice caps) can furthermore impact the accuracy of mass change estimates for certain individual basins. The accuracy of GRACE(-FO) data also depends on geophysical corrections such as, amongst others, those for Glacial Isostatic Adjustment (GIA) and atmospheric/oceanic mass changes, which can introduce additional uncertainties. The error values of the GrIS mass change dataset are relatively high and should therefore be handled with care. For some measurements, the errors in the provided data are really high, and can even exceed 400 Gt. At last, gaps between the GRACE and GRACE-FO missions, as well as occasional missing data within the missions, can affect the continuity of mass change time series.

Apart from those of the main ice sheet body, the mass changes of GRACE(-FO) data also include data from the peripheral glaciers and ice caps. To exclude these areas from the GRACE(-FO) time series, a scaling factor of 0.84 is proposed (Bolch et al., 2013; Colgan et al., 2015). One thing to remember is that only grounded ice is considered in the GRACE(-FO) mass change derivation, as mass changes of floating ice (past the groundling line) are not considered.

Using GRACE(-FO) mass change data in an ice sheet modeling framework for Greenland thus on the one hand offers significant strengths, such as large-scale mass change detection and a high temporal resolution. On the other hand, it also presents limitations related to coarse spatial resolution, ungridded data structure, occasional high uncertainties, and temporal data gaps in the time series. To mitigate these limitations, GRACE(-FO) data can for example be combined with other observational datasets (e.g. an integrated CryoSat (surface elevation changes), GRACE (mass changes) and Sentinel-1 (ice flow velocity) product, combined with firn compaction and snow surface density models to isolate the M term in the continuity equation) (e.g. Simonsen et al., 2021). Another option is to not use mass changes with a high uncertainty, or to weigh the mass changes with their respective uncertainties:

$$w_i = \frac{1}{(\varepsilon_{\Delta M_{GRACE}})^2}$$

When using these weights in data calibration or validation, each data point's contribution to the model can be weighed accordingly. For instance, in the least-squares fitting procedure, the weighted sum of squared residuals can be minimized:

$$\text{minimize} \quad \sum_i w_i (y_i - f(x_i))^2$$

where w_i is the weight for the ith data point in the time series.

A proposed procedure would be to first extract monthly mass change from the cumulative data time series, then use the appropriate formula to convert the mass change from gigatonnes to mass balance in m/yr ice equivalents, and lastly use these data (whether or not weighted according to their uncertainty) to adjust unknown parameters in the mass balance equations. These impact the mass balance term M in the continuity equation for ice thickness change, and are needed to match modelled values to the observed mass changes from GRACE(-FO) data at the basin or ice sheet-wide scale.

If you want to know more

Key resources

- "Gravimetric mass balance data for the Antarctic and Greenland ice sheets from 2003 to 2022 derived from satellite observations" on the CDS.
- C3S EQC custom functions, `c3s_eqc_automatic_quality_control` prepared by BOpen.

References

- Bolch, T., Sørensen, L.S., Simonsen, S. B., Mölg, N., Machguth, H., Rastner, P., & Paul, F. (2013).

Mass loss of Greenland's glaciers and ice caps 2003–2008 revealed from ICESat laser altimetry data. Geophysical Research Letters, 40(5), 875-881. https://doi.org/10.1002/grl.50270.

- Colgan, W., Abdalati, W., Citterio, M., Csatho, B., Fettweis, X., Luthcke, S., Moholdt, G., Simonsen, S.B., and Stober, M. (2015). Hybrid glacier Inventory, Gravimetry and Altimetry (HIGA) mass balance product for Greenland and the Canadian Arctic. Remote Sensing of Environment, 168, 24–39. https://doi.org/10.1016/j.rse.2015.06.016
- Forsberg, R., Sørensen, L.S. and Simonsen, S.B. (2017). Greenland and Antarctica Ice Sheet Mass Changes and Effects on Global Sea Level. Surv. Geophys., 38, 89–104. https://doi.org/10.1007/s10712-016-9398-7.
- Groh, A., Horwath, M., Horvath, A., Meister, R., Sørensen, L.S., Barletta, V.R., Forsberg, R., Wouters, B., Ditmar, P., Ran, J., Klees, R., Su, X., Shang, K., Guo, J., Shum, C.K., Schrama, E., and Shepherd, A. (2019). Evaluating GRACE Mass Change Time Series for the Antarctic and Greenland Ice Sheet, Geosciences, 9(10). https://doi.org/10.3390/geosciences9100415.
- Otosaka, I. N., Shepherd, A., Ivins, E. R., Schlegel, N.-J., Amory, C., van den Broeke, M. R., Horwath, M., Joughin, I., King, M. D., Krinner, G., Nowicki, S., Payne, A. J., Rignot, E., Scambos, T., Simon, K. M., Smith, B. E., Sørensen, L. S., Velicogna, I., Whitehouse, P. L., A, G., Agosta, C., Ahlstrøm, A. P., Blazquez, A., Colgan, W., Engdahl, M. E., Fettweis, X., Forsberg, R., Gallée, H., Gardner, A., Gilbert, L., Gourmelen, N., Groh, A., Gunter, B. C., Harig, C., Helm, V., Khan, S. A., Kittel, C., Konrad, H., Langen, P. L., Lecavalier, B. S., Liang, C.-C., Loomis, B. D., McMillan, M., Melini, D., Mernild, S. H., Mottram, R., Mouginot, J., Nilsson, J., Noël, B., Pattle, M. E., Peltier, W. R., Pie, N., Roca, M., Sasgen, I., Save, H. V., Seo, K.-W., Scheuchl, B., Schrama, E. J. O., Schröder, L., Simonsen, S. B., Slater, T., Spada, G., Sutterley, T. C., Vishwakarma, B. D., van Wessem, J. M., Wiese, D., van der Wal, W., and Wouters, B. (2023). Mass balance of the Greenland and Antarctic ice sheets from 1992 to 2020, Earth Syst. Sci. Data, 15, 1597–1616, https://doi.org/10.5194/essd-15-1597-2023.
- Sasgen, I., Wouters, B., Gardner, A.S., King, M.D., Tedesco, M., Landerer, F.W., Dahle, C., Save, H., and Fettweis, X. (2020). Return to rapid ice loss in Greenland and record loss in 2019 detected by the GRACE-FO satellites. Commun. Earth Environ., 1, no. 1, 8, https://doi.org/10.1038/s43247-020-0010-1.
- Simonsen, S. B., Barletta, V. R., Colgan, W. T. and Sørensen, L. S. (2021). Greenland Ice Sheet Mass Balance (1992–2020) From Calibrated Radar Altimetry. Geophysical Research Letters 48, https://doi.org/10.1029/2020GL091216.
- Zwally, H., Giovinetto, M., Beckley, M., and Saba, J. (2012). Antarctic and Greenland drainage systems, GSFC cryospheric sciences laboratory. URL: https://earth.gsfc.nasa.gov/cryo/data/polar-altimetry/antarctic-and-greenland-drainage-systems.