



PROGRESS REPORT

SUMMARY OF WORK AT THE NASA JET PROPULSION LABORATORY

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REPORT A001

1. Overview

There is currently no fully coupled model capable of fully simulating ice sheet mass changes. The ultimate goal of an effort to couple the Ice Sheet System Model (ISSM) and the Modèle Atmosphérique Régional (MAR) is to develop a fully coupled ice-sheet-atmosphere model (initially applied over the Greenland Ice Sheet). As part of this project it will be necessary to (1) assess the MAR model's simulation of surface mass balance (SMB), which includes an assessment of the SMB uncertainty, and (2) to determine how ISSM and MAR can be coupled. To begin the initial stages of this project, I spent this summer working with the ISSM group at the NASA Jet Propulsion Laboratory (JPL).

2. Objectives

The overall objectives of this summer's work were to lay the groundwork for a collaboration between the MAR and ISSM teams, and to begin an evaluation of mass balance estimates from MAR and ISSM. Some specific objectives were to:

1. Install the new version of MAR (v. 3.2) on JPL servers and clusters.
2. Install MAR v.3.2 at the CUNY High Performance Computing Center (HPCC)
3. Teach the ISSM group in the basics of running MAR.
4. Begin sensitivity studies with MAR to assess uncertainty of simulated SMB.
5. Install ISSM at the Cryospheric Processes Laboratory and at the CUNY HPCC.
6. Learn the basics of setting up a Greenland Ice Sheet simulation with ISSM.
7. Compare MAR SMB, mass changes from ISSM, and mass balance data from the Gravity Recovery and Climate Experiment (GRACE) to evaluate MAR's simulation of SMB as well as ISSM's simulation of dynamic changes.
8. Develop strategy for future coupling of MAR and ISSM.

3. Latest Results

3.1 Installing and compiling MAR

During the first week at JPL I worked with the ISSM team to set up MAR on ISSM servers and at the CUNY HPCC. A MAR tutorial is being developed for new users of MAR as a Google doc. It is based on work with the ISSM team and contains instructions for installing, compiling and running MAR on a new server. A screenshot of the start of the tutorial is provided below.

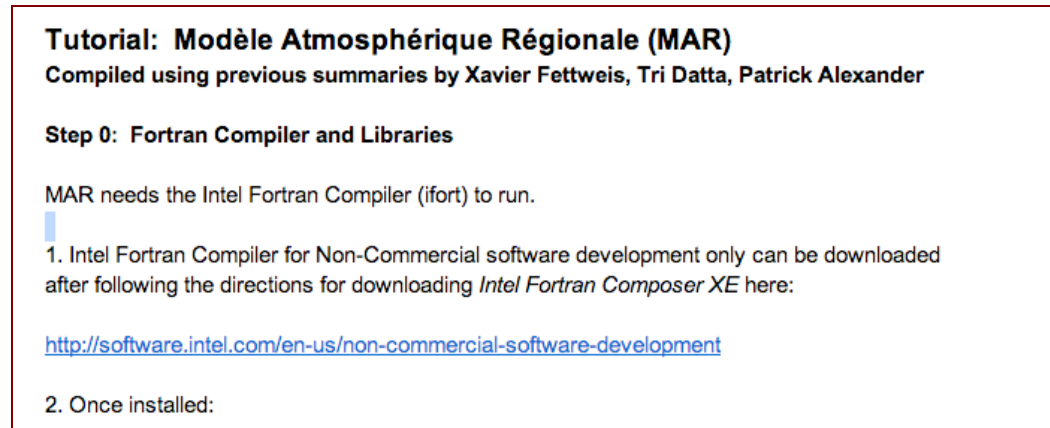


Figure 1: MAR tutorial.

The ISSM team has installed MAR v.3.2 on their servers and on their account on our local servers. I have also installed MAR v. 3.2 at the CUNY HPCC and on another account on one of our local servers. The ISSM team is now familiar with the process of running MAR's preprocessing software, NESTOR, to create a new MAR domain, and the steps needed to compile and run a MAR simulation, and have the data necessary for running MAR.

Numerous obstacles were encountered during installation and compilation of MAR, which necessitated renaming or moving of files and modification of initialization files. A new Fortran compiler has been installed locally and is being used at the HPCC. Unfortunately, we are encountering an error when running MAR v 3.2 at the HPCC and locally on ISSM servers, which has delayed the start of running MAR v. 3.2. MAR apparently experiences a segmentation fault after initialization of the radiative scheme. This error occurs on the ISSM server and at the HPCC when the same procedure is followed for running NESTOR and compiling MAR. The error appears to occur regardless of the Fortran compiler used (ifort 11.0 vs. ifort 13.0), and the compiler options used.

```
forrtl: severe (174): SIGSEGV, segmentation fault occurred
```

Image	PC	Routine	Line	Source
MAR_a07.exe	000000000833D83	Unknown		Unknown Unknown
MAR_a07.exe	0000000008304C3	Unknown		Unknown Unknown
MAR_a07.exe	00000000082CD3D	Unknown		Unknown Unknown
MAR_a07.exe	0000000007BA966	Unknown		Unknown Unknown
MAR_a07.exe	0000000005D16C4	phyrad2cep_	840	PHYrad2CEP.F90
MAR_a07.exe	0000000005CC30B	phyrad_cep_	384	PHYrad_CEP.f
MAR_a07.exe	000000000546688	MAIN__	4020	MAR__.f
MAR_a07.exe	0000000004A0036C	Unknown		Unknown Unknown
MAR_a07.exe	0000000004CEAE4	Unknown		Unknown Unknown
MAR_a07.exe	000000000400239	Unknown		Unknown Unknown

Figure 2: MAR segmentation fault.

We were able to compile MAR in “debug” mode and ran MAR through the “valgrind” program to try to determine what was causing the segmentation fault. The procedure allowed us to identify the scripts and line numbers where the segmentation fault occurred, but we have not yet identified the reason for the crash. The crash appears to be occurring within the MAR radiative scheme. We will continue to try to determine the reasons for the crash. In the meantime I will try to replicate an earlier setup of MAR at the HPCC, and then replace the original MAR source code with the new MAR v 3.2 source code, as suggested by Xavier Fettweis.

3.1 Sensitivity studies with MAR and Incorporation of Crocus into ISSM

Once MAR is running, sensitivity experiments can potentially begin at the CUNY HPCC. However, the best way to understand the sensitivity of SMB to albedo maybe be to conduct sensitivity experiments with solely with MAR’s snow model, *Crocus*. If the *Crocus* model is incorporated with ISSM, sensitivity studies could be performed with the DAKOTA uncertainty quantification software built into ISSM. This would reduce the computational time to allow a sufficient number of simulations to be performed for a statistical analysis. However, limited studies could still be performed once MAR v. 3.2 is running at the CUNY HPCC. In particular a comparison of SMB and albedo between MAR v. 3.2 and v. 2.0 could help reveal the impact of the MAR ablation zone albedo parameterization on SMB. Running MAR’s entire surface model independently would be another option that would reduce computational time. However, a

drawback of running MAR's surface model or snow model independently is that the influence of feedbacks between the surface and the atmosphere are not captured.

3.2 Installation and Simulations with ISSM

After arriving at JPL I worked with the ISSM team to install ISSM on a local computer, following instructions on the ISSM website. This process was relatively straightforward and ISSM (with uncertainty quantification software) was compiled and installed easily. Following the installation of ISSM I reviewed examples of ISSM simulations, including a Greenland Ice Sheet simulation. Results from a more detailed simulation have been made available for comparison with MAR SMB and GRACE mass balance data.

Some difficulties were encountered in installing ISSM on the CCNY and CUNY clusters. These difficulties are associated with the specific system setup and therefore may or may not be encountered again on a different system. It should be noted that modules used with ISSM should be compiled with the same compiler as ISSM. At the HPCC, some compilation issues prevented us from using ISSM to run Matlab. Additionally, there are restrictions at the CUNY HPCC regarding use of Matlab. However, it is possible to run matlab locally to create an ISSM batch job, which can then be automatically or manually copied to an external cluster through a secure connection for external processing. We have carried out successful test simulations of ISSM in which batch jobs are manually copied to the HPCC servers. In summary, with a few small additional steps, we can run ISSM on the CCNY servers and at the CUNY HPCC, thanks mainly to the work of Nicole Schlegel.

3.3 Comparison between MAR, GRACE and ISSM data

In order to better understand the components of mass change over Greenland, and in order to better evaluate the MAR simulation of surface mass balance, I began a comparison between mass change data from the Gravity Recovery and Climate Experiment (GRACE), MAR

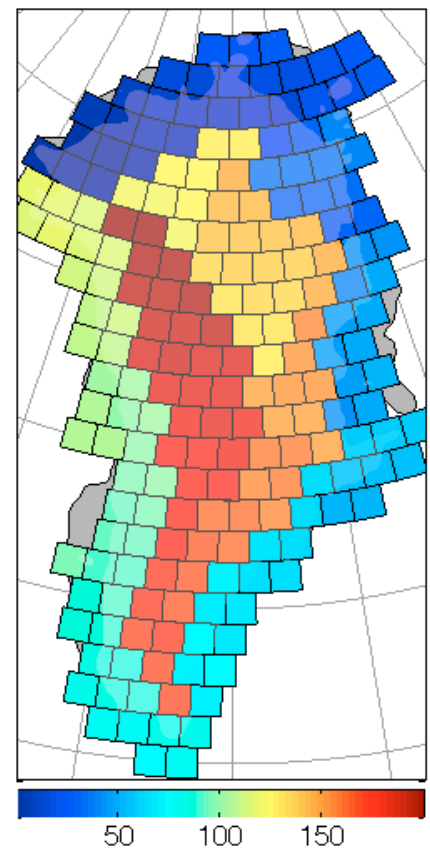


Figure 3: GRACE Greenland mascons (colors indicate the mascon's number: between 1 and 199)

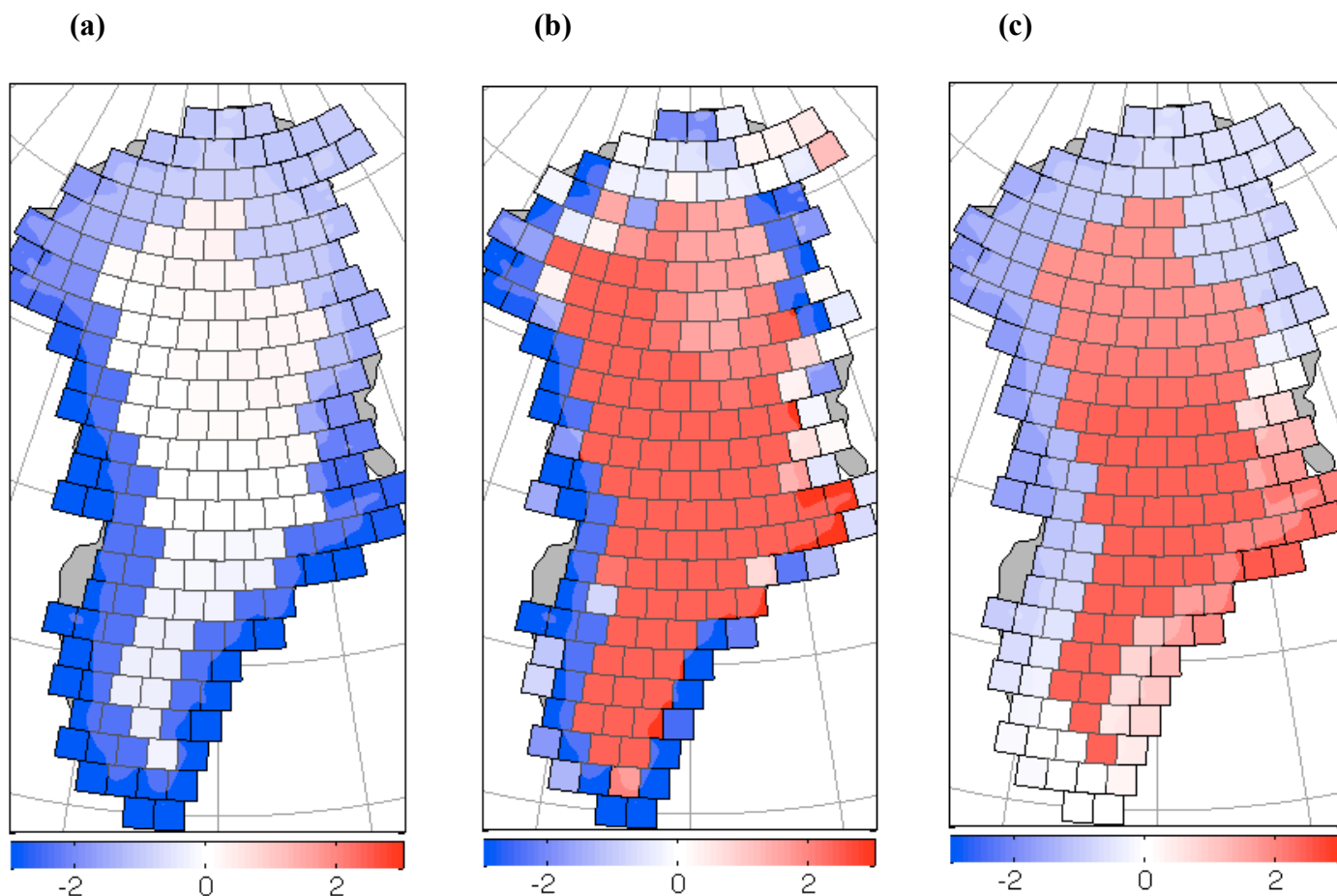


Figure 4: (a) Mean annual mass balance (Gt/yr) for GRACE (2003-2011), (b) Mean annual surface mass balance (Gt/yr) from MAR aggregated to the GRACE grid (2003-2011), (c) Mean annual surface mass balance data from MAR (Gt/yr) spatially filtered by Scott Luthcke to match GRACE filtering.

SMB data and mass change data from ISSM. Initial work with GRACE consisted in creating a means of spatially plotting the irregular GRACE grid, for which matlab scripts were created. The GRACE mascons from Scott Luthcke (a ~100 km grid) for Greenland are plotted in **Figure 3**.

Before conducting comparisons between MAR, GRACE, and ISSM, it was necessary to first investigate spatial filtering of MAR data to match GRACE data. GRACE data for each grid box include information from surrounding grid boxes. Scott Luthcke has already provided spatially filtered MAR data that is filtered in a manner similar to the GRACE data. However, the procedure is time and computationally intensive. In order to replicate the same filtering procedure on other datasets (such as MAR data before 2003 and ISSM data), Scott suggested

constructing a Gaussian spatial filter to approximate the GRACE filtering. This has been the focus of my work with GRACE up to this point.

Mean annual MAR Surface Mass Balance (SMB) data are plotted along with GRACE mass balance data and filtered MAR data in **Figure 4**. It is clear that spatial filtering of MAR data has a substantial influence on spatial pattern of mean annual SMB especially in areas closer to the coast. This can also be seen from timeseries of MB and SMB within individual basins (**Figure 5**). In some areas, the filtering procedure shifts the MAR timeseries' to be closer to those of GRACE (**Figures 5a,b**), but sometimes, especially in high accumulation areas, does not produce a major change (**Figure 5c**).

I am attempting to reproduce the original filtering process using a simple Gaussian filter. The Gaussian can be expressed as a function of distance from the center of the distribution ($x-\mu$) and a standard deviation (σ) as:

$$g(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2} \quad (1)$$

The Gaussian function can be used to weight the data for surrounding grid boxes as a function of distance from a central grid box. In this case, $x-\mu$ is replaced by the distance from a central location (r), and a discrete approximation to the Gaussian is used, based on matlab's 2-D filtering function "fspecial". I could not directly use *fspecial* because GRACE data are not arranged on a regular grid. The following set of functions is therefore used to filter MAR data:

$$g_i(r_j) = e^{-\frac{1}{2}\left(\frac{r_j}{\sigma}\right)^2}$$

$$w(r_j) = \frac{g(r_j)}{\sum_{j=1}^n g(r_j)} \quad (2)$$

The weight, w , assigned to a given grid box, j , at a distance r_j from the central grid box, i , is given by the value of the Gaussian function at that grid box divided by the sum of all Gaussian values surrounding the central grid box i . The weights for grid boxes j surrounding a central grid box i are then used to create a weighted average of surrounding grid box values at each time step, to create filtered values for each central grid box.

The value of σ can be varied to achieve the least root mean squared error (RMSE) between the Gaussian-filtered MAR SMB cumulative values and the original filtered SMB

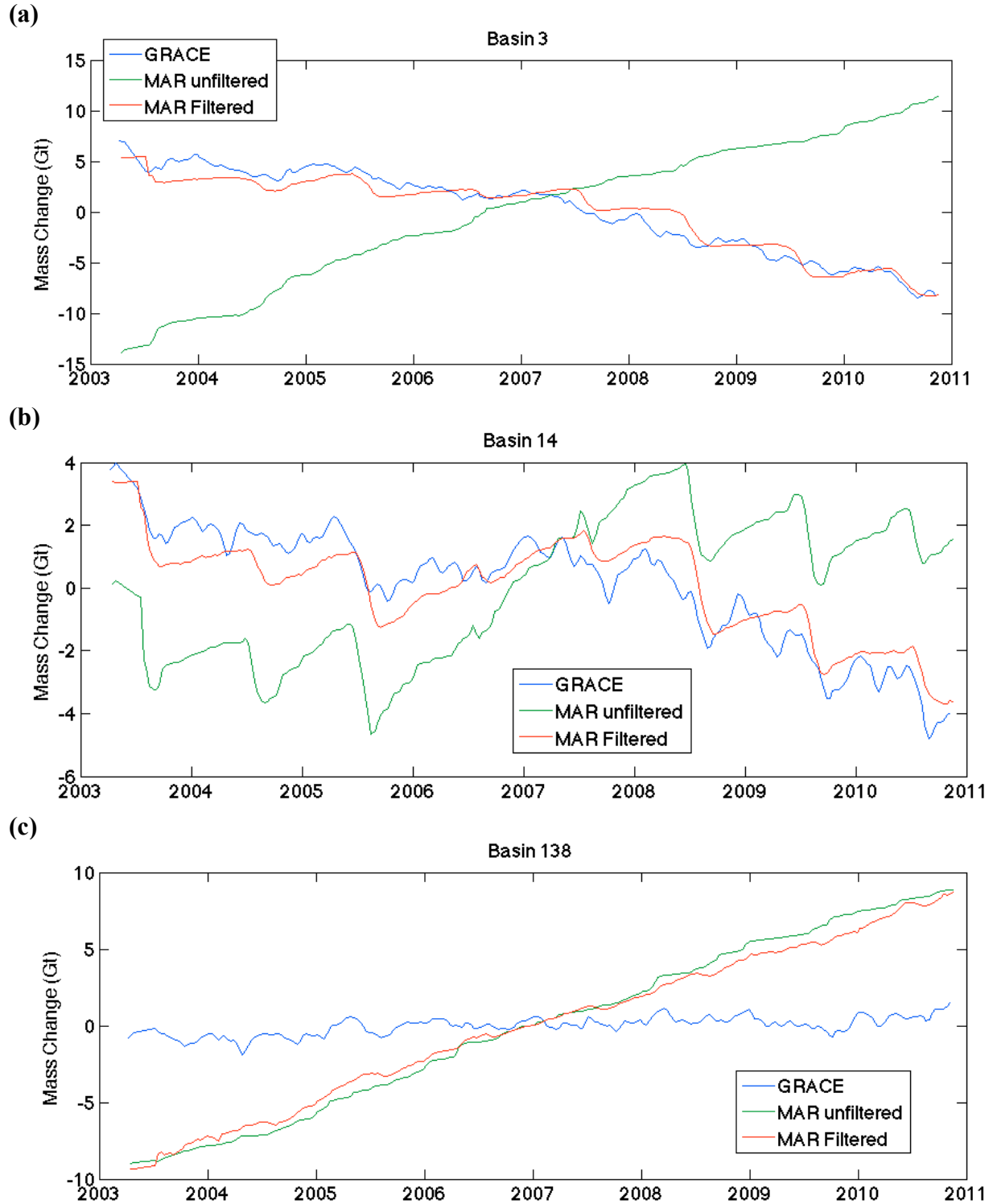


Figure 5: Cumulative mass changes from selected Greenland Ice Sheet basins, showing GRACE mass balance data (blue), as well as filtered (red) and un-filtered (green) MAR data.

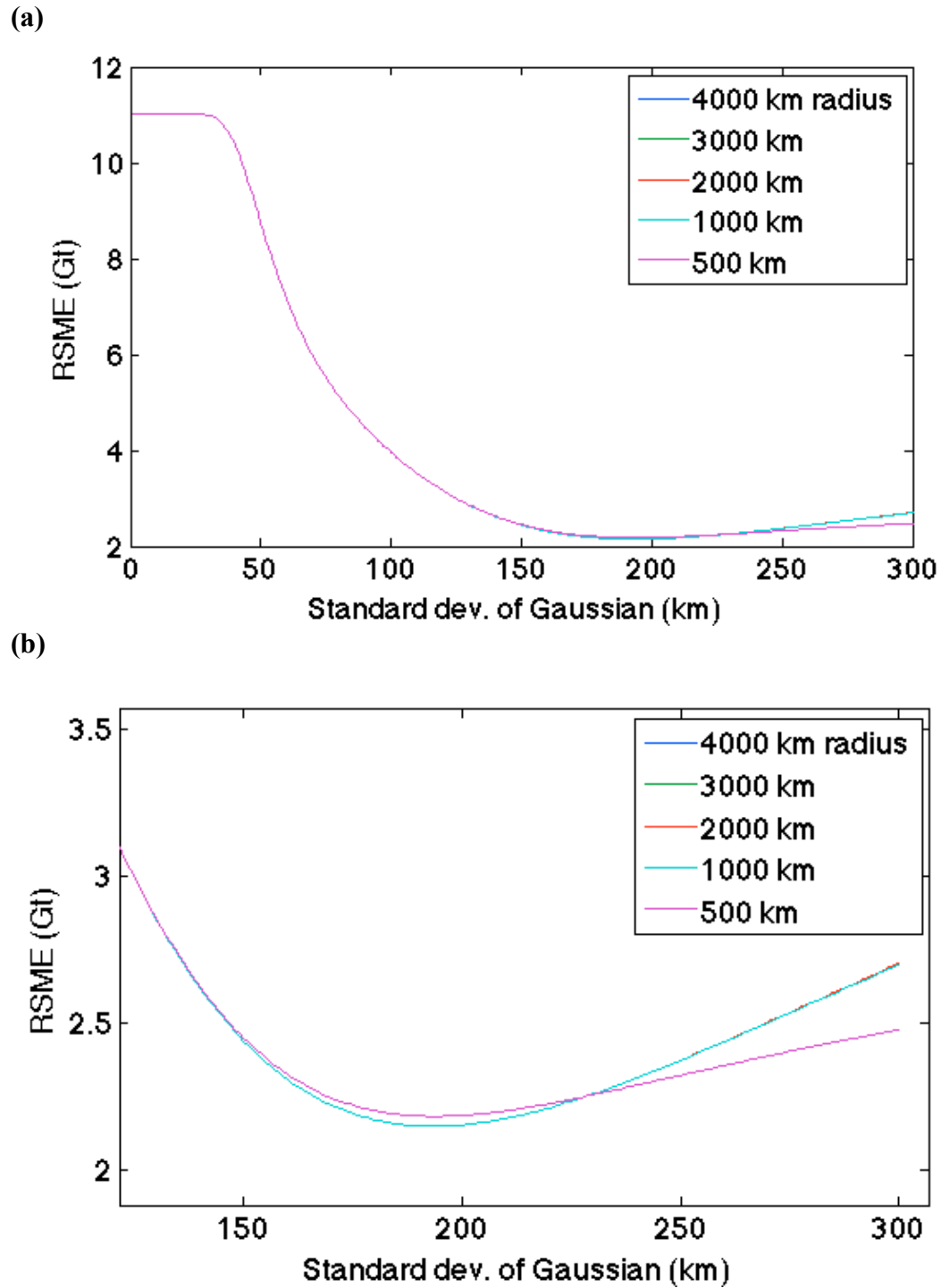


Figure 6: (a) RMSE in Gigatons for Gaussian-filtered MAR data relative to GRACE-filtered data, and (b) a subset of 6a. Colors indicate the maximum radius used for Gaussian filtering.

values. Initially, the value of σ was kept constant across all grid boxes and varied between 1 and 300 km. The standard deviation that produced the lowest RMSE for the Gaussian filtered data relative to the GRACE-filtered data was taken to be the optimal σ sigma value. A maximum radius ranging between 500 and 3000 km was also applied to the data used for each grid box. As can be seen in **Figure 6**, the RMSE for the new filtered data decreases beyond a σ of ~50 km. The optimal σ is 193.24 km for radii > 1000 km, giving an RMSE of 2.14 Gt. For a radius of 500 km, the minimum RMSE is larger, suggesting that beyond a radius of ~1000km, the radius has no major effect in this case.

A comparison between timeseries' of Gaussian-filtered and original filtered SMB reveals that the optimal Gaussian filtering does not fully capture the results of the original filtering (**Figure 7**). A map of the difference in mean annual SMB (**Figure 8**) reveals that using the Gaussian filtering method tends to lead to discrepancies along the boundary between the ablation and accumulation zones, where annual filtered SMB is generally underestimated by the Gaussian-filtered data. Figure 8 suggests that Gaussian filtering is "too smooth" and doesn't capture a sharp gradient between mass loss and mass gain from low to high elevation that can be seen in the original filtered data.

As an alternative method I decided to optimize σ for each grid box rather than for all grid boxes. The same method of least squares was used, but the optimal σ was determined for each grid box. A maximum radius of 10,000 km was used for all grid boxes and σ was varied between 1 and 4,000 km. In cases where the optimal σ was 4000 km, sigma values up to 20,000 km were tested as possible values.

In general this new technique resulted in a better agreement with the original filtered timeseries (**Figure 9**). Some areas in the northern part of Greenland still show relatively large errors. **Figure 10** shows results for individual grid boxes obtained with the new filtering technique. In some cases there is little change in Gaussian-filtered data (**Figure 10a vs. Figure 7a**) and in other cases the new Gaussian-filtered data exhibit little variability, perhaps because the averaging area was very wide (**Figure 7b**). While this may result in a lower RMSE, the Gaussian-filtered data are still not capturing all the fluctuations seen in the GRACE-filtered timeseries. In most cases (e.g. **Figure 10c vs. Figure 7c**), there is now a better agreement between the Gaussian- and GRACE-filtered timeseries.

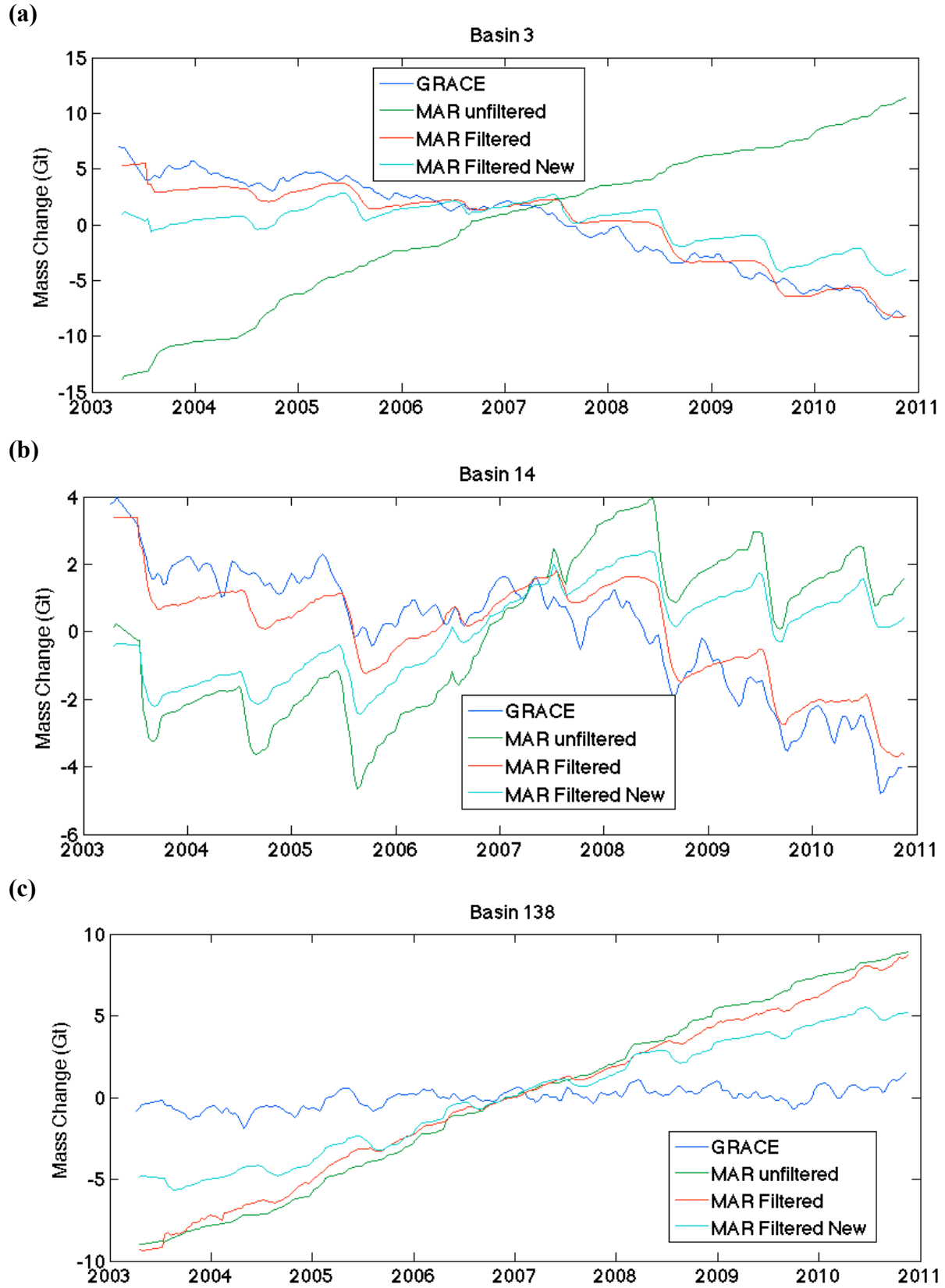


Figure 7: Same as Figure 5 with Gaussian filtered timeseries' included.

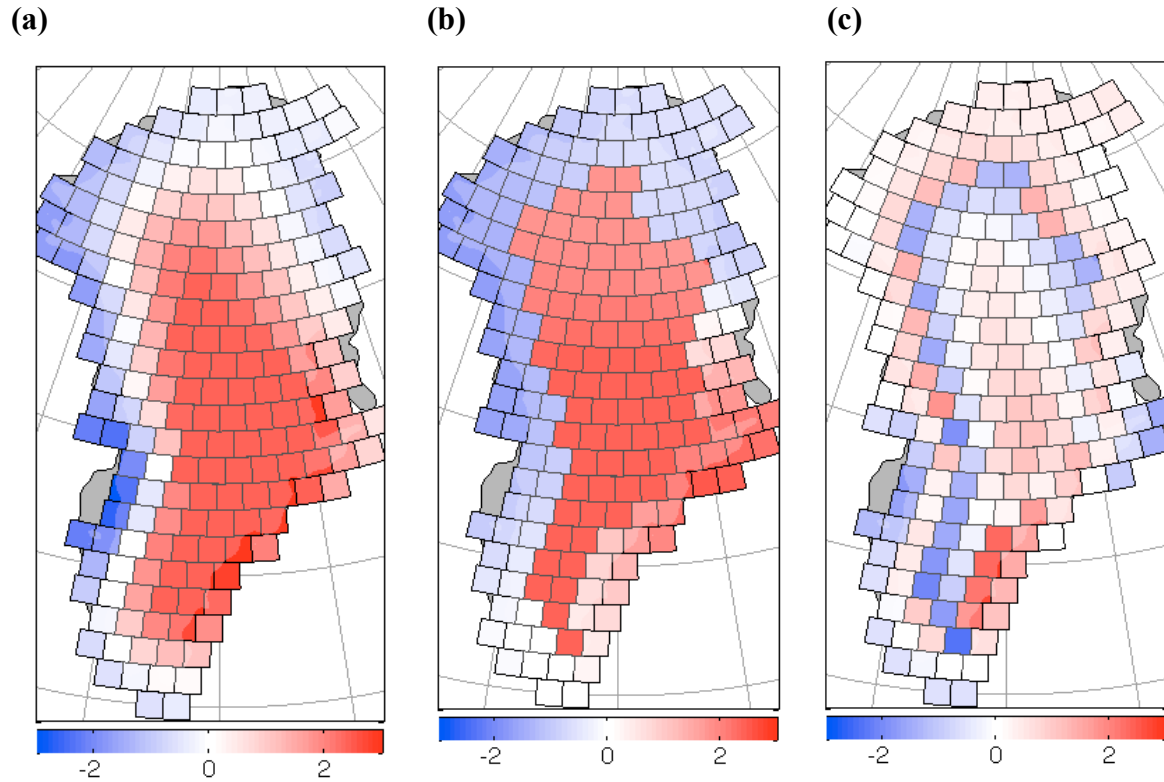


Figure 8: a) Mean annual SMB (Gt/yr) for Gaussian-filtered MAR data and b) GRACE-filtered MAR data. c) Difference in mean annual SMB (Gt/yr): (a) minus (b).

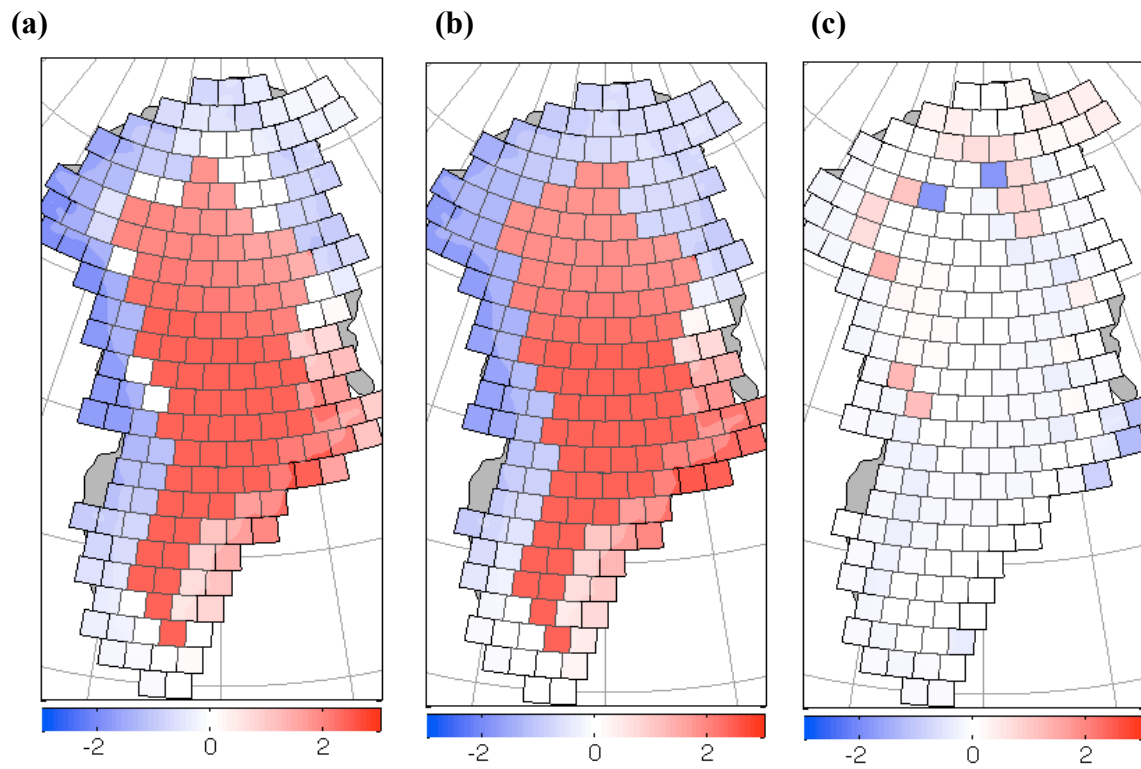


Figure 9: Same as Figure 8, but a Gaussian filter with a variable standard deviation is used.

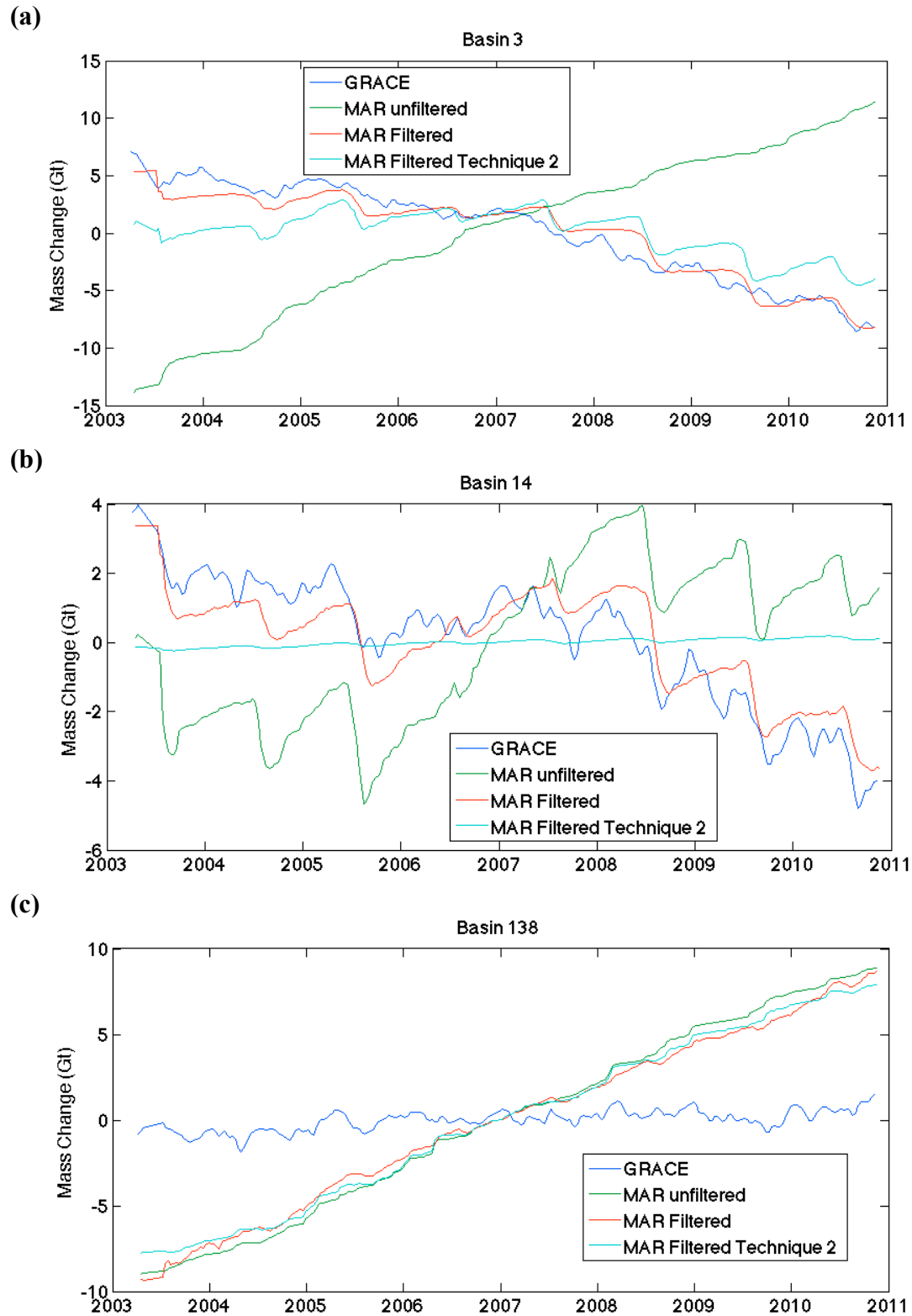


Figure 10: Same as Figure 7 but data are shown for Gaussian-filtered data for which a variable radius Gaussian filter was used.

4. Planned Future Work

The first step for future work will be to troubleshoot MAR crashes on the CCNY and JPL servers so that MAR v.3.2 can be used for future analysis. Once this is completed, sensitivity studies with MAR can be initialized at these two locations. Sensitivity studies may include changing the MAR albedo scheme to determine the effects of albedo on simulated SMB. It may also involve running the MAR surface model offline forced by MAR. If possible, we may also conduct sensitivity studies using an offline version of MAR's surface model, *Crocus*; eventually this uncertainty analysis could include ISSM as well.

Future work with GRACE data should involve investigating why some of the filtered timeseries don't show large fluctuations. Possibly an asymmetric Gaussian function or a different weighting scheme (e.g. using principle component analysis?) would produce more accurate results. Following this work, we will incorporate ISSM mass change estimates to compare GRACE with estimates from MAR+ISSM. This comparison may reveal errors within MAR, ISSM, GRACE, or mass change processes not captured by either model, although it may be difficult to distinguish the causes for the discrepancies identified.