

This discussion paper is/has been under review for the journal The Cryosphere (TC).  
Please refer to the corresponding final paper in TC if available.

# Improving a priori regional climate model estimates of Greenland ice sheet surface mass loss through assimilation of measured ice surface temperatures

M. Navari<sup>1</sup>, S. A. Margulis<sup>1</sup>, S. M. Bateni<sup>2</sup>, M. Tedesco<sup>3</sup>, P. Alexander<sup>3,4</sup>, and X. Fettweis<sup>5</sup>

<sup>1</sup>Department of Civil and Environmental Engineering, University of California Los Angeles, Los Angeles, California, USA

<sup>2</sup>Department of Civil and Environmental Engineering and Water Resources Research Centre, University of Hawaii at Manoa, Hawaii, USA

<sup>3</sup>Department of Earth and Atmospheric Sciences, City College of New York, New York, New York, USA

<sup>4</sup>Graduate Center of the City University of New York, New York, New York, USA

<sup>5</sup>Department of Geography, University of Liège, Liège, Belgium

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Received: 20 April 2015 – Accepted: 18 May 2015 – Published: 19 June 2015

Correspondence to: M. Navari (navari@ucla.edu)

Published by Copernicus Publications on behalf of the European Geosciences Union.

**TCD**

9, 3205–3255, 2015

**Data  
assimilation-based  
estimation of  
Greenland surface  
mass loss**

M. Navari et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## Abstract

The Greenland ice sheet (GrIS) has been the focus of climate studies due to its considerable impact on sea level rise. Accurate estimates of surface mass fluxes would contribute to understanding the cause of its recent unprecedented changes and would help to better estimate the past, current and future contribution of the GrIS to sea level rise. Though the estimates of the GrIS surface mass balance have improved significantly over the last decade, there is considerable disparity between the results from different methodologies that need to be addressed. In this study, an Ensemble Batch Smoother data assimilation approach was developed to assess the feasibility of generating a reanalysis estimate of the GrIS surface mass fluxes via integrating remotely sensed ice surface temperature measurements with a regional climate model (a priori) estimate. The performance of the proposed methodology for generating an improved posterior estimate was investigated within an observing system simulation experiment (OSSE) framework using synthetically generated ice surface temperature measurements. The results showed that assimilation of ice surface temperature time series were able to overcome uncertainties in near-surface meteorological forcing variables that drive the GrIS surface processes. Our findings show that the proposed methodology is able to generate posterior reanalysis estimates of the surface mass fluxes that are in good agreement with the synthetic true estimates. The results also showed that the proposed data assimilation framework improves the root-mean-square-error (RMSE) of the posterior estimates of runoff, sublimation/evaporation, surface condensation and surface mass loss fluxes by 61, 64, 76, and 62% respectively over the nominal a priori climate model estimates.

## 1 Introduction and background

Due to a warmer climate, the Greenland ice sheet (GrIS) has recently experienced unprecedented changes including: (1) significant thinning of the marginal ice (e.g.

TCD

9, 3205–3255, 2015

### Data assimilation-based estimation of Greenland surface mass loss

M. Navari et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## Data assimilation-based estimation of Greenland surface mass loss

M. Navari et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Thomas et al., 2006; Pritchard et al., 2009; Straneo et al., 2013; Khan et al., 2014), (2) thickening of the ice in the GrIS interior (Fettweis, 2007), (3) acceleration and increase in ice discharge from many of Greenland’s outlet glaciers (e.g. Rignot et al., 2008, 2010; Rignot and Kanagaratnam, 2006; Wouters et al., 2013; Enderlin et al., 2014), and (4) enhanced surface melt (e.g. Tedesco, 2007; Tedesco et al., 2008, 2011, 2013; Fettweis et al., 2007, 2011, 2013; Nghiem et al., 2012; Hall et al., 2013; Vernon et al., 2013). The melting of the GrIS due to increased temperature associated with climate change has the potential to affect deep ocean circulation, and sea level rise (Mote, 2000; Hanna et al., 2002, 2005; Abdalati and Steffen, 2001; Velicogna and Wahr, 2005; Chen et al., 2006; Fettweis et al., 2005, 2007, 2013; Tedesco, 2007, 2008; Rignot et al., 2008; Franco et al., 2013; Hu et al., 2011). While recent estimates (e.g. van den Broeke et al., 2009; Rignot et al., 2011) suggest that melt water runoff and ice discharge from outlet glaciers contribute roughly equally to the GrIS net mass loss, other studies (e.g. van Angelen et al., 2012 and Fettweis et al., 2013) suggest that melt-water runoff will be the dominant mass loss process in the future due to the retreat of the tidewater glaciers above sea level.

Many studies (e.g. Steffen et al., 1996; Thomas, 2001; Andersen et al., 2004, van de Wal et al., 2012) have taken advantage of in situ measurements to provide a direct point-scale estimate of the surface mass balance (SMB, i.e. the difference between accumulation and ablation terms). However, with these limited in situ measurements alone, large-scale mapping of the GrIS surface mass fluxes (i.e. precipitation, evaporation, sublimation, condensation, and runoff) is difficult, if not impossible. The availability of remote sensing data and/or products has taken GrIS from a remote “data poor” region that is reliant mostly on sparse in situ measurements to a potentially “data rich” environment. In this regard, a key research objective is to better understand how such data can be optimally leveraged for quantitatively estimating the surface mass balance (SMB) and its associated fluxes.

Surface remote sensing data and products (i.e., surface or skin temperature, multi-frequency brightness temperature, and albedo) have been used to characterize various

## Data assimilation-based estimation of Greenland surface mass loss

M. Navari et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

aspects of SMB such as snow melt, melt extent, melt duration, new snow, extreme melt events (e.g. Abdalati and Steffen, 1995, 1997; Mote et al., 1993; Chylek et al., 2007; Tedesco et al., 2007, 2008, 2011; Shuman et al., 1995; Bindschadler et al., 2005; Box et al., 2012; van Angelen et al., 2012; Hall et al., 2006, 2009, 2013). However, the relationship between surface remote sensing data/products and surface mass fluxes are most often indirect and implicit. This makes the possibility of quantitatively characterizing the surface mass fluxes from remote sensing retrieval algorithms difficult if not impossible. For example, ice surface temperature can be indicative of melt, but it fails to quantitatively estimate the amount of melt. More importantly, other surface mass fluxes such as evaporation, condensation, sublimation, and runoff cannot be directly quantified via remote sensing. It can therefore be argued that the information content of remotely sensed data remains underutilized due to indirect and implicit links between the various data streams and surface mass fluxes.

Given the limitations of the observation-based methods, numerical models offer an alternative mechanism to quantify the GrIS surface mass fluxes. Several model-based approaches have been used to characterize the spatio-temporal variability of the GrIS surface mass fluxes in both historical and future contexts (e.g. Hanna et al., 2008, 2011, 2013; Box et al., 2006; Fettweis, 2007, 2011, 2013; Ettema et al., 2009; Lewis and Smith, 2009; Burgess et al., 2010; Vernon et al., 2013; Franco et al., 2012). Although the aforementioned methodologies have provided the ability to estimate the GrIS SMB and related fluxes, their estimates vary considerably, mainly due to simplified assumptions in the models, the inherent uncertainty of each method, error in model and input data, and the length of data records (e.g. Hanna et al., 2005; Ettema et al., 2010; Rignot et al., 2011; Vernon et al., 2013; Smith et al., 2015). Therefore, it is imperative to design techniques that bridge the gap between different methods by merging relevant data streams with a physical model with the aim of better spatial–temporal characterization of the GrIS surface mass fluxes. In this study, we provide an example of taking advantage of information in the relevant data streams to provide a better spatial–temporal characterization of the model outputs (i.e., the GrIS surface

mass fluxes). This can be done by constraining the probability density function of the model solution using the available observations in the context of Bayes theorem, which is also known as data assimilation (Evensen, 2009).

## 2 Motivation and science questions

To date, to the best of the authors' knowledge, there have been no attempts at merging surface remote sensing data with models using a data assimilation (DA) framework to fully resolve and quantify estimates of the GrIS surface mass fluxes. Data assimilation techniques have been heavily used in hydrology to estimate soil moisture (e.g. Reichle et al., 2002; Margulis et al., 2002; Huang et al., 2008a; Al-Yaari et al., 2014), predict snow water equivalent (SWE) (e.g. Durand et al., 2006, 2008; De Lannoy et al., 2012; Giroto et al., 2014a; Zhang et al., 2014), estimate runoff (e. g. Crow and Ryn, 2009; Pauwels et al., 2001; Franz et al., 2014), improve estimates of radiative fluxes (e.g. Forman and Margulis, 2010; Xu et al., 2011), and characterize snowpack properties and freeze–thaw state of the underlying soil (Bateni et al., 2013, 2015). DA so far has been underutilized in applications aimed at characterizing GrIS dynamics. Recently, Heimbach (2009), Goldberg and Heimbach (2013), and Morlighem et al. (2013) used variational DA methods to characterize the interior and basal properties of ice sheets and ice shelves. Larour et al. (2014) assimilated surface altimetry data into the reconstructions of transient ice flow dynamics to infer basal friction and surface mass balance of the northeast Greenland ice stream. However, the use of DA for estimating GrIS SMB terms remains relatively unexplored. Assessing the feasibility of such approaches in providing a mechanism for improving quantitative estimates of SMB is the key motivation of this work.

This study utilizes an observing system simulation experiment (OSSE) framework to assess the feasibility of the proposed DA system. The OSSE framework uses synthetically generated ice surface temperature (IST) measurements consistent with a “true” realization of SMB evolution. This study addresses the following

### Data assimilation-based estimation of Greenland surface mass loss

M. Navari et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



science questions: (1) Can assimilation of IST measurements overcome errors and uncertainties in the near-surface meteorological forcing variables for snow/ice modelling? (2) Can a DA framework be used to reduce the uncertainty and/or correct biases in a priori estimates of surface mass fluxes from a regional climate model?

This paper is arranged as follows: Sect. 3 contains the description of the models and methods used in this work. The experimental design is given in Sect. 4. The results and evaluation of the proposed methodology are discussed in Sect. 5. Finally, key conclusions and future research directions are reported in Sect. 6.

### 3 Models and methods

#### 3.1 Study domain

The study domain covers the entire GrIS, which is discretized with a grid size of 25 by 25 km to match the domain used in the regional atmospheric model described below. The focus is on fully snow/ice covered pixels. Figure 1 shows the different GrIS mass balance zones based on a forward simulation for the year 2010. The ablation zone is defined as the region of the GrIS where the annual surface mass balance is negative. The dry snow zone is defined as the region where the mean annual temperature is less than  $-25^{\circ}\text{C}$  (Cuffey and Paterson, 2010) and melt generally does not occur. The area between the ablation zone and the dry snow zone is considered the percolation zone where surface melt-water percolates downward into the snow layers. It should be noted that the digital elevation model (DEM) over the ice sheet originates from a high-resolution map generated by Bamber et al. (2001). The elevation of the ice sheet increases from almost zero in the coastal regions up to about 3400 m at the summit.

## 3.2 Data

Surface temperature plays an important role in the coupled GrIS surface energy and surface mass budget. It is the key factor that regulates partitioning of net radiation into the subsurface snow/ice, sensible and latent heat fluxes. Surface temperature also influences the generation of runoff, the temperature profile evolution, and even basal melt (Hall et al., 2013). Space-borne instruments can provide estimates of IST. The retrieved IST is directly related to snow surface emissivity (Hook et al., 2007). The emissivity of the snow surface is a function of grain size and liquid water content, which both are under the influence of surface processes (Hall et al., 2009). These facts support the idea that clear-sky IST may contain the most information about physical processes that drive the GrIS accumulation and mass loss. Therefore, this work focuses on testing the feasibility of using products such as Moderate Resolution Imaging Spectroradiometer (MODIS) IST as an extra source of information to enhance the utility of modelling techniques. The possibility of using additional remotely-sensed data streams (e.g. passive microwave brightness temperature and albedo) will be investigated in future studies.

The Greenland Ice Surface Temperature product (GrIS IST) is available from the MODIS Terra satellite (<http://modis-snow-ice.gsfc.nasa.gov/?c=greenland>) and provides up to one (clear-sky) measurement per day at a native resolution of 1.5 km and an accuracy of  $\sim 1\text{--}1.5\text{K}$  (Hall et al., 2012). However, cloud contamination and occasional instrument outages play an important role in the availability of the MODIS IST measurements. These two factors along with some other technical and quality considerations can reduce the availability of the IST measurements to less than 10 high quality clear-sky measurements in some months (Hall et al., 2012). In the context of the OSSE used in this work, synthetic IST was generated based on the temporal resolution and acquisition time of the actual GrIS IST product by perturbing the modelled surface temperature with assumed measurement error described below.

### 3.3 Regional climate model

The a priori (or prior) estimate used in the DA framework in this study is based on output from the regional climate model Modèle Atmosphérique Régional (MAR; Gallée and Schayes, 1994 and Gallée and Duynkerke, 1997). The version of the model used here (i.e. MARv2) has been applied extensively over the GrIS and is described in more detail in previous studies (Lefebvre et al., 2003, 2005; Fettweis et al., 2005, 2006, 2007, 2011; Franco et al., 2012, 2013; Vernon et al., 2013). This version has also been used to generate future projections for the ICE2SEA European project (Fettweis et al., 2013). For this study, MAR was used to generate hourly near-surface meteorological outputs (i.e., temperature, pressure, wind speed and direction, longwave and shortwave radiation, precipitation, pressure, humidity, etc.) at a horizontal spatial resolution of 25 km to force an offline snow/ice model. The ERA-Interim reanalysis from the European Centre for Medium-Range Weather Forecasts (ECMWF) was used to initialize the MAR meteorological fields at the beginning of the simulation (1979) and to force the atmospheric lateral boundaries as well as the oceanic conditions (surface temperature and sea ice extent) every 6 h over 1979–2010. MAR was not reinitialized every day by the ECMWF reanalysis and its results were not recalibrated after the simulation to better compare with observations as in other approaches (e.g. Box et al., 2004, 2006). The reader is referred to Fettweis et al. (2005), Lefebvre et al. (2005) and Fettweis et al. (2011) for detailed information on the MAR setup used here.

### 3.4 Surface mass/energy balance and snow physical model

The key equations related to SMB are the water and energy balance of the near-surface ice sheet. The bulk surface mass balance for each model pixel (i.e., integrated over the surface layers) can be written as:

$$\text{SMB} = P - E + C - R \quad (1)$$

where  $P$  is the surface precipitation,  $E$  is the surface evaporation/sublimation,  $C$  includes both liquid and solid condensation, and  $R$  is the melt runoff from the snowpack. Evaporation, sublimation, condensation and runoff are the key variables that drive the surface mass loss (SML), while precipitation is the key meteorological driver for GrIS surface accumulation.

Surface and sub-surface melting (which ultimately contribute to runoff) are dictated by the evolving snow temperature driven by energy inputs. The temporal evolution of snow temperature in a vertical snow column is constrained by the conservation of energy equation, i.e. (Brun et al., 1989):

$$\frac{\partial(\rho c_p T)}{\partial t} = \frac{\partial^2(\kappa T)}{\partial z^2} \quad (2)$$

where  $\rho$  is the snow density,  $c_p$  is the snow heat capacity,  $T$  is the snow temperature at depth  $z$  and time  $t$ , and  $\kappa$  is the snow heat conductivity. It is worth noting that Eq. (2) is valid for  $T < 273.15$  K; any energy inputs that would raise the temperature beyond freezing instead contribute directly to melt. Equation (2) is subject to the surface energy balance as a boundary condition, which is the key driver of the snowpack energy budget:

$$R_s^\downarrow(1 - \alpha) + R_l^\downarrow - R_l^\uparrow = R_n = Q_{SH} + Q_{LH} + Q_G \quad (3)$$

where  $R_s^\downarrow$  is the downward shortwave radiation,  $\alpha$  is the (broadband) snow albedo,  $R_l^\downarrow$  and  $R_l^\uparrow$  are the downward and upward longwave radiation.  $R_n$  is the net radiation that is partitioned among the surface sensible ( $Q_{SH}$ ), latent ( $Q_{LH}$ ), and surface ( $Q_G$ ) heat fluxes.  $Q_G$  is the energy conducted into the snow surface and hence highly affects the ice/snow melt and runoff. Based on Eq. (3),  $R_s^\downarrow$ ,  $R_l^\downarrow$ ,  $\alpha$ , and air temperature, specific humidity, and wind speed (embedded in  $Q_{SH}$  and  $Q_{LH}$ ) are the key meteorological variables controlling the downward energy into the snowpack ( $Q_G$ ), which ultimately contributes to runoff ( $R$ ).

Data  
assimilation-based  
estimation of  
Greenland surface  
mass loss

M. Navari et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## Data assimilation-based estimation of Greenland surface mass loss

M. Navari et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



The above coupled surface mass/energy balance represented by the CROCUS snow physical model was used in this study to provide a prior estimate of the GrIS surface mass fluxes that is consistent with the nominal forcings provided by MAR. The physics of CROCUS and its validation are detailed in Brun et al. (1989, 1992). The use of a fully coupled MAR-CROCUS system to generate an a priori ensemble estimate would be computationally prohibitive. To reduce the computational burden, an offline version of CROCUS was implemented (i.e., MAR was run over the whole modelling period, and then MAR outputs were used to force CROCUS over the same period). One can think of the DA framework outlined below as providing an update to an initial (prior) estimate of the surface mass fluxes from MAR (or any other regional climate model) using IST data as an additional constraint.

Of particular relevance to this study is the connection between CROCUS states and the measured variables used in the DA (i.e. IST). Surface temperature (synthetic IST) is an output of the forward model (CROCUS), therefore, it can directly be used as a prediction of the measurement in the DA system. One key aspect is that the raw measurements are available at higher spatial resolution than the model state (i.e. 1.5 vs. 25 km). This was handled via an assumed change in the measurement error due to aggregation as described in more detail below.

### 3.5 Model adaptation

The CROCUS snow/ice model was originally developed for operational avalanche forecasting. Therefore, the model must be modified for SMB ice sheet applications. Following Fettweis (2006), the bottom boundary condition was modified for simulating only the first 10 m of snow/ice of the ice sheets. This method consists of the following rules: first, if during the model integration the sum of the snow and ice layer heights becomes less than 8 m, the bottom layer is extended for two meters. Second, in the case that the sum of the snow and ice layer heights becomes larger than 15 m, the bottom layer is divided by two. This is consistent with the methodology used in nominal MAR simulations.

### 3.6 Ensemble Batch Smoother (EnBS) framework

The EnBS is a technique that conditions a prior estimate of model states on measurements taken over an assimilation window to generate a posterior reanalysis estimate rather than a real-time (or sequential) estimate (Giroto et al., 2014a; Bateni et al., 2013, 2015). In the context of this paper, the assimilation window is a full annual cycle and measurements consist of IST data over this period. Using the generated forcing fields from MAR, the CROCUS model was run forward in time to provide an ensemble of a priori estimates of snow/ice state variables (e.g. surface temperature, snow/ice layer temperature, density, grain size, etc.) and different surface mass fluxes (e.g. evaporation, sublimation, runoff, etc.). The propagation of the CROCUS model forward in time can be shown in state-space form as:

$$\mathbf{y}_j(t) = f(\mathbf{y}_j(\tau), \mathbf{u}_j(t), \boldsymbol{\beta}_j) \quad (4)$$

where  $\mathbf{y}_j(t)$  is the vector of states for the  $j$ th realization at time  $t$ ,  $f(\cdot)$  represents the CROCUS model operator,  $\mathbf{y}_j(\tau)$  is the vector of states at previous times ( $\tau$ ),  $\mathbf{u}_j(t)$  is the forcing fields for realization  $j$ , and  $\boldsymbol{\beta}_j$  is the model parameter vector for replicate  $j$ . Conventionally, the generated snow/ice states and surface mass fluxes by the forward propagation of CROCUS are called the open-loop (prior) estimates.

The main source of uncertainty in a priori snow/ice states and surface mass fluxes is hypothesized to be most likely due to errors in the meteorological forcings ( $\mathbf{u}_j(t)$ , see Eq. 4) generated by a parent model (in this case MAR): incoming shortwave and longwave radiation, air temperature ( $T_a$ , which is implicit in the latent and sensible heat fluxes), precipitation, wind speed, relative humidity, and cloudiness. Herein, our focus is on the sub-set of key forcings that are the postulated main drivers of SMB (i.e.,  $P$ ,  $R_i$ ,  $R_s$ , and  $T_a$ ). It is hypothesized that the a priori uncertainty in forcings can be modeled



## Data assimilation-based estimation of Greenland surface mass loss

M. Navari et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

information about surface mass fluxes. Hence, here we took a different approach. Rather than estimating the states directly, we treated the multiplicative coefficients  $\gamma_{i,j}$  in Eq. (5) as the “states” to be estimated. This strategy, which was also used specifically for precipitation in Durand et al. (2008) and Giroto et al. (2014a), is in direct recognition of the fact that the primary source of uncertainty in surface mass fluxes is due to error in the near-surface meteorological forcing inputs. The added benefit of this approach is that the size of the state vector is significantly reduced even in the case of time variant multiplicative states. Such a strategy derives a posterior estimate of the forcing variables directly (via the updated  $\gamma_{i,j}$ ), and consequently allows for improved estimates of the surface mass fluxes via a posterior integration of CROCUS (with the posterior forcing inputs). The DA system theoretically allows the multiplicative states to vary on any arbitrary time scale. However, for simplicity, we implemented time-invariant perturbations (i.e., assumed  $\gamma_{i,j}$  were unchanged over the annual modelling period) herein. In this way the update to the states was designed to allow for biases and/or low-frequency errors in individual realizations in the prior multiplicative states.

It would be ideal to characterize the uncertainties for all inputs from the information content in the assimilated data stream(s). However, in many cases available measurements are not relevant to some sources of uncertainty in the models. For instance, in this study, IST is less likely to have information about precipitation because there is no expected meaningful correlation between precipitation and IST. With regard to the fact that precipitation cannot be updated using the IST data, and the fact that uncertainty of precipitation estimates from different modelling frameworks are less than that of the other terms (Fettweis, 2007), the focus of this work has involved constraining the GrIS surface mass loss (SML) components (i.e., sublimation/evaporation, condensation, and runoff), while still including the expected uncertainty in the accumulation term (precipitation). In other words, all forcing inputs were perturbed to take into account their respective postulated uncertainties, but only longwave, shortwave and surface air temperature coefficients were updated as part of the assimilation system.

## Data assimilation-based estimation of Greenland surface mass loss

M. Navari et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



In the update step, the EnBS merges IST measurements with prior multiplicative states in order to generate a posterior estimate of those multiplicative states. In this study, we used an EnBS, which was implemented in a batch mode over a pre-defined window (i.e., applied over one year) with a single update. This feature of the EnBS (i.e., the batch mode update) allows running MAR and CROCUS in an offline mode that could be applied to the historical record. The open-loop (prior) estimate of the variables of interest (i.e.,  $\boldsymbol{\gamma}_S$ ,  $\boldsymbol{\gamma}_j$ , and  $\boldsymbol{\gamma}_T$ ) were collected into the state matrix  $\boldsymbol{\Gamma}^-$ . Similarly, the vector of synthetically generated IST measurements was assembled into a vector:

$$\mathbf{T}_{\text{measurement}} = \mathbf{T}_{\text{true}} + \mathbf{v} \quad (6)$$

where  $\mathbf{v}$  is the assumed additive white Gaussian error and  $\mathbf{T}_{\text{true}}$  is the synthetic truth (see Sect. 4.1). Finally, each ensemble member was updated individually via a Kalman-type update equation (Durand and Margulis, 2008; Bateni et al., 2013, 2015),

$$\boldsymbol{\Gamma}_j^+ = \boldsymbol{\Gamma}_j^- + \mathbf{K} [\mathbf{T}_{\text{measurement}} + \mathbf{V}_j - \mathbf{T}_{\text{predicted},j}] \quad (7)$$

where  $\boldsymbol{\Gamma}_j^-$  and  $\boldsymbol{\Gamma}_j^+$  represent the  $j$ th ensemble member before and after the update, respectively,  $\mathbf{T}_{\text{predicted}}$  is the matrix of predicted measurements consisting of predicted IST.  $\mathbf{V}$  is the measurement error that was synthetically produced and added to the measurements in order to avoid correlation among the replicates (Burgers et al., 1998), and  $\mathbf{K}$  is the Kalman gain matrix which is given by

$$\mathbf{K} = \mathbf{C}_{\Gamma T} [\mathbf{C}_{TT} + \mathbf{C}_V]^{-1} \quad (8)$$

where  $\mathbf{C}_V$  is the error covariance of the measurements,  $\mathbf{C}_{\Gamma T}$  is the cross-covariance between the prior states and predicted measurements, and  $\mathbf{C}_{TT}$  is the covariance of the predicted measurements. In this framework, the state variables are related to the measurements in the batch through the covariance matrices that are obtained from the ensemble.

## Data assimilation-based estimation of Greenland surface mass loss

M. Navari et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



The update in Eq. (7) can be seen as a projection of measurement-prediction misfits onto the states. The updated (posterior) multiplicative states were used in Eq. (5) to retrieve updated (posterior) forcing. The posterior forcings were used as inputs in CROCUS to estimate the posterior surface mass fluxes. The proposed methodology can simply be extended to multiple years by applying the DA sequentially and independently for each year (e.g. Giroto et al., 2014b) or via applying the DA to a moving window (e.g. Dunne et al., 2005). A schematic illustration of the methodology is presented in Fig. 2. The proposed methodology can be thought of as a post-processing (reanalysis) of MAR estimates by constraining the model using independent IST observations.

## 4 Experimental design

An OSSE or synthetic twin experiment offers a controlled setting in which the true forcing variables (i.e.,  $\gamma_S$ ,  $\gamma_I$ , and  $\gamma_T$ ) are available. The goal of an OSSE is to evaluate the feasibility of the new methodology prior to assimilating real spaceborne measurements. In an OSSE, a synthetic true state and corresponding noisy measurements of the system are generated and used to evaluate the feasibility of the DA framework (e.g. Durand and Margulis, 2006; Crow and Ryu, 2009; De Lannoy et al., 2010).

### 4.1 True selection

The synthetic truth uses realistic input and measurement error characteristics in conjunction with the forward models to generate a realistic realization of the true system. In this study, the synthetic truth was selected as an outlier (defined below) from the generated ensemble due to the fact that errors in forcings can yield differences between a forward model (open-loop) estimate and the true surface mass fluxes.

## Data assimilation-based estimation of Greenland surface mass loss

M. Navari et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



The ensemble of forcing data was generated via Eq. (5) for the year 2010 and then the offline CROCUS implementation was run using the ensemble of forcing data to generate estimates of the GrIS surface mass fluxes in 2010. The year 2010 was chosen, at least in part, since it was characterized by an extreme melt rate (Tedesco et al., 2011). Considering the fact that runoff is the main component of the GrIS surface mass loss, the true ensemble (synthetic truth) was selected in a way that the integrated true runoff over the GrIS was an outlier relative to the median of the ensemble simulations. The forcing variables, states, and fluxes corresponding to the synthetic truth were also considered as the true forcings, the true states and the true fluxes respectively. It should be highlighted that in a synthetic DA experiment, any generated realization from the forward model (CROCUS) can be used as the synthetic truth, but one that is significantly different from the prior mean/median allows for a more robust assessment of the value of the assimilated measurements. In other words, in an OSSE the goal is to assess whether a DA framework can replicate the randomly selected true by merging the measurements with the prior (open-loop) estimates.

### 4.2 Assimilated measurement characteristics

Surface temperature from the forward model can be considered as a close approximation of the remotely-sensed IST. Here, the synthetic DA experiments were designed to mimic reality as much as possible. Hence, the DA system was run with a realistic representation of the temporal frequency of real space-borne IST measurements; e.g. the GrIS IST measurements from MODIS have a daily temporal resolution. However, in many instances daily observations are not available due to cloud contamination, instrument outage, and quality related considerations. To take this issue into account, the number of available daily IST measurements (i.e., synthetic measurements) for assimilation in each month was derived from the spatial average seen in the actual Greenland IST product (e.g., Hall et al., 2012). The days with measurements were selected randomly so that the total number per month was consistent with the real number of available measurements.

## Data assimilation-based estimation of Greenland surface mass loss

M. Navari et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Since the raw MODIS IST measurements are available at a much finer spatial resolution (i.e.  $\sim 1.5$  km) than the model scale (25 km), the measurements themselves and their error characteristics would require a pre-processing spatial aggregation to match the resolution of computational pixels ( $\sim 25$  km). In the context of the OSSE in this study, the synthetic measurements and forward model both have the same spatial resolution therefore there is no need for spatial aggregation of the predicted measurement. However, specification of realistic measurement errors need to take into account the difference in spatial resolution between MODIS IST measurements and the model pixel scale. Measurement errors for MODIS IST at its raw resolution (i.e. 1.5 km) are expected to be  $\sim 1$ –1.5 K (e.g. Hall et al., 2012). Hence the measurement errors at the model scale (25 km) are expected to be less than or equal to this value depending on the level of correlation of the measurement errors at the sub-pixel scale. In the case of perfectly uncorrelated sub-pixel measurement errors, the aggregated measurement would be expected to have a measurement error equal to the fine-scale value divided by the number of sub-grid MODIS pixels. Assuming uncorrelated sub-grid errors are likely overly optimistic, we postulated that the measurement error standard deviation of IST at the 25 km scale is 1 K.

### 4.3 Implementation

The feasibility of the new DA system was evaluated via assimilation of IST as follows: a synthetically generated data stream was assimilated within an EnBS framework to assess the information content of the IST and explore whether it can overcome errors in forcing inputs. This was examined by comparing the open-loop and EnBS estimates of multiplicative states with the synthetic truth. Thereafter, the posterior meteorological forcings were fed into CROCUS to estimate the surface mass fluxes. The performance of the EnBS algorithm was further evaluated through the comparison of the posterior estimates with the prior estimates and the true estimate for all surface mass fluxes. It is worth noting that in the OSSE in this study the ensemble size was set to 100 replicates

which has been shown to be adequate in previous relevant studies (e.g. Margulis et al., 2002; Huang et al., 2008; Evensen, 2009).

## 5 Results

### 5.1 Performance of the EnBS via assimilation of IST

5 To provide an illustrative example of the methodology, Fig. 3a–c shows the distribution of prior (open-loop) and posterior (obtained by assimilating IST) multiplicative state variables corresponding to the different forcings for a sample pixel in the ablation zone (latitude 67° N longitude 49.8° W), which is the critical zone in terms of the GrIS surface mass loss. The prior distribution of multiplicative coefficients for each forcing variable is wide, representing the postulated uncertainty in the prior forcings. In contrast, Fig. 3a shows that the histogram of the posterior estimates of  $\gamma_T$  is tightly distributed around the true estimate. A narrow distribution around the true estimate means that the DA system uses the information contained in the IST sequence and moves the ensemble members toward the true estimate while reducing the uncertainty of  $\gamma_T$ . The reduction in uncertainty is evident by comparing the base of the posterior histogram with that from the prior estimates. The positive update by the DA system can be explained based on the fact that IST and air temperature are coupled and each one affects the other (Hall et al., 2008). Figure 3b illustrates that the median of the posterior estimate of  $\gamma_l$  agrees well with the corresponding synthetic truth. Incoming longwave radiation is correlated with the effective (near-surface) air temperature and as stated above, IST and surface air temperature are closely tied to each other. Prior to melt, solar radiation goes into heating the snow/ice surface and during the melt period, energy input drives sublimation or evaporation and melt (Box and Steffen, 2001). Therefore, it can be stated that IST is positively correlated with the incoming shortwave radiation. 20 The EnBS system takes advantage of this correlation and provides improved estimates of the multiplicative state related to shortwave radiation (Fig. 3c).

## Data assimilation-based estimation of Greenland surface mass loss

M. Navari et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Figure 3d presents the time series of the IST for the prior, posterior, synthetic true, and assimilated measurements during a portion of the assimilation window. For the purpose of illustration, IST data for 10 days during the dry period (January) and beginning of the melt period (April) were selected to show the ability of the algorithm to estimate the true IST (Fig. 3d and e). It is evident in Fig. 3d and e that the EnBS captures the diurnal variability of IST and closely estimates the true IST both during the daytimes and nighttimes during the dry and melt periods. Moreover, Fig. 3d shows that the EnBS successfully estimates the true IST even when the temporal resolution of the IST measurements significantly decreases. This is important since the IST record shows that there are fewer measurements available during the months of December and January (Hall et al., 2012) where in some years the available measurements during these two months drop to fewer than 10 measurements per month. Comparing Fig. 3d with Fig. 3e also shows that during the month of January when there are fewer IST measurements the posterior estimates are in good agreement with the true IST, however, the uncertainty of the estimates is slightly larger. These results illustrate that information from IST measurements can be exploited to estimate the multiplicative states (i.e.  $\gamma_S$ ,  $\gamma_I$ , and  $\gamma_T$ ) and consequently the IST.

Results for the whole domain are presented in terms of relevant bulk metrics that capture the integrated impact of the forcings. Specifically, the pixel-wise cumulative incoming shortwave and incoming longwave radiation (in  $\text{MJ m}^{-2} \text{year}^{-1}$ ) were used to represent the total energy input into the ice sheet and provide insight into the surface energy balance of the GrIS. For the air temperature, negative degree-day temperature (NDD) (i.e., cumulative mean daily air temperature for days in which the mean daily air temperature is below  $0^\circ\text{C}$ ) and the positive degree-day temperature (PDD) (i.e., cumulative mean daily air temperature for days in which the mean daily air temperature is above  $0^\circ\text{C}$ ) are two other metrics which are indicative of snow accumulation and melt periods, respectively. These bulk metrics were used to evaluate the performance of the DA algorithm over the entire ice sheet using RMSE and an improvement factor.

## Data assimilation-based estimation of Greenland surface mass loss

M. Navari et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



The spatial mean bias and the spatial RMSE of the prior and posterior estimates of the integrated forcing variables over the GrIS were computed using the prior, posterior, and true cumulative longwave, shortwave, and air temperature (i.e., PDD and NDD). Table 2 summarizes the spatial mean bias and the spatial RMSE of the different forcing variables. As can be seen for the entire simulation period, the mean bias (RMSE) of cumulative shortwave, longwave, PDD, and NDD are, respectively,  $-12.8$  ( $241.3$ )  $\text{MJ m}^{-2} \text{ year}^{-1}$ ,  $4.6$  ( $97.9$ )  $\text{MJ m}^{-2} \text{ year}^{-1}$ ,  $-1$  ( $9.7$ )  $^{\circ}\text{C-day}$ , and  $-2.8$  ( $55$ )  $^{\circ}\text{C-day}$ , which are 84 % (70 %), 82 % (85 %), 94 % (71 %), and 65 % (86 %) less than the mean bias (RMSE) of the prior estimates.

An alternative method to evaluate the DA system is to determine the contribution of RS data to the estimate explicitly. Following Durand et al. (2006) and Bateni et al. (2013) an improvement factor based on the prior and posterior error relative to the true was defined as follows:

$$\kappa_i = \left| \bar{Y}_i(-) - Y_i^{\text{True}} \right| - \left| \bar{Y}_i(+) - Y_i^{\text{True}} \right| \quad (9)$$

where the  $\bar{Y}_i(-)$  and  $\bar{Y}_i(+)$  represent the cumulative ensemble median of the prior and posterior estimates of the forcing  $i$  respectively and  $Y_i^{\text{True}}$  is the cumulative synthetic true for the forcing  $i$ . The improvement factor  $\kappa_i$  can be used to interpret the contribution of the IST measurements to the posterior estimates of the forcing. This formulation suggests a value greater than 0 when the posterior error is less than the prior error (i.e., measurement improves the posterior estimates), a value equal to 0 when the prior and posterior errors are equal, and a value less than 0 when the error in the posterior estimates is greater than that in the prior estimates (the measurement degrades the posterior estimates). Table 2 shows that IST measurements make a large contribution to correct the forcing variables. IST contributed an integrated sum of 452 ( $\text{MJ m}^{-2} \text{ year}^{-1}$ ), 375 ( $\text{MJ m}^{-2} \text{ year}^{-1}$ ), 14 ( $^{\circ}\text{C-day}$ ), and 257 ( $^{\circ}\text{C-day}$ ) to correct the shortwave, longwave, PPD, and NDD. The improvement factor of the PDD is much smaller than that of the NDD due the fact that there are many fewer days in which the mean daily near-surface air temperature is above the freezing point.

**Data  
assimilation-based  
estimation of  
Greenland surface  
mass loss**

M. Navari et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



In order to further investigate the performance of the EnBS, the prior errors (i.e., prior – true) and the posterior errors (i.e., posterior – true) were computed for each forcing variable. Figure 4a–d show the histograms of the prior and posterior errors for cumulative  $R_s$ ,  $R_l$ , PDD, and NDD over the spatial domain. The EnBS reduces the uncertainty of the posterior estimates for all forcing variables and effectively removes any of the prior biases.

## 5.2 Updating the SML terms

While updating the forcing variables is the mechanism by which the EnBS transfers information from IST into the posterior estimates, the main objective of the DA framework in this study is to assess the feasibility of providing better estimates of the GrIS SML and related fluxes using the improved forcings. To generate a benchmark for our analysis, CROCUS was run in open-loop mode using the prior forcings (explained above). The SML terms obtained from the prior (open-loop) simulation constitute a basis for evaluation of the methodology implemented in this study. Using the posterior forcing, CROCUS was executed for each grid cell to obtain posterior estimates of surface mass fluxes (i.e., runoff, sublimation/evaporation, and condensation) and consequently SML.

Runoff plays an important role in the GrIS net mass loss and is the main component of the GrIS SML. The GrIS melt-water runoff is heavily concentrated in the ablation zone along the ice sheet margin where the width of the ablation zone in the GrIS in some regions is very narrow and does not exceed tens of kilometres. The map of synthetic true runoff (Fig. 5a) shows that the west and southwest margins experience the highest rates of runoff that exceeds 6 m water equivalent per year. It is worth remembering that the true runoff is an outlier in the context of ensemble modelling as explained previously. Figure 5b–c show the runoff anomaly for the prior (i.e. prior-true) and the runoff anomaly for the posterior (i.e. posterior-true) respectively. The gray areas represent the percolation and dry snow zones, which do not generally contribute to surface runoff during the simulation period. The prior anomaly map (Fig. 5b) shows

## Data assimilation-based estimation of Greenland surface mass loss

M. Navari et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

that the open-loop simulation consistently underestimates the true runoff across the domain with a strong negative anomaly in the southwest margin (more than 1600 mm water equivalent below the true). Comparing the GrIS margin pixels in the prior and posterior maps (Fig. 5b and c) shows that the anomaly of the posterior estimates is significantly lower than that of the prior estimates. Reduced anomalies indicate that the EnBS successfully recovers the true estimates of the runoff in most pixels. However, the posterior results are not perfect and the algorithm slightly underestimates and overestimates runoff in some pixels.

Scatter plots of the runoff for the prior and posterior estimates vs. the true estimates are illustrated in Fig. 5d and e. Each data point in Fig. 5d and e represents the ensemble median of the estimate (i.e., prior, posterior) vs. the true estimate in a single pixel; and the error bar illustrates the corresponding ensemble interquartile range of the estimates in the same pixel. The scatter plot of the prior runoff shows that almost all data points lie below the 1 : 1 line, indicating that the prior estimates were significantly biased (by construct in this OSSE). The posterior scatter plot (Fig. 5e) displays that the data points are narrowly distributed around the 1 : 1 line and the error bars are much smaller than that in the prior estimates, implying that the proposed algorithm significantly removes the bias and decreases the uncertainty of the estimates.

Sublimation and evaporation play an important role in the GrIS surface mass loss (Lenaerts et al., 2012) and after runoff are the main components of the GrIS SML. Here, the discussion focuses on sublimation rather than evaporation due to the fact that sublimation is one order of magnitude larger than evaporation. The map of synthetic true sublimation (Fig. 6a) shows that the west and southwest of the GrIS in the ablation zone experience the largest sublimation rates. Box and Steffen (2001) explained that at the edge of the ice sheet, where slopes become steeper, the katabatic wind accelerates and tends to increase sublimation. Furthermore, the net radiation increases during the summertime, especially at lower latitudes, which in turn generates a vertical temperature gradient and increases the sublimation. Higher energy input also contributes to a positive albedo feedback (e.g. Tedesco et al., 2011)

**Data  
assimilation-based  
estimation of  
Greenland surface  
mass loss**

M. Navari et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

and further increases the sublimation rates. The prior anomaly map (Fig. 6b) illustrates that the open-loop model underestimates the sublimation at the ice sheet margin and slightly overestimates it in the ice sheet interior. The results demonstrate that posterior sublimation estimates from the assimilation of IST are much closer to the truth than are the prior estimates (Fig. 6c). Comparing the scatter plots of the posterior vs. the true estimates with that of the prior vs. the true estimates, reveals that the methodology successfully overcomes the bias and significantly reduces the uncertainty of the sublimation estimates and increases the confidence of the results (see Fig. 6d and e).

Surface solid condensation (deposition) also influences surface mass fluxes of the GrlS by adding mass to the ice sheet. Similar to sublimation, wind and the vertical specific humidity gradient are two key factors that control the deposition. To be more precise, colder temperatures and lower winds enhance the deposition rates. In contrast with sublimation, deposition occurs at night and during winter, mainly due to radiative cooling (Box and Steffen, 2001). Figure 7a shows that the surface solid condensation (SSC) is greater in the ice sheet interior where winds are weak and there is sufficient moisture in the air column. The high elevation central regions, however, show less condensation due to distance from moisture sources. High speed winds in the ice sheet margins prevent condensation despite the availability of moisture. Figure 7b shows that the prior estimates for SSC is not in good agreement with the truth and that the prior simulation both underestimates and overestimates surface solid condensation across the domain. A comparison between the prior and posterior anomaly maps (Fig. 7b and c) suggests that the posterior estimates closely recover the true estimates. Figure 7e shows that the data points are clustered around the 1 : 1 line; indicating that the EnBS corrects the bias in the prior estimates (Fig. 7d). In addition, posterior error bars are significantly smaller than that of the prior error bars, indicating that the EnBS effectively uses the information content of the IST measurements to eliminate the bias and reduce the uncertainties of the posterior estimates.

## Data assimilation-based estimation of Greenland surface mass loss

M. Navari et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Herein, the SML is defined as the sum of the mass loss terms (i.e. runoff and sublimation/evaporation) and mass gain term (i.e. surface solid condensation) discussed above. Figure 8a shows that SML is greater in the west and southwest of the ice sheet where runoff is the dominant mass loss mechanism and is smaller in the ice sheet interior where mass loss mainly occurs through sublimation. Similar to runoff, the prior anomaly is largely concentrated in the ablation zone and since runoff is roughly two orders of magnitude larger than sublimation and condensation, the anomaly due to these two fluxes is almost undetectable in the anomaly map (see Fig. 8b). Comparing the posterior anomaly map (Fig. 8c) with that of the prior, clearly shows that the posterior SML is closely matched with the true estimates across the domain. Scatter plots (Fig. 8d and e) also confirm that the EnBS effectively removes the bias and increases the confidence level of SML estimates.

To provide an integrated picture over the full domain, Fig. 9a–d show the time series of the cumulative runoff, sublimation, surface solid condensation, and SML over the GrIS respectively in 2010. As illustrated in Fig. 9a, the true runoff starts in late April and increases rapidly during the melt season (to a cumulative value of 408 mm) until late August. The central tendency of the prior simulation (as indicated by the ensemble median) underestimates the runoff by about 35 % owing to errors in the forcing inputs. The posterior estimates show a cumulative runoff of 394 mm over the GrIS, which is in good agreement with the truth. Table 3 shows that the EnBS reduces the spatial mean bias (RMSE) of the prior estimates of runoff by 90 % (61 %) from –552 mm (646 mm) to –54 mm (250 mm). As evident in Fig. 9b, sublimation accelerates during the summer season owing to increased energy input to the snow/ice surface. The true estimate suggests that in total net sublimation (i.e. sublimation and evaporation) accounts for about 66 mm (~ 15 %) mass loss over the GrIS. The median of the prior simulation shows a total sublimation loss of ~ 56 mm which is 10 mm less than the truth. The EnBS significantly improves the results where the posterior median estimate shows a total sublimation of 65 mm. From Table 3 the spatial mean bias (RMSE) of the posterior estimate shows a 90 % (64 %) reduction relative to the prior. In general surface solid

condensation accelerates during the winter and decelerates in the summer season (Fig. 9c). The true simulation suggests a cumulative SCC of 27 mm, and the median of the prior and posterior estimates are 25 and 27 mm, respectively. The 76 % reduction of the spatial RMSE of the posterior estimates and 80 % reduction of the spatial mean bias (Table 3) also supports the accuracy of the posterior estimates. Finally, the true SML estimate is 450 mm, the prior and posterior median of SML are 295, 435 mm, respectively. Clearly the posterior SML estimate is in better agreement with the truth. The IST measurements contribute an integrated sum of 140 mm to correct the posterior estimates of the GrIS SML and also reduce the spatial mean bias and the spatial RMSE of the estimates by 90 and 62 % respectively (Table 3).

A probabilistic approach also provides information about the uncertainty of the estimates. Figure 9a–d show that the prior estimates of all surface mass fluxes have a large ensemble spread, reflecting the propagation of a priori forcing uncertainties to SML terms. During the update process the EnBS significantly reduces the uncertainties of the posterior estimates of forcing variables and consequently the posterior estimates of the surface mass fluxes. Comparing the narrow blue shaded area with the wide red shaded area illustrates that the EnBS increases the confidence of the model predictions by decreasing the error and uncertainties of the posterior estimates relative to the prior estimates.

### 5.3 Sensitivity to the synthetic truth values

As in any OSSE, the synthetic measurements are, by construct, a function of the chosen true and therefore the posterior results could be impacted by the particular selection of the true realization. To address this concern, and show the robustness of the proposed algorithm, the simulation was repeated for two different true values; one smaller than the baseline simulation and the other larger. In the first case the synthetic true runoff was set to 330 mm, which is the average of the runoff estimates from the open-loop simulation (i.e. ~ 260 mm) and the true runoff from the baseline simulation (i.e., ~ 400 mm). In the second case the true runoff was set to 470 mm, which is 70 mm

Data  
assimilation-based  
estimation of  
Greenland surface  
mass loss

M. Navari et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



larger than the baseline simulation. Table 4 shows the RMSE of the surface mass fluxes for all simulation cases. The posterior RMSE of each mass flux for all simulation cases are very similar even when the prior RMSE of the estimates are significantly different. For example, the prior RMSE of the runoff (SML) for the second simulation case (true runoff equal to 470 mm) is 2.5 (2.6) times larger than the prior RMSE of the first simulation case (true runoff equal to 330 mm), but the posterior RMSE differs by only 4 % (10 %). Therefore, it can be stated that the DA algorithm robustly retrieve the true estimates of the surface mass fluxes and the performance of the algorithm is relatively insensitive to the selected truth.

## 6 Discussion and conclusions

A new data assimilation methodology for improving estimates of the GrIS surface mass loss fluxes has been tested and presented using an observing system simulation experiment framework. The prior estimates were derived from an offline surface module (CROCUS) forced by an ensemble of meteorological forcing fields that were based on a nominal regional climate model simulation (in this case MAR). A posterior estimate was generated by conditioning the forcings on the synthetically generated IST measurements using an ensemble batch smoother (EnBS) approach. Specifically, it was shown that using the EnBS with IST measurements was able to improve nominal estimates derived from MAR that result from erroneous forcing fields that drive surface mass and energy balance processes. The results illustrated that IST measurements have potential information on shortwave, longwave, and surface air temperature that allows for correction of errors in these terms. However, due to the lack of meaningful correlation between precipitation and IST measurements, the precipitation flux was not updated in this context. Hence the assimilation of IST is primarily beneficial for estimating the surface mass loss terms and not the accumulation term.

The new methodology has several advantages over the traditional state-space data assimilation approaches. First, in this new application the multiplicative perturbation

Data  
assimilation-based  
estimation of  
Greenland surface  
mass loss

M. Navari et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## Data assimilation-based estimation of Greenland surface mass loss

M. Navari et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

variables are considered as states to be updated. Reduction of the size of the state vector and consequently computational costs is the direct outcome of this approach. Second, mass loss terms cannot directly be sensed by the means of satellite sensors; using this methodology, the mass loss fluxes were estimated indirectly by reducing the error in forcing variables. Finally, the modularity of the proposed methodology would allow for incorporation of any regional climate model and additional remotely-sensed observations in future applications. All of these advantages should make such data assimilation approaches an attractive and complementary approach to better resolve and diagnose the ice sheet surface mass fluxes. The improved mass loss estimates could also be used as input to net mass balance estimates and ultimately a sea level rise projection when applied to real data over the remote sensing record.

The next logical step is to apply the methodology with real IST measurements to further validate the robustness of the proposed approach. This future work will include the use of the MODIS IST product for estimating GrIS SML. The data assimilation framework is general and could also include the potential application of assimilation of passive microwave and albedo to further constrain GrIS SMB estimates.

*Acknowledgements.* This work was partially sponsored by NSF through grant #0909388.

## References

- Abdalati, W. and Steffen, K.: Passive microwave derived snow melt regions on the Greenland ice sheet, *Geophys. Res. Lett.*, 22, 787–790, 1995.
- Abdalati, W. and Steffen, K.: Snowmelt on the Greenland ice sheet as derived from passive microwave satellite data, *J. Climate*, 10, 165–175, 1997.
- Abdalati, W. and Steffen, K.: Greenland ice sheet melt extent: 1979–1999, *J. Geophys. Res.*, 106, 33983–33988, doi:10.1029/2001JD900181, 2001.
- Al-Yaari, A., Wigneron, J.-P., Ducharne, A., Kerr, Y., de Rosnay, P., de Jeu, R., Govind, A., Al Bitar, A., Albergel, C., Muñoz-Sabater, J., Richaume, P., and Mialon, A.: Global-scale evaluation of two satellite-based passive microwave soil moisture datasets (SMOS and

## Data assimilation-based estimation of Greenland surface mass loss

M. Navari et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

AMSR-E) with respect to Land Data Assimilation System estimates, *Remote Sens. Environ.*, 149, 181–195, doi:10.1016/j.rse.2014.04.006, 2014.

Andersen, K. K., Azuma, N., Barnola, J.-M., Bigler, M., Biscaye, P., Caillon, N., Chappellaz, J., Clausen, H. B., Dahl-Jensen, D., Fischer, H., Flückiger, J., Fritzsche, D., Fujii, Y., Goto-Azuma, K., Grønbold, K., Gundestrup, N. S., Hansson, M., Huber, C., Hvidberg, C. S., Johnsen, S. J., Jonsell, U., Jouzel, J., Kipfstuhl, S., Landais, a, Leuenberger, M., Lorrain, R., Masson-Delmotte, V., Miller, H., Motoyama, H., Narita, H., Popp, T., Rasmussen, S. O., Raynaud, D., Rothlisberger, R., Ruth, U., Samyn, D., Schwander, J., Shoji, H., Siggard-Andersen, M.-L., Steffensen, J. P., Stocker, T., Sveinbjörnsdóttir, a E., Svensson, a, Takata, M., Tison, J.-L., Thorsteinsson, T., Watanabe, O., Wilhelms, F., and White, J. W. C.: High-resolution record of Northern Hemisphere climate extending into the last interglacial period, *Nature*, 431, 147–151, doi:10.1038/nature02805, 2004.

Andreadis, K. M. and Lettenmaier, D. P.: Assimilating remotely sensed snow observations into a macroscale hydrology model, *Adv. Water Resour.*, 29, 872–886, doi:10.1016/j.advwatres.2005.08.004, 2006.

Bamber, J. L. and Layberry, R. L.: 1. Measurement, data reduction, and errors ice sheet was reestimated and found to have a value at a sample, *J. Geophys. Res.*, 106, 33773–33780, 2001.

Bateni, S. and Huang, C.: Feasibility of Characterizing Snowpack and the Freeze–Thaw State of Underlying Soil Using Multifrequency Active/Passive Microwave Data, *IEEE T. Geosci. Remote*, 51, 4085–4102, 2013.

Bateni, S. M., Margulis, S. A., Podest, E., Mcdonald, K. C., and Member, S.: Characterizing Snowpack and the Freeze–Thaw State of Underlying Soil via Assimilation of Multifrequency Passive/Active Microwave Data: A Case Study (NASA CLPX 2003), *IEEE T. Geosci. Remote*, 53, 173–189, 2015.

Bindschadler, R., Choi, H., Shuman, C., and Markus, T.: Detecting and measuring new snow accumulation on ice sheets by satellite remote sensing, *Remote Sens. Environ.*, 98, 388–402, doi:10.1016/j.rse.2005.07.014, 2005.

Box, J. E.: Greenland ice sheet surface mass balance 1991–2000: application of Polar MM5 mesoscale model and in situ data, *J. Geophys. Res.*, 109, D16105, doi:10.1029/2003JD004451, 2004.

**Data  
assimilation-based  
estimation of  
Greenland surface  
mass loss**

M. Navari et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

Box, J. E. and Steffen, K.: Sublimation on the Greenland ice sheet from automated weather station observations, *J. Geophys. Res.*, 106, 33965–33981, doi:10.1029/2001JD900219, 2001.

Box, J. E., Bromwich, D. H., Veenhuis, B. A., Bai, L.-S., Stroeve, J. C., Rogers, J. C., Steffen, K., Haran, T., and Wang, S.-H.: Greenland ice sheet surface mass balance variability (1988–2004) from calibrated Polar MM5 output, *J. Climate*, 19, 2783–2800, doi:10.1175/JCLI3738.1, 2006.

Box, J. E., Fettweis, X., Stroeve, J. C., Tedesco, M., Hall, D. K., and Steffen, K.: Greenland ice sheet albedo feedback: thermodynamics and atmospheric drivers, *The Cryosphere*, 6, 821–839, doi:10.5194/tc-6-821-2012, 2012.

Brun, B. E., Martin, E., Simon, V. and Gendre, C.: An energy and mass model of snow cover suitable for operational avalanche forecasting, *J. Glaciol.*, 35, 333–342, 1989.

Brun, E., David, P., Sudul, M., and Brunot, G.: A numerical model to simulate snow-cover stratigraphy for operational avalanche forecasting, *J. Glaciol.*, 38, 13–22, 1992.

Burgers, G., Jan van Leeuwen, P., and Evensen, G.: Analysis scheme in the ensemble Kalman filter, *Mon. Weather Rev.*, 126, 1719–1724, doi:10.1175/1520-0493(1998)126<1719:ASITEK>2.0.CO;2, 1998.

Burgess, E. W., Forster, R. R., Box, J. E., Mosley-Thompson, E., Bromwich, D. H., Bales, R. C., and Smith, L. C.: A spatially calibrated model of annual accumulation rate on the Greenland ice sheet (1958–2007), *J. Geophys. Res.*, 115, 1–14, doi:10.1029/2009JF001293, 2010.

Chen, J. L., Wilson, C. R., and Tapley, B. D.: Satellite gravity measurements confirm accelerated melting of Greenland ice sheet, *Science*, 313, 1958–1960, doi:10.1126/science.1129007, 2006.

Chylek, P., McCabe, M., Dubey, M. K., and Dozier, J.: Remote sensing of Greenland ice sheet using multispectral near-infrared and visible radiances, *J. Geophys. Res.*, 112, 1–12, doi:10.1029/2007JD008742, 2007.

Crow, W. T. and Ryu, D.: A new data assimilation approach for improving runoff prediction using remotely-sensed soil moisture retrievals, *Hydrol. Earth Syst. Sci.*, 13, 1–16, doi:10.5194/hess-13-1-2009, 2009.

Cuffey, K. M. and Paterson, W. S. B.: *The Physics of Glaciers*, 4th Ed., Butterworth-Heinemann/Elsevier, Amsterdam, The Netherlands, 704 pp., 2010.

## Data assimilation-based estimation of Greenland surface mass loss

M. Navari et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



- De Lannoy, G. J. M., Reichle, R. H., Houser, P. R., Arsenault, K. R., Verhoest, N. E. C., and Pauwels, V. R. N.: Satellite-scale snow water equivalent assimilation into a high-resolution land surface model, *J. Hydrometeorol.*, 11, 352–369, doi:10.1175/2009JHM1192.1, 2010.
- De Lannoy, G. J. M., Reichle, R. H., Arsenault, K. R., Houser, P. R., Kumar, S., Verhoest, N. E. C., and Pauwels, V. R. N.: Multiscale assimilation of advanced microwave scanning radiometer–EOS snow water equivalent and moderate resolution imaging spectroradiometer snow cover fraction observations in northern Colorado, *Water Resour. Res.*, 48, W01522, doi:10.1029/2011WR010588, 2012.
- Dunne, S. and Entekhabi, D.: An ensemble-based reanalysis approach to land data assimilation, *Water Resour. Res.*, 41, 1–18, doi:10.1029/2004WR003449, 2005.
- Durand, M. and Margulis, S.: Feasibility test of multifrequency radiometric data assimilation to estimate snow water equivalent, *J. Hydrometeorol.*, 7, 443–457, doi:10.1175/JHM502.1, 2006.
- Durand, M. and Margulis, S. A.: Effects of uncertainty magnitude and accuracy on assimilation of multiscale measurements for snowpack characterization, *J. Geophys. Res.*, 113, 1–17, doi:10.1029/2007JD008662, 2008.
- Durand, M., Molotch, N. P., and Margulis, S. A.: A Bayesian approach to snow water equivalent reconstruction, *J. Geophys. Res.*, 113, 1–15, doi:10.1029/2008JD009894, 2008.
- Durand, M., Kim, E. J., and Margulis, S. A.: Radiance assimilation shows promise for snowpack characterization, *Geophys. Res. Lett.*, 36, 1–5, doi:10.1029/2008GL035214, 2009.
- Enderlin, E. M., Howat, I. M., Jeong, S., Noh, M.-J., van Angelen, J. H., and van den Broeke, M. R.: An improved mass budget for the Greenland ice sheet, *Geophys. Res. Lett.*, 41, 866–872, doi:10.1002/2013GL059010, 2014.
- Ettema, J., van den Broeke, M. R., van Meijgaard, E., van de Berg, W. J., Bamber, J. L., Box, J. E., and Bales, R. C.: Higher surface mass balance of the Greenland ice sheet revealed by high-resolution climate modeling, *Geophys. Res. Lett.*, 36, 1–5, doi:10.1029/2009GL038110, 2009.
- Ettema, J., van den Broeke, M. R., van Meijgaard, E., van de Berg, W. J., Box, J. E., and Steffen, K.: Climate of the Greenland ice sheet using a high-resolution climate model – Part 1: Evaluation, *The Cryosphere*, 4, 511–527, doi:10.5194/tc-4-511-2010, 2010.
- Evensen, G.: *Data Assimilation: The Ensemble Kalman Filter*, 2nd Edn., Springer, New York, USA, 307 pp., 2009.

**Data  
assimilation-based  
estimation of  
Greenland surface  
mass loss**

M. Navari et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

Fettweis, X.: Reconstruction of the 1979–2005 greenland ice sheet surface mass balance using satellite data and the regional climate model MAR, PhD thesis, Universit'e catholique de Louvain, Leuven, Belgium, 2006.

Fettweis, X., Gallée, H., Lefebvre, F., and Ypersele, J.-P.: Greenland surface mass balance simulated by a regional climate model and comparison with satellite-derived data in 1990–1991, *Clim. Dynam.*, 24, 623–640, doi:10.1007/s00382-005-0010-y, 2005.

Fettweis, X., van Ypersele, J.-P., Gallée, H., Lefebvre, F., and Lefebvre, W.: The 1979–2005 Greenland ice sheet melt extent from passive microwave data using an improved version of the melt retrieval XPGR algorithm, *Geophys. Res. Lett.*, 34, 1–5, doi:10.1029/2006GL028787, 2007.

Fettweis, X., Tedesco, M., van den Broeke, M., and Ettema, J.: Melting trends over the Greenland ice sheet (1958–2009) from spaceborne microwave data and regional climate models, *The Cryosphere*, 5, 359–375, doi:10.5194/tc-5-359-2011, 2011.

Fettweis, X., Franco, B., Tedesco, M., van Angelen, J. H., Lenaerts, J. T. M., van den Broeke, M. R., and Gallée, H.: Estimating the Greenland ice sheet surface mass balance contribution to future sea level rise using the regional atmospheric climate model MAR, *The Cryosphere*, 7, 469–489, doi:10.5194/tc-7-469-2013, 2013.

Forman, B. A. and Margulis, S. A.: Assimilation of multiresolution radiation products into a downwelling surface radiation model: 1. Prior ensemble implementation, *J. Geophys. Res.*, 115, 1–14, doi:10.1029/2010JD013920, 2010.

Franco, B., Fettweis, X., Lang, C., and Erpicum, M.: Impact of spatial resolution on the modelling of the Greenland ice sheet surface mass balance between 1990–2010, using the regional climate model MAR, *The Cryosphere*, 6, 695–711, doi:10.5194/tc-6-695-2012, 2012.

Franco, B., Fettweis, X., and Erpicum, M.: Future projections of the Greenland ice sheet energy balance driving the surface melt, *The Cryosphere*, 7, 1–18, doi:10.5194/tc-7-1-2013, 2013.

Franz, K. J., Hogue, T. S., Barik, M., and He, M.: Assessment of SWE data assimilation for ensemble streamflow predictions, *J. Hydrol.*, 519, 2737–2746, doi:10.1016/j.jhydrol.2014.07.008, 2014.

Gallée, H. and Duynkerke, P.: Air-snow interactions and the surface energy and mass balance over the melting zone of west Greenland during the Greenland Ice Margin Experiment, *J. Geophys. Res.*, 102, 13813–13824, 1997.

**Data  
assimilation-based  
estimation of  
Greenland surface  
mass loss**

M. Navari et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

- Gallée, H. and Schayes, G.: Development of a three-dimensional meso- $\gamma$  primitive equation model: katabatic winds simulation in the area of Terra Nova Bay, Antarctica, *Mon. Weather Rev.*, 122, 671–685, doi:10.1175/1520-0493(1994)122<0671:DOATDM>2.0.CO;2, 1994.
- Giroto, M., Cortés, G., Margulis, S. A., and Durand, M.: Examining spatial and temporal variability in snow water equivalent using a 27 year reanalysis: Kern River watershed, Sierra Nevada, *Water Resour. Res.*, 50, 446, doi:10.1002/2014WR015346, 2014a.
- Giroto, M., Margulis, S., and Durand, M.: Probabilistic SWE reanalysis as a generalization of deterministic SWE reconstruction techniques, *Hydrol. Process.*, 28, 3875–3895, doi:10.1002/hyp.9887, 2014b.
- Goldberg, D. N. and Heimbach, P.: Parameter and state estimation with a time-dependent adjoint marine ice sheet model, *The Cryosphere*, 7, 1659–1678, doi:10.5194/tc-7-1659-2013, 2013.
- Hall, D. K., Williams, R. S., Casey, K. A., DiGirolamo, N. E., and Wan, Z.: Satellite-derived, melt-season surface temperature of the Greenland ice sheet (2000–2005) and its relationship to mass balance, *Geophys. Res. Lett.*, 33, L11501, doi:10.1029/2006GL026444, 2006.
- Hall, D. K., Box, J., Casey, K., Hook, S., Shuman, C., and Steffen, K.: Comparison of satellite-derived and in-situ observations of ice and snow surface temperatures over Greenland, *Remote Sens. Environ.*, 112, 3739–3749, doi:10.1016/j.rse.2008.05.007, 2008.
- Hall, D. K., Nghiem, S. V., Schaaf, C. B., DiGirolamo, N. E., and Neumann, G.: Evaluation of surface and near-surface melt characteristics on the Greenland ice sheet using MODIS and QuikSCAT data, *J. Geophys. Res.*, 114, 1–13, doi:10.1029/2009JF001287, 2009.
- Hall, D. K., Comiso, J. C., DiGirolamo, N. E., Shuman, C. A., Box, J. E., and Koenig, L. S.: Variability in the surface temperature and melt extent of the Greenland ice sheet from MODIS, *Geophys. Res. Lett.*, 40, 2114–2120, doi:10.1002/grl.50240, 2013.
- Hanna, E. and Huybrechts, P.: Runoff and mass balance of the Greenland ice sheet: 1958–2003, *J. Geophys. Res.*, 110, 1–16, doi:10.1029/2004JD005641, 2005.
- Hanna, E., Huybrechts, P., and Mote, T. L.: Surface mass balance of the Greenland ice sheet from climate-analysis data and accumulation/runoff models, *Ann. Glaciol.*, 35, 67–72, doi:10.3189/172756402781816744, 2002.
- Hanna, E., Huybrechts, P., Steffen, K., Cappelen, J., Huff, R., Shuman, C., Irvine-Fynn, T., Wise, S., and Griffiths, M.: Increased runoff from melt from the Greenland ice sheet: a response to global warming, *J. Climate*, 21, 331–341, doi:10.1175/2007JCLI1964.1, 2008.

## Data assimilation-based estimation of Greenland surface mass loss

M. Navari et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

- Hanna, E., Huybrechts, P., Cappelen, J., Steffen, K., Bales, R. C., Burgess, E., McConnell, J. R., Peder Steffensen, J., Van den Broeke, M., Wake, L., Bigg, G., Griffiths, M., and Savas, D.: Greenland ice sheet surface mass balance 1870 to 2010 based on twentieth century reanalysis, and links with global climate forcing, *J. Geophys. Res.*, 116, 121, doi:10.1029/2011JD016387, 2011.
- Hanna, E., Jones, J. M., Cappelen, J., Mernild, S. H., Wood, L., Steffen, K., and Huybrechts, P.: The influence of North Atlantic atmospheric and oceanic forcing effects on 1900–2010 Greenland summer climate and ice melt/runoff, *Int. J. Climatol.*, 33, 862–880, doi:10.1002/joc.3475, 2013.
- Heimbach, P. and Bugnion, V.: Greenland ice-sheet volume sensitivity to basal, surface and initial conditions derived from an adjoint model, *Ann. Glaciol.*, 50, 67–80, doi:10.3189/172756409789624256, 2009.
- Hook, S. and Vaughan, R.: in-flight validation of mid infrared and thermal infrared data from ASTER and MODIS on the Terra spacecraft using the Lake Tahoe, CA/NV, USA, automated validation, *IEEE T. Geosci. Remote*, 45, 1798–1807, doi:10.1109/TGRS.2007.894564, 2007.
- Hu, A., Meehl, G. A., Han, W., and Yin, J.: Effect of the potential melting of the Greenland ice sheet on the meridional overturning circulation and global climate in the future, *Deep-Sea Res. Pt. II*, 58, 1914–1926, doi:10.1016/j.dsr2.2010.10.069, 2011.
- Huang, C., Li, X., and Lu, L.: Retrieving soil temperature profile by assimilating MODIS LST products with ensemble Kalman filter, *Remote Sens. Environ.*, 112, 1320–1336, doi:10.1016/j.rse.2007.03.028, 2008.
- Khan, S. A., Kjær, K. H., Bevis, M., Bamber, J. L., Wahr, J., Kjeldsen, K. K., Bjørk, A. A., Korsgaard, N. J., Stearns, L. A., van den Broeke, M. R., Liu, L., Larsen, N. K., and Muresan, I. S.: Sustained mass loss of the northeast Greenland ice sheet triggered by regional warming, *Nature Climate Change*, 4, 292–299, doi:10.1038/nclimate2161, 2014.
- Larour, E., Utke, J., Csatho, B., Schenk, A., Seroussi, H., Morlighem, M., Rignot, E., Schlegel, N., and Khazendar, A.: Inferred basal friction and surface mass balance of the Northeast Greenland Ice Stream using data assimilation of ICESat (Ice Cloud and land Elevation Satellite) surface altimetry and ISSM (Ice Sheet System Model), *The Cryosphere*, 8, 2335–2351, doi:10.5194/tc-8-2335-2014, 2014.
- Lefebre, F.: Modeling of snow and ice melt at ETH Camp (West Greenland): a study of surface albedo, *J. Geophys. Res.*, 108, 4231, doi:10.1029/2001JD001160, 2003.

**Data  
assimilation-based  
estimation of  
Greenland surface  
mass loss**

M. Navari et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

Lefebre, F., Fettweis, X., Gallee, H., Ypersele, J. Van, Marbaix, P., Greuell, W., and Calanca, P.: Evaluation of a high-resolution regional climate simulation over, *Clim. Dynam.*, 25, 99–116, doi:10.1007/s00382-005-0005-8, 2005.

Lenaerts, J. T. M., van den Broeke, M. R., van Angelen, J. H., van Meijgaard, E., and Déry, S. J.: Drifting snow climate of the Greenland ice sheet: a study with a regional climate model, *The Cryosphere*, 6, 891–899, doi:10.5194/tc-6-891-2012, 2012.

Lewis, S. and Smith, L.: Hydrologic drainage of the Greenland ice sheet, *Hydrol. Process.*, 23, 2004–2011, doi:10.1002/hyp.7343, 2009.

Margulis, S. A., McLaughlin, D., Entekhabi, D., and Dunne, S.: Land data assimilation and estimation of soil moisture using measurements from the Southern Great Plains 1997 Field Experiment, *Water Resour. Res.*, 38, 35–1–35–18, doi:10.1029/2001WR001114, 2002.

Morlighem, M., Seroussi, H., Larour, E., and Rignot, E.: Inversion of basal friction in Antarctica using exact and incomplete adjoints of a higher-order model, *J. Geophys. Res.-Earth*, 118, 1746–1753, doi:10.1002/jgrf.20125, 2013.

Mote, T. L.: Ablation rate estimates over the Greenland ice sheet from microwave radiometric data from microwave radiometric data, *Prof. Geogr.*, 52, 322–331, doi:10.1111/0033-0124.00228, 2000.

Mote, T. L., Anderson, M. R., Kuivinen, K. C., and Rowe, C. M.: Passive microwave-derived spatial and temporal variations of summer melt on the Greenland ice sheet, *Ann. Glaciol.*, 17, 233–238, 1993.

Nghiem, S. V., Hall, D. K., Mote, T. L., Tedesco, M., Albert, M. R., Keegan, K., Shuman, C. A., DiGirolamo, N. E., and Neumann, G.: The extreme melt across the Greenland ice sheet in 2012, *Geophys. Res. Lett.*, 39, 1–6, doi:10.1029/2012GL053611, 2012.

Pauwels, V. R. N., Hoeben, R., Verhoest, N. E. C., and De Troch, F. P.: The importance of the spatial patterns of remotely sensed soil moisture in the improvement of discharge predictions for small-scale basins through data assimilation, *J. Hydrol.*, 251, 88–102, doi:10.1016/S0022-1694(01)00440-1, 2001.

Pritchard, H. D., Arthern, R. J., Vaughan, D. G., and Edwards, L. A.: Extensive dynamic thinning on the margins of the Greenland and Antarctic ice sheets, *Nature*, 461, 971–975, doi:10.1038/nature08471, 2009.

Reichle, R. H.: Data assimilation methods in the Earth sciences, *Adv. Water Resour.*, 31, 1411–1418, doi:10.1016/j.advwatres.2008.01.001, 2008.

## Data assimilation-based estimation of Greenland surface mass loss

M. Navari et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

- Reichle, R. H., McLaughlin, D. B., and Entekhabi, D.: Hydrologic data assimilation with the ensemble Kalman filter, *Mon. Weather Rev.*, 130, 103–114, doi:10.1175/1520-0493(2002)130<0103:HDAWTE>2.0.CO;2, 2002.
- Rignot, E. and Kanagaratnam, P.: Changes in the velocity structure of the Greenland ice sheet, *Science*, 311, 986–990, doi:10.1126/science.1121381, 2006.
- Rignot, E., Box, J. E., Burgess, E., and Hanna, E.: Mass balance of the Greenland ice sheet from 1958 to 2007, *Geophys. Res. Lett.*, 35, L20502, doi:10.1029/2008GL035417, 2008.
- Rignot, E., Koppes, M., and Velicogna, I.: Rapid submarine melting of the calving faces of West Greenland glaciers, *Nat. Geosci.*, 3, 187–191, doi:10.1038/ngeo765, 2010.
- Rignot, E., Velicogna, I., van den Broeke, M. R., Monaghan, A., and Lenaerts, J. T. M.: Acceleration of the contribution of the Greenland and Antarctic ice sheets to sea level rise, *Geophys. Res. Lett.*, 38, L05503, doi:10.1029/2011GL046583, 2011.
- Shuman, C. A., Alley, R. B., Anandakrishnan, S., White, J. W. C., Grootes, P. M., and Stearns, C. R.: Temperature and accumulation at the Greenland Summit: comparison of high-resolution isotope profiles and satellite passive microwave brightness temperature trends, *J. Geophys. Res.*, 100, 9165, doi:10.1029/95JD00560, 1995.
- Smith, L. C., Chu, V. W., Yang, K., Gleason, C. J., Pitcher, L. H., Rennermalm, A. K., Legleiter, C. J., Behar, A. E., Overstreet, B. T., Moustafa, S. E., Tedesco, M., Forster, R. R., LeWinter, A. L., Finnegan, D. C., Sheng, Y., and Balog, J.: Efficient meltwater drainage through supraglacial streams and rivers on the southwest Greenland ice sheet, *P. Natl. Acad. Sci. USA*, 2000, 201413024, doi:10.1073/pnas.1413024112, 2015.
- Steffen, K., Box, J. E., and Abdalati, W.: Greenland Climate Network: GC-Net, 96-27 Special Report on Glaciers, Ice Sheets and Volcanoes, trib. to M. Meier, cooperative institute for research in environmental sciences (CRREL), CO, USA, 103 pp., 1996.
- Straneo, F. and Heimbach, P.: North Atlantic warming and the retreat of Greenland's outlet glaciers, *Nature*, 504, 36–43, doi:10.1038/nature12854, 2013.
- Tedesco, M.: Snowmelt detection over the Greenland ice sheet from SSM/I brightness temperature daily variations, *Geophys. Res. Lett.*, 34, 1–6, doi:10.1029/2006GL028466, 2007.
- Tedesco, M., Serreze, M., and Fettweis, X.: Diagnosing the extreme surface melt event over southwestern Greenland in 2007, *The Cryosphere Discuss.*, 2, 383–397, doi:10.5194/tcd-2-383-2008, 2008.

---

**Data  
assimilation-based  
estimation of  
Greenland surface  
mass loss**

M. Navari et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

Tedesco, M., Fettweis, X., van den Broeke, M. R., van de Wal, R. S. W., Smeets, C. J. P. P., van de Berg, W. J., Serreze, M. C., and Box, J. E.: The role of albedo and accumulation in the 2010 melting record in Greenland, *Environ. Res. Lett.*, 6, 014005, doi:10.1088/1748-9326/6/1/014005, 2011.

5 Tedesco, M., Fettweis, X., Mote, T., Wahr, J., Alexander, P., Box, J. E., and Wouters, B.: Evidence and analysis of 2012 Greenland records from spaceborne observations, a regional climate model and reanalysis data, *The Cryosphere*, 7, 615–630, doi:10.5194/tc-7-615-2013, 2013.

10 Thomas, R. H. and Investigators, P.: Program for Arctic Regional Climate Assessment (PARCA): goals, key findings, and future directions, *J. Geophys. Res.*, 106, 33691–33705, doi:10.1029/2001JD900042, 2001.

Thomas, R., Frederick, E., Krabill, W., Manizade, S., and Martin, C.: Progressive increase in ice loss from Greenland, *Geophys. Res. Lett.*, 33, 2–5, doi:10.1029/2006GL026075, 2006.

15 van Angelen, J. H., Lenaerts, J. T. M., Lhermitte, S., Fettweis, X., Kuipers Munneke, P., van den Broeke, M. R., van Meijgaard, E., and Smeets, C. J. P. P.: Sensitivity of Greenland ice sheet surface mass balance to surface albedo parameterization: a study with a regional climate model, *The Cryosphere*, 6, 1175–1186, doi:10.5194/tc-6-1175-2012, 2012.

20 Van den Broeke, M., Bamber, J., Ettema, J., Rignot, E., Schrama, E., van de Berg, W. J., van Meijgaard, E., Velicogna, I., and Wouters, B.: Partitioning recent Greenland mass loss, *Science*, 326, 984–986, doi:10.1126/science.1178176, 2009.

van de Wal, R. S. W., Boot, W., Smeets, C. J. P. P., Snellen, H., van den Broeke, M. R., and Oerlemans, J.: Twenty-one years of mass balance observations along the K-transect, West Greenland, *Earth Syst. Sci. Data*, 4, 31–35, doi:10.5194/essd-4-31-2012, 2012.

25 Velicogna, I. and Wahr, J.: Greenland mass balance from GRACE, *Geophys. Res. Lett.*, 32, 10–13, doi:10.1029/2005GL023955, 2005.

Vernon, C. L., Bamber, J. L., Box, J. E., van den Broeke, M. R., Fettweis, X., Hanna, E., and Huybrechts, P.: Surface mass balance model intercomparison for the Greenland ice sheet, *The Cryosphere*, 7, 599–614, doi:10.5194/tc-7-599-2013, 2013.

30 Wan, Z., Zhang, Y., Zhang, Q., and Li, Z.: Validation of the land-surface temperature products retrieved from terra moderate resolution imaging spectroradiometer data, *Remote Sens. Environ.*, 83, 163–180, doi:10.1016/S0034-4257(02)00093-7, 2002.

**Data  
assimilation-based  
estimation of  
Greenland surface  
mass loss**

M. Navari et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



- Wouters, B., Bamber, J. L., van den Broeke, M. R., Lenaerts, J. T. M., and Sasgen, I.: Limits in detecting acceleration of ice sheet mass loss due to climate variability, *Nat. Geosci.*, 6, 613–616, doi:10.1038/ngeo1874, 2013.
- 5 Xu, T., Liu, S., Liang, S., and Qin, J.: Improving predictions of water and heat fluxes by assimilating MODIS land surface temperature products into the common land model, *J. Hydrometeorol.*, 12, 227–244, doi:10.1175/2010JHM1300.1, 2011.
- 10 Zhang, Y.-F., Hoar, T. J., Yang, Z.-L., Anderson, J. L., Toure, A. M., and Rodell, M.: Assimilation of MODIS snow cover through the data assimilation research testbed and the community land model version 4, *J. Geophys. Res.-Atmos.*, 119, 7091–7103, doi:10.1002/2013JD021329, 2014.

## Data assimilation-based estimation of Greenland surface mass loss

M. Navari et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

**Table 1.** Postulated parameters (coefficient of variation, CV, and cross-correlation) for multiplicative perturbations to hourly meteorological forcing inputs (the units for each forcing are:  $P$  in mm,  $R_s$  and  $R_l$  in  $\text{W m}^{-2}$  and  $T_a$  in K).

Perturbation	CV	Cross correlation			
		$P$	$R_s$	$R_l$	$T_a$
Precipitation ( $P$ )	0.5	1.0	-0.1	0.5	-0.1
Shortwave ( $R_s$ )	0.2	-0.1	1.0	-0.3	0.3
Longwave ( $R_l$ )	0.1	0.5	-0.3	1.0	0.6
Air temperature ( $T_a$ )	0.005	-0.1	0.3	0.6	1.0

## Data assimilation-based estimation of Greenland surface mass loss

M. Navari et al.

**Table 2.** The spatial mean bias, the spatial RMSE, and improvement factor  $\kappa$  for the prior and posterior estimates of the forcing variables via assimilation of IST over the entire GrIS.

	$R_s$ ( $\text{MJm}^{-2}\text{yr}^{-1}$ )	$R_l$ ( $\text{MJm}^{-2}\text{yr}^{-1}$ )	PDD ( $^{\circ}\text{C}\text{-day}$ )	NDD ( $^{\circ}\text{C}\text{-day}$ )
Prior Bias	−82.0	−25.6	−16.7	−8.0
Posterior Bias	−12.8	+4.6	−1.0	−2.8
Prior RMSE	791.6	549.1	33.3	394.6
Posterior RMSE	241.3	97.9	9.7	55.4
$\kappa$	452.2	375.0	13.8	257.0

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

## Data assimilation-based estimation of Greenland surface mass loss

M. Navari et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**Table 3.** The spatial mean bias and the spatial RMSE of runoff, sublimation/evaporation, surface solid condensation, and net mass loss estimates via assimilation of IST measurements.

	Runoff (mm WE)	Sublimation (mm WE)	SSC (mm WE)	Surface mass loss (mm WE)
Prior Bias	−551.6	−3.1	−0.5	−38.9
Posterior Bias	−54.0	−0.3	−0.1	−3.8
Prior RMSE	646.1	14.7	4.6	174.1
Posterior RMSE	249.8	5.3	1.1	66.9

## Data assimilation-based estimation of Greenland surface mass loss

M. Navari et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

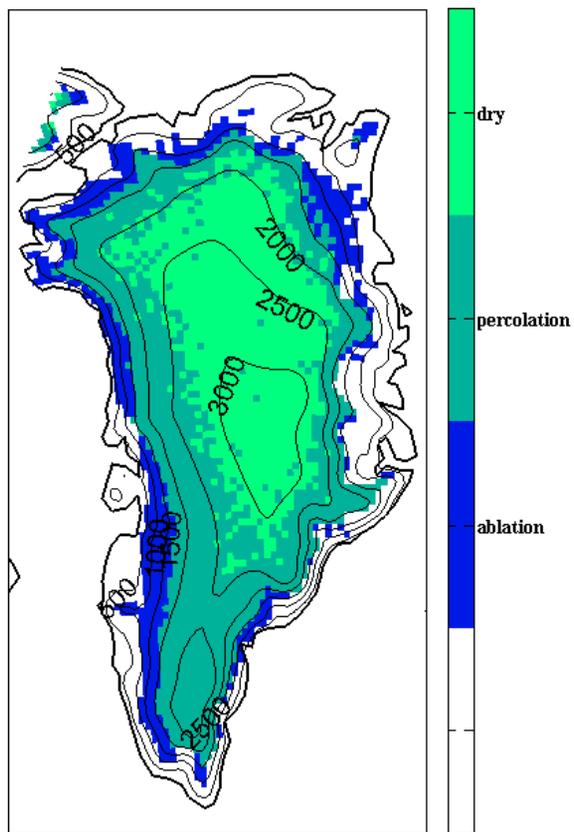
Full Screen / Esc

Printer-friendly Version

Interactive Discussion

**Table 4.** The spatial RMSE of runoff, sublimation/evaporation, surface solid condensation, and net mass loss estimates via assimilation of IST measurements for three different true values.

True Runoff (mm)		Runoff (mm)	Sublimation (mm)	SSC (mm)	Surface mass loss (mm)
330	Prior	348.9	13.4	4.7	92.8
	Posterior	249.2	4.8	1.1	63.6
400 (baseline)	Prior	646.1	14.7	4.6	174.1
	Posterior	249.8	5.3	1.1	66.9
470	Prior	894.4	16.0	4.6	245.1
	Posterior	259.4	5.2	1.1	70.7



**Figure 1.** The Greenland ice sheet mask (filled area), including the ablation zone (blue), the percolation zone (dark green), and the dry snow zone (bright green) based on an offline CROCUS simulation for the year 2010. The contour lines show the topography of the ice sheet with an interval of 500 m.

Data  
assimilation-based  
estimation of  
Greenland surface  
mass loss

M. Navari et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

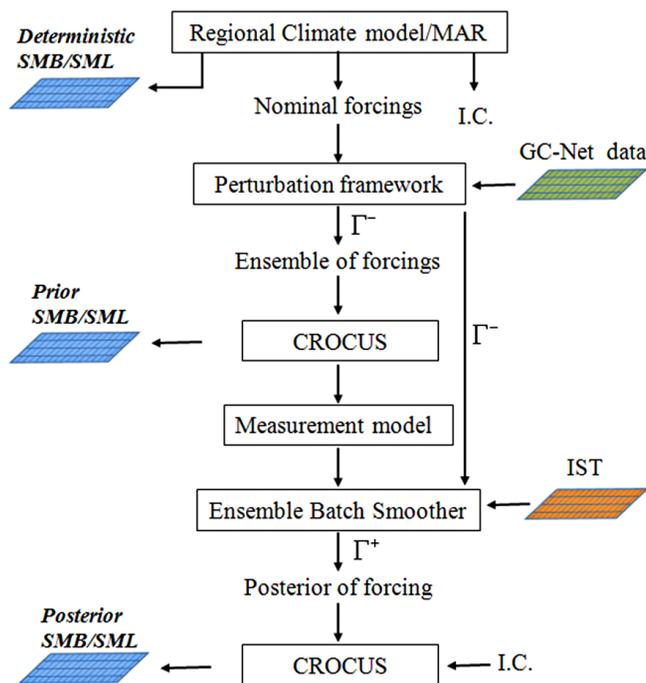
Printer-friendly Version

Interactive Discussion



## Data assimilation-based estimation of Greenland surface mass loss

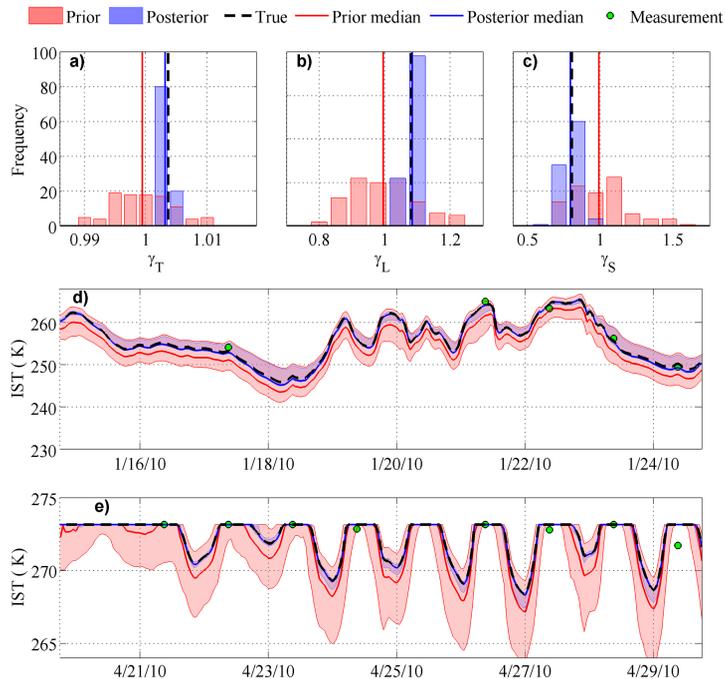
M. Navari et al.



**Figure 2.** Schematic illustration of the proposed methodology. The posterior SMB/SML is effectively a post-processing (reanalysis) of regional climate model (in this case MAR) estimates conditioned on IST measurements.

## Data assimilation-based estimation of Greenland surface mass loss

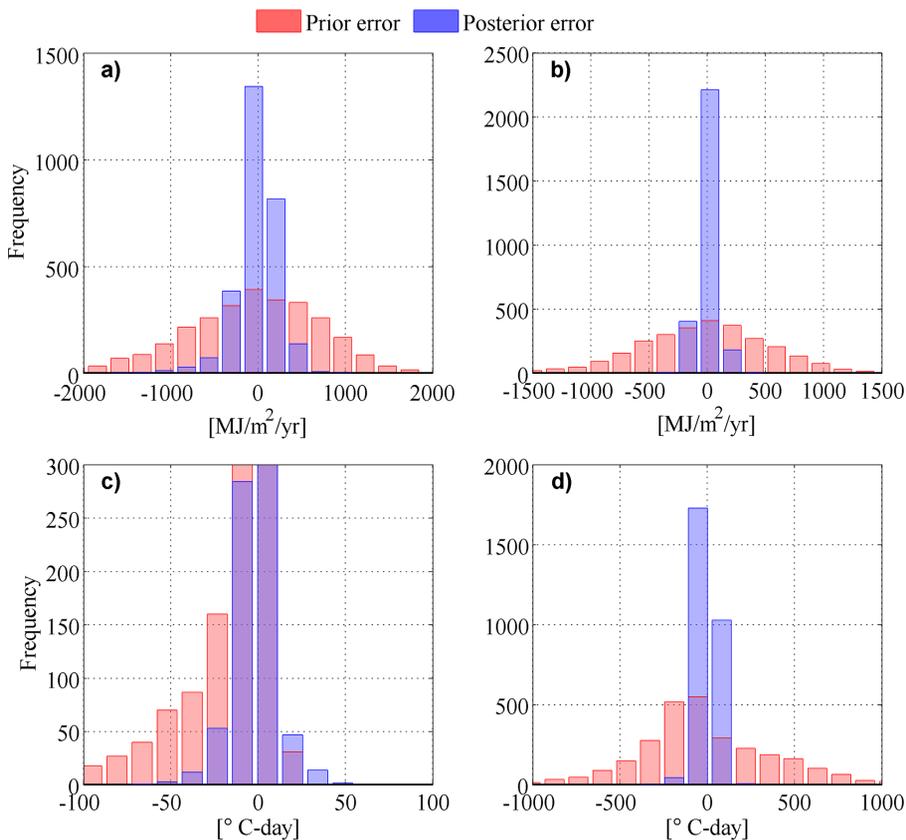
M. Navari et al.



**Figure 3.** Ensemble histogram of the prior (red bars) and the posterior (after assimilation of IST) multiplicative states (blue bars) for **(a)** surface air temperature, **(b)** longwave radiation, **(c)** shortwave radiation for a sample pixel in the ablation zone. The prior (red line) and posterior (blue line) median values and truth (black line) are also shown for reference. The time series of: **(d)** the IST for the 10 day period during the dry season and **(e)** the IST for the 10 day period during the melt season. The red and blue shaded areas represent the prior and posterior uncertainty band (interquartile range) and the red, blue, and black lines represent the median of the prior, the median of the posterior and the truth, respectively. The green circles represent the synthetically generated (noisy) IST measurements that are assimilated to generate the posterior estimates.

Data assimilation-based estimation of Greenland surface mass loss

M. Navari et al.



**Figure 4.** The histogram of the prior errors (red) and posterior (after assimilation of IST) errors (blue) for cumulative (a) shortwave radiation, (b) longwave radiation, (c) PDD, and (d) NDD over the full GrIS.

Title Page

Abstract Introduction

Conclusions References

Tables Figures

◀ ▶

◀ ▶

Back Close

Full Screen / Esc

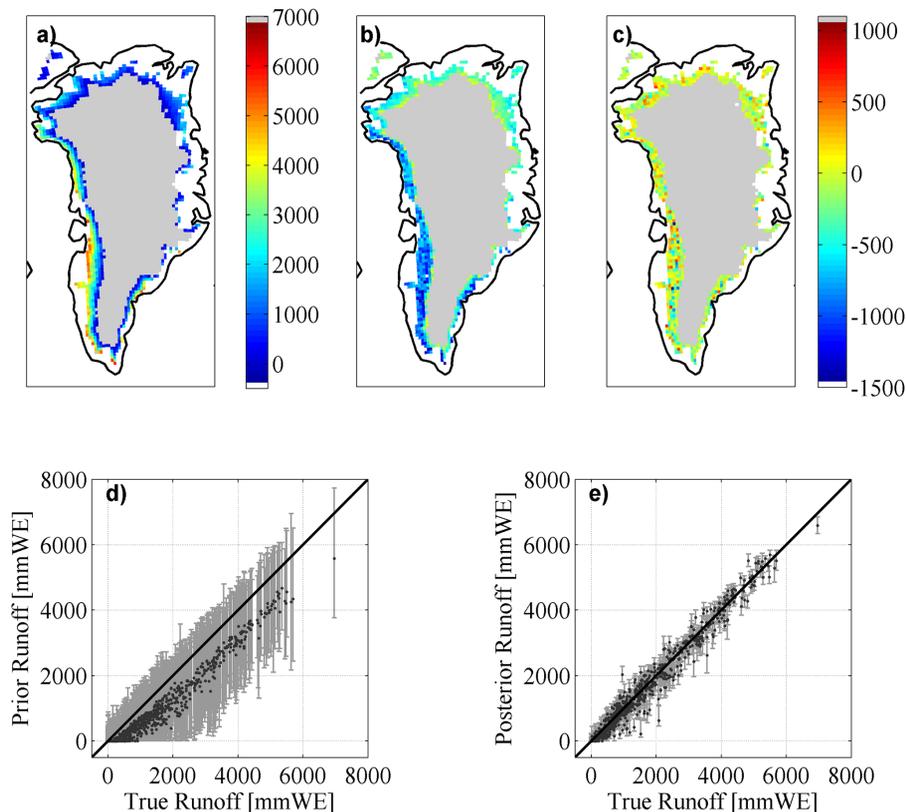
Printer-friendly Version

Interactive Discussion



Data  
assimilation-based  
estimation of  
Greenland surface  
mass loss

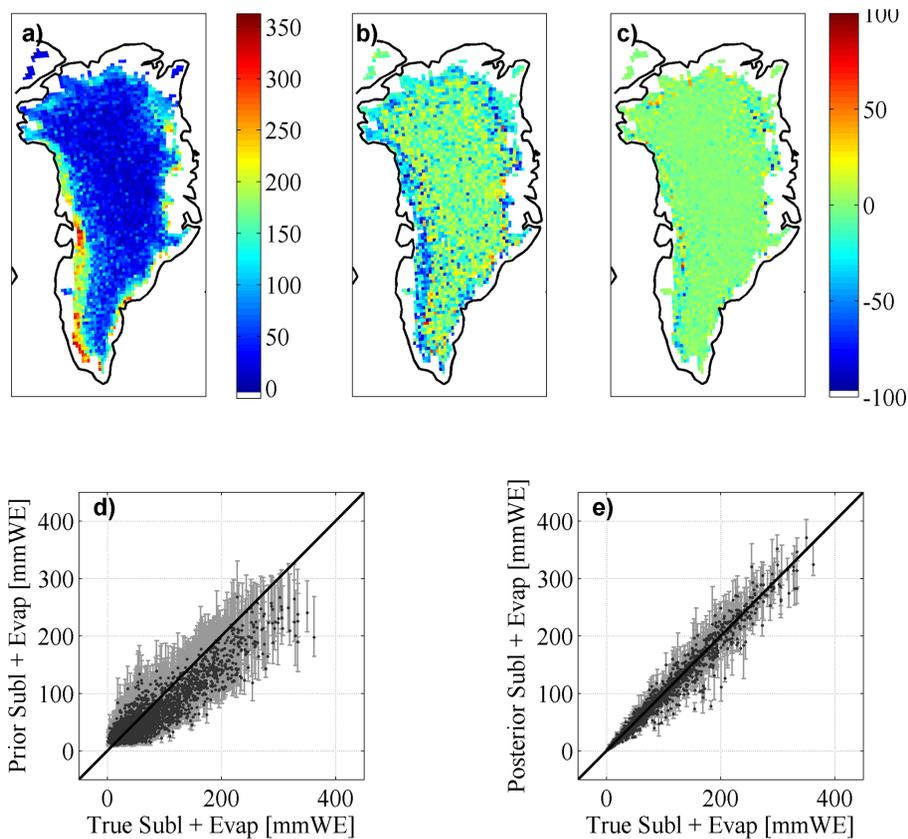
M. Navari et al.



**Figure 5.** The (a) synthetic true runoff ( $\text{mm WE yr}^{-1}$ ) for the year 2010, (b) runoff anomaly ( $\text{mm WE yr}^{-1}$ ) for the prior (i.e., difference between the prior and true runoff), (c) runoff anomaly ( $\text{mm WE yr}^{-1}$ ) for the posterior, (d) scatter plot of the prior runoff estimates, (e) scatter plot of the posterior runoff estimates. Black dots are the ensemble median of the estimates and the error bars represent the corresponding ensemble interquartile range of the estimates.

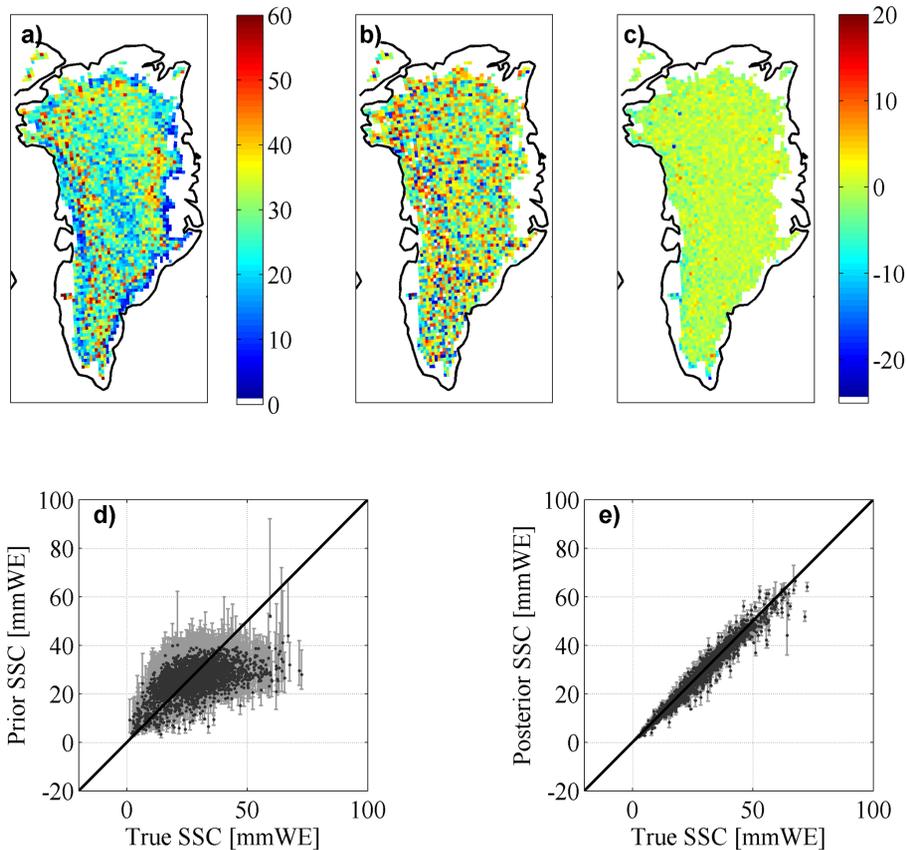
Data  
assimilation-based  
estimation of  
Greenland surface  
mass loss

M. Navari et al.



**Figure 6.** The same as Fig. 5 but for sublimation and evaporation.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)



**Figure 7.** The same as Fig. 5 but for surface solid condensation (SSC).

**Data  
assimilation-based  
estimation of  
Greenland surface  
mass loss**

M. Navari et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

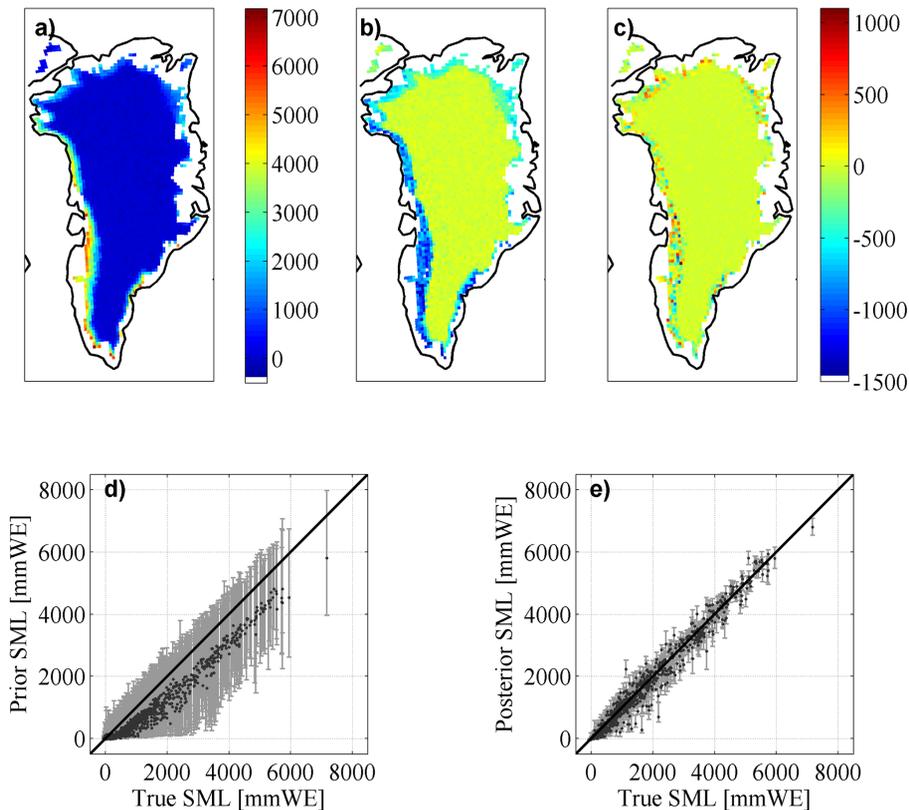
Printer-friendly Version

Interactive Discussion



**Data  
assimilation-based  
estimation of  
Greenland surface  
mass loss**

M. Navari et al.



**Figure 8.** The same as Fig. 5 but for the GrIS surface mass loss (SML).

Title Page

Abstract Introduction

Conclusions References

Tables Figures

◀ ▶

◀ ▶

Back Close

Full Screen / Esc

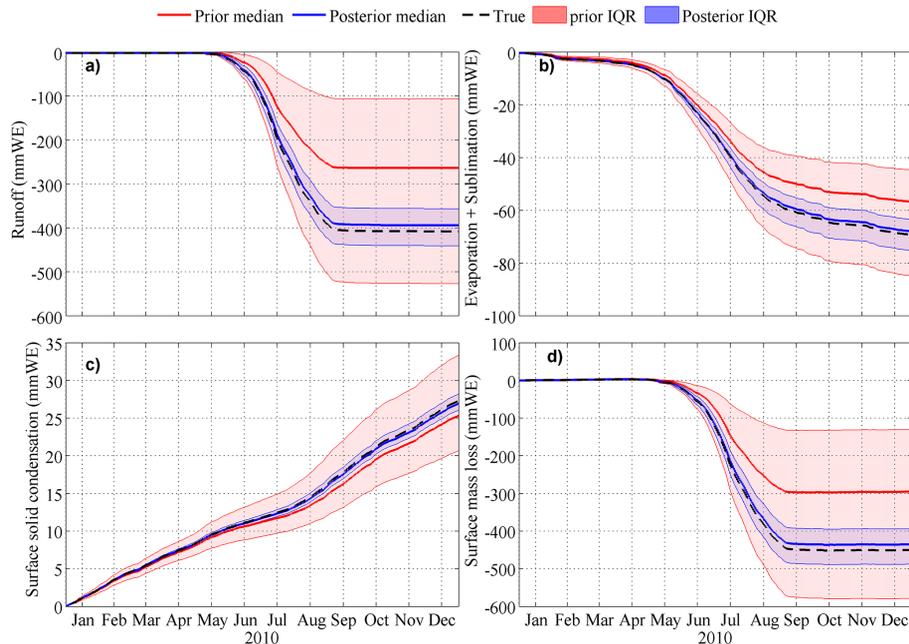
Printer-friendly Version

Interactive Discussion



## Data assimilation-based estimation of Greenland surface mass loss

M. Navari et al.



**Figure 9.** The time series of: **(a)** cumulative runoff, **(b)** cumulative sublimation and evaporation, **(c)** cumulative surface solid condensation, and **(d)** cumulative mass loss over the GrIS (in millimetres of water equivalent). The truth is the black dashed line, the prior ensemble median is the red line and the posterior ensemble median is the blue line. The red shaded area corresponds to the ensemble interquartile range (IQR) for the prior simulation and the blue shaded area corresponds to the ensemble IQR for the posterior estimates.

[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)
[◀](#)
[▶](#)
[◀](#)
[▶](#)
[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)