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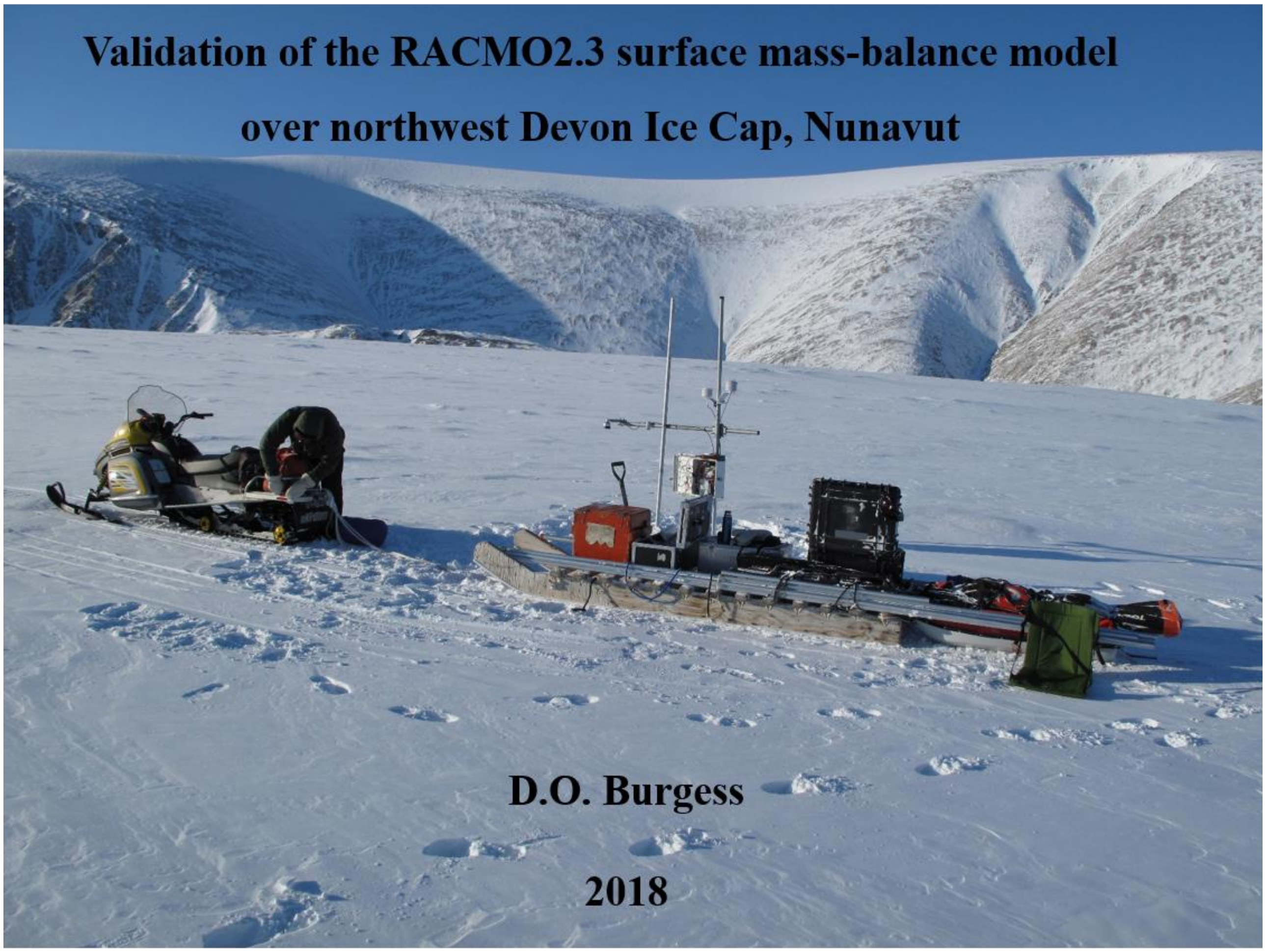

Validation of the RACMO2.3 surface mass-balance model over northwest Devon Ice Cap, Nunavut

D.O. Burgess

2018

Canada

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ABSTRACT

The RACMO2.3 regional climate model has been validated against *in-situ* mass-balance measurements along the northwest Devon ice cap transect (herein after referred to as Devon(NW)) at annual, pentadal, and decadal time scales over the period spanning 2006 to 2015. Results show close agreement between *Summer Balance* measurements at the pentadal and decadal time scales, with a bias towards suppressed melt by ~200 mm w.e. in the RACMO2.3 data averaged over the entire transect (ie. 100 – 1800 m a.s.l.), and maximum biases to ~600 mm w.e. between 400 and 900 m a.s.l. Comparisons at the annual scale indicate greatest discrepancies for 2010 for which RACMO2.3 was up to 80 cm w.e. less negative than the *in-situ* values. *Winter Balance* in the RACMO2.3 data showed an inverse elevational trend relative to the *in-situ values* with an overall bias towards greater accumulation by ~120 mm w.e. along the entire transect. At the basin-wide scale, RACMO2.3 under (over) estimates of summer (winter) balance values combine to result in basin-wide estimates of net balance for the Devon (NW) basin to be 37% less negative than the *in-situ* measurements over the 2006-2015 period. Reasonable agreement with *in-situ* derived *Summer Balance* values indicates RACMO2.3 can provide estimates of seasonal freshwater flux to oceans close to and within error of the measurements. However, significant biases in the RACMO2.3 *Net Annual Balance* modeled values must be accounted for when estimating annual or multi-annual contributions to global sea-level rise from glaciers and ice caps in the Canadian high Arctic.

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1. INTRODUCTION

Canada's Arctic glaciers lose ice mass primarily through surface melting (and runoff), and ice-calving from tidewater terminating glaciers. Recent climate warming has significantly enhanced melting of Canada's Arctic glaciers and ice caps resulting in mass losses ~5 times higher since 2005 relative to the 1960-2004 average. This recent shift to accelerated glacier melting has resulted in Canada's ice caps and glaciers becoming important contributors to global sea-level rise (Gardner et al., 2011), with additional implications for marine ecosystems and ocean circulation patterns in response to changes in the freshwater budget of the Arctic ocean.

Assessing the impacts of enhanced run-off from glaciers and ice caps in the Canadian Arctic requires knowledge of the broad-scale patterns of surface mass-balance gained primarily through regional mass-balance models. In this study, performance of the Regional Atmospheric Climate Model, or RACMO2.3, is validated through comparison with results from the NRCan in-situ glacier monitoring over the Devon Ice Cap (NW) basin. The level of correspondence between the modeled and measured summer mass-balance values provide an indication of the accuracy with which meltwater flux and the ice cap and drainage basin scales can be quantified over Canadian ice caps from RACMO2.3. Comparisons between RACMO2.3 and *In-situ* derived mass-balance values focus on the post-2005 period, during which time mass loss from ice caps and glaciers in the Canadian high Arctic has been significantly more negative than the historical averages (Sharp et al., 2011; Fisher et al., 2011).

2. STUDY SITE

Occupying approximately 14,000 km^2 of eastern Devon Island, Nunavut, the Devon Ice Cap is located in the Southeast sector of the QEI (Figure 1). The elevation of the Devon Ice Cap ranges from sea-level where most outlet glaciers that drain the ice cap terminate, to ~1920 m a.s.l. at the ice cap summit. While the ice cap does lose some mass through iceberg calving (Burgess et. al., 2005), the main form of ablation is through surface mass-balance which is controlled primarily by the intensity and duration of summer melt (Koerner, 2005; Gardner, et. al., 2011; Millan et. al., 2017). Surface mass-balance measurements on Devon Ice Cap began in 1960 along the Northwest transect (Figure 2) spanning nearly the entire elevation range (0 –

1800 m a.s.l.) of the ice cap. Mass-balance of the Devon Ice Cap (NW) remained only slightly negative up to the mid 1990's, then shifted to a period of increasingly negative mass-balance after 2005 when melt rates became ~4 times greater than the long-term average (Sharp, et al., 2011).

3. DATA and METHOD

3.1 RACMO2.3

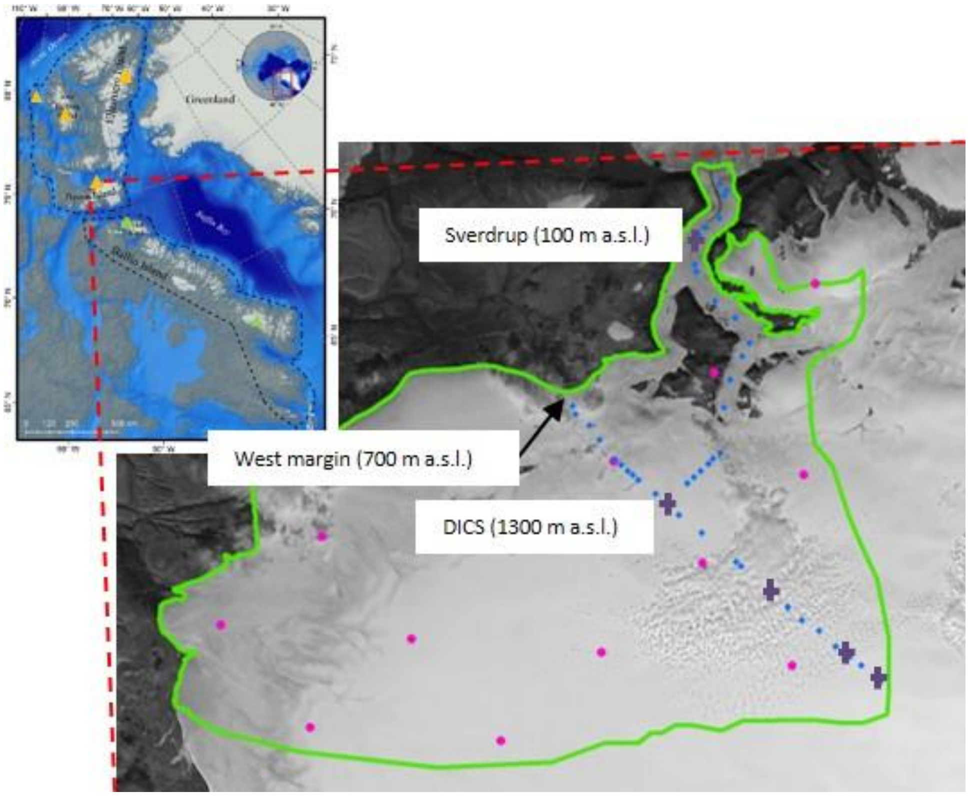
RACMO2.3 is a Regional Atmospheric Climate Model developed by the Royal Netherlands Meteorological Institute in-conjunction with the Danish Meteorological Institute to provide surface mass-balance (ie. accumulation and melting) of glacierized surfaces a the scale of ice sheets and polar ice caps, including those in the Canadian Arctic. The model incorporates the High Resolution Limited Area Model (HIRLAM) atmospheric model with a multi-layer snow model that accounts for meltwater percolation, refreezing, and run-off (Noel et al., 2015). An important improvement to RACMO2.3 over the previous version (RACMO2.1) is better atmospheric physics, which more accurately discriminates between liquid (rain) and solid (snow) precipitation at the glacier surface, both of which have significant but contrasting influences on surface melt and runoff. RACMO2.3 models surface mass-balance at a spatial resolution of 11 km which limits coverage at lower elevations of smaller ice masses such as those in the Canadian Arctic.

3.2 *In-situ* Mass-balance Measurements

Annual glacier mass-balance surveys are conducted along the Devon Ice Cap (NW) monitoring transect which extends from ~1800 m a.s.l. near the ice cap summit, to the terminus of the Sverdrup Glacier, with a second transect branching off at Devon Ice Cap Station (DICS) at 1300m a.s.l. and extending to the west margin at ~800 m a.s.l. (Figure 1). The transects sample surface mass-balance throughout all glaciological zones on the Devon Ice Cap including the percolation (~1800-1600 m a.s.l.), saturation (~1600-1400 m a.s.l.), superimposed ice (~1400-1300 m a.s.l.), and glacier ice (1300-0 m a.s.l.) zones. Surface mass-balance is measured at 38 aluminum poles drilled 1 – 4 meters into the ice cap surface, and high temporal resolution meteorological data collected from 5 automatic weather stations (AWS's) along the transect. AWS's record 2m ambient air temperature and relative changes in height of the snow/ice cap surface at one-minute intervals and record hourly averages. Temperature is measured using Campbell Scientific 44212 temperature probes (+/- 0.1 ^{o}C) mounted 1-2 m above the ice cap surface within R.M. Young Solar radiation shields. Snow/ice surface height is measured using Campbell Scientific SR50A Sonic Rangers (+/- 1 cm). Data from the AWS's provide high temporal resolution information on the occurrence of weather events (ie. melting, snowfall, wind, and rain) that augment and improve interpretation of the pole observations.

Glacier *Net Balance* is derived using the Stratigraphic System (Cogley et al., 2011) whereby mass change of the ice cap surface over the course of one year is calculated as the water equivalent (w.e.) difference between successive annual measurements of pole length above the previous end-of-summer surface. Pole measurements obtained in the spring visits of 2015 and 2016 provide information needed to calculate net balance for the late summer 2014 to late summer 2015 time interval. *Winter Balance* is calculated as the snow water equivalency of the winter snowpack as determined from snow depth and density, which are measured at regular sampling intervals across the networks. *Summer Balance* is calculated as:

$$Summer\ Balance = Net\ Balance - Winter\ Balance \qquad \textit{Equation 1}$$



▲ Long-term mass balance monitoring sites (QEI)
▲ Long-term mass balance monitoring sites (Baffin)
● RACMO model points
◆ In-situ pole
✚ Automatic Weather Station

Figure 1. Location of Devon ice cap (NW basin) site used for validating RACMO2.3 mass-balance model over the Canadian Arctic ice caps. Background image is a panchromatic LandSat satellite scene acquired over the Devon Ice Cap, NU on July 21, 1999.

4. RESULTS

Preliminary assessment of the RACMO2.3 modeled point values was conducted by comparing RACMO2.3 surface mass-balance data points in the Devon Ice Cap (NW) basin, with *in-situ* measurements along the mass-balance transect (Figure 1). Due to lack of coverage at lower elevations, the RACMO2.3 *Summer Balance* data points were extrapolated below 700 m a.s.l as a function of the average mass-balance gradient (ie. 0.8 kg m^{-2} a^{-1} m^{-1}) for 2006-2015 as calculated from the *in-situ* data along the Northwest transect. RACMO2.3 *Winter Balance* was extrapolated simply by assuming a constant value of below 700 m a.s.l.

As only ~10% of the Devon Ice Cap (NW) basin area is situated below 700 m a.s.l. (Figure 2), extrapolating seasonal balance values to sea-level has little effect (< 1%) on the basin-wide mass-balance. However, in sectors of the ice cap where large portions of the ice cap area terminate at sea-level (ie. Southeast basin), extrapolation to lower elevations is likely to improve basin-wide estimates of total mass-balance significantly.

4.1 Along Transect Measurements

4.11 Summer Balance (JJA)

Visual inspection of the plots in Figure 3 indicate close agreement between the modeled and measured trends of Summer mass-balance for years 2006, 2008, 2011, 2014, and 2015. Moderate discrepancies occurred in 2009 when RACMO2.3 indicated slightly ***<u>less</u>*** negative summer balance values than the *In-situ* data, and in 2007 when RACMO2.3 indicated slightly ***<u>more</u>*** negative summer balance values than the *In-situ* data. Significant discrepancies between the modeled and measured values occurred in 2010, 2012, and 2013 when RACMO2.3 indicated significantly ***<u>less</u>*** negative summer mass-balance than the *In-situ* measured values. In all cases except 2007, the greatest discrepancies occur between ~400 – 900 m a.s.l. where enhanced melting according to the *In-situ* measurements has likely resulted due to increased heat absorption and radiance from mountain valley walls, while melt suppressing effects of cloud below ~300 m a.s.l. reduce melt rates at the glacier terminus (Koerner, 2005).

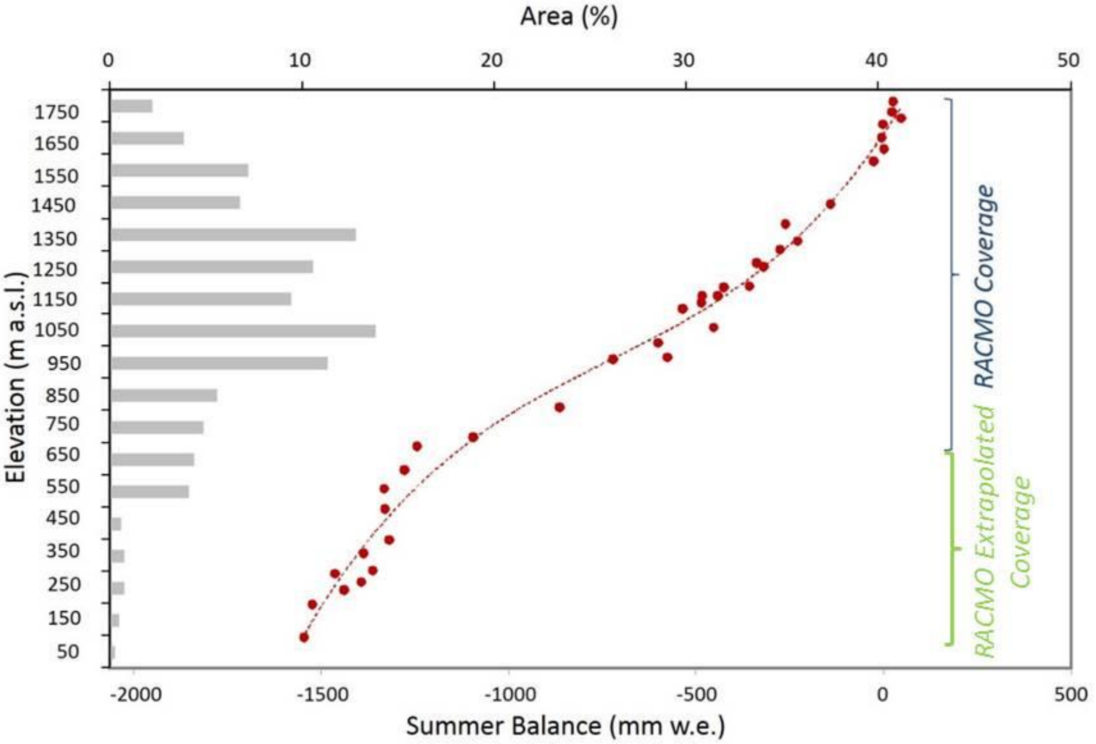


Figure 2. Hypsometry (gray bars) and corresponding in-situ Summer Balance (2006-2015 average) and 3rd order polynomial trend line for the Devon Ice Cap (NW) basin. Brackets on the right hand side of the plot indicate the elevation ranges for which RACMO2.3 data covered (blue) and for which elevations they were extrapolated (green).

In-situ and RACMO2.3 derived summer balance values averaged over five- and ten-year time intervals indicate good agreement time between the measured and modeled estimates of mass-balance (Figure 4). In all cases, there is a slight bias towards less negative (more positive) mass-balance in the RACMO2.3 and extrapolated RACMO2.3 data, with maximum discrepancies occurring between 700 and 400 m a.s.l. This effect is particularly evident in the 2006-2010 and 2006-2015 averages, the causes for which were indicated above.

4.12 Winter Balance (Sept-May)

Plots of the five- and ten-year averaged winter balance (Figure 5) reveal significant discrepancies between the *in-situ* and RACMO2.3 modeled values. The common trend in all plots is for RACMO2.3 to under estimate above 1650 m a.s.l., and significantly overestimate winter precipitation below ~1000 m a.s.l. While some individual years do show good correspondence between RACMO2.3 and *in-situ* winter balance values (not shown here), the pentadal and decadal trends indicate enhanced accumulation towards low elevations by RACMO2.3. If these trends are an artifact of the modelling process whereby precipitation is linked to ‘proximity to the ocean source’ rather than orographic effects, the extrapolated values below 700 m a.s.l. as applied in this study under-estimates the winter balance according to the modelled trend.

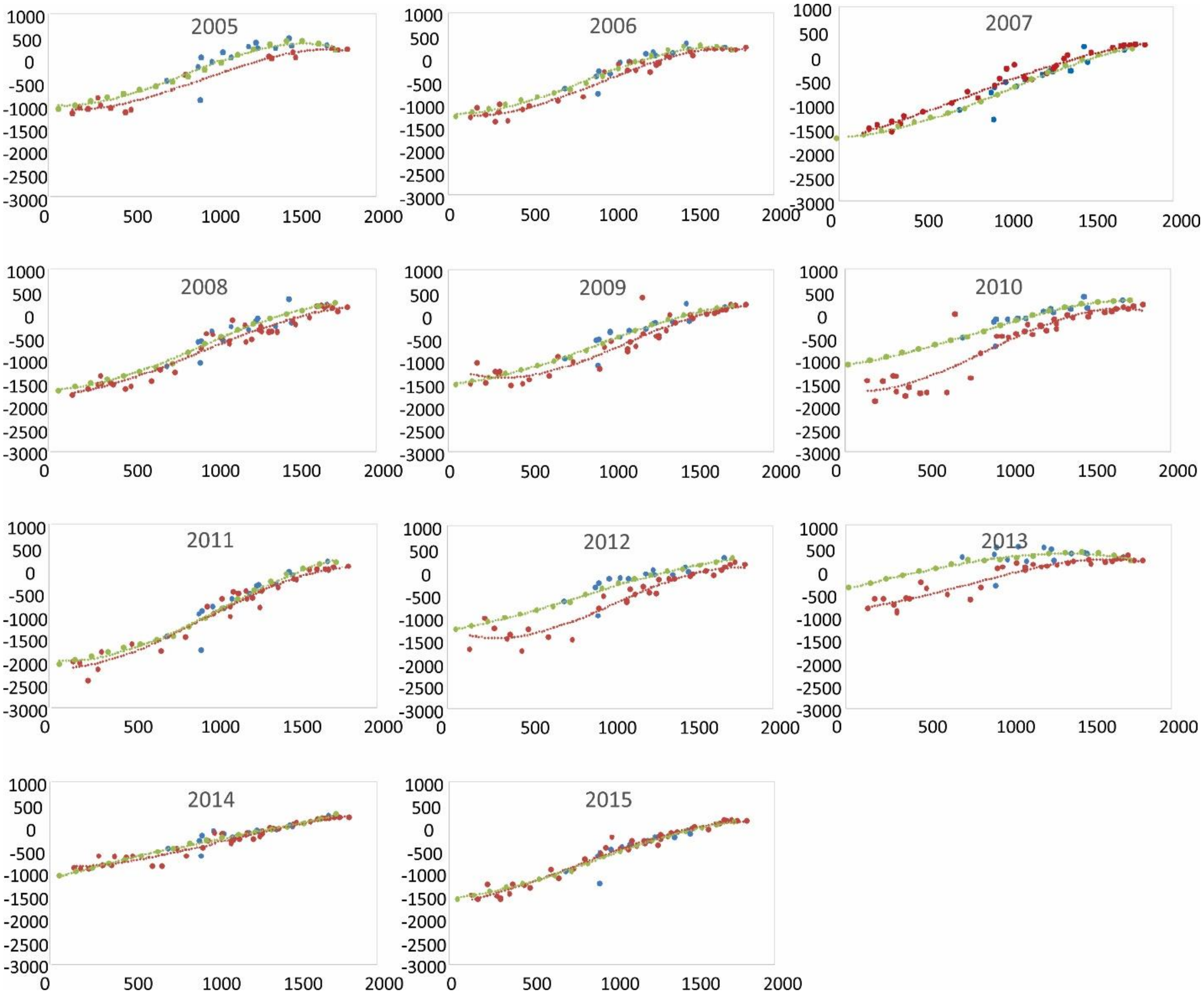


Figure 3. Annual summer mass-balance values (2006-2015) derived from the In-situ pole measurements (red dots) and 3rd order polynomial trend line through the In-situ point values (red dashed line). RACMO2.3 modeled values shown as blue dots, and RACMO2.3 modeled values extrapolated to 50 m a.s.l. as green dots. Y-axes indicates Summer Balance (mm water equivalent) and x-axes indicates Elevation (m a.s.l.).

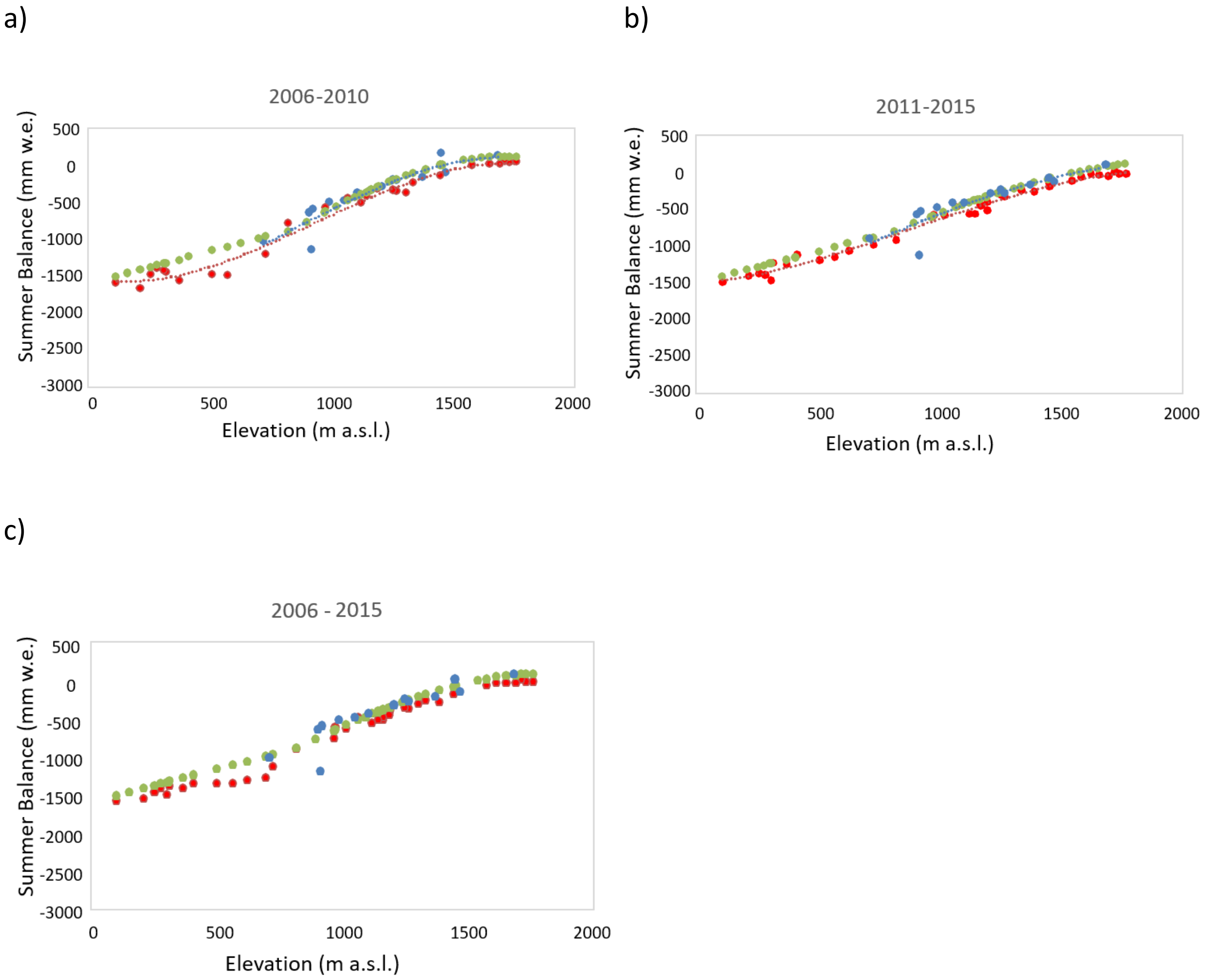


Figure 4. Five (a and b) and ten year (c) average Summer balance values of the In-situ pole measurements (red), RACMO2.3 modeled values (blue), and RACMO2.3 modeled values (green) extrapolated to 50 m a.s.l.

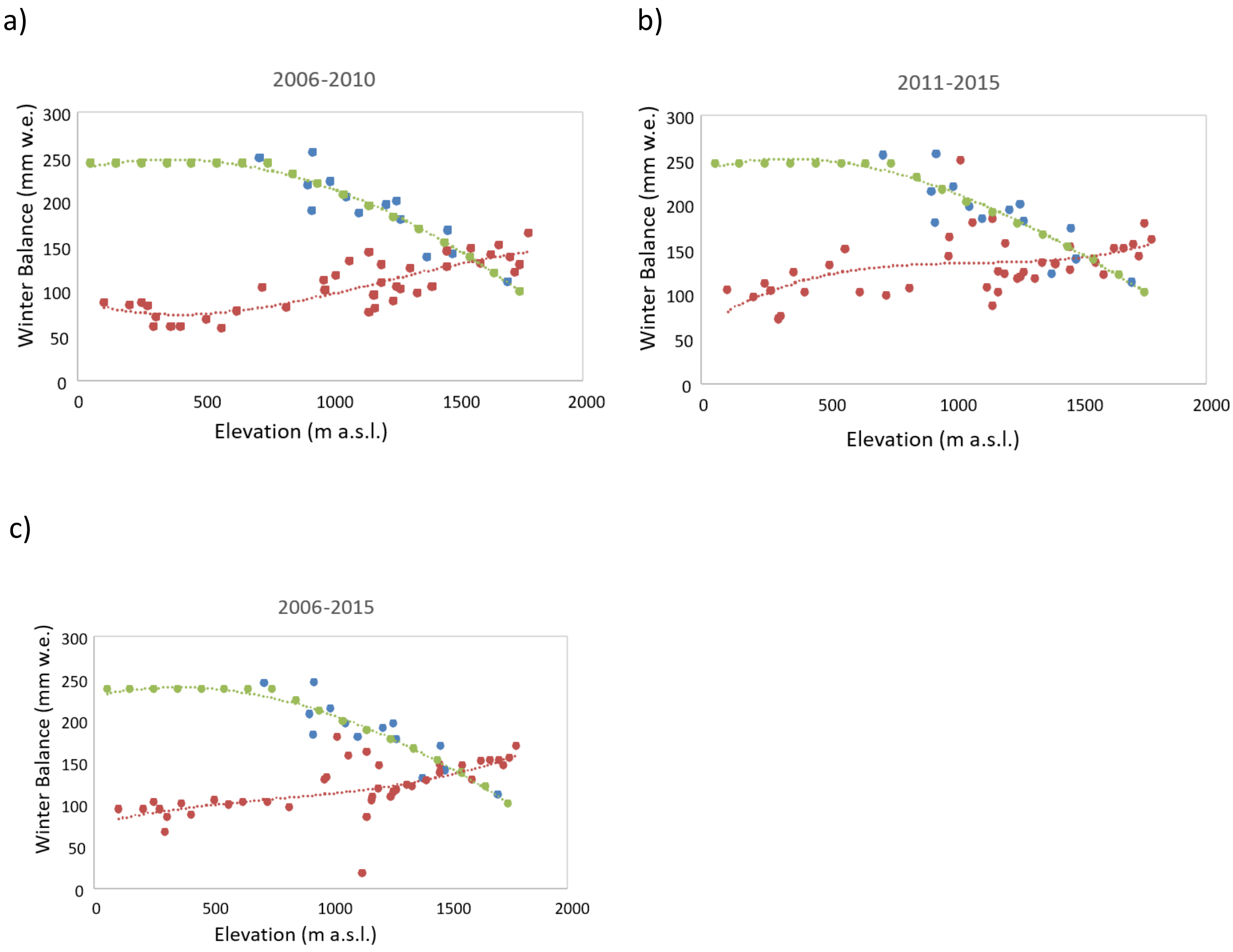


Figure 5. Five (a and b) and ten year (c) average Winter mass-balance (Sept – May) values from In-situ pole measurements (red), RACMO2.3 modeled values (blue), and RACMO2.3 modeled values (green points) extrapolated to 50 m a.s.l.

4.2 Basin-Wide Estimates of Mass Flux

4.21 Annual Summer Balance (JJA)

Basin-wide summer balance (*SBtot*) was calculated for *in*-situ and RACMO2.3 values as area-weighted averages across the Devon Ice Cap (NW) basin annually from 2006-2015 as per:

$$SBtot = \sum_{18}^{n=1} SBband * An/Atot \qquad \textit{Equation 2.}$$

where *n* is number of 100 m elevation bands, *An* is the area of each elevation band, *SBband* is average Summer Balance per elevation band, and *Atot* is the total area of the Devon Ice Cap (NW) basin.

Estimates of basin-wide annual mass flux (Figure 6) indicate general agreement between the RACMO2.3 and *In-situ* estimates, but with significant deviations in the magnitude and sign flux estimates for certain years. Maximum discrepancies occurred in 2007 (and 2012) when RACMO2.3 over (under) estimated total water flux by -0.43 Gt (0.40 Gt). More significantly however, a strong positive bias in 2013 resulted in an incorrect estimation of the 'sign' of the Summer Balance by RACMO2.3 relative to the *in-situ* measured value. The annual RACMO2.3 values deviate by 0.25 Gt, with an overall positive bias of 0.1 Gt over the 2006-2015 time period relative to the *In-situ* values.

4.22 Multi-year Flux Averages: Summer, Winter, and Net

Multi-year basin-wide average fluxes were calculated as per *Equation 2* but substituting pentadal and decadal averages for *Summer, Winter*, and *Net Balance* for *SBband*. Results indicate for the Devon Ice Cap (NW) basin indicated a consistent pattern of lower (higher) melting (precipitation) RACMO2.3 vs *In-situ* balance values (Figure 7a-c). The bias towards lower negative *Summer Balance* values estimated by RACMO2.3 was consistent for the pentadal temporal averages (Figure 7a) as well as decadal averages as indicated in Figure 6. Similarly, positive biases of ~1.2 Gt for RACMO2.3 compared with *in-situ Winter Balance* estimates (Figure 7b) were also fairly consistent for both pentadal and the decadal averages. The cumulative impact of less melting in Summer and more precipitation in winter resulted in a *Net Balance* (where Net = Summer + Winter) value ~37% less negative than the *in-situ* balance values as estimated by RACMO2.3 for pentadal and decadal temporal averages (Figure 7c).

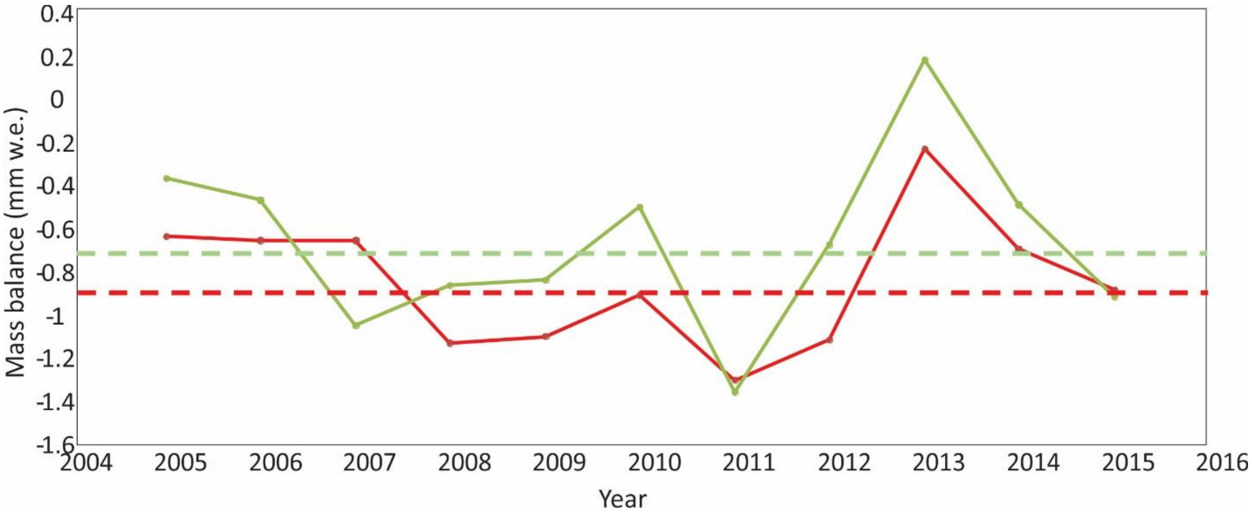
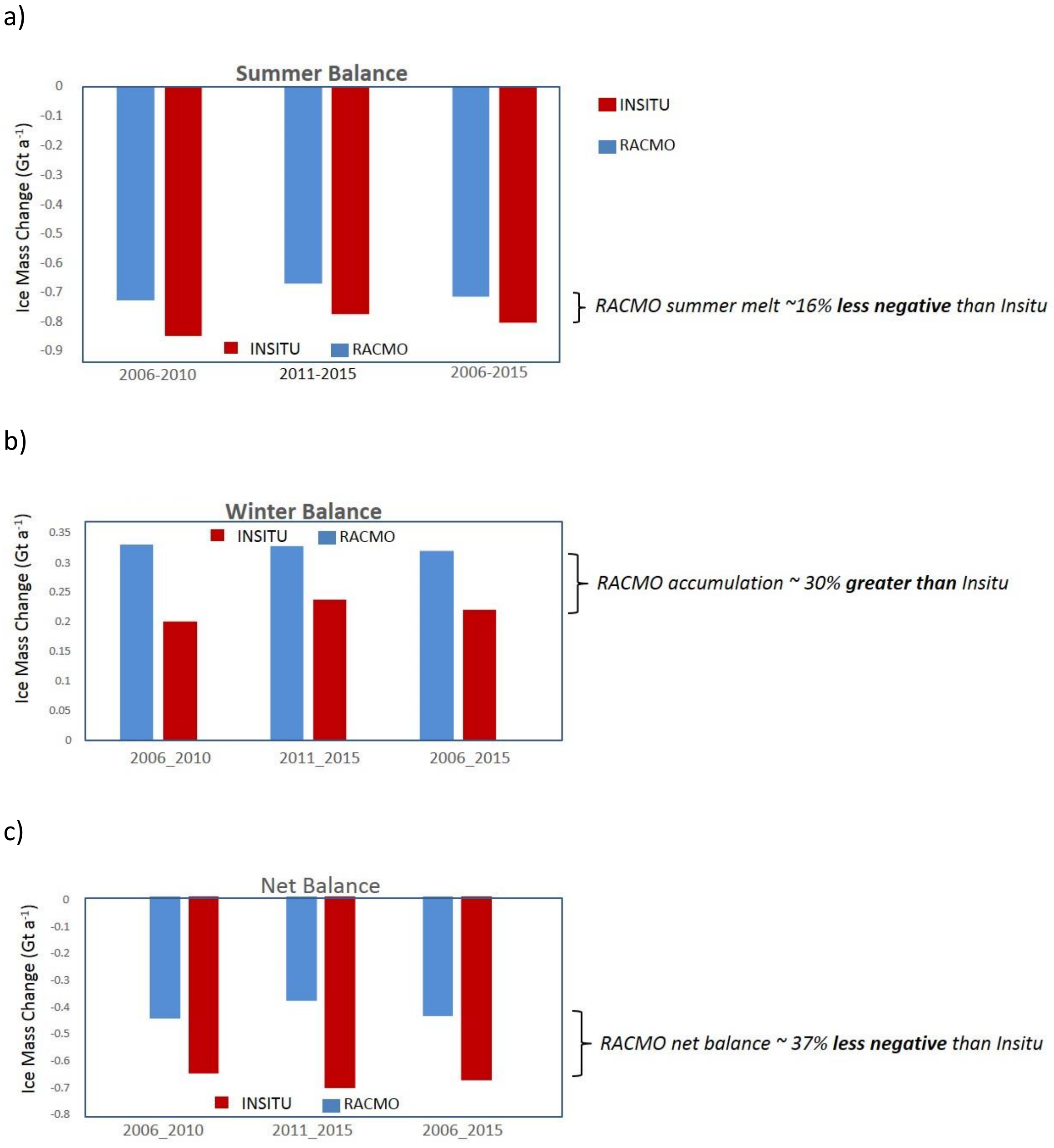


Figure 6. Total annual mass loss due to melt and runoff (ie. summer balance) from the Devon Ice Cap (NW) from 2005 to 2015 estimated by RACMO2.3 modeled (green) and *in-situ* (red) observations*. Average values over the 10-year period for RACMO2.3 and in-situ derived flux values indicated as green and red dashed lines respectively.*



*RACMO summer melt ~16% **less negative** than Insitu*

*RACMO accumulation ~ 30% **greater than** Insitu*

*RACMO net balance ~ 37% **less negative** than Insitu*

Figure 7. Pentadal and decadal estimates of Summer (a), Winter (b), and Net(c) mass flux across the Devon Ice Cap (NW) basin between 2006 and 2015.

5. SUMMARY and CONCLUSIONS

Results indicate constant biases in the RACMO2.3 data towards suppressed melt for the *Summer Balance* values and enhanced precipitation for the *Winter Balance values* from 2006 to 2015 along Devon (NW) transect. While suppressed summer melting as indicated in the RACMO2.3 modeled values is minimal (~10 cm w.e.) along most of the along most of the transect, this bias does increase by up to 20 cm w.e. by up to 70 cm w.e. for the annual (2010) comparisons between 400 and 900 m a.s.l. A possible reason for this bias is that it does coincide with the elevation range for which the RACMO2.3 values have been extrapolated. This same elevation range has however been identified by previous authors as a sector of the ice cap experiencing preferentially high melt rates (Abdalati et al. 2004), and thus may be beyond detection by regional climate models such as RACMO2.3. Increased spatial resolution of 1 km afforded by the most recent version of RACMO (Noel et al., *in review*) better resolves the complex geometry in this sector of the ice cap.

The limitations and shortcomings of RACMO2.3 as revealed from this exercise add insight into the usefulness of this regional mass-balance model as an operational tool for assessing the mass-balance of Arctic Ice caps, and the associated impacts on the local and global hydrological systems. Evaluation of the basin-wide indicate that RACMO2.3 provides reasonable estimates of summer run-off values of ~16% when averaged over the pentadal to decadal time scales, but can lead to discrepancies exceeding 40% relative to the *in-situ* measured values at the annual time scale. The compound effects of suppressed summer melt and enhanced winter precipitation significantly under (over) estimates net mass-balance derived from RACMO2.3 resulting in negatively biased estimates of contributions to global sea-level rise. Knowledge of this particular bias should be accounted for only where RACMO2.3 has been validated with reliable independent observations as it may vary spatially due to regional differences in climatic forcing.

Climatic regimes vary significantly over ice caps in the Canadian Arctic along with the dominant trend occurring between the relatively 'maritime' region of the southeast (~40 cm w.e.) to cold arid continental north west sectors (< 10 cm w.e.) of the archipelago. In order to determine the performance of the 1 km RACMO model over these variable regimes, future work will incorporate data from *in-situ* monitoring sites ranging southern Baffin Island up to northern

Ellesmere Island. In addition, comparisons with shallow ice cores will provide validation at the decadal timescale at point locations over this region. Improved knowledge of the performance of RACMO2.3 over these various climatic and topographic settings should also allow for improved calibration of the winter balance (ie. precipitation in the form of snow) component of RACMO2.3 which are required to reliably quantify the contribution of Canada's Arctic ice caps and glaciers to global sea-level using this regional mass-balance model.

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