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Subglacial hydrology indicates a major shift in dynamics of the West Antarctic Ross Ice Streams within the next two centuries

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Abstract

The mass export of the West Antarctic Ice Sheet (WAIS) is dominated by fast flowing ice streams. Understanding their dynamics is a key to estimate the future integrity of the WAIS and its contributions to global sea level rise. This study focuses on the Ross Ice Streams (RIS) at the Siple Coast. In this sector, observations reveal a high variability of ice stream pathways and velocities which is assumed to be driven by subglacial hydrology. We compute subglacial water pathways for the present-day ice sheet and verify this assumption by finding high correlations between areas of enhanced basal water flow and the locations of the RIS. Moreover, we reveal that the ice flow velocities of the individual ice streams are correlated with the sizes of the water catchment areas draining underneath. The future development of the subglacial hydraulic environment is estimated by applying ice surface elevation change rates observed by ICESat and CryoSat-2 to the present-day ice sheet geometry and thus assessing prognostic basal pressure conditions. Our simulations consistently indicate that a major hydraulic tributary of the Kamb and Whillans Ice Stream (KIS and WIS) will be redirected underneath the Bindschadler Ice Stream (BIS) within the next two centuries. The water catchment area feeding underneath the BIS is estimated to grow by about 50 % while the lower part of the stagnated KIS becomes increasingly separated from its upper hydraulic tributaries. We conclude, that this might be a continuation of the subglacial hydraulic processes which caused the past stagnation of the KIS. The simulated hydraulic rerouting is also capable to explain the observed deceleration of the WIS and indicates a possible future acceleration of the BIS accompanied by an increased ice drainage of the corresponding ice sheet interior.

1 Introduction

The West Antarctic Ice Sheet (WAIS) contains about 10 % of the Antarctic ice and is mainly marine based (Fretwell et al., 2013). A partial collapse under the influence of prospective warming scenarios could contribute to global eustatic sea level rise by 3.3 m (Bamber et al., 2009). Consequently, a deeper understanding of the local ice dynamics and its drivers concerning future developments is essential. In this study, we focus on the West Antarctic Siple Coast, where the ice dynamics are clearly dominated by five major ice streams, also called the Ross Ice Streams: Mercer, Whillans, Kamb, Bindschadler and MacAyeal Ice Stream (Fig. 1). They are responsible for the vast majority of the ice transport from the interior of the WAIS towards the adjacent Ross Ice Shelf.

Observations reveal a high variability in the mass flux of the Ross Ice Streams as well as a significant short-term variability in ice stream shear margin and grounding line positions (Catania et al., 2012). The best-known example is the Kamb Ice Stream, measuring 745 km from the onset of the northernmost tributary to the grounding line. It began to stagnate ~ 150 years ago (Rose, 1979), whereby its former position could be reconstructed from short-pulse radar profiles (Retzlaff and Bentley, 1993). They show scatter from buried crevasses, which were presumed at the surface when the ice stream was still active. The thickness of the undisturbed ice layers over these crevasses allows a back dating and reveals a sequential stagnation. The stagnation wave had its initiation at the grounding line of the ice stream 130 ± 25 years ago, followed by the slow-down of the middle part 100 ± 30 years ago and finally ended at the upstream part only ~ 30 years ago (Retzlaff and Bentley, 1993; Anandakrishnan et al., 2013; Catania et al., 2006). Surface-based ice-penetrating radar profiles show an undulating internal stratigraphy and thus prove its former fast flow conditions with pre-stagnation flow velocities exceeding 350 m a^{-1} in the trunk of the ice stream (Ng and Conway, 2004). With the same observation techniques evidence for a former ice stream crossing the Kamb to the Bindschadler Ice Stream at the northeast flank of the Siple Dome was found (Jacobel et al., 1996). But also the currently existing Whillans Ice Stream was detected to decelerate. Over the period 1974–1997 Joughin et al. (2002) estimated a velocity loss of about 23 % with a combination of conventional interferometry and speckle-tracking methods applied to RADARSAT-1 data. This was confirmed by Scheuchl et al. (2012)

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using full InSAR, revealing a velocity change of $-100\,\mathrm{m\,a^{-1}}$ (−25 %) for the Whillans Ice Stream and $-40\,\mathrm{m\,a^{-1}}$ (−17 %) for the Mercer Ice Stream at their grounding lines between the years 1997 and 2009.

Since the Ross Ice Streams are responsible for the majority of the mass export from the inner ice sheet to the grounding line, their evolution plays a key role for the future mass balance of the Siple Coast. In order to understand or even predict their dynamic behavior, we consider two of the most commonly controls on ice stream locations defined by literature (e.g., Winsborrow et al., 2010): subglacial geology and subglacial melt water routing.

The prime control which creates the precondition for ice streams to evolve in this area of investigation is clearly given by the subglacial geology. Numerous seismic campaigns detected a layer of till under the Ross Ice Streams (e.g., Rooney et al., 1987). Beneath the Whillans Ice Stream this unconsolidated layer of sediment was estimated to be 5–6 m thick on average and presumed to be glacial till (e.g., Alley et al., 1986). The ratio of till viscosity to effective ice viscosity is small (MacAyeal, 1989). Consequently, the vertical shear associated with horizontal flow is confined to the deforming bed alone and thus the deformation of till can be regarded as the primary mechanism by which the ice streams move (Alley et al., 1987). Borehole measurements with a *tethered stake* apparatus by Engelhardt and Kamb (1998) yielded a basal sliding in the amount of 83–100 % of the total ice motion. However, rigid bedrock substrata may contact the ice base beside the deformable till in small areas and cause vorticity in the velocity field. At these spots the ice surface appears rumpled, visible, e.g., at Landsat images of the MacAyeal Ice Stream (MacAyeal, 1992). Peters et al. (2006) also observed sedimentary basins in seismic reflections upstream of the Kamb and Bindschadler Ice Streams, which are considered to control the onsets of these ice streams. The inland termination of these sediments suggests that a possible future migration of the latter onsets is unlikely (Siegert et al., 2004). At the grounding line of the Whillans Ice Stream, Alley et al. (1989) discovered a till delta tens of meters thick and tens of kilometers long. These sediments originate from upstream locations and are transported downstream by the moving ice. Beyond, this sedimentary wedge at the grounding line is believed to stabilize the position of the grounding line even despite moderate changes in sea level (Anandakrishnan et al., 2007).

The existence of subglacial till gives the precondition for the development of ice streams at the Siple Coast. However, their exact locations seem to be defined by the pathways of melt water flow. The general prevalence of basal water at the Siple Coast is confirmed by a range of radar sounding campaigns (e.g., Alley et al., 1986; Bentley et al., 1998; Jacobel et al., 2009). They found high reflection strengths at the trunks of the ice streams, interpreted as wet bed, and lower reflections at the ice rises in between, interpreted as dry bed. The transitions between the areas with detected wet and dry beds show exact correlation with ice stream margins. Boreholes drilled to the ice bottom confirm that the ice base is at melting point inside the confines of the ice streams and reveal a dry bed outside (e.g., Engelhardt et al., 1990; Engelhardt, 2004). In addition, seismic investigations discovered a highly porous basal till layer which is saturated by water (e.g., Blankenship et al., 1987, for the Whillans Ice Stream).

Following the above considerations, the evolution of subglacial melt water pathways due to changing basal pressure conditions is most likely capable to explain the observed spatial and temporal variability of the ice streams at the Siple Coast. In this study, we use the hydrology module of the ice flow model RIMBAY (Goeller et al., 2013; Thoma et al., 2014) in combination with current ice geometry data (Fretwell et al., 2013) and observed ice surface elevation changes (Pritchard et al., 2012; Helm et al., 2014) to simulate present-day and prognostic basal water catchment areas and subglacial pathways of water flow. Subsequently, their patterns are investigated with respect to correlations with present-day ice velocity observations and possible implications for future migrations and velocity changes of the Ross Ice Streams are derived.

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2 Methods

2.1 Basal melting

Observations of many (active) subglacial lakes at the Siple Coast reveal a widespread, dynamic subglacial water system (e.g., Gray et al., 2005; Fricker et al., 2007; Fricker and Scambos, 2009; Wright and Siegert, 2012; Carter and Fricker, 2012; Horgan et al., 2012). However, the precise local melt rates are barely known since they elude direct measurements and model results partly contradict each other. Analytical model results, e.g., for the Whillans Ice Stream, indicate melt rates between 3–7 $\mathrm{mm\,a^{-1}}$ for the upstream and 20–50 $\mathrm{mm\,a^{-1}}$ for the downstream domain (Beem et al., 2010). In contrast, Joughin et al. (2003) used another modeling approach and found that most melting occurs beneath the tributaries where larger basal shear stresses and thicker ice favor higher melt rates in the order of 10–20 $\mathrm{mm\,a^{-1}}$. The ice stream tributaries and the inland ice are accounted for about 87 % of the total melting generated beneath the Ross Ice Streams including their catchments (Joughin et al., 2004). Following Parizek et al. (2003), this melt water transports latent heat from beneath inland ice to the base of the ice streams, while temperatures at the bottom of the ice streams itself and accordingly the melt rates are low, caused by the scarce internal ice deformation and the consequently lacking internal frictional heating.

In all following simulations, the hydrology-module within the ice model RIMBAY (Goeller et al., 2013; Thoma et al., 2014) is forced with a constant basal melt rate for all grounded ice nodes. In this way, the influence of the entire basal water catchment area of the Siple Coast is equally represented and the fluxes can be expressed as percentage of this total catchment area. Thus, the above discussed uncertainties discussed above related to the calculation of basal melt rates beneath the Ross Ice Streams are avoided and the focus is set on catchment areas sizes and water pathways.

2.2 Basal water routing

In general, melt water at the base of an ice sheet follows the gradient of the hydraulic potential p (Shreve, 1972)

$$p = \rho_w g z + p_w \tag{1}$$

with ρ_w the water density, g the gravitational acceleration and p_w the water pressure at the considered point of elevation z. The effective pressure $p_{eff.}$ at the ice base is defined as the ice overburden pressure p_i minus water pressure p_w.

At the ice base of the Siple Coast, borehole measurements and seismic investigations reveal the prevalence of a meters-thick layer of unconsolidated sediments (glacial till). This layer is highly porous and locally saturated by water, whereby the water pressure was determined to be within 0.5 to 1.5 bar of the overburden ice pressure (e.g. Alley et al., 1986; Blankenship et al., 1987; Engelhardt et al., 1990; Kamb, 2001). For example, a column of 1000 m ice (a common ice thickness at the main trunk of the Whillans Ice Stream) with an ice density of 910 kg m^{-3} applies a gravitational pressure of 89.27 bar to the bed. The measured difference between basal water and ice pressure of 0.5 to 1.5 bar corresponds to a deviation of only 0.6 to 1.7 % for the above example. Hence, the water pressure at these measuring sites is very close to the ice pressure and one can assume a distributed water flow system with an effective pressure of zero (e.g., Budd and Jenssen, 1987; Alley, 1996). Sparse borehole measurements show $p_w > 0.95\, p_i$ (e.g., Kamb, 2001) and confirm this approximation. Consequently, the hydraulic potential p can be approximated by

$$p = \rho_w g z + p_i \qquad \text{or} \tag{2}$$

$$p = \rho_w g B + \rho_i g H, \tag{3}$$

where B is the bedrock elevation and H the ice thickness.

The flow of basal melt water is assumed to follow the basal hydraulic potential (Eq. 3) and to be in a steady state. Thus, it can be taken advantage of the balance flux concept (e.g., Budd and Warner, 1996) to calculate the melt water pathways with scalar water flux Φ by solving

$$\operatorname{div}\Phi = M_\mathrm{b}, \tag{4}$$

where $\Phi = W\,\bar{v}^{(\mathrm{w})}$ with water layer thickness W, vertical averaged water velocity $\bar{v}^{(\mathrm{w})}$ and basal melt rate M_b. Hereby, a preceding modification of the hydraulic potential guarantees flux conservation (Goeller et al., 2013).

2.3 Model domain

Our study area encompasses parts of Marie Byrd Land and the Siple Coast, being enclosed by ice divides in the north and in the east (Fig. 1a). We assume that these ice divides act as subglacial watersheds, whereby the area of interest can be also considered as hydrologically enclosed at these margins. Beyond the Transantarctic Mountains a small part of the East Antarctic Ice Sheet is included, because it belongs to the basal hydrological catchment area of the Siple Coast. In the west, the area of investigation is bounded by the Ross Ice Shelf.

2.4 Ice sheet geometry

For present-day simulations of basal melt water pathways, the basal hydraulic potential (Eq. 3) is calculated by using the bedrock elevation and ice thickness data provided by the BEDMAP2 data set (Fretwell et al., 2013). For this purpose, the BEDMAP2 data set is resampled to resolutions of 5, 10 and 20 km for the Siple Coast region.

In order to enable prognostic simulations of the subglacial drainage system, satellite-derived surface elevation change rates from the ICESat (Pritchard et al., 2012) and the CryoSat-2 (Helm et al., 2014) campaign are applied to the present-day ice sheet geometry (Fretwell et al., 2013) in all stated resolutions with a time step of one year for the next 200 years. The consequent dynamic changes of the basal hydraulic potential subsequently allow assessments of the future basal water pathways. The applied basal

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melt rates are not affecting the ice thickness in these simulations, since all processes which have an influence on the local mass balance are assumed to be included in the observed surface elevation changes. They are exclusively used for the calculation of the balance flux.

3 Results and discussion

3.1 Present-day subglacial water pathways

The simulated pathways of basal melt water for three different model resolutions are shown in Fig. 2, with the color scale illustrating the local drainage in percent of the total catchment area. The outflow concentrates towards six embayments at the grounding line. This finding is consistent with results from Carter and Fricker (2012) who investigated the variable supply of subglacial melt water to the grounding line, using a similar steady-state water model and estimates for lake volume changes derived from ICESat data.

Our simulated water pathways correspond to the areas of fast ice flow depicted in Fig. 1. That significantly supports the assumption, that the locations of the ice streams are controlled by subglacial water routing. Furthermore, the flow patterns of the two coarser model resolutions clearly show how upstream water tributaries of the former Kamb Ice Stream (C) are partly draining into the Willans Ice Stream (D). The 5 km model run reveals a more finely branching flow system which also covers the trunks of all present-day ice streams. However, there are still non-negligible melt water contributions towards the downstream part of the stagnated Kamb Ice Stream (C). This does not necessarily mean the model results are wrong. Airborne radio echo sounding field campaigns detected a wet bed derived from strong reflections for the main trunk of the Whillans *and* the stagnated Kamb Ice Stream (e.g., Bentley et al., 1998). The detected transitions towards dry bed areas in the inter-ice stream regions match precisely the margins of the Kamb Ice Stream, which already slowed down 150–30 years

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ago. Within the former Kamb Ice Stream margins low radar reflectivity was limited to so-called sticky spots (small areas with high basal ice traction) and along the Kamb margins (Jacobel et al., 2009). A borehole drilled to the ice bottom at a sticky spot also found a dry bed there (Jacobel et al., 2009). This supports the hypothesis that sticky spots control the stagnation and possible reactivation of ice streams, once the basal melting passes a certain threshold (Joughin et al., 2004). Anandakrishnan and Alley (1997) assumed that the loss of lubrication on localized sticky spots at the ice bed interface can cause a shutdown or redirection of an entire ice stream. On the other hand sticky spots, often observed to be located along the ice streams margins, act as water sources and supply the ice stream with melt water. The ice sliding at high basal traction in combination with strong internal deformation provides a powerful heat source for basal melting from which the adjacent, comparatively cold ice stream benefits by enhanced lubrication. Additionally, the ice-thickness perturbations induced by ice flow over variable traction create local hydraulic minima. That explains the observed collocation of sticky spots and subglacial lakes (Sergienko and Hulbe, 2011).

3.2 Present-day subglacial water catchments

The relative sizes of the water catchment areas for all Ross Ice Streams are listed in Table 1. They refer to the total upstream area of five defined cross sections of approximately 140 km length, corresponding to the locations of the main trunks of the five major ice streams (Figs. 1 and 2).

Neglecting small variations, the calculated water catchment areas agree very well for the different model resolutions. The Whillans Ice Stream (B) overspreads the heaviest flow of water which is draining 31.3 ± 4.6 % of the upstream catchments. This supports the fact, that Whillans Ice Stream is the fastest flowing Ross Ice Stream with ice surface velocities up to about 700 m a^{-1}. Beneath Bindschadler (D) and MacAyeal Ice Stream (E) drain the comparable percentages of 22.2 ± 0.5 and 24.0 ± 0.8 % of the total upstream catchment area, well-fitting to their similar velocities of about 670 m a^{-1}. Accordingly, the flow beneath the smaller and slower Mercer Ice Stream (A) drains the

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smallest part with 9.3 ± 2.1 % of the total upstream catchment. Despite the fact that the Kamb Ice Stream (C) stagnated tens of years ago, the basal flow underneath drains the considerable amount of 13.2 ± 3.1 % of the total upstream Siple Coast catchment. Here, complex and yet not fully understood control mechanisms at the ice base appear to rule the ice motion in the face of a observation-proved wet bed as already discussed above.

3.3 Prognostic subglacial water pathways

The simulated basal water pathways after adding observed ICESat (Pritchard et al., 2012) and CryoSat-2 (Helm et al., 2014) surface elevation change rates to the present-day ice geometry (Fretwell et al., 2013) at the Siple Coast for a timespan of 200 years are shown in Fig. 3 for a model resolution of 5 km. Again, the color scale illustrates the percentual drainage of the total catchment area. Beneath the outer Mercer (A) and MacAyeal (E) Ice Streams, the water flow patterns show no remarkable changes within the next 200 years. However, underneath the central three ice streams the water pathways show a very dynamic behavior. Here, in the middle part of the stagnated Kamb Ice Stream (C), the strongest growth in ice thickness occurs following the satellite observations. This area is marked with a red circle in all figures (Figs. 2c and 3). The arising and thickening ice bulge increasingly diverts the basal melt water flow at this spot and leads to a lateral separation of the flow patterns. At present, a major upstream water tributary (tagged with a red star) is feeding into the Kamb (C) and the Whillans Ice Stream (B) area (Fig. 2c). Within the next 200 years this water influx will be entirely redirected towards the Bindschadler Ice Stream (D). Consequently, the water flow beneath the Kamb Ice Stream will be lacking this contributions (Fig. 3). This main characteristic of the computed future water pathways is found consistently for both satellite surface elevation change rate data sets at all three applied model resolution (5, 10 and 20 km) emphasizing the robustness of the result.

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3.4 Prognostic subglacial water catchments

The basal water fluxes towards the grounding line through five cross sections corresponding to the locations of the main trunks of the Ross Ice Streams under the influence of the ICESat and CryoSat-2 surface change rates are estimated for the next 200 years. Due to the prescribed constant melt rate, the temporal evolution of the water catchment area upstream of every cross section can be computed as a percentage of the total upstream catchment area of all cross sections. Figure 4a shows the evolution of the catchment areas for the experiments with 5 km resolution at a time step of 1 year. The graphs confirm the above analysis of the water pathways. The water catchment areas feeding underneath Mercer (A) and MacAyeal Ice Stream (E) remain stationary over the period of the next 200 years. The water catchment area of the Kamb Ice Stream (C) first gains about 2 % in size from the Whillans (B) catchment within the next 10 years. Thereafter, it continuously loses area in favour of the Bindschadler Ice Stream (D). Again the analogy of the influences of the two satellite derived surface change rates on the evolution of the basal hydraulic system is striking. Additionally, the black line in Fig. 4a shows the development of the total upstream catchment areas which reveal very slight variations in size due to the shifting of water sheds by the applied ice thickness changes. Remarkable features are the occurring steps within all graphs. They indicate points in time when larger water tributaries are linked to (or delinked from) a catchment due to the dynamics of the basal water pathways.

The variations of all catchment areas at all model resolutions after 200 years are summarized in Fig. 4b and c. Both ICESat and CryoSat-2 surface change rates indicate a future loss of about 12 % (at 5 km model resolution) of the water catchment area feeding underneath the Kamb Ice Stream (C) while the water catchment area of the Bindschadler Ice Stream (D) increases by the same amount. In this way, the water catchment area of the Bindschadler Ice Stream grows by roughly 50 % and the lower part of the stagnated Kamb Ice Stream becomes almost hydrologically separated from the upper regions of the Siple Coast. Due to the revealed spatial correlations be-

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tween simulated basal water flow and observed ice surface velocities, this might indicate a continuation of the processes which caused the stagnation of the Kamb Ice Stream in the past and could lead to an acceleration of the Bindschadler Ice Stream in the future. The experiments with a resolution of 20 km show this redirection to a lesser extent (Fig. 4b and c). Obviously, this resolution is too coarse to point out details within the evolution of local water flow patterns.

4 Conclusion

At the Siple Coast, the recent stagnation of the Kamb Ice Stream and the discovery of numerous relict ice-flow features indicate a steady competition between several preferred ice-flow paths of the Ross Ice Streams. While an observed basal layer of unconsolidated sediments beneath the ice sheet enables high basal sliding rates by sediment deformation (e.g., Alley et al., 1986), the subglacial melt water routing is considered to be the main control on the current ice stream locations at the Siple Coast and has the potential to explain their observed variability in the past.

The application of a steady-state approach to simulate the basal melt water pathways supports this assumption as all current ice stream outlines are found to be clearly associated with areas of enhanced modeled water flow. Furthermore, the ice velocities of the ice streams are found to be related to the water catchment area sizes draining underneath. Applying observed present-day surface elevation changes of two different satellite campaigns (Pritchard et al., 2012; Helm et al., 2014) to the present-day ice sheet surface for 200 years allows an estimation of future basal drainage routes. According to this simulation, the basal water pathways at the Siple Coast are highly sensitive to small ice thickness changes due to the prevailing smooth bedrock. A major hydraulic tributary of the Kamb and Whillans Ice Streams is estimated to be redirected underneath the Bindschadler Ice Stream within the next 200 years. Accordingly, the water catchment area feeding underneath the Bindschadler Ice Stream is estimated to grow by about 50 % while the lower part of the stagnated Kamb Ice Stream becomes

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increasingly separated from the upper hydraulic tributaries of the Siple Coast. This might be a continuation of the subglacial hydraulic processes which caused the past stagnation of the Kamb Ice Stream (e.g., Rose, 1979). Furthermore, this might explain the observed deceleration of the Whillans Ice Stream (Joughin et al., 2002) and might also lead to a future increase of the ice velocity within the Bindschadler Ice Stream followed by an increased ice drainage of the corresponding hinterland.

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Table 1. Water catchments of the Ross Ice Streams draining underneath their main trunks in percentage of their total upstream catchment area corresponding to the cross sections in Fig. 2 for all model resolutions.

Model resolution	20 km	10 km	5 km	⌀
Mercer (A)	8.1 %	8.0 %	11.7 %	9.3 %
Whillans (B)	36.5 %	30.0 %	27.5 %	31.3 %
Kamb (C)	9.6 %	14.4 %	15.5 %	13.2 %
Bindschadler (D)	21.8 %	22.8 %	22.0 %	22.2 %
MacAyeal (E)	24.0 %	24.8 %	23.3 %	24.0 %

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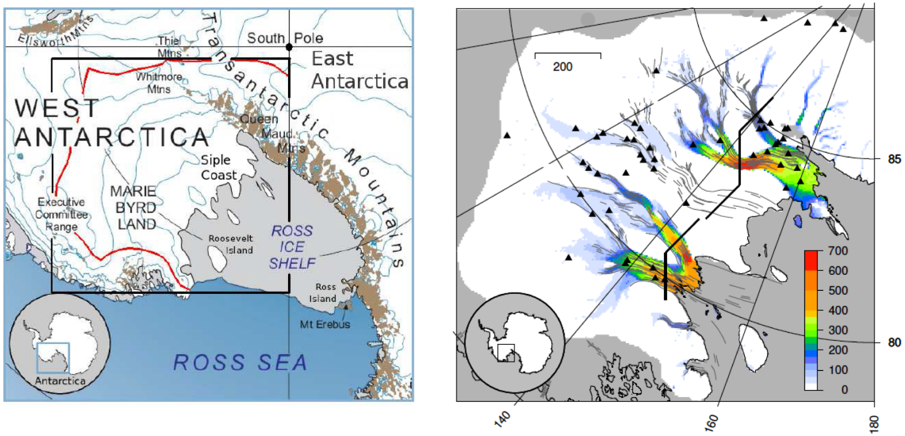

(a) (b)

Figure 1. (a) West Antarctica with Marie Byrd Land, Siple Coast and Ross Ice Shelf, model domain defined by black rectangle. Bounding ice divides by AGAP (Antarctica's Gamburtsev Province Project) are marked in red (Fig. after British Antarctic Survey, 2007). **(b)** Ice surface velocities of Ross Ice Streams after Rignot et al. (2011) with main trunks marked by A–E. Positions of observed subglacial lakes (black triangles, inventory by Wright and Siegert, 2012). Ice stream shear margins (gray lines) by RAMP (RADARSAT-1 Antarctic Mapping Project).

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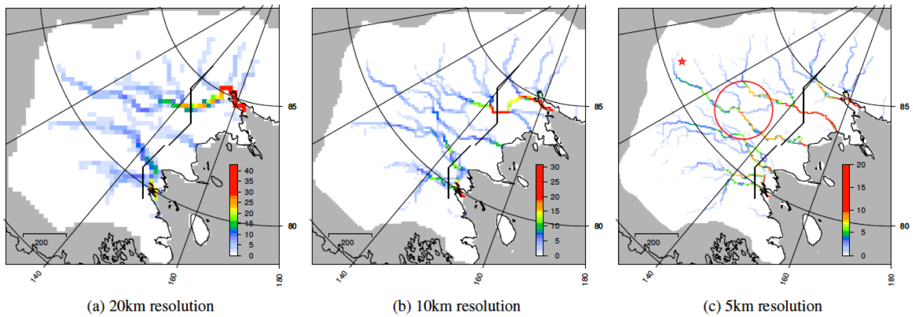

Figure 2. Simulated basal water pathways for present-day bedrock elevation and ice thickness. Color scales show the drainage in percent of the total catchment area. Figures show also five defined cross sections, corresponding to the locations of the main trunks of the Ross Ice Streams A–E, Fig. 1) to quantify the associated water drainage. (Red star and circle, see caption of Fig. 3.)

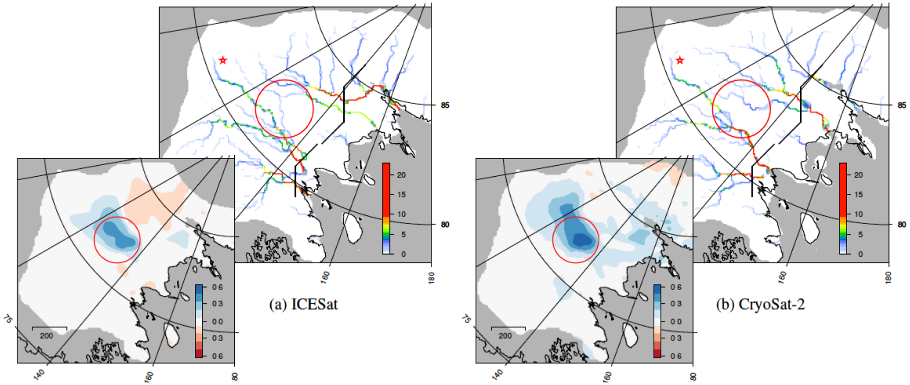

Figure 3. Lower left panels show observed ICESat **(a)** and CryoSat-2 **(b)** surface elevation change rates for the Siple Coast region. Upper right panels show simulated basal water pathways after adding these ICESat and CryoSat-2 surface elevation change rates to the present-day ice geometry for a timespan of 200 years. The color scale shows the drainage in percent of the total catchment area at a model resolution of 5 km. The red circle marks the region where a redirection of a major hydraulic tributary (marked with a red star, compare to Fig. 2c) of the Kamb (C) and Whillans Ice Stream (B) towards the Bindschadler Ice Stream (D) takes place.

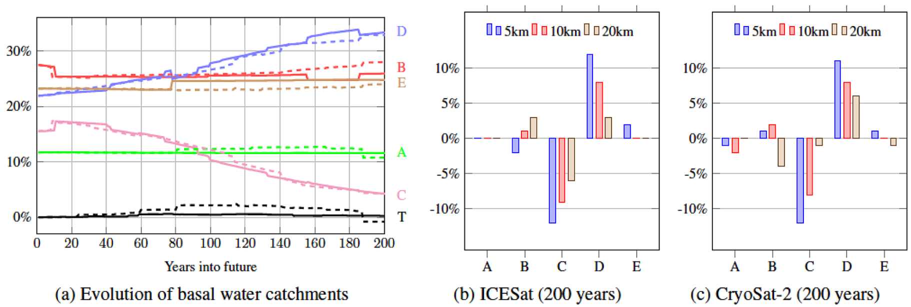

Figure 4. (a) Temporal evolution of the water catchment areas upstream of the defined cross sections for all Ross Ice Streams A–E, Fig. 3) under the impact of the observed surface elevation changes from ICESat (solid) and CryoSat-2 (dashed) for the next 200 years. T shows the variation of the total upstream catchment area. Model resolution is 5 km. **(b, c)** Change of the above catchment areas after 200 years at 5, 10 and 20 km model resolution.

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