PROGRAMA FONDECYT
INFORME FINAL
ETAPA 2016

COMISIÓN NACIONAL DE INVESTIGACION CIENTÍFICA Y TECNOLÓGICA
VERSION OFICIAL Nº 2
FECHA: 30/10/2016

Nº PROYECTO : 3140135  
DURACIÓN : 3 años  
AÑO ETAPA : 2016

TÍTULO PROYECTO : MODELING THE PATAGONIAN ICE FIELDS IN A WARMING CLIMATE

DISCIPLINA PRINCIPAL : GEOFISICA
GRUPO DE ESTUDIO : CS. DE LA TIERRA
INVESTIGADOR(A) RESPONSABLE : MARIUS ROMAN SCHAEFER
DIRECCIÓN :
COMUNA :
CIUDAD : Valdivia
REGIÓN : XIV REGION

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## OBJETIVOS

Cumplimiento de los Objetivos planteados en la etapa final, o pendientes de cumplir. Recuerde que en esta sección debe referirse a objetivos desarrollados, NO listar actividades desarrolladas.

<table>
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<th>Nº</th>
<th>OBJETIVOS</th>
<th>CUMPLIMIENTO</th>
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<td>1</td>
<td>Generate a reliable data-set of bedrock topography for the Patagonian Icefields using the approach of Huss and Farinotti [2012] and new radar echo sounding data [Zamora et al., 2009; Blindow et al., 2011, 2012].</td>
<td>TOTAL</td>
<td>A first bedrock topography of the Patagonian Icefields was published recently by Carrivick et al., [2016]. The data of Carrivick were validated against radio echo sounding data at Nef Glacier and it was found that the agreement was satisfactory for that specific glacier. However on other glaciers, like for example PioXI glacier, Carrivick et al., [2016] clearly overestimate the ice thickness and therefore underestimate the bedrock elevation.</td>
</tr>
<tr>
<td>2</td>
<td>Identify the best-suited a calving law, which is able to predict the calving behavior of some well monitored example glaciers such as O’Higgins Glacier, Jorge Montt Glacier, San Rafael Glacier or Nef Glacier.</td>
<td>TOTAL</td>
<td>Considering our simulations on Jorge Montt Glacier, we can state that the water-depth calving criterion seems to be more adequate to simulate the timing of the glacier's tongue. Considering surface elevation changes and velocities, however, the code developed in Colgan et al., [2012] is the most successful in reproducing the behavior of Jorge Montt Glacier.</td>
</tr>
<tr>
<td>3</td>
<td>Run surface mass balance simulations for the Patagonian Icefields for 2000-2100 under the different emission scenarios of the Intergovernmental Panel on Climate Change Assessment Report 5 (IPCC-AR5) to predict their surface mass balance under different future climate scenarios.</td>
<td>TOTAL</td>
<td>Surface mass balance simulations were run with climate data from two CMIP5-models under two different radiative pathways (RCP2.6 and RCP8.5).</td>
</tr>
<tr>
<td>4</td>
<td>Run a 2d-iceflow code [Colgan, 2011] for both Patagonian Icefields, which is able to reproduce past ice thicknesses and outlines. Run this code into the future using the surface mass balance data of (3) as input.</td>
<td>PARCIAL</td>
<td>In the end it was decided to use more complex models, like ELMER-ice and BISCILES to simulate the ice flow of the Patagonian Icefields. This is ongoing work which is the reason why the objective is only partially reached in the moment.</td>
</tr>
</tbody>
</table>

Otro(s) aspecto(s) que Ud. considere importante(s) en la evaluación del cumplimiento de objetivos planteados en la propuesta original o en las modificaciones autorizadas por los Consejos.
RESULTS OBTAINED:
For each specific goal, describe or summarize the results obtained. Relate each one to work already published and/or manuscripts submitted. In the Annex section include additional information deemed pertinent and relevant to the evaluation process.

The specific goals of the project were:


2. Identify the best-suited a calving law, which is able to predict the calving behavior of some well monitored example glaciers such as O’Higgins Glacier, Jorge Montt Glacier, San Rafael Glacier or Nef Glacier.

3. Run surface mass balance simulations for the Patagonian Icefields for 2000-2100 under the different emission scenarios of the Intergovernmental Panel on Climate Change Assessment Report 5 (IPCC-AR5) to predict their surface mass balance under different future climate scenarios.

4. Run a 2d-iceflow code [Colgan, 2011] for both Patagonian Icefields, which is able to reproduce past ice thicknesses and outlines. Run this code into the future using the surface mass balance data of (3) as input.

A bedrock topography map of the Glaciers of Southern South America was published recently (Figure 1, Carrivick et al. [2016]). A perfect plasticity approach was used to model the ice thickness of the most important glaciers in Southern South America. According to these results the bedrock elevation of the Patagonian Icefields varies between -1000 and +2000 m a.s.l.. That is, considerable overdeepenings were obtained at several outlet glaciers of the Patagonian Icefield, which could indicate that further retreat is expected in the near future. However some care has to be taken with these results as they were not validated at many glaciers. For example for Pio XI Glacier, we know that the modelled overdeepening does not exist!

(a) Measured by Blindow et al. [2012] (b) Modeled by Carrivick et al. [2016] (c) Modeled by Huss and Farinotti [2012]

Figure 2: Comparison of ice thickness estimations at Nef Glacier obtained by different methods.
In Figure 2 we compare the results of Carrivick et al. [2016] to the measurements of Blin-dow et al. [2012] and the results obtained by Huss and Farinotti [2012]. We can observe that the results of Huss and Farinotti [2012] clearly underestimate the measured ice thickness, whilst Carrivick et al. [2016] slightly overestimate it. But, at least at Nef Glacier, the model of Carrivick et al. [2016] seems to perform better than the one of Huss and Farinotti [2012]. To understand this strong disagreement, the dataset of Huss and Farinotti [2012] was analyzed in more detail. Mass losses due to calving were not incorporated in the original dataset of Huss and Farinotti [2012], which causes the ice thickness to be zero at the glaciers’ fronts. This has to be modified to improve the performance of the model of Huss and Farinotti [2012] to predict the ice thickness of the Patagonian Icefields.

On the other hand, ice thickness models allow us to estimate the amount of sweet water stored in the glaciers of Southern South America. Table 1 gives an overview over the results by different studies obtained for the Northern Patagonian Icefield (NPI), the Southern Patagonian Icefield (SPI) and glaciers in Southern South America in general. As a summary we can state that the amount of sweet water stored in the Glaciers of Southern South America has the potential to rise the oceans sea-level by approximately 18.4 mm, which equals to a mass of 6651 Gigatons of water!

<table>
<thead>
<tr>
<th>Volume-Area-Scaling: $V = cA^\gamma$</th>
<th>NPI</th>
<th>SPI</th>
<th>Southern South America</th>
</tr>
</thead>
<tbody>
<tr>
<td>(This study $\gamma = 1.25$, $c = 0.0538 km^{0.5}$)</td>
<td>4.3 mm</td>
<td>17.7 mm</td>
<td>&gt; 22 mm</td>
</tr>
<tr>
<td>Carrivick et al. [2016]</td>
<td>3.1 ± 0.8 mm</td>
<td>10.8 ± 2.2 mm</td>
<td>15.1 ± 3.0 mm</td>
</tr>
<tr>
<td>Huss and Farinotti [2012]</td>
<td>-</td>
<td>-</td>
<td>16.6 ± 1.3 mm</td>
</tr>
<tr>
<td>Radic and Hock [2010]</td>
<td>-</td>
<td>-</td>
<td>20 ± 2 mm</td>
</tr>
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</table>

Table 1: Ice volume of the Patagonian Icefields and Glaciers in Southern South America in Sea Level Rise equivalent inferred from different studies.

Two calving laws have been tested at Jorge Montt Glacier: the flotation criterion and the
empirical water-depth law. Using a code that makes use of the shallow-ice approximation (SIA), we obtained the result that the water depth criterion performed much better in terms of the timing of the retreat (Figure 3).

![Figure 3: Comparison of three simulations of the retreat of Jorge Montt Glacier between the years 1975 (red profile) and 2000 (green profile) using a code the employs SIA with flotation calving criterion (a) with the water-depth calving criterion (b) and the code of William Colgan (c). Model ice elevation profiles are plotted every five years.](image)

This result confirms earlier results of Nick et al. [2007], using a similar code. The evolution of ice elevations and velocities however were not reproduced very well by the code with none of the calving criteria, which is probably due to the application of the shallow-ice approximation, which neglects longitudinal stresses. These stresses seem to be of importance to be able to explain the observed evolution of the ice elevations. The code of William Colgan [Colgan et al., 2012], which approximately resolves the equation of conservation of momentum in the downstream direction, and herewith considers longitudinal stresses, showed clearly better performance in reproducing the observed changes in ice elevation (Figure 3).

The future surface mass balance (SMB) of the Southern Patagonian Icefield was simulated using different climate data as input that were generated as follows: the output of the CMIP5 Global Circulations Models (GCMs) EC-EARTH and MPI-ESM-LR was used to drive the Rossby Centre regional atmospheric model (RCA4) under different emission scenarios. The resolution of this regional climate simulations was of approximately 50 km. These climate data were used to drive the future SMB simulations of the Southern Patagonian Icefield. The results are presented in Figure 4. The difference of the simulated mean specific SMB of SPI using the two CMIP5-GCMs as drivers is striking. When using EC-EARTH model the simulated mean specific SMB is approximately 2 mweq. lower, which makes a difference in the annual mass budget of 26 Gigatons. Analyzing the reasons for this strong difference, we found that the EC-EARTH model is producing both lower values of accumulation and higher values of melt over the SPI. Comparing both model results to the SMB data obtained when using the meteorological dataset which was examined in detail by Schaefer et al. [2013], we can state that the EC-EARTH model is strongly underestimating the precipitation in Patagonia and slightly overestimating the ablation. MPI-ESM-LR seems to slightly underestimate ablation due to slight bias in temperature towards colder temperatures which was detected when comparing these data to meteorological measurements in the region.

In Table 2 we resume the projected SLR contribution of SPI in the 21st century using the SMB
data obtained by the simulations driven by the MPI-ESM-LR data and the meteorological dataset generated in Schaefer et al. [2013], since the results obtained using EC-EARTH model as driver seem to be unrealistic. Here we assumed that the annual calving losses of SPI during the 21st century will be 48 Gt, similar to the ones inferred for the recent past [Schaefer et al., 2015], and that the surface extension of SPI is not changing considerably during the 21st century. Both ass-

![Graph of annual mean specific surface mass balance of SPI projected for the 21st century using different climate data input.](image)

Table 2: Ice loss from the Southern Patagonian Icefield projected for the 21st century using different models and different future radiative pathways expressed in potential sea level rise.

<table>
<thead>
<tr>
<th>Model(radiative pathway)</th>
<th>projected SLR in mm</th>
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<tr>
<td>MPI (8.4)</td>
<td>7.8</td>
</tr>
<tr>
<td>MPI (2.6)</td>
<td>4.7</td>
</tr>
<tr>
<td>ECHAM5 (A1B), Schaefer et al. [2013]</td>
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</table>

Sumptions are probably not very realistic especially considering that for the radiative pathway 8.4 the data generated with the MPI-ESM-LR data as drivers, the mass loss of SPI is of similar order of magnitude than the total ice volume estimated by Carrivick et al. [2016]. At this point it becomes evident that a parametrization of the retreat of the glaciers and a better estimates of future calving losses are necessary in order to get more reliable projections of the contribution of Patagonia’s glaciers to sea level rise in the 21st century.

I am currently involved in different efforts of 2d and 3d ice-flow modeling on the Patagonian Icefields:

1. The efforts of PhD candidate Gabriela Collao at the University of Grenoble: Gabriela is using the 3D full stokes model Elmer-Ice to reproduce the flow of ice of San Rafael Glacier on the Northern Patagonian Icefield.

2. The work of PhD candidate Claire Donnelly at University of Bristol: Claire is using the advanced ice-flow models BISICLES [Cornford et al., 2013] to model the flow behavior of several glaciers of the Patagonian Icefields. Here I am forming part of the supervisory team.

Both efforts are ongoing PhD thesis which are supervised by international expert teams and are promising to deliver new knowledge about dynamic of ice flow on the Patagonian Icefields.
References


Blindow, N., C. Salat, and G. Casassa, Airborne GPR sounding of deep temperate glaciers - examples from the Northern Patagonian Icefield, in Proceedings of the 14th International Conference on Ground Penetrating Radar (GPR2012), Tongji University, Shanghai, China, June 4-8, 2012.


A. Science:

- December 2015: visit of the AGU Fall Meeting in San Francisco, Unites Sates of America.
- January/February 2016: Scientific leader of the international expedition to Grey Glacier with participation of:
  - Austral University: Dr Marius Schaefer + several students
  - University of Magallanes: Dra Guisella Gacitua + students
  - University of Hokkaido: Dr Shin Sugiyama + student
  - University of Erlangen: Dr Tobias Sauter + student
- July 2016: visit of collaborators at the University of Bristol, UK. Invited talk: “Glaciology in Chile - Challenges and Opportunities” for the members of the glaciology group at the University of Bristol.

B. Capacity building:

- “Modelación de glaciares que producen témanos”, Tesis de Juan Pablo Tolosa Sanzana para optar al título profesional de geofísico que otorga la Carrera Ciencias Físicas y Astronómicas de la Universidad de Concepción, Guiding Professor.

C. Outreach:

- February 2016: Informative talk about general concepts in glaciology and activities at Grey Glacier for personal of CONAF and Bigfoot Patagonia company in the Torres del Paine National Park.
- April 2016: “Glaciares en Chile y el mundo - un pequeno viaje por los hielos”, at Campus Patagonia UACH and one middle-school in Coyhaique en the frame of the CONICYT explora “Dia internacional de la Tierra”.
- September 2016: “Glaciares en Chile y el mundo - un pequeno viaje por los hielos”, invited talk at opening ceremony of the escuela de talentos ALTA UACH 2016 in Coyhaique, Chile.
- October 2016: “Glaciares en Chile y el mundo - un pequeno viaje por los hielos”, talk at the Escuela Mexico, Valdivia for the CONICYT explora program: 1000C/1000A.
Mediante este informe se evalúa el trabajo científico del Dr Marius Schaefer en el proyecto “Modeling the Patagonian Icefields in a warming climate” Proyecto Postdoctoral No. 3140135.

En el último año de ejecución Dr. Schaefer ha avanzado considerablemente en todos los objetivos del proyecto: Ha realizado avances significativos sobre la estimación del monto total de agua dulce almacenada en los Glaciares de la Patagonia. También pudo comparar y validar los diferentes métodos que se han usado para determinar el lecho de glaciares en la Patagonia. El Dr. Schaefer examinó diferentes proyecciones climatológicas para la Patagonia y contrastó cómo estas proyecciones influirían el comportamiento de los glaciares. Esto en conjunto con sus avances en la modelación del movimiento del hielo provee información muy valiosa que nos permitirá planificar mejor el manejo de estos recursos hídricos importantes en el sur de nuestro país.

Dejo constancia que el Dr. Schaefer ha sido una persona con la que se puede trabajar armónicamente en equipo. Por un lado trabaja de manera muy independiente, pero por otro lado también busca el diálogo y el intercambio con otros científicos, por lo que ha sido una grata experiencia el haber sido su profesor patrocinante. Su alto entusiasmo y dedicación a su estudio explica las buenas conexiones nacionales e internacionales que tiene el Dr. Schaefer, que le ha permitido exponer su trabajo en grupos líderes de su ámbito de trabajo y también colaborar en diferentes esfuerzos de modelación de glaciares en la Patagonia.

En el año transcurrido destaca la adjudicación de un proyecto de colaboración internacional titulado: “Glacial Hazards In Chile: Processes, Assessment, Mitigation And Risk Management Strategies”, proyecto de gran impacto para el país en el cual el Dr. Schaefer actúa como director del equipo Chileno. Y por otro lado también destaca el liderazgo de Dr. Schaefer de una expedición científica internacional al Glaciar Grey.

En resumen, calificaría el trabajo científico del Dr. Marius Schaefer como sobresaliente.
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Quantifying mass balance processes on the Southern Patagonia Icefield

Climate and Surface Mass Balance of Mocho Glacier, 2 Chilean Lake District, 40° S

Proyecto interno UACH: DID 2015-72

Ice2Sea


CONGRESOS

Nº : 1
Autor (a)(es/as) : Marius Schaefer, Horst Machguth, Gino Casassa
Título (Idioma original) : Modeling the Patagonian Icefields
Nombre del Congreso : International Symposium on Glaciers and Ice Sheets Contribution to Sea-Level Change
País : FRANCIA
Ciudad : Chamonix
Fecha Inicio : 25/05/2014
Fecha Término : 30/10/2014
Nombre Publicación :
Año :
Vol. :
Nº :
Páginas :
Envía documento en papel : no
Archivo Asociado :
poster-IGS.pdf

Nº : 2
Autor (a)(es/as) : Schaefer M
Título (Idioma original) : Quantifying mass balance processes on the Patagonian Icefields by means of a multi-model surface mass balance reconstruction and remote sensing data
Nombre del Congreso : Special session: 30 years of Japanese glaciological research in Patagonia
País : JAPON
Ciudad : Sapporo
Fecha Inicio : 18/11/2015
Fecha Término : 19/11/2015
Nombre Publicación :
Año :
Vol. :
Nº :
Páginas :
Envía documento en papel : no
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<td>Marius Schaefer; Jose Luis Rodriguez; Matthias Scheiter; Gino Casassa</td>
<td>Mass Balance of Mocho Glacier, 40 S Chile</td>
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<td>Collao-Barrios, G. ; Gillet-Chaulet, F. ; Favier, V. ; Casassa, G. ; Gourlet, P. ; Mouginit, J. ; Rignot, E. ; Schaefer, M.</td>
<td>Using a 3D full Stokes ice flow model to constrain the surface mass balance and ice discharge of San Rafael Glacier, northern Patagonia</td>
<td>International Symposium on The Cryosphere in a Changing Climate</td>
<td>NUEVA ZELANDIA</td>
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<td>Shin Sugiyama; Masahiro Minowa; Marius Schaefer</td>
<td>Calving front of Grey Glacier in Patagonia is sticking out to the lake under the water surface</td>
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ANEXOS

A continuación se detallan los anexos físicos/papel que no se incluyen en el informe en formato PDF.