Bilan de masse des calottes polaires et points de bascule

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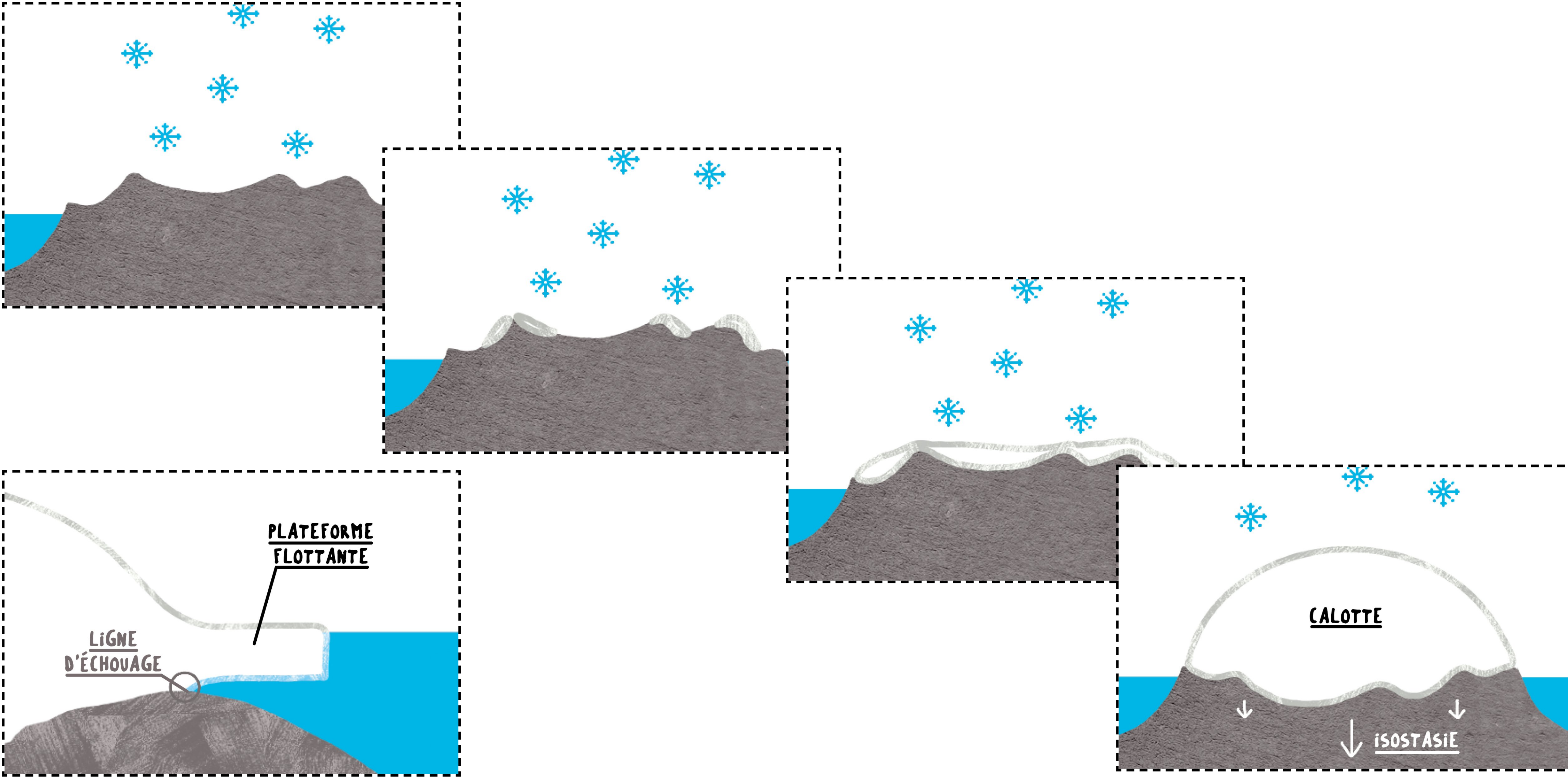
GDR Défis Théoriques pour les sciences du climat
04/10/2023

Contexte – Paleo, historique et projections

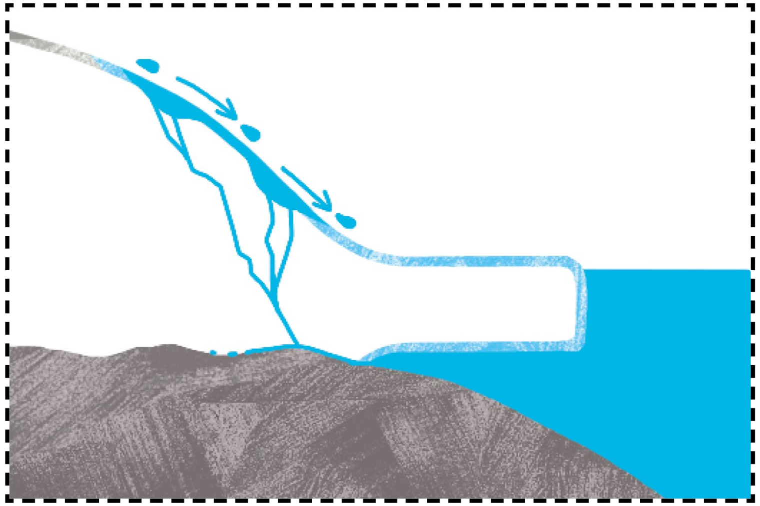
Instabilités :

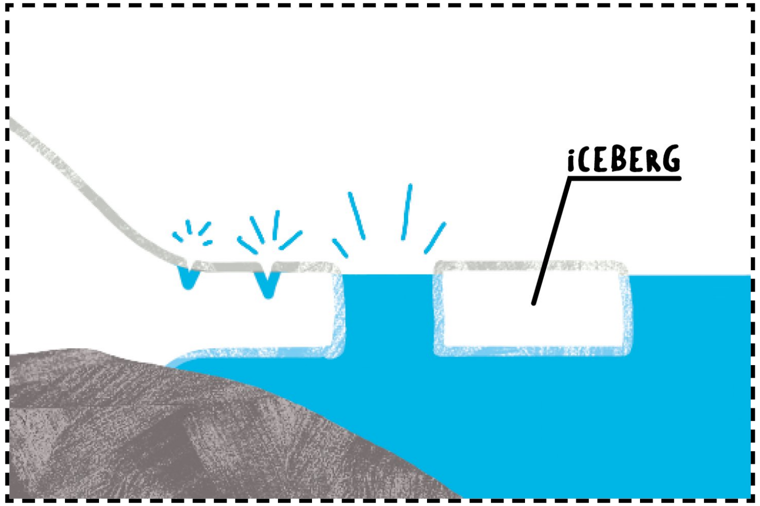
- des petites calottes – Groenland
- des calottes marines – Antarctique
- Des falaises de glace - Antarctique

Formation des calottes polaires – gain de masse



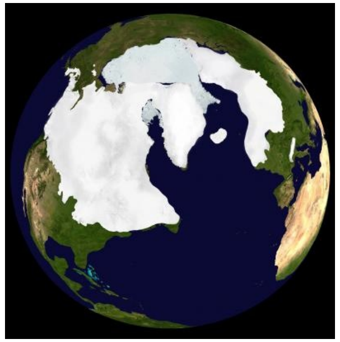
Formation des calottes polaires – Perte de masse

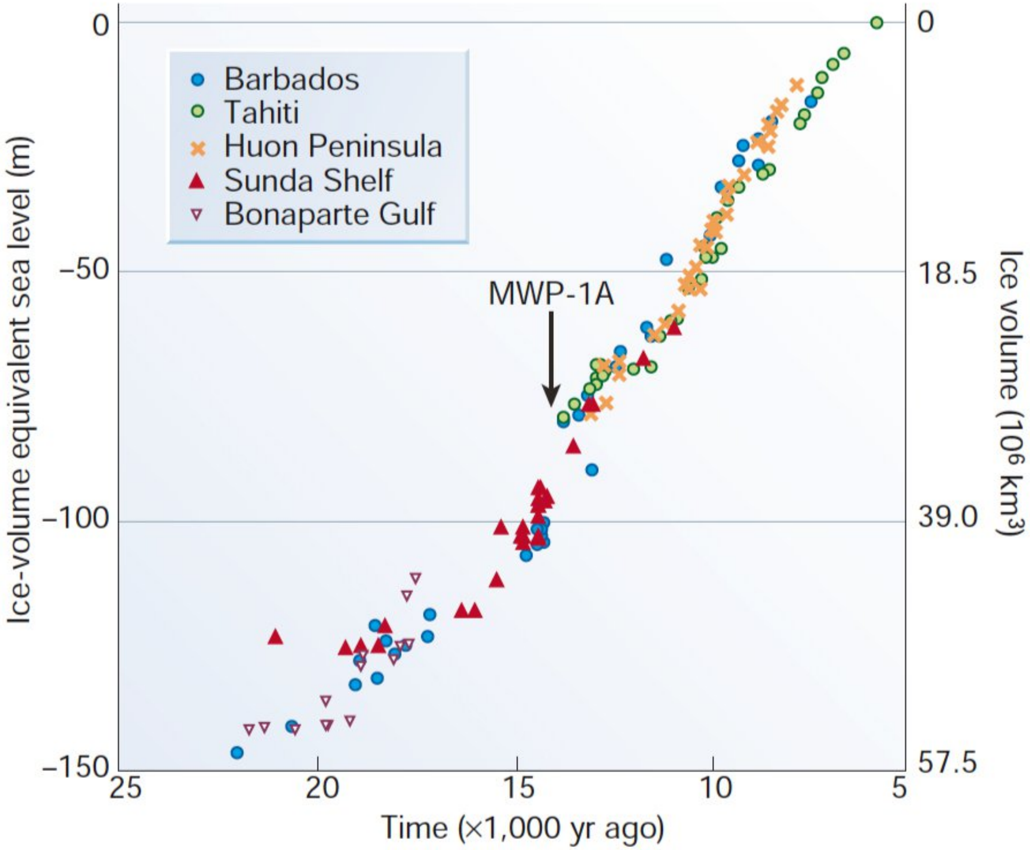




Bilan de masse = Gain - perte

Evolution du niveau moyen de la mer
Perspectives paléoclimatiques





Lambeck et al. 2002

Marine Isotope Stage (MIS) 11	about 424–395 ka	0.5°C ± 1.6°C[a]	265 to 286 ppm	+6 to +13 m
Last Interglacial (LIG)	about 129–116 ka	+0.5°C to +1.5°C	266 to 282 ppm	+5 to +10 m

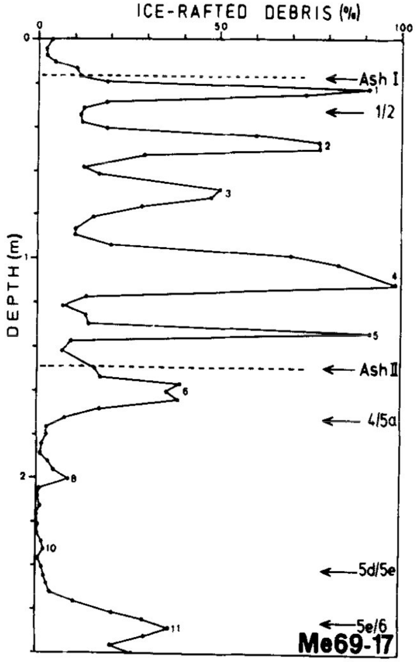
AR6

Des “purges” glaciaires

Des observations paleo, des mécanismes

Origin and Consequences of Cyclic Ice Rafting in the Northeast Atlantic Ocean during the Past 130,000 Years

HARTMUT HEINRICH



Heinrich 1988

The problem of junction stability that Hughes' work has emphasized is important. Large shifts in the position of the ice sheet–ice shelf junction produce relatively large changes in the thickness of an ice sheet. In this paper we attempt to obtain, for the two dimensional problem, the basic equations that determine the position of the region in which an ice sheet turns into a floating ice shelf; we also examine the conditions that must be satisfied if the ice sheet is even to exist.

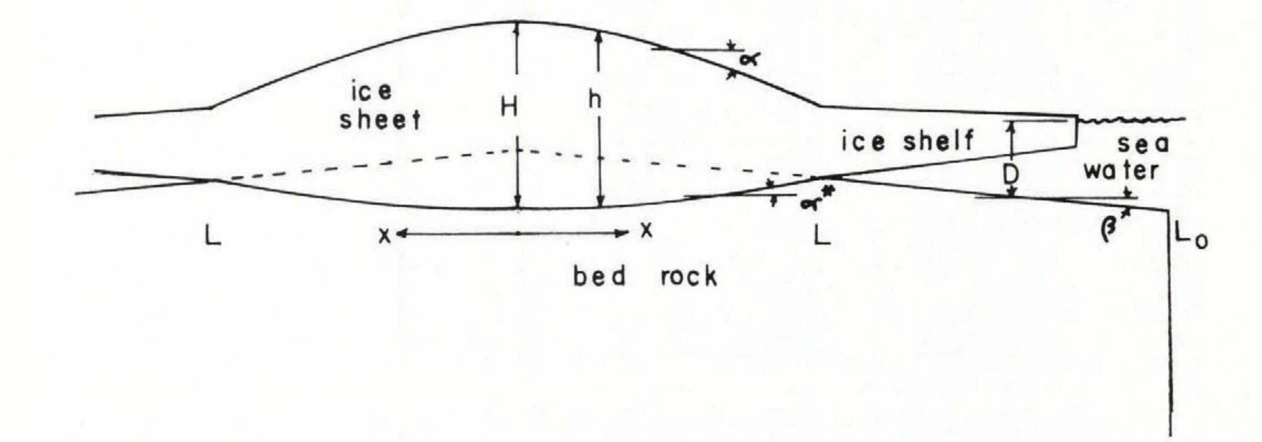


Fig. 1. Cross-section of ice sheet with attached ice shelves.

Weertman 1974

Une prophétie ?

West Antarctic ice sheet and CO_2 greenhouse effect: a threat of disaster

J. H. Mercer

If the global consumption of fossil fuels continues to grow at its present rate, atmospheric CO_2 content will double in about 50 years. Climatic models suggest that the resultant greenhouse-warming effect will be greatly magnified in high latitudes. The computed temperature rise at lat 80° S could start rapid deglaciation of West Antarctica, leading to a 5 m rise in sea level.

Mercer 1978

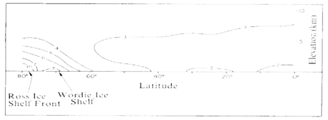


Fig. 1 Computed rise in mean atmospheric temperature, as a function of latitude and elevation, that would result from a doubling of atmospheric CO_2 content (after Manabe and Wetherald[9] who emphasise that, because of the various simplifications of the model, the quantitative aspects of the results should not be taken too seriously).

Manabe and Wetherald[9] shows greatly magnified warming in high latitudes caused by the lack of vertical mixing, and by the feedback effect of decreased albedo as snow and sea ice cover recede: temperatures would rise by ~ 2 K between the equator and lat 30° north or south, by 4 K at lat 60°, by 7 K at lat 70°, and by > 10 K at lat 80° (Fig. 1). Schneider[7] agrees that this effect is likely and points out that warming in the polar regions could be crucial because of their sensitivity to changes in the energy balance.

Manabe and Wetherald[9] emphasise that because their model is highly simplified—it has idealised global topography, fixed cloudiness, no heat transport by ocean currents and no seasonal variability—these figures for the rise in temperature should not be taken at their face value. Smagorinsky[11] discusses the model and points out that seasonal variability is of fundamental importance in high latitudes because it determines the extent of snow and ice cover; if this factor, and the reactions of the oceans and clouds were taken into account, a very different result might be obtained; it is even possible that global cooling would be indicated. Keeling and Bacastow[8] conclude that until the feedback effect of the slow response of subsurface ocean waters can be correctly modelled, the regional climatic changes that are of greatest interest to mankind will be hard to predict. Nevertheless, as Bolin[1] points out, although the model of Manabe and Wetherald has serious shortcomings it is the most advanced that has yet been developed, and to gamble with the Earth's climate by ignoring it would be highly irresponsible. In the same vein Schneider[12] sums up the dilemma facing mankind: despite the crudities and inadequacies of present techniques for modelling the climatic effects of increasing atmospheric CO_2 content and the resultant doubts about the magnitude of the warming that would actually occur, we cannot afford to let the atmosphere carry out the experiment before taking action because if the results confirm the prognosis, and we should know one way or the other by the end of the century, it will be too late to remedy the situation on account of the long residence time of CO_2 in the atmosphere (Keeling and Bacastow[8] estimate that, if all accessible fossil fuels were burnt, restoration of pre-industrial levels of CO_2 would take at least 10,000 yr).

Is the CO_2 greenhouse effect detectable in recent climatic trends?

Since about 1940, temperatures over much of the Northern Hemisphere have dropped despite rising atmospheric CO_2 content. Broecker[13] suggests that this may have lulled us into a sense of false security about the danger of increasing CO_2 levels; the cooling does not disprove or cast doubt on

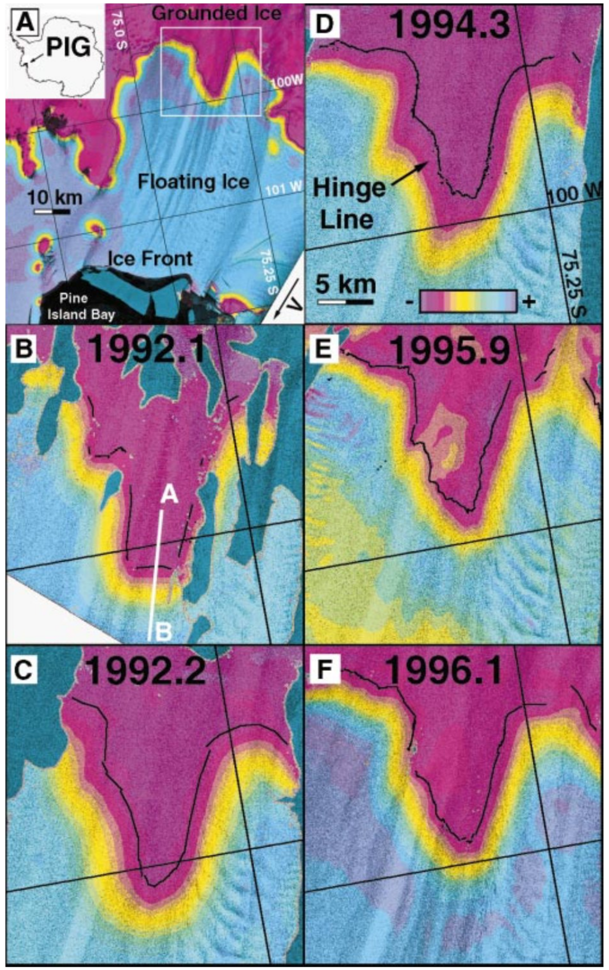
believes that the quasi-cyclical pattern of climatic fluc
in the recent past, which is shown by the oxygen isotop
from the Greenland Ice Sheet[14], implies that this coo
soon level out, to be followed by a period of rapid
as the natural climatic trend is reinforced by the e
increasing atmospheric CO_2. In fact, the cooling sir
seems to have been mainly confined to middle a
latitudes in the Northern Hemisphere, and some inve
believe that the southern part of the Southern Her
has warmed during the same interval. Damon and
have studied climatic records from 67 Southern Her
stations that meet certain specifications and that have
that go back to 1954 or earlier. They find that since 1
peratures have changed little between the equator and l
except in Australia and New Zealand which, as other
also point out[16,17], have warmed by about 1° C si
1940s. South of lat 45° S, however, they conclude that
annual temperatures increased between the 1960–64 an
74 pentads, particularly in West Antarctica where tl
about 2° C at Argentine Island (lat 65° S), McMu
78° S), and Byrd (lat 80° S) (Fig 2). Thomas'[18,19] obs
that temperatures at 10 m depth in the eastern part
Ross Ice Shelf rose about 1° C between 1958 and 19
firms the warming trend in West Antarctica.

Damon and Kunen[15] suggest that the climate of the S
Hemisphere is now responding to the CO_2 greenhous
whereas in the Northern Hemisphere this has recent
overwhelmed by cooling caused by man-made pa
pollution and also, possibly, from greater volcanic
Budd[19], however, while noting the recent warming
Antarctica, finds no clear evidence that Antarctica as
either warmed or cooled between 1958 and 1972; furth
at the South Pole 1976 was the coldest year since recor
there in 1957[20]. So far, apparently, despite recent
warming over Australasia and West Antarctica, the
unequivocal evidence for a global rise in temperature
by increasing atmospheric CO_2 content. If Broecker's
is correct that average global CO_2-caused warming
have amounted to no more than a fifth of a degre
past 30 years, this is perhaps not surprising.

Fig. 2 West Antarctica, showing ice shelves, ice gro
below sea level, ice covering land above sea level, and p
of the 0 °C January isotherm in the Antarctic Peninsula
on information up to the year 1962)[36]. 1, Prince Gustav Ch
2, Wordie Ice Shelf; 3, George VI Sound; 4, Wilkins S
5, Argentine Island.

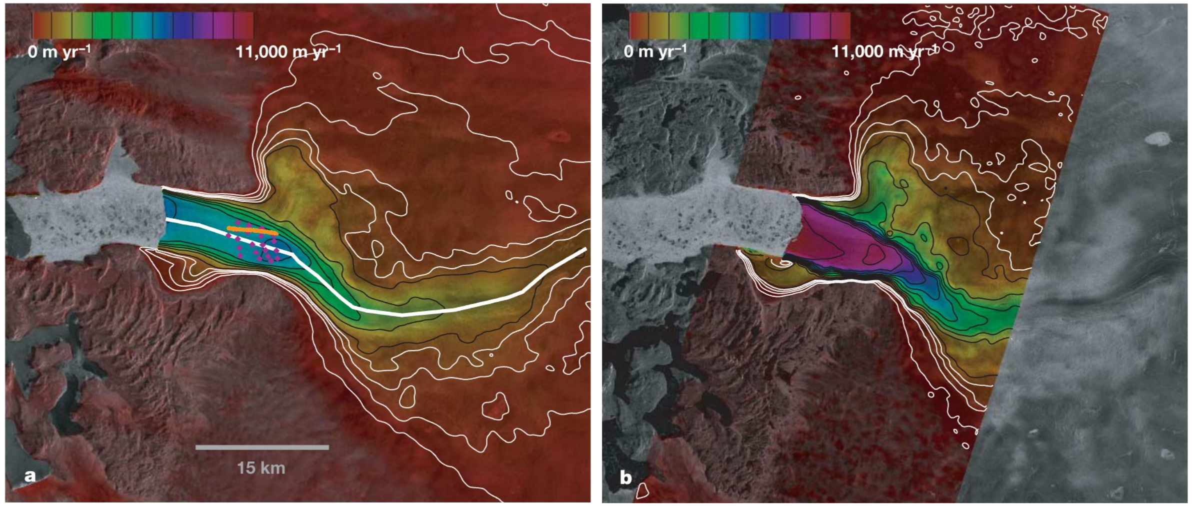
Antarctique & Groenland : des retraits, des démantellements

Pine Island Glacier, Antarctique



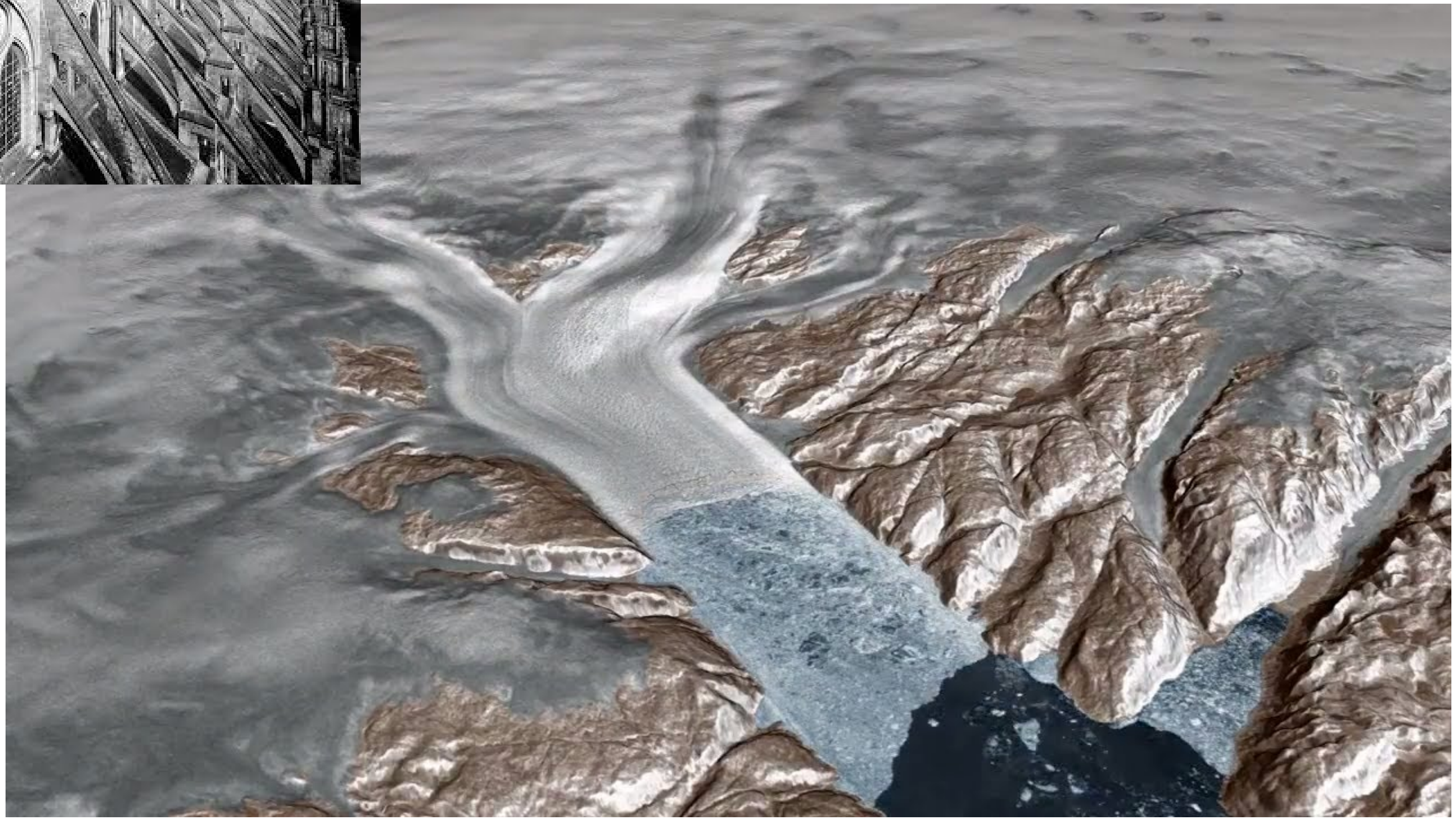
Rignot 1998

Jakobshavn Isbrae, Groenland

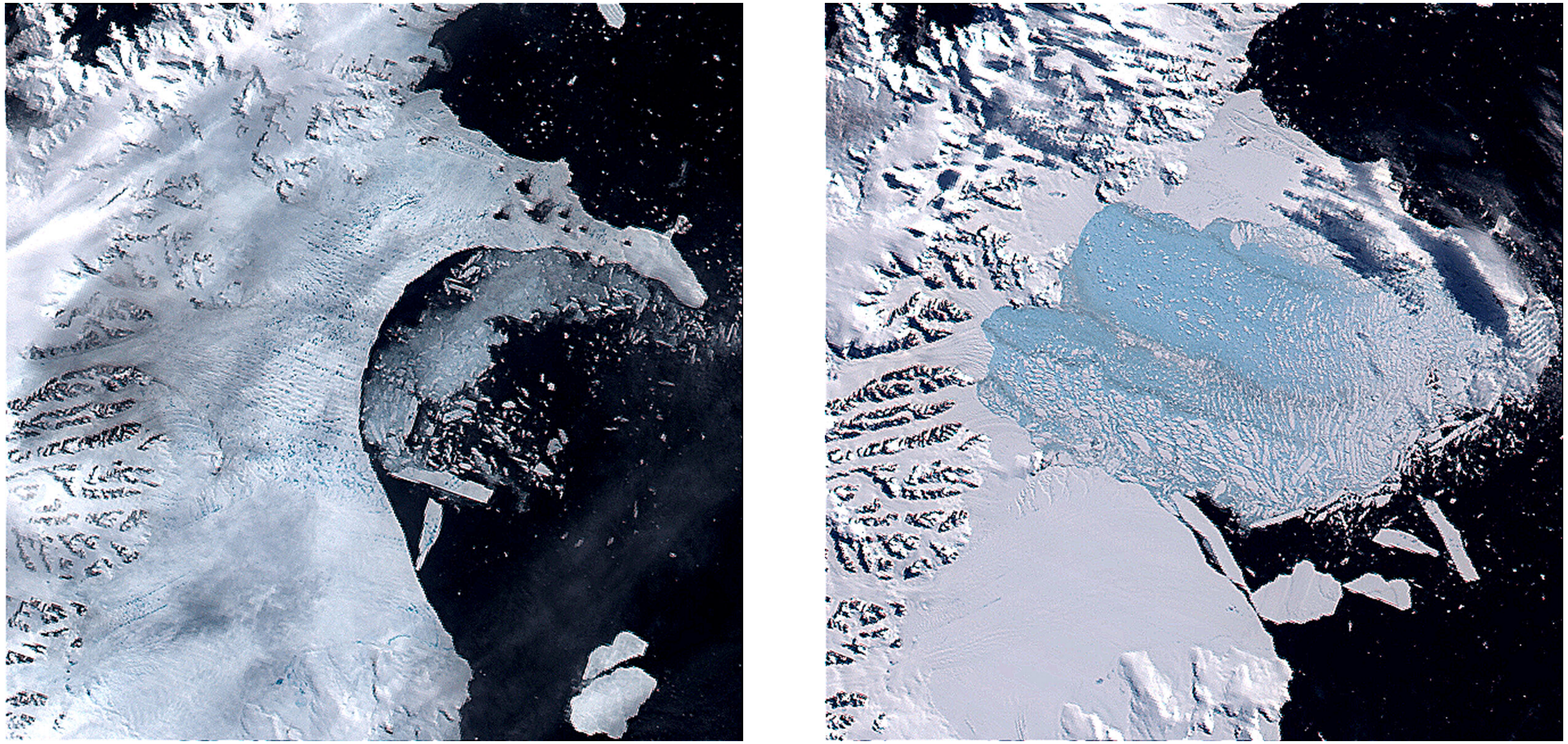


Joughin et al., 2004

Buttressing effect

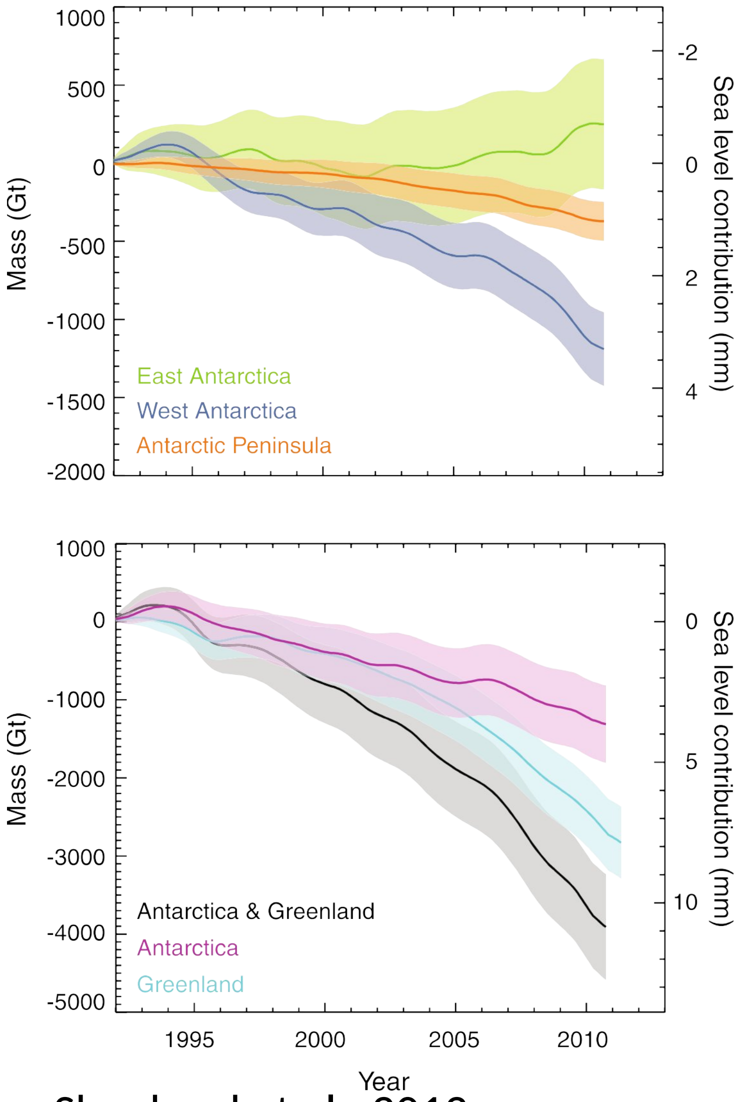


Antarctique & Groenland : des retraits, des démantellements



Larsen B 2002

Une perte de masse avérée et grandissante



Shepherd et al., 2012

A Reconciled Estimate of Ice-Sheet Mass Balance

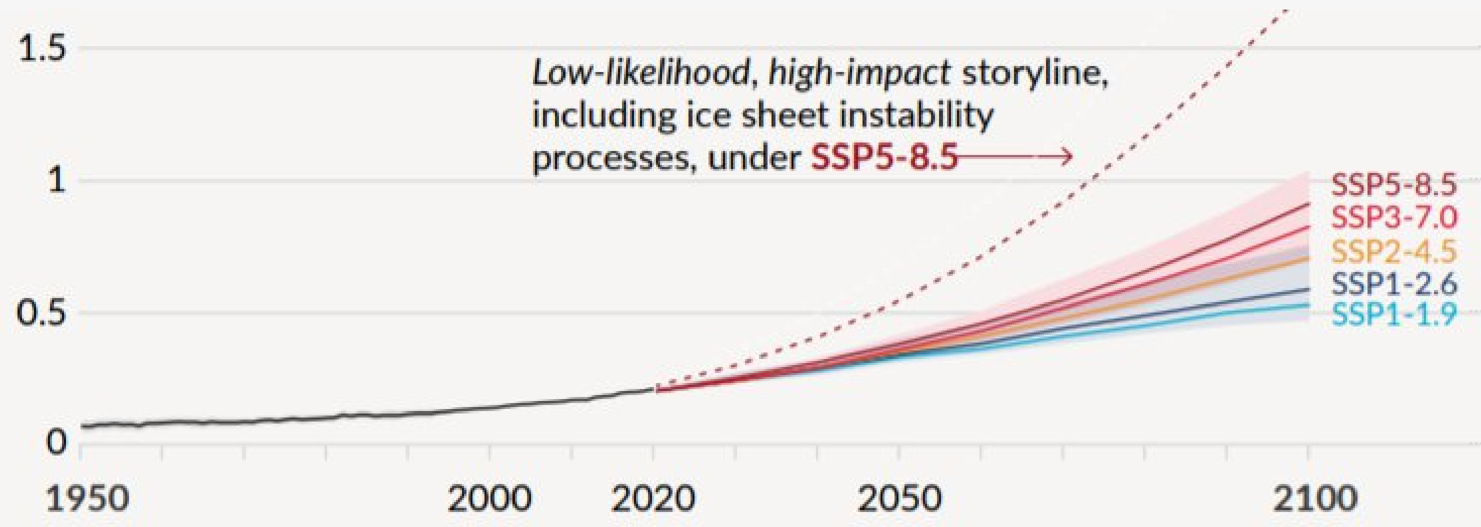
Andrew Shepherd,[1*] Erik R. Ivins,[2*] Geruo A,[3] Valentina R. Barletta,[4] Mike J. Bentley,[5] Srinivas Bettadpur,[6] Kate H. Briggs,[1] David H. Bromwich,[7] René Forsberg,[4] Natalia Galin,[8] Martin Horwath,[9] Stan Jacobs,[10] Ian Joughin,[11] Matt A. King,[12,27] Jan T. M. Lenaerts,[13] Jilu Li,[14] Stefan R. M. Ligtenberg,[13] Adrian Luckman,[15] Scott B. Luthcke,[16] Malcolm McMillan,[1] Rakia Meister,[8] Glenn Milne,[17] Jeremie Mouginot,[18] Alan Muir,[8] Julien P. Nicolas,[7] John Paden,[14] Antony J. Payne,[19] Hamish Pritchard,[20] Eric Rignot,[18,2] Helmut Rott,[21] Louise Sandberg Sørensen,[4] Ted A. Scambos,[22] Bernd Scheuchl,[18] Ernst J. O. Schrama,[23] Ben Smith,[11] Aud V. Sundal,[1] Jan H. van Angelen,[13] Willem J. van de Berg,[13] Michiel R. van den Broeke,[13] David G. Vaughan,[20] Isabella Velicogna,[18,2] John Wahr,[3] Pippa L. Whitehouse,[5] Duncan J. Wingham,[8] Donghui Yi,[24] Duncan Young,[25] H. Jay Zwally[26]

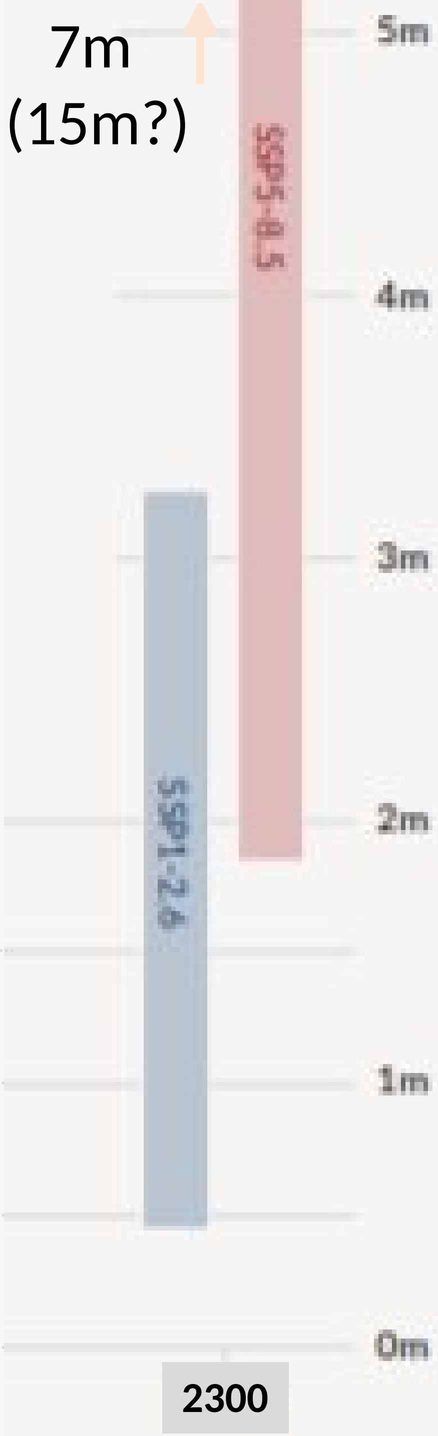
Contributeurs niveau des mers AR6 (2006-2018)

Groenland 0.91 mm/an
Antarctique 0.55 mm/an
Glaciers 0.62 mm/an
Dilatation thermique 1.39 mm/an
Stockage continent 0.60 mm/an

L’élévation du niveau de la mer se poursuivra pendant des siècles

- Elle sera d’autant plus rapide que les émissions seront élevées
- On ne peut pas exclure un scénario d’élévation du niveau de la mer très rapide



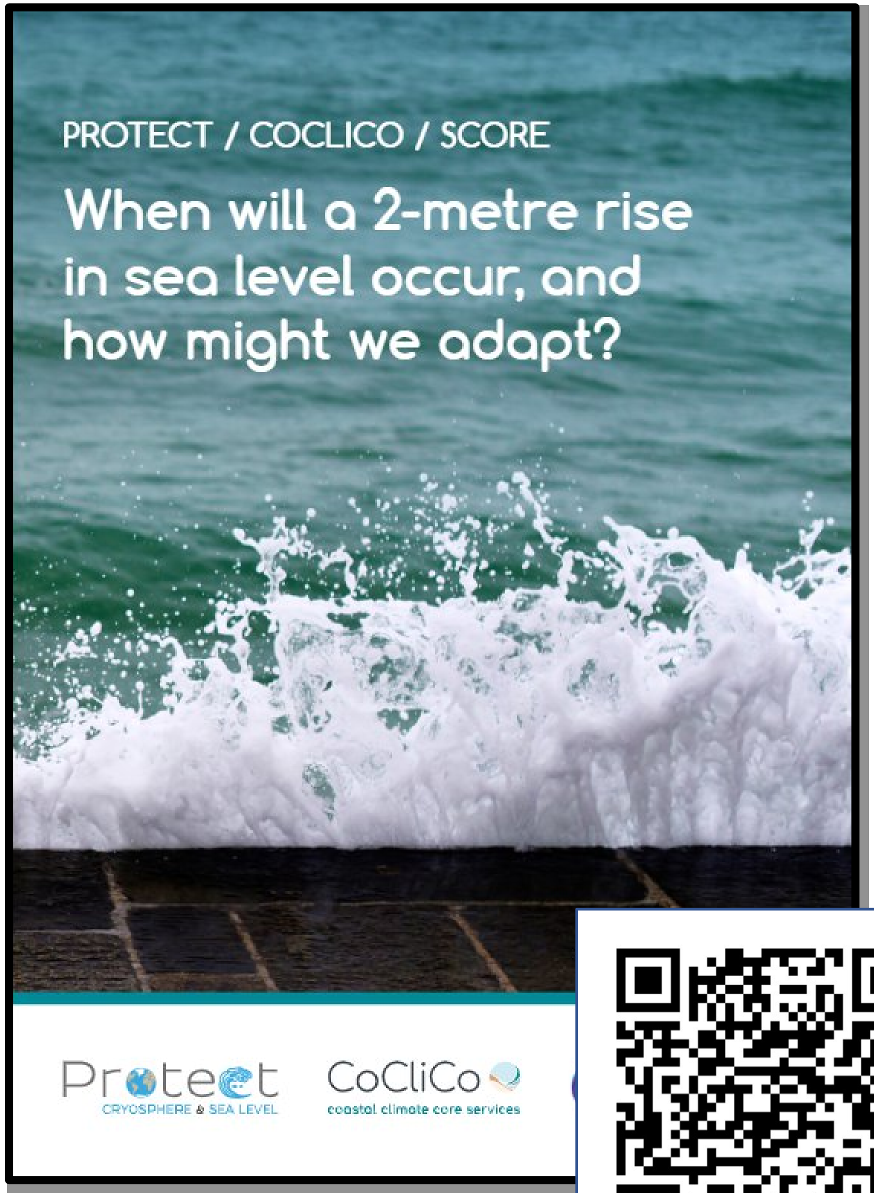


AR6 WG1 SPM

Tôt ou tard, l’élévation du niveau marin global dépassera deux mètres

- L’élévation du niveau de la mer ne s’arrêtera pas lorsque le réchauffement climatique aura été stabilité
- L’élévation du niveau de la mer continuera pendant des siècles et des millénaires
- Lors du dernier interglaciaire:
    - Températures globales: 0.5 à 1.5°C au-dessus de celles de la période préindustrielle
    - Niveaux marin 5 à 10 m supérieurs aux niveaux actuels

La question n’est pas « si ? », mais « quand ? » !



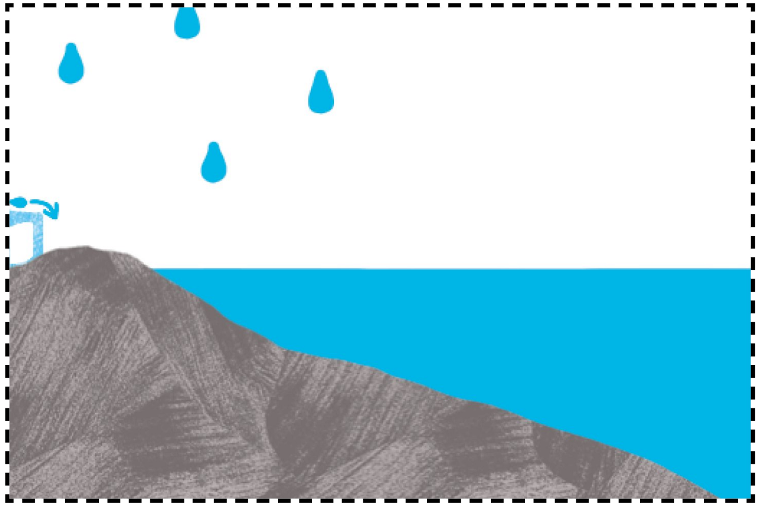
Protect
CRYOSPHERE & SEA LEVEL

Contexte – Paleo, historique et projections

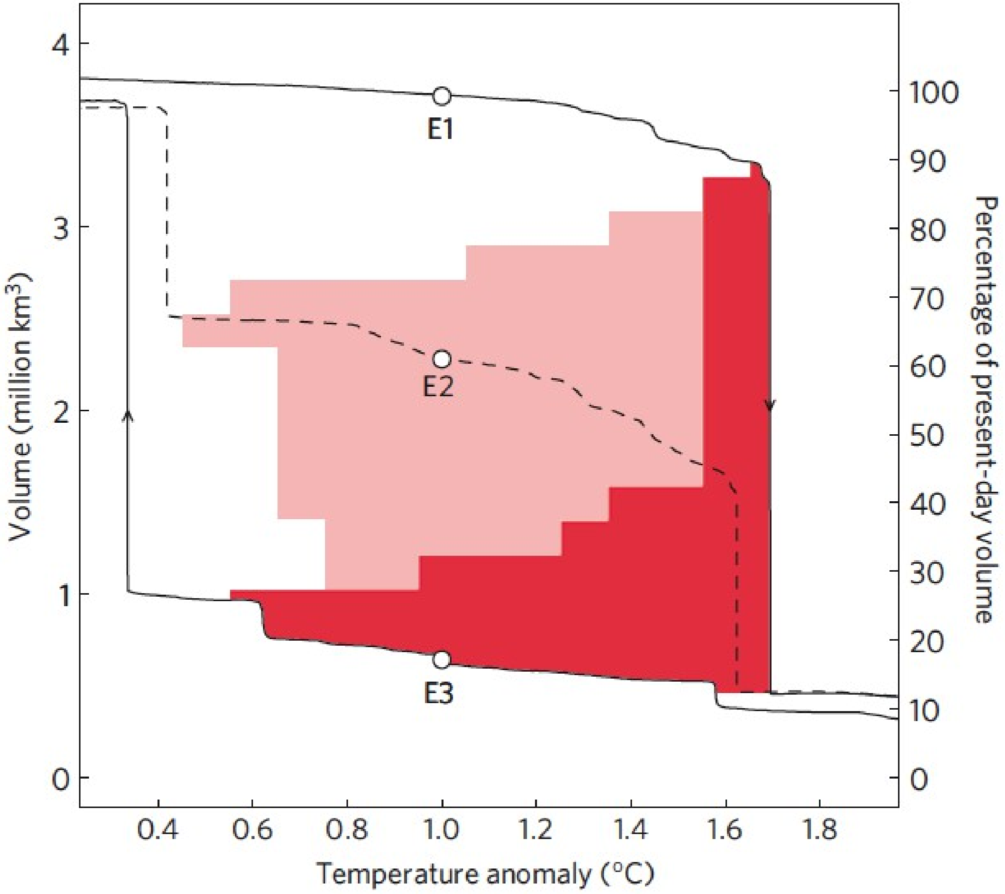
Instabilités :

- **des petites calottes – Groenland**
- des calottes marines – Antarctique
- Des falaises de glace - Antarctique

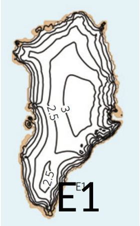
Instabilité des petites calottes - Groenland

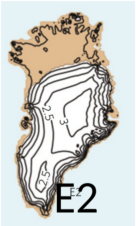


Albedo-elevation feedbacks
Greenland - multistability



Robinson et al. 2012





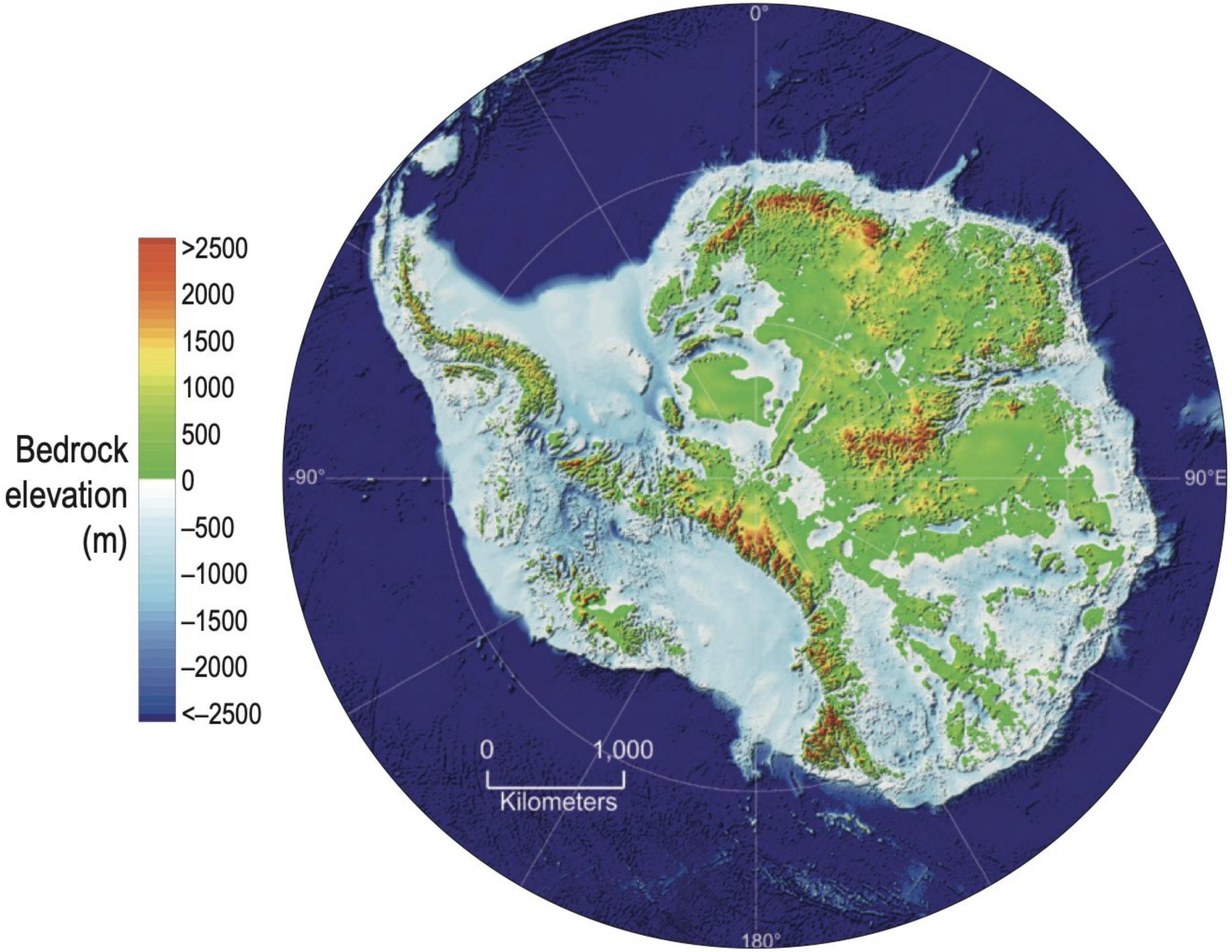
Timescale depends strongly on magnitude and duration of the temperature overshoot

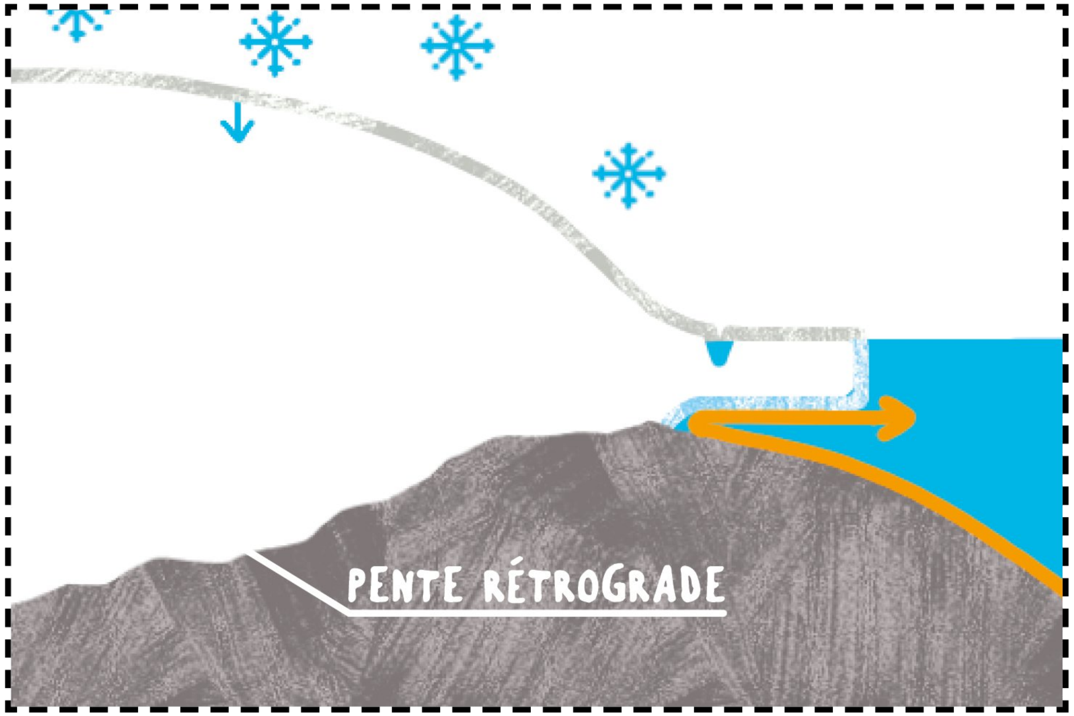
Contexte – Paleo, historique et projections

Instabilités :

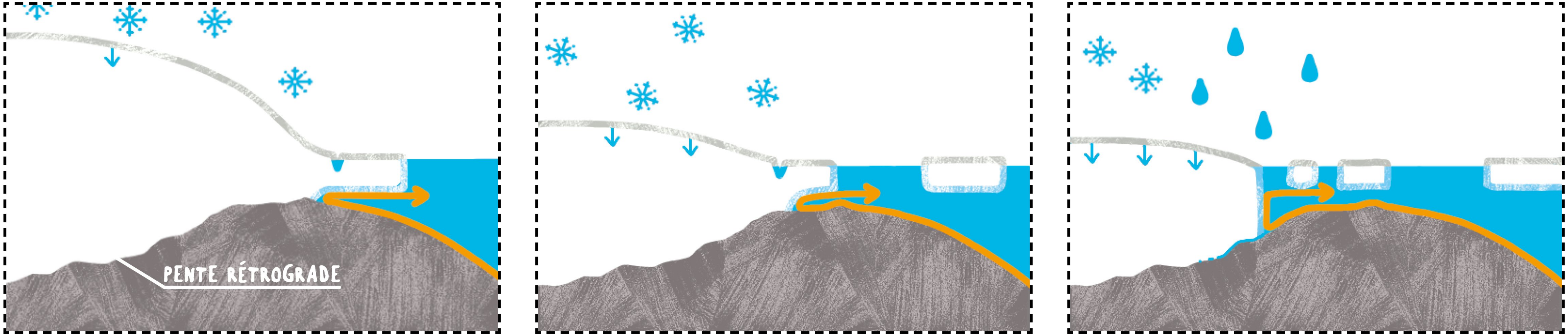
- des petites calottes – Groenland
- **des calottes marines – Antarctique**
- Des falaises de glace - Antarctique

Antarctique - instabilité des calottes marines (MISI)

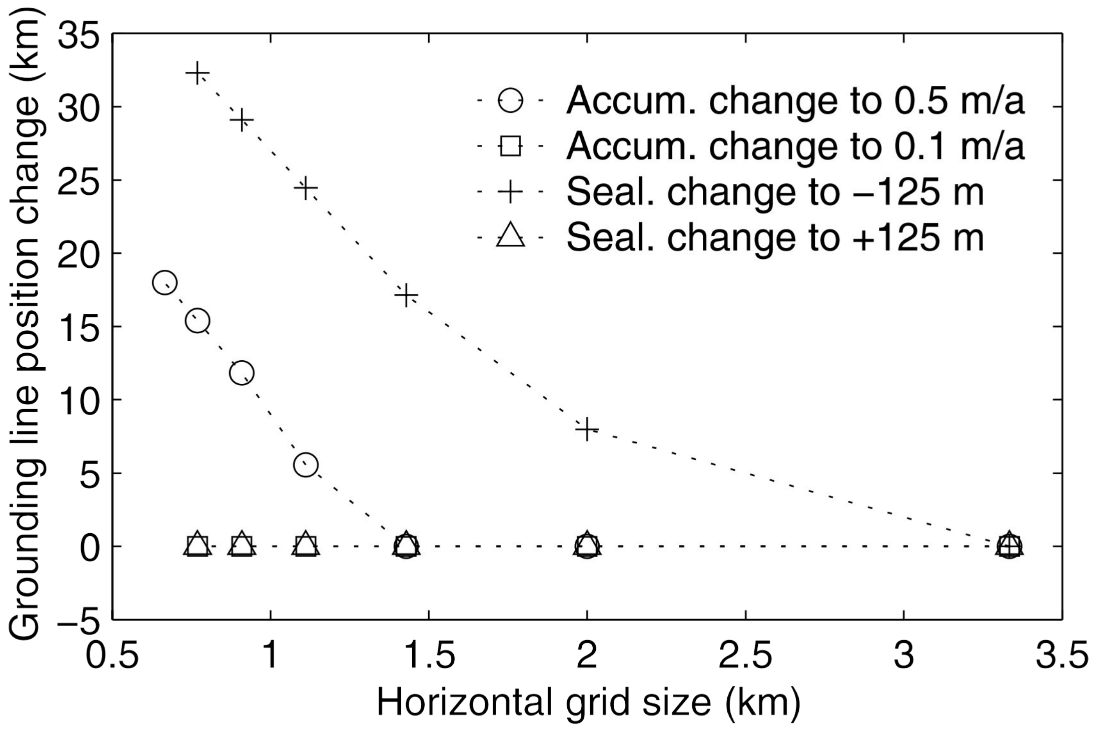




Antarctique - Instabilité des calottes marines, des falaises de glace



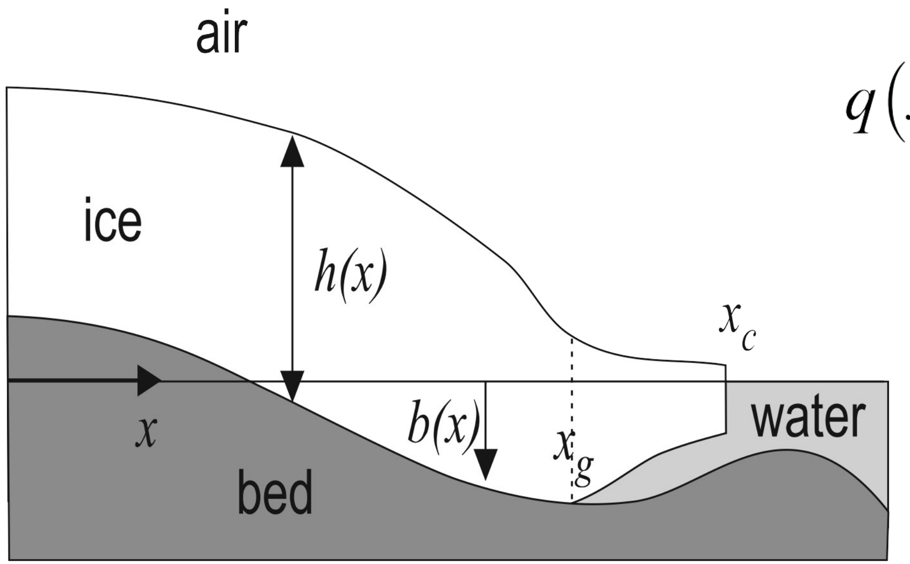
Un talon d’Achille : la ligne d’échouage



Vieli and Payne, 2005

”We conclude that at present, no reliable model of the grounding line is available, and further model development is urgently needed”

La solution en une équation



$$q(x_g) = \left(\frac{\bar{A}(\rho_i g)^{n+1}(1-\rho_i/\rho_w)^n}{4^n C} \right)^{\frac{1}{m+1}} \left[h(x_g) \right]^{\frac{m+n+3}{m+1}}, \qquad (16)$$

Ligne d'écoulement :

- solution unique sur une pente prograde
- Instable socle retrograde
- Hysteresis socle avec surcreusement

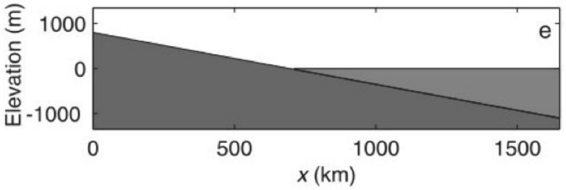
Schoof 2007

Marine ice sheet and hysteresis

Steady state - graphical resolution (from model B)

for a monotonic bed rock

$$a x_g = q_B(x_g) = \left(\frac{\bar{A}(\rho_i g)^{n+1}(1-\rho_i/\rho_w)^n}{4^n C} \right)^{\frac{1}{m+1}} h(x_g)^{\frac{m+n+3}{m+1}}$$



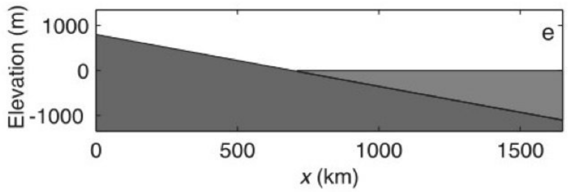
with $\begin{cases} h = \dfrac{\rho_w}{\rho_i} b \\ b(x) = \beta . x \end{cases} \Longrightarrow a.x_g \propto x_g^5$

Marine ice sheet and hysteresis

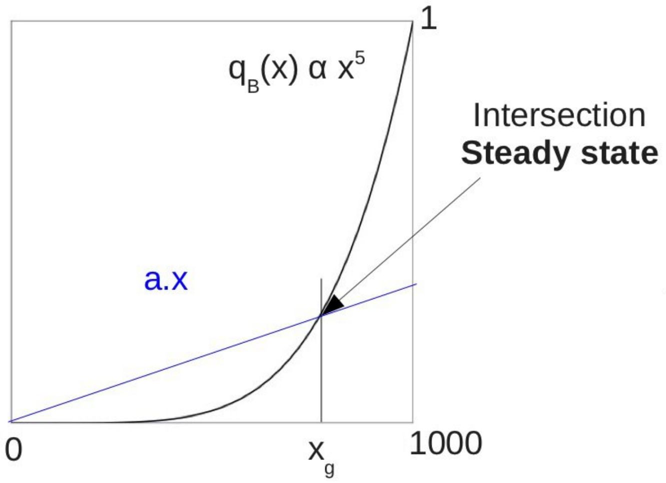
Steady state - graphical resolution (from model B)

for a monotonic bed rock

$$a x_g = q_B(x_g) = \left(\frac{\bar{A}(\rho_i g)^{n+1}(1-\rho_i/\rho_w)^n}{4^n C}\right)^{\frac{1}{m+1}} h(x_g)^{\frac{m+n+3}{m+1}}$$



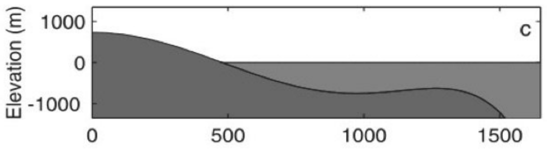
with $\begin{cases} h = \dfrac{\rho_w}{\rho_i} b \\ b(x) = \beta . x \end{cases} \Longrightarrow a.x_g \propto x_g^5$



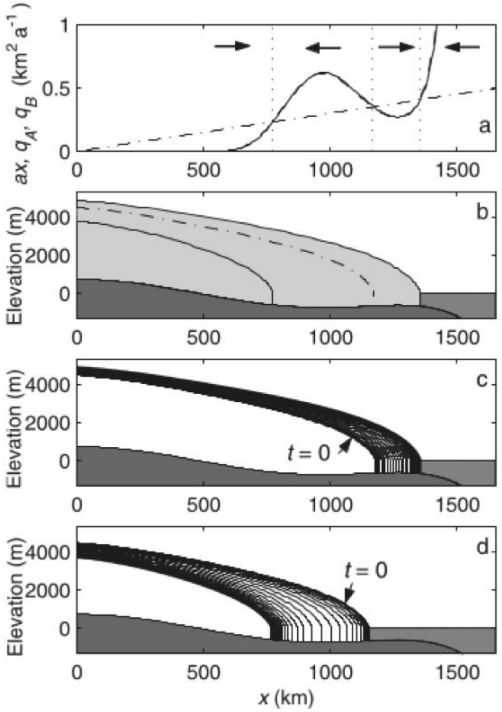
with a **monotonic bed rock** we have only **one steady state**

Marine ice sheet and hysteresis

Steady state – none monotonic bed rock (from model B)



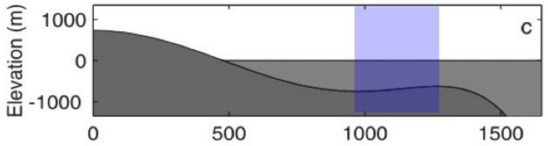
We can find **3 steady state** are possible

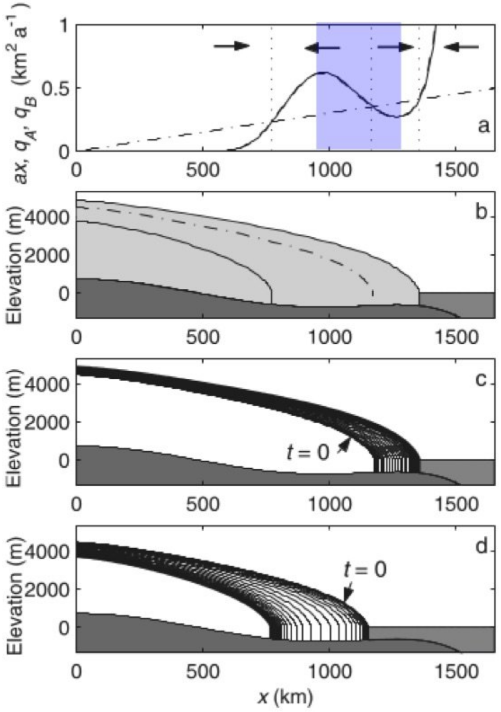


Schoof, C. (2007)

Marine ice sheet and hysteresis

Steady state – none monotonic bed rock (from model B)





Schoof, C. (2007)

We can find **3 steady state** are possible

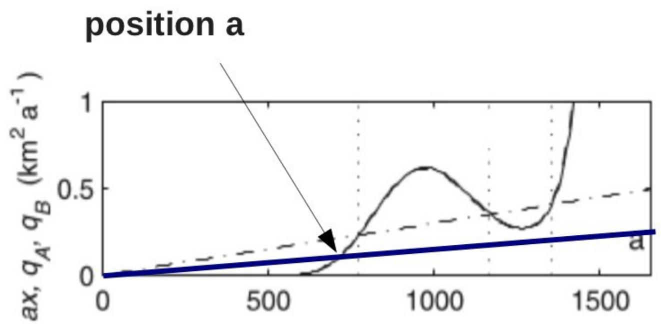
The blue zone <=> **upward** bed rock

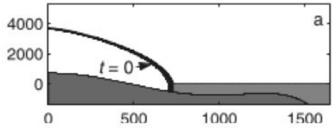
it is a **unstable** zone for the grounding line

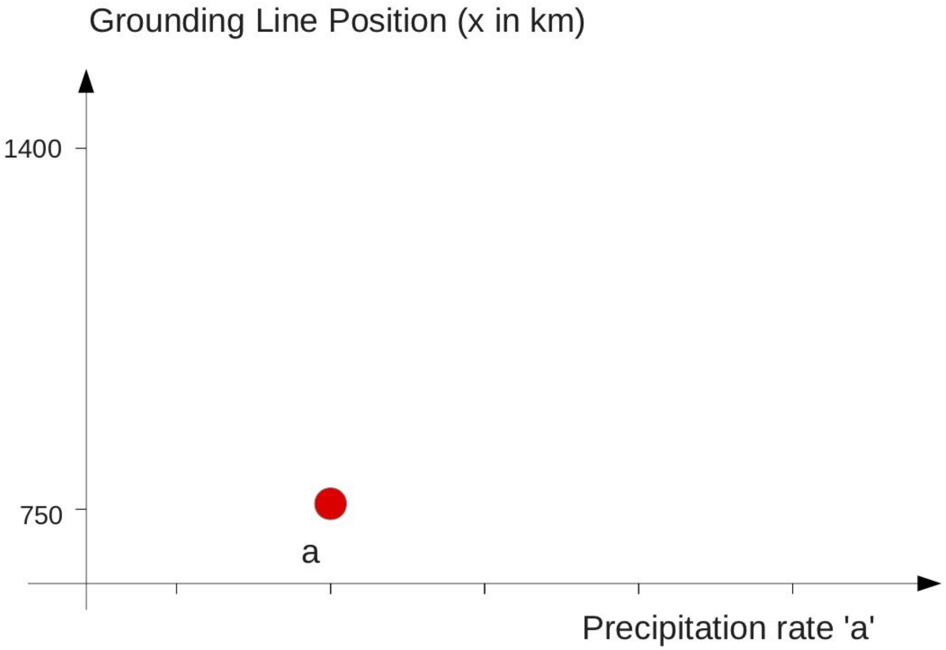
2 stable grounding line are **possible**

=> hysteresis possible

Marine ice sheet and hysteresis

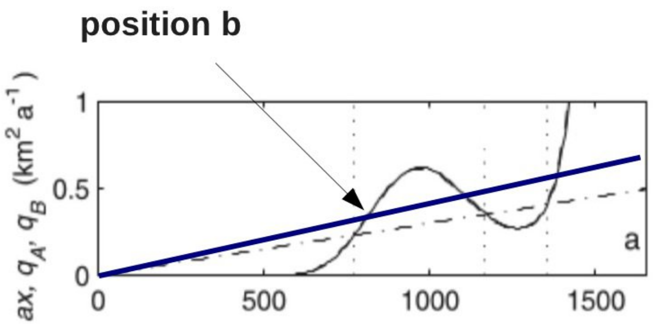


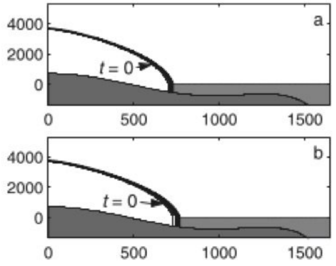


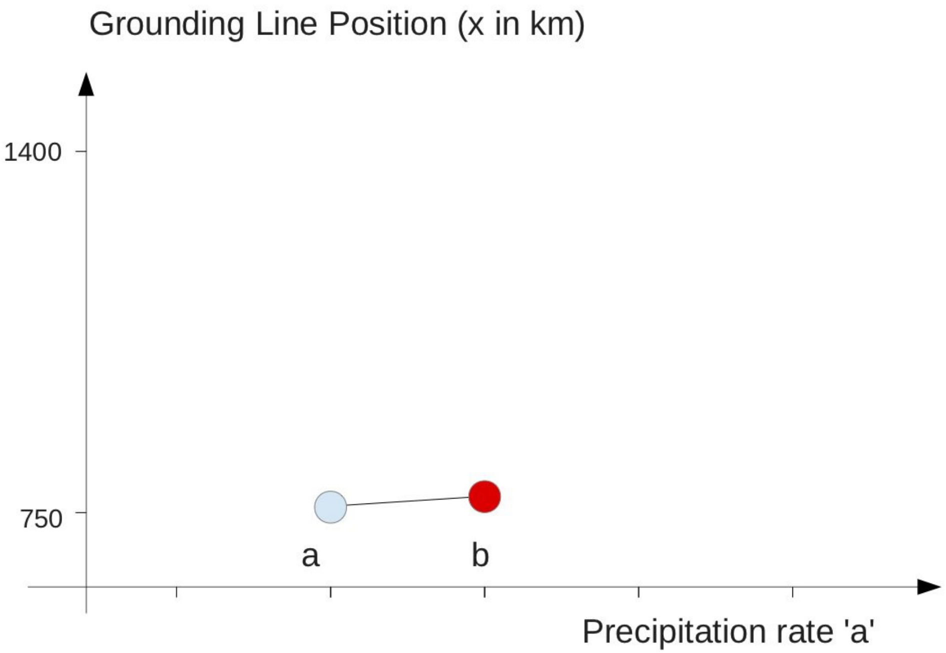


Schoof, C. (2007)

Marine ice sheet and hysteresis

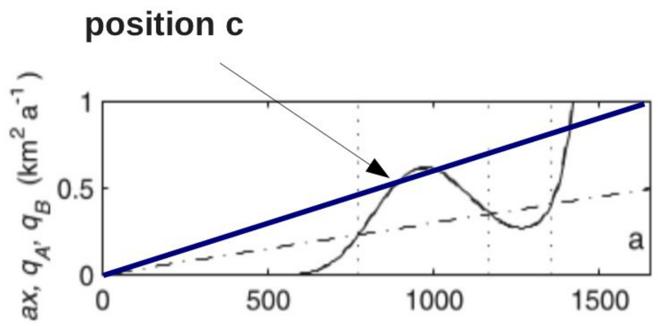


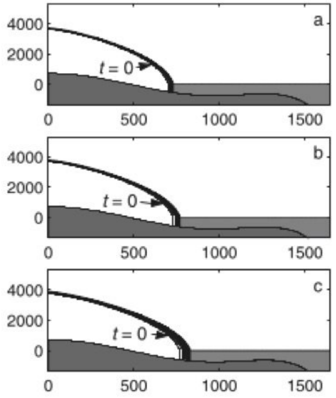


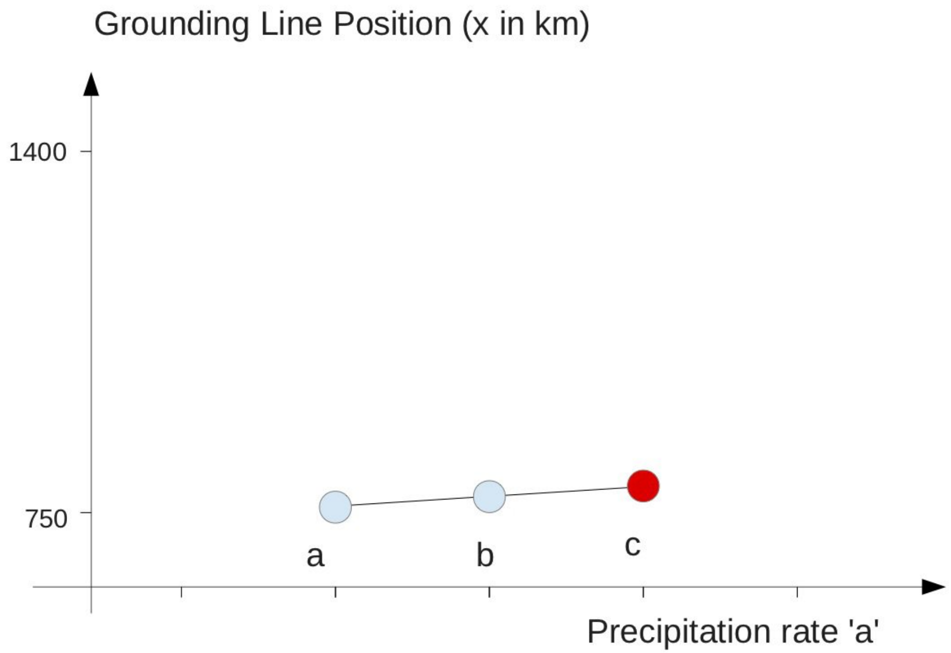


Schoof, C. (2007)

Marine ice sheet and hysteresis







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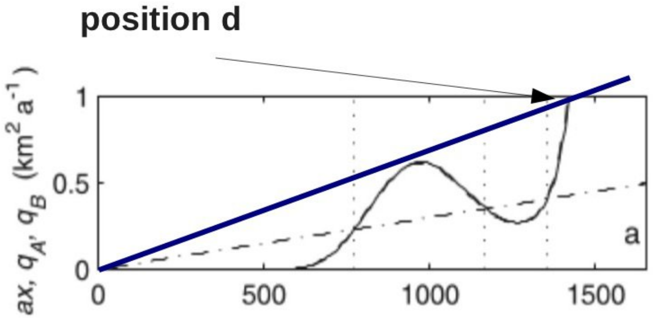
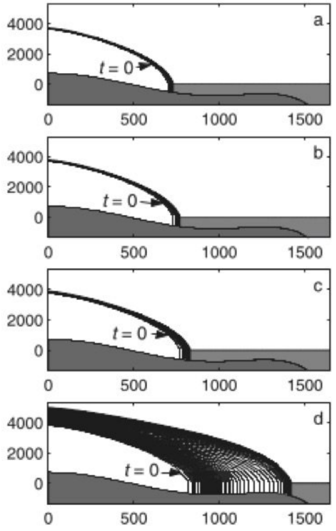
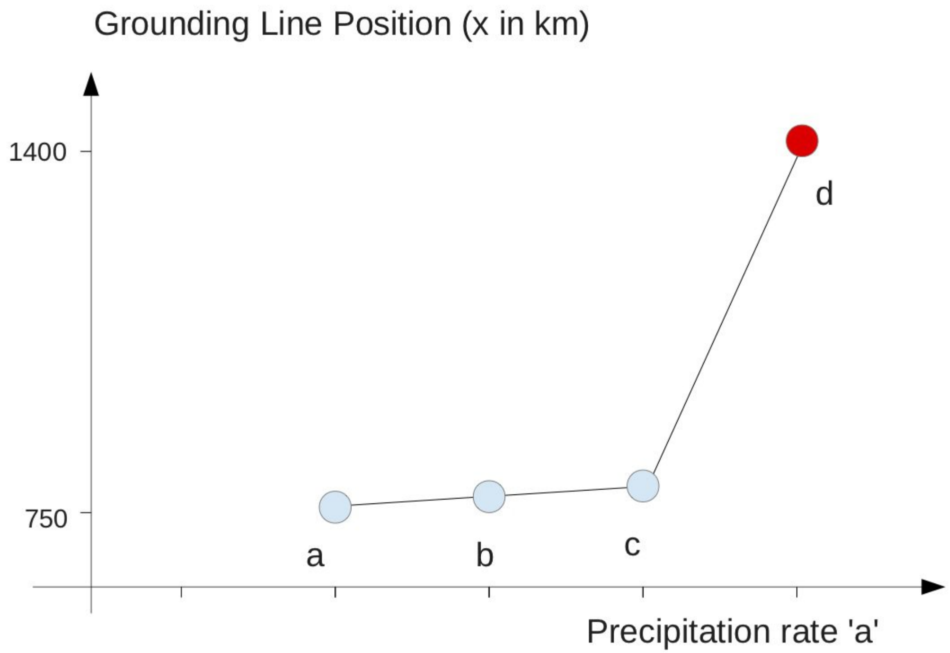
Marine ice sheet and hysteresis

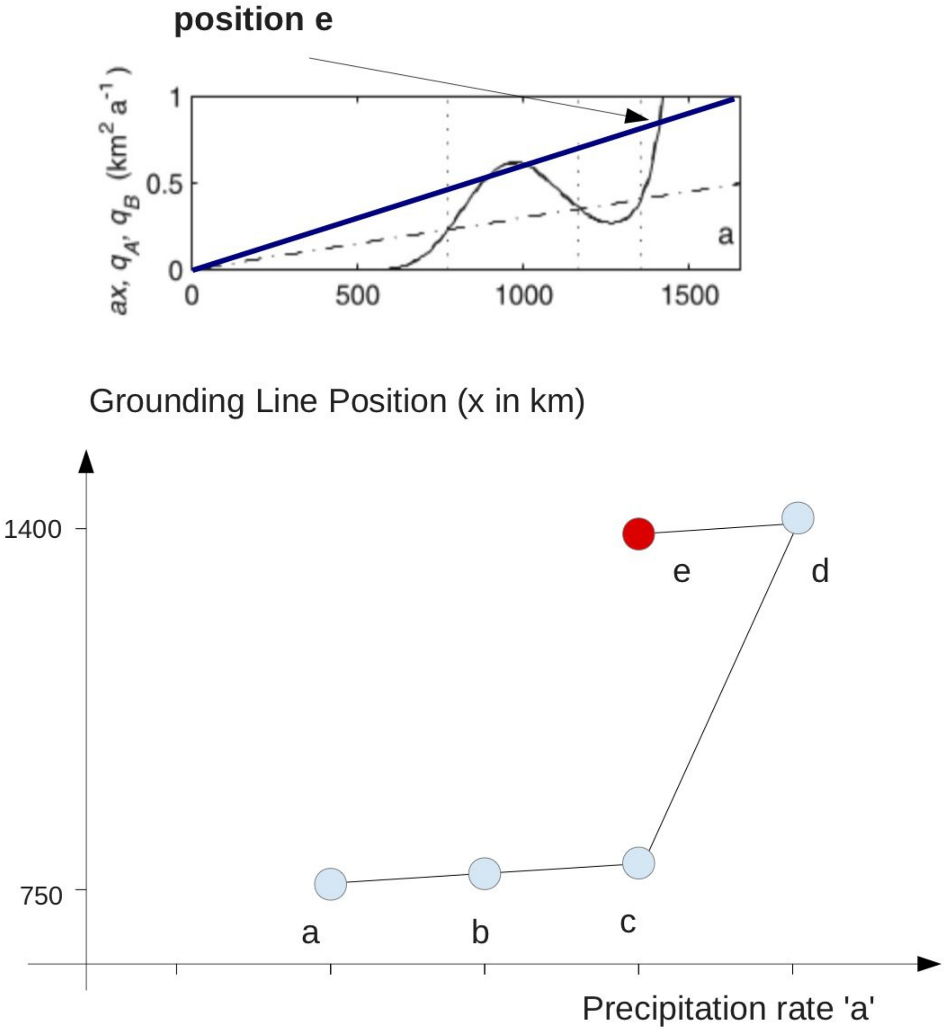


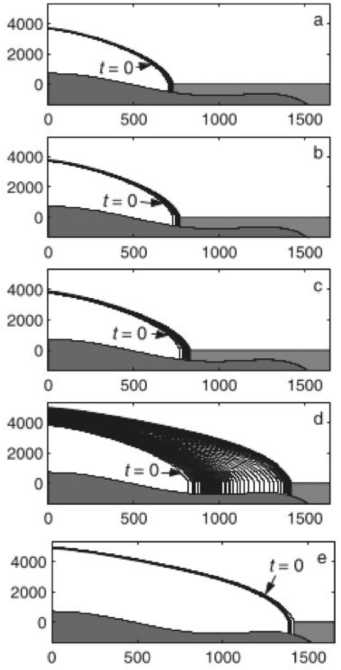




Schoof, C. (2007)

Marine ice sheet and hysteresis





Schoof, C. (2007)

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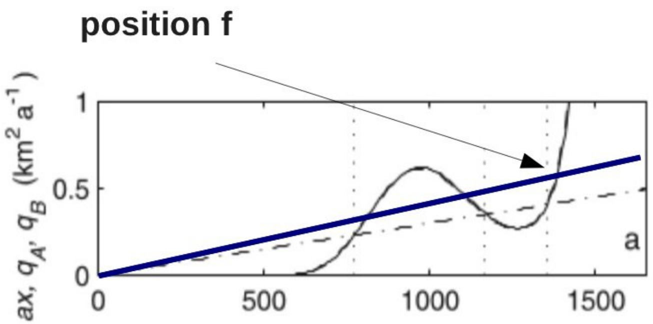

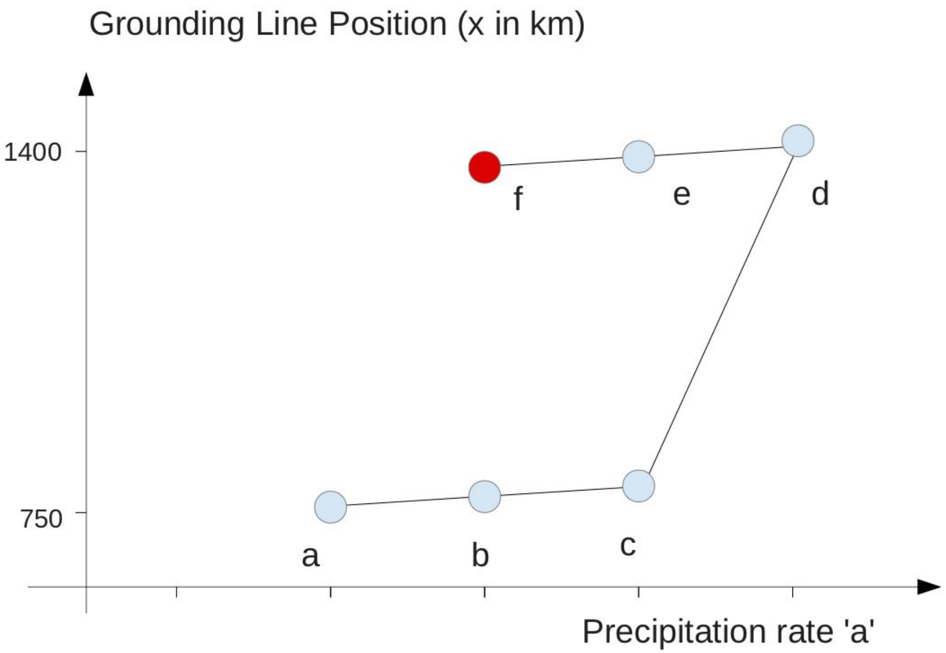

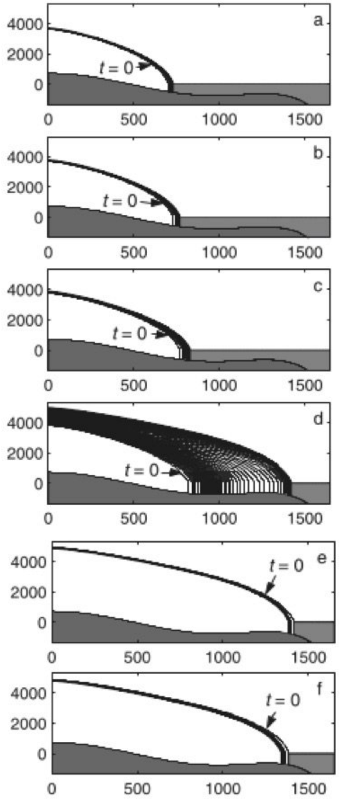

Schoof, C. (2007)

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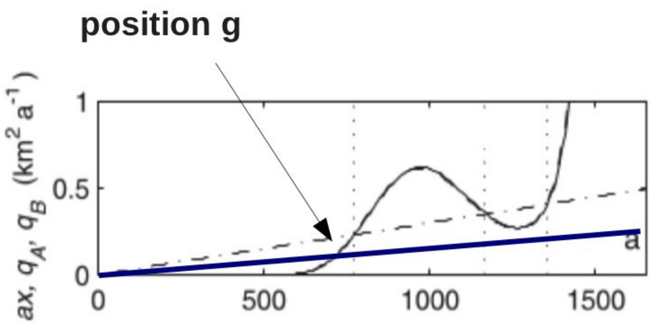
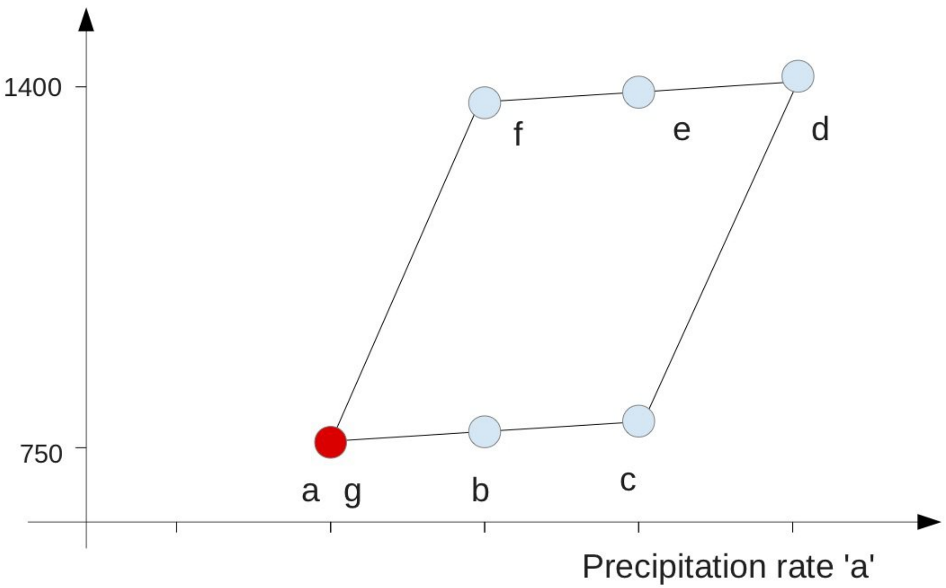
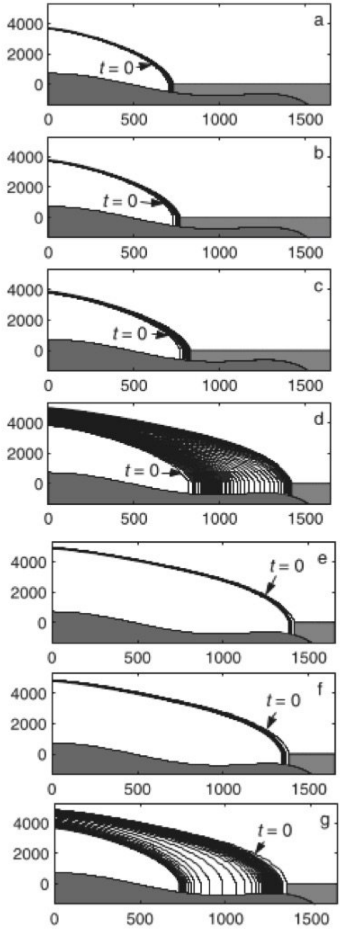
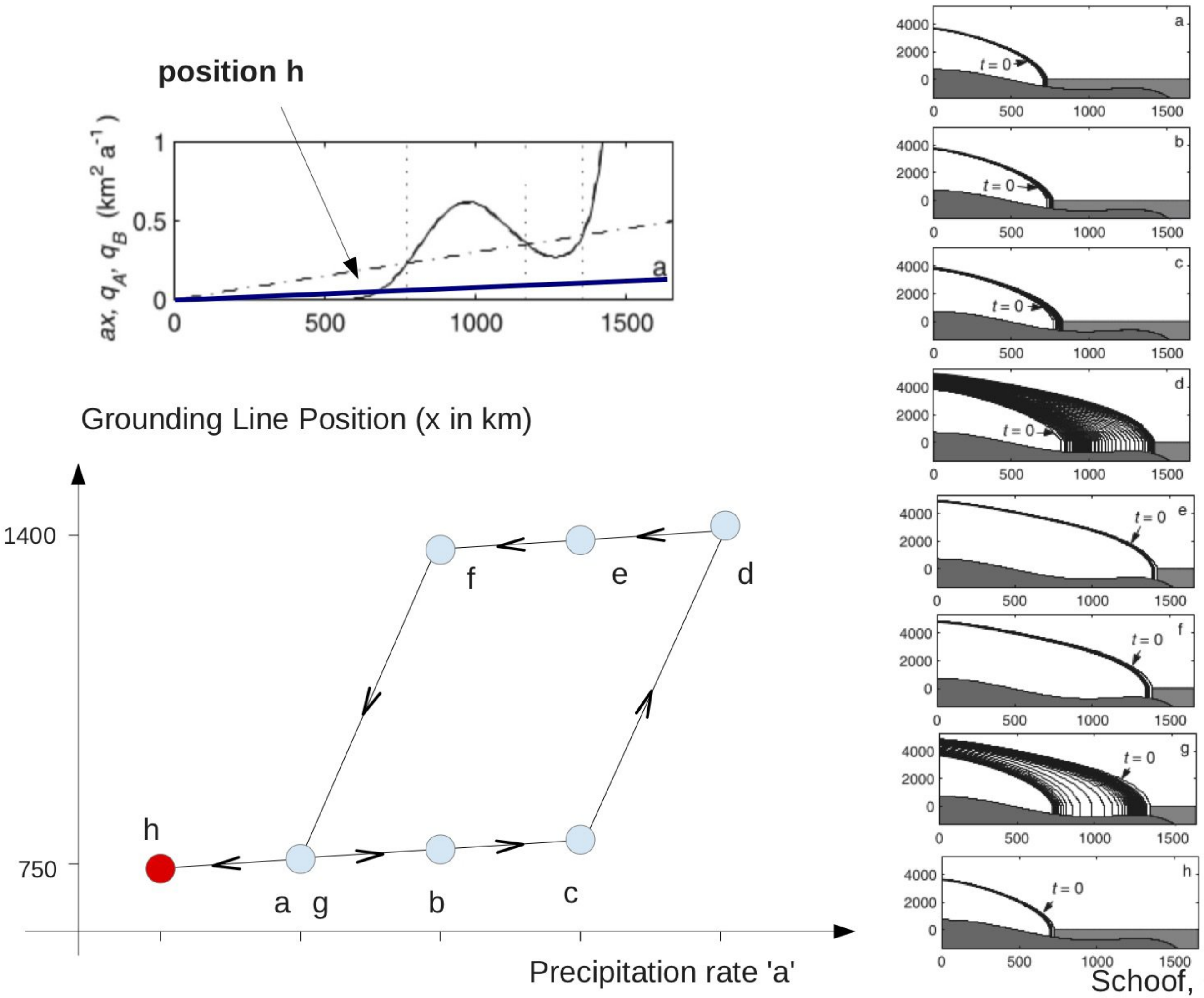






Schoof, C. (2007)

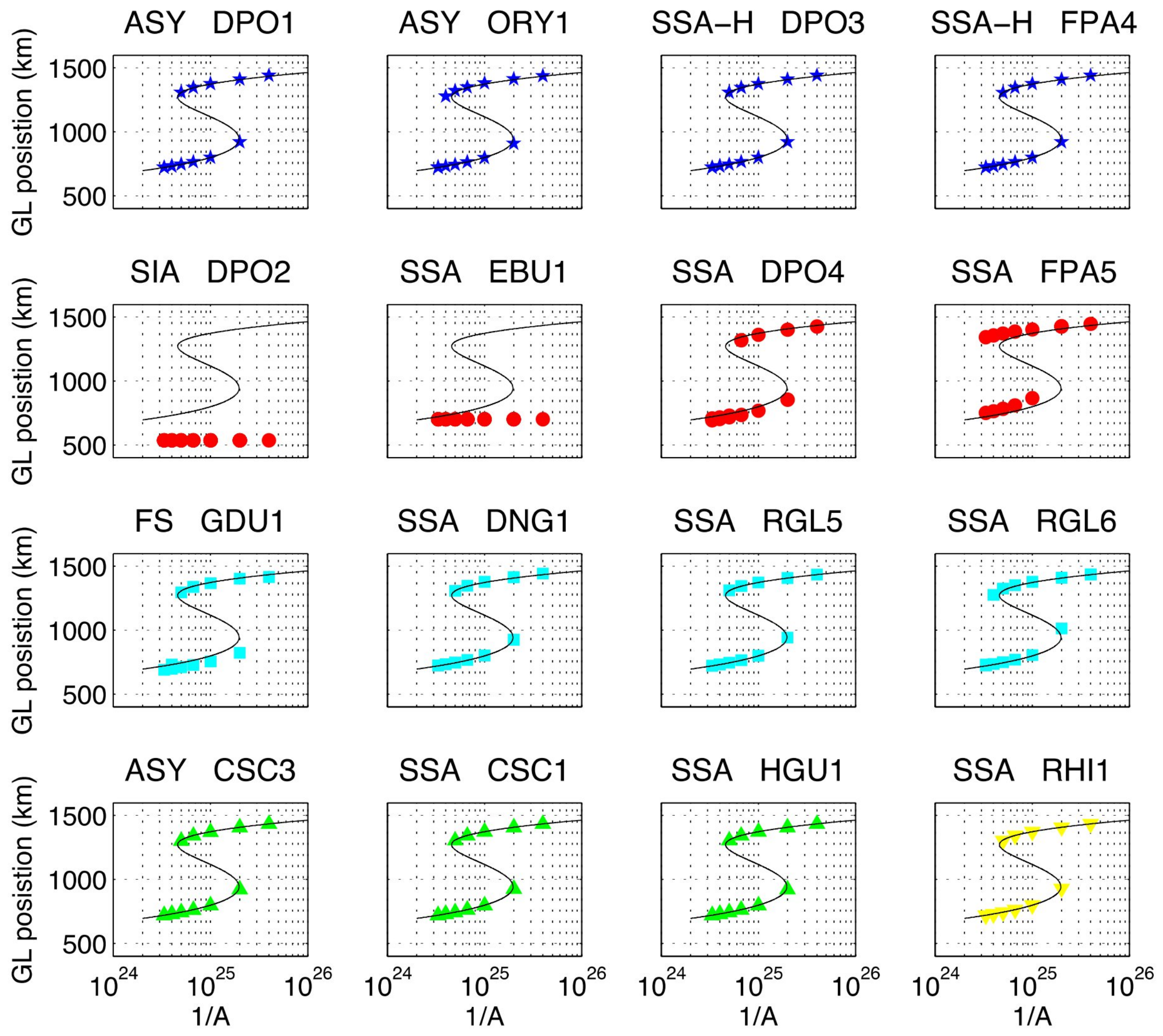
Marine ice sheet and hysteresis



Schoof, C. (2007)

Une solution analytique, des modèles qui progressent

Un MIP, des MIPs



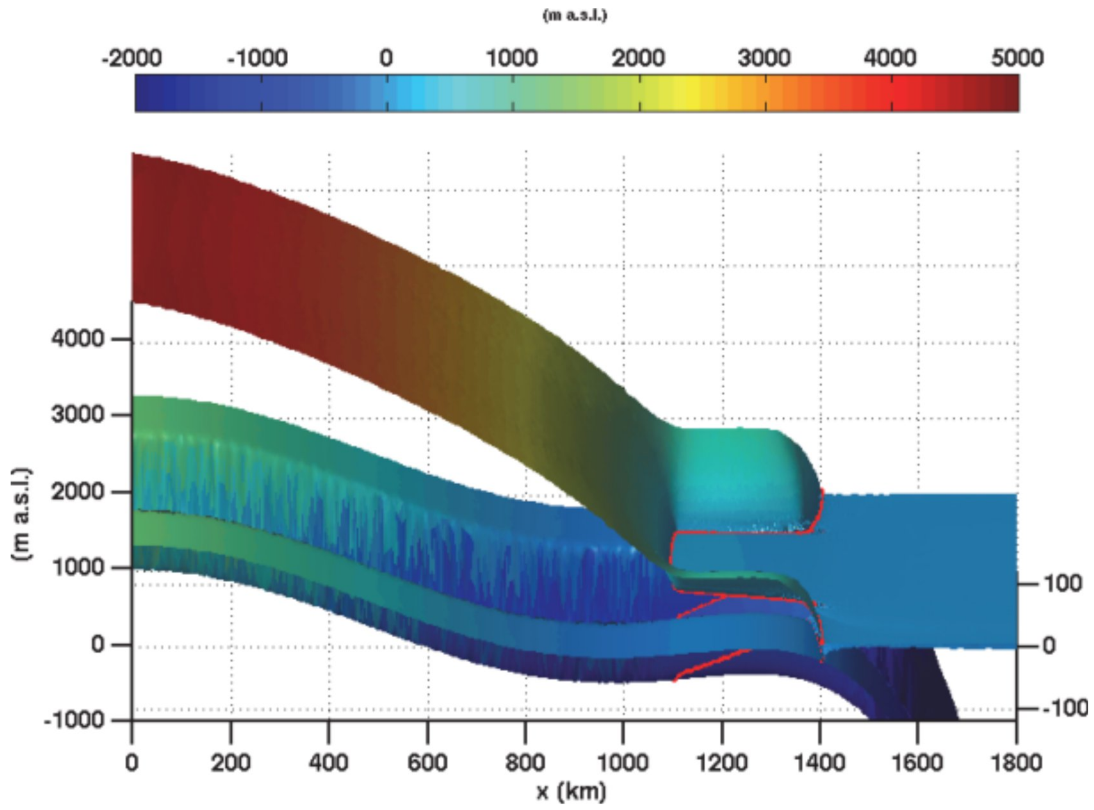
Pattyn et al., 2012

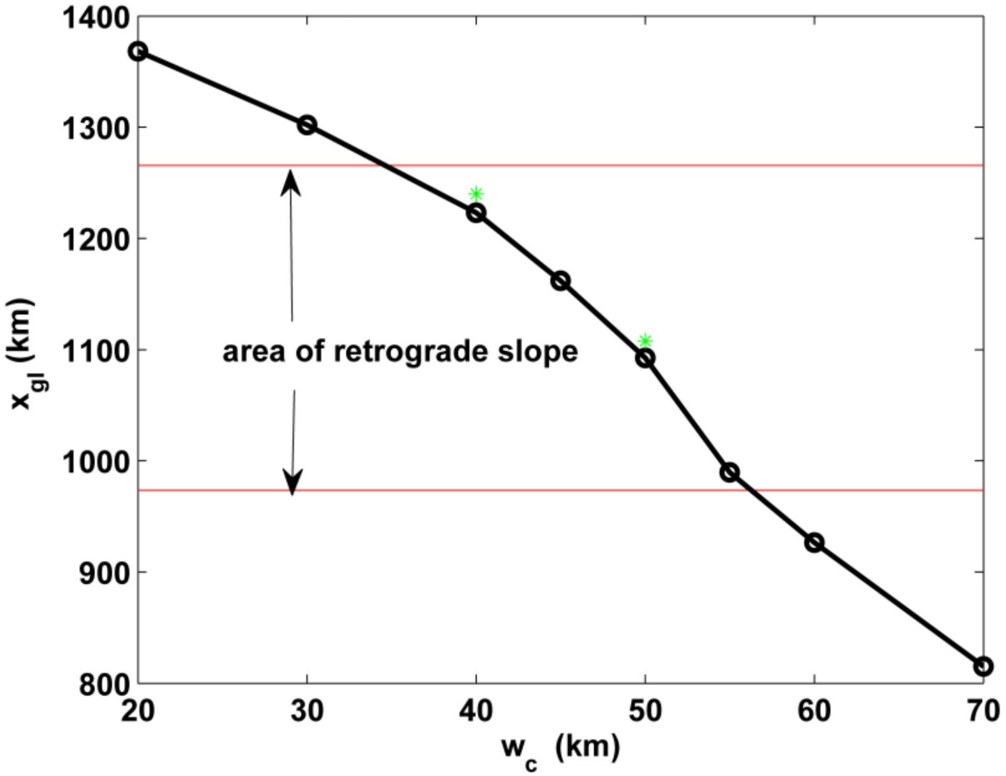
MISMIP puis MISMIP3D (2010s)
ligne d'échouage

MISOMIP (2015s)
Circulation cavité, ligne d'échouage, couplage

Calving MIP (2022…)
Vêlage

La subtilité est dans l’effet d’arc-boutant

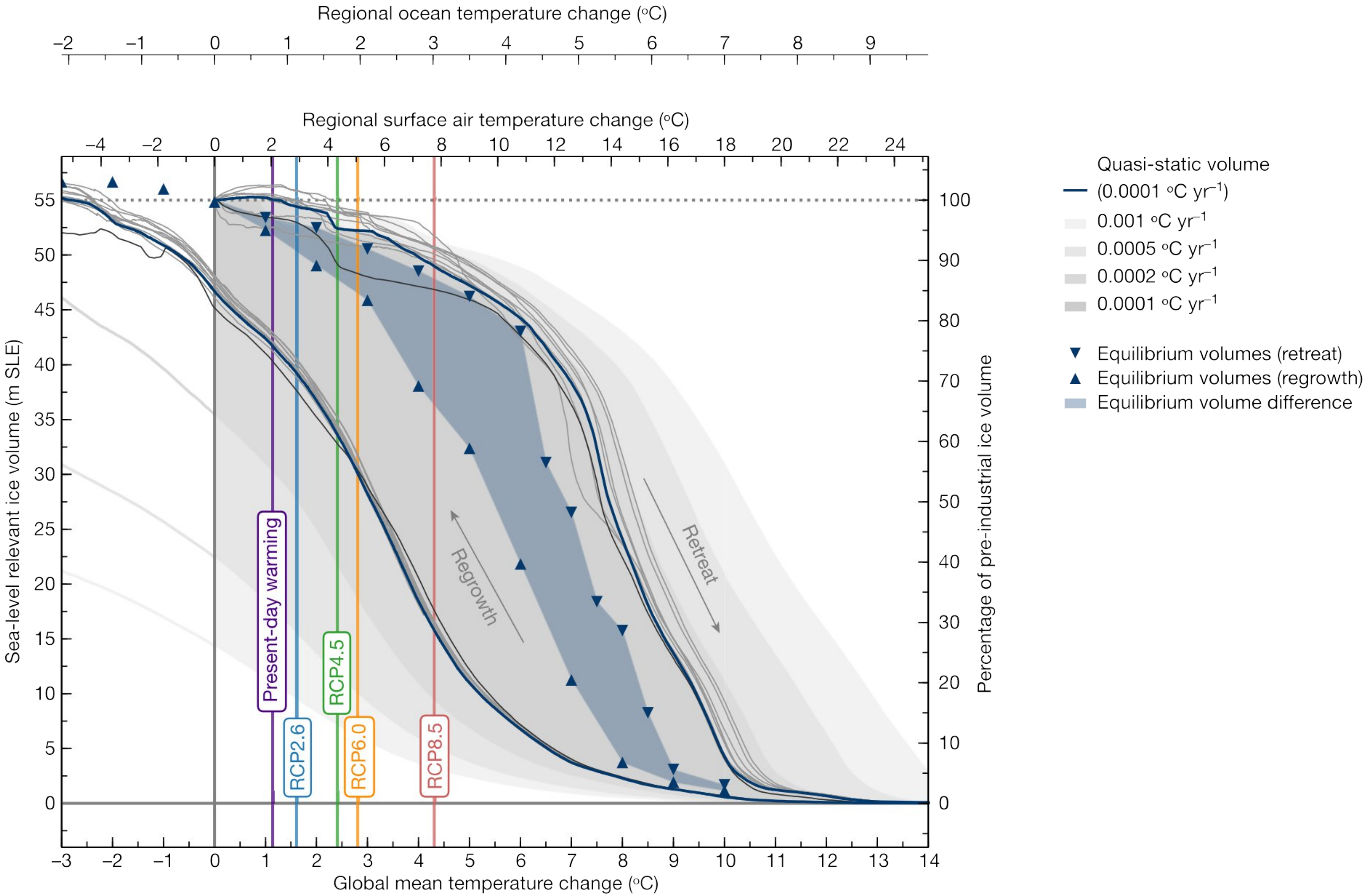




Gudmundsson et al., 2012

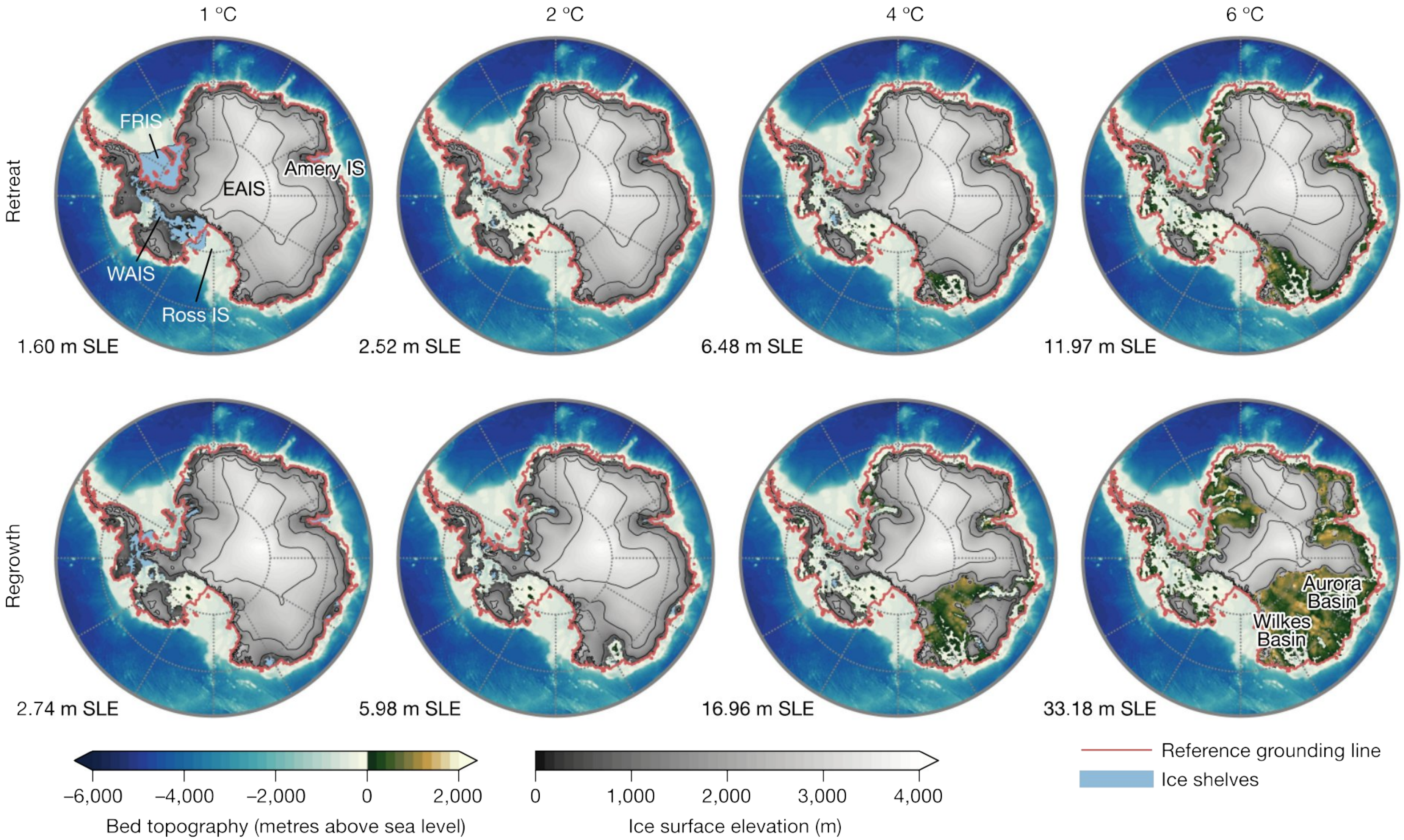
Une pente retrograde n’est pas une condition suffisante pour avoir une instabilité

The hysteresis of the Antarctic ice sheet

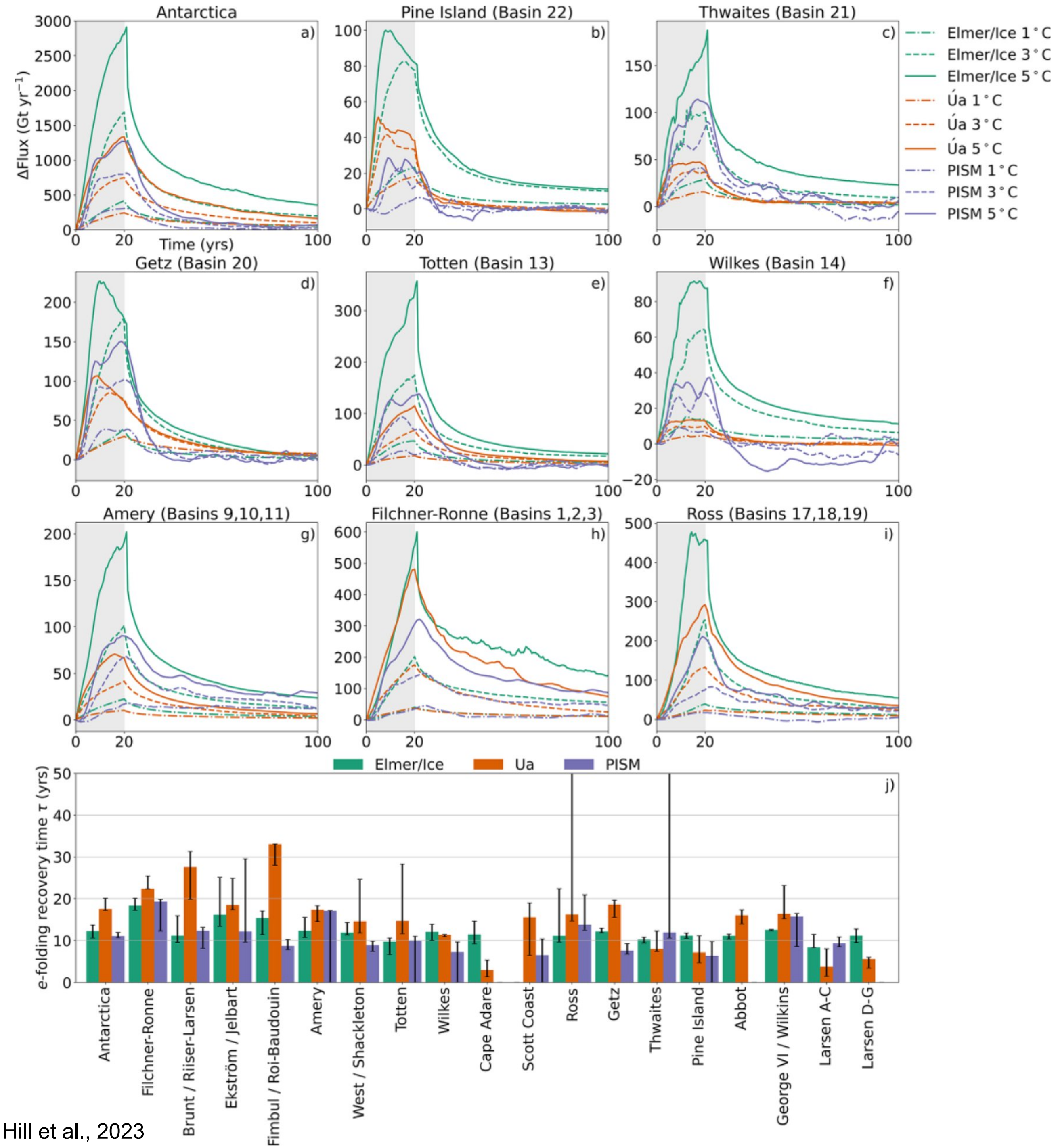


Garbe et al., 2020

The hysteresis of the Antarctic ice sheet

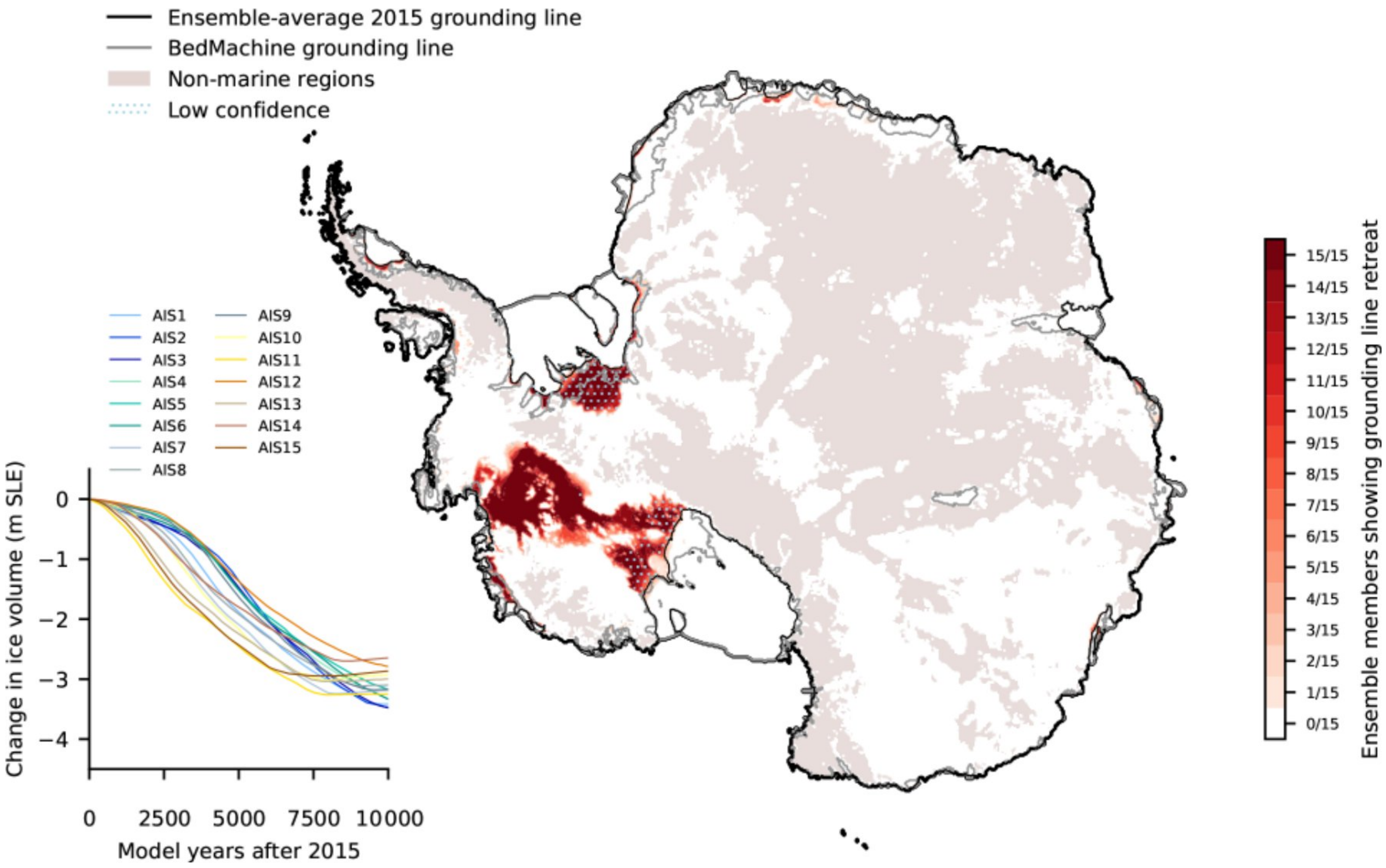


Garbe et al., 2020



Hill et al., 2023

La géométrie actuelle de l'Antarctique (à l'équilibre) n'est pas intrinsèquement instable…



On ne peut exclure que la perte de masse actuelle entraine un MISI de l’Antarctique de l’ouest

Reeze et al., 2023

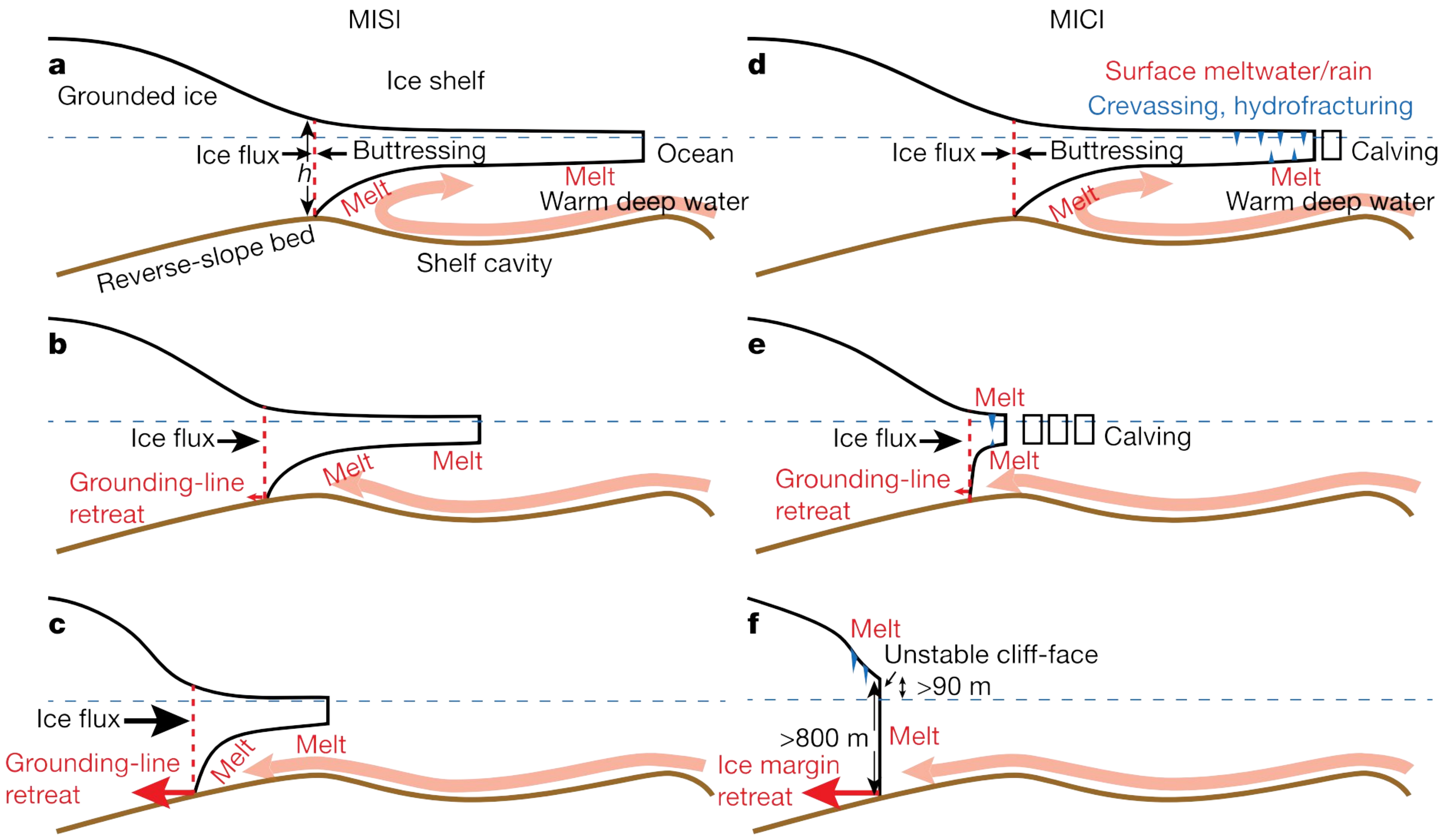
Contexte – Paleo, historique et projections

Instabilités :

- des petites calottes – Groenland
- des calottes marines – Antarctique
- **Des falaises de glace - Antarctique**

Marine Ice Cliff Instability – MICI

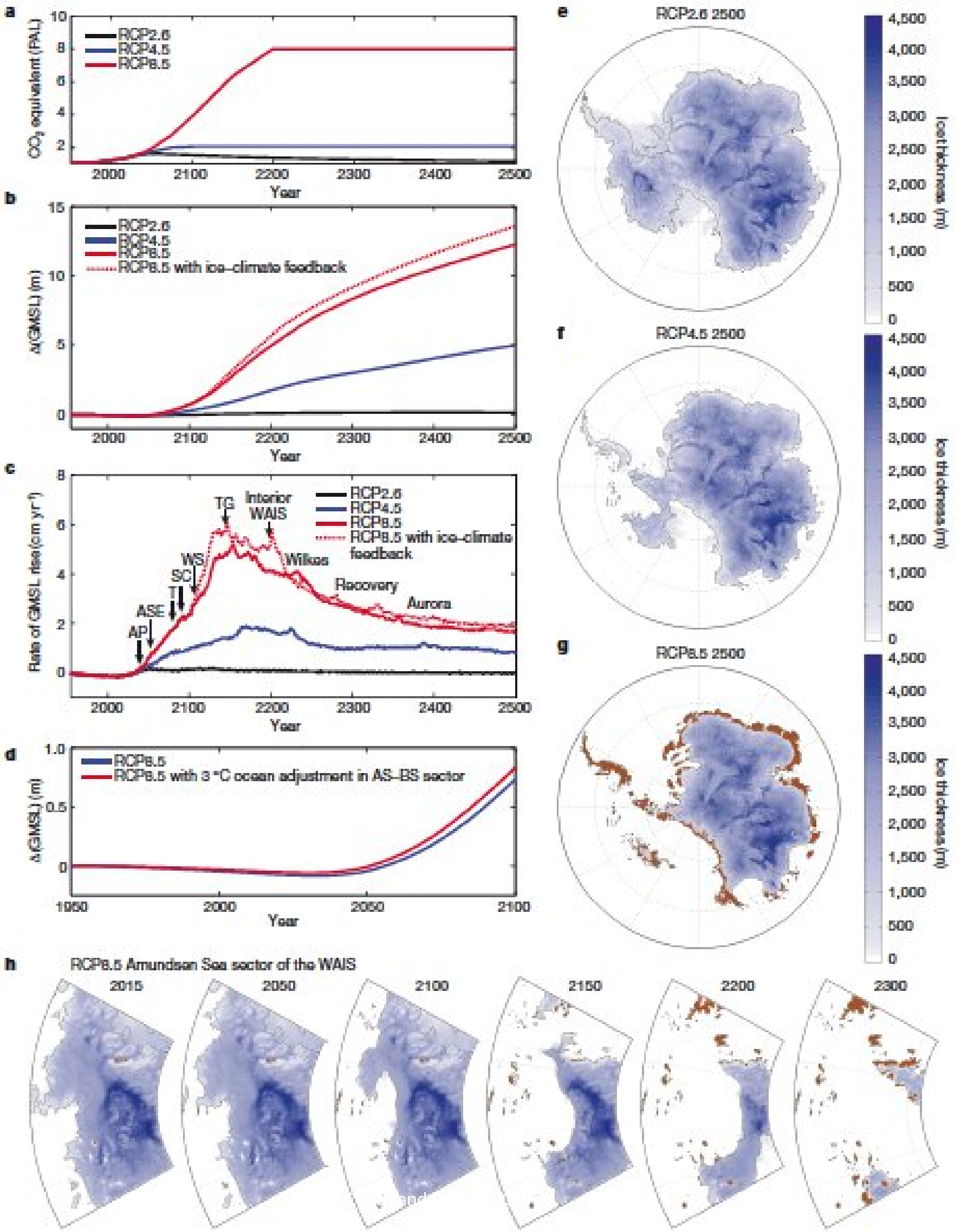
Le cygne noir



Un processus plausible, non observé

DeConto and Pollard 2016

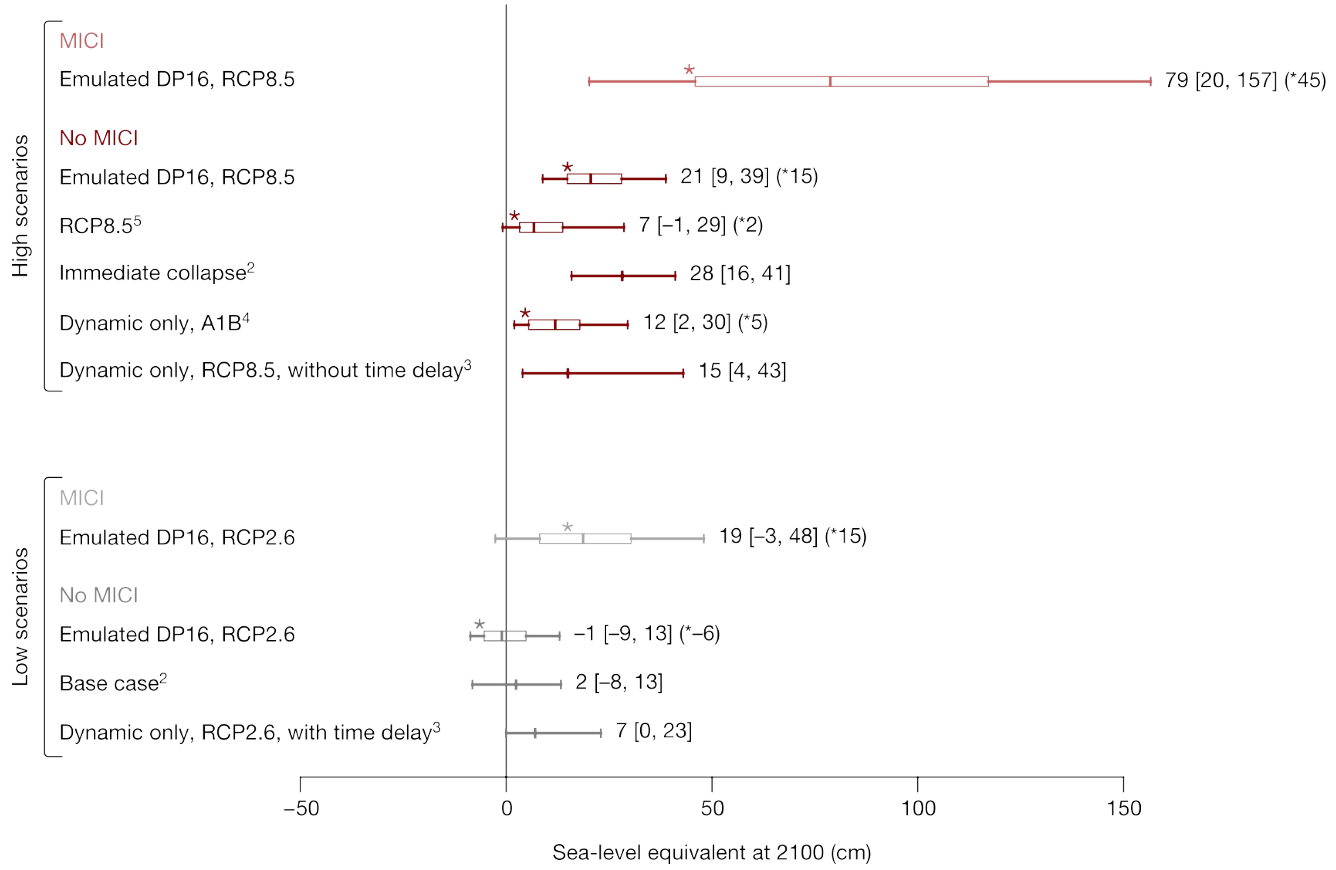
MICI - Conséquence



Des contributions de l'Antarctique de l'ordre du mètre par siècle

DeConto and Pollard 2016

MICI or not MICI?



Edwards et al. 2019

Take-home message

Antarctique comme Groenland ont vraisemblablement des points de bascule (suivant des processus différents)

les seuils associés sont estimés autour de 1.5/2°C de réchauffement vs la période préindustrielle

Les conditions d’initialisation des instabilités comme la vitesse des démantelements qui suivent restent très incertain (MICI or no MICI?)

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Hill 2023
Reese 2023
DeConto and Pollard 2016 - https://doi.org/10.1038/nature17145
Edwards 2019