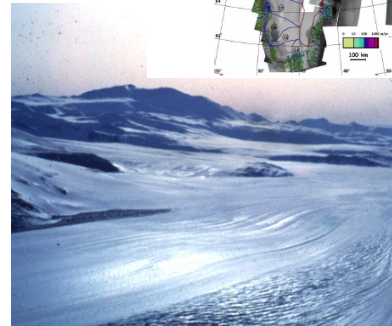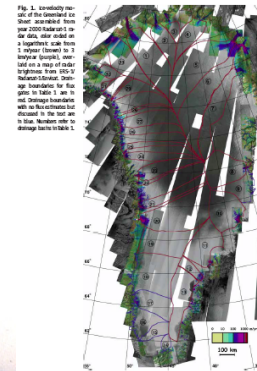# 氷床と海水準と気候

東京大学大気海洋研究所
阿部彩子

2018.12.27 気候システム

Ref.
IPCC AR5 （第5次報告書, WG1, 2013）
Golledge et al, 2015, Nature
DeConte and Pollard, 2016, Nature
IMBIE team, 2018, Nature
Fyke et al, 2018, Rev. of Geophysics
Pattyn et al,2018, Nature Clim. Change
Obase,Abe-Ouchi,Kusahara, Hasumi 2017, J. Clim.
Abe-Ouchi, et al, 2013, Nature

Contents

1. Observation of Ice sheet and Sea Level Change　氷床と海水準変化の観測
2. Cause of Sea level change and its estimation for the 20 century　海水準変化の原因
3. Global climate projection　将来予測の方法
4. Modelling the past and future ice sheet change　過去の変化の再現と将来予測
5. Summary　まとめ

Global Sea Level Rise = Ocean Volume / Global Ocean area
海水準変化の定義：海水の体積変化／全海洋面積

ポイント

- IPCCAR5までは、経験則が多く、また南極の不安定性が物理的に扱われなかった。（経験則による予測は不自然なほど大きかった）。
- その後の研究で、予測が海水準にして20cm ほど加わり、21C末の予測がRCP8.5では1m を超えた。
- 南極の力学的寄与が不確実
- 海洋が氷床棚氷部分をどれほど融かし、それが内部からの氷床の流動や流出にどれほど寄与するか？大気が氷床表面を融かした結果がどれほど氷床崩壊に結びつくか？このような現象について、推定幅が広い。
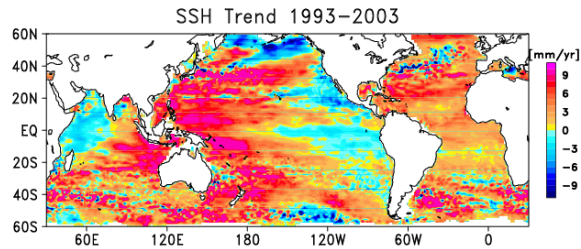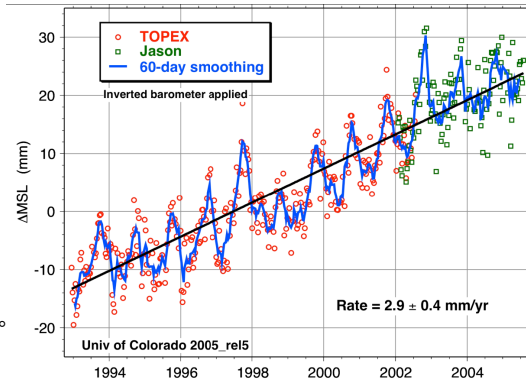- 気候と氷床について過去の氷床が大きく変化した時代状況をモデリングすることが課題となる
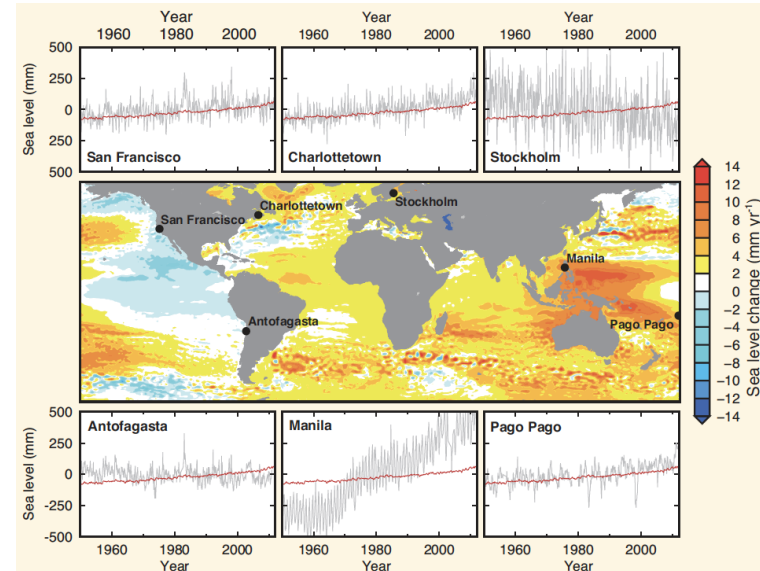
過去数百年の
海面変化

(1) 古気候
(2) Tide Gauge
（潮位計）
(3) 衛星（高度計）
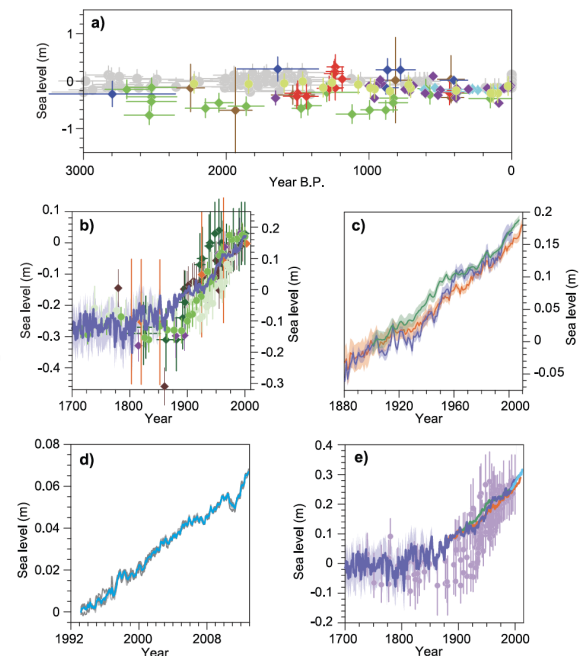
IPCC AR5 Fig.13.3

衛星データによる海水準推定
Observed Sea level change by satellite

Continuous Increase of Sea level, Although a regional difference!
平均した海面上昇が観測されている。
～ 3 mm in 1 year

最近の各地の海面変化

海水準変化の原因
Cause of Sea level change

短期的には、潮の満ち引き、嵐、エルニーニョや太平洋十年規模変動などの気候変動による。（風向風速、海流、温度、塩分などの変化が地域的な海面に変化を与える。）

長期的に（数年以上）は、
1. 海水の熱膨張Thermal Expansion of ocean water
2. 南極やグリーンランド氷床の質量変化Mass change of Antarctica and Greenland ice sheet）
3. 山岳氷河の質量変化 (Mass change of Mountain Glaciers）
4. 固体地球の変形による長期変化、テクトニクス変動や後氷期による地球変形 (Long term change due to tectonics and post-glacial rebound）
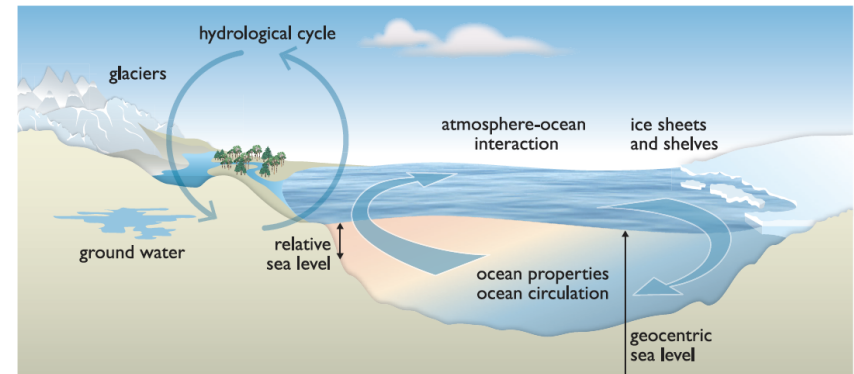
海面上昇に関わるプロセス

Figure 13.1 | Climate-sensitive processes and components that can influence global and regional sea level and are considered in this chapter. Changes in any one of the components or processes shown will result in a sea level change. The term 'ocean properties' refers to ocean temperature, salinity and density, which influence and are dependent on ocean circulation. Both relative and geocentric sea level vary with position. Note that the geocenter is not shown.

世界の雪と氷

雪（白）と氷河（灰色）と海氷（水色）

2004-11-15
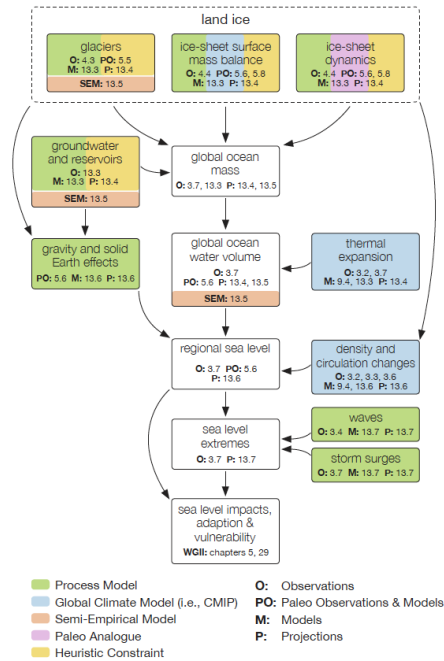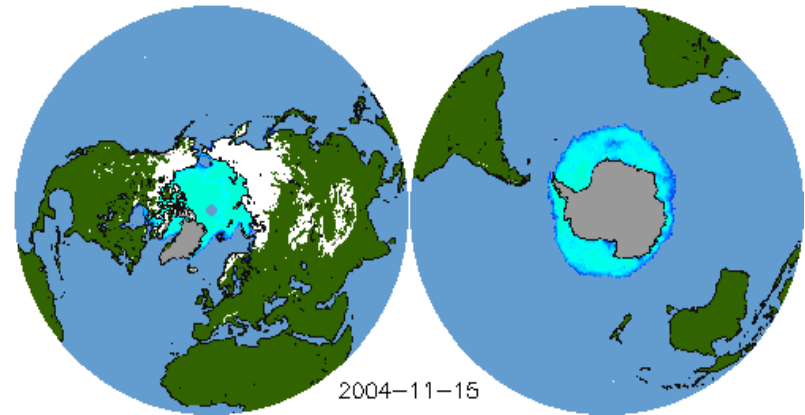
山岳氷河

Rhone Glacier
In Switzerland
スイスのローヌ氷河

Rhonegletscher
Konsequenzen der Klimaerwärmung

1856
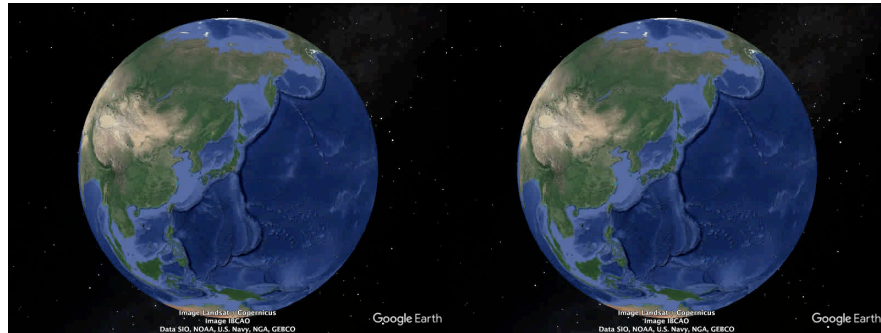Rekonstruktion des letzten Hochstandes (kleine Eiszeit) nach den ersten topographischen Kartierungen (Dufourkarte)

heute

2050
Zukunftsszenario mit klimatischen Bedingungen wie im Extremjahr 2003
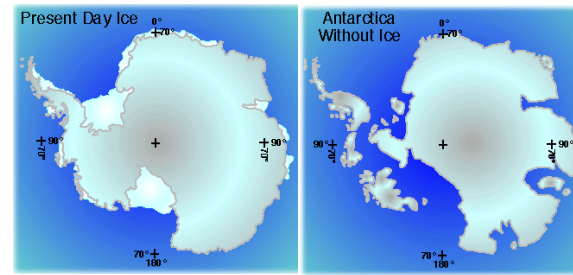
現在気候下で存在する２つの大陸氷床

グリーンランド氷床

Google Earth

面積：1.80 x 10⁶ km² (陸地の1.2%)
体積：2.85 x 10⁶ km³
海水準相当：7.36 m

南極氷床

Google Earth

面積：12.30 x 10⁶ km² (陸地の8.3%)
体積：26.5 x 10⁶ km³
海水準相当：58.3 m

南極氷床が全て融解すると…
駒場（34 m）、本郷（20 m）、柏（20 m）キャンパスは全て水没 (国土地理院)

南極氷床 大陸規模氷河

90% の淡水は氷床にある。
南極、グリーンランドの氷床が融ければ、各々70m, 7m 海面上昇する
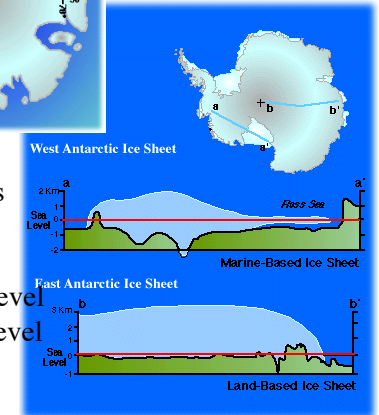
More than 90 % of Fresh Water Volume is Stored in ice sheet (land ice)

Antartica ice sheet rises ~ 70 meter Sea level
Greenland ice sheet rises ~ 7 meter Sea level

http://www.glacier.rice.edu/land/5_tableofcontents.html

グリーンランド氷床

内陸と沿岸域の雪氷表面の違い

グリーンランド氷床沿岸域（Qaanaaq）

南極氷床沿岸域（Nansen Ice Shelf）

(Bell et al., 2017 Nature)

グリーンランド氷床内陸

南極氷床内陸（ドームふじ基地）

http://polaris.nipr.ac.jp/~icc/NO

氷床は陸起源

氷床と海氷は異なるもの！！！

海氷(sea ice)：
海水が凍結して
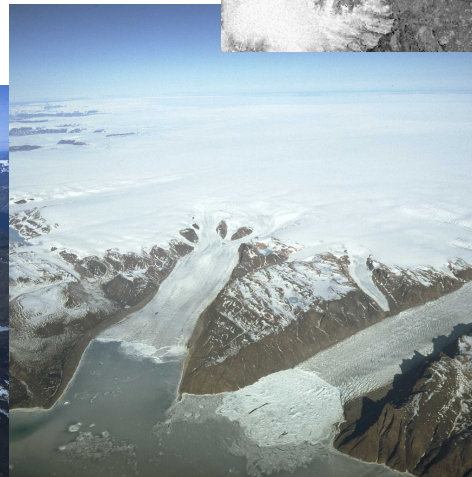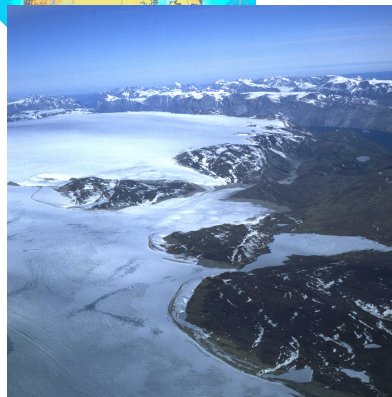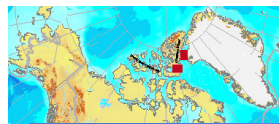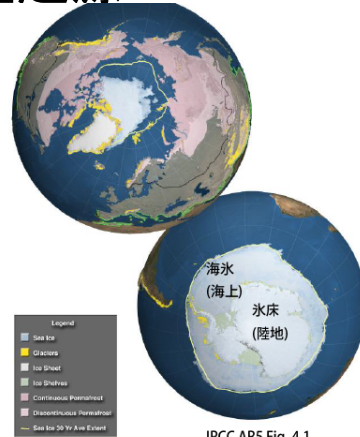海に浮いているもの,
厚さ〜1m

氷床,棚氷(ice shelf)
：陸上に降った雪が
固まったもの,
厚さ〜数百m
海洋にでてくると
氷山(iceberg)とよばれる

https://nsidc.org/sites/nsidc.org/files/images//seaice_04.jpg
https://www.nasa.gov/image-feature/getting-to-know-the-getz-ice-shelf

Legend
- Sea Ice
- Glaciers
- Ice Sheet
- Ice Shelves
- Continuous Permafrost
- Discontinuous Permafrost
- Isolated Permafrost
- Sea Ice 30-Yr Ave Extent

海氷
(海上)
氷床
(陸地)

IPCC AR5 Fig. 4.1

- 氷床のうち、海に張り出しているものを棚氷(ice shelf)とよぶ
- 南極の海岸線のおよそ半分, 面積のおよそ1割が棚氷

海氷は海面上昇に寄与しないが、大気や海洋や氷床との相互作用を通じて気候や海面変化における役割は重要）

南極氷床の質量収支

Melt rate (m/yr)
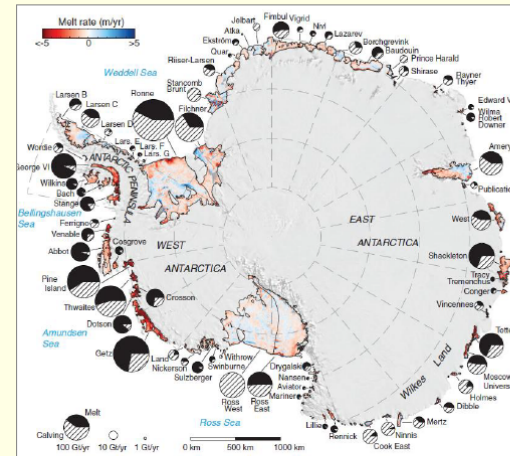
	質量収支(Gt/yr)
涵養量	2240〜2295
棚氷底面融解	-1325±235
氷山分離	-1089±139

涵養量：Wild et al. 2003; Crinner et al. 2006
棚氷底面融解,氷山分離：Rignot et al. 2013

棚氷底面融解量・氷山分離量の分布 (Gt/yr) Rignot et al. 2013

大気による氷床の融解は小さい
海洋からの熱による融解・氷山の分離が主要な消耗プロセス

氷床の地形｜内陸と沿岸域の気温

グリーンランド氷床

南極氷床

昭和基地

ドームふじ基地

Qaanaaq

Summit

(Helm et al., 2014)

(Helm et al., 2014)

Elevation in (m)
0 500 1000 1500 2000 2500 3000 3500 / km 0 500

Elevation in (m)
0 1000 2000 3000 4000 / km 0 900
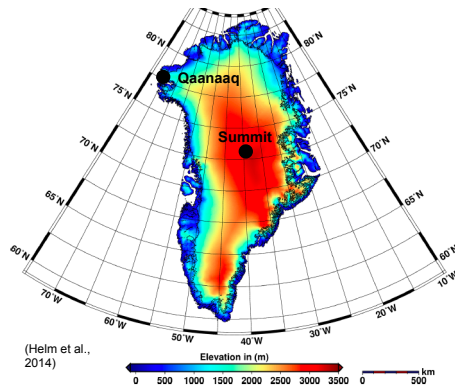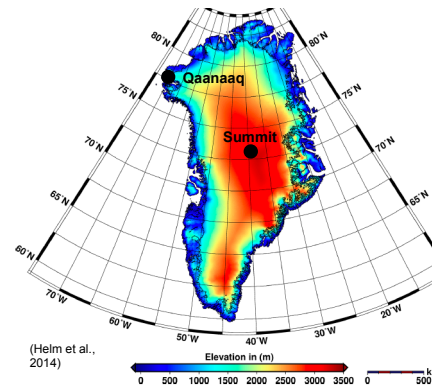
年平均気温
沿岸：−8℃（Qaanaaq; 16 m）
内陸：−29℃（Summit; 3208 m）

(Sugiyama et al., 2014; Steffen and Box, 2001)
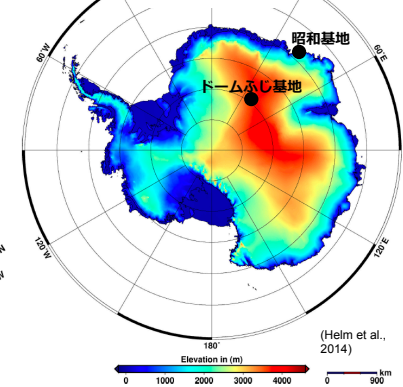
年平均気温
沿岸：−10℃（昭和基地; 29 m）
内陸：−54℃（DF基地; 3810m）

（気象庁, 国立極地研究所）

南極とグリーンランド氷床の降水量
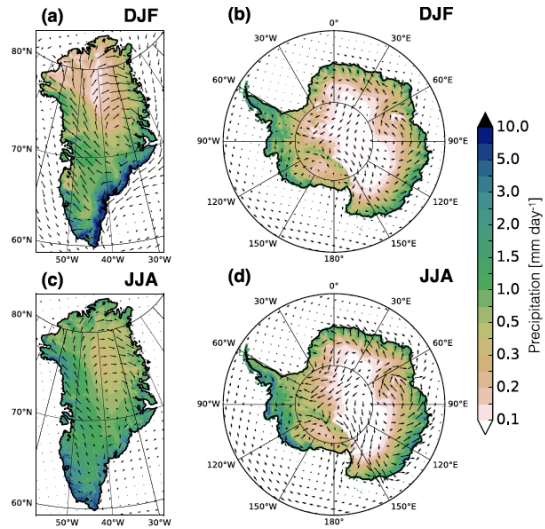
Figure 4. Daily average precipitation (mm/day) (shading) and 10 m wind (arrows) in (a, b) the December, January, and February (DJF) and (c, d) June, July, and August (JJA) seasons, separated between (a, c) Greenland and (b, d) Antarctica. The longest arrows correspond to approximately 10 m/s. Data are adopted from the Regional Atmospheric Climate Model version 2.3 (van den Broeke et al., 2017; van Wessem et al., 2018).

グリーンランド氷床の表面融解
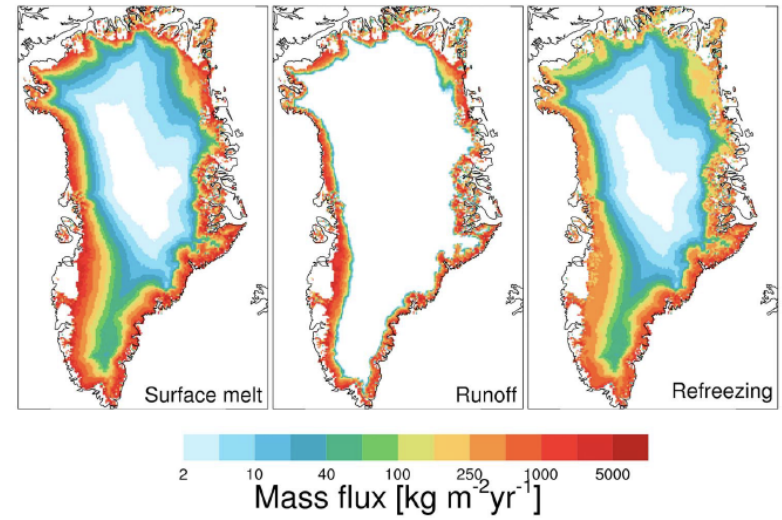
Figure 6. GrIS surface melt and resulting runoff versus refreezing as simulated by Regional Atmospheric Climate Model version 2 (Noël et al., 2017).

南極の棚氷における融解分布

南極氷床の平均流動速度(2007-2009年)

Rignot et al. (2011) Science
http://svs.gsfc.nasa.gov/3849

南極とグリーンランドにおける氷床流動速度分布

Speed (km/yr)
<0.001 0.1 1>3

1000 km

Speed (km/yr)
<0.001 0.1 1>3

400 km

Figure 9. (a) Antarctic ice sheet surface velocity. (b) Greenland ice sheet surface velocity. Figures are reproduced with permission from Mouginot et al. (2017).

氷床の融解による地形や海面の変化

B 粘弾性地球の応答

C 粘弾性＋地球重力の応答
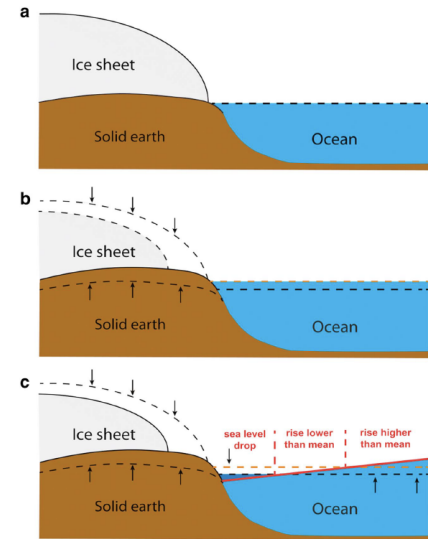
Figure 13. Schematic illustration showing the impacts of ice sheet, viscoelastic, and gravitational model coupling on simulated sea level change. (a) An initial, equilibrium ice sheet (gray), solid Earth (brown), and ocean (blue) configuration. (b) Only the ice sheet and viscoelastic Earth models are coupled, so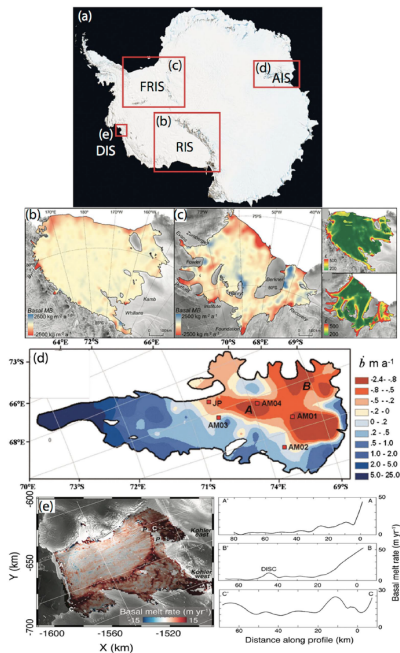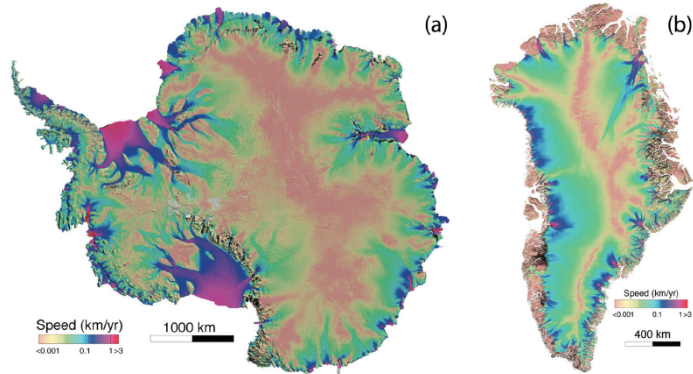 that a reduction in ice thickness (e.g., via a mass balance perturbation) leads to uplift of the bedrock beneath the ice sheet and a uniform increase in sea level (dashed black lines indicate initial reference surfaces). (c) When a gravitation model is also coupled, simulated ice sheet mass loss also leads to a simulated sea level drop proximal to the ice sheet and SLR far from the ice sheet (solid red line), relative to the case with no gravitational coupling (dashed red line). The image has been reproduced with permission from de Boer et al. (2017).

氷床融解と地球変形による海面上昇も

Sea level change (mm yr⁻¹)
-3.0 -2.0 -1.0 0.0 0.2 0.4 0.6 0.8 1.0 1.1 1.2 1.3
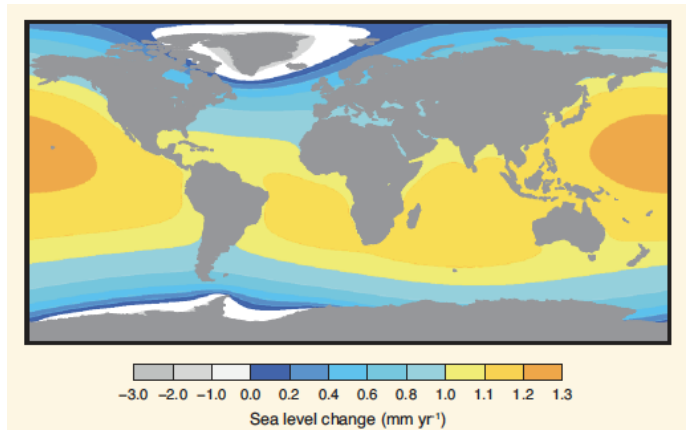
FAQ13.1, Figure 2 | Model output showing relative sea level change due to melting of the Greenland ice sheet and the West Antarctic ice sheet at rates of 0.5 yr⁻¹ each (giving a global mean value for sea level rise of 1 mm yr⁻¹). The modelled sea level changes are less than the global mean value in areas

氷床の外力に対する応答

Fyke, et al, 2017, Rev. Geo

正

負
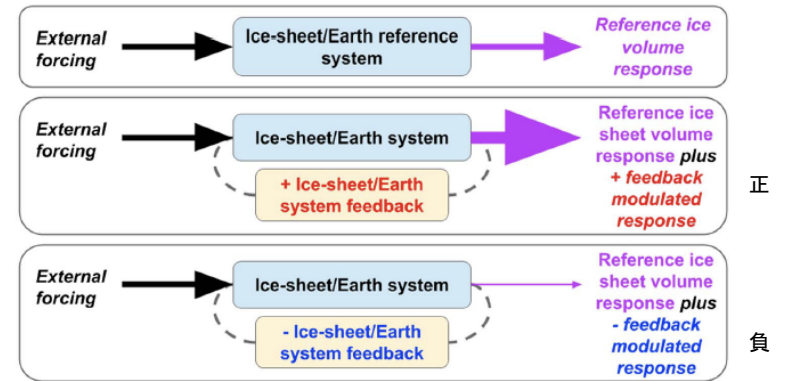
Figure 10. Schematic illustrating the operation of ice sheet/Earth system feedbacks. External forcings (forcings that are

地球システムにおける気候ー海洋ー氷床
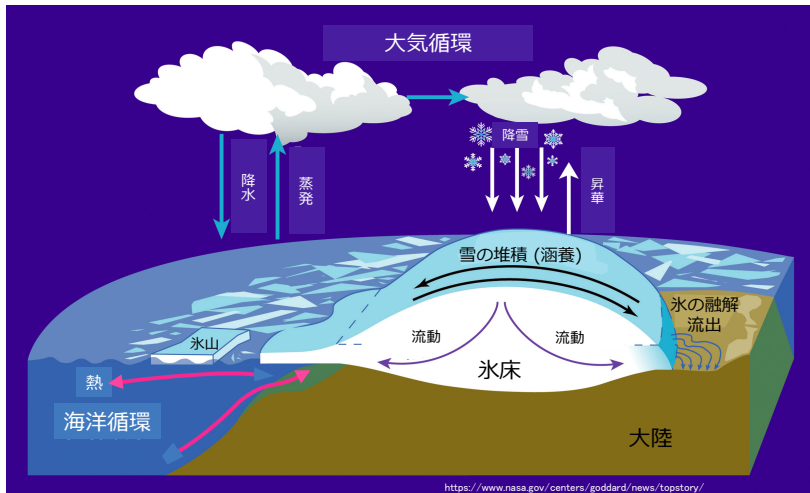
氷床の変動は、大気・海洋の変動と密接に関係している
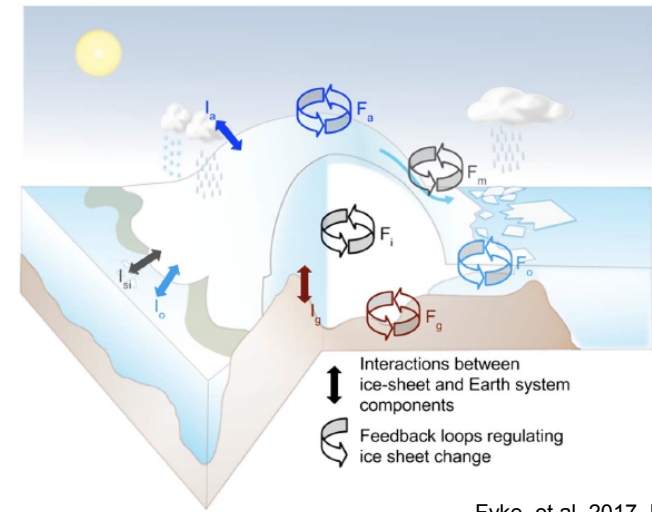
Fyke, et al, 2017, Rev. Geo

Figure 3. Summary of family of interactions (I) between ice sheets with other components of the Earth system: atmosphere (I_a), ocean (I_o), sea ice (I_{si}), and the solid Earth (I_g). These interactions, along with interactions between other Earth system components (a, o, si, and g), give rise to feedback loops (F). Feedback loops include those between the ice sheets and the atmosphere (F_a), ocean (F_o), and solid Earth (F_g). In addition, feedbacks likely exist that transit multiple Earth system components (F_m). Finally, internal (F_i) ice sheet feedbacks also exist.

熱塩循環：氷床と密接な関係

(http://wwwoa.ees.hokudai.ac.jp/)
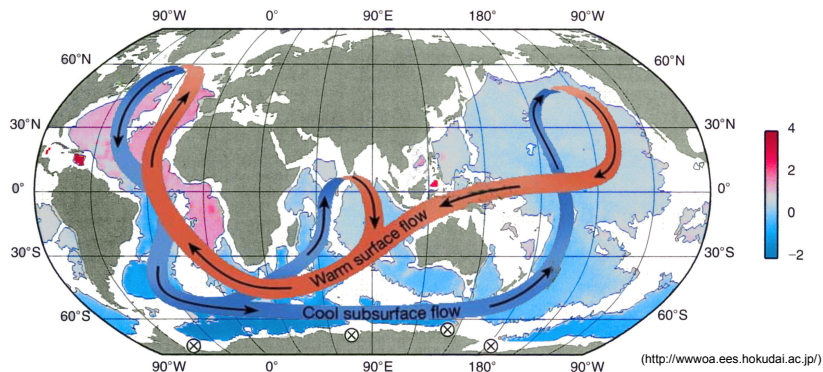
おもに中深層（数百メートル以深）で起こる地球規模の海洋循環
海水の「温度」と「塩分濃度」の変化で駆動される

表層 ➔ 深層：北大西洋
深層 ➔ 表層：インド洋、北太平洋

南極ドームふじ基地で掘削された氷床コア
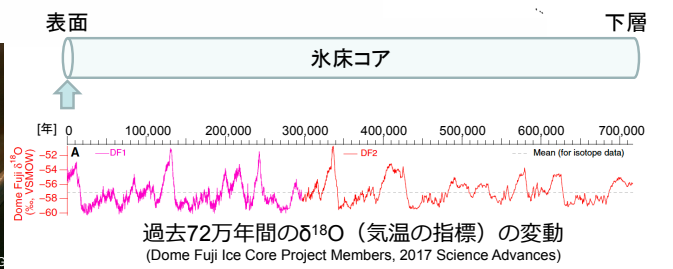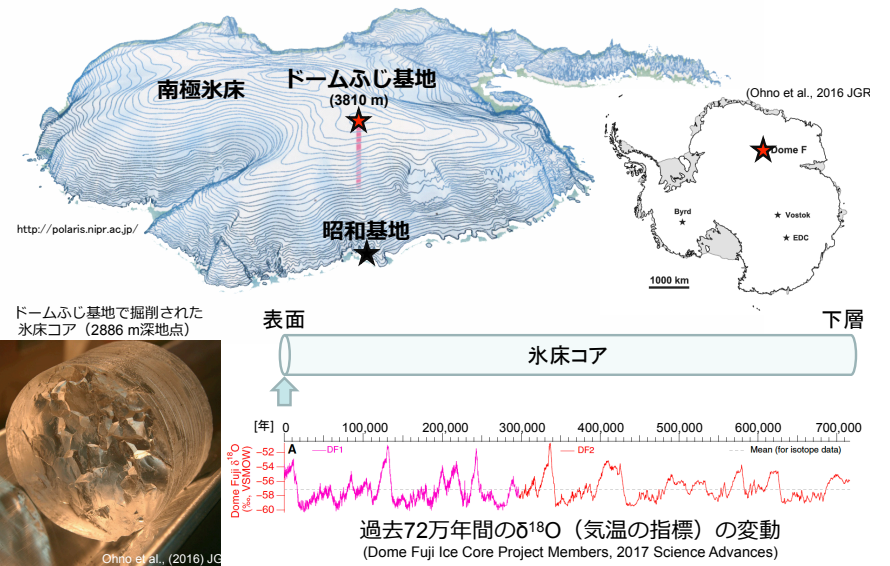
過去72万年間のδ¹⁸O（気温の指標）の変動
(Dome Fuji Ice Core Project Members, 2017 Science Advances)

南極New Dome Fuji 基地周辺の氷床内部（レーダー）

http://polaris.nipr.ac.jp/

ドームふじ基地で掘削された
氷床コア（2886 m深地点）

表面

Ohno et al., (2016) JG

南極New Dome Fuji 基地周辺の氷床内部（レーダー）
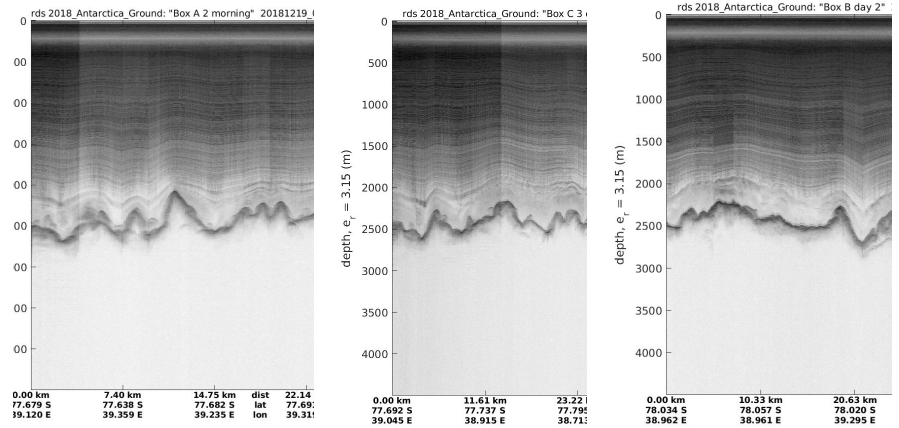
氷床モデル

氷床力学を記述する方程式系

基本的には流体力学（非ニュートン性流体 → 応力とひずみ速度の関係が非線形）

主要な式：　　　　　　　　　　　式が意味すること：

- 運動方程式　$\rho \frac{\partial \boldsymbol{v}}{\partial t} = \nabla \cdot \boldsymbol{\sigma} + \rho \boldsymbol{g}$ → 重力と応力がつりあう

  加速度項　応力(stress)　重力
  　　　　　テンソル

- 質量保存の式　$\frac{\partial H}{\partial t} = -\nabla \cdot (\boldsymbol{v} H) + m_s - m_b$ → 氷の厚さ変化は氷の流入, 流出と涵養・融解の和

  氷厚さ　　氷の　　涵養量　融解量
  時間変化　（流入—流出）

- 構成方程式　$\dot{\boldsymbol{\varepsilon}} = mA(T)\ \tau_e'^{\,n-1}\ \boldsymbol{\sigma}'$ → 氷の変形が流動に現れる

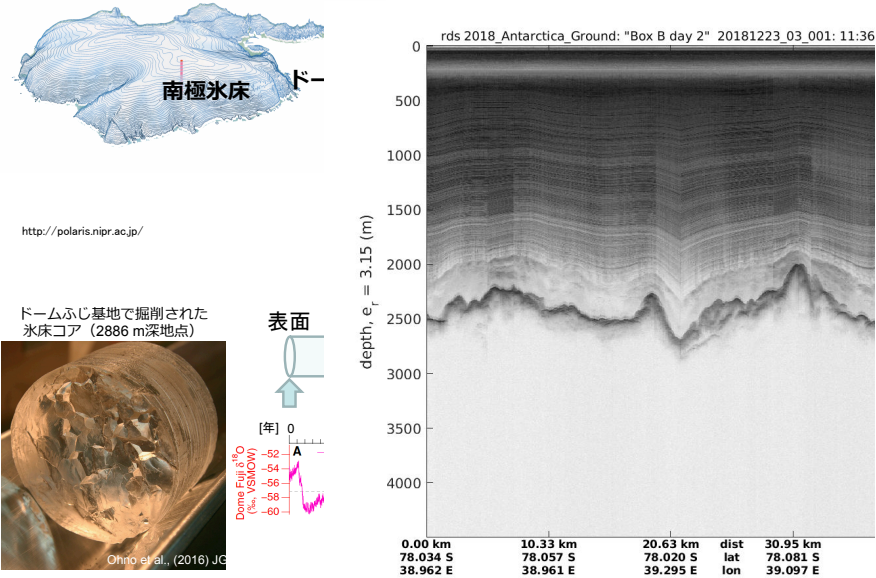 ひずみ速度　　応力第二 deviatric　m, A(T)：応力に対する
  　　　　　　　不変量　　stress　　　　変形のしやすさを表すパラメータ

（＋熱力学の式）　　　　　　　　　　　→ 温度は移流と拡散で決まる

大気海洋との違い：流れが診断的（流れの時間微分が流れに直接よらない）
→ 基本的には時間・空間スケールの問題

氷床モデリング

モデルを作ってうごかしてみる：近似, 離散化, プログラムの作成

- 氷床の空間スケール近似
  (静水圧, Shallow Ice Approximation)

  $$\frac{\partial \sigma_{xx}}{\partial x} + \frac{\partial \sigma_{xy}}{\partial y} + \frac{\partial \sigma_{xz}}{\partial z} = 0$$

  $$\frac{\partial \sigma_{xy}}{\partial x} + \frac{\partial \sigma_{yy}}{\partial y} + \frac{\partial \sigma_{yz}}{\partial z} = 0$$

  $$\frac{\partial \sigma_{xz}}{\partial x} + \frac{\partial \sigma_{yz}}{\partial y} + \frac{\partial \sigma_{zz}}{\partial z} = \rho g$$

  $$\sigma_{xx} = \sigma_{yy} = \sigma_{zz} = -p$$

- 数値計算のための離散化
  例として質量保存の式：

  www.AntarcticGlaciers.org

  Modified from the Glimmer-CISM User Guide

- X-Z平面で計算するルーチンの作成

  [0] 時刻=0
  [1] すべてのnx[xグリッド数]に対して
  　　[1a] 氷厚Hから s, ∇s, ∇Hを求める
  　　[1b] 運動方程式からuの鉛直分布を求める
  　　[1c] uの鉛直平均値から(uH)を求める
  　　[1d] 氷厚Hの時間発展を記述する
  　　　　 nx個の連立方程式を立てる
  [2] [1d]の連立方程式を計算して、
  　　 新しい時刻のHの分布を求める
  [3] 時刻を進めて[1]に戻る

  基本的にはこれだけ！！！

  連立方程式はこんなかたち

  1番目の点　$b_1 \quad c_1 \qquad\qquad 0$
  2番目の点　$a_2 \quad b_2 \quad c_2$
  ・
  ・
  ・　　　　　　　　　$a_{n-1} \quad b_{n-1} \quad c_{n-1}$
  N番目の点　$0 \qquad\qquad a_n \quad b_n$
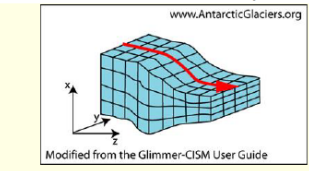
  $\begin{pmatrix} H_1 \\ H_2 \\ \vdots \\ H_{n-1} \\ H_n \end{pmatrix} = \begin{pmatrix} r_1 \\ r_2 \\ \vdots \\ r_{n-1} \\ r_n \end{pmatrix}$

  未知数：新しい時刻のH（N個ある）　　古い時刻のH

古環境プロキシデータの比較と数値モデリング

南極・グリーンランド氷床コア 石筍等のδ18Oの比較
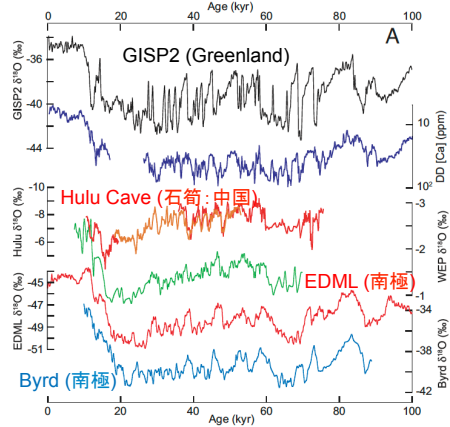
(Barker and Knorr, 2007 PNAS)

数値モデリングによる 過去40万年の北半球氷床の再現実験
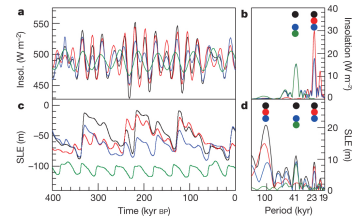
Supplementary Video V1.

Simulated ice sheet change for the last 400 kyr with IcIES-MIROC model

(Abe-Ouchi et al., 2013 Nature)

グリーンランド氷床の最近の変化

Table 13.2 | Surface mass balance (SMB) and rates of change of SMB of the Greenland ice sheet, calculated from ice-sheet SMB models using meteorological observations and reanalyses as input, expressed as sea level equivalent (SLE). A negative SLE number for SMB indicates that accumulation exceeds runoff. A positive SLE for SMB anomaly indicates that accumulation has decreased, or runoff has increased, or both. Uncertainties are one standard deviation. Uncertainty in individual model results reflects temporal variability (1 standard deviations of annual mean values indicated); the uncertainty in the model average is 1 standard deviation of variation across models.

| Reference and Model[a]	Time-Mean SMB 1961–1990 mm yr^{-1} SLE	Rate of Change of SMB 1991–2010 mm yr^{-2} SLE	Time-Mean SMB Anomaly (With Respect to 1961–1990 Time-Mean SMB)[b] mm yr^{-1} SLE		
			1971–2010	1993–2010	2005–2010
RACMO2, Van Angelen et al. (2012), 11 km RCM	−1.13 ± 0.30	0.04 ± 0.01	0.07 ± 0.33	0.23 ± 0.30	0.47 ± 0.24
MAR, Fettweis et al. (2011), 25 km RCM	−1.17 ± 0.31	0.05 ± 0.01	0.12 ± 0.38	0.36 ± 0.33	0.64 ± 0.22
PMM5, Box et al. (2009), 25 km RCM	−0.98 ± 0.18	0.02 ± 0.01	0.00 ± 0.19	0.10 ± 0.22	0.23 ± 0.21
ECMWFd, Hanna et al. (2011), 5 km PDD	−0.77 ± 0.27	0.02 ± 0.01	0.02 ± 0.28	0.12 ± 0.27	0.24 ± 0.19
SnowModel, Mernild and Liston (2012), 5 km EBM	−0.54 ± 0.21	0.03 ± 0.01	0.09 ± 0.25	0.19 ± 0.24	0.36 ± 0.23
Model Average	−0.92 ± 0.26	0.03 ± 0.01	0.06 ± 0.05	0.20 ± 0.10	0.39 ± 0.17

Notes:

[a] The approximate spatial resolution is stated and the model type denoted by PDD = positive degree day, EBM = Energy Balance Model, RCM = Regional Climate Model.

[b] Difference from the time-mean SMB of 1961–1990. This difference equals the sea level contribution from Greenland SMB changes if the ice sheet is assumed to have been near zero mass balance during 1961–1990 (Hanna et al., 2005; Sasgen et al., 2012).

グリーランドにおける変化

Figure 12. Ice evolution in Tasermiut Fjord, southern Greenland, between 2009 and 2015. Note that retreat of Tasermiut Sermeq (red arrow) from a marine to a terrestrial terminus. The red star in the red box on the inset map denotes the location of the fjord. Image courtesy of Mauri Pelto/American Geophysical Union.

グリーンランド氷床の最近の変化

表面質量収支（質量の変化）＝積雪量ー表面融解量
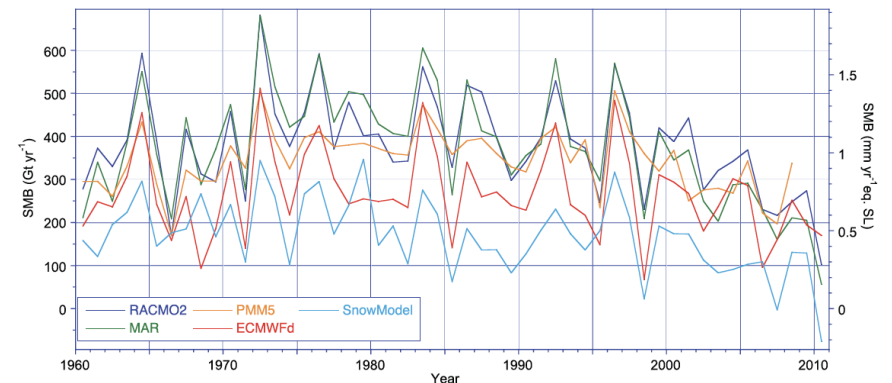
Figure 13.5 | Annual mean surface mass balance (accumulation minus ablation) for the Greenland ice sheet, simulated by five regional climate models for the period 1960–2010.

巨大氷床の変動を"計測する"
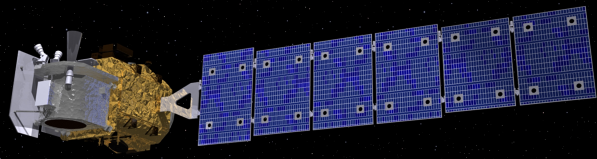
衛星高度計 ICESat-2

人工衛星による氷床変動観測

※ 衛星高度計（氷床表面の高度）
- 1975-1979：GEOS 3 (Brooks et al., 1978 Nature)
- 1978 ：SEASAT (Zwally et al., 1983 JGR)
- 1991-2011：ERS-1/ERS-2 (Zwally et al., 2005 J. Glaciol.)
- 2002-2012：Envisat (Horwath et al., 2012 Geophys. J. Int.)
- 2003-2009：ICESat (Pritchard et al., 2009 Nature)
- 2010- ：CryoSat-2 (Helm et al., 2014 Cryosphere)

※ 衛星重力計（氷床の質量）

https://icesat-2.gsfc.nasa.gov/

グリーンランド / 南極氷床の質量変動(2002-2016年)

グリーンランド氷床 　　　　　　　南極氷床

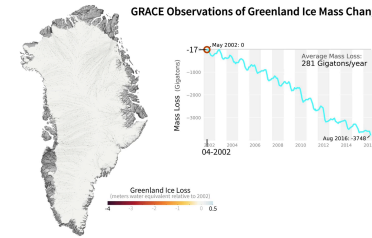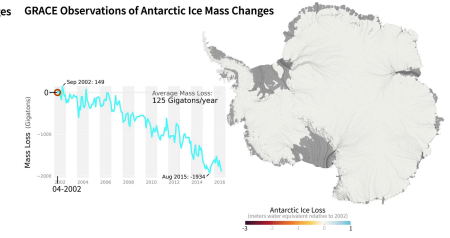Talpe et al. (2017) J. Geod.
https://svs.gsfc.nasa.gov/30879

Talpe et al. (2017) J. Geod.
https://svs.gsfc.nasa.gov/30880

※琵琶湖の貯水量：27.5 Gt

1993-2010：-121±28 Gt / year
2005-2010：-229±61 Gt / year
(IPCC, 2013)

1993-2010： -97±28 Gt / year
2005-2010：-147±61 Gt / year
(IPCC, 2013)

・過去にはどのような氷床変動があったか？
・氷床変動と、気候・海洋環境変動との関わりは？
・将来はどのように変動するのか？

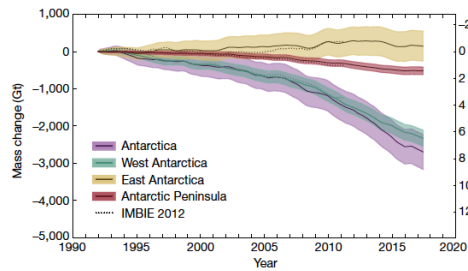## 南極の最近の変化

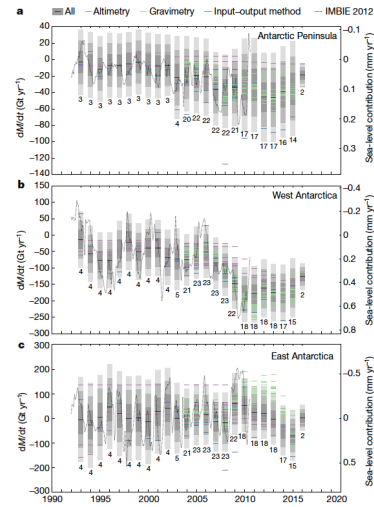IMBIE team, 2018 6月14日号, Nature

有意な質量減少が観測されている。

Fig. 1 | Antarctic Ice Sheet mass balance. a–c, Rate of mass change (dM/dt) of the APIS (a), WAIS (b) and EAIS (c), as determined from the various satellite-altimetry (purple), input–output-method (blue) and gravimetry (green) assessments included in this study. In each case, dM/dt is computed from time series of relative mass change using a three-year window at annual intervals. An average of estimates across each class of measurement technique is also shown for each year (black). The estimated 1σ, 2σ and 3σ ranges of the class averages are shaded in dark, mid and light grey, respectively; the number of individual mass-balance estimates collated at each epoch is shown below.

Table 1 | Rates of ice-sheet mass change

	1992–1997 (Gt yr⁻¹)	1997–2002 (Gt yr⁻¹)	2002–2007 (Gt yr⁻¹)	2007–2012 (Gt yr⁻¹)	2012–2017 (Gt yr⁻¹)
EAIS	11 ± 58	8 ± 56	12 ± 43	23 ± 38	−28 ± 30
WAIS	−53 ± 29	−41 ± 28	−65 ± 26	−148 ± 27	−159 ± 26
APIS	−7 ± 13	−6 ± 13	−20 ± 15	−35 ± 17	−33 ± 16
AIS	−49 ± 67	−38 ± 64	−73 ± 53	−160 ± 50	−219 ± 43

Rates were determined from all satellite measurements over various epochs for the EAIS, WAIS and APIS, which combined constitute the AIS. The previous assessment[18], which reported mass-balance estimates of 14 ± 43 Gt yr⁻¹ for the EAIS, −65 ± 26 Gt yr⁻¹ for the WAIS, −20 ± 14 Gt yr⁻¹ small differences in our updated estimates for this period are due to our inclusion of more data. Errors are 1σ.

20世紀の海面変動の要因別寄与

mm/yr

Table 13.1 | Global mean sea level budget (mm yr⁻¹) over different time intervals from observations and from model-based contributions. Uncertainties are 5 to 95%. The Atmosphere–Ocean General Circulation Model (AOGCM) historical integrations end in 2005; projections for RCP4.5 are used for 2006–2010. The modelled thermal expansion and glacier contributions are computed from the CMIP5 results, using the model of Marzeion et al. (2012a) for glaciers. The land water contribution is due to anthropogenic intervention only, not including climate-related fluctuations.

| Source	1901–1990	1971–2010	1993–2010
Observed contributions to global mean sea level (GMSL) rise			
Thermal expansion	–	0.8 [0.5 to 1.1]	1.1 [0.8 to 1.4]
Glaciers except in Greenland and Antarctica[a]	0.54 [0.47 to 0.61]	0.62 [0.25 to 0.99]	0.76 [0.39 to 1.13]
Glaciers in Greenland[a]	0.15 [0.10 to 0.19]	0.06 [0.03 to 0.09]	0.10 [0.07 to 0.13][b]
Greenland ice sheet	–	–	0.33 [0.25 to 0.41]
Antarctic ice sheet	–	–	0.27 [0.16 to 0.38]
Land water storage	−0.11 [−0.16 to −0.06]	0.12 [0.03 to 0.22]	0.38 [0.26 to 0.49]
Total of contributions	–	–	2.8 [2.3 to 3.4]
Observed GMSL rise	1.5 [1.3 to 1.7]	2.0 [1.7 to 2.3]	3.2 [2.8 to 3.6]
Modelled contributions to GMSL rise			
Thermal expansion	0.37 [0.06 to 0.67]	0.96 [0.51 to 1.41]	1.49 [0.97 to 2.02]
Glaciers except in Greenland and Antarctica	0.63 [0.37 to 0.89]	0.62 [0.41 to 0.84]	0.78 [0.43 to 1.13]
Glaciers in Greenland	0.07 [−0.02 to 0.16]	0.10 [0.05 to 0.15]	0.14 [0.06 to 0.23]
Total including land water storage	1.0 [0.5 to 1.4]	1.8 [1.3 to 2.3]	2.8 [2.1 to 3.5]
Residual[c]	0.5 [0.1 to 1.0]	0.2 [−0.4 to 0.8]	0.4 [−0.4 to 1.2]

Notes:
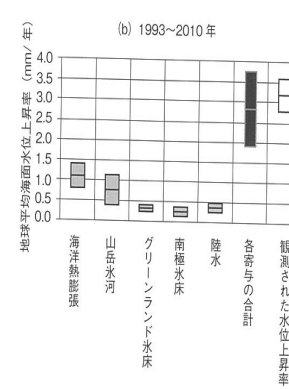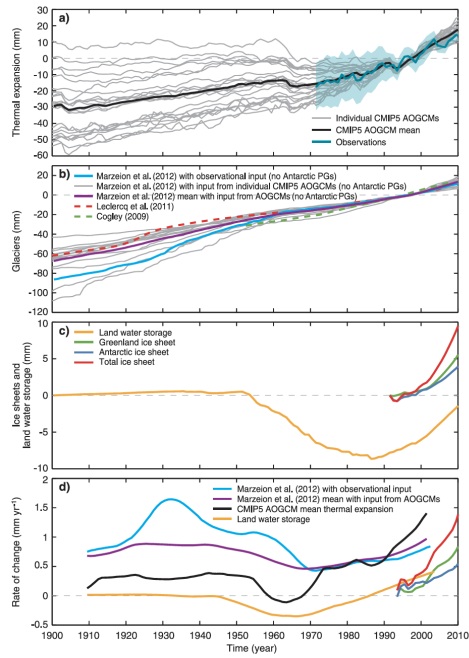[a] Data for all glaciers extend to 2009, not 2010.
[b] This contribution is not included in the total because glaciers in Greenland are included in the observational assessment of the Greenland ice sheet.
[c] Observed GMSL rise − modelled thermal expansion − modelled glaciers − observed land water storage

最近の海面変化と将来予測
(AR5, 気象学会、朝倉書店、2014)
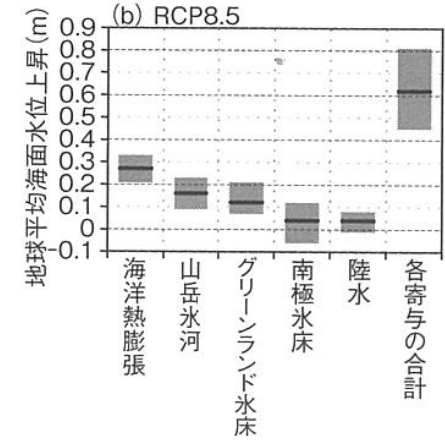
放射強制力と気温の将来予測（AR5）
シナリオ別、1850～2100 and 2300、マルチモデルAOGCM結果
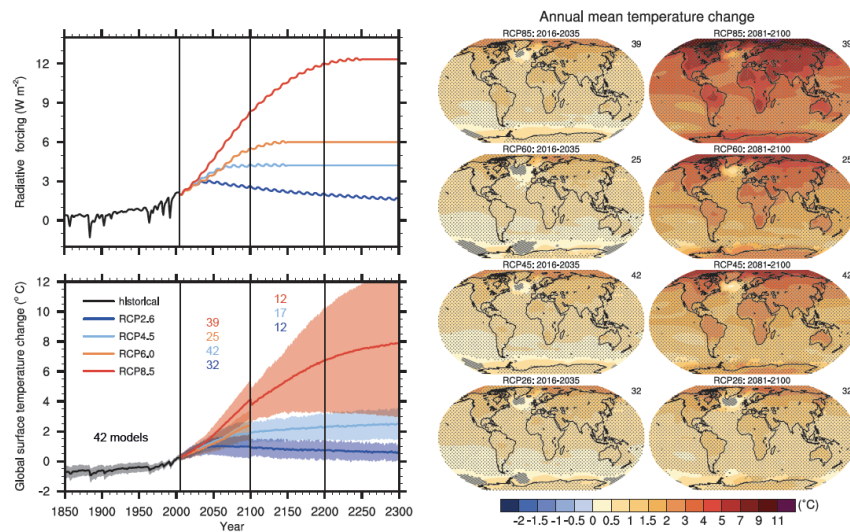
気温と降水量変化（AR5）
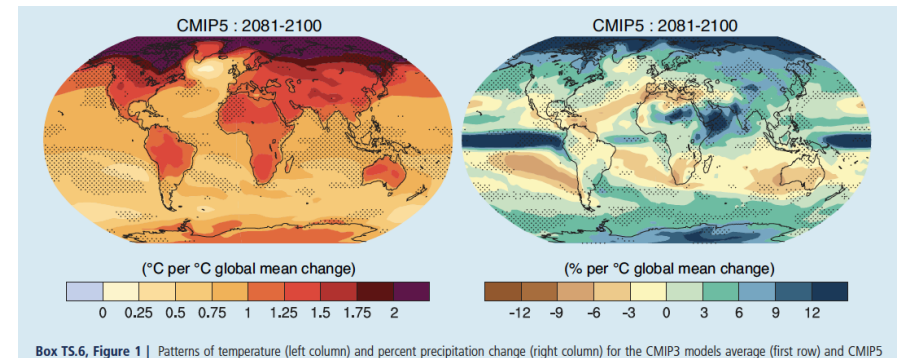
CO2排出量と気温将来予測比較（AR5）
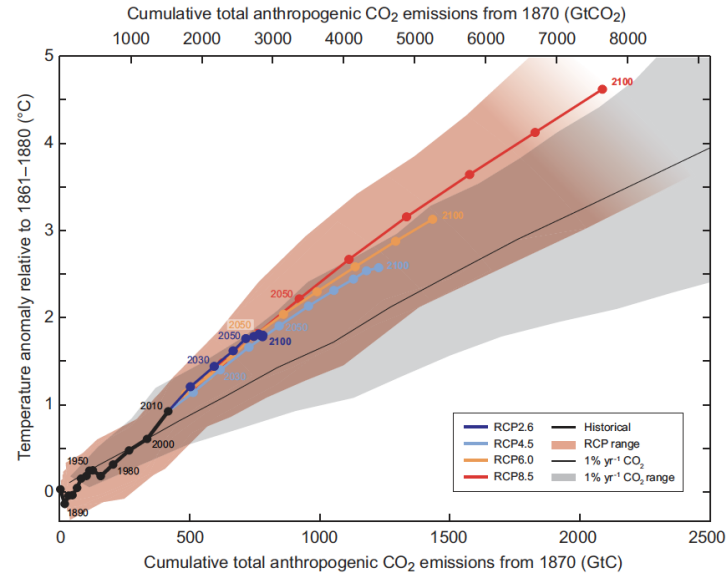
海面上昇の将来予測（AR5）

Global mean sea level will continue to rise during the 21st century (see Figure SPM.9). Under all RCP scenarios, the rate of sea level rise will *very likely* exceed that observed during 1971 to 2010 due to increased ocean warming and increased loss of mass from glaciers and ice sheets. {13.3–13.5}
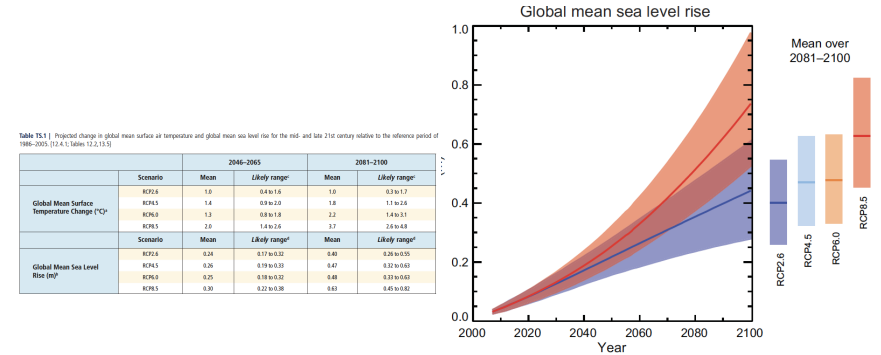
シナリオごとの海面上昇AR5予測
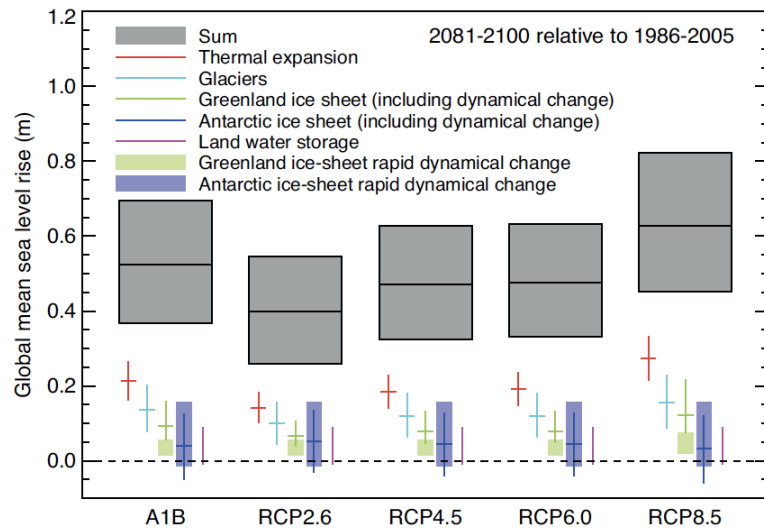
表面質量収支と氷床流出の21世紀末までの変化 (南極A1B, グリーンランドRCP4.5)

21世紀末までの全球海面変化予測
(AR5)

Table 13.5 | Median values and *likely* ranges for projections of global mean sea level (GMSL) rise and its contributions in metres in 2081–2100 relative to 1986–2005 for the four RCP scenarios and SRES A1B, GMSL rise in 2046–2065 and 2100, and rates of GMSL rise in mm yr⁻¹ in 2081–2100. See Section 13.5.1 concerning how the *likely* range is defined.

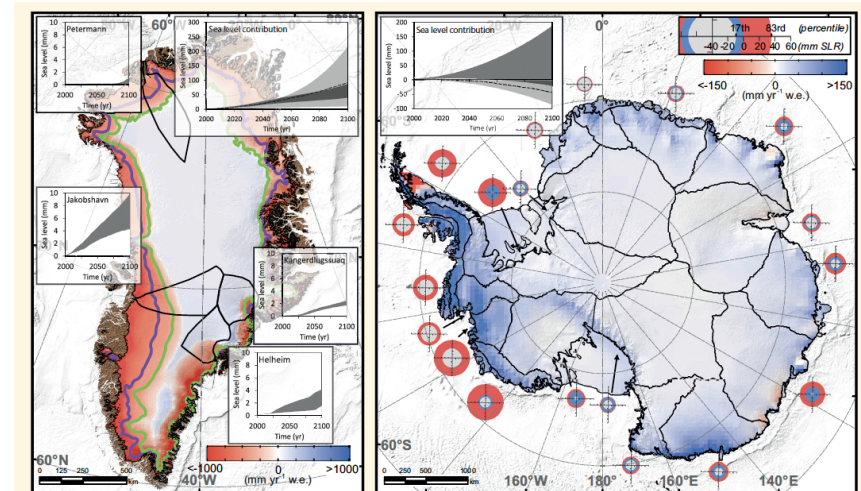|	SRES A1B	RCP2.6	RCP4.5	RCP6.0	RCP8.5
Thermal expansion	0.21 [0.16 to 0.26]	0.14 [0.10 to 0.18]	0.19 [0.14 to 0.23]	0.19 [0.15 to 0.24]	0.27 [0.21 to 0.33]
Glaciersᵃ	0.14 [0.08 to 0.21]	0.10 [0.04 to 0.16]	0.12 [0.06 to 0.19]	0.12 [0.06 to 0.19]	0.16 [0.09 to 0.23]
Greenland ice-sheet SMBᵇ	0.05 [0.02 to 0.12]	0.03 [0.01 to 0.07]	0.04 [0.01 to 0.09]	0.04 [0.01 to 0.09]	0.07 [0.03 to 0.16]
Antarctic ice-sheet SMBᶜ	−0.03 [−0.06 to −0.01]	−0.02 [−0.04 to −0.00]	−0.02 [−0.05 to −0.01]	−0.02 [−0.05 to −0.01]	−0.04 [−0.07 to −0.01]
Greenland ice-sheet rapid dynamics	0.04 [0.01 to 0.06]	0.04 [0.01 to 0.06]	0.04 [0.01 to 0.06]	0.04 [0.01 to 0.06]	0.05 [0.02 to 0.07]
Antarctic ice-sheet rapid dynamics	0.07 [−0.01 to 0.16]	0.07 [−0.01 to 0.16]	0.07 [−0.01 to 0.16]	0.07 [−0.01 to 0.16]	0.07 [−0.01 to 0.16]
Land water storage	0.04 [−0.01 to 0.09]	0.04 [−0.01 to 0.09]	0.04 [−0.01 to 0.09]	0.04 [−0.01 to 0.09]	0.04 [−0.01 to 0.09]
Global mean sea level rise in 2081–2100	0.52 [0.37 to 0.69]	0.40 [0.26 to 0.55]	0.47 [0.32 to 0.63]	0.48 [0.33 to 0.63]	0.63 [0.45 to 0.82]
Greenland ice sheet	0.09 [0.05 to 0.15]	0.06 [0.04 to 0.10]	0.08 [0.04 to 0.13]	0.08 [0.04 to 0.13]	0.12 [0.07 to 0.21]
Antarctic ice sheet	0.04 [−0.05 to 0.13]	0.05 [−0.03 to 0.14]	0.05 [−0.04 to 0.13]	0.05 [−0.04 to 0.13]	0.04 [−0.06 to 0.12]
Ice-sheet rapid dynamics	0.10 [0.03 to 0.19]	0.10 [0.03 to 0.19]	0.10 [0.03 to 0.19]	0.10 [0.03 to 0.19]	0.12 [0.03 to 0.20]
Rate of global mean sea level rise	8.1 [5.1 to 11.4]	4.4 [2.0 to 6.8]	6.1 [3.5 to 8.8]	7.4 [4.7 to 10.3]	11.2 [7.5 to 15.7]
Global mean sea level rise in 2046–2065	0.27 [0.19 to 0.34]	0.24 [0.17 to 0.32]	0.26 [0.19 to 0.33]	0.25 [0.18 to 0.32]	0.30 [0.22 to 0.38]
Global mean sea level rise in 2100	0.60 [0.42 to 0.80]	0.44 [0.28 to 0.61]	0.53 [0.36 to 0.71]	0.55 [0.38 to 0.73]	0.74 [0.52 to 0.98]

Only the collapse of the marine-based sectors of the Antarctic ice sheet, if initiated, could cause GMSL to rise substantially above the *likely* range during the 21st century. This potential additional contribution cannot be precisely quantified but there is *medium confidence* that it would not exceed several tenths of a meter of sea level rise.

Semi empirical modelによる予測

	From	To	5%	50%	95%
Scenario SRES A1B					
IPCC AR4ᵃ	1990	2100	0.22	0.37	0.50
IPCC AR4ᵃᵇ	1990	2100	0.22	0.43	0.65
IPCC AR5 (also in Table 13.5)	1996	2100	0.42	0.60	0.80
Rahmstorf (2007a)ᶜ	1990	2100	—	0.85	—
Horton et al. (2008)ᵈ	2000	2100	0.62	0.74	0.88
Vermeer and Rahmstorf (2009)	1990	2100	0.98	1.24	1.56
Grinsted et al. (2010) with Brohan et al. (2006) temperature for calibration	1990	2100	0.32	0.83	1.34
Grinsted et al. (2010) with Moberg et al. (2005) temperature for calibration	1990	2100	0.91	1.12	1.32
Jevrejeva et al. (2010) with Crowley et al. (2003) forcing for calibration	1990	2100	0.63	0.86	1.06
Jevrejeva et al. (2010) with Goosse et al. (2005) forcing for calibration	1990	2100	0.60	0.75	1.15
Jevrejeva et al. (2010) with Tett et al. (2007) forcing for calibration	1990	2100	0.87	1.15	1.40
Scenario RCP4.5					
IPCC AR5 (also in Table 13.5)	1986–2005	2081–2100	0.32	0.47	0.63
Grinsted et al. (2010) calibrated with Moberg et al. (2005) temperature	1986–2005	2081–2100	0.63	0.88	1.14
Rahmstorf (2012b) calibrated with Church and White (2006) GMSL	1986–2005	2081–2100	0.79	0.86	0.93
Rahmstorf (2012b) calibrated with Church and White (2011) GMSL	1986–2005	2081–2100	0.57	0.63	0.68
Rahmstorf (2012b) calibrated with Jevrejeva (2008) GMSL	1986–2005	2081–2100	0.82	0.97	1.12
Rahmstorf (2012b) calibrated with proxy data	1986–2005	2081–2100	0.56	0.88	1.24
Jevrejeva et al. (2012a) calibrated with Goosse et al. (2005) radiative forcing	1986–2005	2081–2100	0.43	0.56	0.69
Jevrejeva et al. (2012a) calibrated with Crowley et al. (2003) radiative forcing	1986–2005	2081–2100	0.48	0.65	0.80

長期予測 500年後?

気候モデルによる海洋温度、氷河氷床の表面質量収支変化などを考慮。
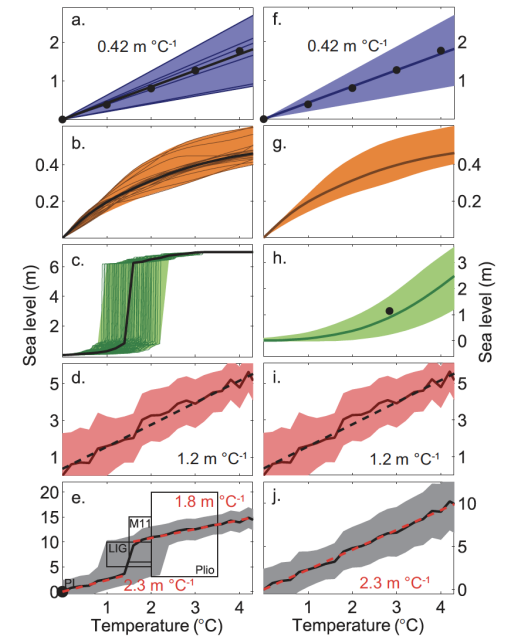（南極氷床の力学効果が入っていないことに注意）
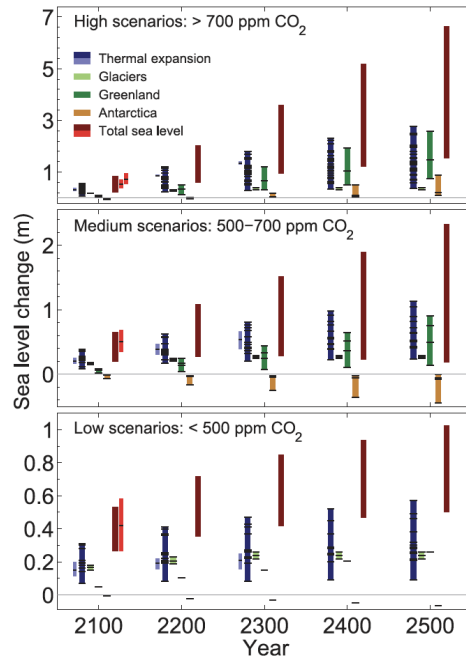
長期予測と古気候

Figure 13.14 | (Left column) Multi-millennial sea level commitment per degree Celsius of warming as obtained from physical model simulations of (a)
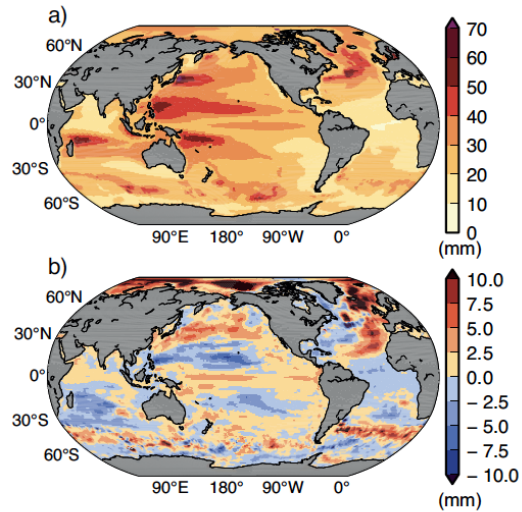
海面の
地域的変化
20世紀まで

Figure 13.15 | (a) Root-mean square (RMS) interannual dynamic sea level variability (millimetres) in a CMIP5 multi-model ensemble (21 models), built from the historically forced experiments during the period 1951–2005. (b) Changes in the ensemble average interannual dynamic sea level variability (standard deviation (SD), in millimetres) evaluated over the period 2081–2100 relative to the reference period 1986–2005. The projection data (2081–2100) are from the CMIP5 RCP4.5 experiment.
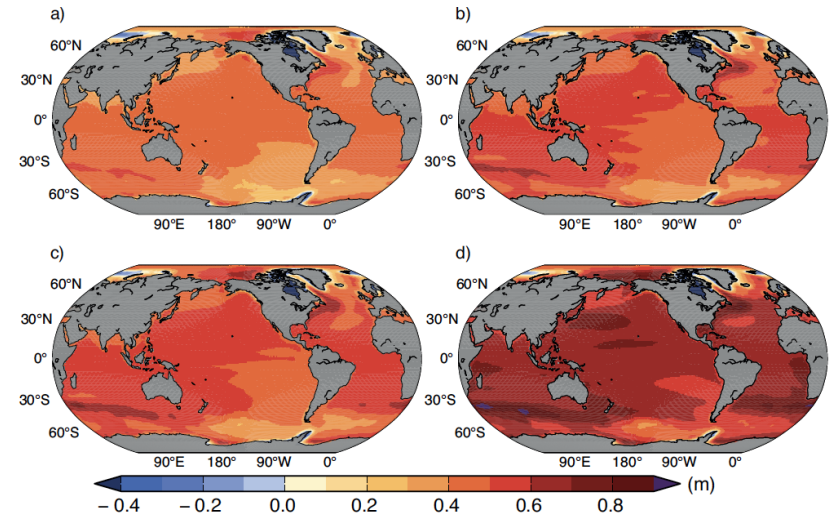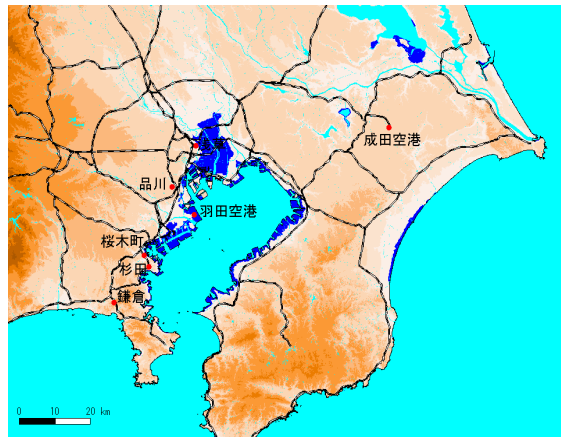
21世紀末海面の地域的変化予測

Figure 13.20 | Ensemble mean regional relative sea level change (metres) evaluated from 21 CMIP5 models for the RCP scenarios (a) 2.6, (b) 4.5, (c) 6.0 and (d) 8.5 between 1986–2005 and 2081–2100. Each map includes effects of atmospheric loading, plus land ice, glacial isostatic adjustment (GIA) and terrestrial water sources.

Sea level influence of 1m
海水準 1 m 上昇の浸水域

北海道地図株式会社のGISMAPを使用

Sea level influence of 3 m
海水準 3 m 上昇の浸水域
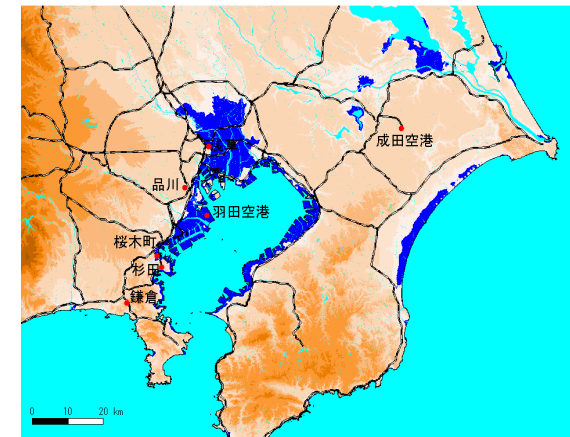
北海道地図株式会社のGISMAPを使用
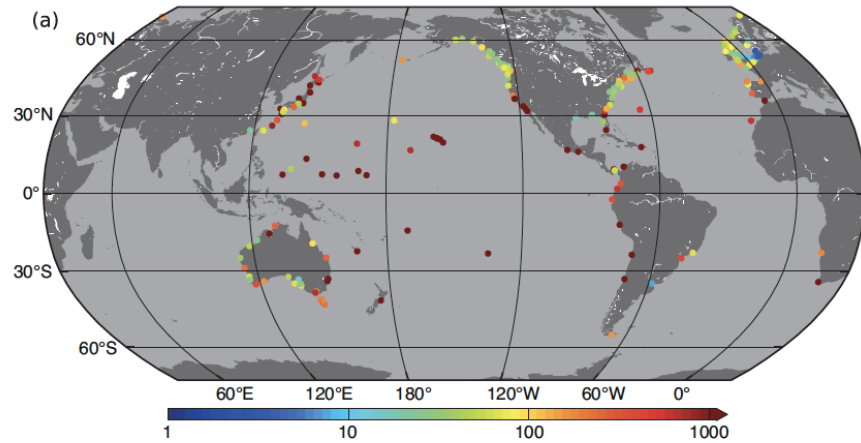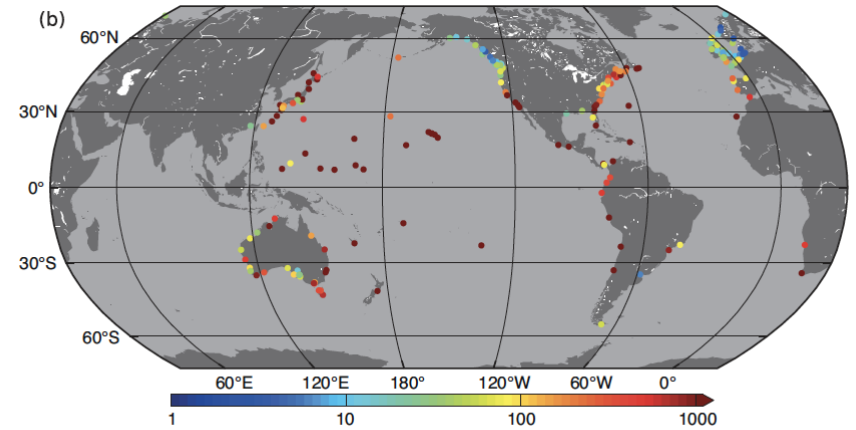
海面上昇 50cm による洪水頻度の増加

(a)

Figure 13.25 | The estimated multiplication factor (shown at tide gauge locations by colored dots), by which the frequency of flooding events of a given height increase for (a) a mean sea level (MSL) rise of 0.5 m (b) using regional projections of MSL for the RCP4.5 scenario, shown in Figure13.19a.

海面上昇 RCP4.5 による洪水頻度の増加

(b)

5 | The estimated multiplication factor (shown at tide gauge locations by colored dots), by which the frequency of flooding events of a given height i el (MSL) rise of 0.5 m (b) using regional projections of MSL for the RCP4.5 scenario, shown in Figure13.19a.
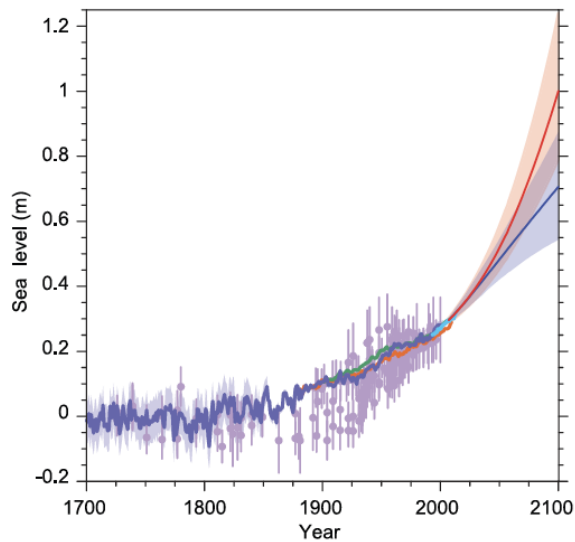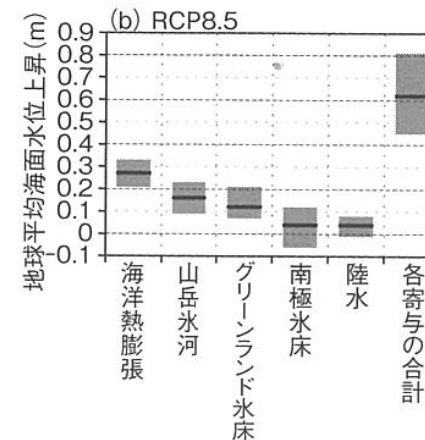
まとめ

Figure 13.27 | Compilation of paleo sea level data, tide gauge data, altimeter data (from Figure 13.3), and central estimates and *likely* ranges for projections of global mean sea level rise for RCP2.6 (blue) and RCP8.5 (red) scenarios (Section 13.5.1), all relative to pre-industrial values.
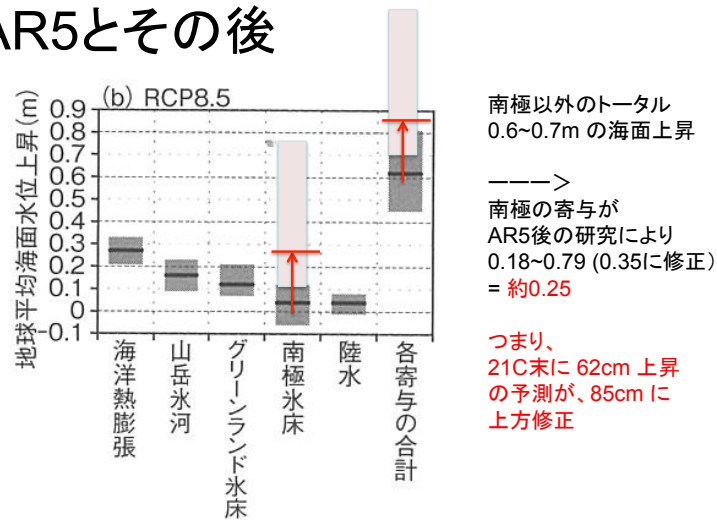
RCP8.5の21世紀の海面上昇： AR5

(b) RCP8.5

南極以外のトータル
0.6~0.7m の海面上昇

RCP8.5の21世紀の海面上昇：AR5とその後

(b) RCP8.5

地球平均海面水位上昇 (m)

海洋熱膨張 / 山岳氷河 / グリーンランド氷床 / 南極氷床 / 陸水 / 各寄与の合計

南極以外のトータル
0.6~0.7m の海面上昇

―――＞
南極の寄与が
AR5後の研究により
0.18~0.79（0.35に修正）
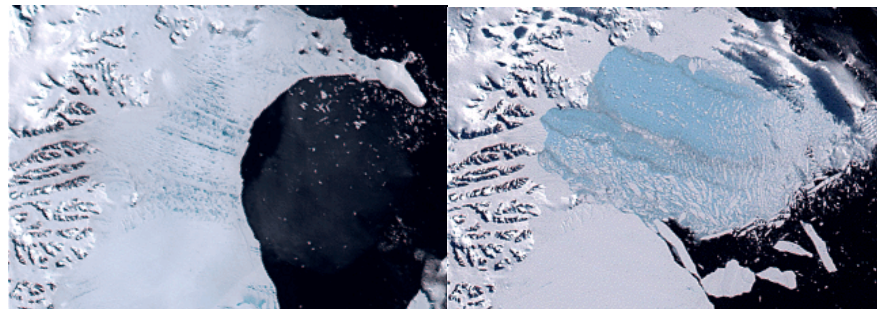= 約0.25

つまり、
21C末に 62cm 上昇
の予測が、85cm に
上方修正

南極氷床の寄与

- Based on current understanding, only the collapse of marine-based sectors of the Antarctic ice sheet, if initiated, could cause global mean sea level to rise substantially above the *likely* range during the 21st century. However, there is *medium confidence* that this additional contribution would not exceed several tenths of a meter of sea level rise during the 21st century. {13.4, 13.5}

予測を大きく上回るとしたら、南極氷床の海洋着床部分の崩壊がある場合だけだ。
しかし、21C 中に50cm 以上ということはない。

Some observation of rapid retreat of ice shelf and fast flow of ice stream in West Antarctica (Larsen Ice Shelf)
西南極：棚氷や氷流の急速な消失が一部観測される

- 南極半島のLarsen 棚氷が数ヶ月で3250km²が消失した。（衛星写真MODIS, http://wwwnsidc.colorado.edu/sotc/iceshelves.html）。
- 温暖化により棚氷消失がすすむと西南極氷床の力学的不安定をもたらすのでは？という説があるが、数値モデル化も観測も不足していて今後の研究課題となっている。

2002.1.31   Retreat of 3250 km²   2002.3.17

Marine ice sheet instability (MISI)

(a) accumulation / floating ice shelf outflow / grounded ice sheet / iceberg calving / ocean / melt / grounding line

(b) 平衡状態 / Q in / Q out / mass of ice = mass of displaced ocean

(c) 気候に対する応答 / thinning / melt ponds / Q in / Q out / flotation and retreat / enhanced melt / warm water intrusion

(d) 気候応答後の自発的応答（by 海底地形） / further thinning / Q in / Q out / further retreat
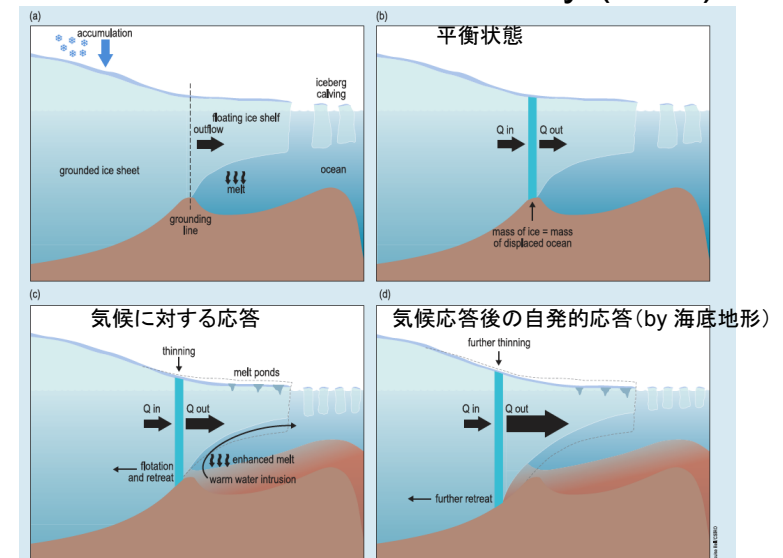
Box 13.2, Figure 1 | Schematic of the processes leading to the potentially unstable retreat of a grounding line showing (a) geometry and ice fluxes of a marine ice sheet, (b) the grounding line in steady state, (c) climate change triggering mass outflow from the ice sheet and the start of grounding line retreat and (d) self-sustained retreat of the grounding line.

南極氷床の不確実性
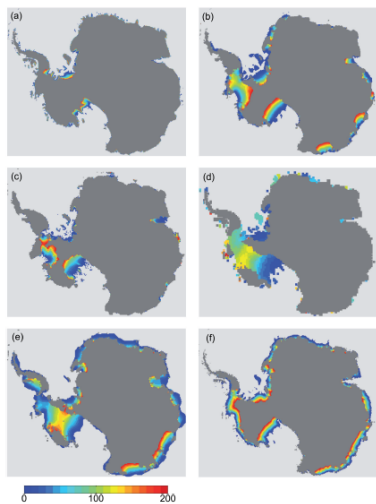
Grounding line の後退
〜 海面変化を決める。

海洋温度上昇だけでなく、
氷床流動過程の表現が結果を左右
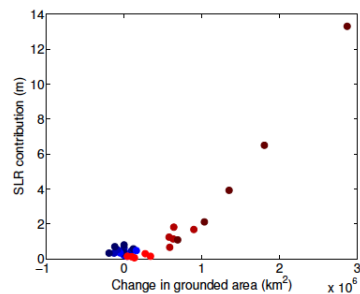
Durand and Pattyn, 2015, TC

Figure 2. Evolution of the Antarctic grounded area as computed by the five models which participated to SeaRISE experiment M3 (a to e) and similar results obtained by SISM (f). Colors corresponds to the time of ungrounding.
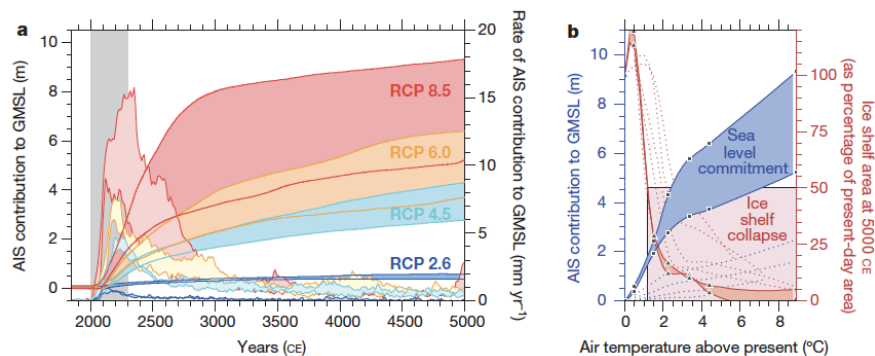
南極氷床の温暖化に対する応答シミュレーション

Golledge et al, 2015, Nature

南極氷床の温暖化に対する応答シミュレーション

Golledge et al, 2015, Nature

南極氷床の温暖化に対する応答シミュレーション (2)
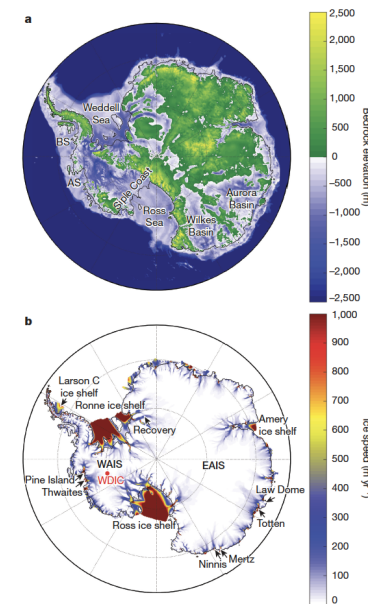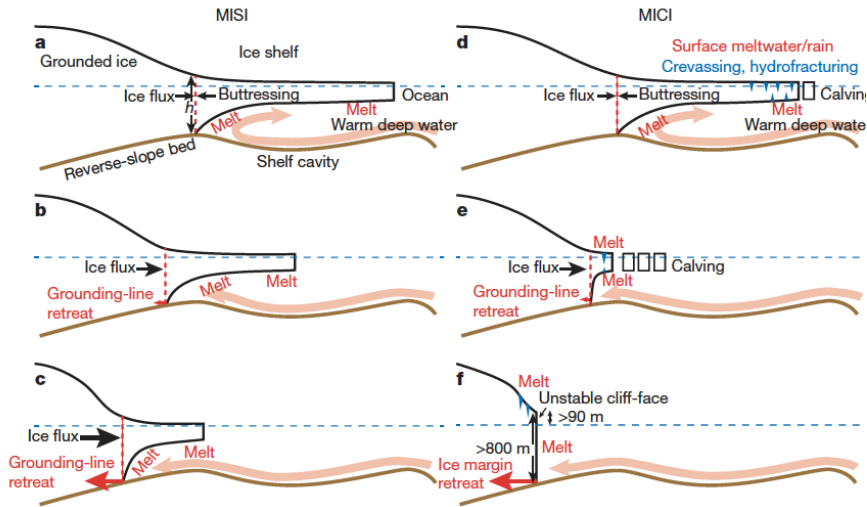

DeConte and Pollard, 2016, Nature

Figure 1 | Antarctic sub-glacial topography and ice sheet features.
a, Bedrock elevations[13] interpolated onto the 10-km polar stereographic ice-sheet model grid and used in Pliocene, LIG, and future ice-sheet simulations. b, Model surface ice speeds and grounding lines (black lines)
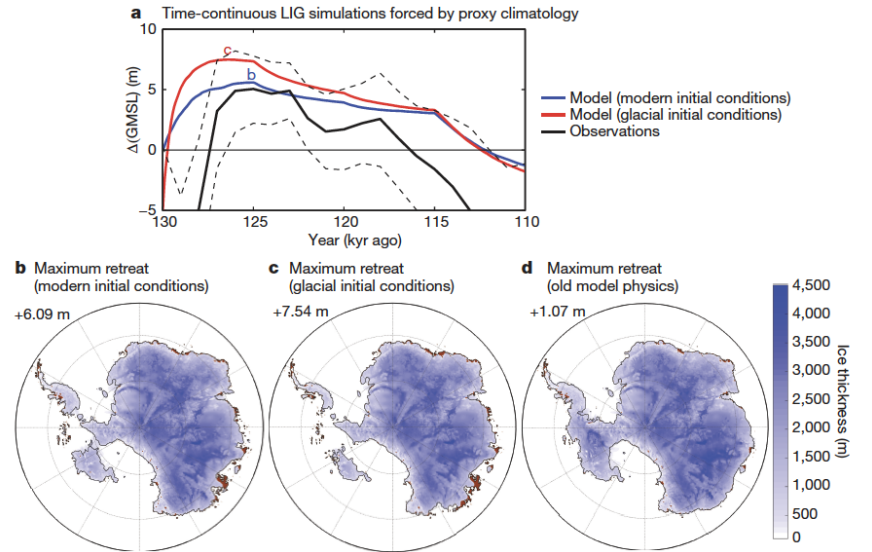
南極氷床におけるMISIとMICI
Marine Ice Sheet instability and Marine Ice Cliff instability
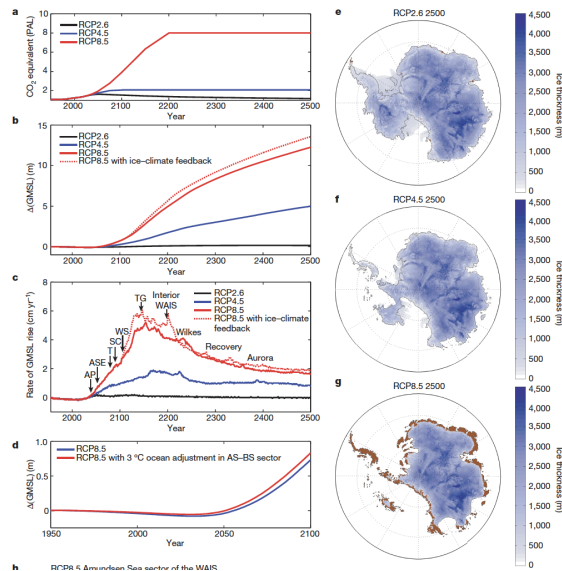
DeConte and Pollard, 2016, Nature

南極氷床モデル変化の古気候変化による制約

DeConte and Pollard, 2016, Nature

南極氷床の温暖化に対する応答シミュレーション

DeConte and Pollard, 2016, Nature
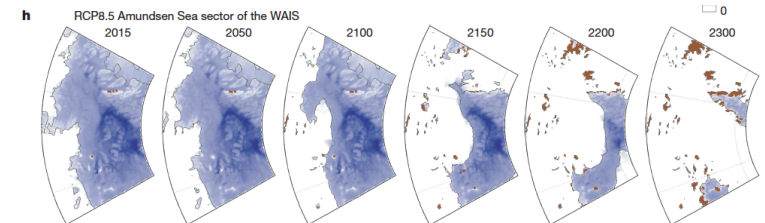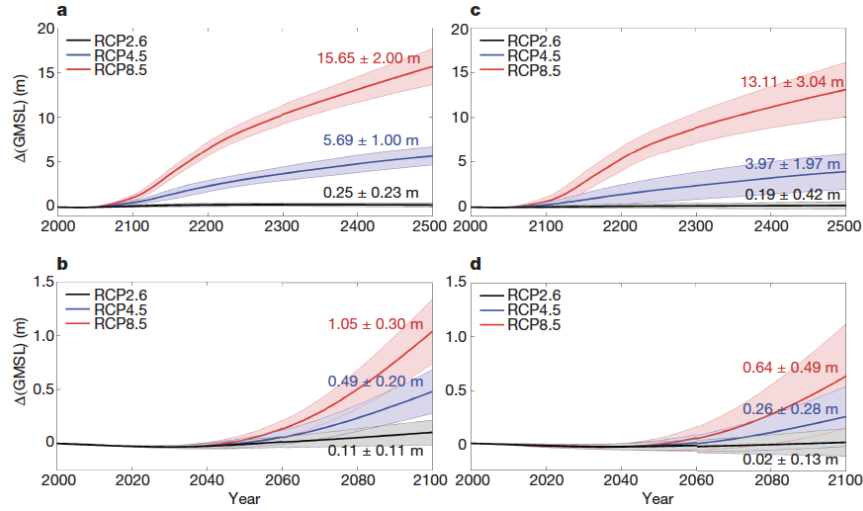

南極氷床の温暖化に対する応答シミュレーション

Figure 4 | Future ice-sheet simulations and Antarctic contributions to GMSL from 1950 to 2500 driven by a high-resolution atmospheric model and 1° NCAR CCSM4 ocean temperatures. a, Equivalent CO$_2$ forcing applied to the simulations, following the RCP emission scenarios in ref. 36, except limited to 8 × PAL (preindustrial atmospheric level, where 1 PAL = 280 p.p.m.v.). b, Antarctic contribution to GMSL. c, Rate of sea-level rise and approximate timing of major retreat and thinning in the Antarctic Peninsula (AP), Amundsen Sea Embayment (ASE) outlet glaciers, AS–BS, Amundsen Sea–Bellingshausen Sea; the Totten (T), Siple Coast (SC) and Weddell Sea (WS) grounding zones, the deep Thwaites Glacier basin (TG), interior WAIS, the Recovery Glacier, and the deep EAIS basins (Wilkes and Aurora). d, Antarctic contribution to GMSL over the next 100 years for RCP8.5 with and without a +3 °C adjustment in ocean model temperatures in the Amundsen and Bellingshausen seas as shown in Extended Data Fig. 5d. e–g, Ice-sheet snapshots at 2500 in the RCP2.6 (e), RCP4.5 (f) and RCP8.5 (g) scenarios. Ice-free land surfaces are shown in brown. h, Close-ups of the Amundsen Sea sector of WAIS in RCP8.5 with bias-corrected ocean model temperatures.

DeConte and Pollard, 2016, Nature

南極氷床の温暖化に対する応答

DeConte and Pollard, 2016, Nature
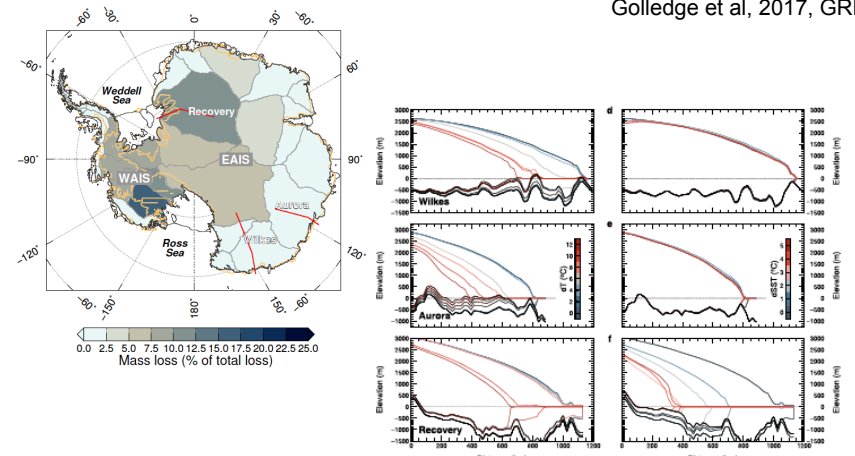
南極氷床の温度に対する応答実験

Golledge et al, 2017, GRL

南極氷床の温度に対する応答実験

地域によって大気に対する応答と海洋に対する応答が異なることを表す

南極氷床の温度に対する応答実験

南極氷床周辺の海洋の温度の21世紀末の変化

Figure 4. (a) Sea-surface temperature anomalies at 2100 CE (colored shading) with respect to preindustrial values as represented in the CMIP5 ensemble mean. Note the widespread coastal warming around West Antarctica arising from upwelling circumpolar deep water and (b) the peak warmth anomaly in the eastern Weddell Sea adjacent to the Filchner Ice Shelf (FIS). (c) Vertical ocean temperature differences revealed in World Ocean Circulation Experiment (WOCE) data. Bright colors in the Southern Ocean identify the location of the Antarctic Circumpolar Current. Areas of low thermal gradient adjacent to the continent coincide with the location of Antarctic Bottom Water formation areas, including (d) in the eastern Weddell Sea. Data shown as interpolations that fill gaps between available data points, for example, beneath ice shelves. Air temperature anomalies (in degrees C) over land shown as contours in Figures 4a and 4c. Dark gray shading in Figures 4b and 4d depicts areas of bed topography more than 500 m below sea level.

氷床の気温に対する応答（表面の応答 vs 力学応答）

The Greenland and Antarctic ice sheets under 1.5 °C global warming

Frank Pattyn[1]*, Catherine Ritz[2], Edward Hanna[3], Xylar Asay-Davis[4,5], Rob DeConto[6], Gaël Durand[2], Lionel Favier[1,2], Xavier Fettweis[7], Heiko Goelzer[1,8], Nicholas R. Golledge[9,10], Peter Kuipers Munneke[8], Jan T. M. Lenaerts[11], Sophie Nowicki[12], Antony J. Payne[13], Alexander Robinson[14], Hélène Seroussi[15], Luke D. Trusel[16] and Michiel van den Broeke[8]
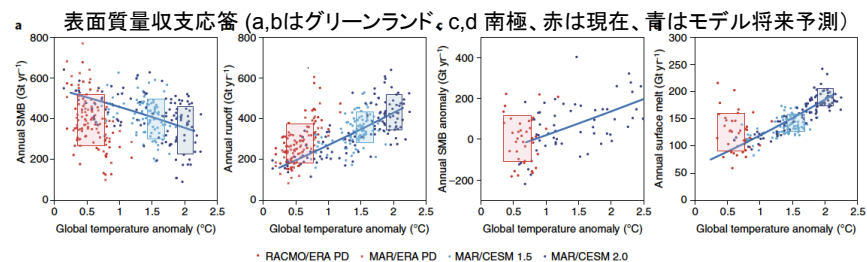
Even if anthropogenic warming were constrained to less than 2 °C above pre-industrial, the Greenland and Antarctic ice sheets will continue to lose mass this century, with rates similar to those observed over the past decade. However, nonlinear responses cannot be excluded, which may lead to larger rates of mass loss. Furthermore, large uncertainties in future projections still remain, pertaining to knowledge gaps in atmospheric (Greenland) and oceanic (Antarctica) forcing. On millennial timescales, both ice sheets have tipping points at or slightly above the 1.5–2.0 °C threshold; for Greenland, this may lead to irreversible mass loss due to the surface mass balance–elevation feedback, whereas for Antarctica, this could result in a collapse of major drainage basins due to ice-shelf weakening.

表面質量収支応答 (a,bはグリーンランド、c,d 南極、赤は現在、青はモデル将来予測）

· RACMO/ERA PD   · MAR/ERA PD   · MAR/CESM 1.5   · MAR/CESM 2.0

Fig. 1 | Annual mean surface mass fluxes as a function of global mean temperature anomalies. Temperature anomalies are referenced to the pre-industrial era (1850–1920). **a**, GrIS SMB. **b**, GrIS runoff. **c**, Antarctic SMB. **d**, Antarctic surface melt. Red colours indicate model realizations of present-day ice sheets (RACMO2 and MAR forced by ERA reanalysis data). Blue colours indicate model realizations of future ice sheets. In **a** and **b**, MAR is forced with CESM-

グリーンランド氷床の気温に対する応答

Robinson et al, 2012, Nature Clim. Change
Pattyn et al, 2018, Nature Clim. Change
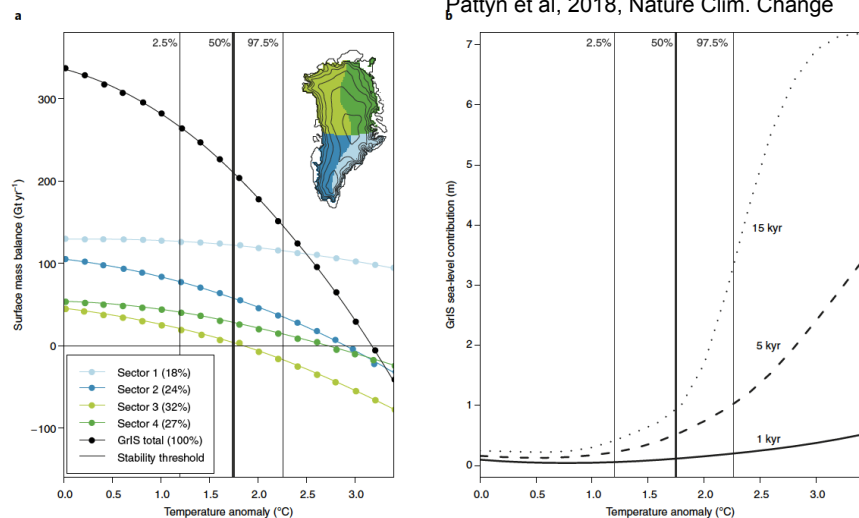
南極氷床の気温に対する応答

Golledge et al, 2015, Nature
Pattyn et al, 2018, Nature Clim. Change
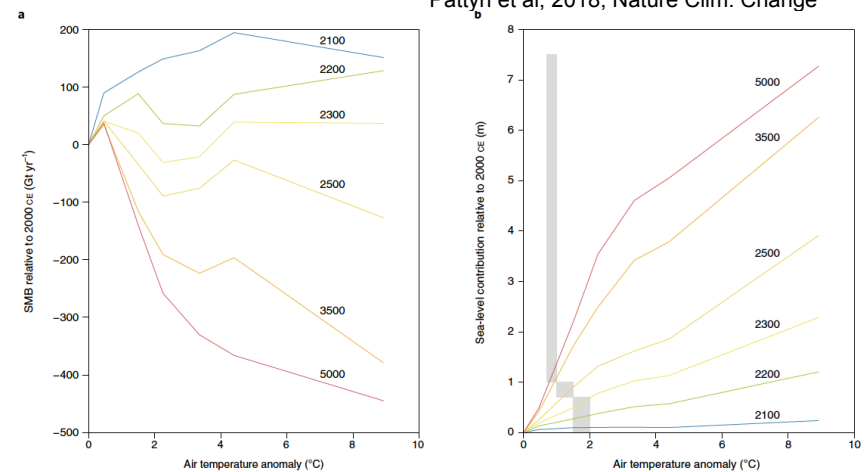
Fig. 4 | AIS stability as a function of the imposed regional annual mean temperature anomaly. a,b, Changes in SMB (**a**) and SLR contribution (**b**) for the AIS relative to 2000 CE as simulated under spatially uniform temperature increases that follow RCP trajectories to 2300 CE and then stabilize[81]. Coloured lines denote different years (CE); data are averages of high and low scenarios, denoting two different grounding-line parameterizations. Grey shading shows the approximate equivalent global mean temperature anomaly for an Antarctic mean temperature anomaly of 1.5–2.0 °C, accounting for polar amplification.

Tipping points

- 南極氷床のTipping point は2種類ある。1つは、Ocean 側のtipping pointである。Ocean melt が5m/yr以上になるtipping point. これは大陸棚周辺の地形など海底地形や海洋循環に依存している。
- 2つめは、大きなocean melt に対して、棚氷／氷床システムがどのくらい解けるか、という氷床側のTipping pointである。

Tipping points

- 海洋モデル：温度の上昇-→melt の関係を地域ごとに出す。 (Obase, Abe-Ouchi, Kusahara and Hasumi, 2017, Journal of Climate)
- 氷床モデル：大きな温度変化に対して（海洋および大気）、棚氷／氷床システムがどのくらい解けるか？

棚氷と海洋

Observed basal melt rate/ocean temperature

Inactive melting / Inactive melting / Active melting / Inactive melting / Active melting

Active melting in Pine Island Glacier (Jacobs et al., 2011)

Inactive melting in Filchner-Ronne Ice shelf (Petty et al., 2013)

Basal Melt Rate (freshwater m/yr)
−1.0 −0.5 0.0 0.5 1.0 2.0 4.0
Subsurface Ocean Temperature (°C)
−1.5 −1.0 0.0 1.0 1.5 2.0

Data is from Rignot et al., 2013 (basal melt), WOCE (ocean temp.)

- Observations: difference in **ocean temperature above continental shelf** is responsible to regional difference in basal melt rate (Pritchard et al., 2012), due to difference in shelf water formation in the shelf seas (Petty et al., 2013), and wind along Antarctic Coast (Hattermann et al., 2012).

Inactive melting in Dronning Maud Land (Noest et al., 2011)

海洋温度の気候に対する非線形応答

Obase, Abe-Ouchi et al, 2017

Ross (180E) / Amundsen (107W) / Bellingshausen (77W) / Dronning Maud Land (17W)

LGM / CTL / 2xCO2

Basal Melt Rate [m/yr] / Sea Ice Production Rate [m/yr]

- Intrusion of warm water onto continental shelves are widely found in the 2xCO2, while cold and dense shelf water is found in the LGM.
- **Appearance of ocean structure depends on regions/background climates**