Potsdam Institute for Climate Impact Research

Meeresspiegelanstieg
Projektion vs Risikoanalyse

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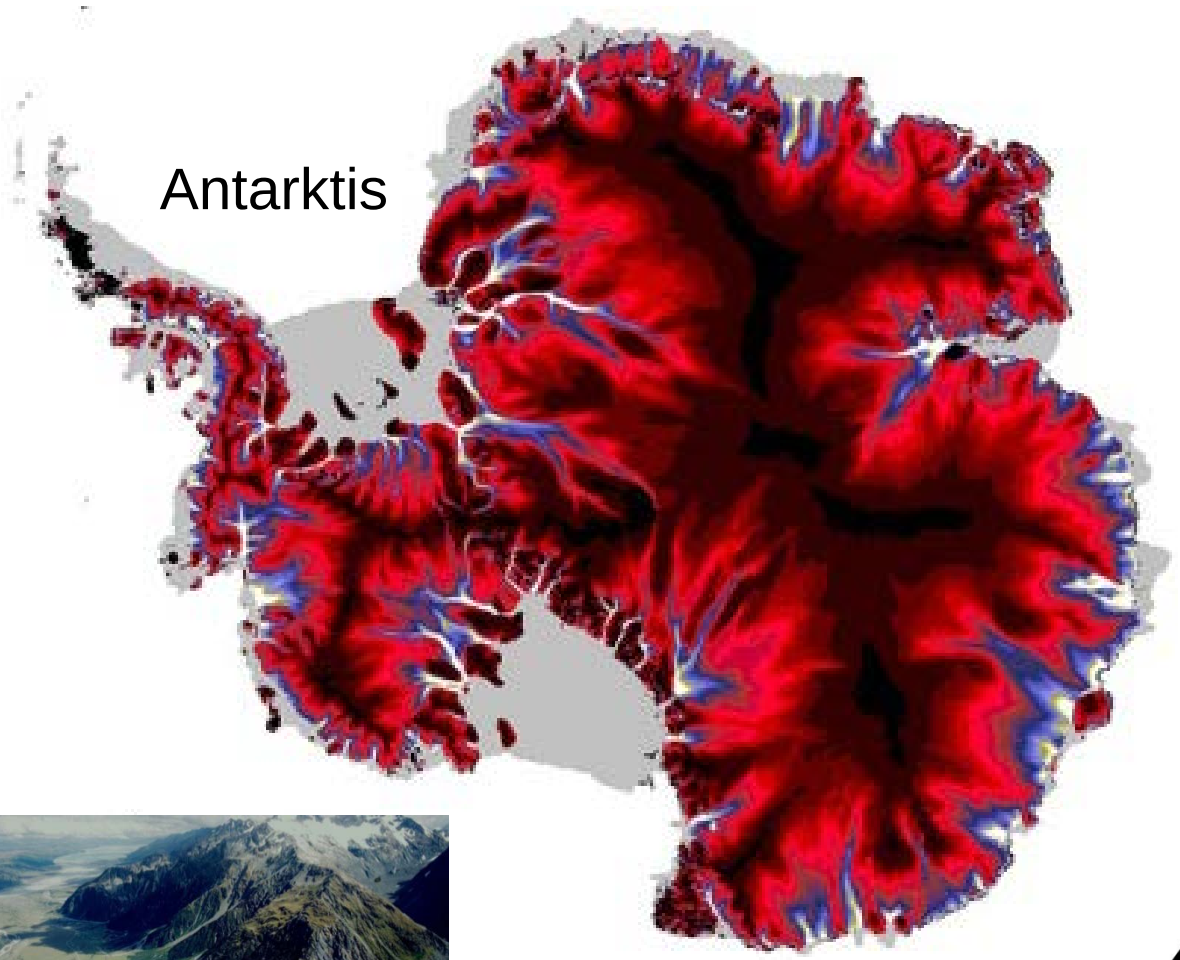
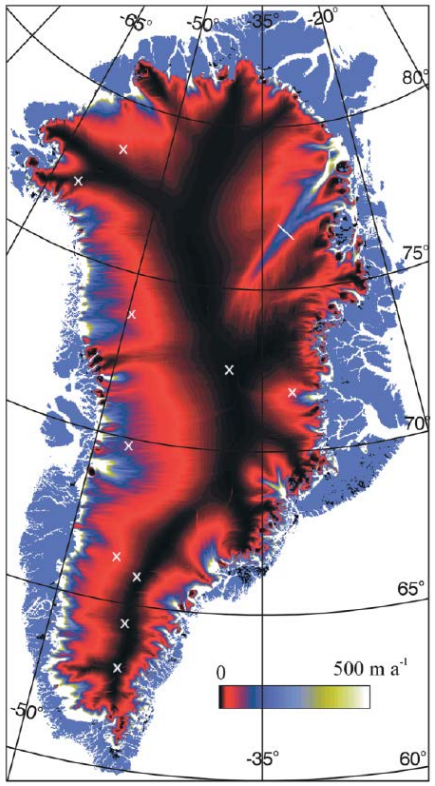
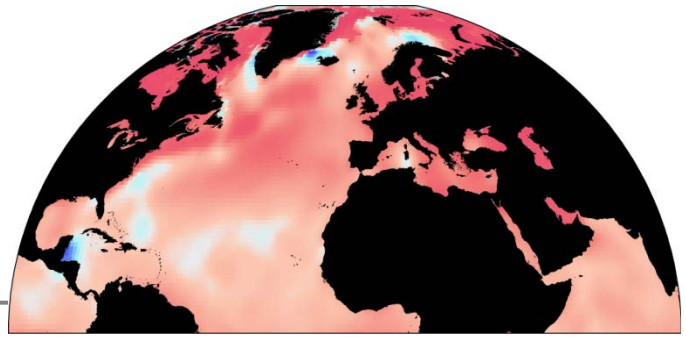
Beiträge zum Meeresspiegel





Grönland

Gletscher

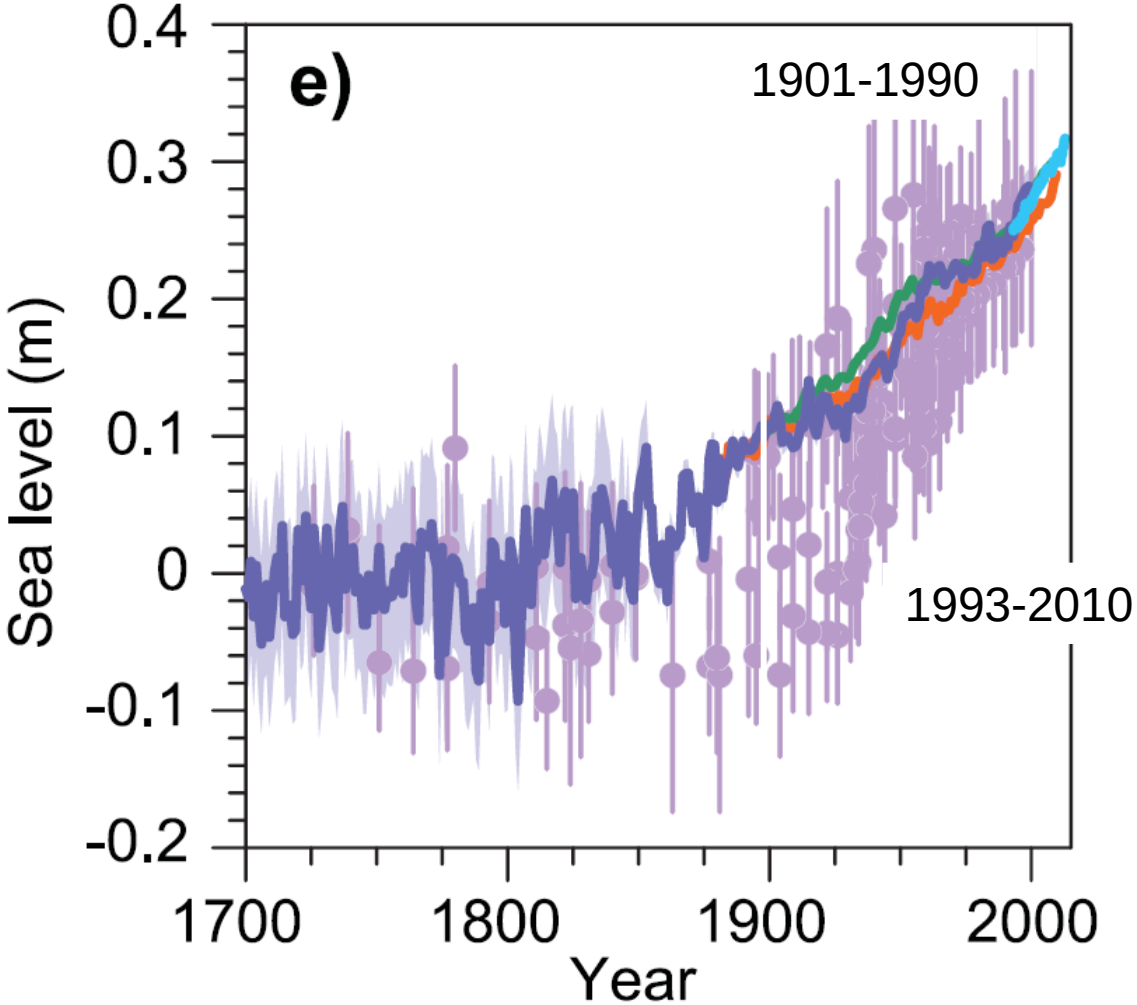


Ausdehnung der Meere

Der Meeresspiegel steigt immer schneller an.

Der Meeresspiegel steigt immer schneller an

Mittlere Rate während der letzten 2000 Jahre war einige Zehntel mm yr^{-1}.



Rate zwischen 1901-1990:
1.5 [1.3 to 1.7] mm yr^{-1}.

Wahrscheinlich Rate im 19. Jahrhundert beschleunigt.

Rate zwischen 1993-2010:
3.2 [2.8 to 3.6] mm yr^{-1}.

IPCC- AR5, 2013, Fig. 13.3e

Die Zusammensetzung der Beiträge könnte sich verändern

Beiträge der Vergangenheit

Beiträge (mm/yr)	1971-2010		1993-2010	
Therm. Ausdehnung	0.8	40%	1.1	34%
Gletscher	0.68	34%	0.86	27%
Grönland	?	?	0.33	10%
Antarktis	?	?	0.27	8%
Wasser auf Land	0.12	6%	0.38	12%
Summe	1.6	80%	2.8	88%
Beobachtet Gesamt	2.0	100%	3.2	100%

Bisher keine klare Veränderung nachweisbar.

PIK

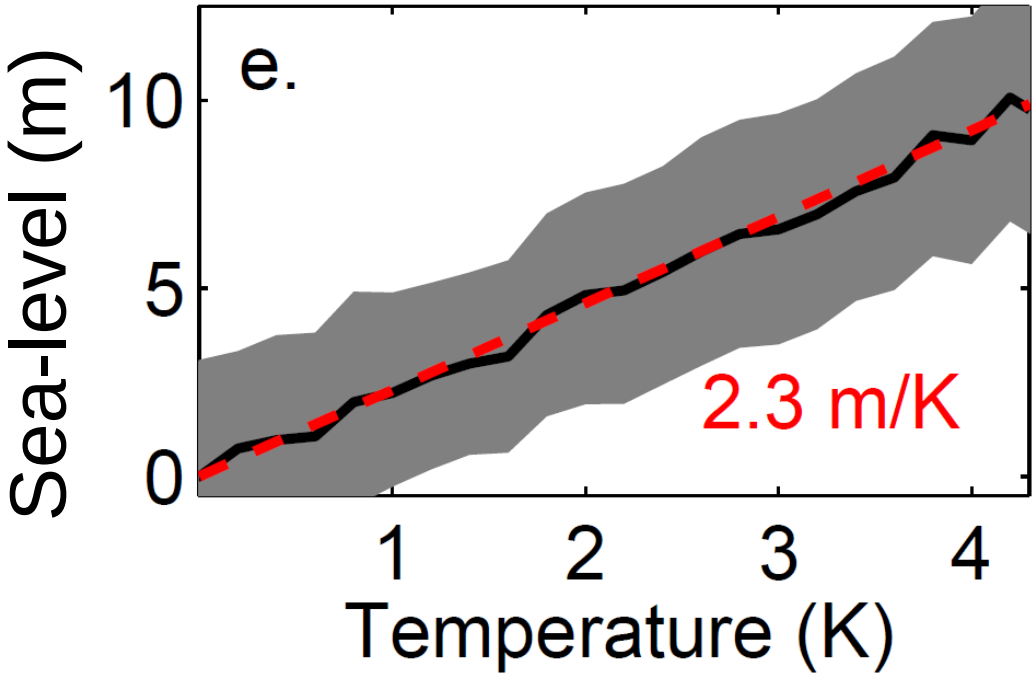
IPCC- AR5, 2013, Tab. 13.1

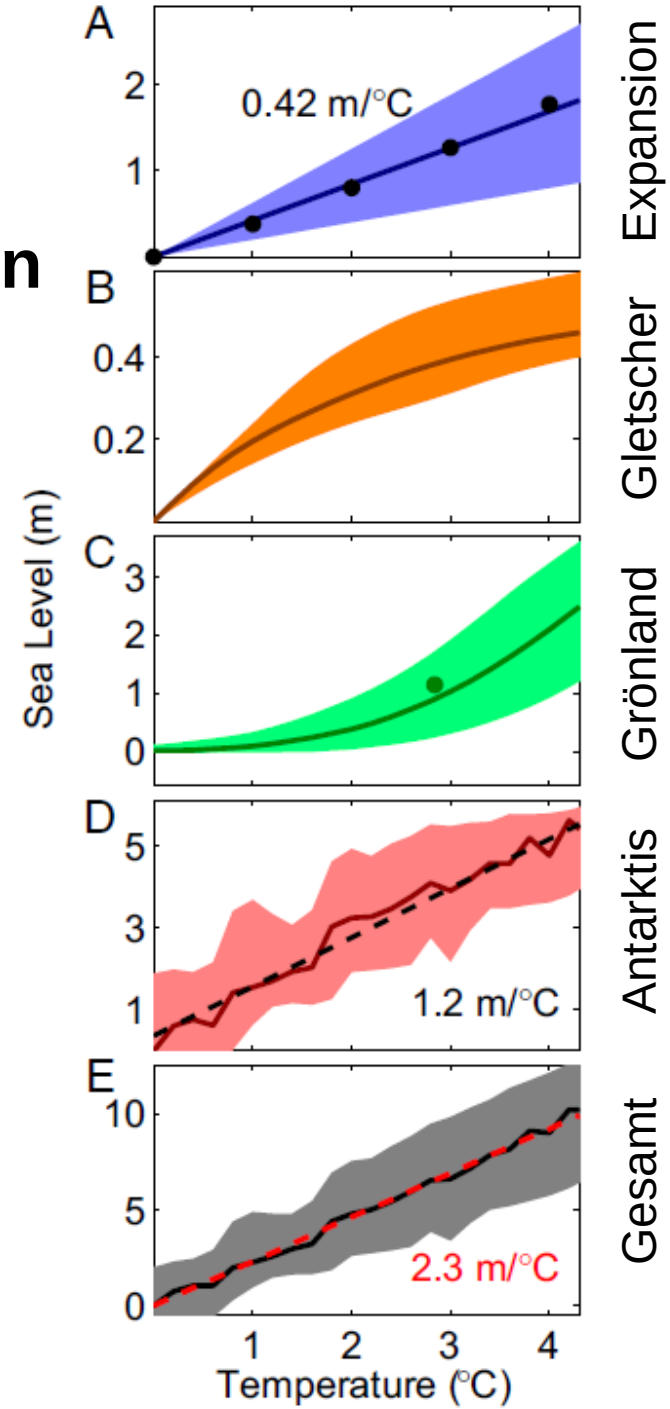
Ein Blick in die ferne Zukunft

Zusammensetzung wird sich ändern

18% Ozeanische Ausdehung

52% Antarktis





Levermann, et al. PNAS, 2013.

IPCC- AR5, 2013, Fig. 13.14

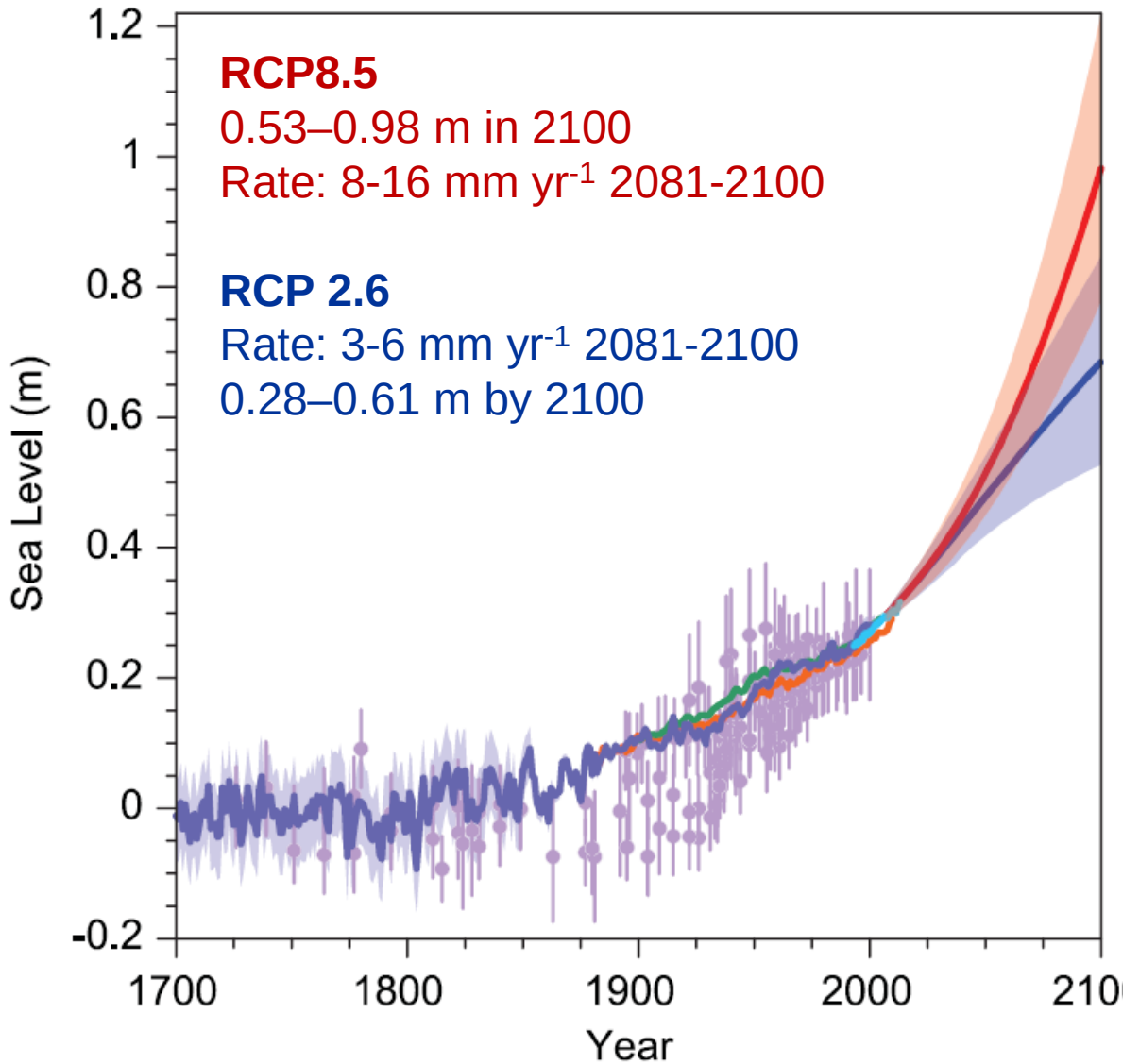
Projektionen für die Zukunft

Projektionen bis 2100

Sehr wahrscheinlich: mittlere Rate 21. Jahrhundert größer als zwischen 1971-2010.

RCP8.5
0.5-1.0 m

RCP2.6
0.3-0.6 m



IPCC- AR5, 2013
Fig. 13.27

P I K

Zukünftige Beitragsverteilung im Vergleich

Beiträge	1971-2010	1993-2010	RCP2.6	RCP4.5	RCP6.0	RCP8.5	Jahr 4000
Ausdehnung	40 %	34 %	35 %	40 %	40 %	44 %	18 %
Gletscher	34 %	27 %	25 %	26 %	26 %	26 %	5 %
Grönland	?	10 %	18 %	17 %	17 %	21 %	25 %
Antarktis	?	8 %	13 %	11 %	11 %	5 %	52 %
Land	6 %	12 %	10 %	9 %	9 %	6 %	-
Gesamt	80%	101%	101%	103%	103%	102%	100%

Irgendwann wecken wir die Antarktis auf.

Aber wann?

IPCC- AR5, 2013, Tab. 13.5

Obergrenze ist sinnvoller als wahrscheinlichster Wert

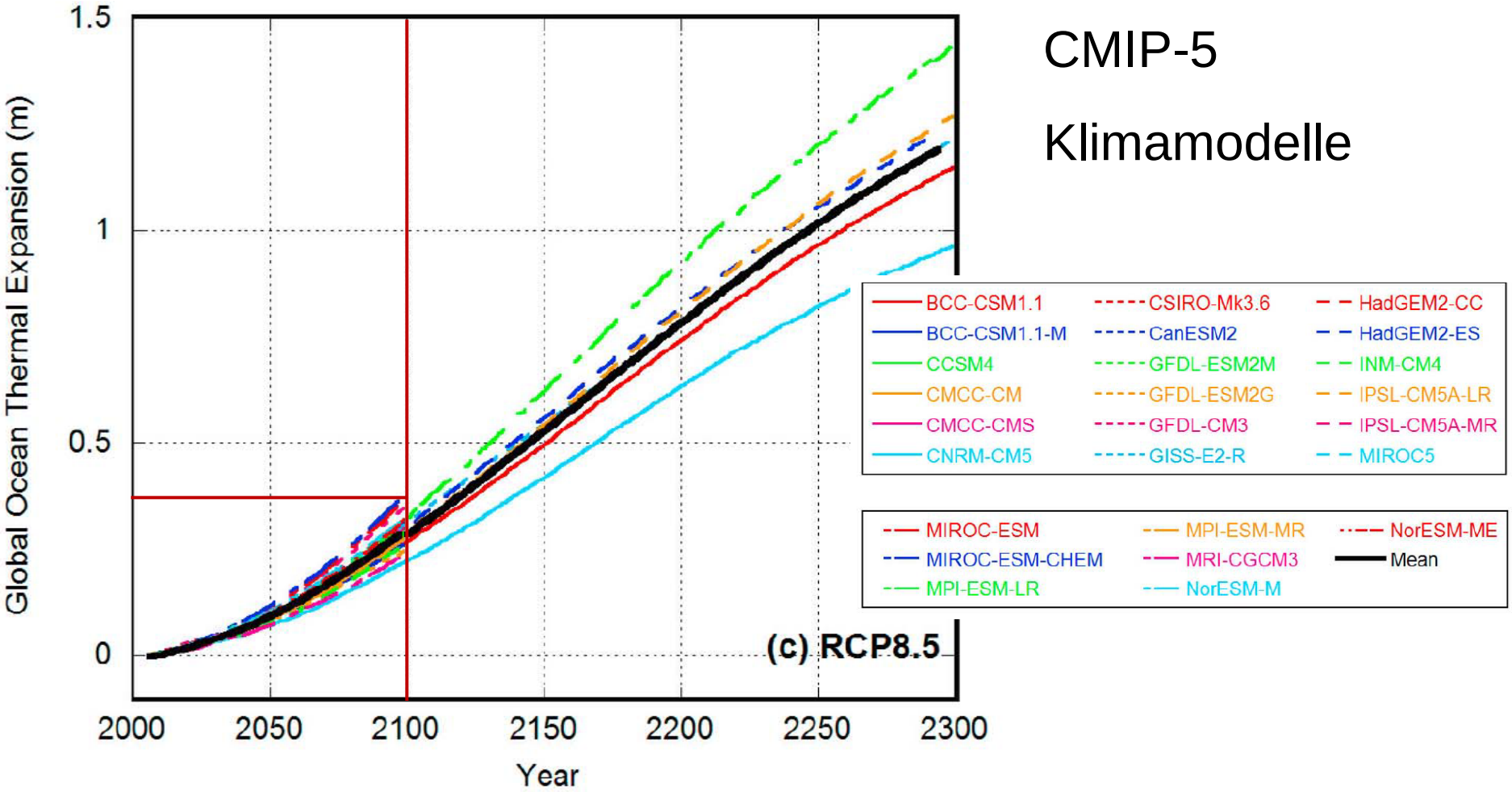
IPCC AR5 SPM

Seite 16: The basis for higher projections of global mean sea level rise in the 21st century has been considered and it has been concluded that there is currently insufficient evidence to evaluate the probability of specific levels above the likely range. 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.*

d.h. 1 m plus mehrere Dezimeter

P I K

Wärmeausdehnung der Meere



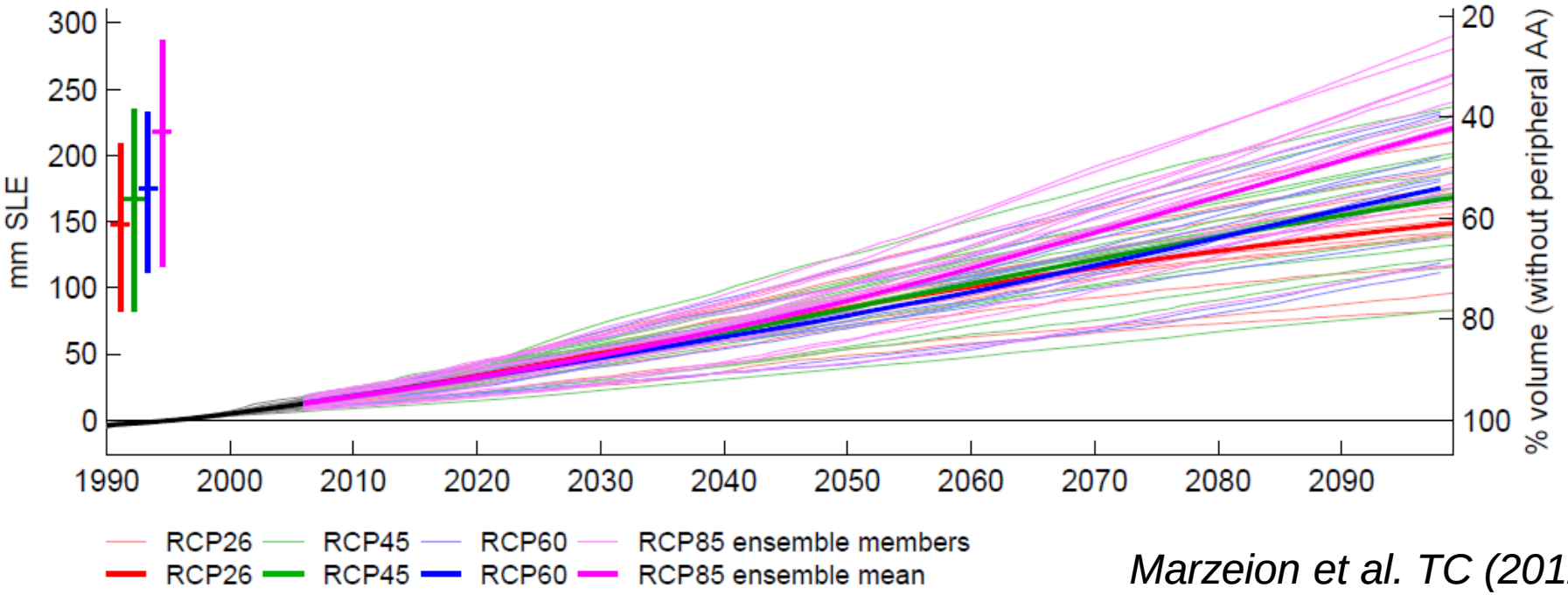
CMIP-5

Klimamodelle

Yin, GRL (2012).

Obergrenze: < 0.4m

Gletscher



Marzeion et al. TC (2012).

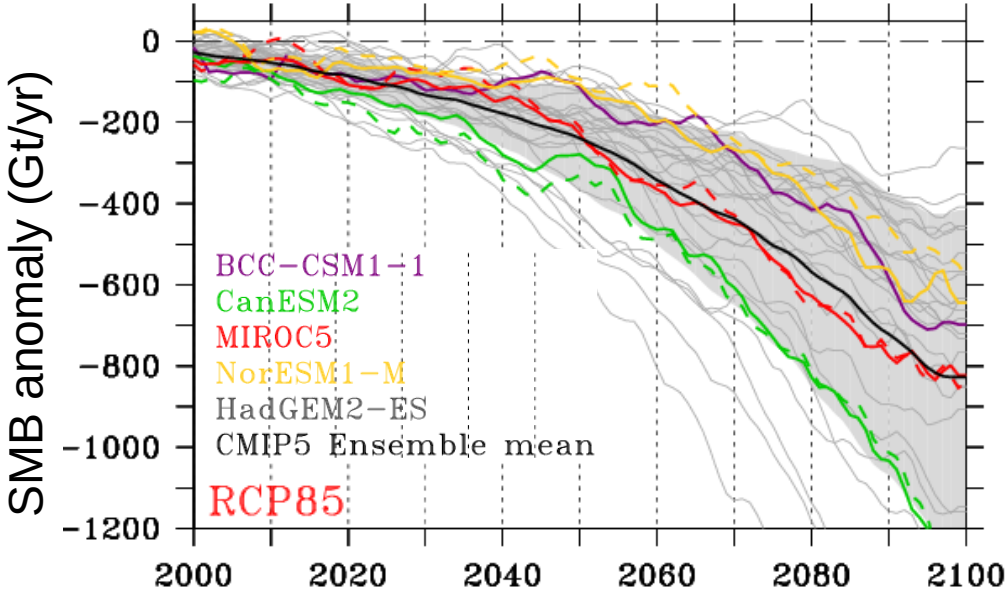
Schätzungen des gesamten Eises in Gletschern

43 ± 6 cm (Huss & Farinotti, 2012)
35 ± 7 cm (Grinsted, 2013)
49 ± 3 cm (Marzeion et al., 2012)

Obergrenze: < 0.3m

Grönland
Oberflächenbilanz nach CMIP-5 Klimamodellen

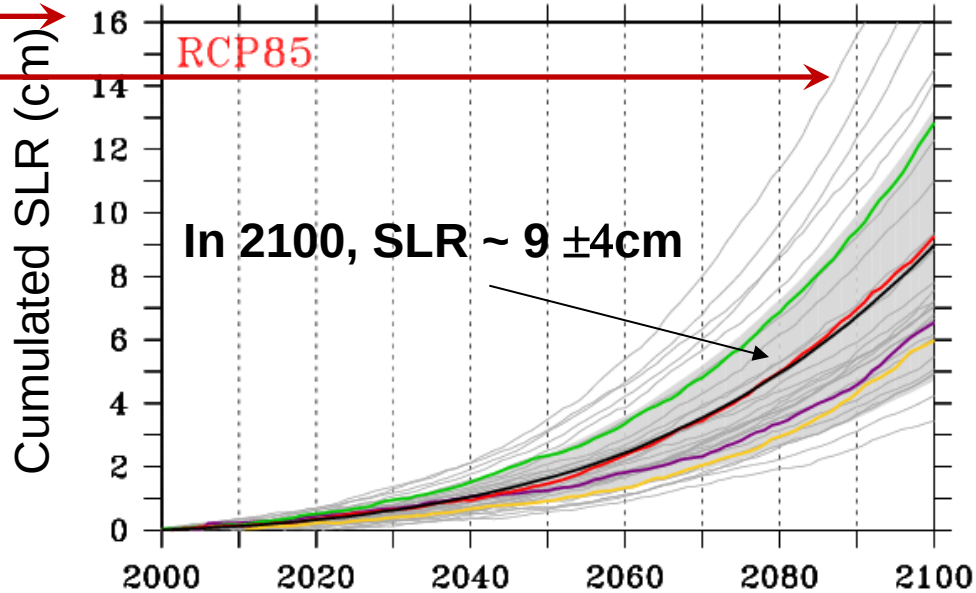
In 2100, ΔSMB_{CMIP5} ~ – **850±450** GT/yr



Offensichtlich sind einige

Modelle höher als die

Standardabweichung



Fettweis et al. TC (2013).

Obergrenze: < 0.2m

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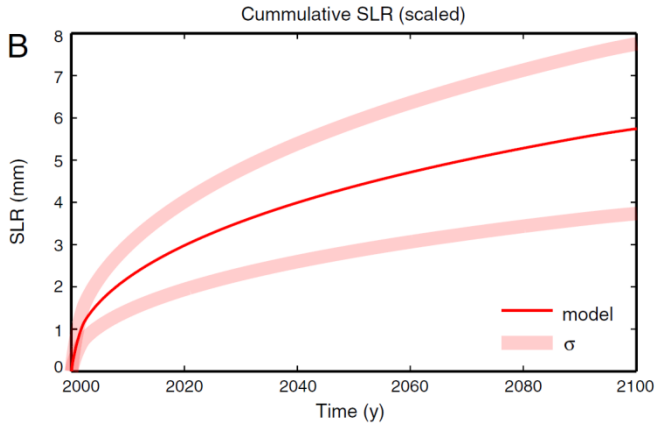
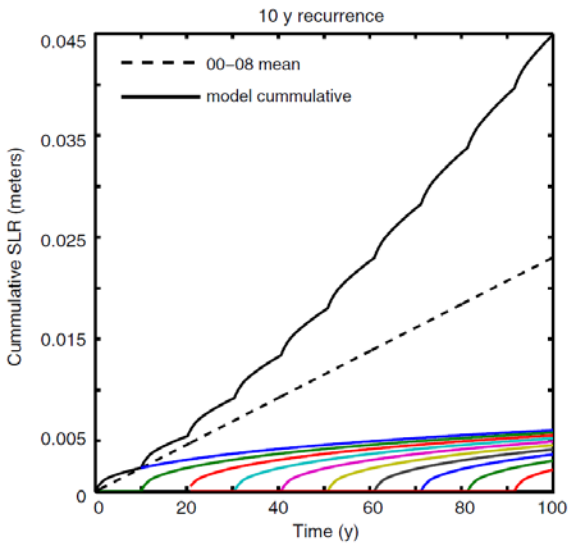
Grönland: Dynamik der Eisberge

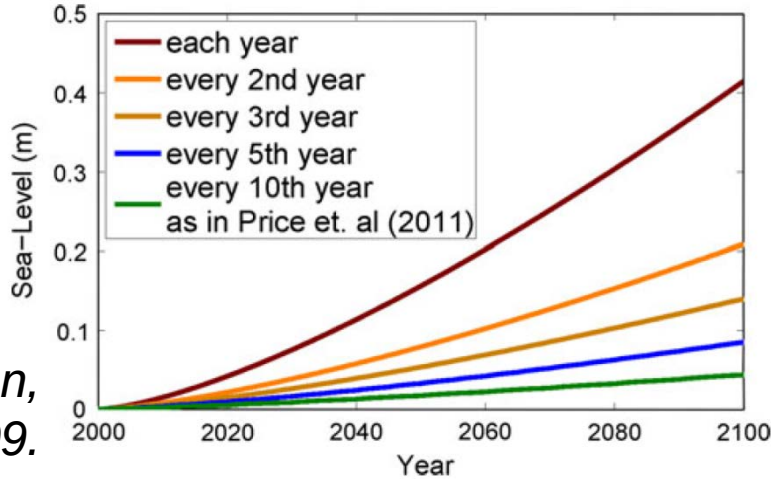




Price et al., PNAS, 2009.

Obergrenze: 4.5 cm

Eis das unter Meeresspiegel aufliegt:
~6-8 cm Meeresspiegeläquivalent.

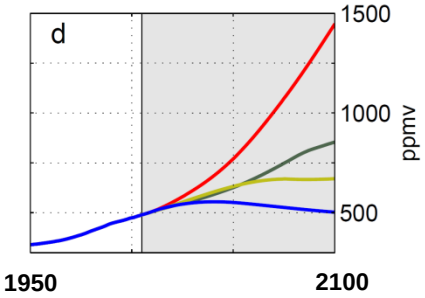


Winkelmann & Levermann, Clim. Dyn, 2009.

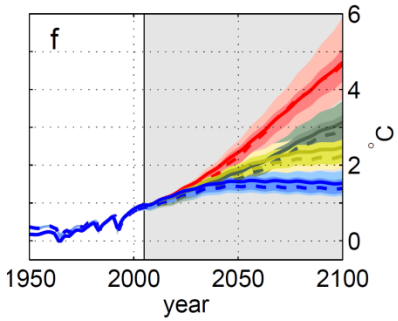
Obergrenze: < 0.1m

Antarktis Eisbergdynamik

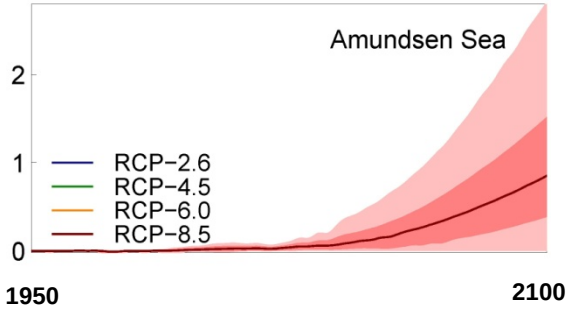
Kombination verschiedener physikalischer Modell



Socio-economic scenarios (RCP)



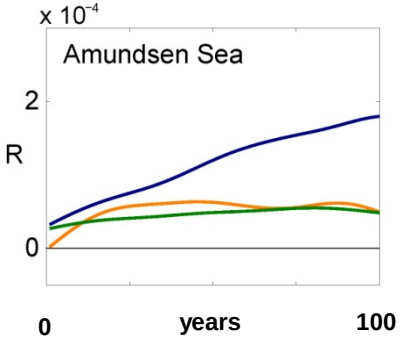
Global mean temperature



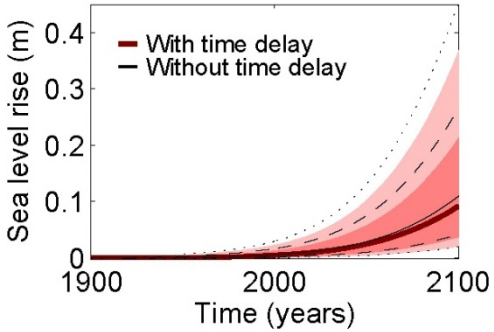
Antarctic subsurface ocean temperature

[7-16] m/a/K

Observed basal-melt sensitivity



Ice-sheet response

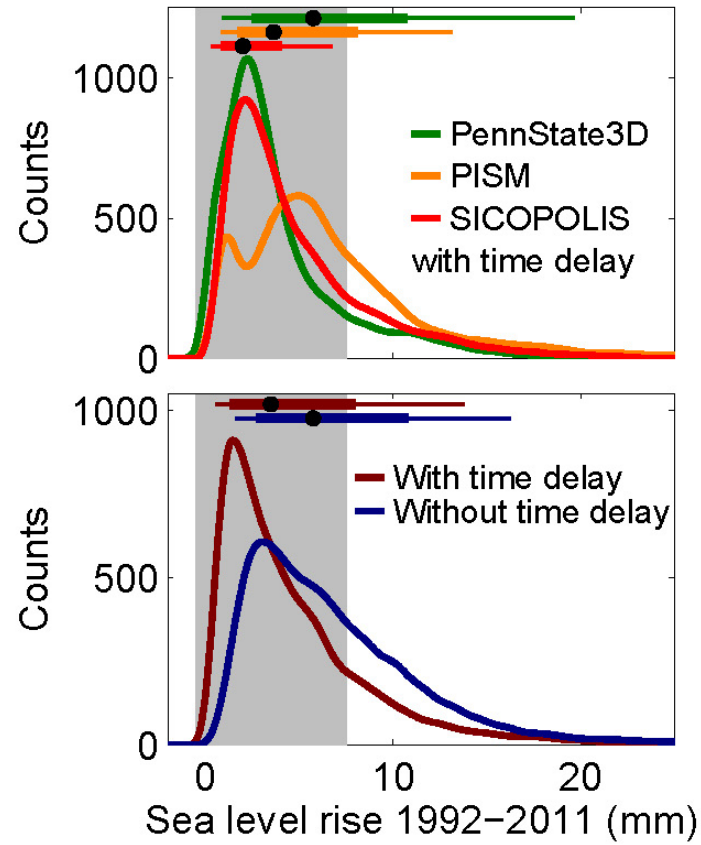


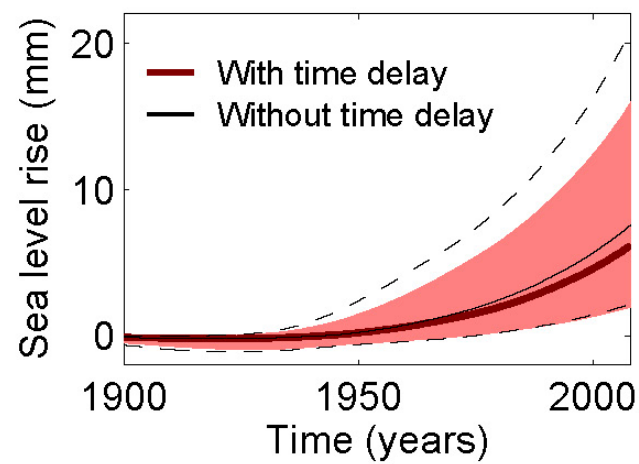
Sea-level contribution

Die Vergangenheit vorhersagen: 1992-2011

- Global mean temperatures anomalies
- **Scaled with time delay** to ocean subsurface
- Multiplied with basal-melt sensitivity
- Convoluted with the ice response function

$$S(t) = \int_0^t d\tau \, R(t-\tau) m(\tau)$$

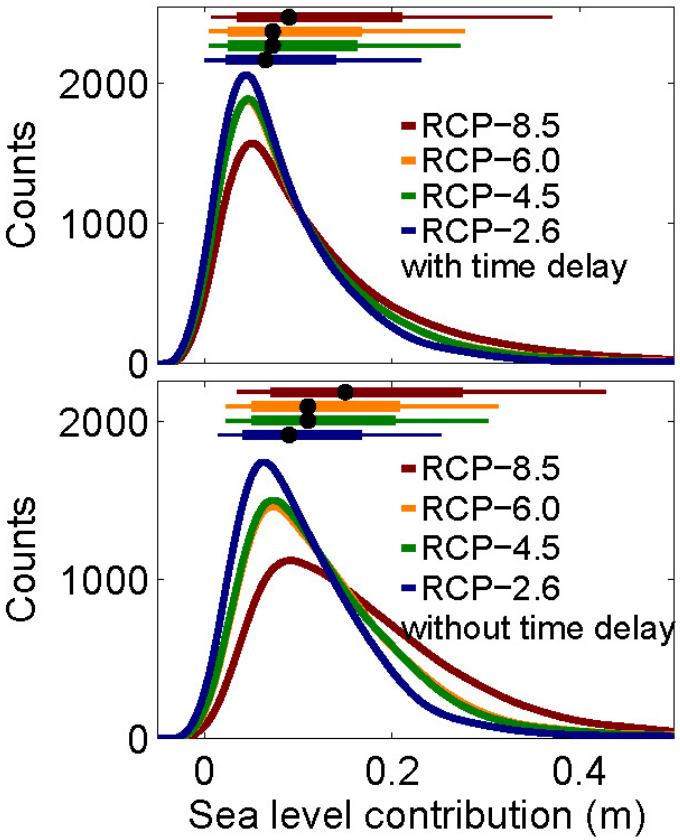


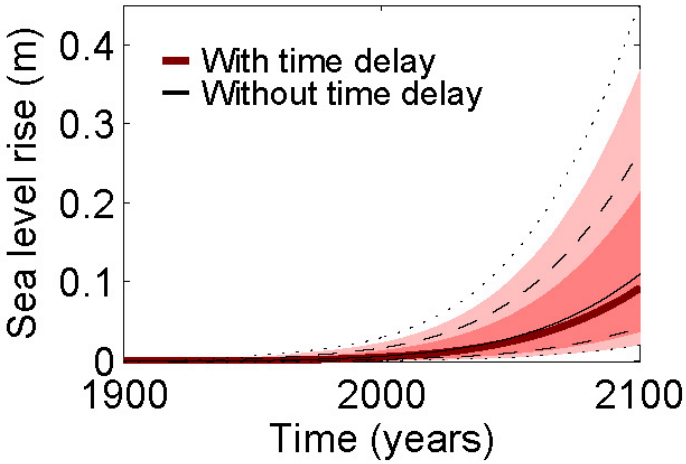


P I K

Die Zukunft vorhersagen: 1900-2100

Set-up	RCP	Median	17%	83%	5%	95%
'Shelf models'	2.6	0.07	0.02	0.14	0.0	0.23
with Δt	4.5	0.07	0.03	0.16	0.01	0.27
	6.0	0.07	0.03	0.17	0.01	0.28
	8.5	0.09	0.04	0.21	0.01	0.37
'Shelf models'	2.6	0.09	0.04	0.17	0.02	0.25
without Δt	4.5	0.11	0.05	0.20	0.02	0.30
	6.0	0.11	0.05	0.21	0.02	0.31
	8.5	0.15	0.07	0.28	0.04	0.43





Obergrenze: < 0.5m

Schätzung einer Obergrenze für den Anstieg

Addieren der höchsten Beiträge der prozessbasierten Modelle

Meeresausdehnung	**< 0.4m**	CMIP-5: MIROC-ESM-CHEM: 0.43m Schewe et al. (2010) (EMIC)
Gletscher	**< 0.3m**	Marzeion et al. (2012)
Grönland Schmelzen	**< 0.2m**	Fettweis et al. (2013)
Grönland Eisberge	**< 0.1m**	Total ice grounded below sea level
Antarktis Schmelzen	**< 0.0m**	Huybrechts et al. (2012)
Antarktis Eisberge	**< 0.5m**	Levermann et al. (2012)
Gesamtanstieg	**< 1.5m**	

Vergleich mit Pfeffer et al. (2008):

Meeresausdehnung ~0.5m
Gletscher ~0.5m
Grönland ~0.5m
Antarktis ~0.5m

Gesamt 2.0m

P I K

Vielen Dank !

Potsdam Institute for Climate Impact Research

P I K

Bisher

Beobachteter Anstieg beschleunigt sich.

Bis 2100

Wahrscheinlich 0.5-1m bei weiter steigenden Emissionen
Emissionsminderung begrenzt Anstieg auf 0.3-0.6m
Obergrenze für Küstenschütz 1.5m

Bis dann

Anstieg geht über Jahrhunderte weiter
Die Temperatur bestimmt den Anstieg: 2.3 m pro Grad.

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Leibniz Gemeinschaft

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Zukünftige Beitragsverteilung im Vergleich

Beiträge	1993-2010	RCP2.6	RCP4.5	RCP6.0	RCP8.5	Jahr 4000
Ausdehnung	34 %	35 %	40 %	40 %	44 %	18 %
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Grönland	10 %	18 %	17 %	17 %	21 %	25 %
Antarktis	8 %	13 %	11 %	11 %	5 %	52 %
Land	12 %	10 %	9 %	9 %	6 %	-
Gesamt	101 %	101%	103 %	103 %	102 %	100 %

Irgendwann wecken wir die Antarktis auf.

Aber wann?

IPCC- AR5, 2013, Tab. 13.5

Zukünftige Beitragsverteilung im Vergleich

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Land	6 %	12 %	10 %	9 %	9 %	6 %	-
Gesamt	80%	101%	101%	103%	103%	102%	100%

Irgendwann wecken wir die Antarktis auf.

Aber wann?

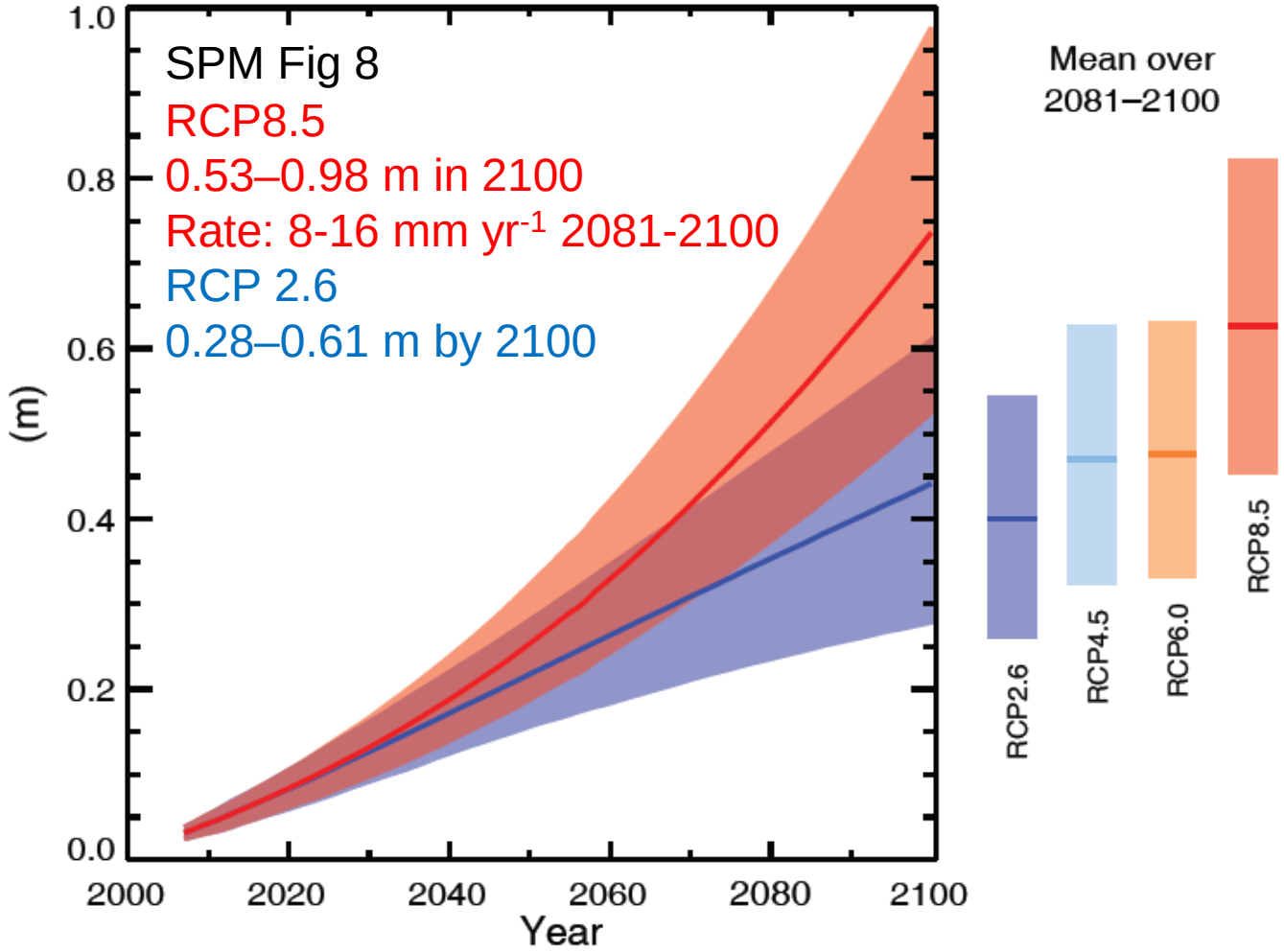
IPCC- AR5, 2013, Tab. 13.5

Projektionen bis 2100

Sehr wahrscheinlich: mittlere Rate 21. Jahrhundert größer als zwischen 1971-2010.

RCP8.5
0.5-1.0 m

RCP2.6
0.3-0.6 m

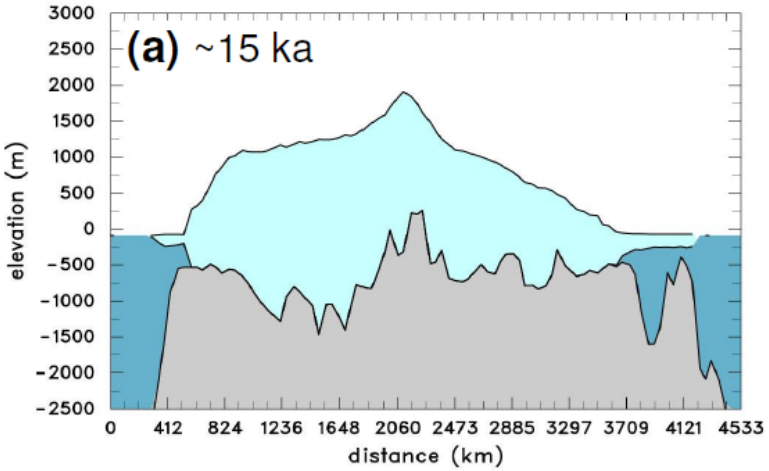


IPCC- AR5, 2013, SPM Fig. 8.

Antarktis: Dynamik – die Rolle von Instabilitäten

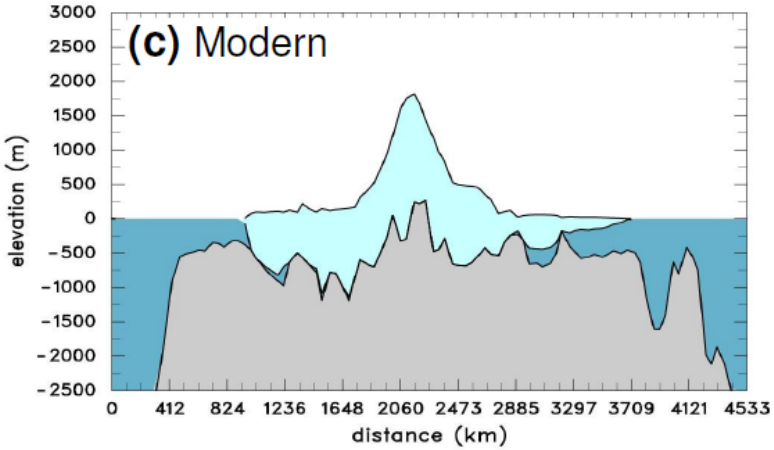
Pollard & De Conto (2009):

7m of sea-level rise took typically a few thousand years, i.e. 0.1-0.7m per century with potentially more initial ice volume.



Hypothesis

Under a rapid warming of up to 5K, the upper limit until 2100 will be set by the forced response not by the instability.



Upper limit estimate: < 0.5m

Comparison of sea-level rates with 24mm/yr

Thermal expansion < 9 mm/yr
Glaciers < 5 mm/yr

That leaves for Greenland and Antarctica 10 mm/yr

The question is can Greenland and Antarctica loose ice in the equivalent of 10 mm in a year over a time span of say a decade?

For further confusion semi-empirical model:
Total rate of sea-level rise 3.4 mm/yr/K x **7K** = 24 mm/yr
(Rahmstorf, 2007)

P I K

Physikalische Beiträge der Vergangenheit

Erste Hinweise auf Veränderung der Zusammensetzung

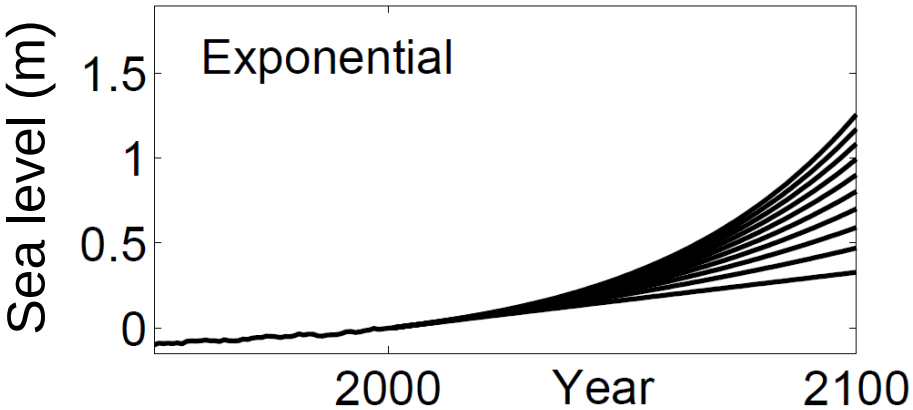
Beiträge (mm/yr)	1971-2010		1993-2010	
Therm. Ausdehnung	0.8	43%	1.10	39%
Gletscher	0.68	36%	0.86	31%
Grönland	?	?	0.33	12%
Antarktis	?	?	0.27	10%
Summe ohne Land	1.48	79%	2.5	89%
Beobachtet ohne Land	1.88	100%	2.8	100%

P I K

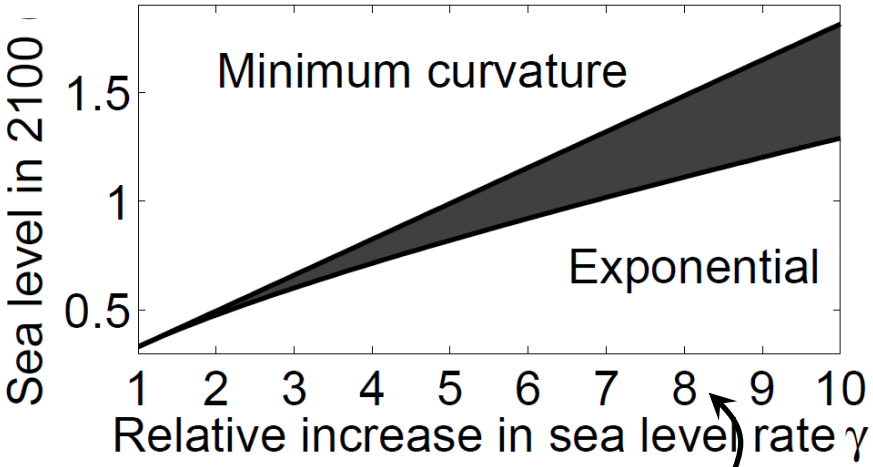
A bird´s view

on the upper limit using maximum sea-level rates

Starting from 3mm/yr sea-level rate what is the sea-level rise that you can reach in 2100 with a smooth curve?



What is the maximum rate of sea-level rise per year that you have reached in the process?

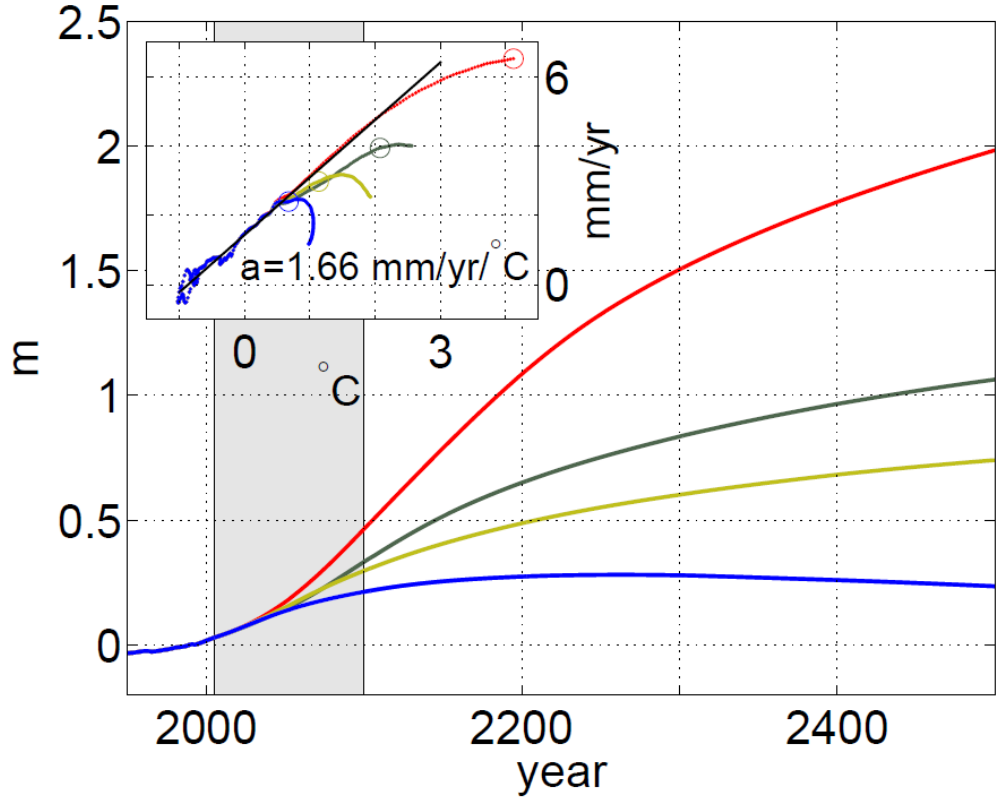


24 mm/yr

Levermann/Vaughan, in the thinking.

Comparison of sea-level rates with 24mm/yr

Thermal expansion

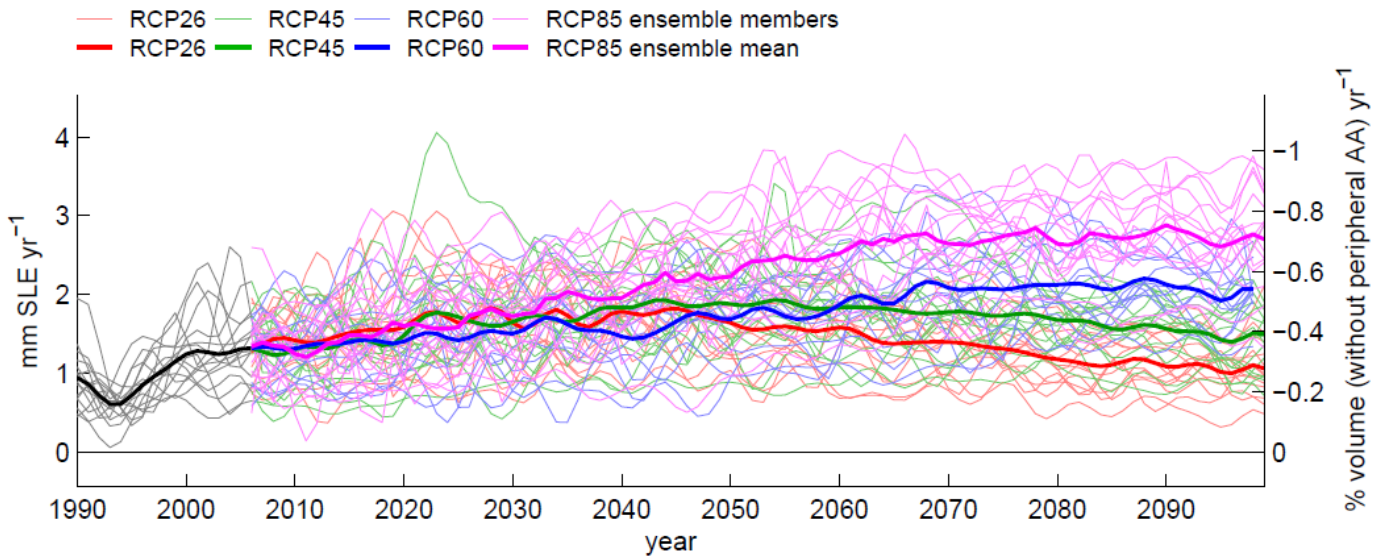


~1.7 mm/yr/K x 5K
= 8.5 mm/yr

Schewe et al. ESD (2011).

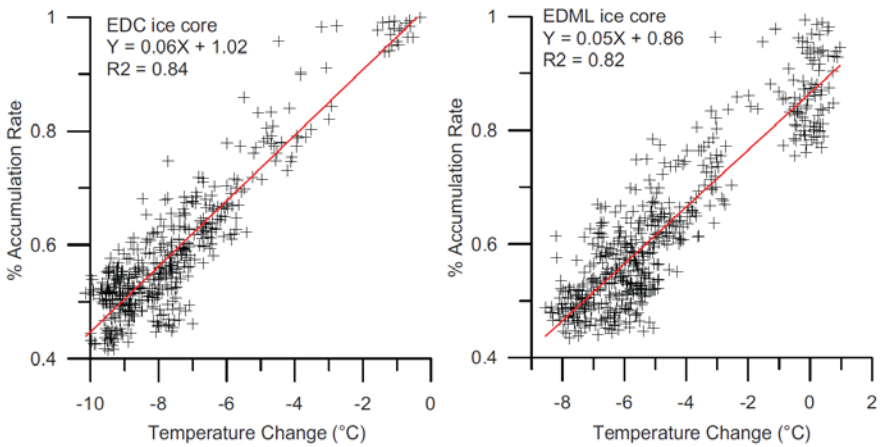
Comparison of sea-level rates with 30mm/yr

Glaciers: Maximum in projections < **4 mm/yr**.
If you lost everything in a century < 0.5 m/century = 5mm/yr.



Marzeion et al. TC (2012).

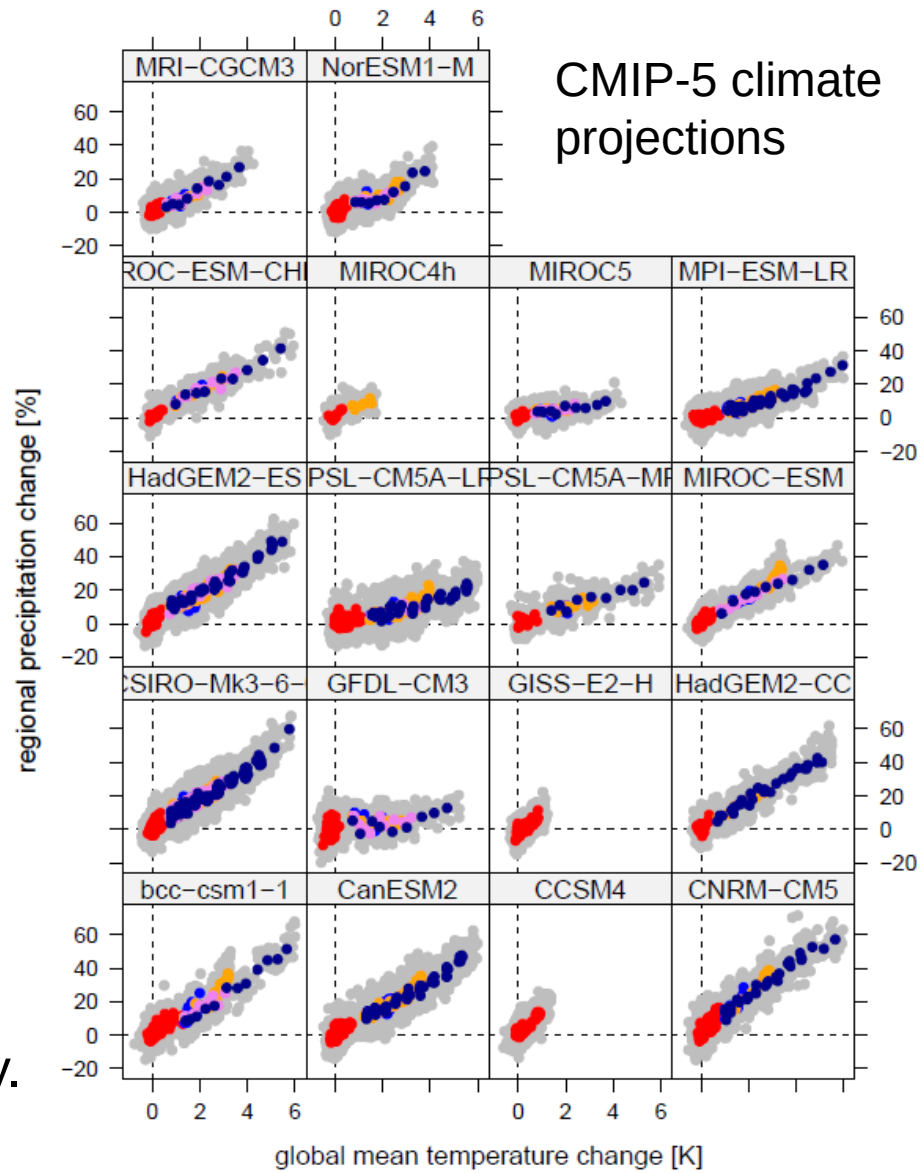
Antarctic surface mass balance



Consistent with ice-core data

~5% increase
per degree of warming

Melting
For high scenarios melting will increase, but models shows no negative SMB within the next century.

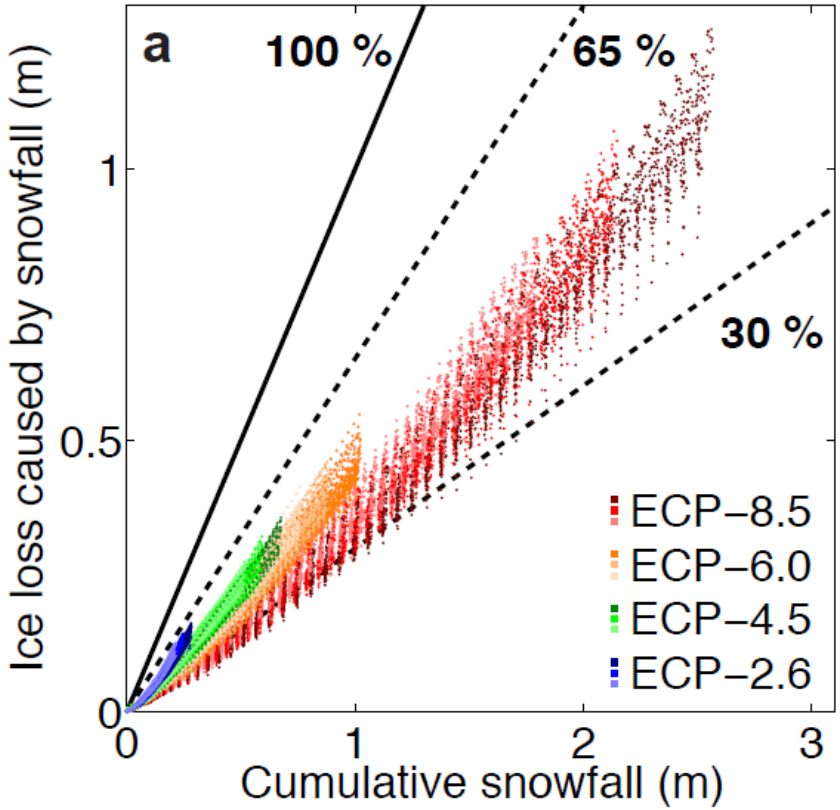


CMIP-5 climate projections

Frieler, Levermann, Clark,
van de Broeke, Winkelmann, in prep.

Upper limit estimate: < 0.0m

Snowfall induces ice-discharge



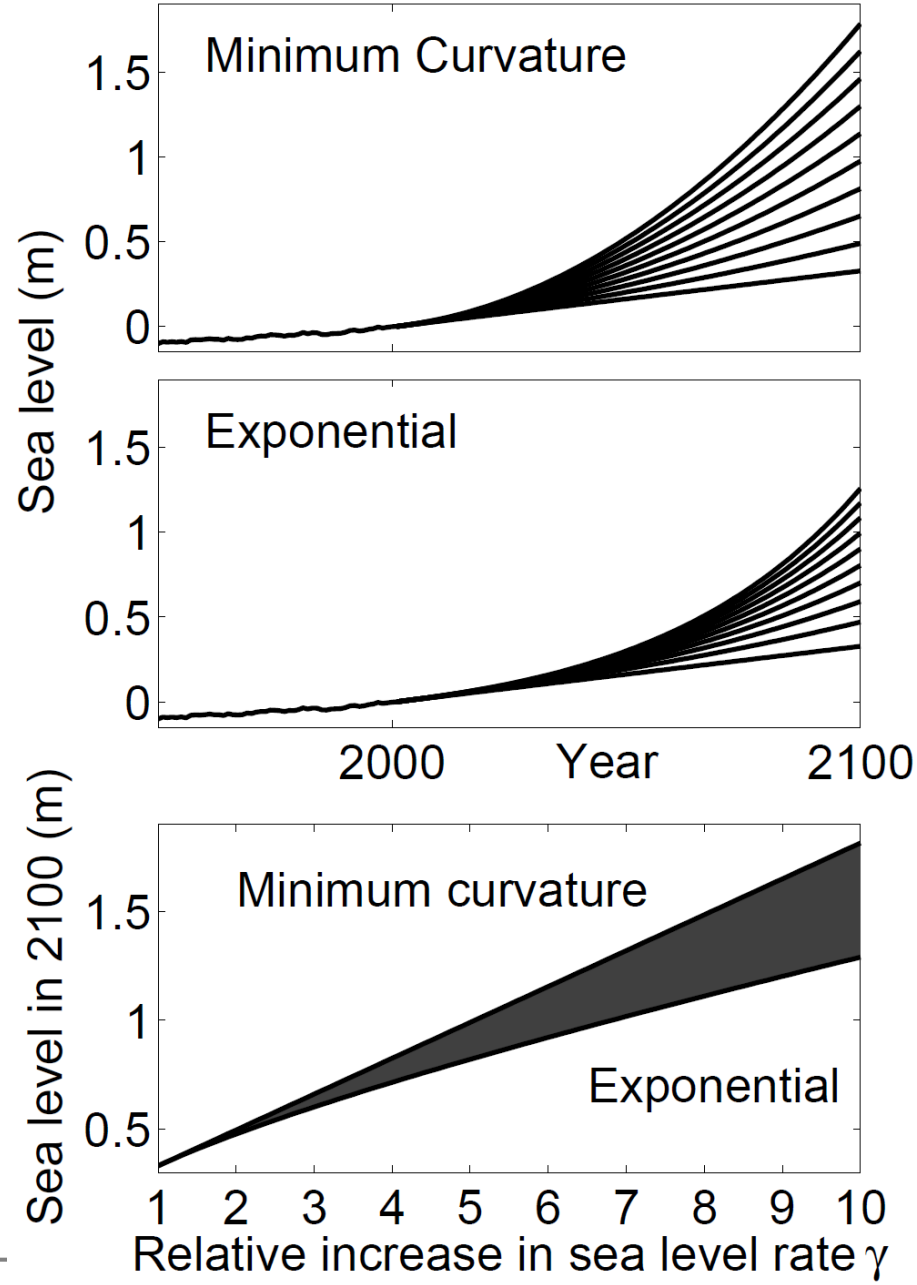
30 - 65 % of additional snowfall is discharged by enhanced driving stress.

Winkelmann, Levermann, Martin, Frieler, Nature (2012).

Upper limit estimate: < 0.0m

A bird´s view

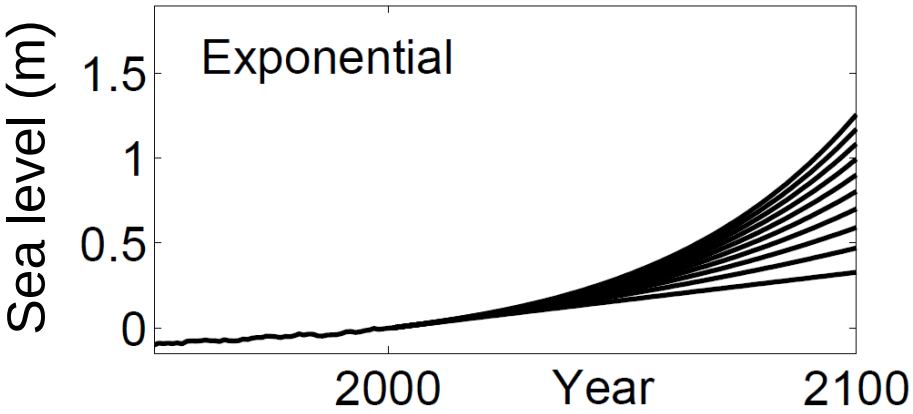
on the upper limit using maximum sea-level rates



Levermann/Vaughan, in the thinking.

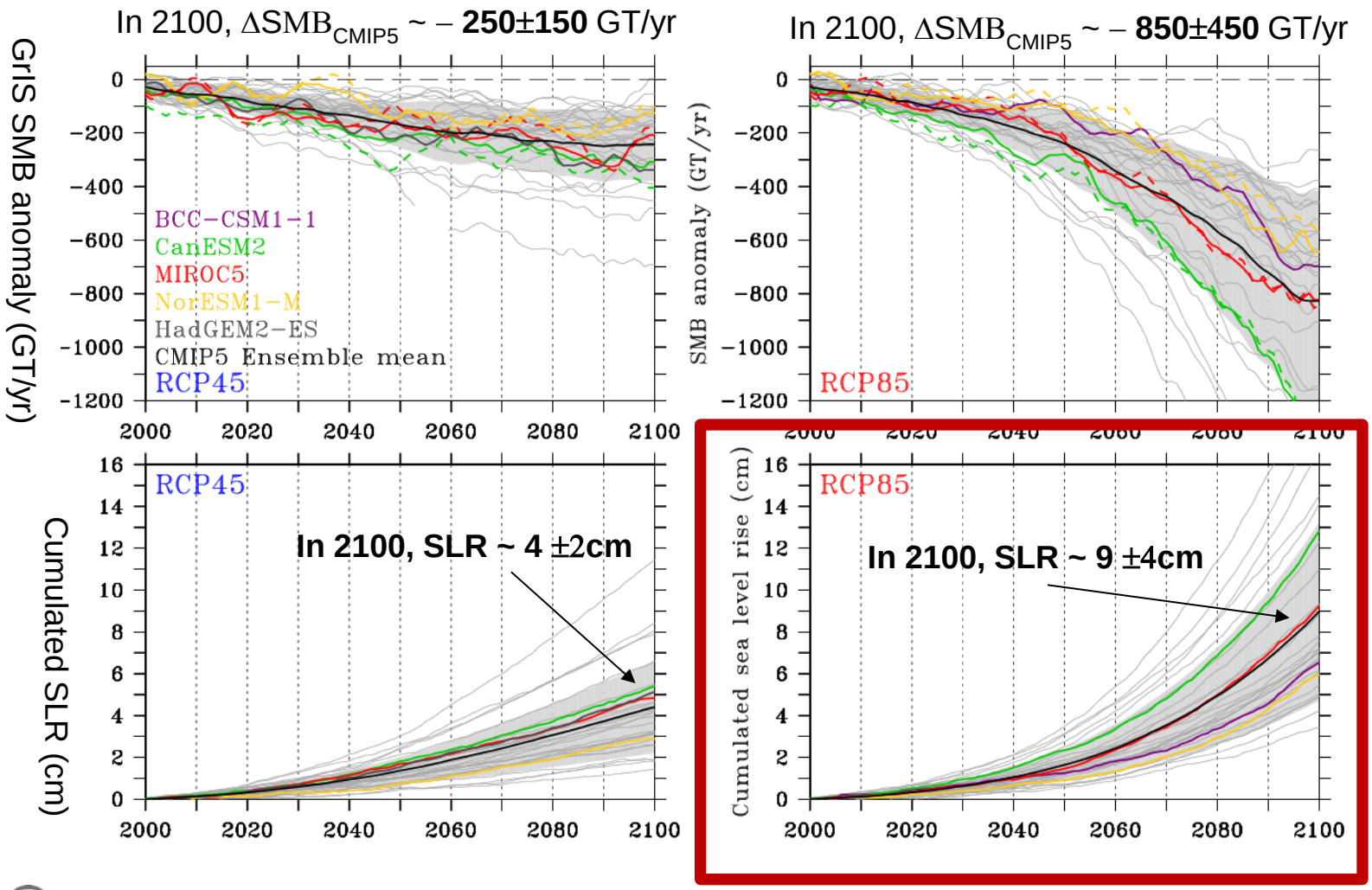
A bird´s view

on the upper limit using maximum sea-level rates



Levermann/Vaughan, in the thinking.

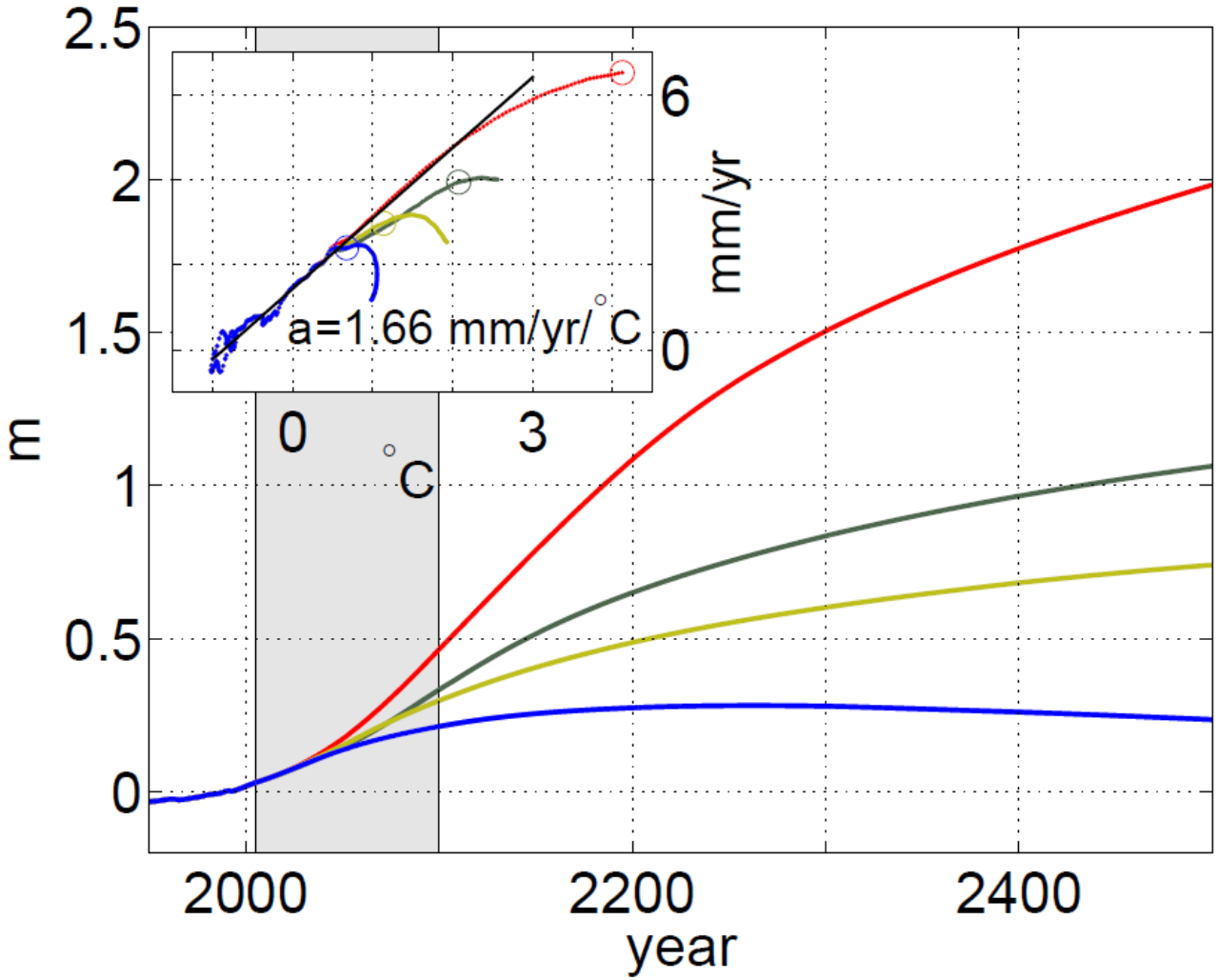
Greenland surface mass balance from CMIP-5



Fettweis et al. TC (2013).

Upper limit estimate: < 0.2m

Thermal expansion of the ocean



Schewe, Levermann, Meinshausen, ESD (2012).

Thermal expansion

CMIP-5: RCP-8.5 until 2100 compared to pre-industrial

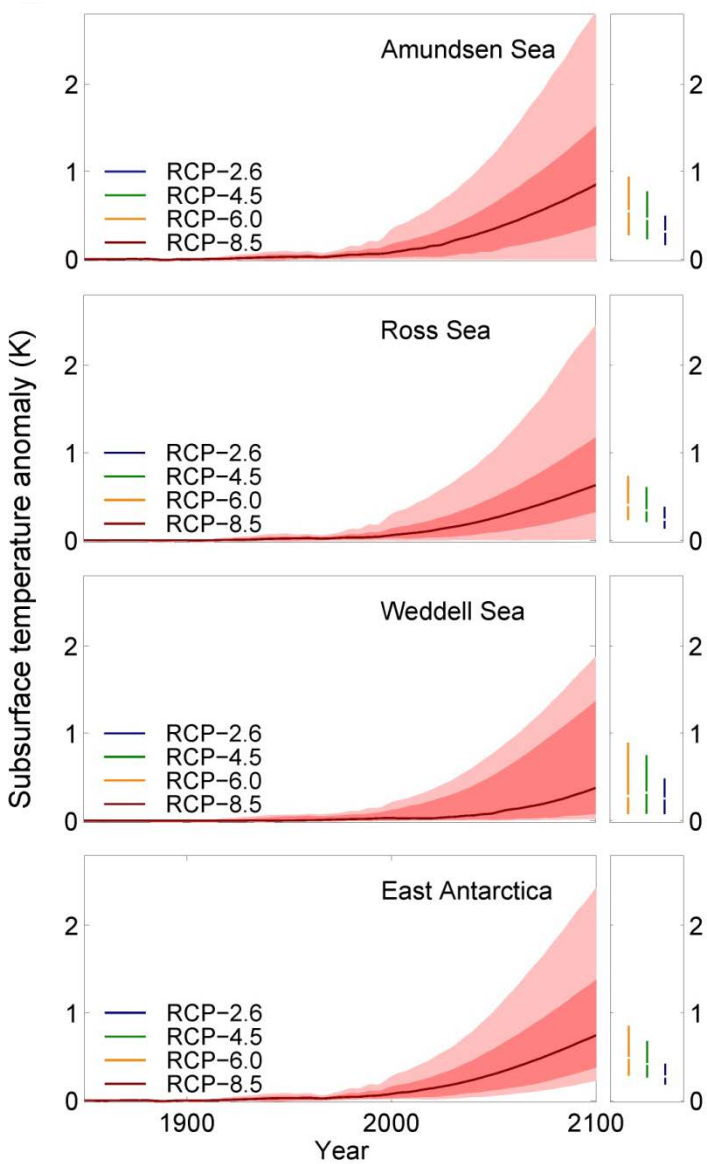
NorESM-1	0.35m	
MRI-CGCM3	0.27m	
MPI-ESM-MR	0.36m	
MIROC-ESM-CHEM	0.43m	
IPSL-CM5A-MR	0.39m	
INMCM4	0.32m	
HadGEM3-ES	0.28m	Show a sea level decrease in 20th century
HadGEM3-CC	0.28m	
CNRM-CM5	0.27m	
CanESM2	0.37m	

Upper limit estimate: < 0.4m

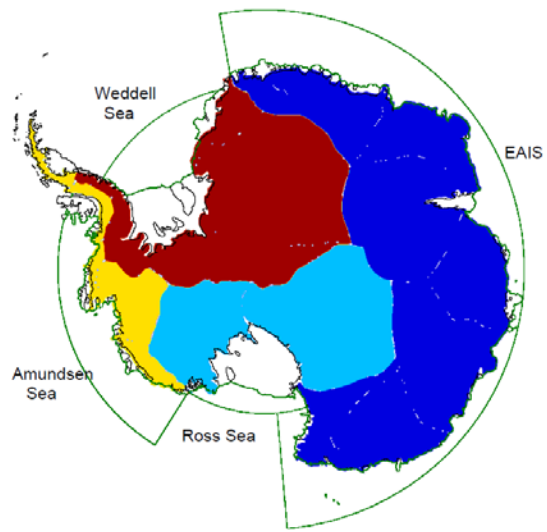
Ocean-ice Convolution

Ice response

Ocean temperature

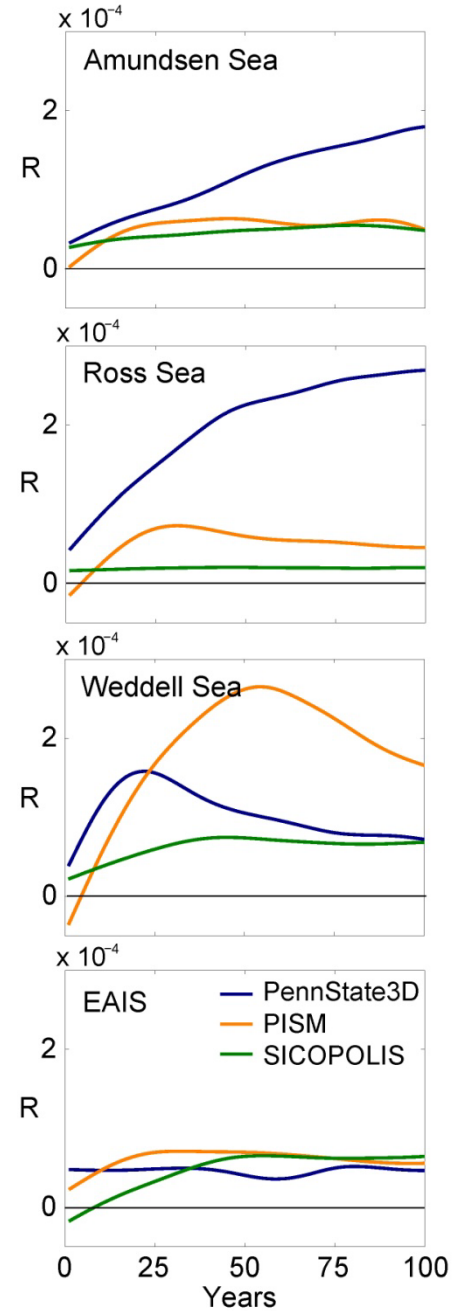


4 drainage basins

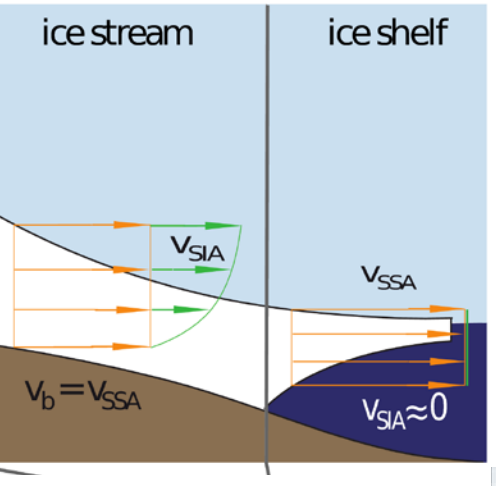


[7-16] m/a/K

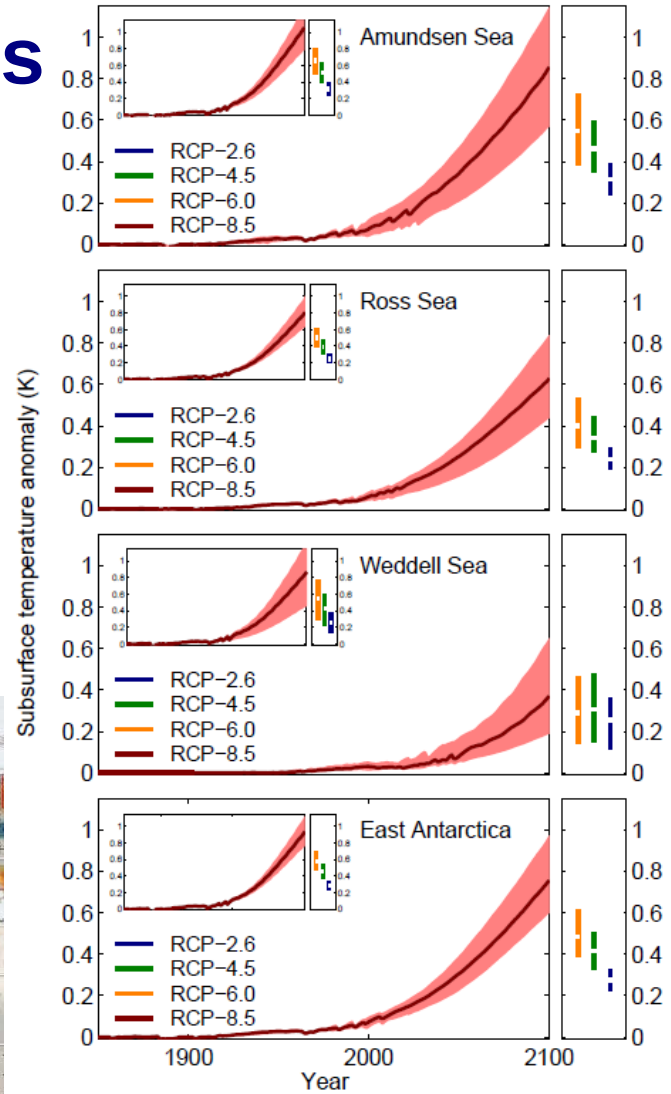
Observed basal-melt sensitivity

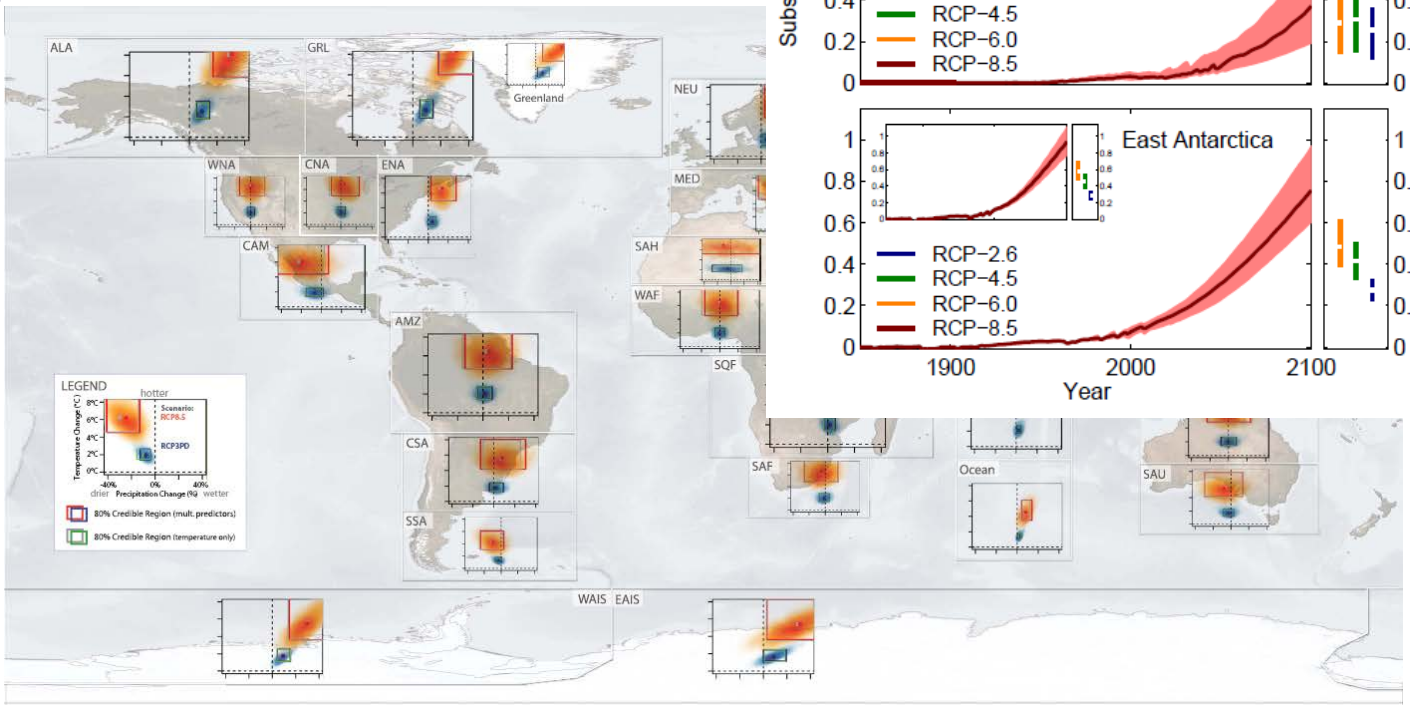


Assembling boundary conditions
or “including climate uncertainty”



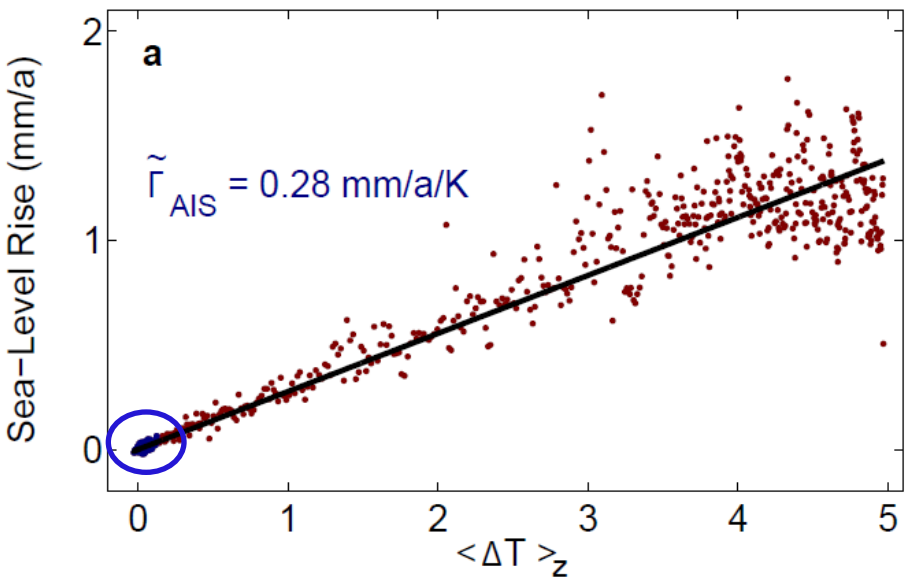
Scaling of oceanic sub-surface temperature change with global mean temperature change for 19 CMIP-5 models





Frieler, Meinshausen et al. J. Clim. (2012).

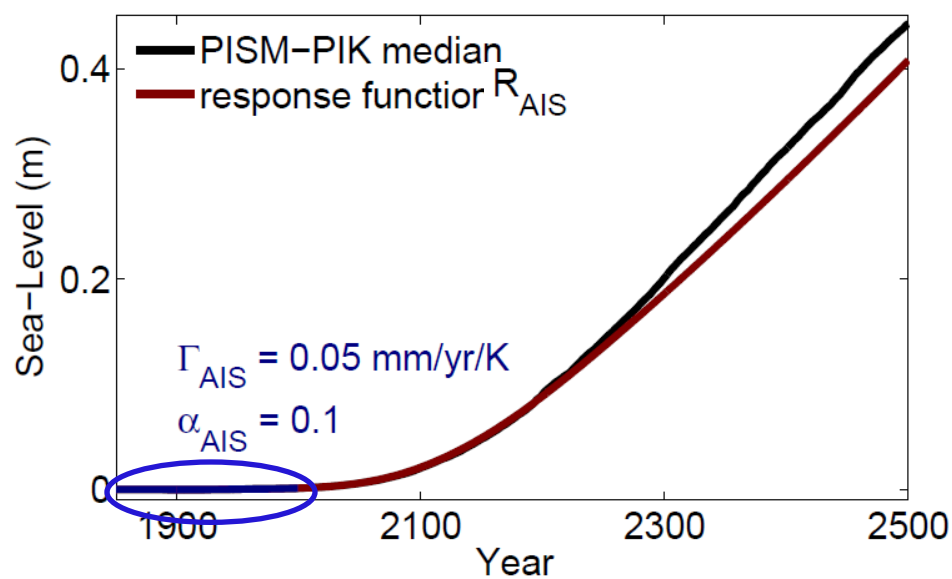
Linear response theory on ice



Assume that for some time period the convolution of forcing with some linear response function represents the response of your system.

$$S(t) = \int_0^t d\tau \, R(t-\tau)\, m(\tau)$$

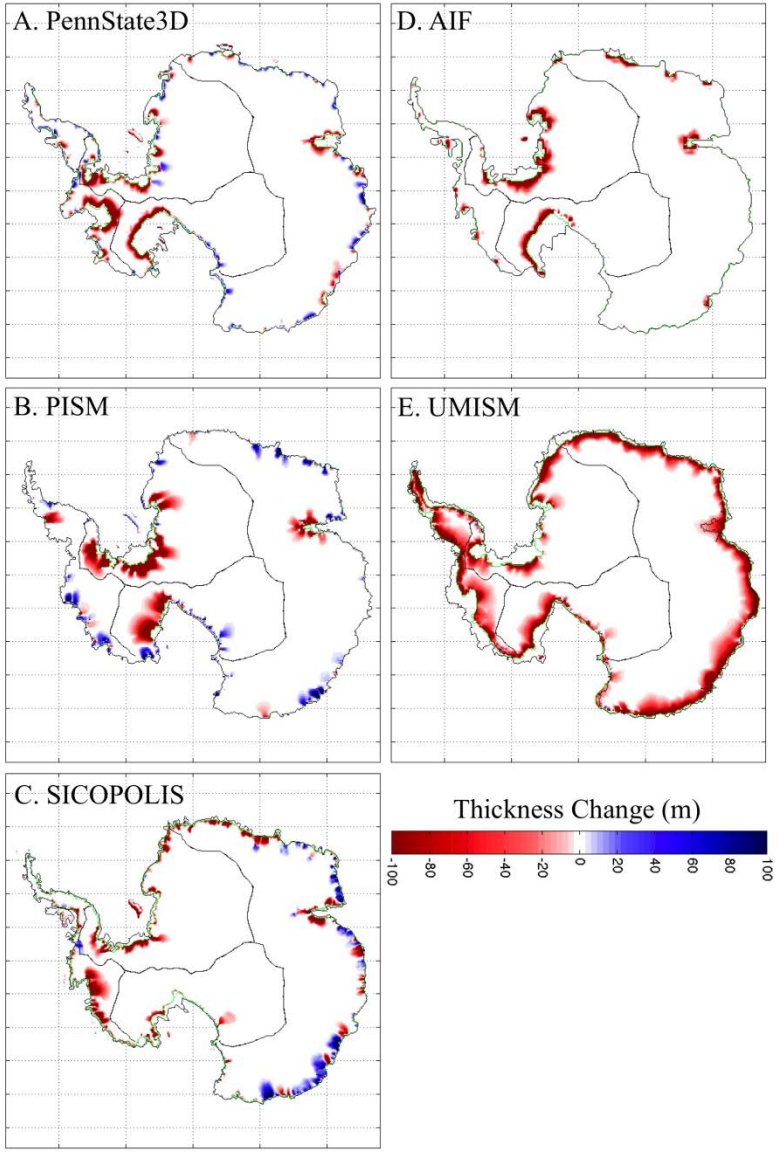
Learning period



Winkelmann & Levermann
Clim. Dyn. ***38*** *(2012), online.*

Accounting for ice-model uncertainty

linear response theory meets SeaRISE model intercomparison



Apply a step-function perturbation of 20 m/a additional basal melt.

The response of the model represents the time integral of the linear response function.

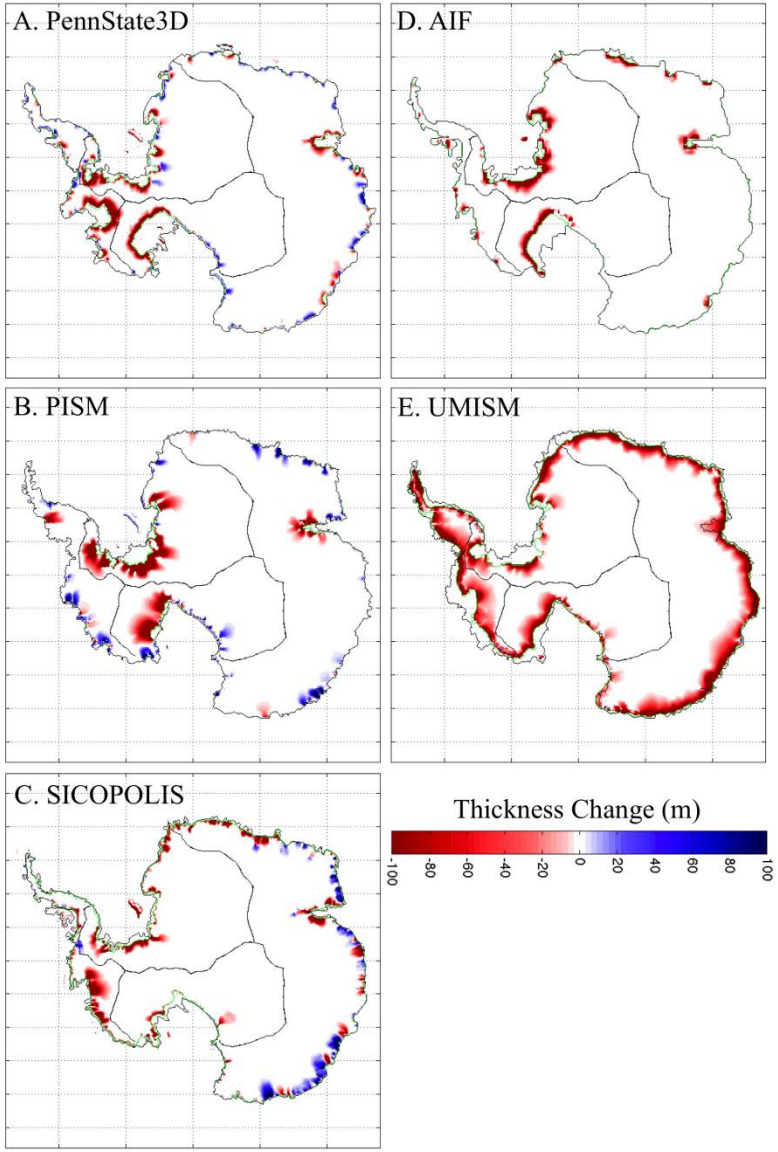
$$S_{\mathrm{sf}}(t) = \int_0^t \mathrm{d}\tau\, R(t-\tau)\,\Delta m_0 \cdot \Theta(\tau) = \Delta m_0 \cdot \int_0^t \mathrm{d}\tau\, R(\tau)$$

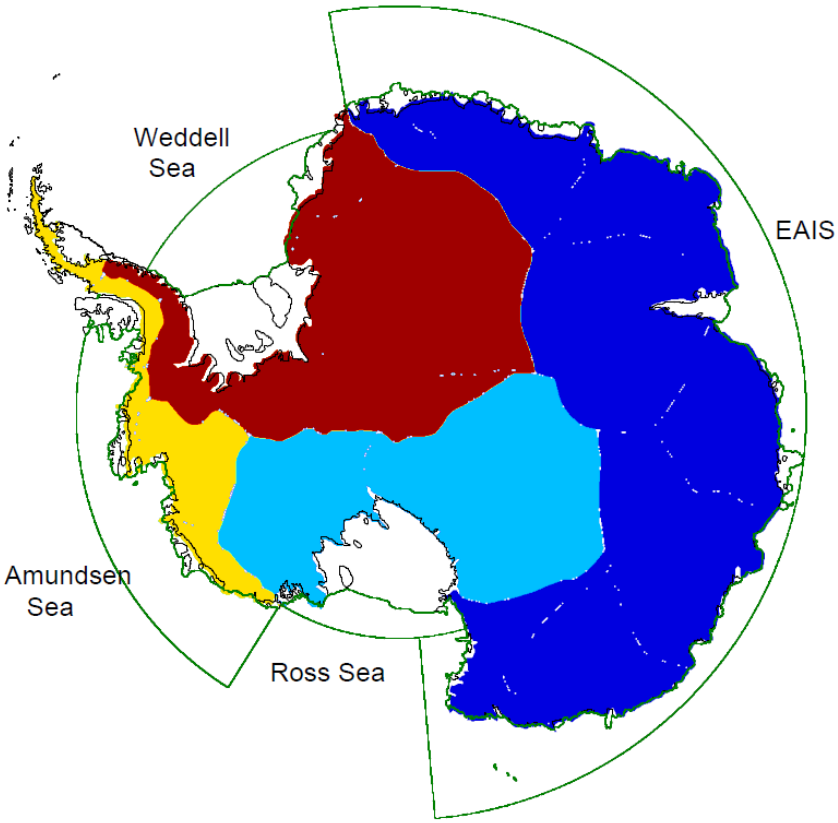
SeaRISE model intercomparison:

Bindschadler et al. (2012), JGR, submitted.
Nowicki et al. (2012), JGR, submitted.

Levermann et al., TCD ***6*** *(2012),* 3447
Winkelmann & Levermann Clim. Dyn. ***38*** *(2012), online.*

Account for different response of different basin

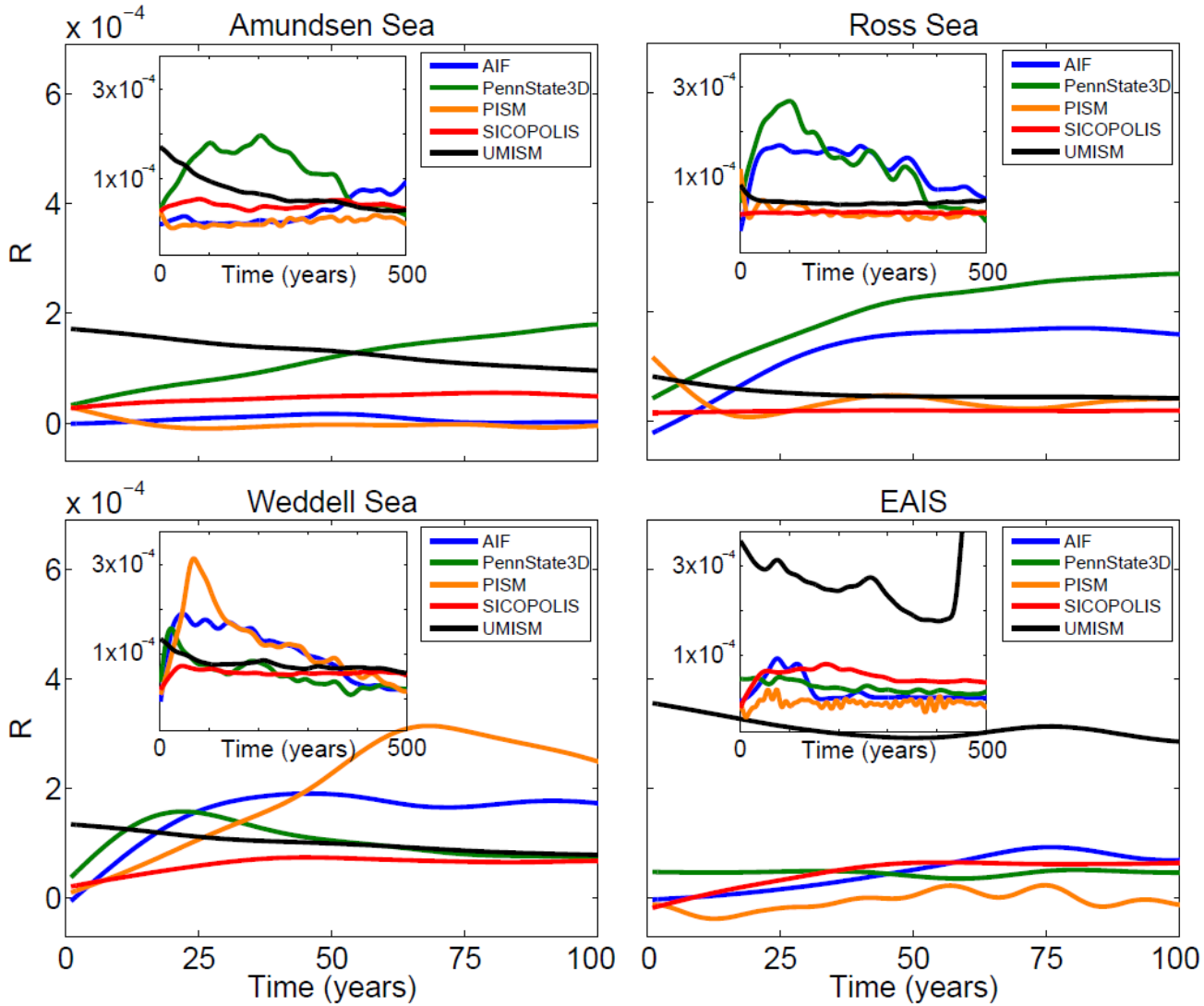




SeaRISE model intercomparison:

Bindschadler et al. (2012), JGR, submitted.
Nowicki et al. (2012), JGR, submitted.

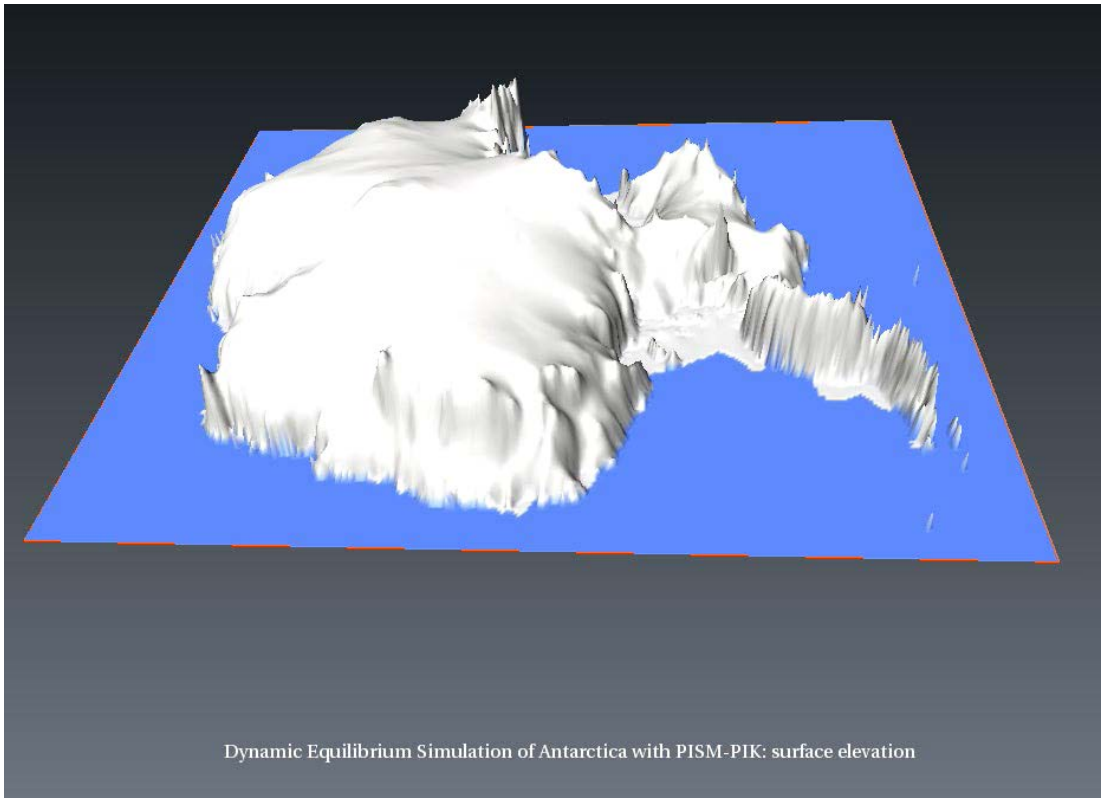
Response functions of Antarctica models



Levermann et al., TCD ***6*** *(2012),* 3447

The Potsdam Parallel Ice Sheet Model: PISM-PIK

- Shallow ice model for Antarctica based on PISM
- Freely evolving grounding line and calving front
- Fast streams from super-position of SIA & SSA



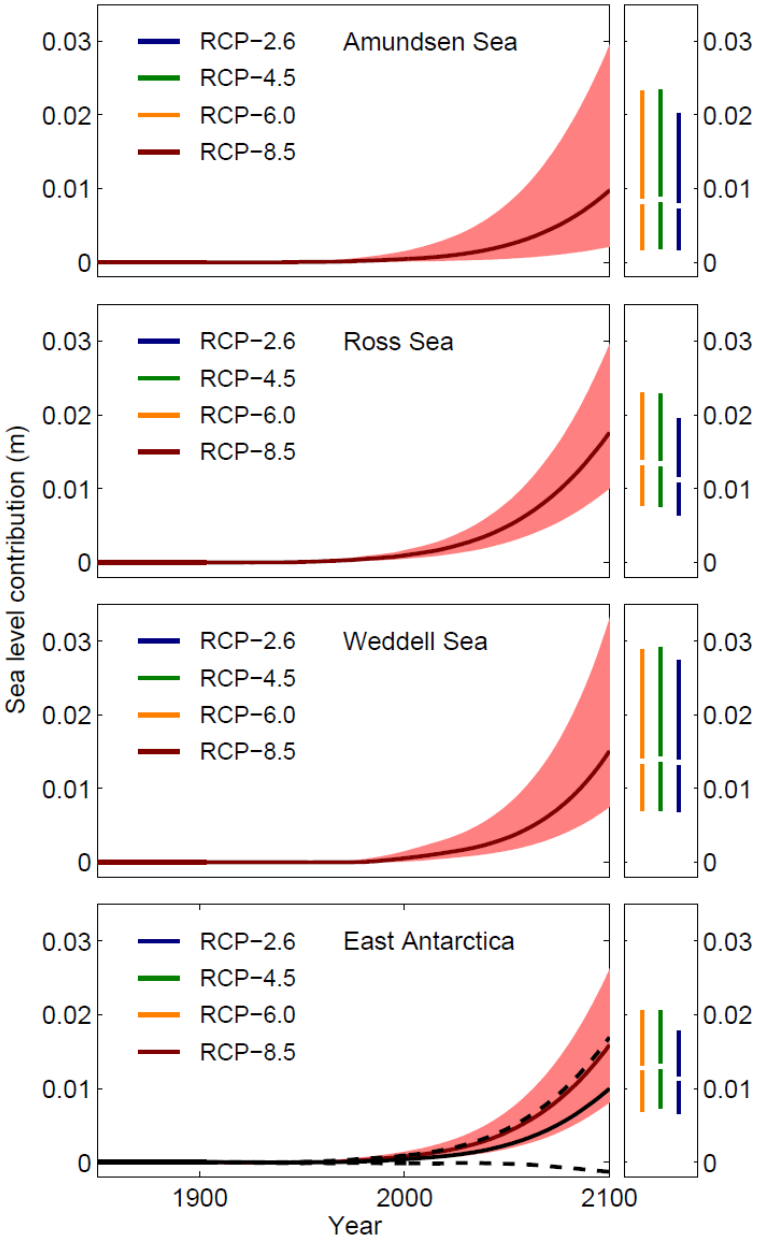
- Dynamic calving law based on eigenvalues of strain rate tensor (eigencalving)
- Ice-ocean frontal boundary condition at calving front.
- All this is now part of PISM starting from stable 0.4

P I K

*Winkelmann et al, The Cryosphere **5** (2011), 715-726 (Model description).*
*Martin et al, The Cryosphere **5** (2011), 727-740 (Model performance).*

Antarctic ice-discharge from ice-shelf melting

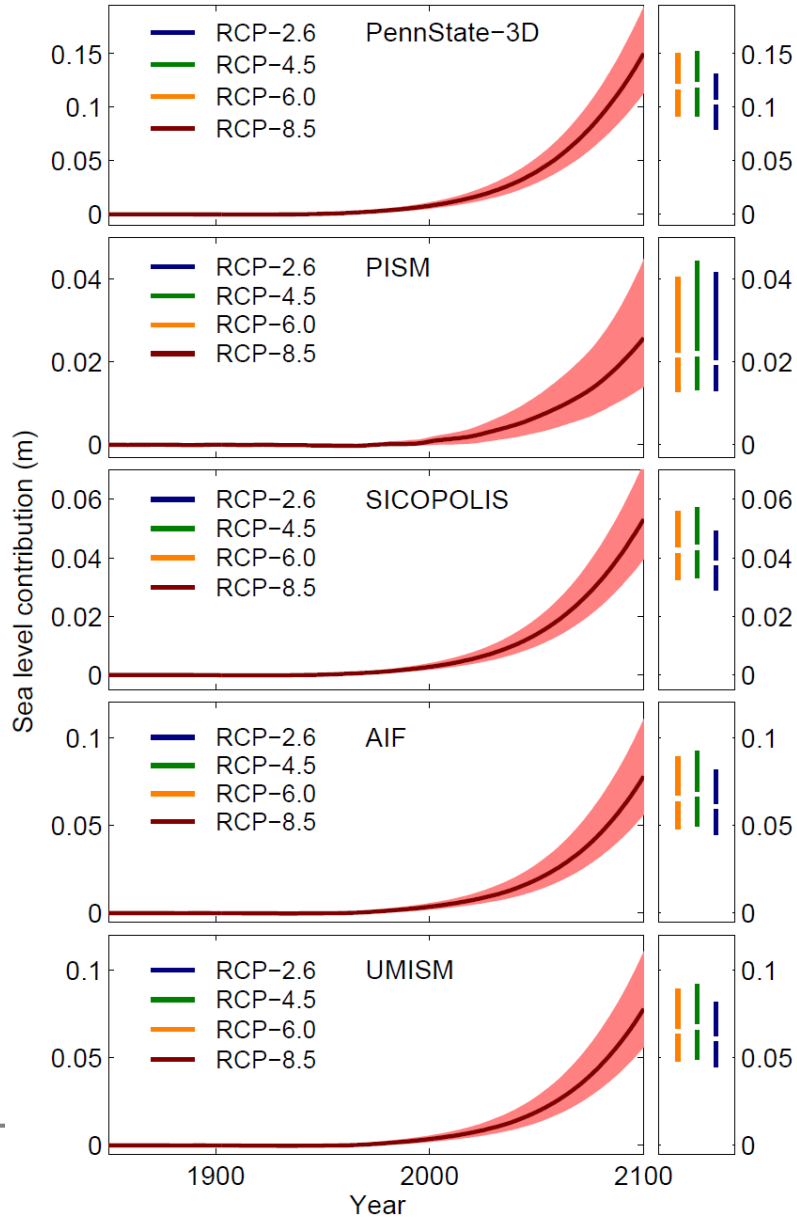
Different basins



Levermann et al.
*TCD **6** (2012)*, 3447

Antarctic ice-discharge from ice-shelf melting

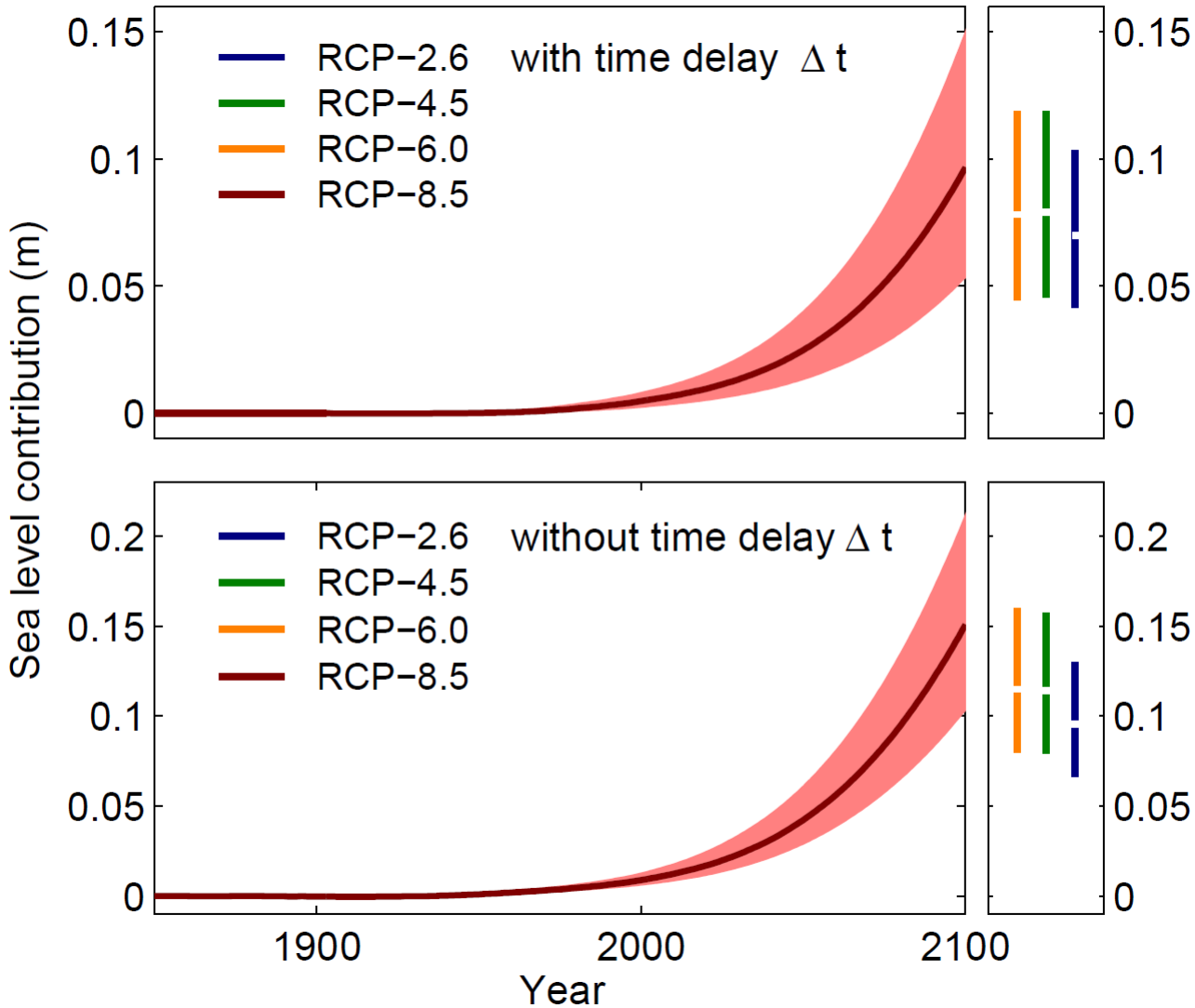
Different models



Levermann et al.
TCD ***6*** *(2012)*, 3447

Antarctic ice-discharge from ice-shelf melting

Without time delay

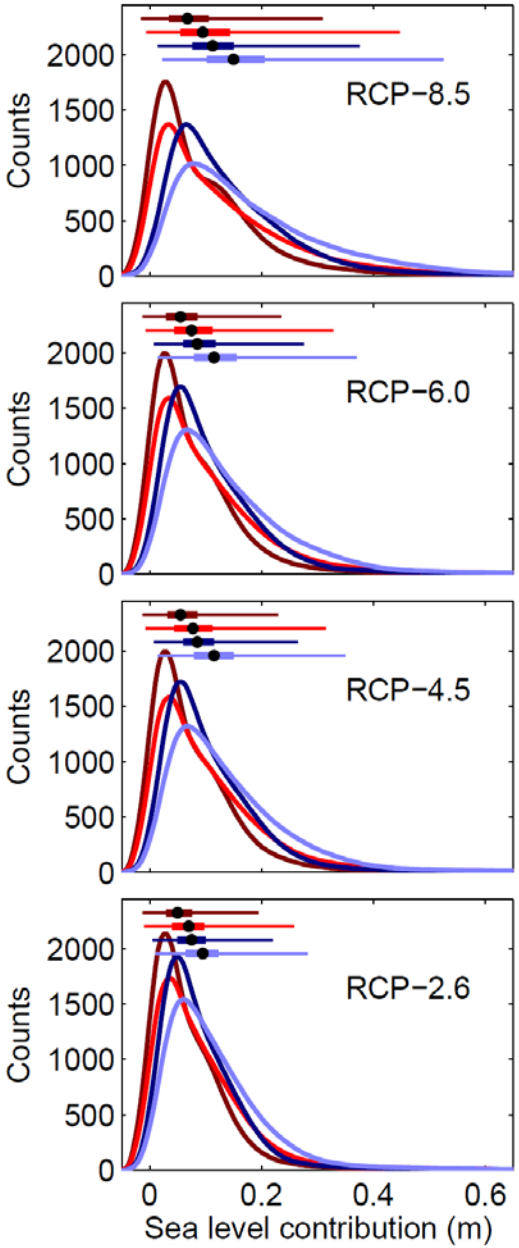


Levermann et al.
TCD ***6*** *(2012)*, 3447

Antarctic ice-discharge from ice-shelf melting

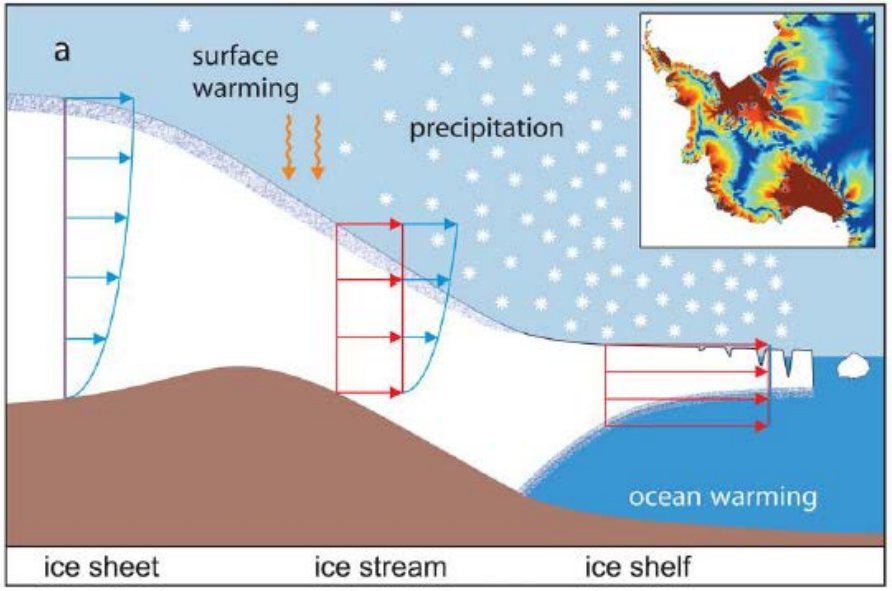
Probability distributions

Set-up	RCP	Median	33 %	66 %	5 %	95 %
All models with Δt	2.6	0.07	0.04	0.10	−0.01	0.26
	4.5	0.08	0.05	0.11	−0.01	0.32
	6.0	0.08	0.05	0.11	−0.01	0.33
	8.5	0.1	0.06	0.14	−0.01	0.45
Only models with explicit ice-shelf representation with Δt	2.6	0.05	0.03	0.08	−0.01	0.20
	4.5	0.06	0.03	0.09	−0.01	0.23
	6.0	0.06	0.03	0.09	−0.01	0.24
	8.5	0.07	0.04	0.11	−0.02	0.31
All models without Δt	2.6	0.10	0.07	0.12	0.01	0.28
	4.5	0.12	0.08	0.15	0.02	0.35
	6.0	0.12	0.08	0.16	0.02	0.37
	8.5	0.15	0.10	0.21	0.02	0.53
Only models with explicit ice-shelf representation without Δt	2.6	0.08	0.05	0.10	0.01	0.22
	4.5	0.09	0.06	0.12	0.01	0.27
	6.0	0.09	0.06	0.12	0.01	0.28
	8.5	0.11	0.08	0.15	0.02	0.38

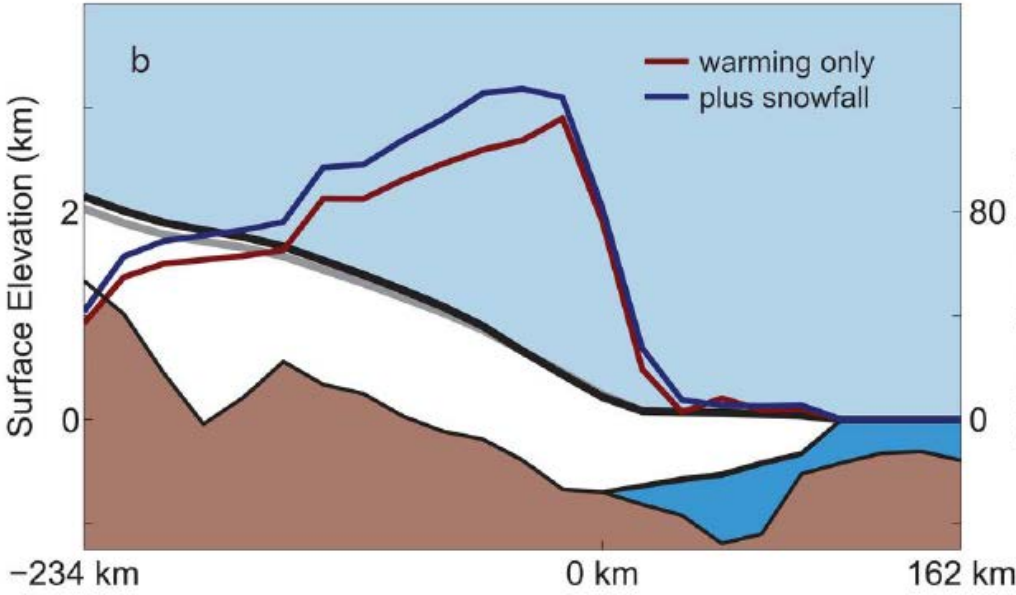


*Levermann et al. TCD **6** (2012), 3447*

Why does snowfall change ice discharge?



- Snow elevates grounded ice 10x more than floating ice.
- This increases the driving stress.

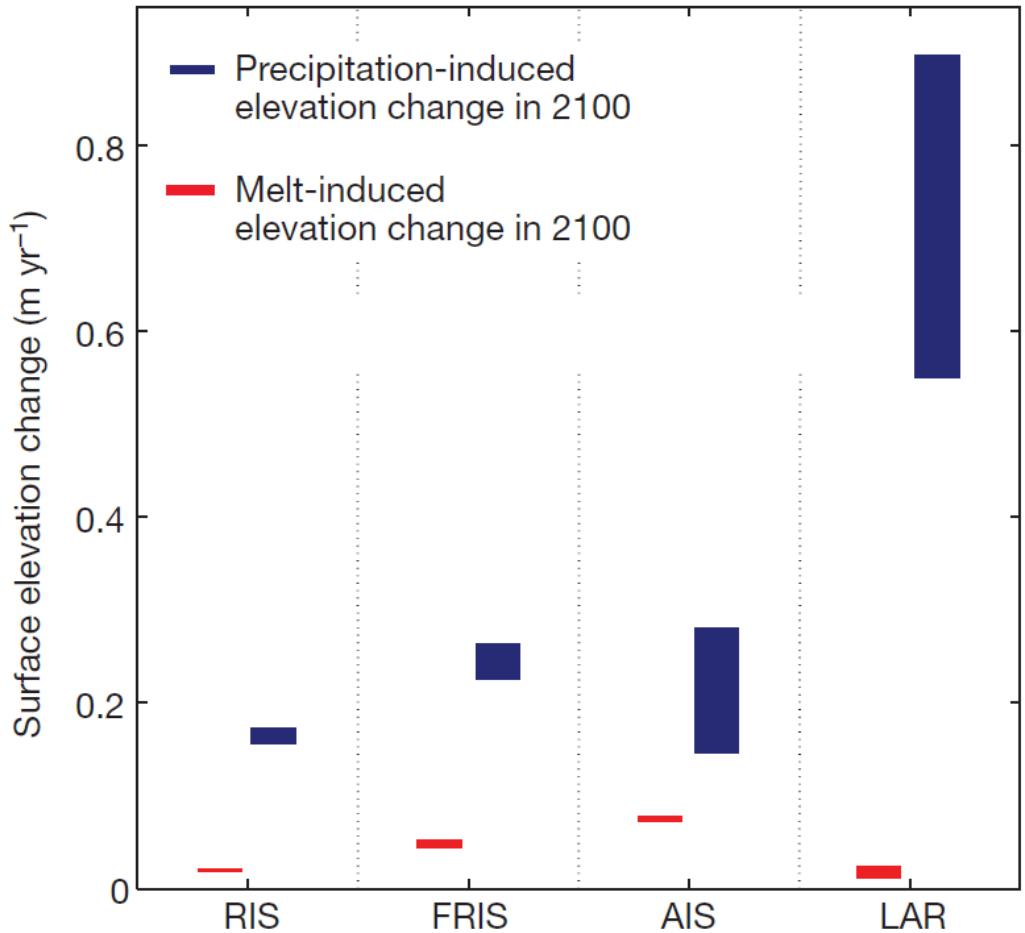


Comparison with basal ice-shelf melt

$$\Delta P_{ground} - (1 - \rho_i/\rho_w) \cdot \Delta P_{float} = (1 - \rho_i/\rho_w) \cdot \Delta B$$

Basal melt has to be **9x stronger** than local snow fall to give the same driving stress increase.

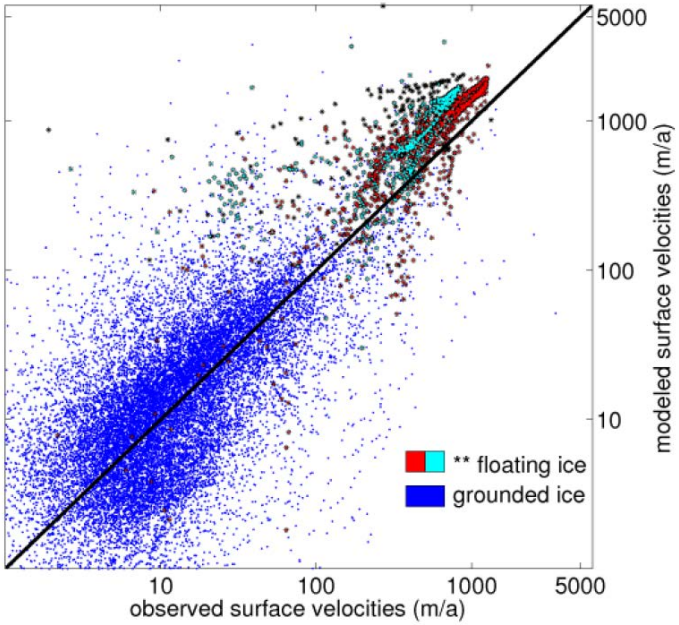
But generally $\Delta P > \frac{\Delta B}{9}$

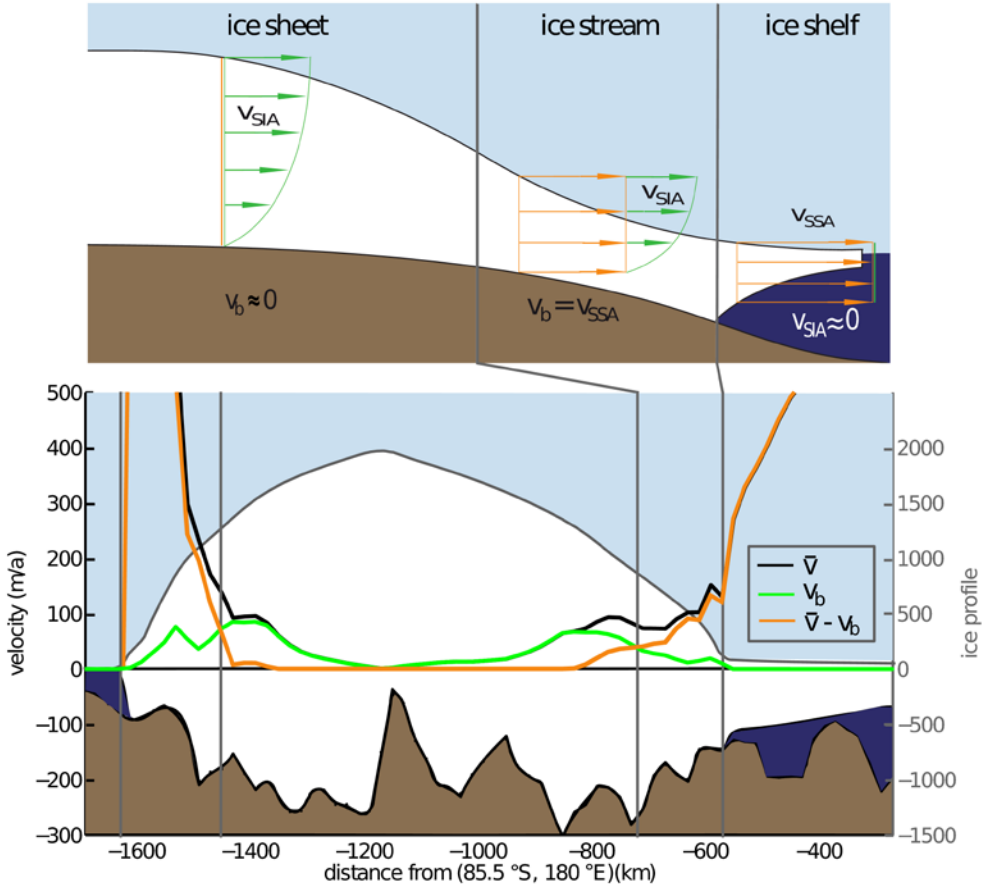


The Potsdam Parallel Ice Sheet Model (PISM-PIK)

- Transition zone representation by SIA-SSA superposition

  (Bueler & Brown, JGR, 2009)

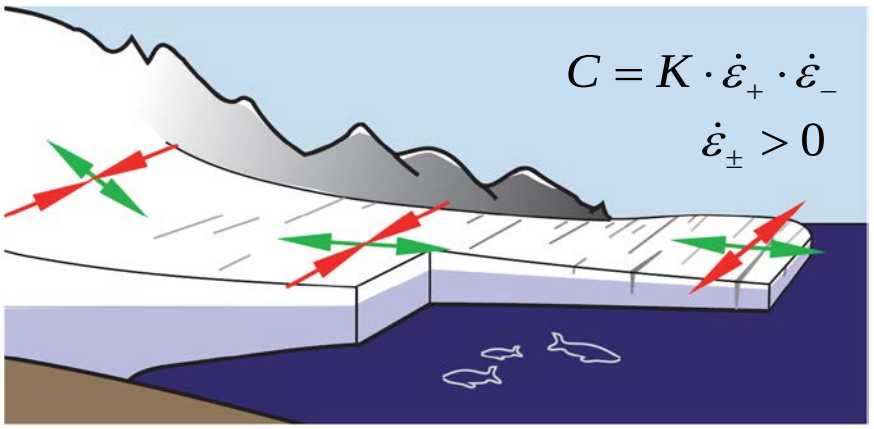


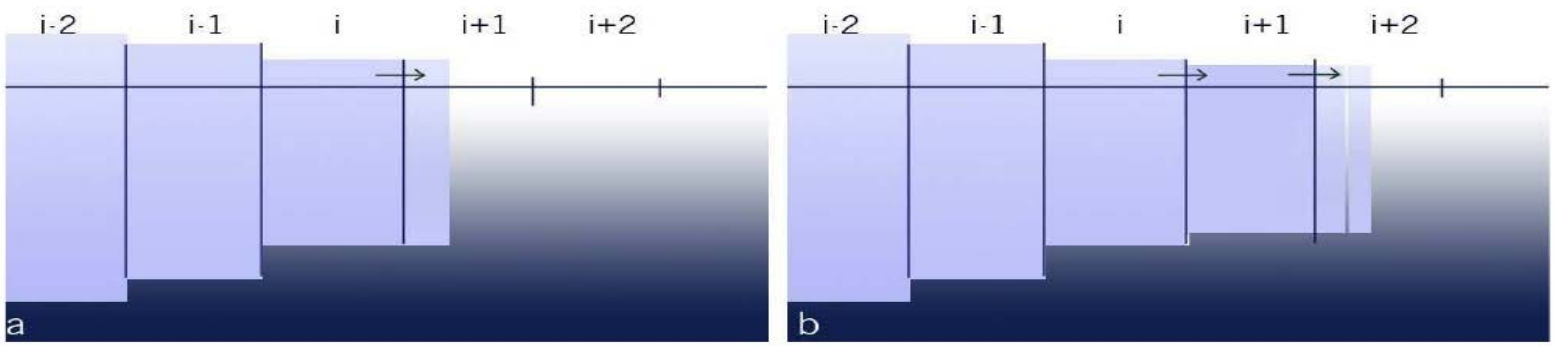


Winkelmann et al. The Cryosphere (2011), 715-726.
Martin et al. The Cryosphere (2011), 272-240.

The Potsdam Parallel Ice Sheet Model (PISM-PIK)

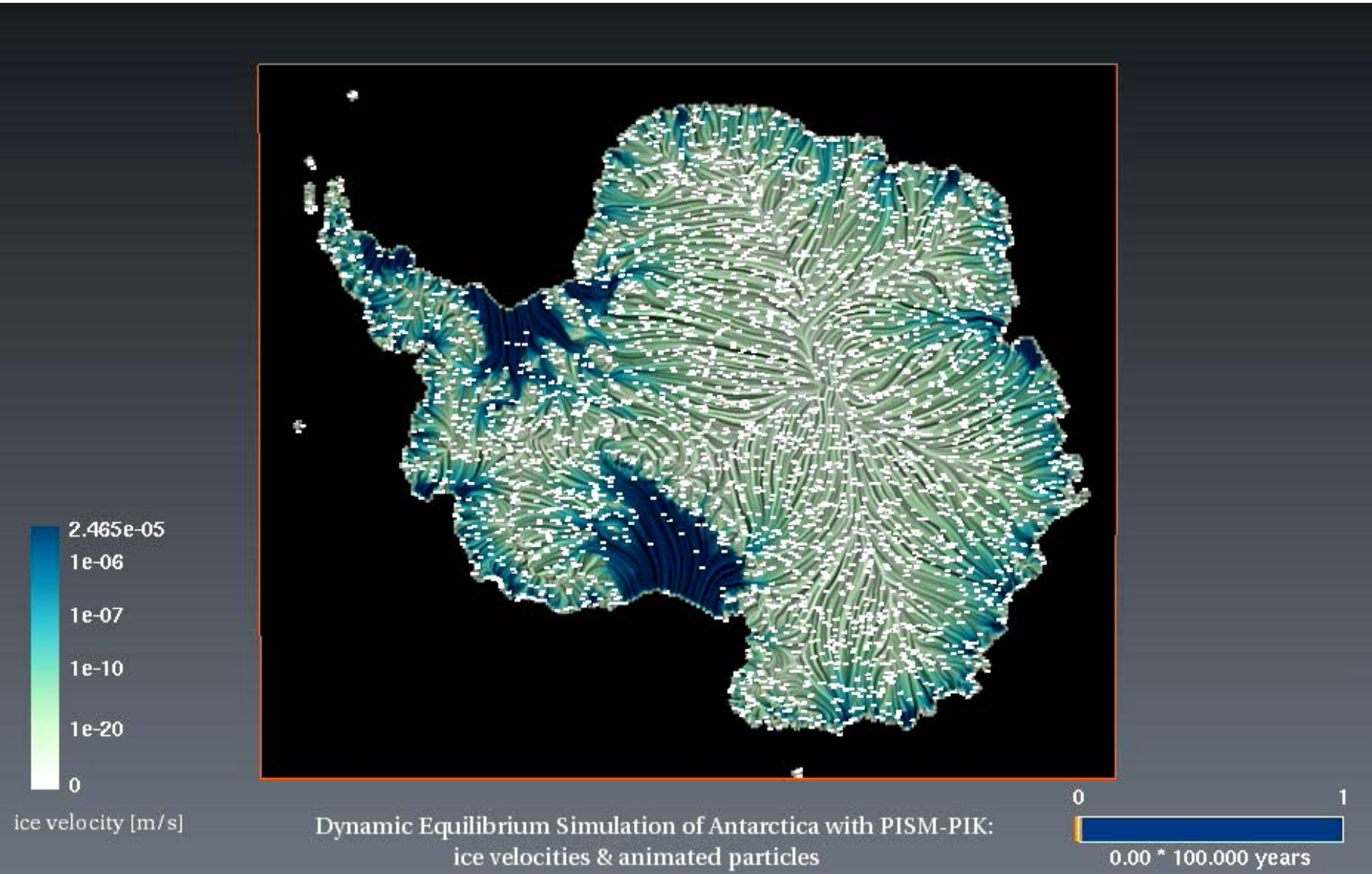
- Transition zone representation by SIA-SSA superposition
  (Bueler & Brown, JGR, 2009)
- Subgrid ice-front parametrization
  (Albrecht et al., TC, 2010)
- Eigencalving
  (Levermann et al., TC, 2012)





Winkelmann et al. The Cryosphere (2011), 715-726.
Martin et al. The Cryosphere (2011), 272-240.

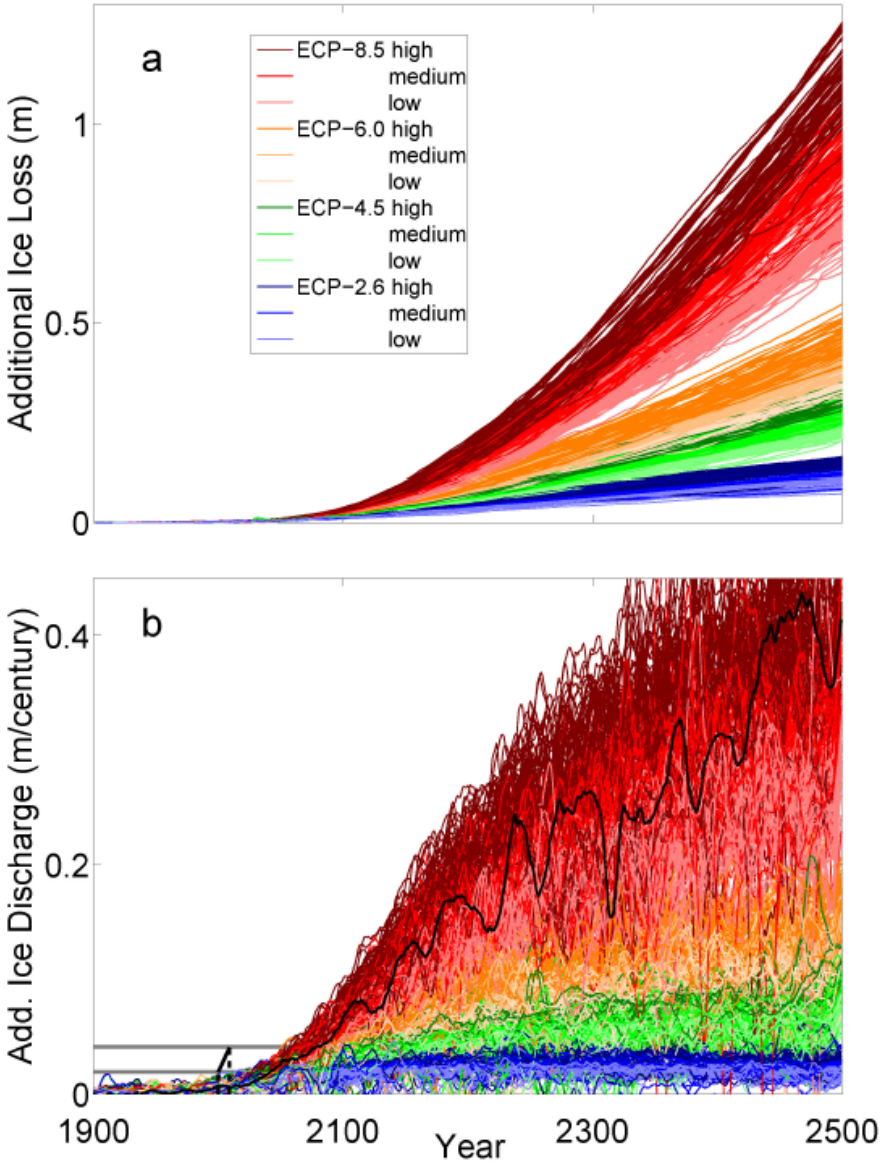
Antarctica's flow field according to PISM-PIK



RCP-Scenarios

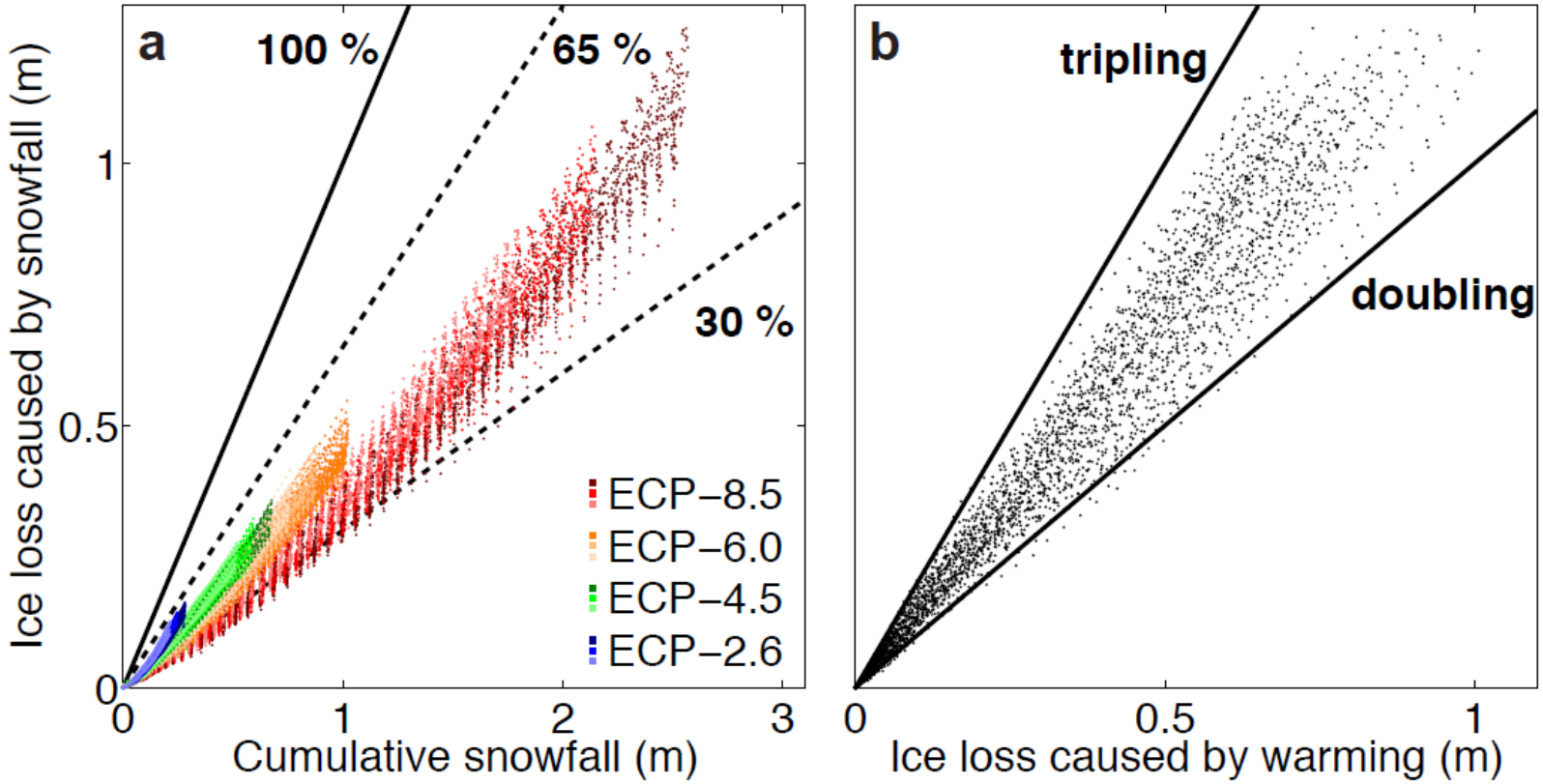
- Surface temperature increase downscaled from global mean temperature
  (Frieler et al. J Clim., 2012)
- *Basal melt from downscaled temperatures and box-model*
  (Olbers & Hellmer, Ocean Dynamics, 2010)
- *Precipitation parameterized as in*
  (Huybrechts & De Wolde, J Clim. 1999)

No net mass loss!
(Winkelmann et al., TCD. 2012)



Winkelmann, Levermann, Martin, Frieler, Nature (2012).

Snowfall induces ice-discharge



30 - 65 % of additional snowfall is discharged by enhanced driving stress.

Winkelmann, Levermann, Martin, Frieler, Nature (2012).

POTSDAM INSTITUTE FOR CLIMATE IMPACT RESEARCH

Ricarda Winkelmann

Thank you!

Increased future ice discharge from Antarctica owing to higher snowfall

Katja Frieler

Ricarda Winkelmann, Anders Levermann,

Maria A. Martin, Katja Frieler

Maria A. Martin

Leibniz Gemeinschaft

Winkelmann, Levermann, Martin, Frieler, Nature (2012).