Ice sheet modelling using the Ice Sheet and Sea Level System Model ISSM

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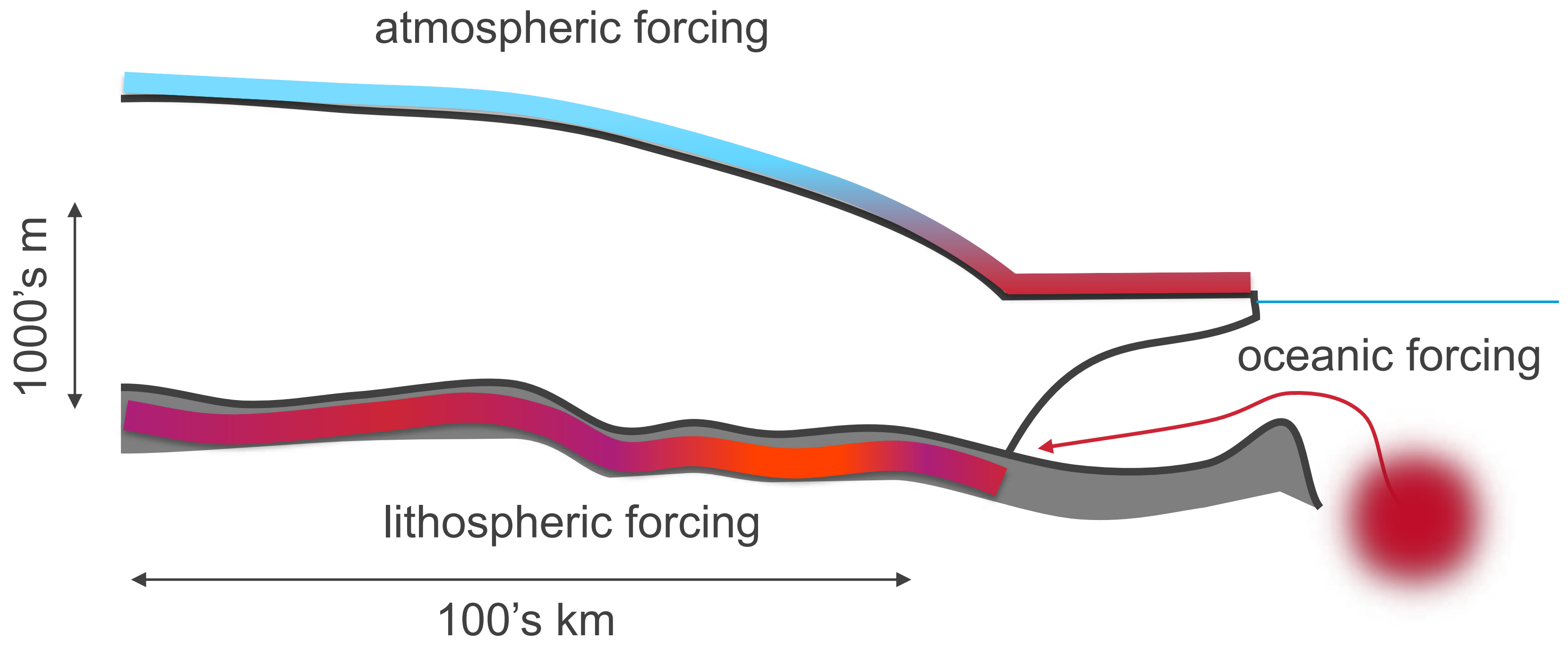
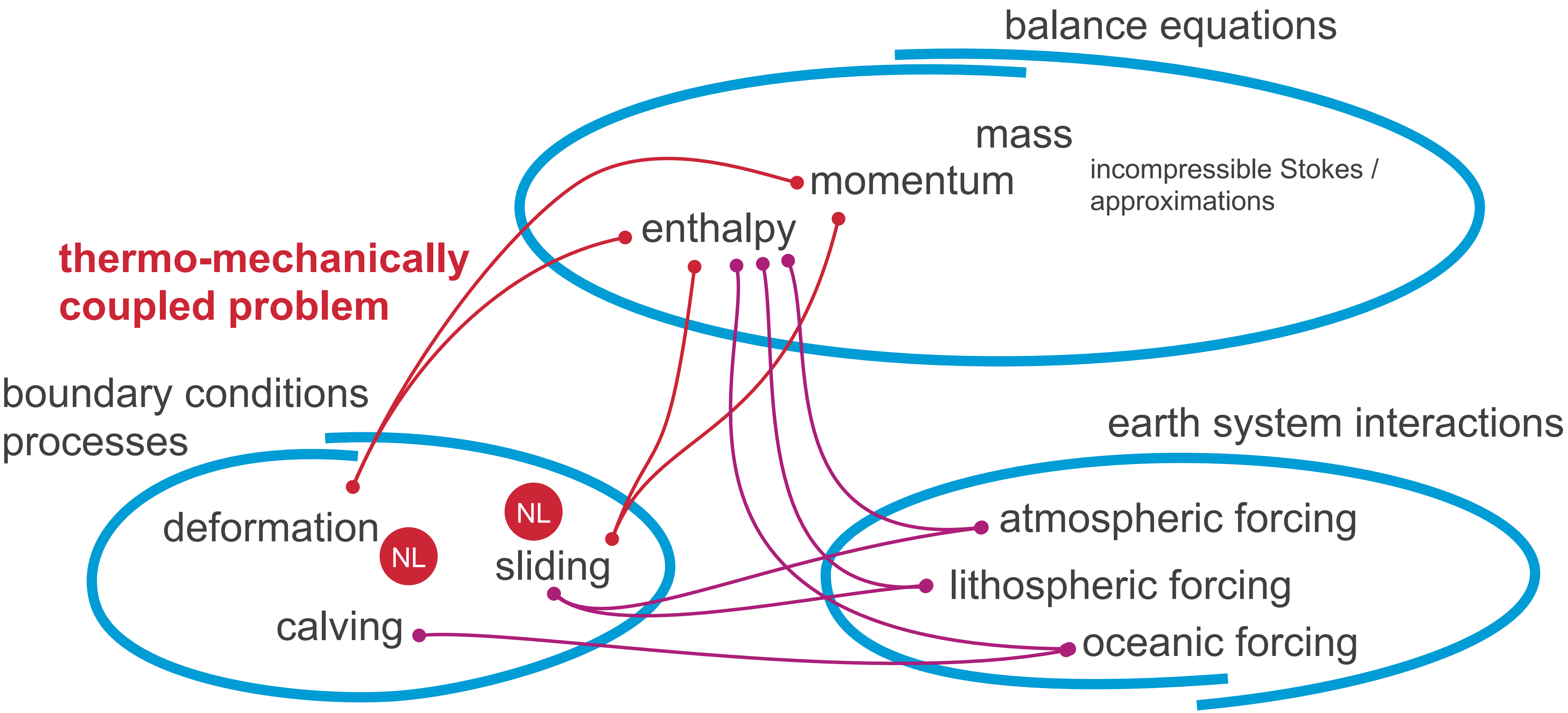
The system

gravity driven lubricated flow

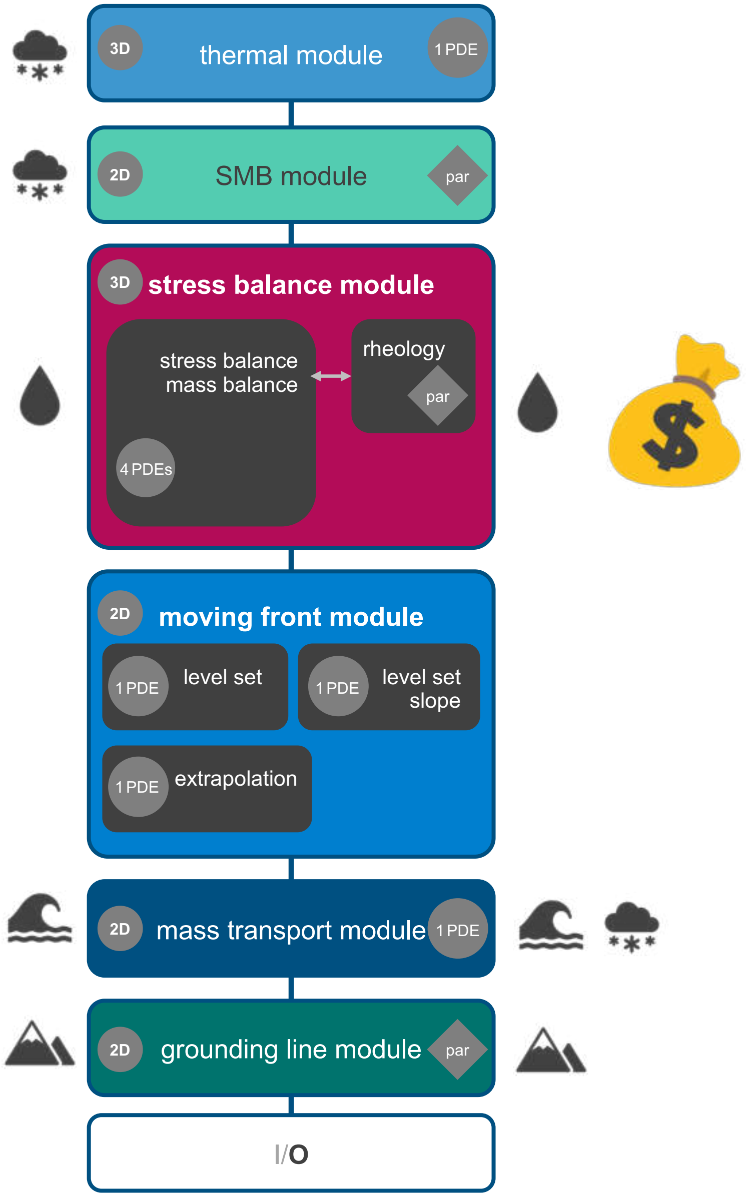


thermo-mechanically coupled problem

The system

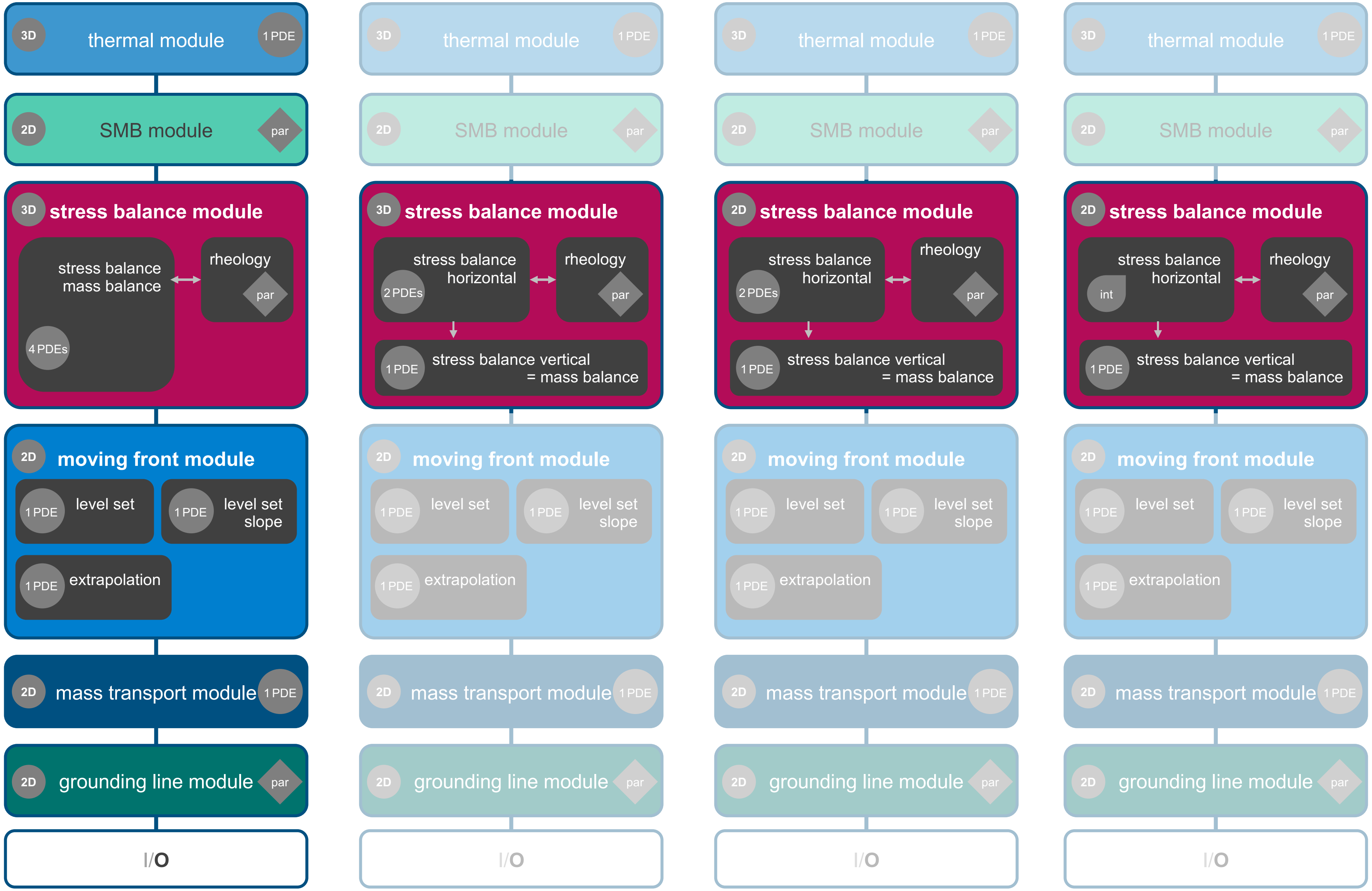

balance equations
mass
momentum
incompressible Stokes /
approximations
enthalpy
thermo-mechanically
coupled problem
boundary conditions
processes
deformation
NL
NL
sliding
calving
earth system interactions
atmospheric forcing
lithospheric forcing
oceanic forcing

Architecture of ice sheet models



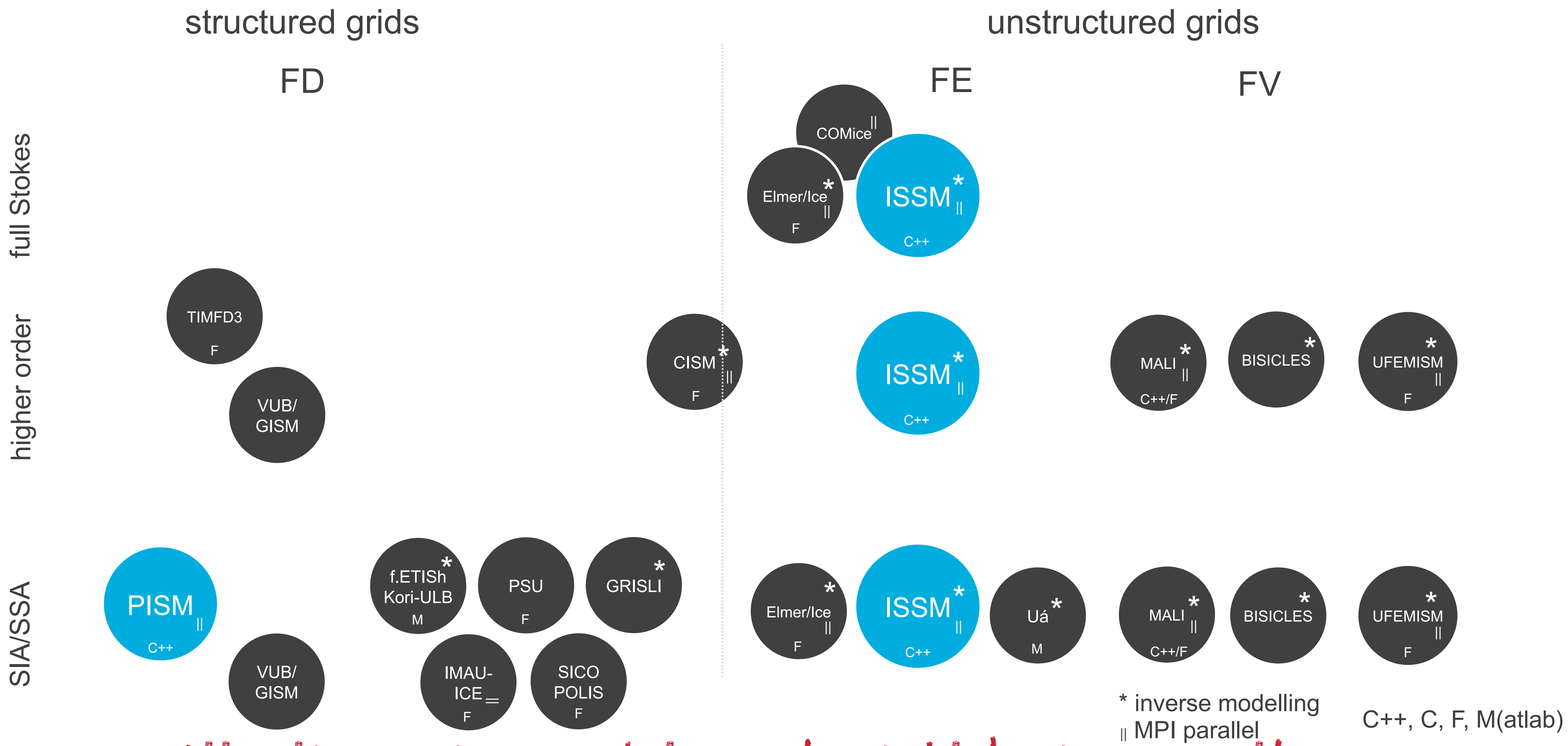
non-monolithic

Architecture of ice sheet models



Architecture of ice sheet models

Landscape



Attention – incomplete and might be incorrect!

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Architecture of ice sheet models

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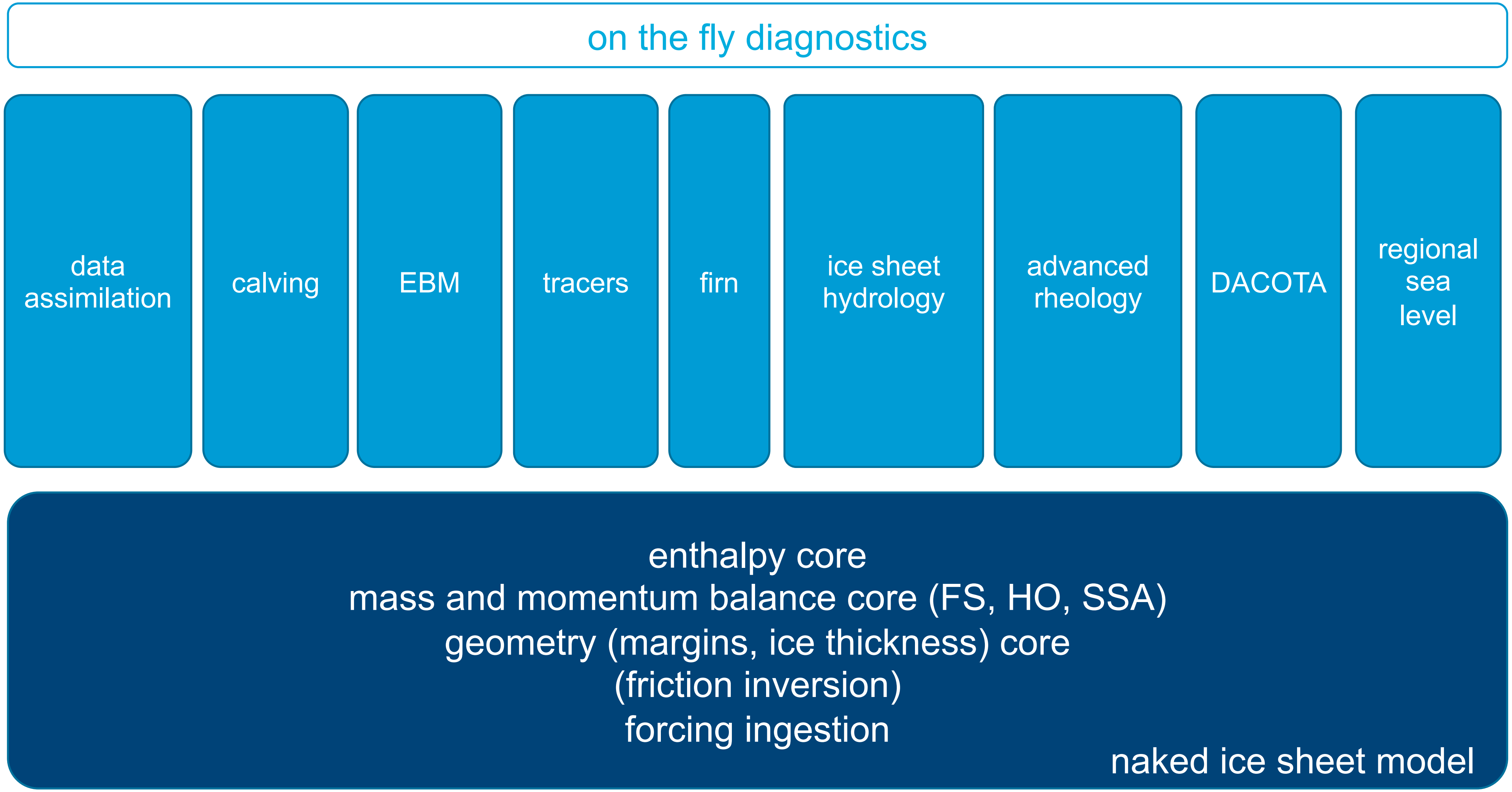

ISSM

on the fly diagnostics

- data assimilation
- calving
- EBM
- tracers
- firn
- ice sheet hydrology
- advanced rheology
- DACOTA
- regional sea level

enthalpy core
mass and momentum balance core (FS, HO, SSA)
geometry (margins, ice thickness) core
(friction inversion)
forcing ingestion

naked ice sheet model

ISSM - Greenland

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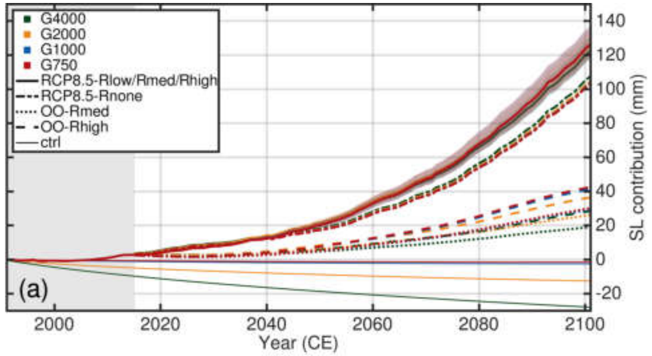
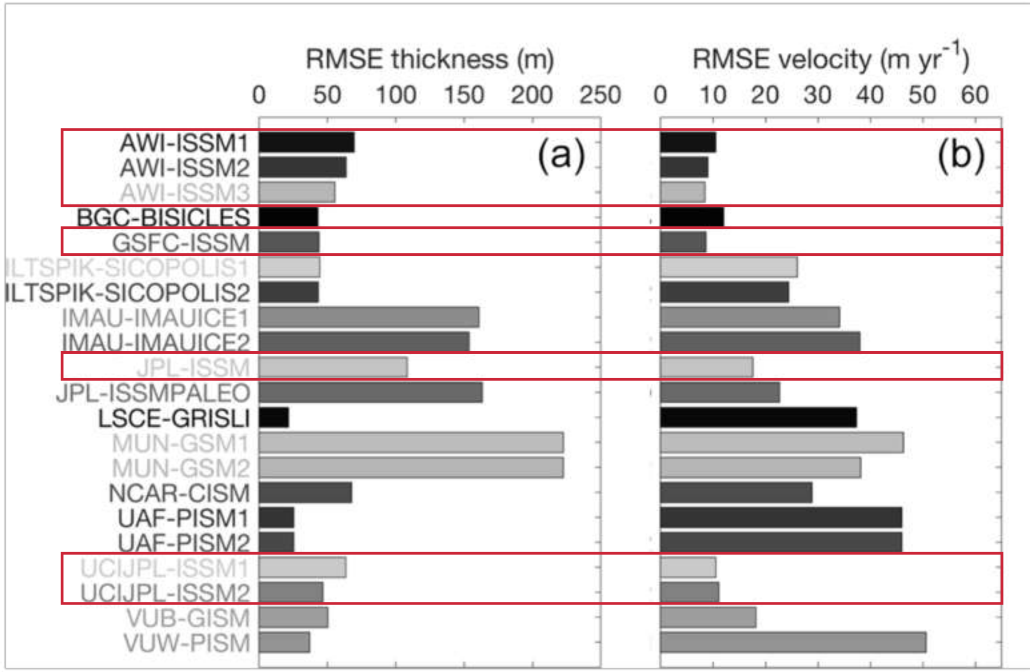
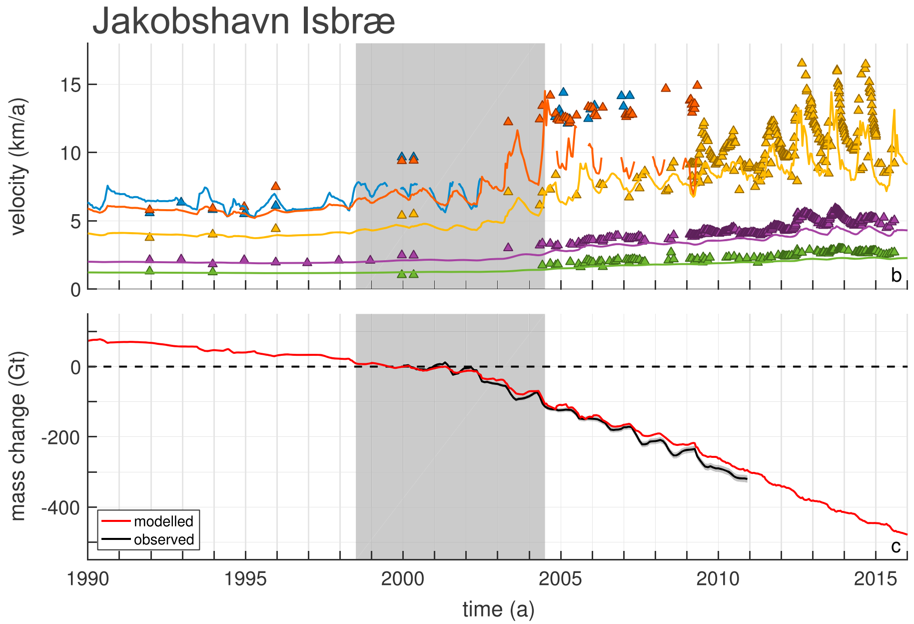


Rückamp et al. 2020



Goelzer et al. 2020



Bondzio et al., 2017

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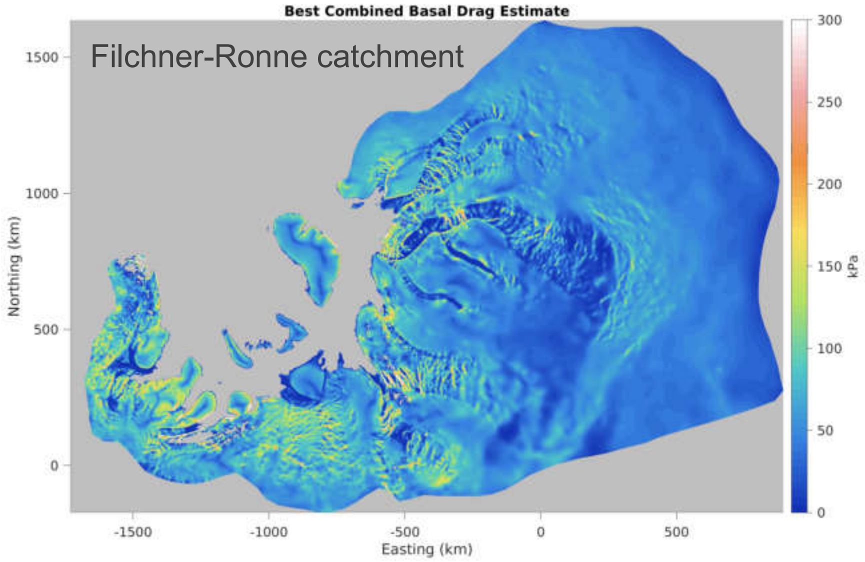
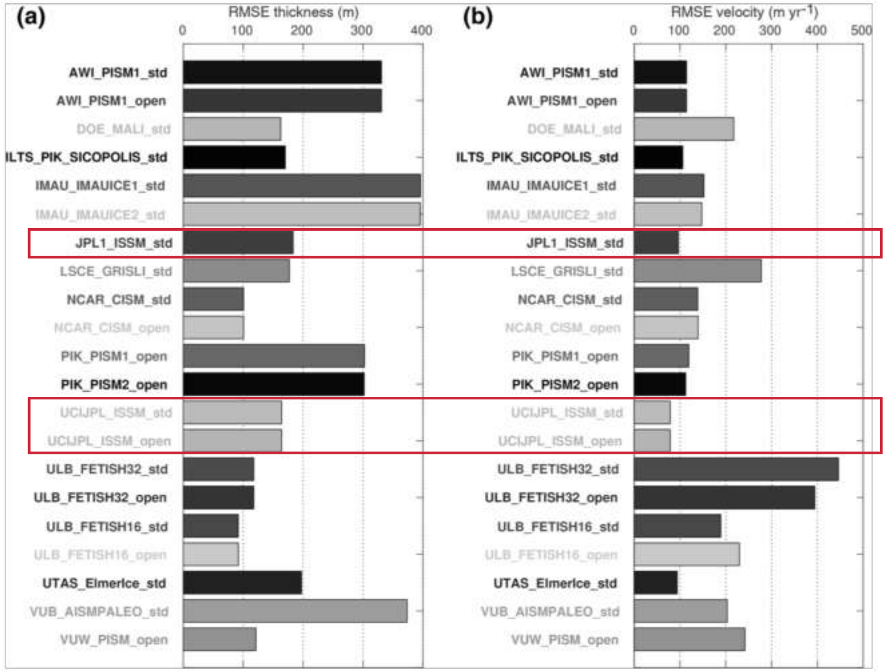
ISSM - Antarctica



Wolovick et al., in print

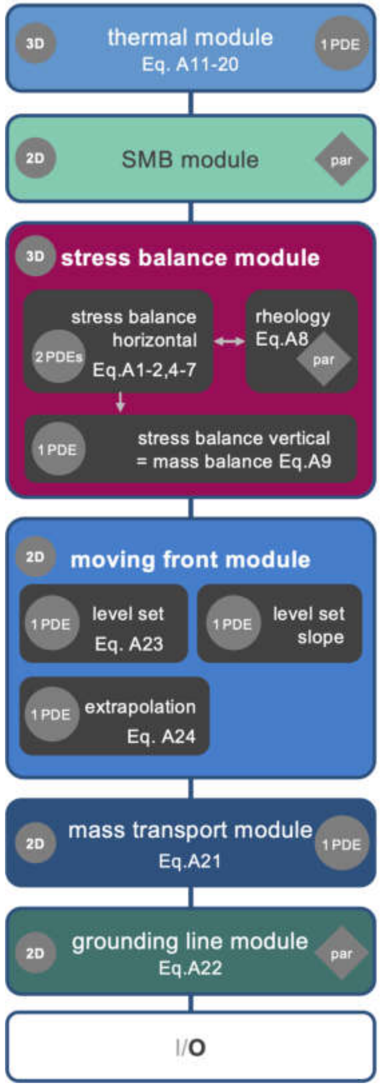


Seroussi et al. 2020

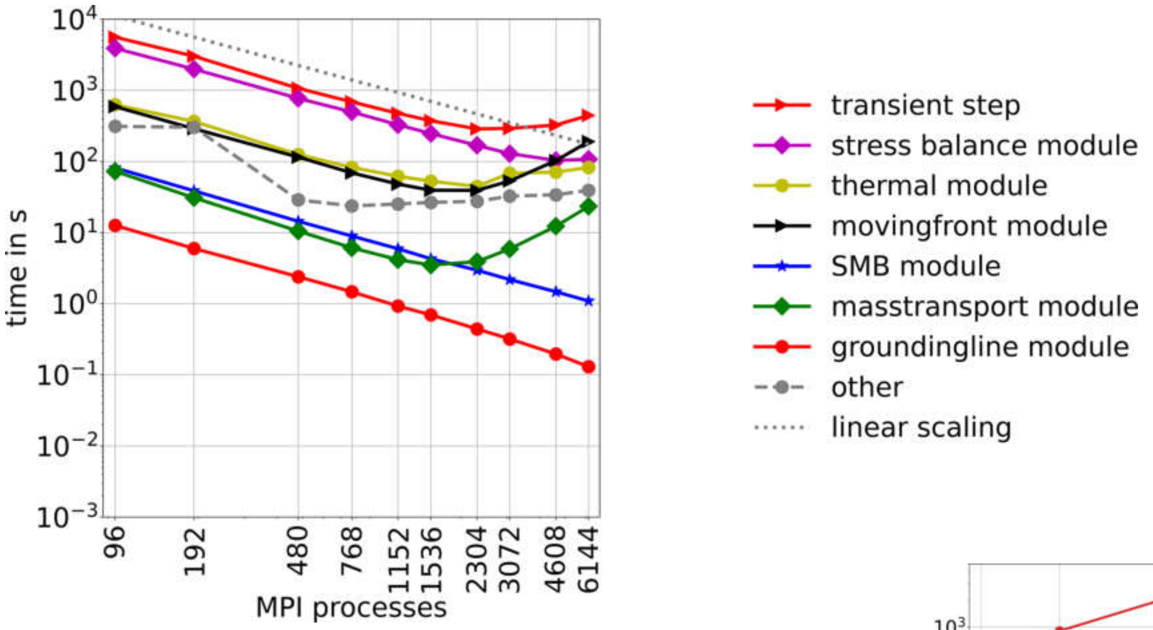
Coupling

	existing	in development	planned
online coupling	preCICE ISSM-MITgcm	Running: Coupling of 3D and 2D fields at the ice surface and ice base tbc: higher order interpolation of fields, extrusion and depth averaging, initialision via preCICE, coupling to multiple codes at surface and base, full 3D coupling, implicit coupling	YAC???
offline coupling	ESMF		RANGO

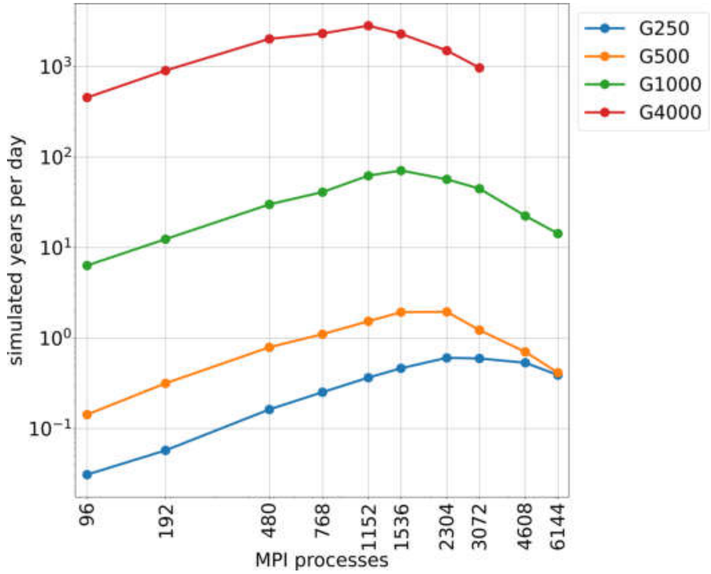
Performance



G4000	G2000	G1000	G500	**G250**	
0.4	0.8	1.7	4.5	**14.3**	#DOF [Mio]
0.9	1.7	3.7	10.0	**31.9**	horizontal
0.4	0.8	1.8	5.0	**16.0**	vertical
0.04	0.1	0.1	0.4	**1.1**	level set function
5x 0.1	5x 0.1	5x 0.2	5x 0.5	**5x 1.1**	extrapolation
0.04	0.1	0.1	0.4	**1.1**	slope
0.03	0.1	0.1	0.3	**1.1**	



higher-order approximation



Fischler et al., GMD, 2022

User community

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Europe (12):
Germany: AWI, BAdW, TU Darmstadt, DLR
Norway: U Bergen, U Oslo, NERSC
Denmark: DTU, GEUS
Sweden: Stockholm University
Netherland: TU Delft
UK: U Edinburgh

50 active developers

America (17):
USA: Dartmouth, JPL, UCI, Georgia Tech, UCLA, UCSD,
U Maryland, Penn State, Buffalo, GSFC, Stanford, U Maine,
UT Austin, UND, UAF
Canada: Waterloo, Newfoundland U.

Publications

Oceania (4):
Australia: Monash, U Tasmania, ANU
New Zealand: U Victoria

Asia (3):
Korea: KOPRI, Kangwon
China: National Academy of Sciences

Technical criteria natESM - ISSM

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Technical criteria for becoming part of the natESM system

1. Well-defined Interfaces between Earth System Components ★★★★★
2. Allows Simulations from Global to Local ★★★★★
3. Exascale-Ready ★★★★★
4. Scalable Workflows? ★★★★★
5. Portability ★★★★★
6. Modularity ★★★★★
7. Data Assimilation Capacity ★★★★★
8. Diagnostic Capacity ★★★★★
9. User-Friendly and Well-Documented ★★★★★
10. Traceability? ★★★★★ Reproducibility ★★★★★ Version Control ★★★★★
11. Standardization? ESMF compliance ★★★★★
12. License of Useful Open-Source Type ★★★★★

@AWI

senior PostDoc PhD

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ISSM – other Benchmarks

MISMIP+ Cornford et al. 2020

Model (submitter)	Result set	Basal stress	Englacial stress
BISICLES (Cornford)	SCO_BISICLES_L1L2a_Tsai_500m	Tsai	L1Lx
	SCO_BISICLES_L1L2b_Tsai_1km	Tsai	L1Lx
	SCO_BISICLES_L1L2b_Tsai_250m	Tsai	L1Lx
	SCO_BISICLES_L1L2b_Weertman_250m	Weertman	L1Lx
	SCO_BISICLES_SSA_Schoof_250m	Schoof	SSA
	SCO_BISICLES_SSA_Tsai_250m	Tsai	SSA
CISM (Leguy)	GLE_CISM_SSA_Schoof_1km	Schoof	SSA
	GLE_CISM_SSA_Weertman_1km	Weertman	SSA
Elmer/Ice (Merino)	IME_ElmerIce_FS_Schoof_250m	Schoof	FS
	IME_ElmerIce_L1L2b_Schoof_250m	Schoof	L1Lx
ISSM (Borstad)	CBO_ISSM_SSA_Tsai_500m	Tsai	SSA
ISSM (Seroussi)	HSE_ISSM_HO_Weertman_1km	Weertman	HO
	HSE_ISSM_SSA_Tsai_1km	Tsai	SSA
	HSE_ISSM_SSA_Tsai_500m	Tsai	SSA
	HSE_ISSM_SSA_Weertman_1km	Weertman	SSA
ISSM (Yu)	HYU_ISSM_FS_Weertman_500m	Weertman	FS
ISSM (Dias dos Santos)	TDI_ISSM_SSA_Tsai_500m	Tsai	SSA
	TDI_ISSM_SSA_Weertman_500m	Weertman	SSA
ISSM (Christmann)	JCH_ISSM_HO_Tsai_200m	Tsai	HO
MALI (Hoffman)	MHO_MPASLI_HO_Weertman_500m	Weertman	HO
PISM (Feldmann)	JFE_PISM_SSA+SIA_Tsai_1km	Tsai	L1Lx
	JFE_PISM_SSA+SIA_Weertman_1km	Weertman	L1Lx
	JFE_PISM_SSA+SIA_Weertman_SG_1km	Weertman	L1Lx
	JFE_PISM_SSA+SIA_Weertman_eta_1km	Weertman	L1Lx
	JFE_PISM_SSA+SIA_Weertman_eta_SG_1km	Weertman	L1Lx
	JFE_PISM_SSA+SIA_eta_Tsai_1km	Tsai	L1Lx
	JFE_PISM_SSA_Weertman_SG_1km	Weertman	SSA
	JFE_PISM_SSA_Weertman_eta_SG_1km	Weertman	SSA
PSU3D (Pollard)	DPO_PSU_HySSA_Weertman_10km	Weertman	HySSA
	DPO_PSU_HySSA_Weertman_1km	Weertman	HySSA
STREAMICE (Goldberg)	DNG_STREAMICE	Schoof	L1Lx
TIMFD3 (Kleiner)	TKL_TIMFD3_HO_Tsai_1km	Tsai	HO
Úa (Gudmundsson)	HGU_UA_SSA_Weertman	Weertman	SSA
	HGU_UA_SSA_Schoof	Schoof	SSA
	HGU_UA_SSA_Tsai	Tsai	SSA
WAVI (Williams)	CWI_WAVI_L1L2c_Weertman_1km	Weertman	L1Lx
	CWI_WAVI_L1L2c_Weertman_2km	Weertman	L1Lx

Model name	Numerics	Stress balance	Resolution km	Initialization	SMB	Basal sliding/friction
ARC-PISM1	FD	Hybrid	16	Sp	RACMO2.1	Coulomb $q = 0.75$
ARC-PISM2	FD	Hybrid	16	Sp	RACMO2.1	Coulomb $q = 0.75$ with sub-grid melting
AWI-PISMPal	FD	Hybrid	16	Sp	RACMO2.3	Coulomb $q = 0.6$
CPOM-BISICLES	FV	SSA*	0.5–8	DA+	Arthern	Weertman $m = 3$/Coulomb
IGE-Elmer/Ice	FE	SSA	1–50	DA	MAR	Weertman $m = 3$
ILTS-PIK-SICOPOLIS	FD	Hybrid	8	SpC	Arthern	Weertman $m = 3$, $p = 2$
IMAU-ICE	FD	Hybrid	32 (★)	Eq	RACMO2.3	Coulomb $q = 0$
JPL-ISSM	FE	SSA	1–50	DA	RACMO2	Weertman $m = 1$
LSCE-GRISLI	FD	Hybrid	16 (★)	EqC+	RACMO2.3	Coulomb $q = 1$
NCAR-CISM	FE/FV	L1L2	4	EqC	RACMO2.3p2	Weertman $m = 3$/Coulomb
PSU-PSU3D1	FD	Hybrid	16 (★)	EqC	Arthern	Weertman $m = 2$
PSU-PSU3D2	FD	Hybrid	16 (★)	EqC	Arthern	Weertman $m = 2$ without cliff instability
ULB-f.ETISh	FD	Hybrid	16 (★)	EqC+	RACMO2.3	Weertman $m = 2$
DOE-MALI	FE/FV	LMLa	2–20	DA+	RACMO2	Weertman $m = 1$
PIK-PISM	FD	Hybrid	4	EqC+	RACMO2.3p2	Coulomb $q = 0.75$

ABUMIP Sun et al. 2020

RCP8.5	Antarctica sea level contribution percentiles (m)				
Model	5 %	16.6 %	50 %	83.3 %	95 %
AISM VUB	0.06	0.08	0.13	0.19	0.33
BISI LBL	0.08	0.11	0.17	0.27	0.46
CISM NCA	0.04	0.06	0.10	0.16	0.27
FETI ULB	0.06	0.09	0.15	0.23	0.39
GRIS LSC	0.03	0.04	0.07	0.11	0.18
IMAU UU	0.11	0.17	0.26	0.42	0.70
ISSM JPL	0.05	0.08	0.12	0.18	0.31
ISSM UCI	0.12	0.18	0.27	0.41	0.71
MALI DOE	0.07	0.10	0.15	0.23	0.40
PISM AWI	0.05	0.07	0.11	0.17	0.30
PISM DMI	0.15	0.22	0.33	0.47	0.83
PISM PIK	0.07	0.11	0.19	0.31	0.48
PISM VUW	0.17	0.24	0.38	0.60	1.03
PS3D PSU	0.08	0.12	0.20	0.31	0.51
SICO ILTS	0.14	0.20	0.33	0.50	0.86
ÚA UNN	0.22	0.30	0.46	0.70	1.25
All models	0.06	0.09	0.18	0.38	0.61

LARMIP2 Levermann et al. 2020