UNIVERSITÉ LIBRE DE BRUXELLES, UNIVERSITÉ D'EUROPE

Results of the ISMIP-HOM: higher-order model intercomparison project

Frank PATTYN – Laura PERICHON
Laboratoire de Glaciologie, Université Libre de Bruxelles, Belgium

... and the ISMIP-HOM group

ULB

Aim

Fix benchmarks for future modeling attempts and detect eventual weaknesses in numerical approaches of higher-order models

Tests for higher-order models, i.e. models that incorporate further mechanical effects, principally longitudinal stress gradients, or that solve the full Stokes system.

Experiments are accessible for many types of models, i.e. flowline models, 2D planform models, full 3D models.

Experiments are valid for both finite difference (FD) and finite element (FE) models.

What kind of experiments?

6 experiments, all except 1 are diagnostic

Glen-type flow law

Isotherm ice mass

Periodic boundary conditions

1 experiment with time-dependent response for a constant viscosity (linear flow law).

1 experiment with data from Haut Glacier d'Arolla

Model specifications

Calculate horizontal velocity field
- Surface velocity
- Basal velocity

Calculate isotropic pressure at the base

Periodic boundary conditions at lateral boundaries

Resolution independent experiments
- Grid size is not important.
- Use a discretization scheme for which the best possible results are obtained

	Code	Full Stokes	LMLa	L1L2	L1L1	Numerical method
Andy Aschwanden	AAS	x				FE
Alun Hubbard	AHU		x	x		FD
Bert De Smedt	BDS		x			FE
Carlos Martin	CMA	x	x			FE
Dave Pollard	DPO			x		FD
Frank Pattyn	FPA	x	x			FD
Fuyuki Saito	FSA		x			FD
Jesse Johnson	JVJ		x			FD
Birgit Breuer	MBR		x			FD
Thomas Kleiner	MTK		x			FD
Olivier Gagliardini	OGA	x				FE
Richard Hindmarsh	RHI	xx	x			Spectral
Steve Price	SPR	x				FV
Shin Sugiyama	SSU	x				FE
Yuri Konovalov	YKO	x				FD
Laura Perichon	LPE				x	FD

Model types vs experiment

	Full Stokes	LMLa	L1L2	L1L1
Exp. A	5	9		
Exp. B	7	9		
Exp. C	4	4	1	1
Exp. D	6	7	1	1
Exp. E	5	4		
Exp. F	2	5		

Results

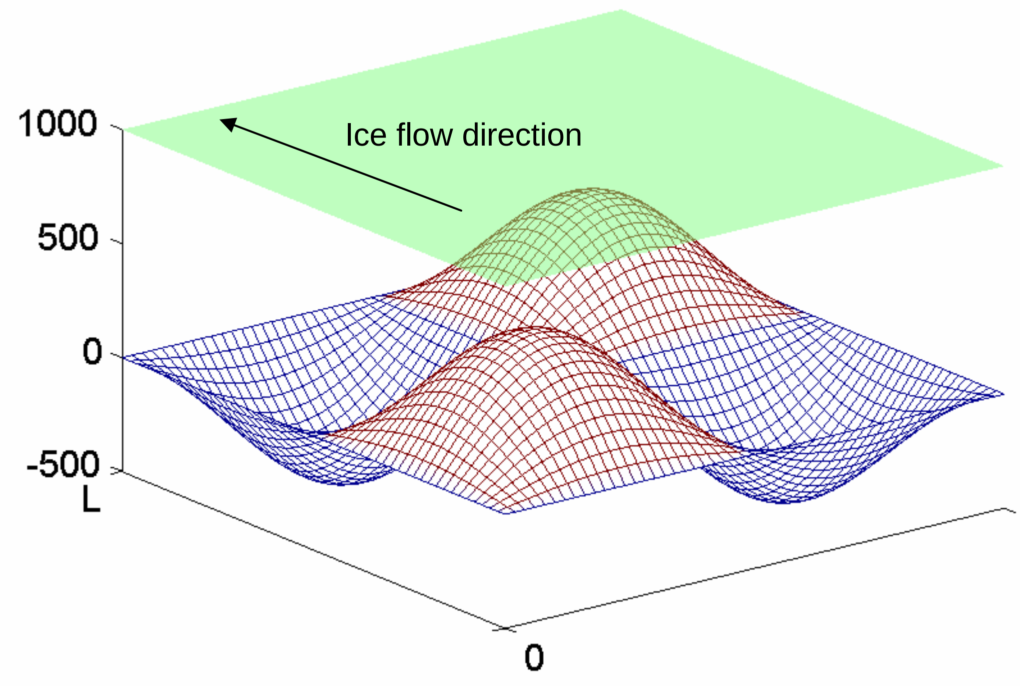
Experiment A

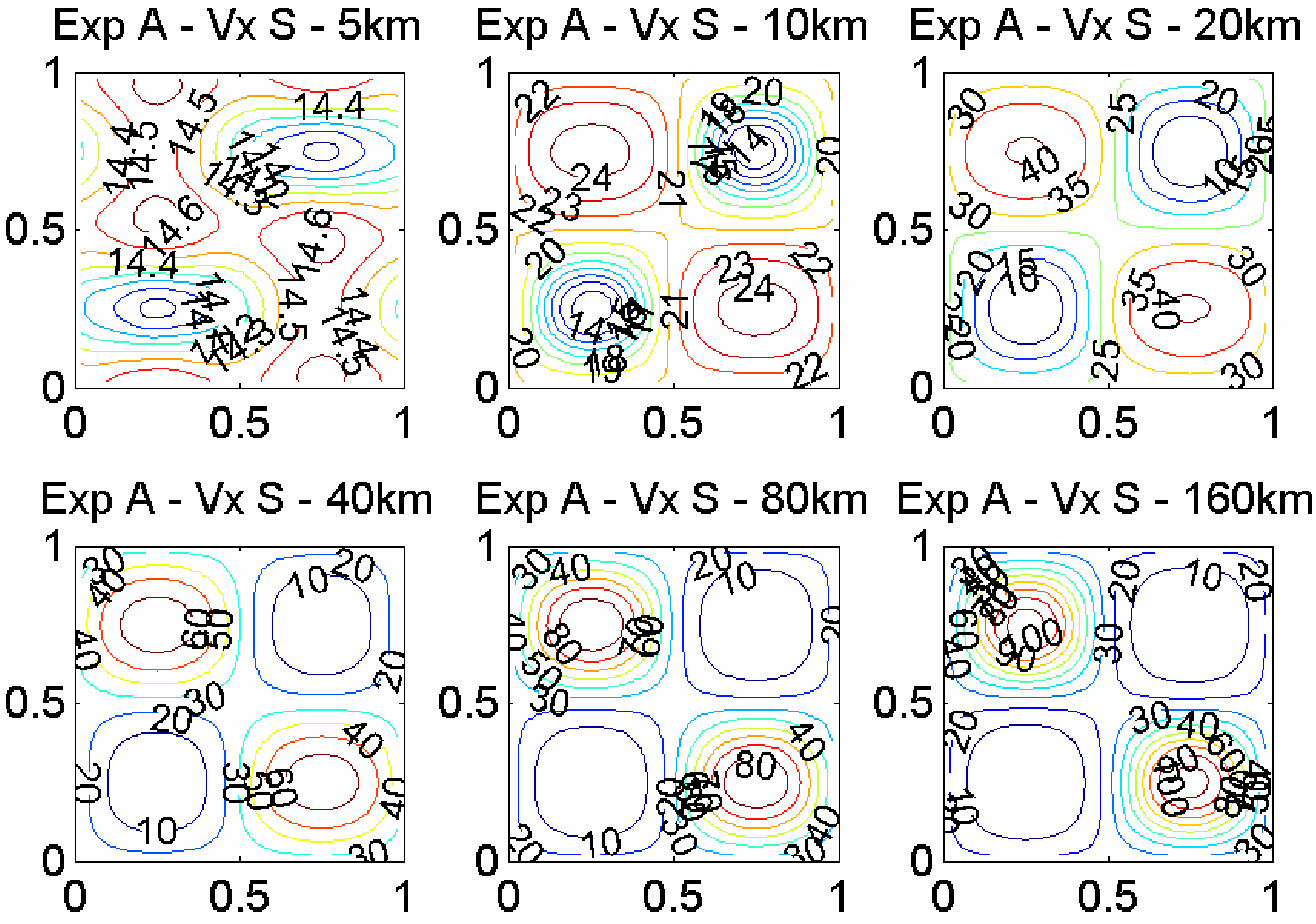
HHVF & HHVC

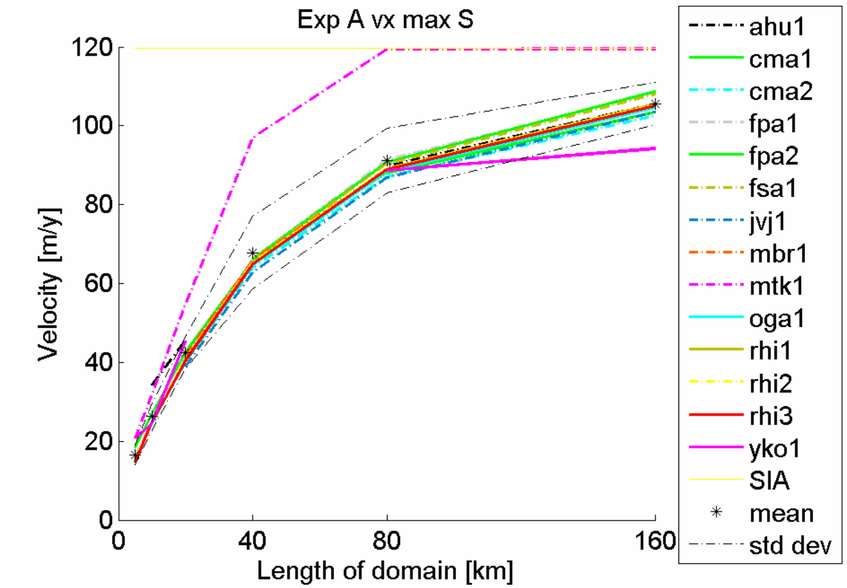
Ice flow over a bumpy bed

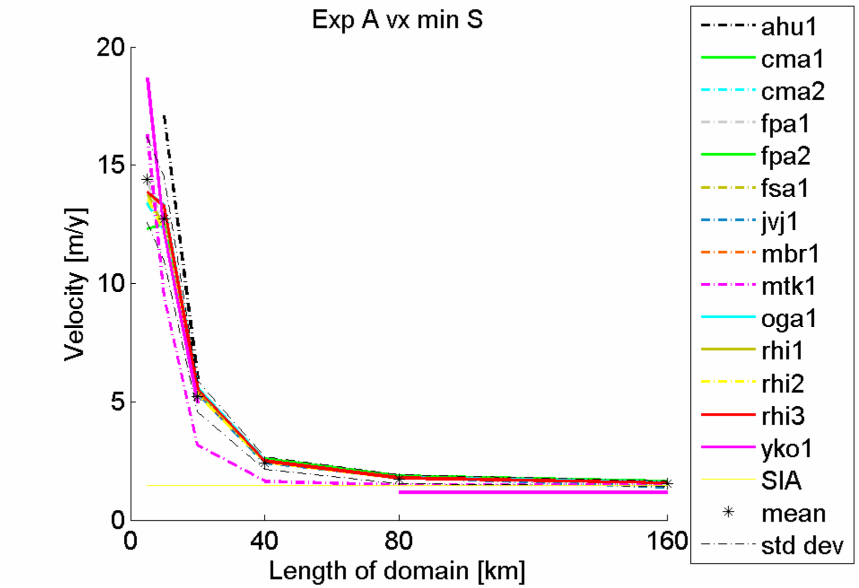
Length scale

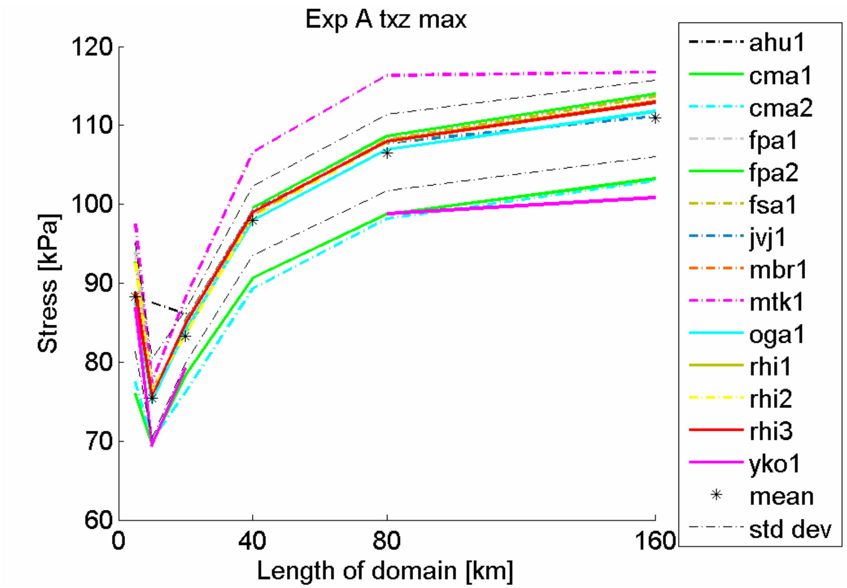
L = 160, 80, 40, 20, 10, 5 km

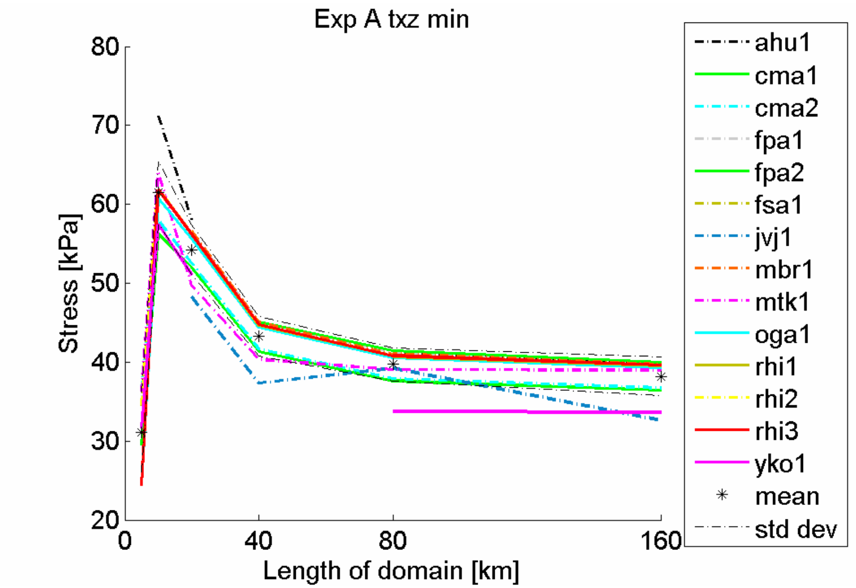


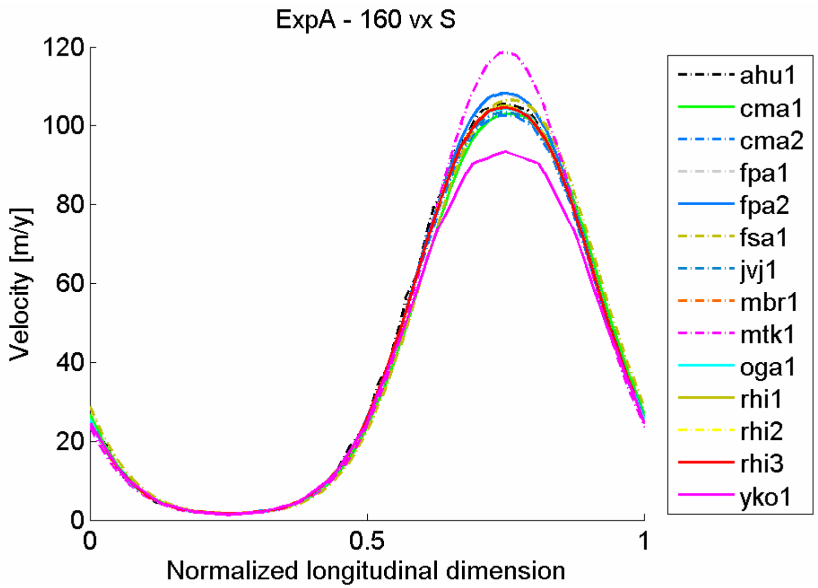

Exp A - Vx S - 5km
Exp A - Vx S - 10km
Exp A - Vx S - 20km
Exp A - Vx S - 40km
Exp A - Vx S - 80km
Exp A - Vx S - 160km
0
0.5
1

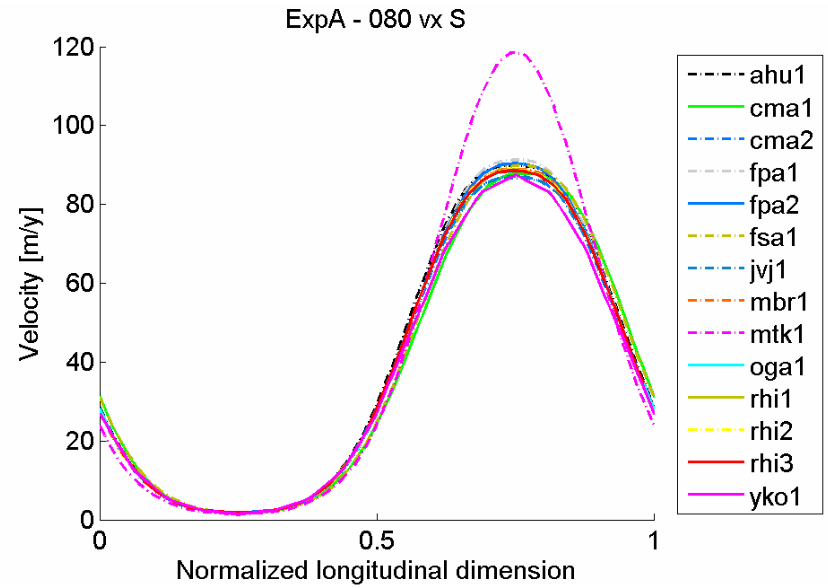

Exp A vx max S
Velocity [m/y]
Length of domain [km]
0
20
40
60
80
100
120
0
40
80
160
ahu1
cma1
cma2
fpa1
fpa2
fsa1
jvj1
mbr1
mtk1
oga1
rhi1
rhi2
rhi3
yko1
SIA
mean
std dev

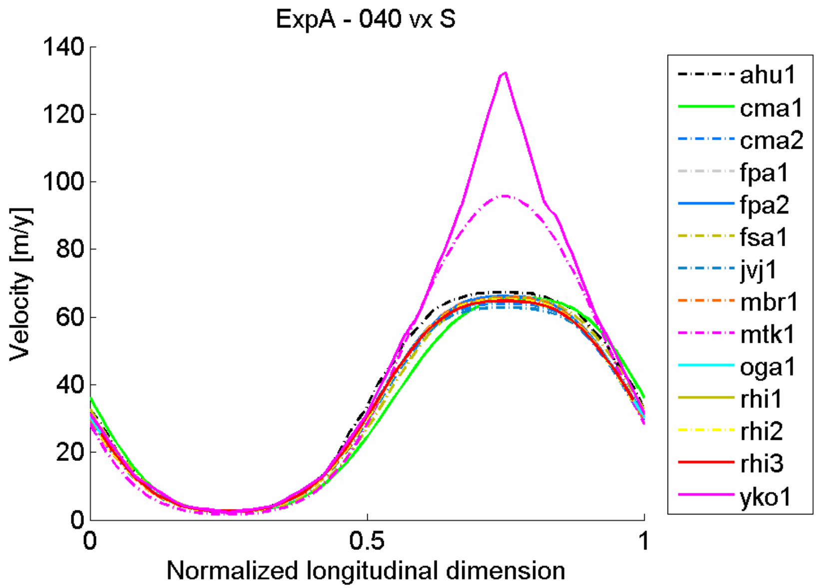

Exp A vx min S
Velocity [m/y]
Length of domain [km]
0
5
10
15
20
0
40
80
160
ahu1
cma1
cma2
fpa1
fpa2
fsa1
jvj1
mbr1
mtk1
oga1
rhi1
rhi2
rhi3
yko1
SIA
mean
std dev

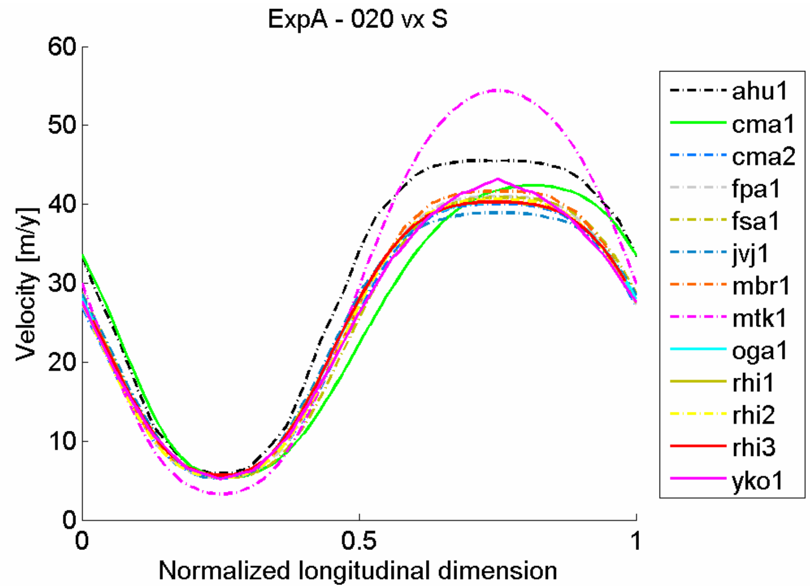

Exp A txz max
Stress [kPa]
Length of domain [km]
60
70
80
90
100
110
120
0
40
80
160
ahu1
cma1
cma2
fpa1
fpa2
fsa1
jvj1
mbr1
mtk1
oga1
rhi1
rhi2
rhi3
yko1
mean
std dev

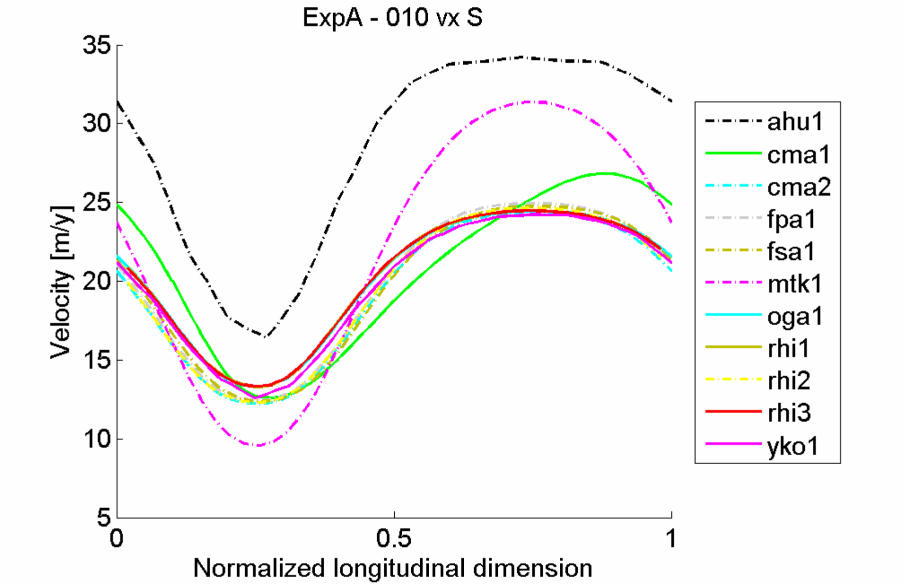

Exp A txz min
Stress [kPa]
Length of domain [km]
20
30
40
50
60
70
80
0
40
80
160
ahu1
cma1
cma2
fpa1
fpa2
fsa1
jvj1
mbr1
mtk1
oga1
rhi1
rhi2
rhi3
yko1
mean
std dev


ExpA - 160 vx S
Velocity [m/y]
Normalized longitudinal dimension
0
20
40
60
80
100
120
0
0.5
1
ahu1
cma1
cma2
fpa1
fpa2
fsa1
jvj1
mbr1
mtk1
oga1
rhi1
rhi2
rhi3
yko1


ExpA - 080 vx S
Velocity [m/y]
Normalized longitudinal dimension
0
20
40
60
80
100
120
0
0.5
1
ahu1
cma1
cma2
fpa1
fpa2
fsa1
jvj1
mbr1
mtk1
oga1
rhi1
rhi2
rhi3
yko1


ExpA - 040 vx S
Velocity [m/y]
Normalized longitudinal dimension
0
20
40
60
80
100
120
140
0
0.5
1
ahu1
cma1
cma2
fpa1
fpa2
fsa1
jvj1
mbr1
mtk1
oga1
rhi1
rhi2
rhi3
yko1

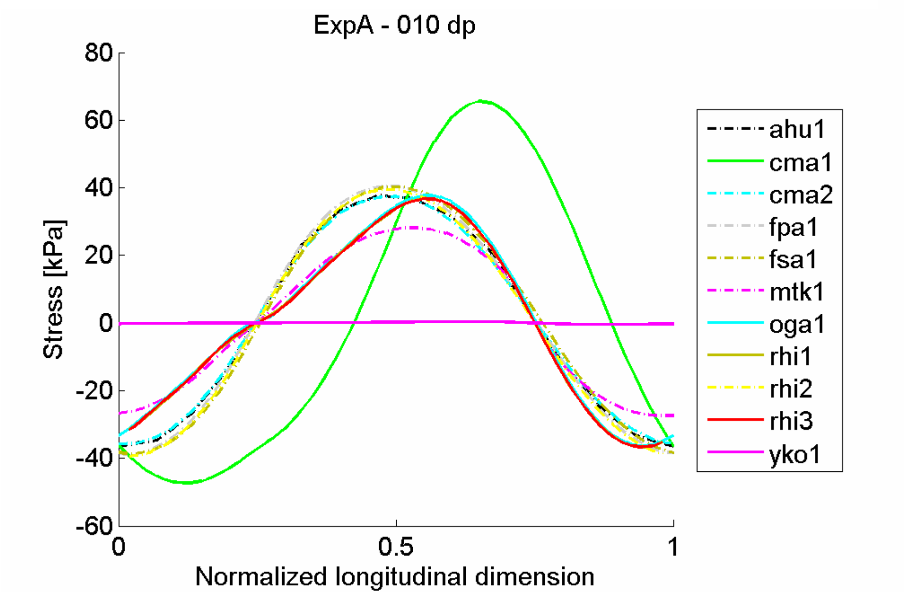

ExpA - 020 vx S
Velocity [m/y]
Normalized longitudinal dimension
0
10
20
30
40
50
60
0
0.5
1
ahu1
cma1
cma2
fpa1
fsa1
jvj1
mbr1
mtk1
oga1
rhi1
rhi2
rhi3
yko1

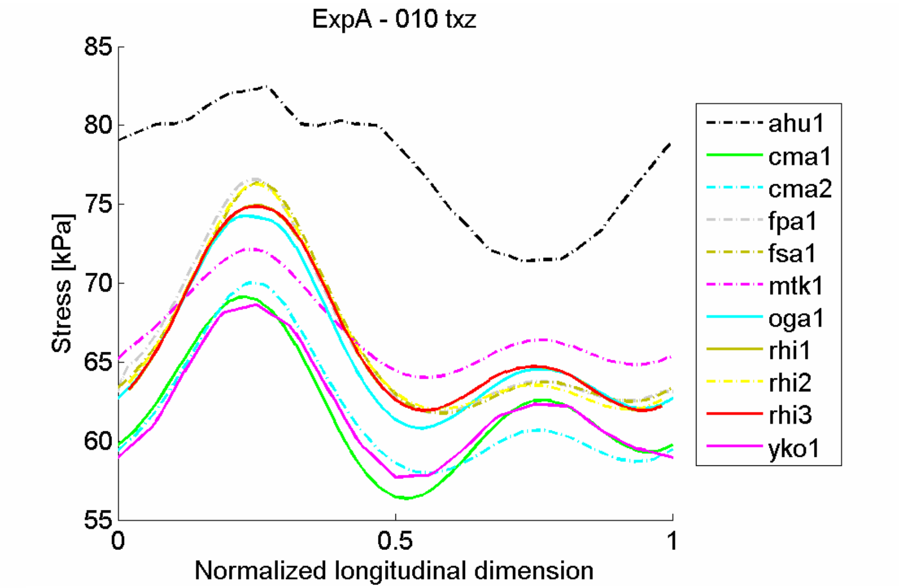


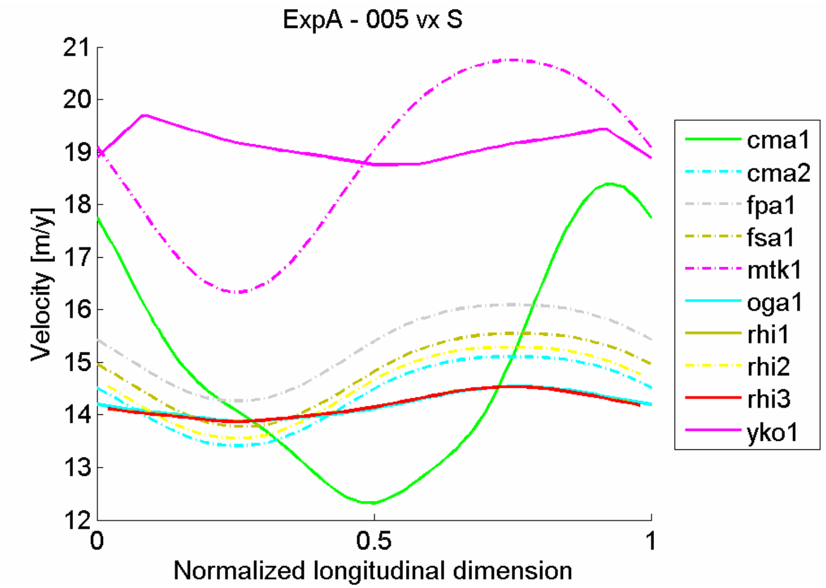
L=10:

Some models missing – a harder to perform excercise: viscosity changes over several orders of magnitude

Discrepancies between models are somewhat larger, but results converge



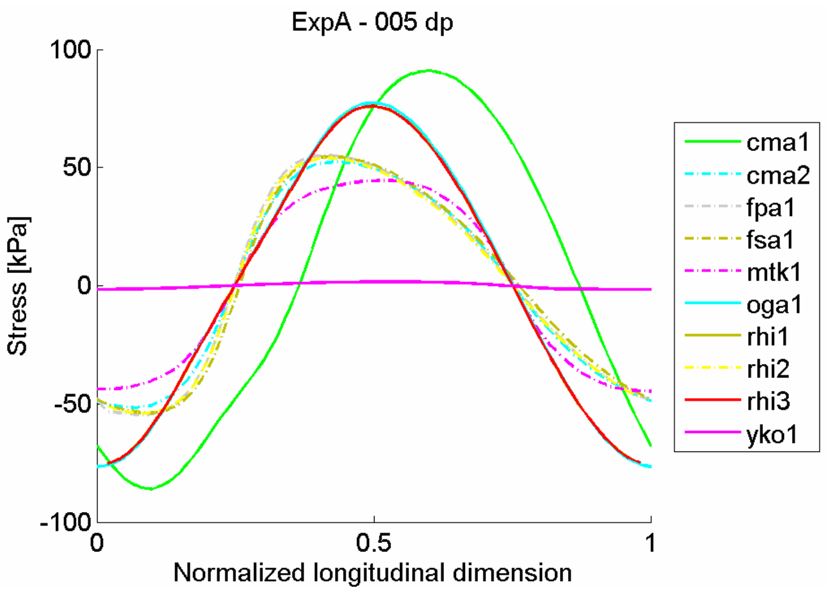


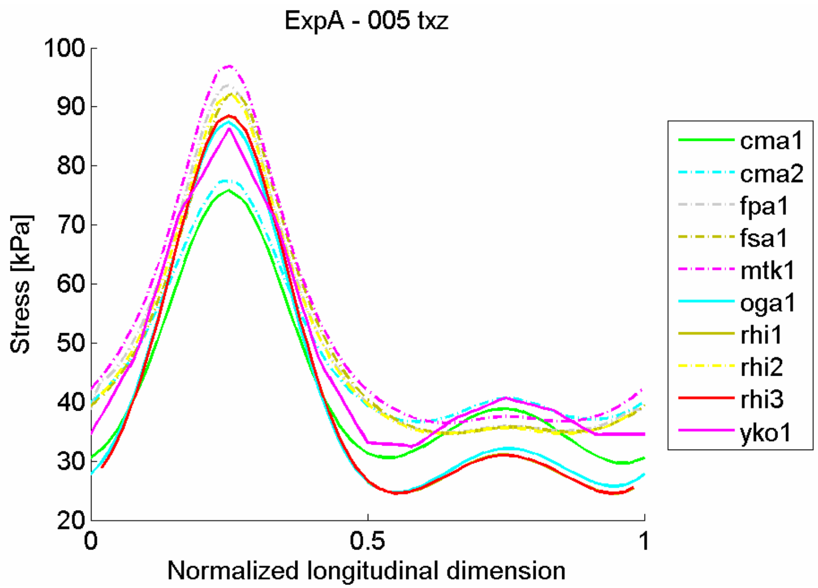


L=5:

Even less models participated – a very hard to perform excercise

Discrepancies between models are larger





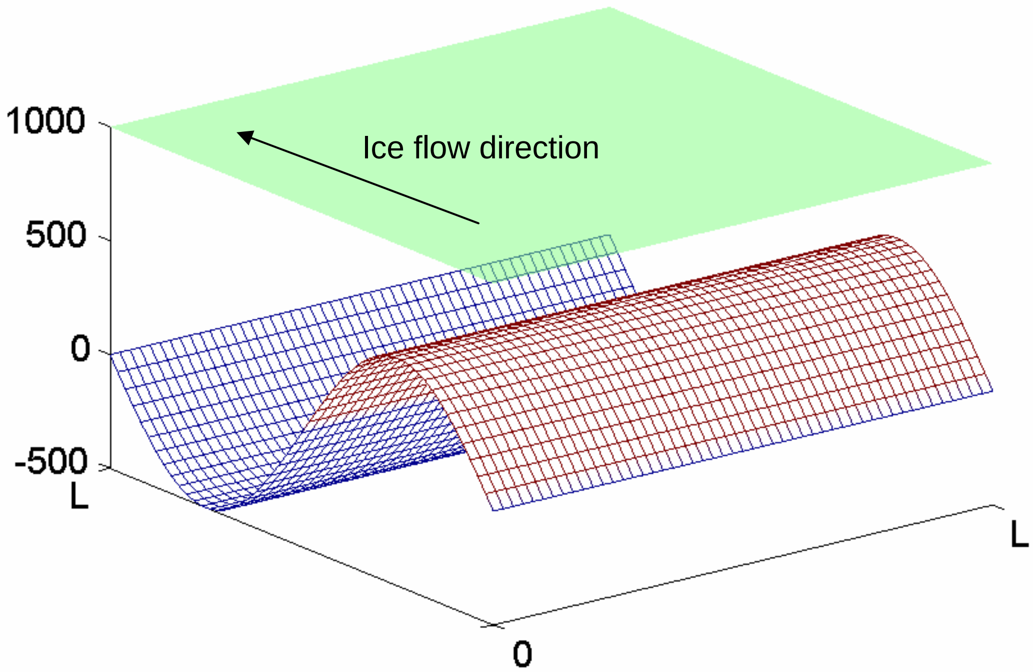
Experiment B

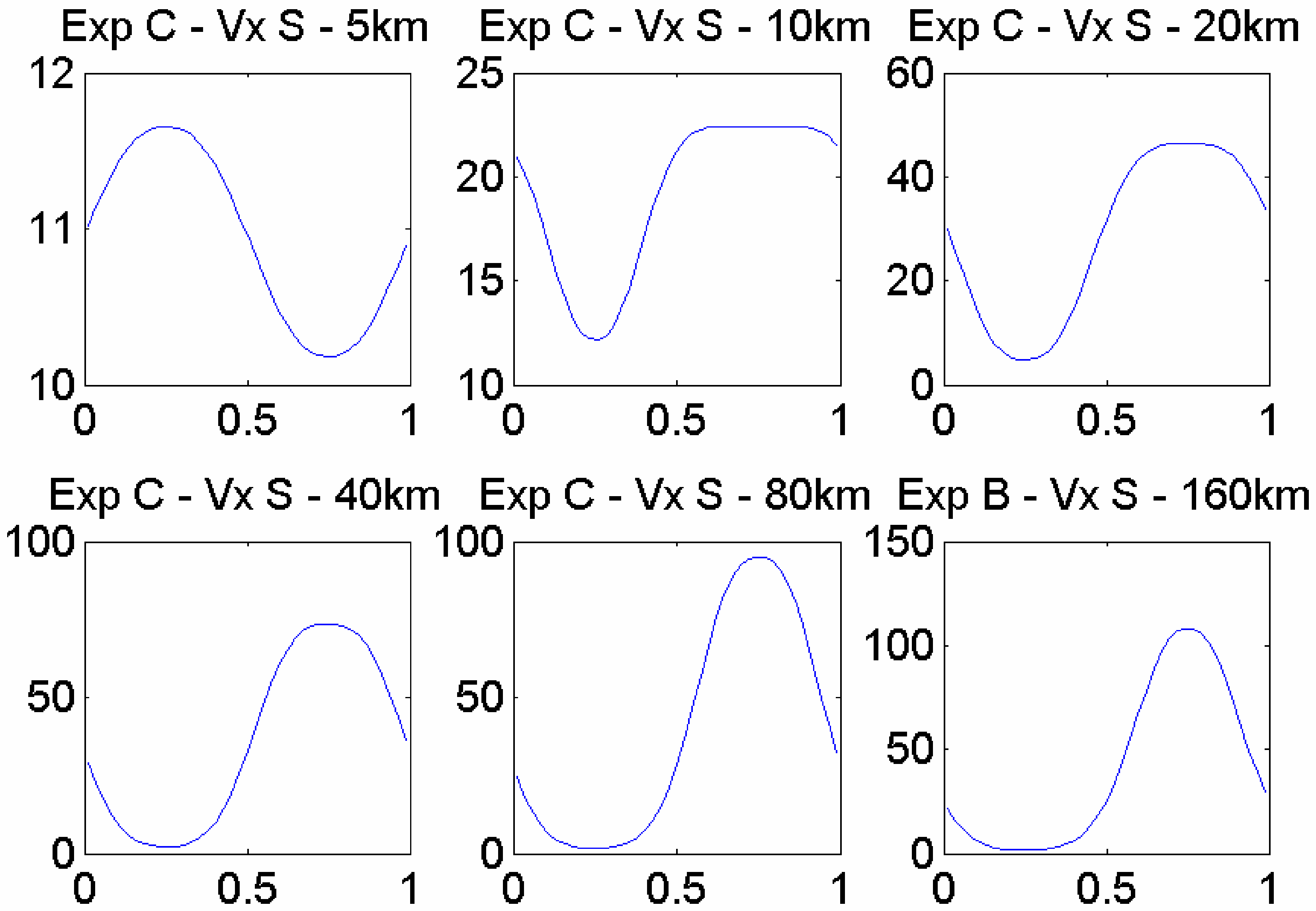
HHVF, HHVC, HVF & HVC

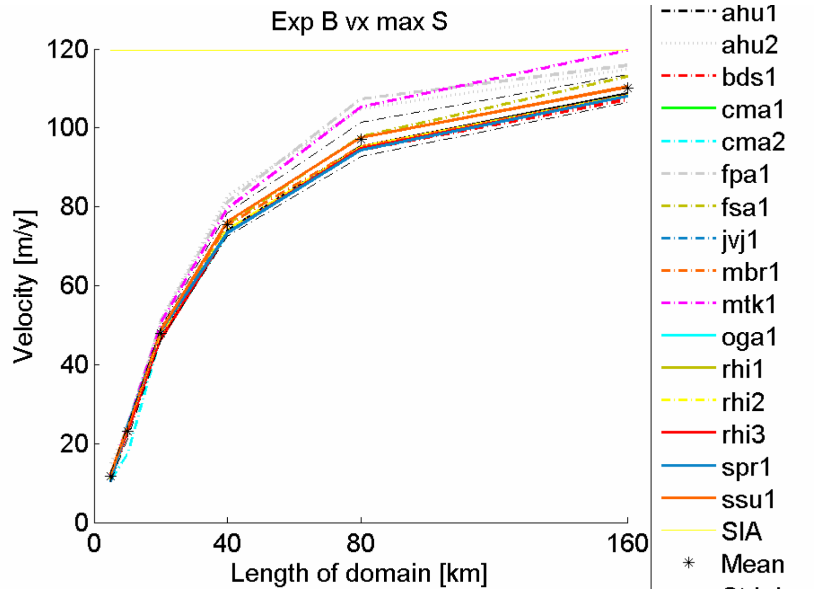
Ice flow over a rippled bed

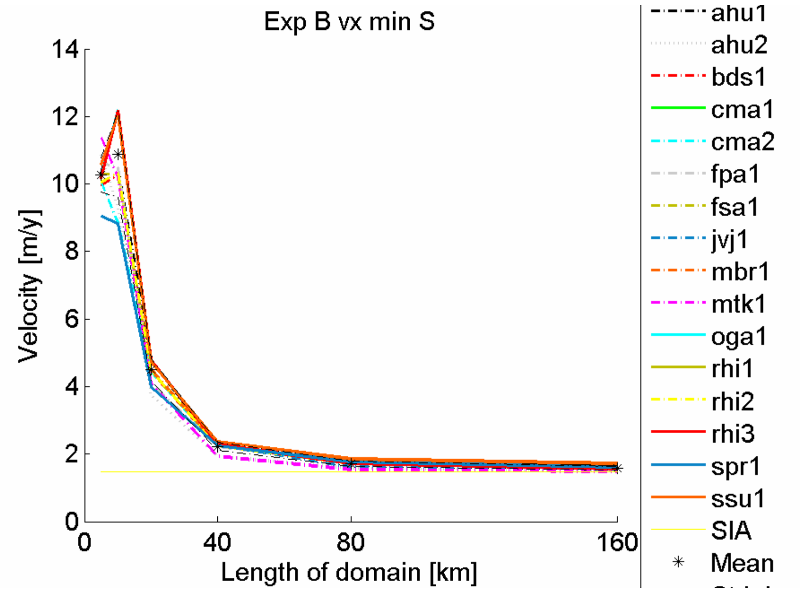
Length scale

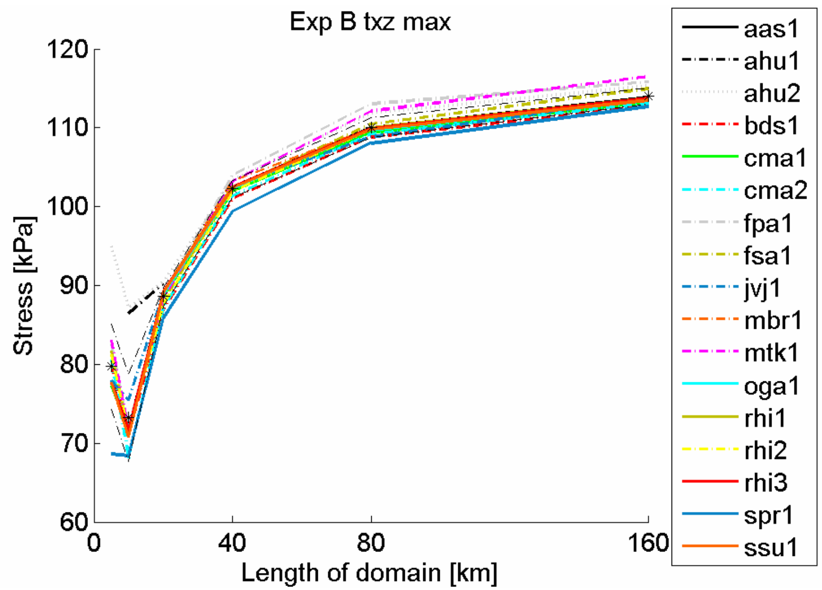
L = 160, 80, 40, 20, 10, 5 km

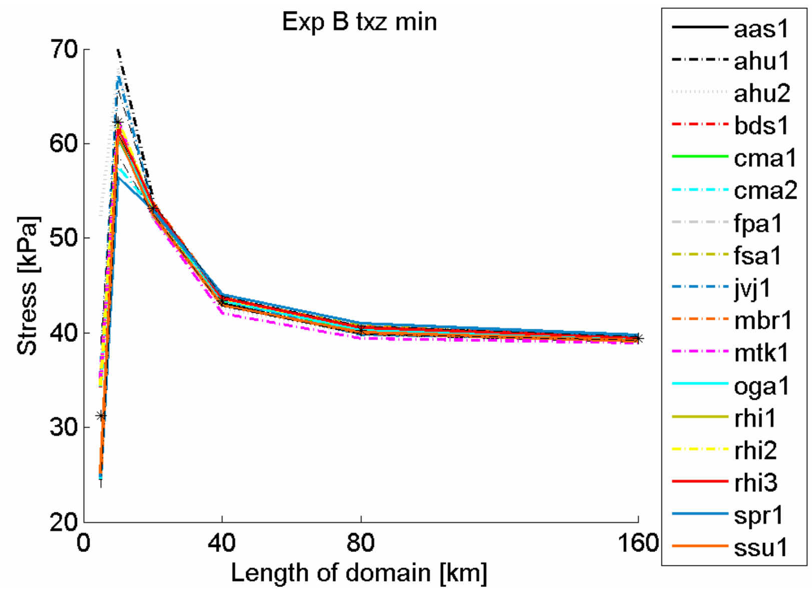


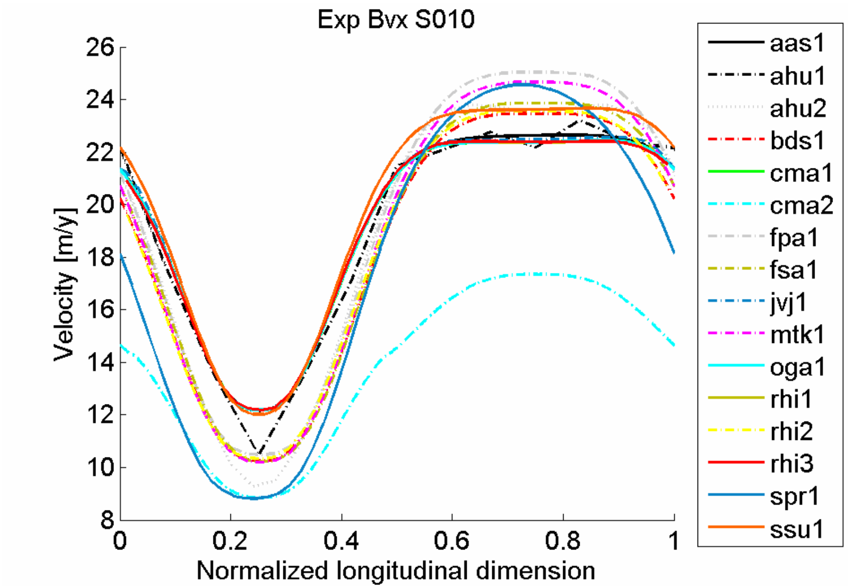

Exp C - Vx S - 5km
12
11
10
0
0.5
1
Exp C - Vx S - 10km
25
20
15
10
0
0.5
1
Exp C - Vx S - 20km
60
40
20
0
0
0.5
1
Exp C - Vx S - 40km
100
50
0
0
0.5
1
Exp C - Vx S - 80km
100
50
0
0
0.5
1
Exp B - Vx S - 160km
150
100
50
0
0
0.5
1


Exp B vx max S
Velocity [m/y]
Length of domain [km]
0
20
40
60
80
100
120
0
40
80
160
ahu1
ahu2
bds1
cma1
cma2
fpa1
fsa1
jvj1
mbr1
mtk1
oga1
rhi1
rhi2
rhi3
spr1
ssu1
SIA
Mean


Exp B vx min S
Velocity [m/y]
Length of domain [km]
0
2
4
6
8
10
12
14
0
40
80
160
ahu1
ahu2
bds1
cma1
cma2
fpa1
fsa1
jvj1
mbr1
mtk1
oga1
rhi1
rhi2
rhi3
spr1
ssu1
SIA
Mean


Exp B txz max
Stress [kPa]
Length of domain [km]
60
70
80
90
100
110
120
0
40
80
160
aas1
ahu1
ahu2
bds1
cma1
cma2
fpa1
fsa1
jvj1
mbr1
mtk1
oga1
rhi1
rhi2
rhi3
spr1
ssu1

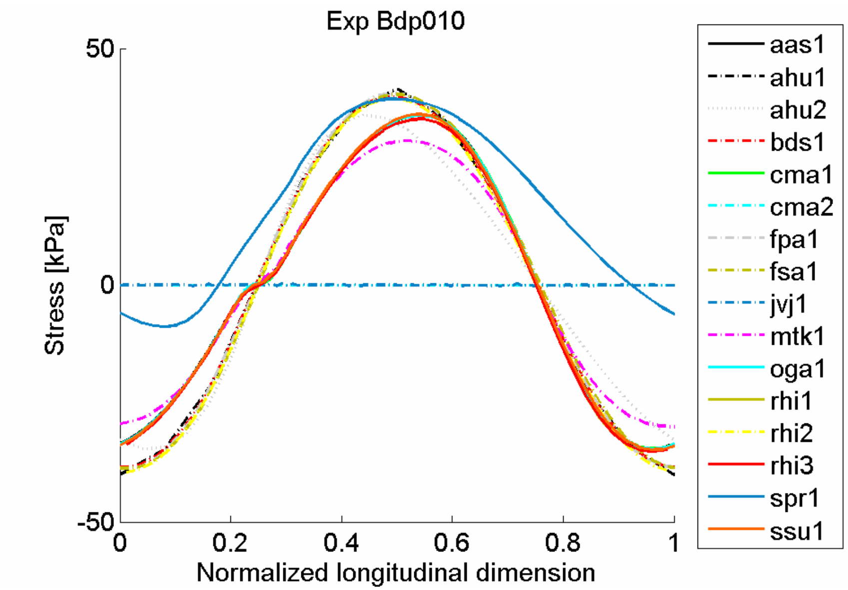

Exp B txz min
Stress [kPa]
Length of domain [km]
20
30
40
50
60
70
0
40
80
160
aas1
ahu1
ahu2
bds1
cma1
cma2
fpa1
fsa1
jvj1
mbr1
mtk1
oga1
rhi1
rhi2
rhi3
spr1
ssu1

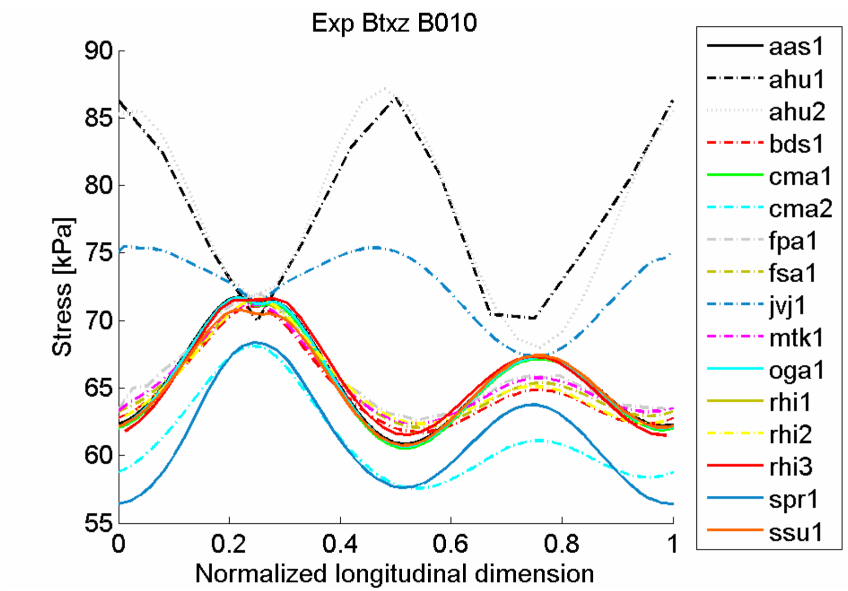


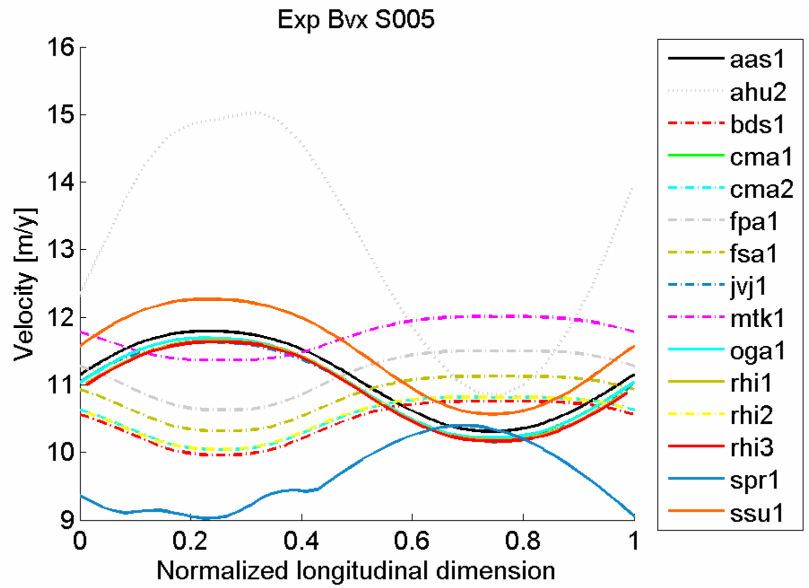
L=10:

Same remarks as A

Not the same models show discrepancies, but a general agreement



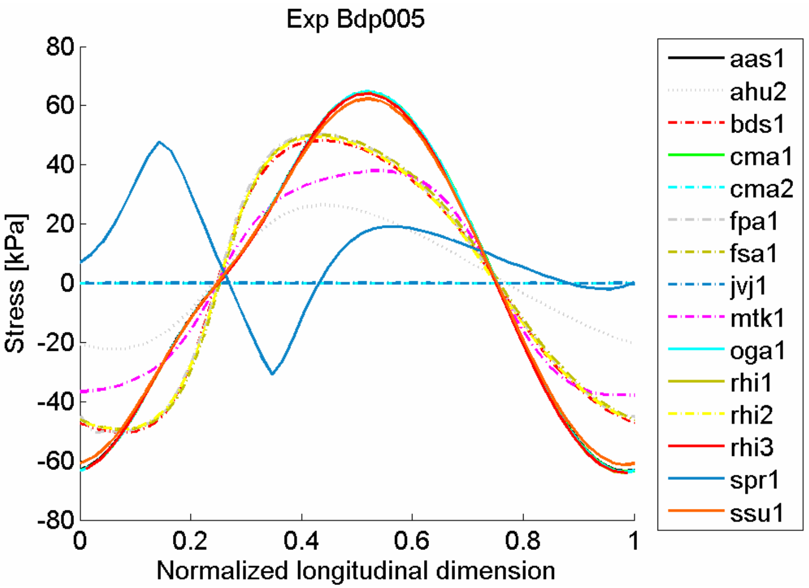


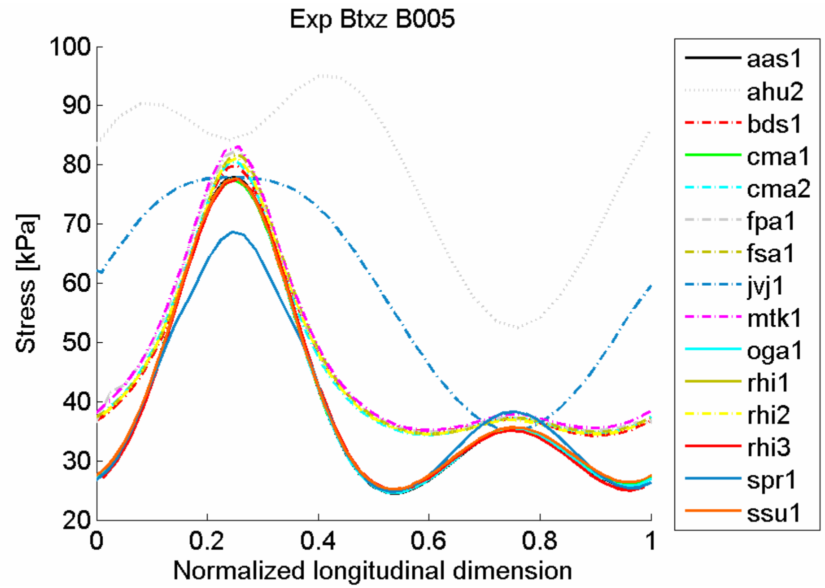


L=5:

Clear distinction in behaviour between HO and FS models

Is also reflected in basal stress field by more pronounced second bump





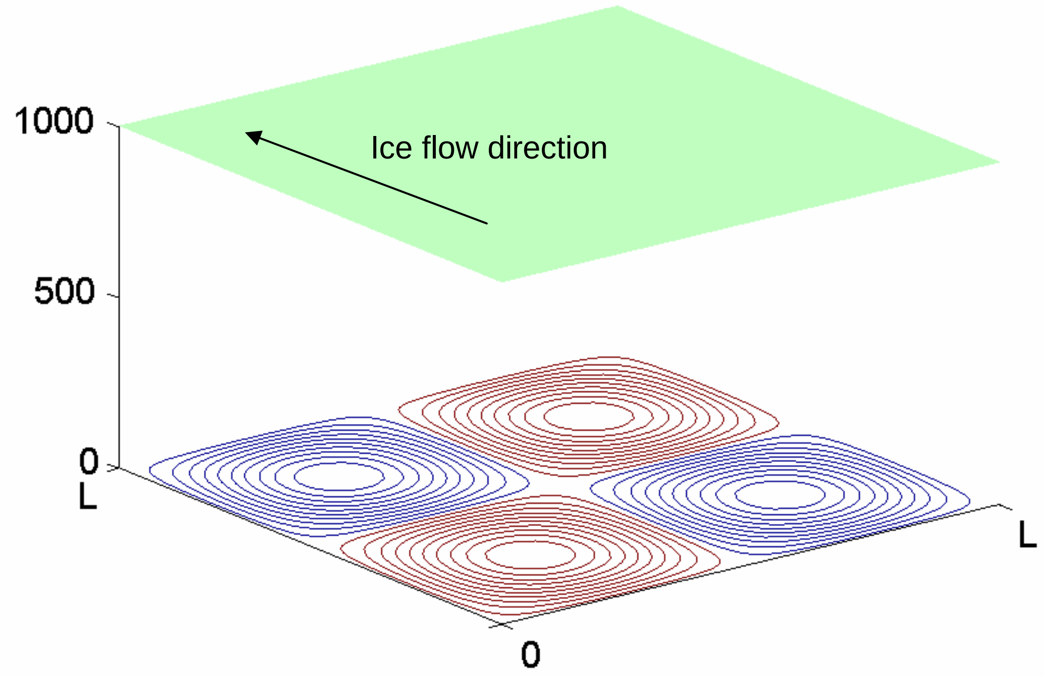
Experiment C

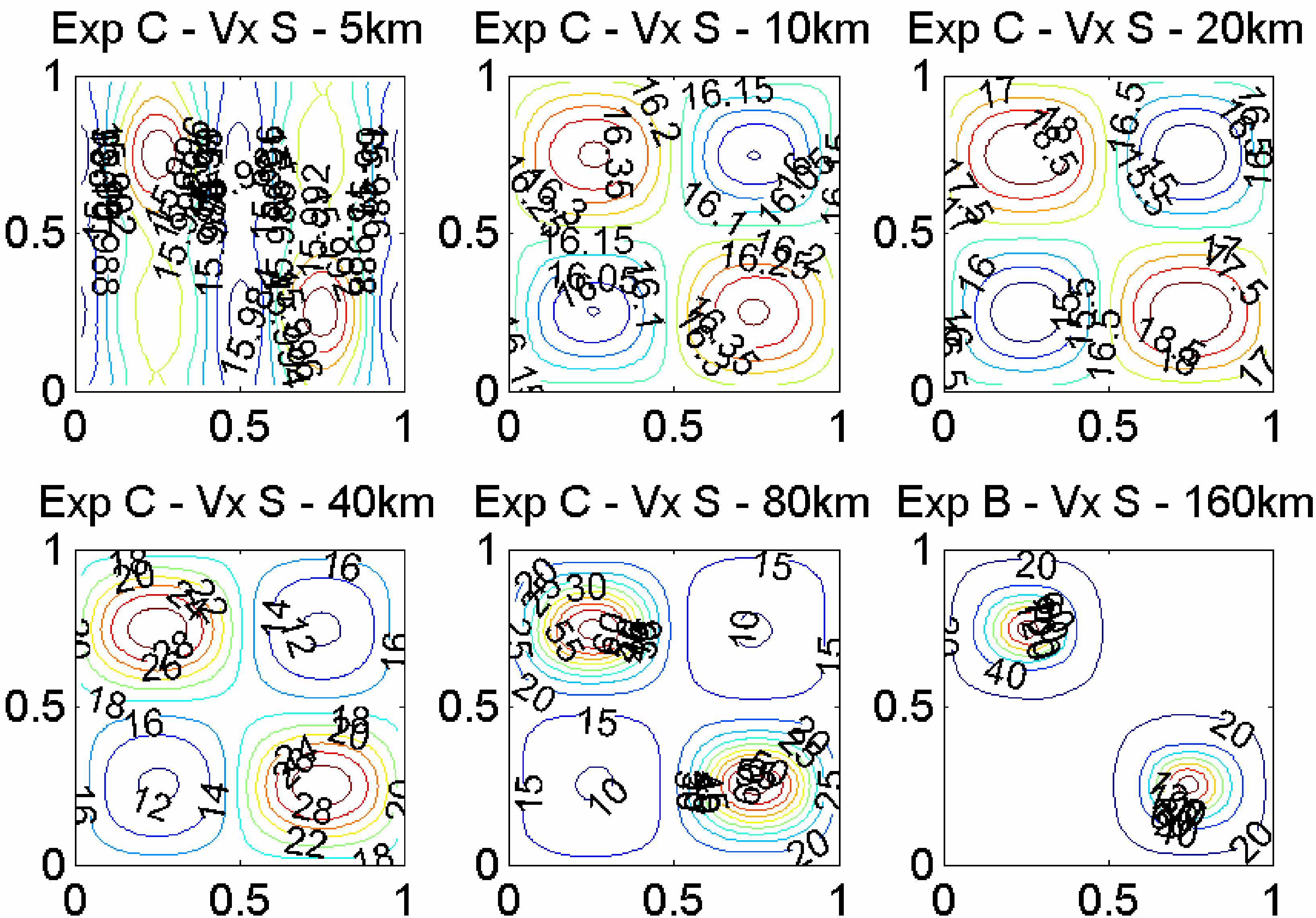
HHVF, HHVC & HHF

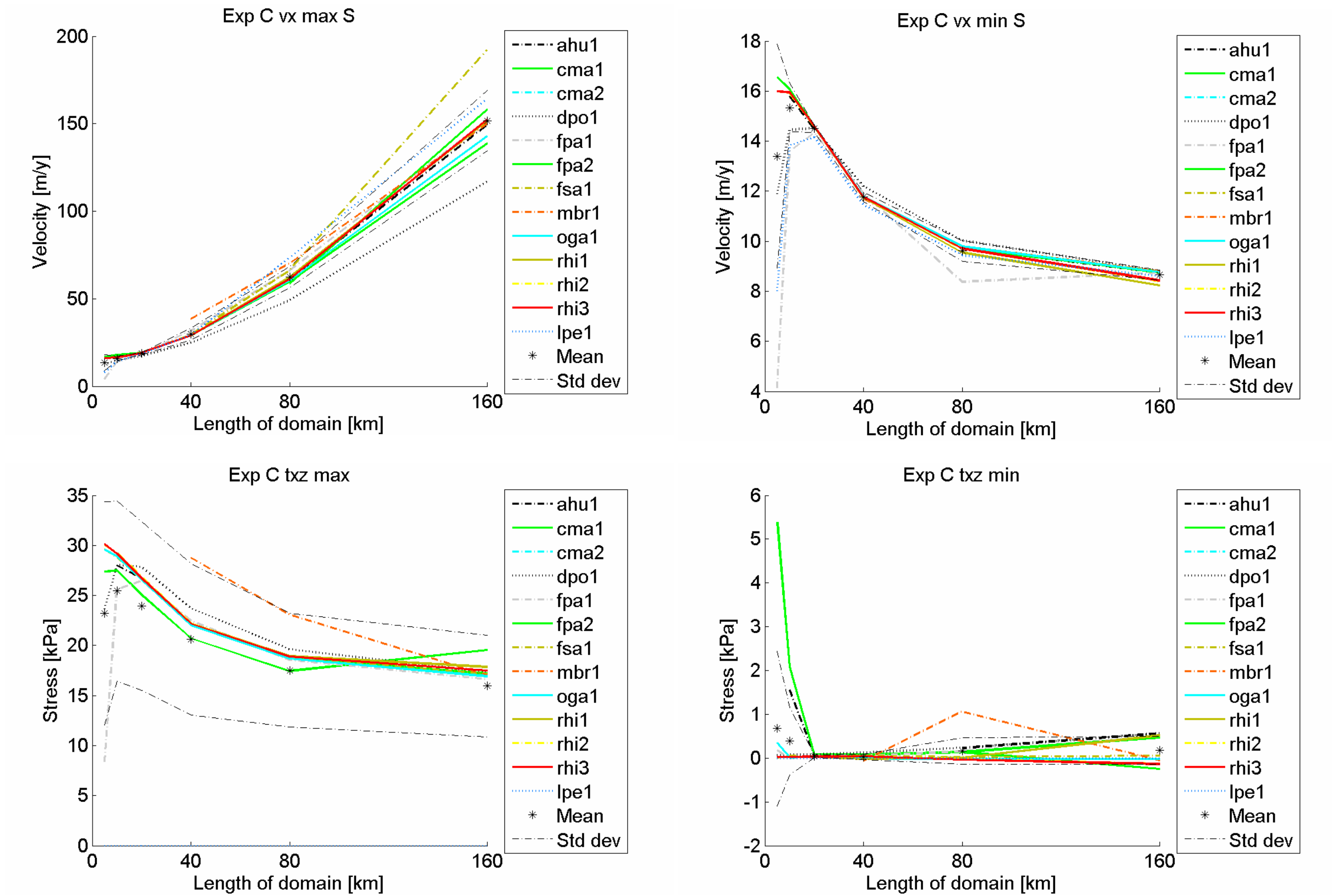
Ice stream flow I: variation in basal friction coefficient

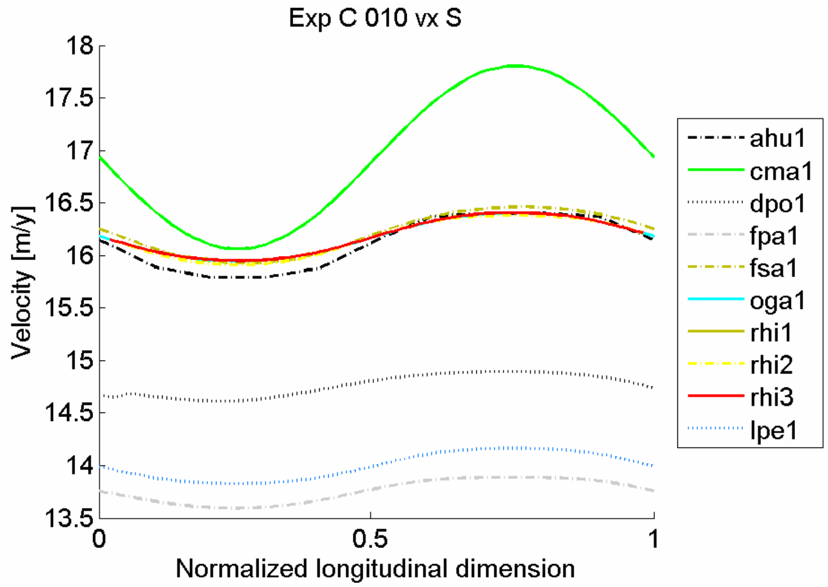
Length scale

L = 160, 80, 40, 20, 10, 5 km




Exp C - Vx S - 5km
Exp C - Vx S - 10km
Exp C - Vx S - 20km
Exp C - Vx S - 40km
Exp C - Vx S - 80km
Exp B - Vx S - 160km

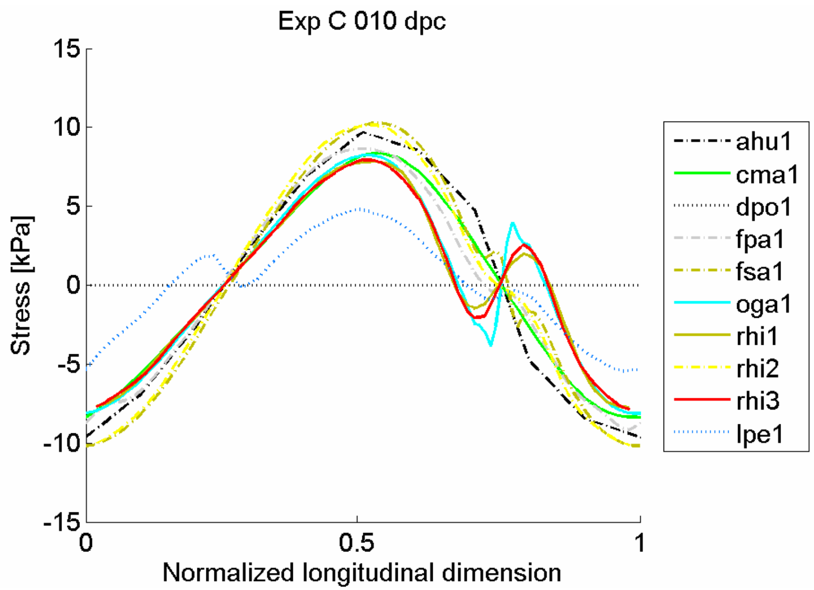

Exp C vx max S
Velocity [m/y]
Length of domain [km]
Exp C vx min S
Velocity [m/y]
Length of domain [km]
Exp C txz max
Stress [kPa]
Length of domain [km]
Exp C txz min
Stress [kPa]
Length of domain [km]
ahu1
cma1
cma2
dpo1
fpa1
fpa2
fsa1
mbr1
oga1
rhi1
rhi2
rhi3
lpe1
Mean
Std dev

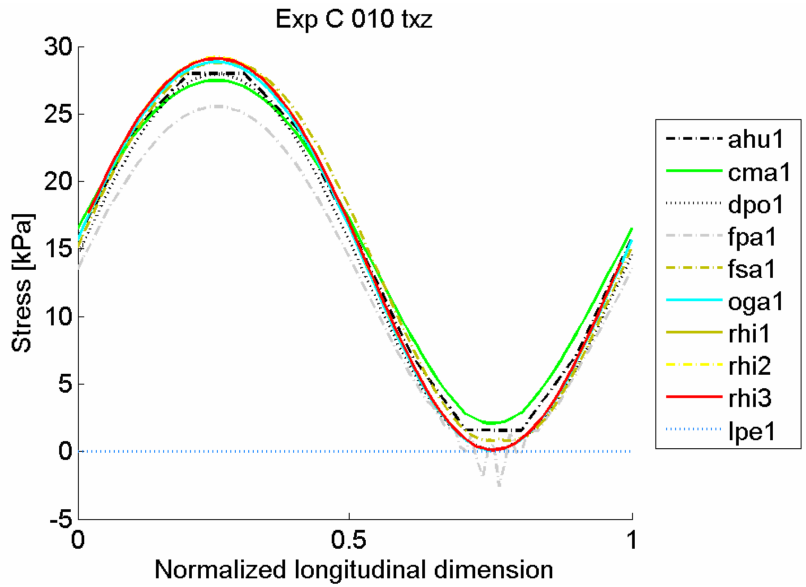


L=10:

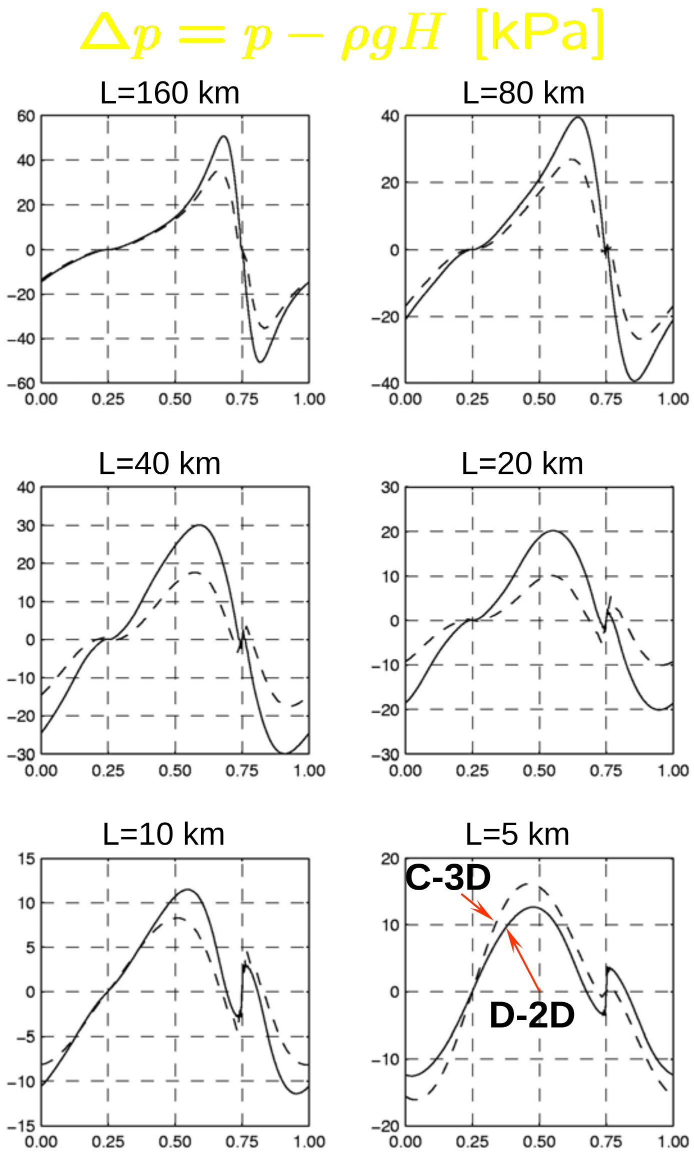
More variability between models compared to A and B

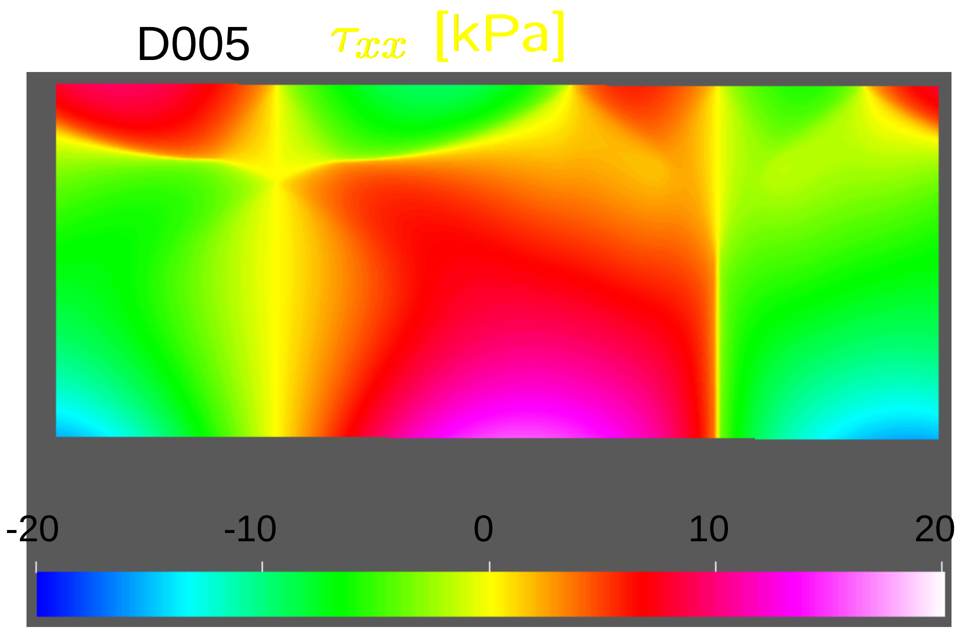
DP field distinct for FS models



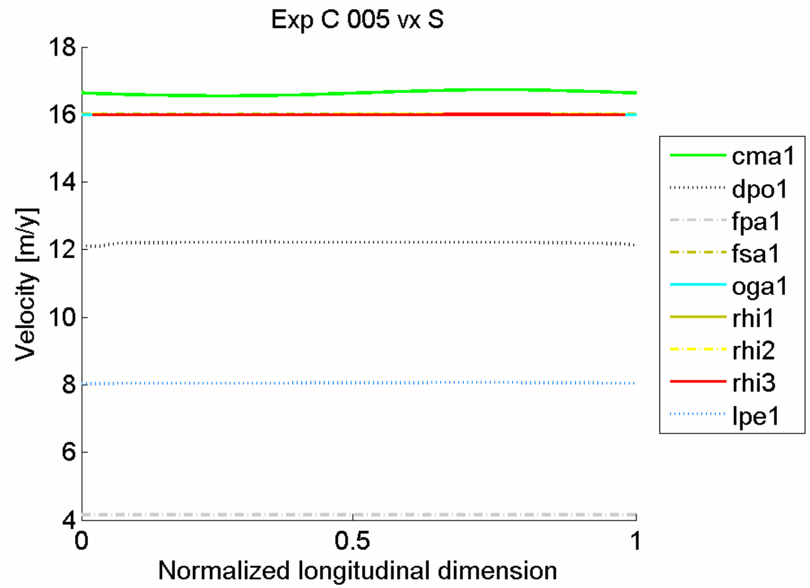


Tests C and D



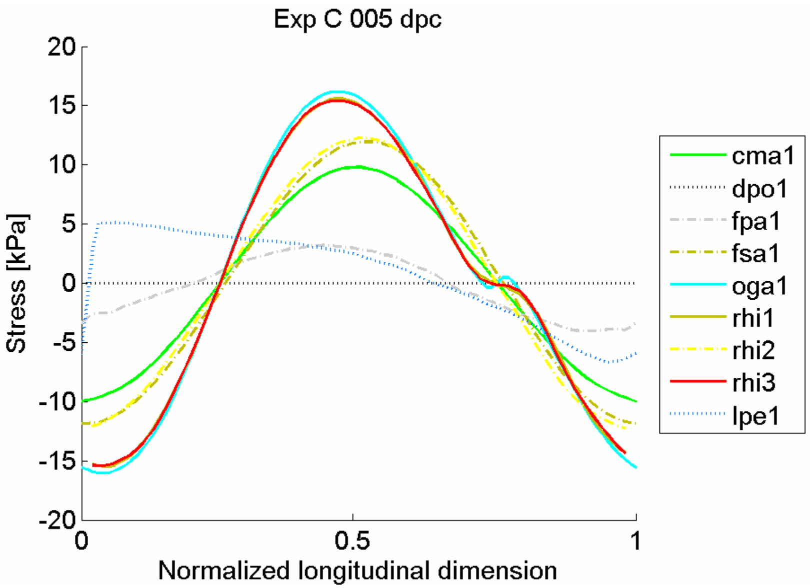


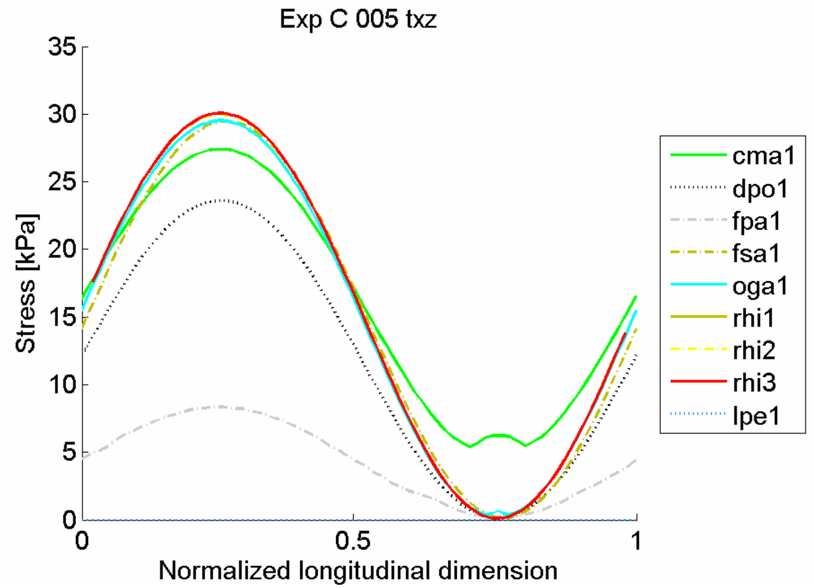
OGA



L=5:

Different levels of velocity





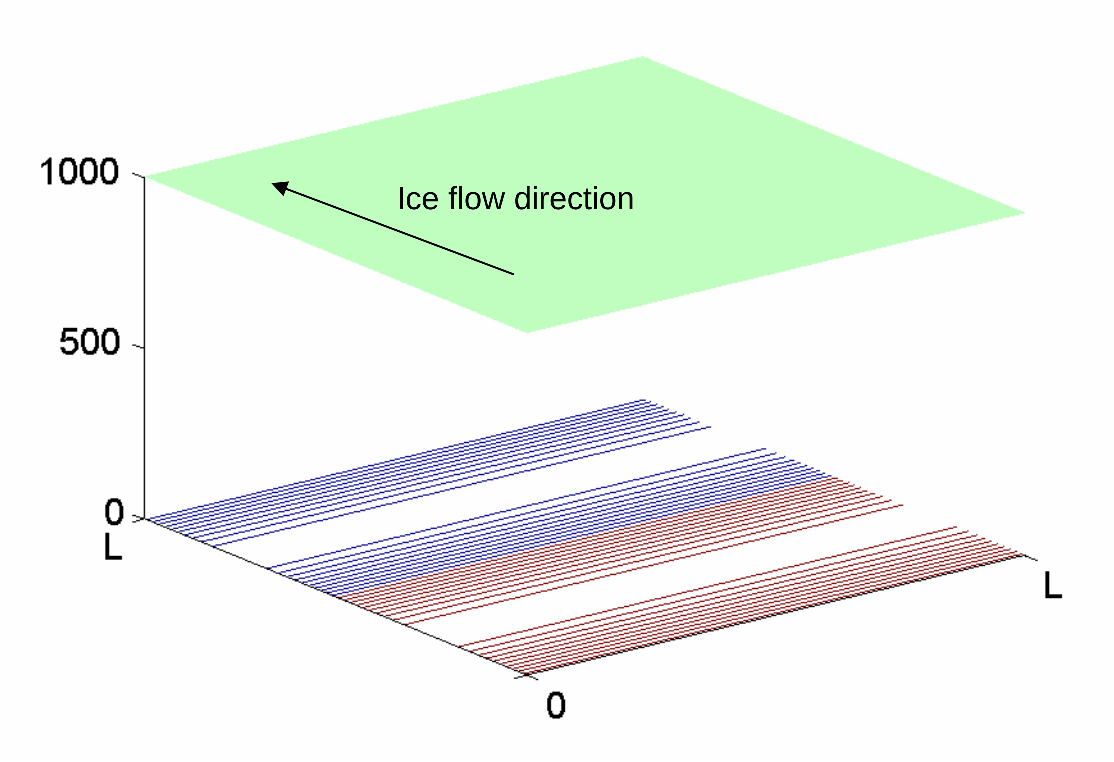
Experiment D

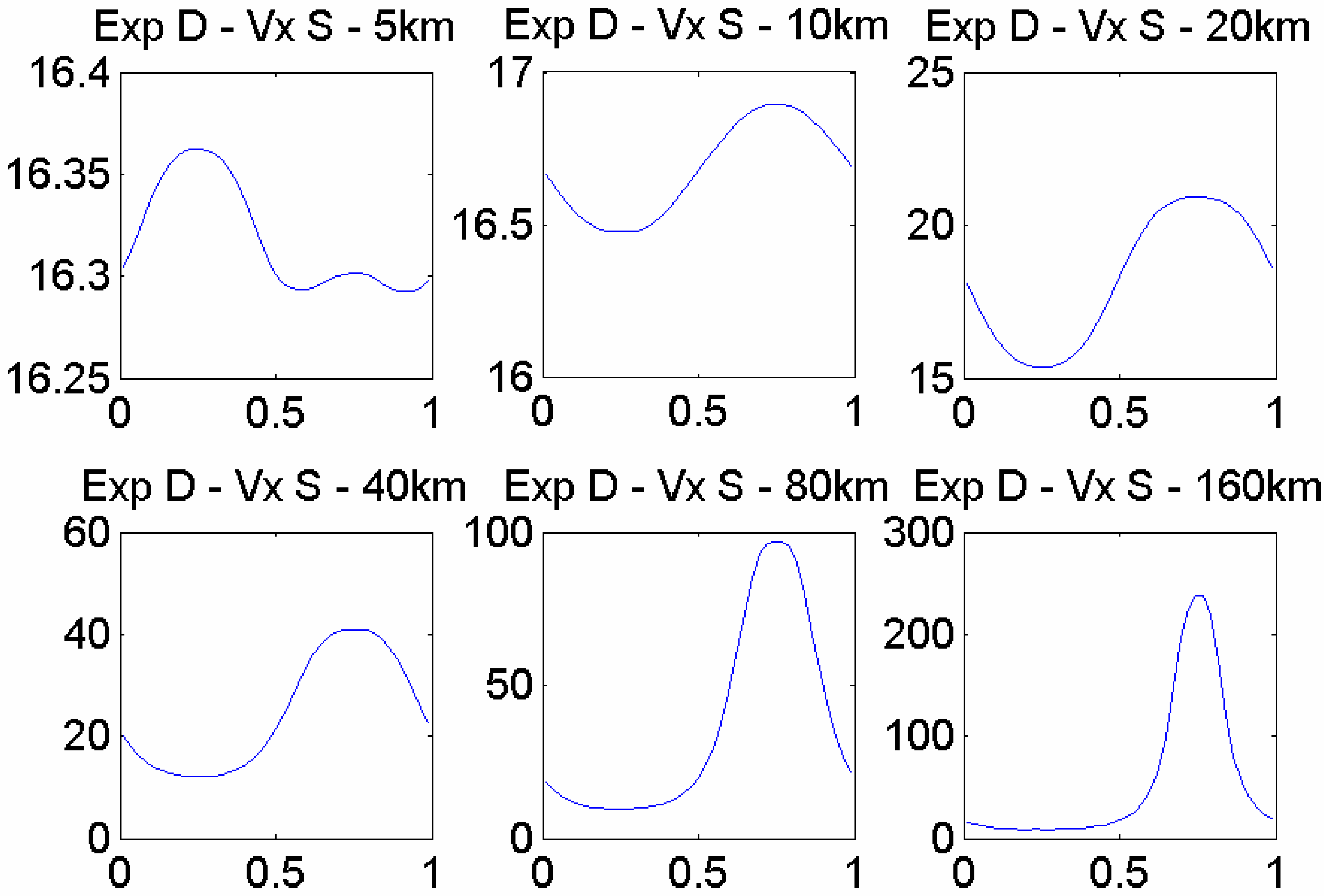
HHVF, HHVC, HHF, HVF & HVC

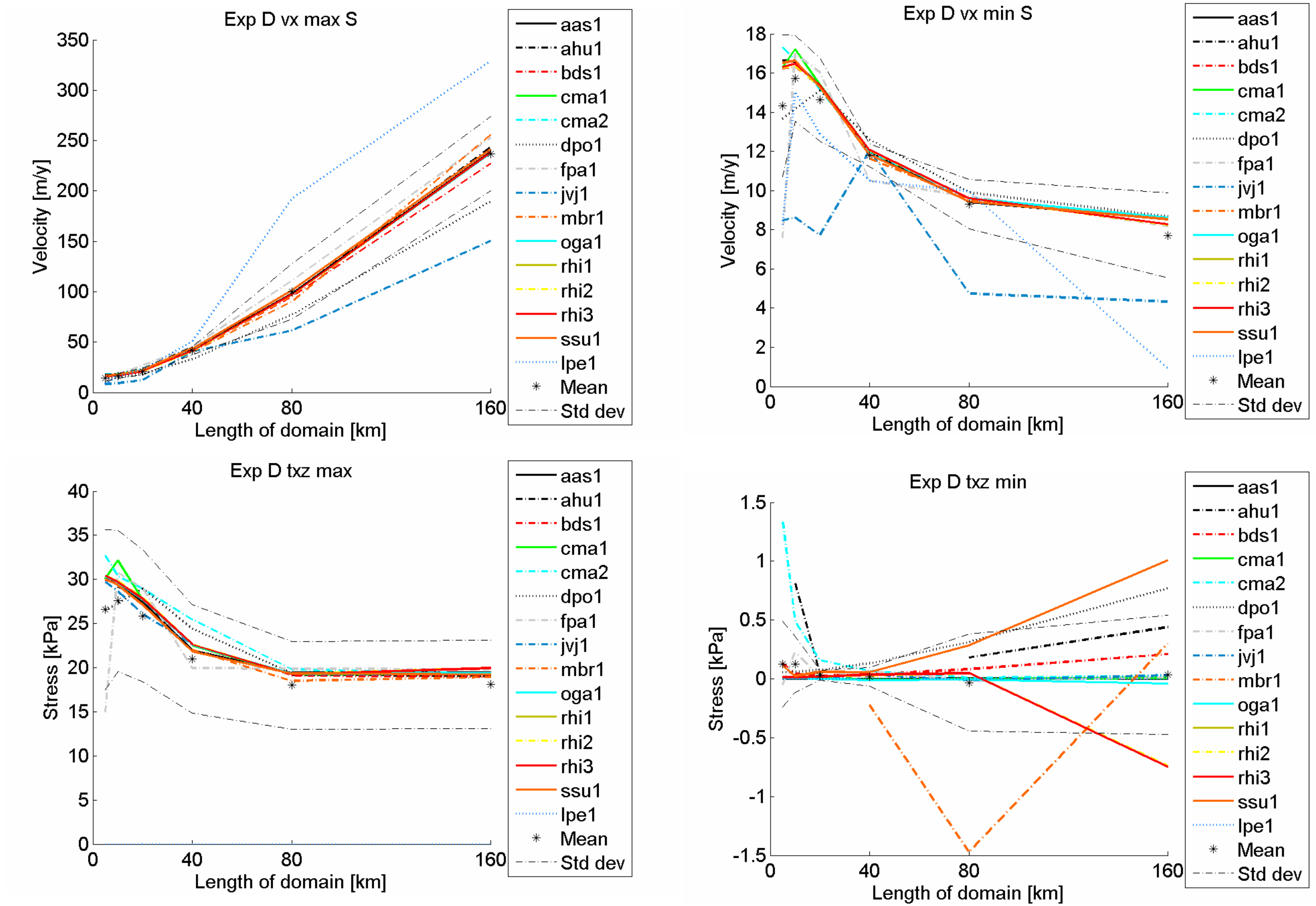
Ice stream flow II

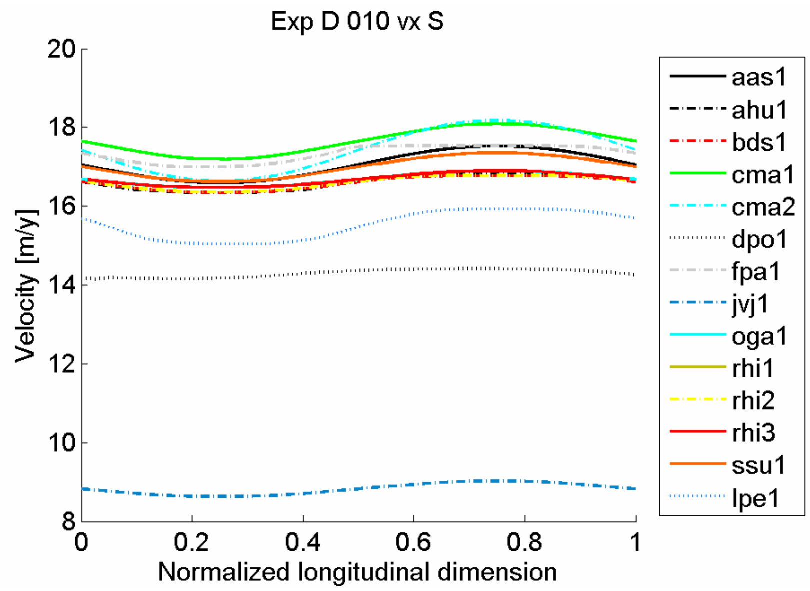
Length scale

L = 160, 80, 40, 20, 10, 5 km



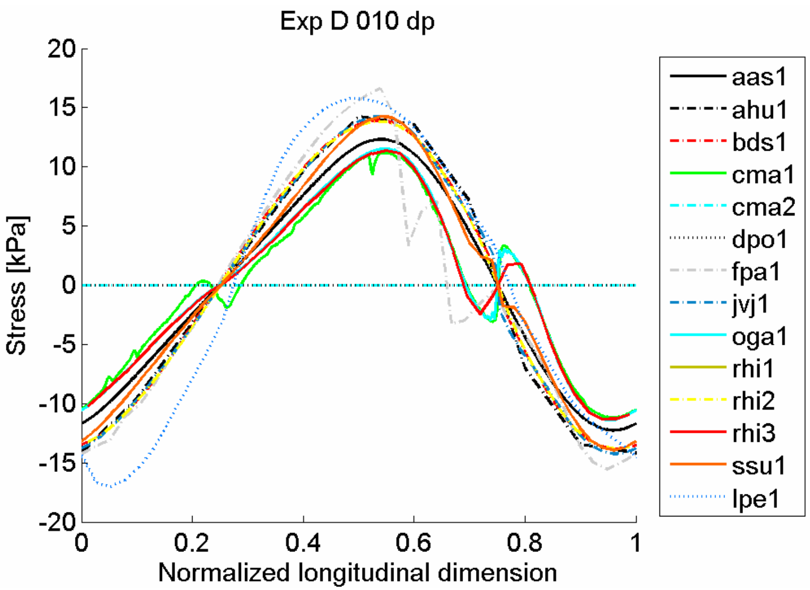

Exp D - Vx S - 5km
Exp D - Vx S - 10km
Exp D - Vx S - 20km
Exp D - Vx S - 40km
Exp D - Vx S - 80km
Exp D - Vx S - 160km
16.4
16.35
16.3
16.25
17
16.5
16
25
20
15
60
40
20
0
100
50
0
300
200
100
0
0
0.5
1

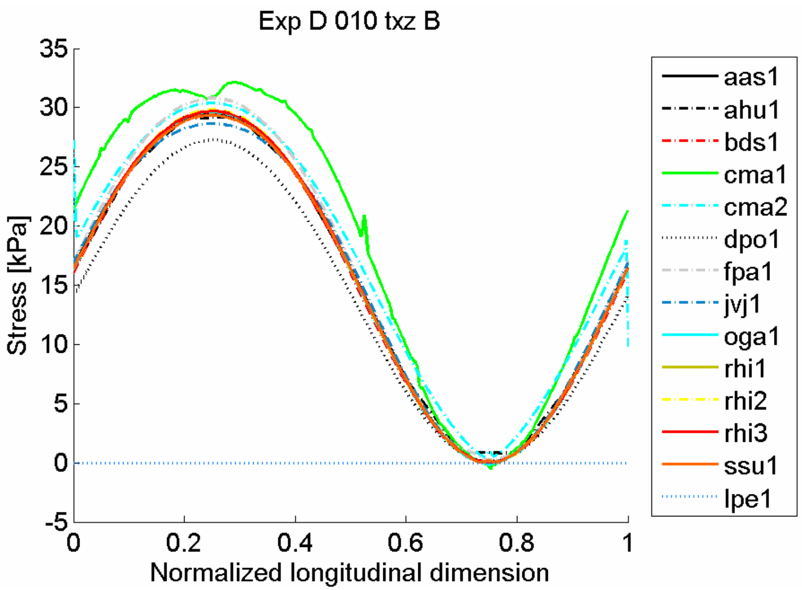

Exp D vx max S
Velocity [m/y]
Length of domain [km]
0
50
100
150
200
250
300
350
0
40
80
160
aas1
ahu1
bds1
cma1
cma2
dpo1
fpa1
jvj1
mbr1
oga1
rhi1
rhi2
rhi3
ssu1
lpe1
Mean
Std dev
Exp D vx min S
Velocity [m/y]
Length of domain [km]
0
2
4
6
8
10
12
14
16
18
0
40
80
160
aas1
ahu1
bds1
cma1
cma2
dpo1
fpa1
jvj1
mbr1
oga1
rhi1
rhi2
rhi3
ssu1
lpe1
Mean
Std dev
Exp D txz max
Stress [kPa]
Length of domain [km]
0
5
10
15
20
25
30
35
40
0
40
80
160
aas1
ahu1
bds1
cma1
cma2
dpo1
fpa1
jvj1
mbr1
oga1
rhi1
rhi2
rhi3
ssu1
lpe1
Mean
Std dev
Exp D txz min
Stress [kPa]
Length of domain [km]
-1.5
-1
-0.5
0
0.5
1
1.5
0
40
80
160
aas1
ahu1
bds1
cma1
cma2
dpo1
fpa1
jvj1
mbr1
oga1
rhi1
rhi2
rhi3
ssu1
lpe1
Mean
Std dev

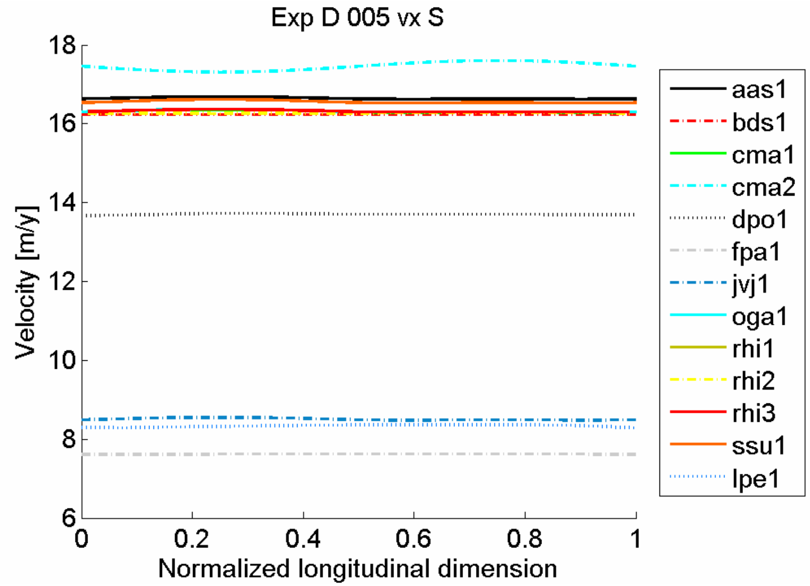


L=5:

Similar remarks

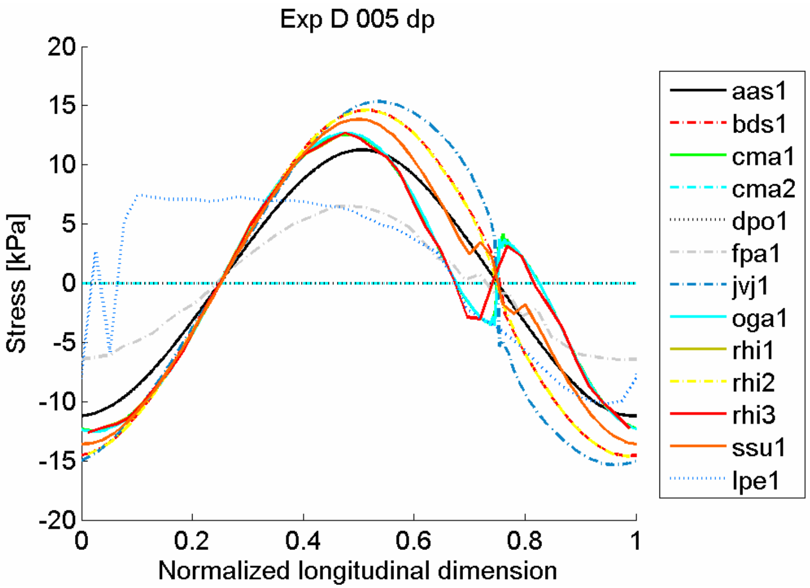


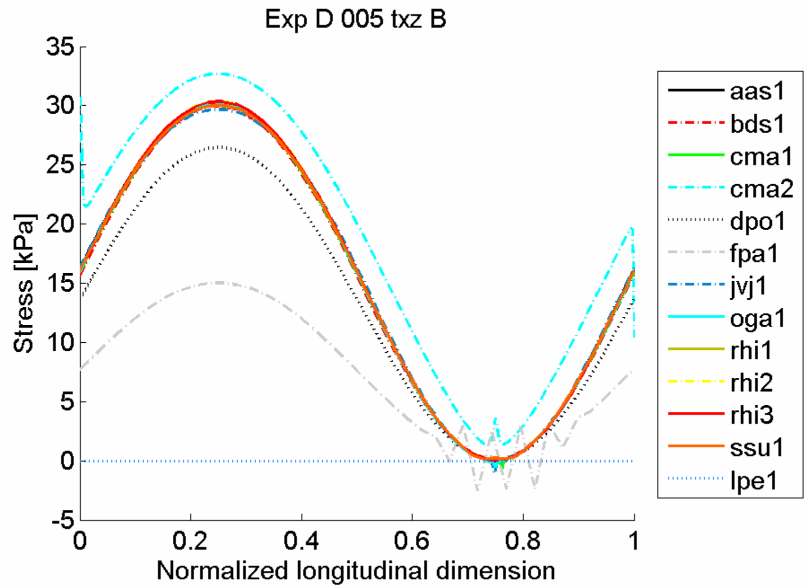




L=5:

Clear distinction in behaviour between HO and FS models: also inversion as in experiment B





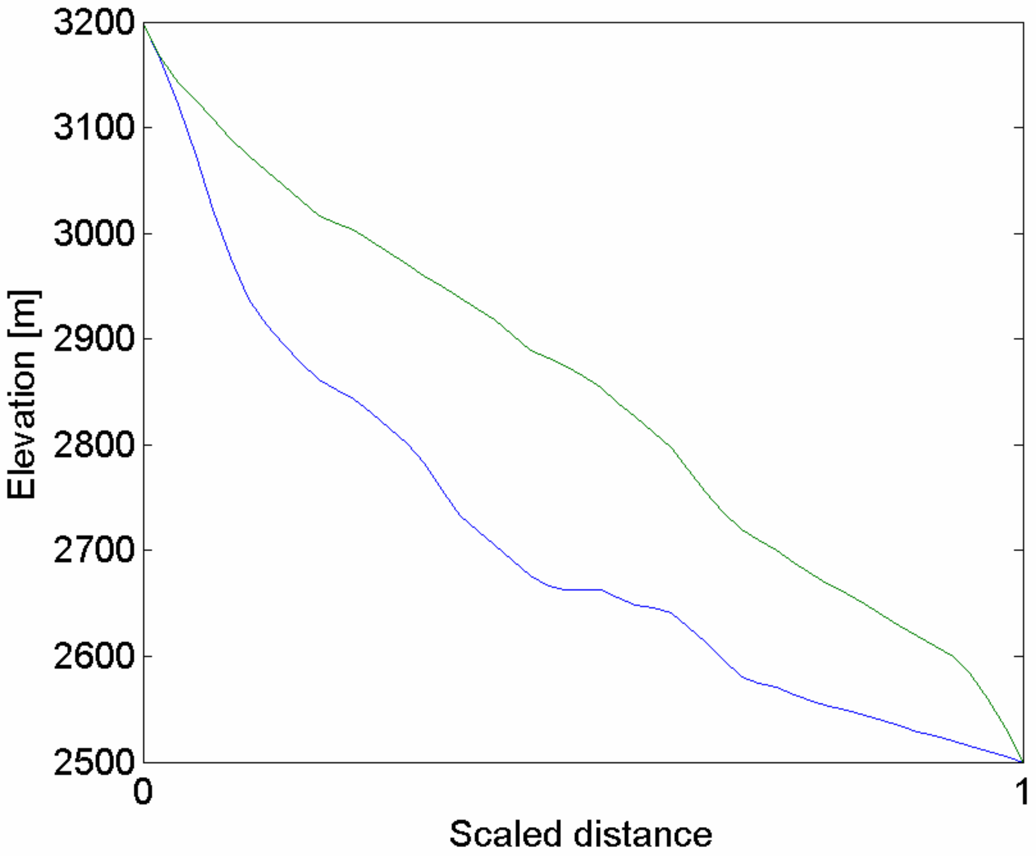
Experiment E

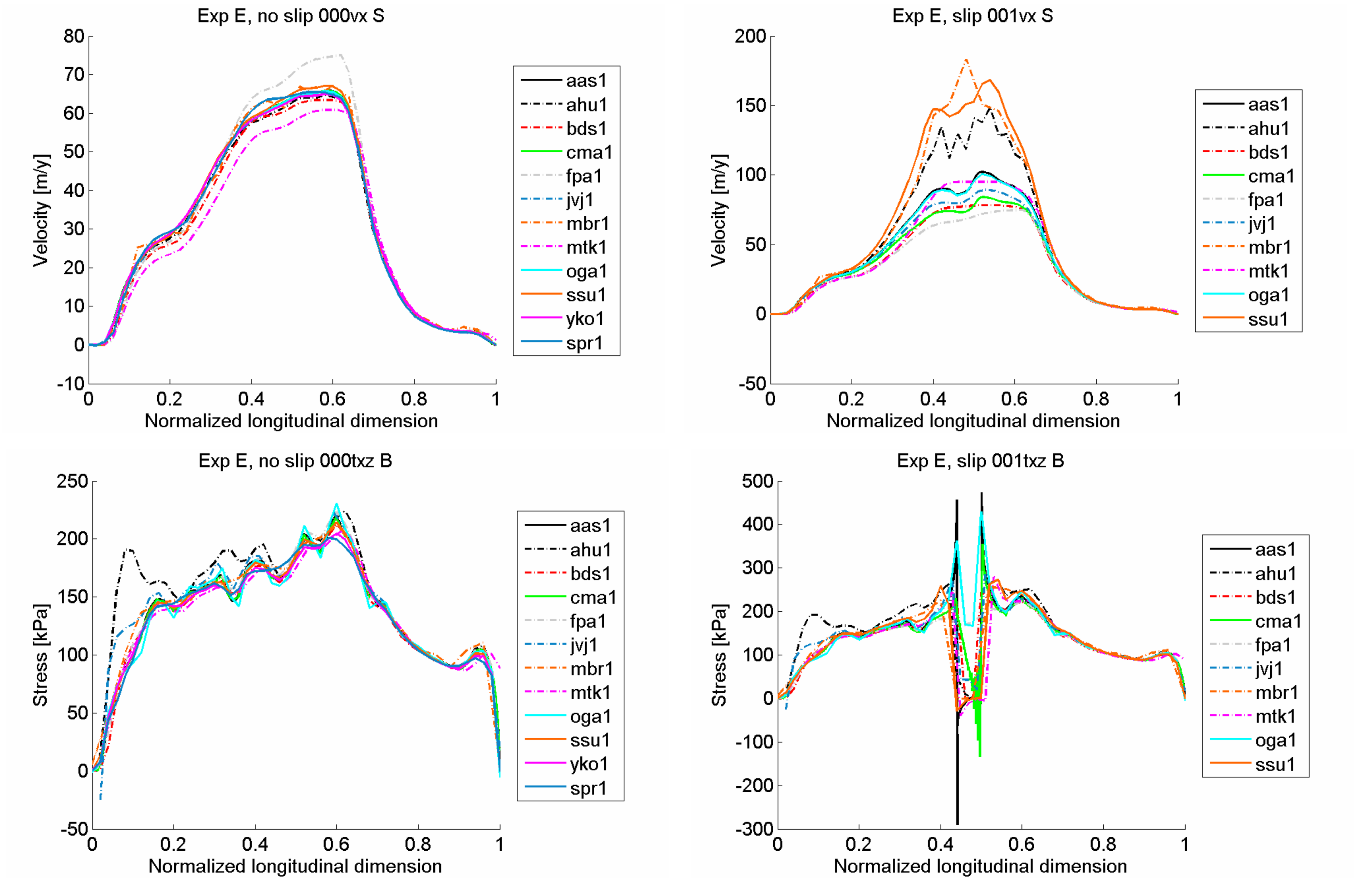
HVC & HVF

Haut Glacier d'Arolla

Input for the model is formed by the longitudinal surface and bedrock profiles

Introduction of a zone with reduced basal friction




Exp E, no slip 000vx S
Velocity [m/y]
Normalized longitudinal dimension
Exp E, slip 001vx S
Velocity [m/y]
Normalized longitudinal dimension
Exp E, no slip 000txz B
Stress [kPa]
Normalized longitudinal dimension
Exp E, slip 001txz B
Stress [kPa]
Normalized longitudinal dimension
aas1
ahu1
bds1
cma1
fpa1
jvj1
mbr1
mtk1
oga1
ssu1
yko1
spr1

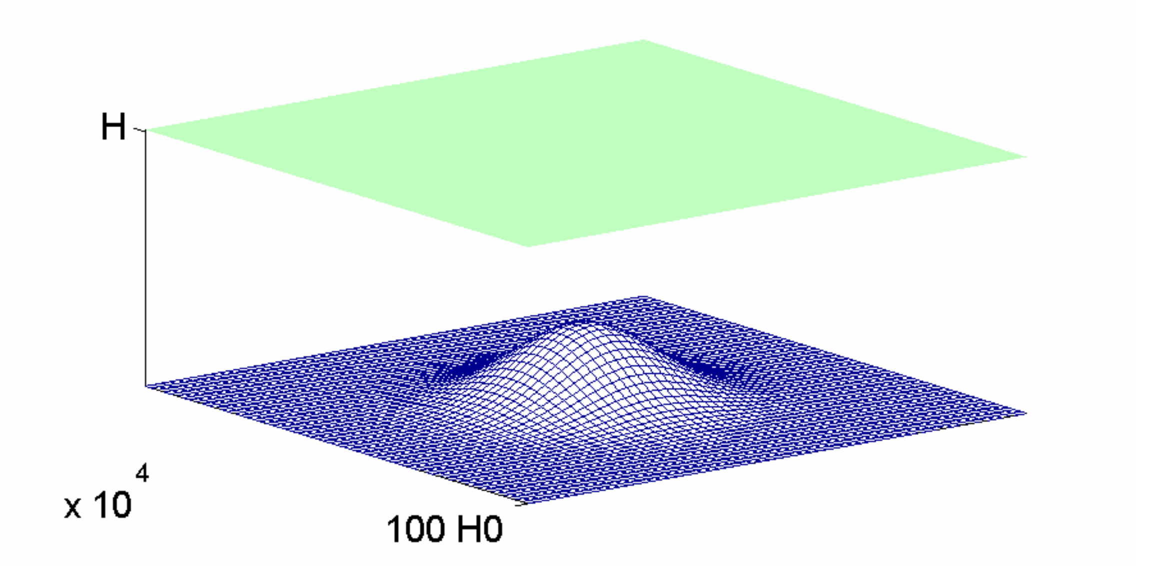
Experiment F

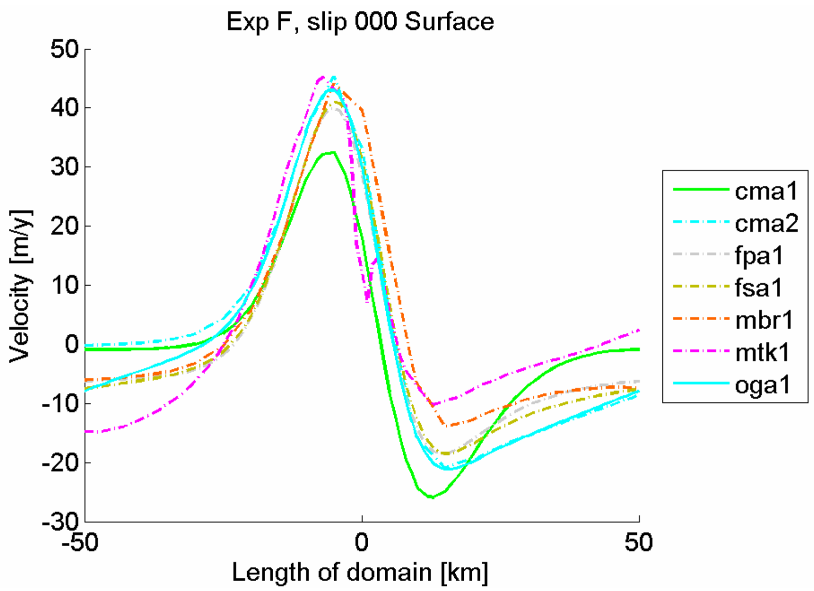
HHVF & HHVC

Prognostic experiment

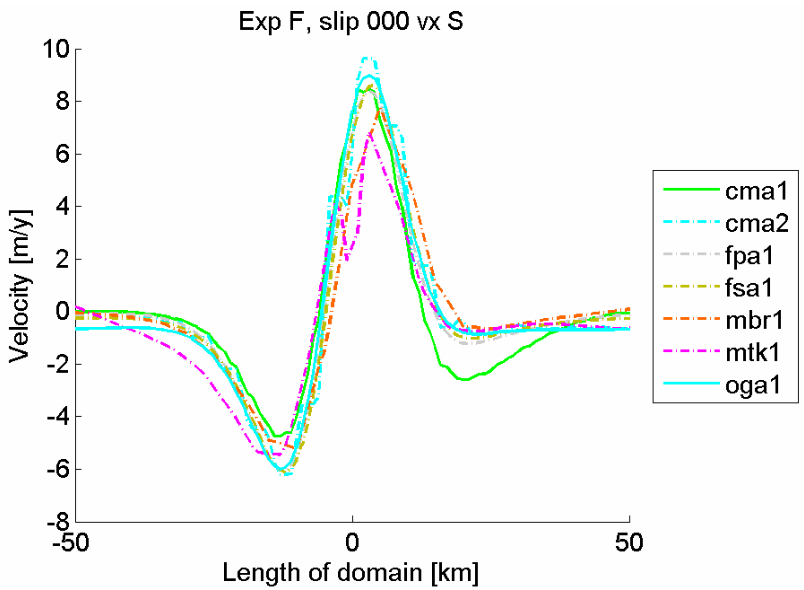
Gaussian perturbation on bed surface

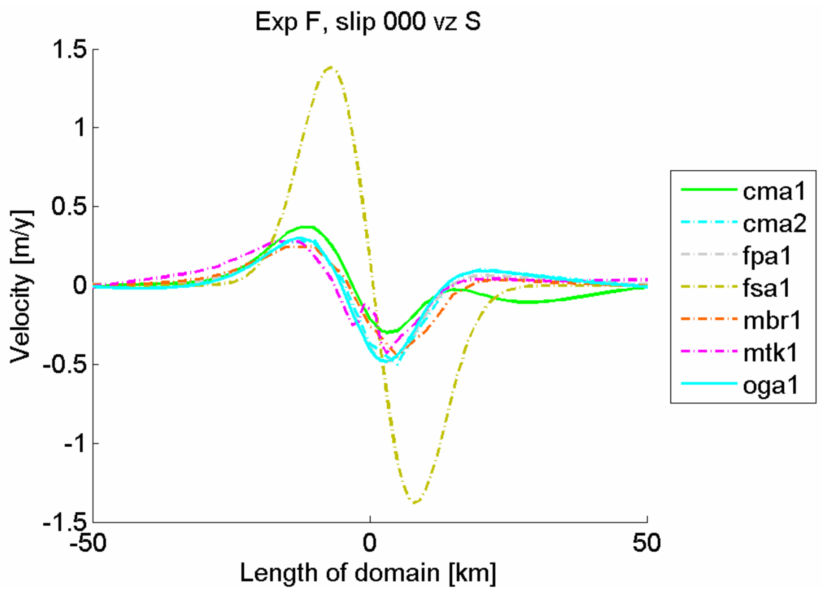
Calculate steady-state surface and velocity fields for different slip ratios: c = 0, 1 and 10

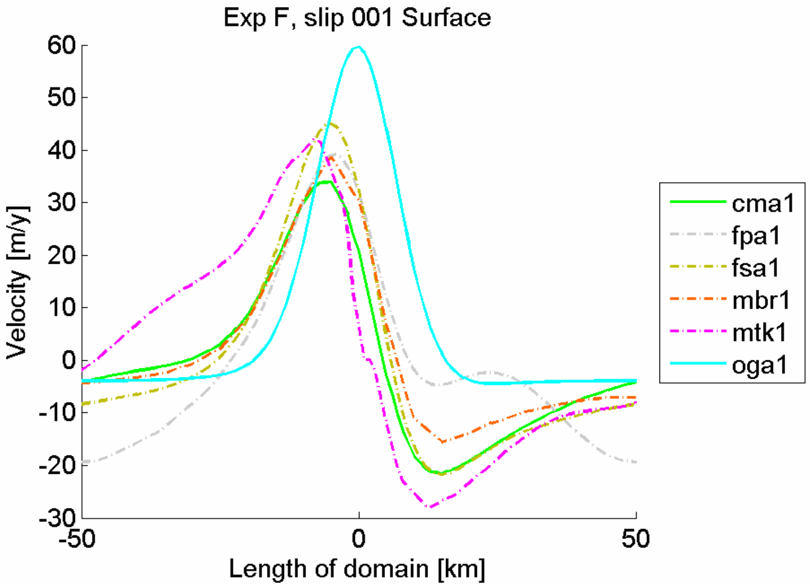



Exp F, slip 000 Surface
Velocity [m/y]
Length of domain [km]
50
40
30
20
10
0
-10
-20
-30
-50
0
50
cma1
cma2
fpa1
fsa1
mbr1
mtk1
oga1

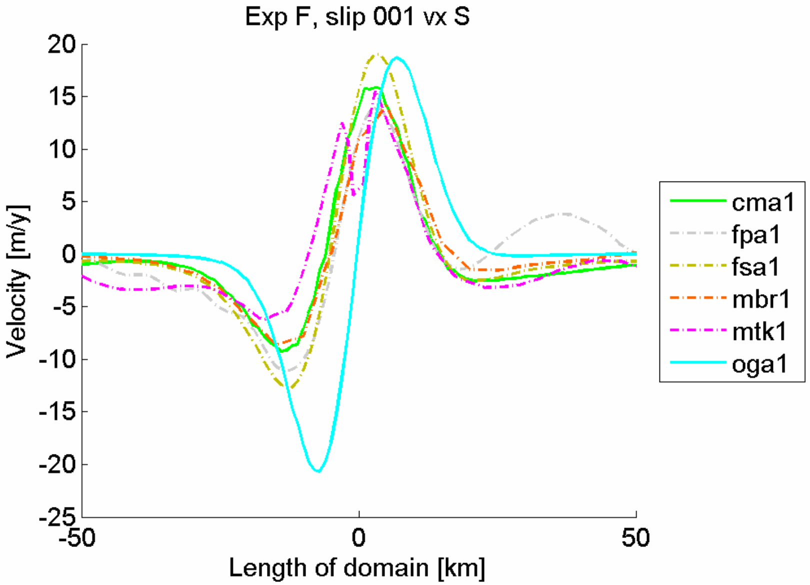
No slip

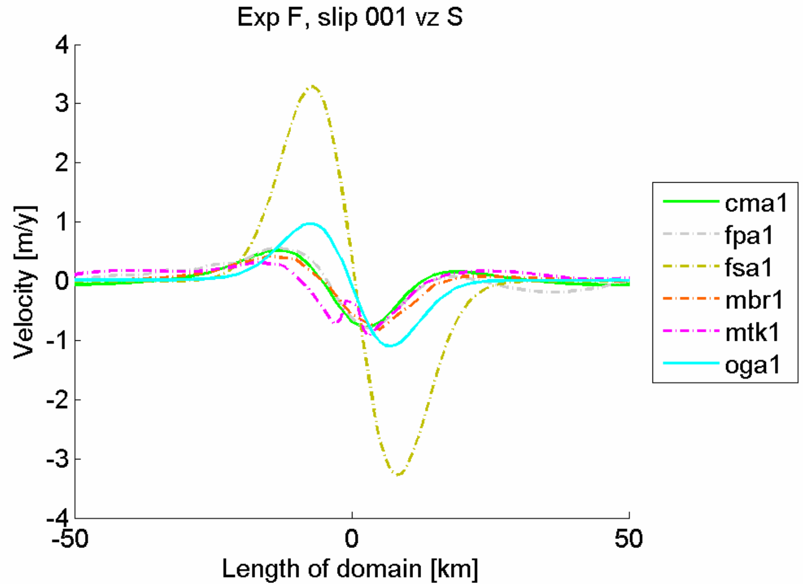

Exp F, slip 000 vx S
Velocity [m/y]
Length of domain [km]
10
8
6
4
2
0
-2
-4
-6
-8
-50
0
50
cma1
cma2
fpa1
fsa1
mbr1
mtk1
oga1


Exp F, slip 000 vz S
Velocity [m/y]
Length of domain [km]
1.5
1
0.5
0
-0.5
-1
-1.5
-50
0
50
cma1
cma2
fpa1
fsa1
mbr1
mtk1
oga1

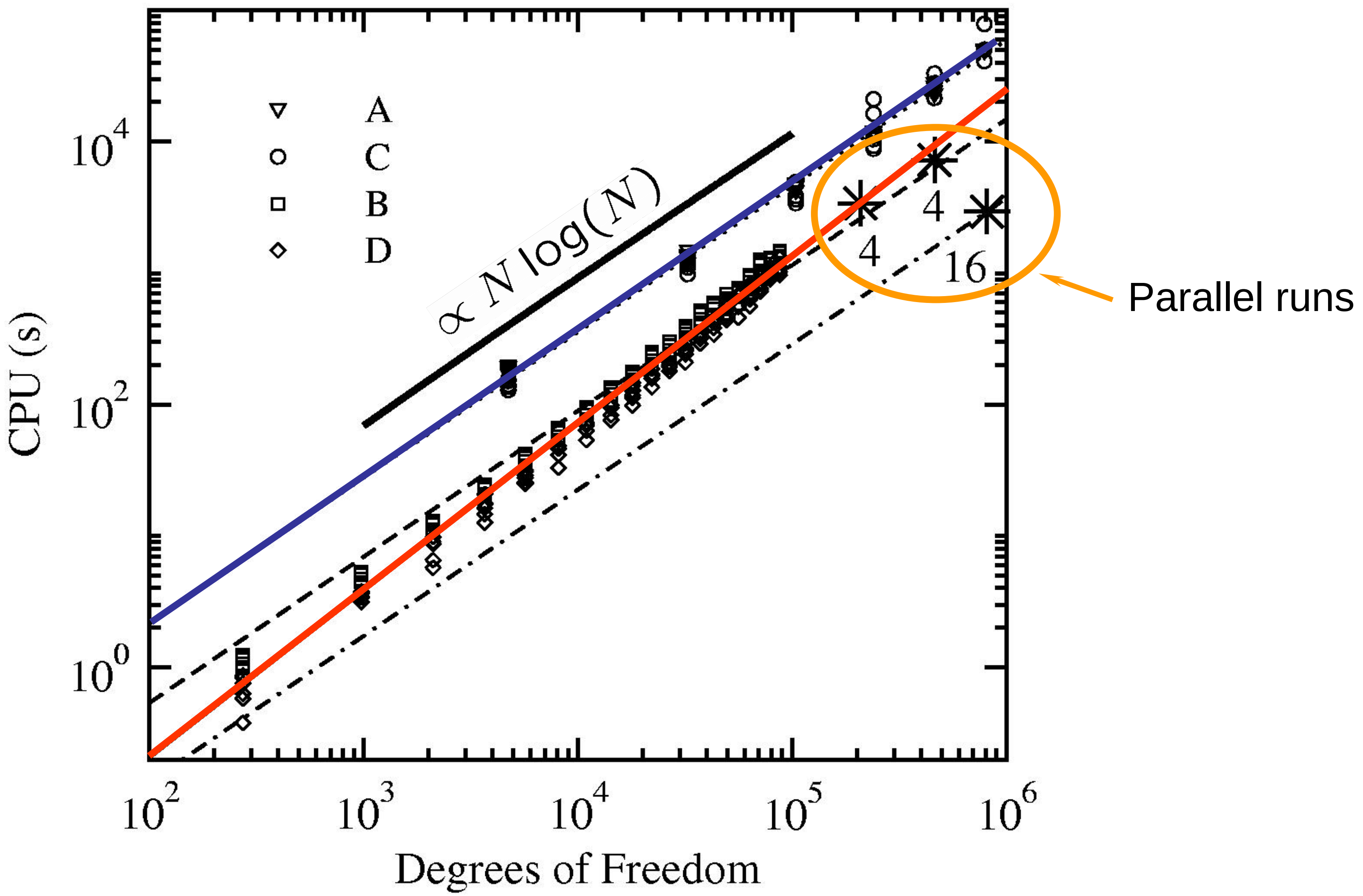

Exp F, slip 001 Surface
Velocity [m/y]
Length of domain [km]
cma1
fpa1
fsa1
mbr1
mtk1
oga1

Slip


Exp F, slip 001 vx S
Velocity [m/y]
Length of domain [km]
cma1
fpa1
fsa1
mbr1
mtk1
oga1


Exp F, slip 001 vz S
Velocity [m/y]
Length of domain [km]
cma1
fpa1
fsa1
mbr1
mtk1
oga1

CPU versus degrees of freedom

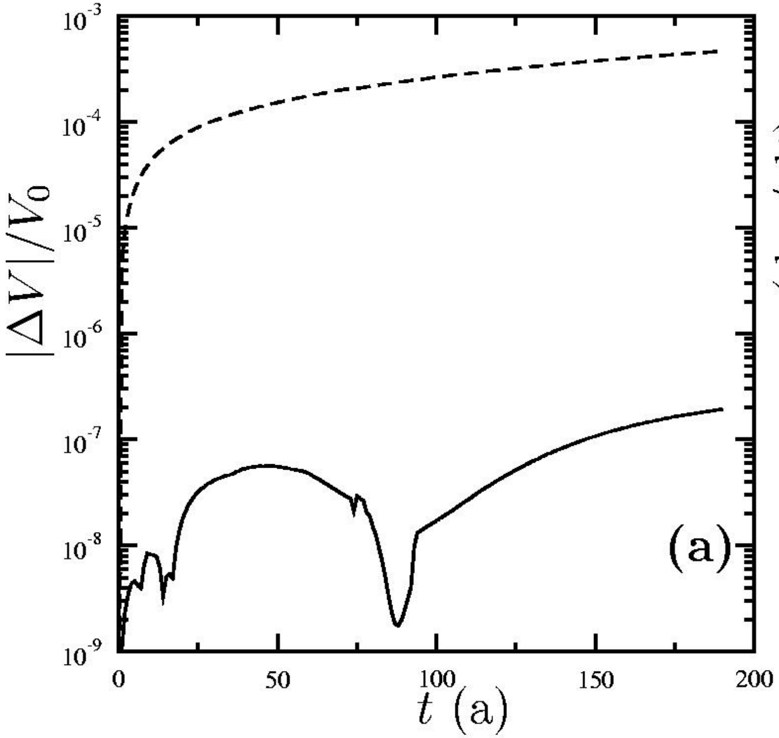


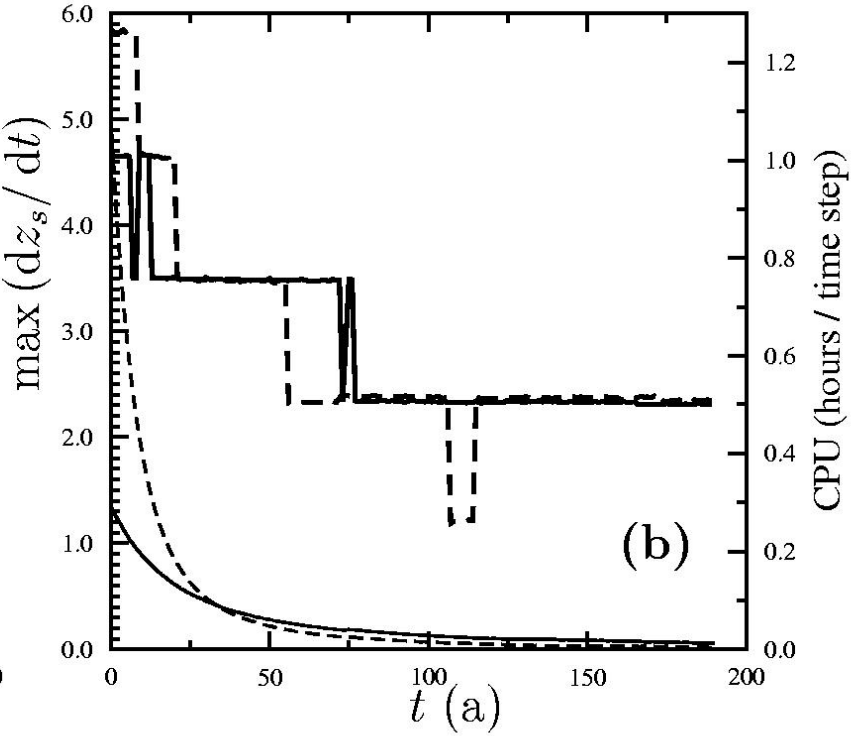
Prognostic test F

$c = 0$ No Sliding

$c = 1$ Sliding

$dt = 1a$





Conclusions

Experiments A-D (ice flow over bumps – slippery spots) are definitely a benchmark that works well for longer length scales

Smaller length scales give problems, due to high viscosty changes

However, interesting features appear at smaller length scales (L=5): distinction between FS and HO models

Differences between models are not due to numerical approaches (FD, FV, FE, spectral), but either physical approximations or numerical problems/inaccuracies.