ISMIP-HOM: Results of the Higher-Order Ice Sheet Model Intercomparison Project

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We present the results of an intercomparison exercise for higher-order ice sheet models (ISMIP-HOM), i.e. models that incorporate further mechanical effects, principally longitudinal stress gradients, or the full Stokes problem. The purpose of these ISMIP-HOM tests is to fix benchmarks for future modeling attempts and to detect differences in the approaches to the full Stokes solutions. The experiments were designed in such a way so that higher order models could be tested for ice flow over a bumpy bed as well as over a slippery spot for different length scales. Numerical details, such as grid size and numerical scheme were completely free to choose. Periodic boundary conditions are applied.

The diagnostic experiments (A-B-C-D-E) are divided in three groups. Experiments A-B are based on ice-sheet flow and focus on the ice flow over bumpy and rippled beds on varying spatial scales, experiments C-D focus on ice-stream flow with varying basal friction, while experiment E is an application to the Haut Glacier d'Arolla geometry. Experiment F investigates the time dependent response of ice flow over a Gaussian bump with a linear flow law.

Overall, 16 participants submitted their results for 21 different models. These can be divided into four basic model types, i.e. Full Stokes models, Blatter Approximation based models (LMLa), L1L2 models and the MacAyeal model (L1L1). In Tab. 1, the number of participants is specified for the different types of higher-order models, according to the Hindmarsh (2004) classification scheme.

	Full Stokes	LMLa	L1L2	L1L1
Exp A	5	9	0	0
Exp B	7	9	0	0
Exp C	4	4	1	1
Exp D	6	7	1	1
Exp E	5	4	0	0
Exp F	2	5	0	0

Table 1: Number of participants for higher-order models used in ISMIP-HOM

Experiment A

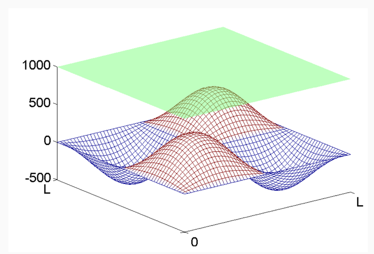

Figure 1: Geometry of Experiment A

- 3D ice-sheet flow over a bumpy bed
- Surface: $Z_s(x,y) = -x\tan(0.5°)$
- Bed: $Z_b(x,y) = Z_s(x,y) - 1000 + 500\sin(\frac{2\pi}{L}x)\sin(\frac{2\pi}{L}y)$
- $5\ km \leq L \leq 160\ km$ (normalized from 0 to 1)

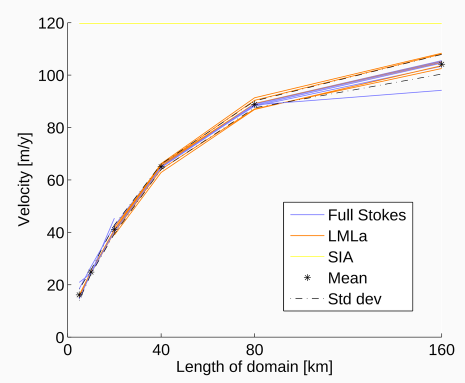

Figure 2: Velocity maxima at surface in the x direction

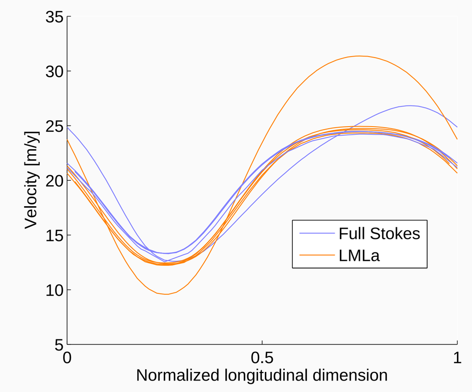

Figure 3: Velocity in the x direction for $y = 0.25$ and $L = 10\ km$

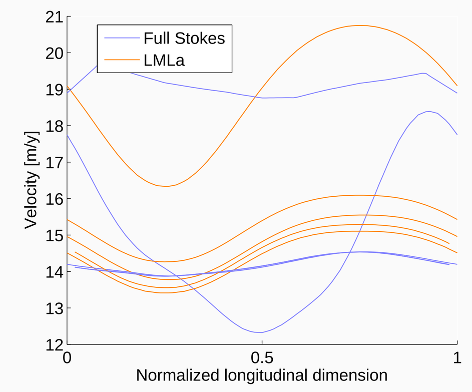

Figure 4: Velocity in the x direction for $y = 0.25$ and $L = 5\ km$.

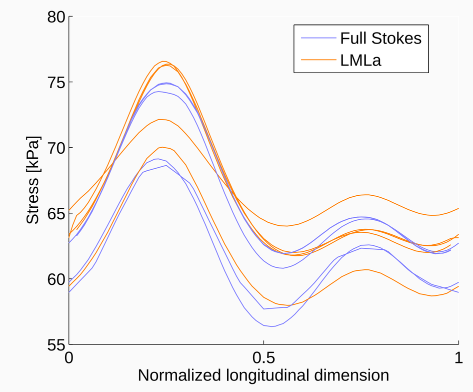

Figure 5: τ_{xz} shear stress for $y = 0.25$ and $L = 10\ km$.

Experiment B

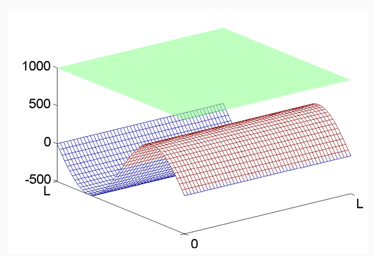

Figure 6: Geometry of experiment B.

- 2D ice-sheet flow over a rippled bed (flowline)
- Surface: $Z_s(x,y) = -x\tan(0.5°)$
- Bed: $Z_b(x,y) = Z_s(x,y) - 1000 + 500\sin(\frac{2\pi}{L}x)$
- $5\ km \leq L \leq 160\ km$ (normalized from 0 to 1)

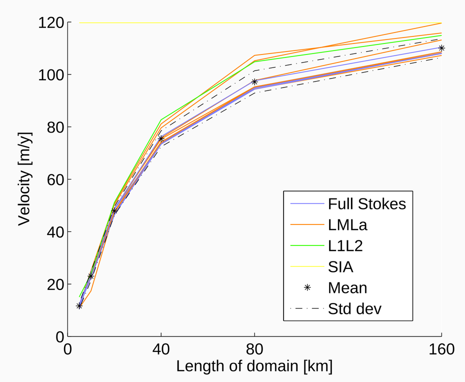

Figure 7: Velocity maxima at surface in the x direction.

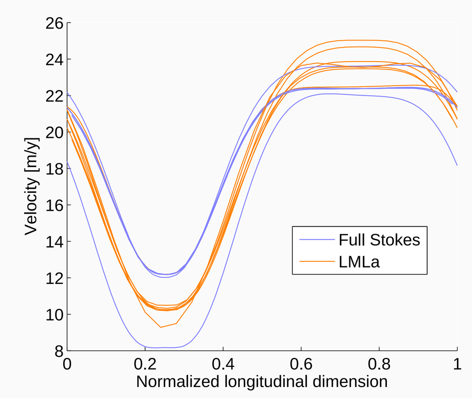

Figure 8: Velocity in the x direction for $y = 0.25$ and $L = 10\ km$.

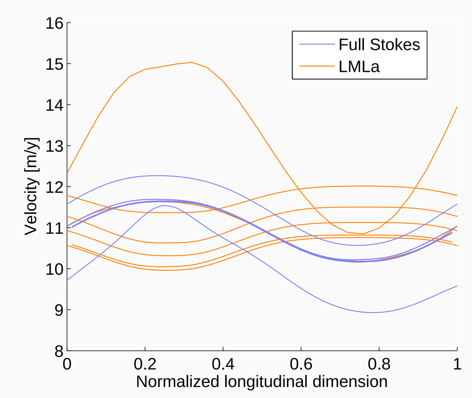

Figure 9: Velocity in the x direction for $y = 0.25$ and $L = 5\ km$.

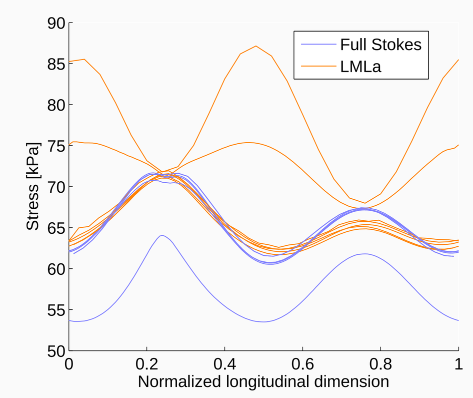

Figure 10: τ_{xz} shear stress for $y = 0.25$ and $L = 10\ km$.

Experiment C

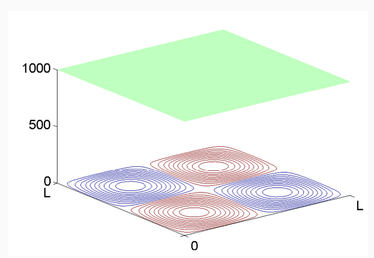

Figure 11: Geometry of experiment C.

- 3D ice stream flow over a slippery bed
- Surface: $Z_s(x,y) = -x\tan(0.1°)$
- Bed: $Z_b(x,y) = Z_s(x,y) - 1000$
- Sliding: $\beta^2(x,y) = 1000 + 1000\sin(\frac{2\pi}{L}x)\sin(\frac{2\pi}{L}y)$
- $5\ km \leq L \leq 160\ km$ (normalized from 0 to 1)

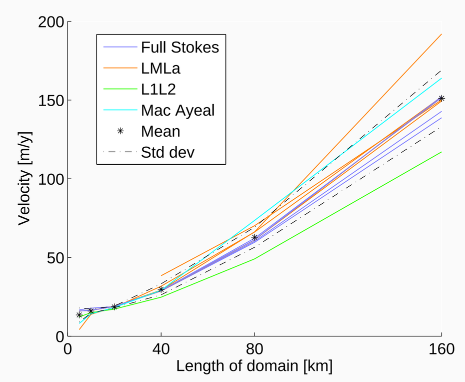

Figure 12: Velocity maxima at surface in the x direction.

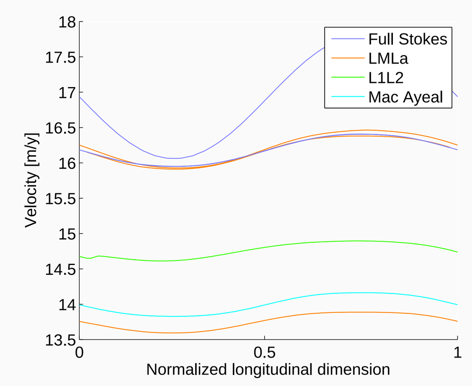

Figure 13: Velocity in the x direction for $y = 0.25$ and $L = 10\ km$.

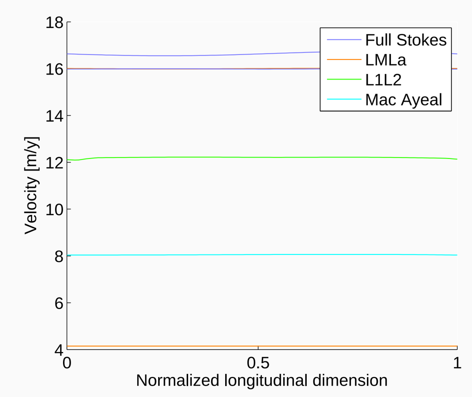

Figure 14: Velocity in the x direction for $y = 0.25$ and $L = 5\ km$.

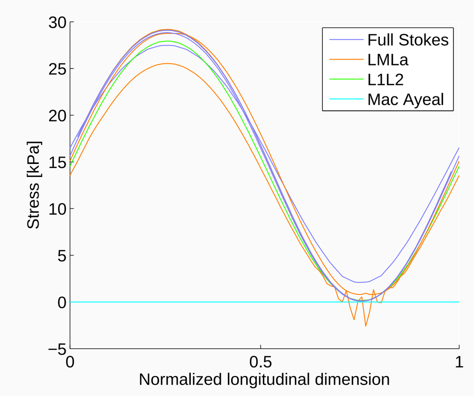

Figure 15: τ_{xz} shear stress for $y = 0.25$ and $L = 10\ km$.

Experiment D

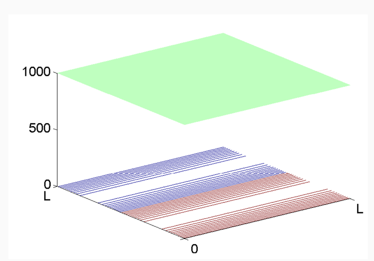

Figure 16: Geometry of experiment D.

- 2D ice stream flow over a slippery bed (flowline)
- Surface: $Z_s(x,y) = -x\tan(0.1°)$
- Bed: $Z_b(x,y) = Z_s(x,y) - 1000$
- $\beta^2(x,y) = 1000 + 1000\sin(\frac{2\pi}{L}x)$
- $5\ km \leq L \leq 160\ km$ (normalized from 0 to 1)

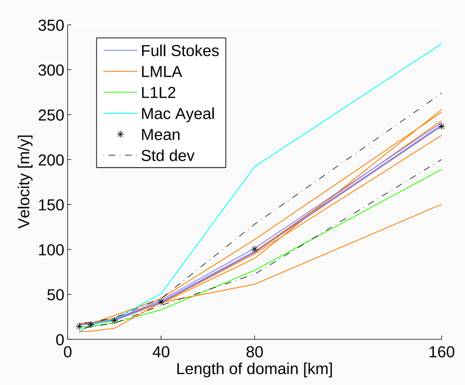

Figure 17: Velocity maxima at surface in the x direction.

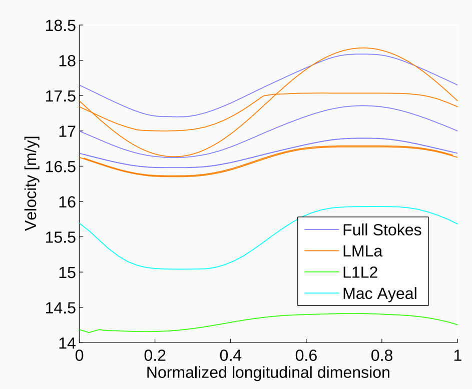

Figure 18: Velocity in the x direction for $y = 0.25$ and $L = 10\ km$.

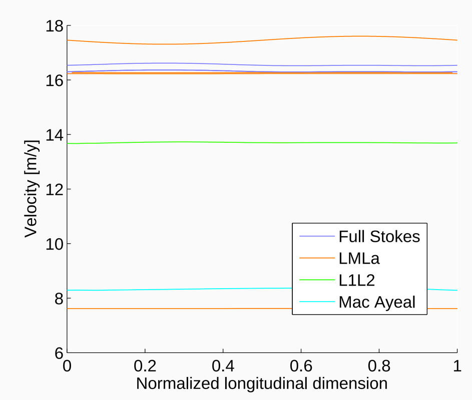

Figure 19: Velocity in the x direction for $y = 0.25$ and $L = 5\ km$.

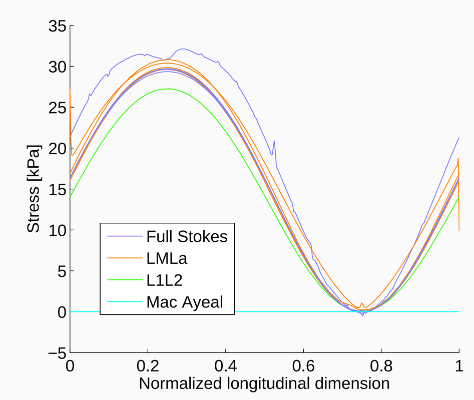

Figure 20: τ_{xz} shear stress for $y = 0.25$ and $L = 10\ km$.

Experiment E

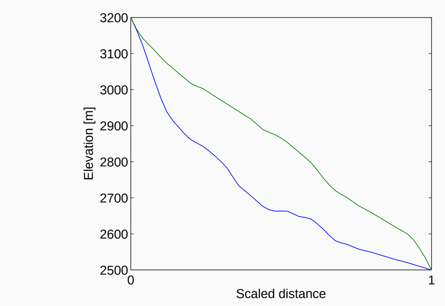

Figure 21: Geometry of Haut Glacier d'Arolla.

- Input data: longitudinal surface and bedrock profiles (Haut Glacier d'Arolla)
- Case 1: basal velocity = 0
- Case 2: zone of $\beta^2 = 0$ for $0.44 \leq x \leq 0.5$

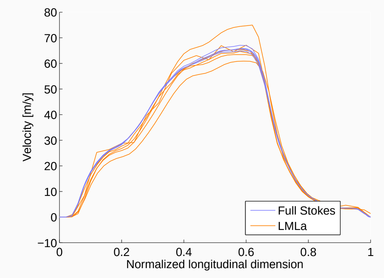

Figure 22: Velocity at surface along profile for case 1.

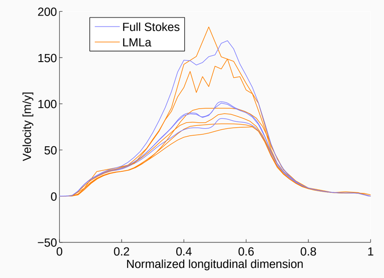

Figure 23: Velocity at surface along profile for case 2.

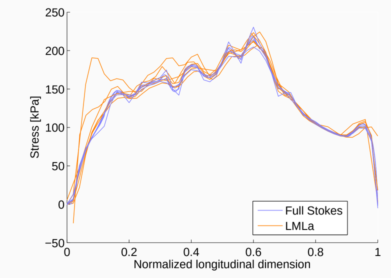

Figure 24: τ_{xz} along profile for case 1.

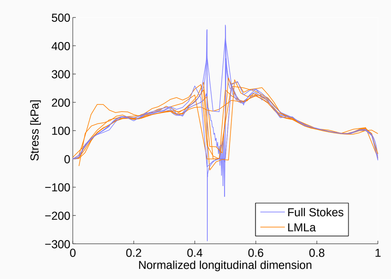

Figure 25: τ_{xz} along profile for case 2.

Experiment F

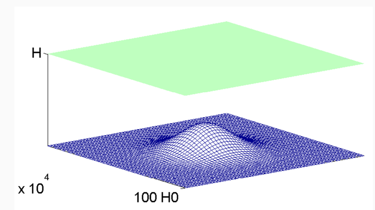

Figure 26: Geometry of experiment F : gaussian bump.

- Time dependent 3D ice flow over a bump
- Surface: slope of $3°$ in x direction
- Bed: slope and gaussian bump
- Case 1: no sliding
- Case 2: slip ratio=1 ($\beta^2 = (AH0)^{-1}$)

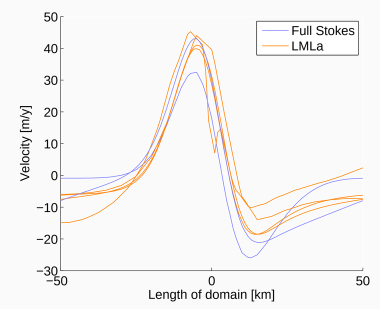

Figure 27: Surface elevation for case 1

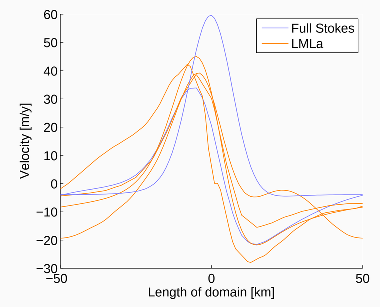

Figure 28: Surface elevation for case 2

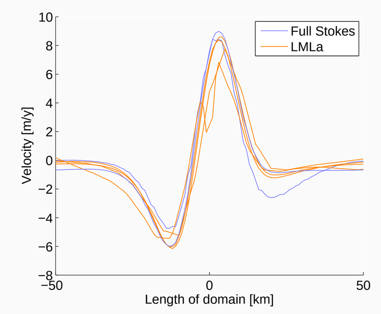

Figure 29: Velocity at surface in x direction for case 1

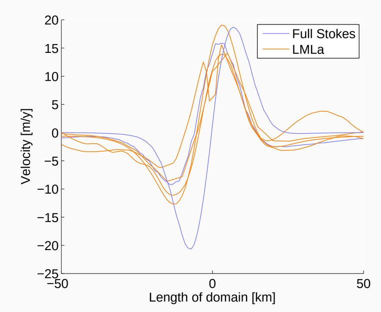

Figure 30: Velocity at surface in x direction for case 2

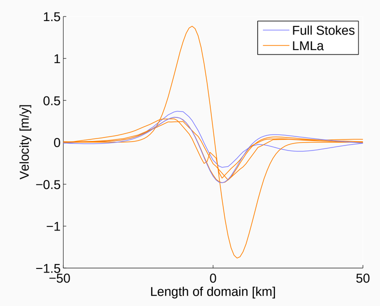

Figure 31: Velocity at surface in z direction for case 1

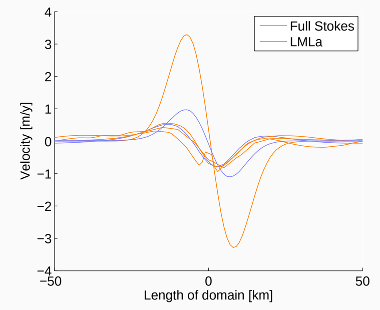

Figure 32: Velocity at surface in z direction for case 2

1. The ISMIP-HOM exercise can be regarded as a true benchmark experiment. The participating models simulate velocity fields with relatively high confidence (low standard deviation).
2. Differences between model types are observed for smaller length scales. At $L = 5\ km$, Full Stokes velocity and stress fields deviate significantly from higher-order ice sheet model results.
3. The benchmark tests are not influenced by numerics such as grid size or numerical methods (FEM, FDM or spectral methods), but differences might be due to employed numerical schemes (e.g. staggered grid).
4. Convergence of experiments with zero or no friction (C, D and E_{slip}) is generally poor; this might be due to the non-uniqueness of the solution with respect to boundary conditions.

References

[Hindmarsh, 2004] *A numerical comparison of approximations to the Stokes equations used in ice sheet and glacier modeling.* JGR, 2004.
[Pattyn and Payne, 2006] *Benchmark experiments for numerical higher-order ice-sheet models.* EGU Vienna, 2006.