

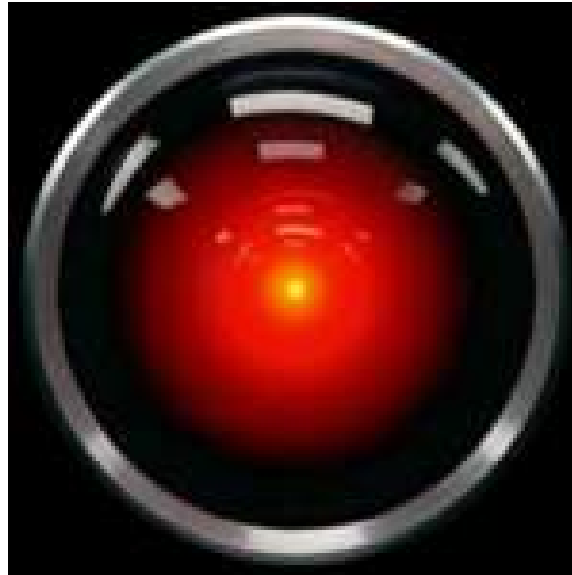


HOKKAIDO UNIVERSITY

Title	Ice-sheet model SICOPOLIS
Author(s)	Greve, Ralf
Relation	Ice flow modelling workshop. Niels Bohr Institute for Astronomy, Physics and Geophysics, University of Copenhagen, Denmark. 9-11 May 2007.
Issue Date	2007-05-09
Doc URL	https://hdl.handle.net/2115/34755
Type	conference presentation
File Information	Greve_2007_SICOPOLIS.pdf



Ice-sheet model SICOPOLIS



HAL 9000's iconic camera eye



Ralf Greve

*Institute of Low Temperature Science,
Hokkaido University, Sapporo, Japan*

SICOPOLIS

```

...
kx=KXMAX
kx=0
lgs_a0(kx) = ccb1+ccb2
lgs_a1(kx) = ccb1
lgs_a2(kx) = ccb3+ccb4
lgs_b(kx) = ccb3+ccb4
do kx=1, KXMAX-1
  lgs_a0(KXMAX+kx) = -0.5d0*(ct1(kx)-ct2(kx)-ct3(kx)-ct4(kx)) &
    -ct5(kx)*ct6(kx)
  lgs_a1(KXMAX+kx) = 1.0d0*ct5(kx)*(ct6(kx)+ct6(kx-1)) &
    -ct5(kx)*ct6(kx)
  lgs_a2(KXMAX+kx) = 0.5d0*(ct1(kx)-ct2(kx)-ct3(kx)-ct4(kx)) &
    -ct5(kx)*ct6(kx)
  #if ADV_HOR==1
    lgs_b(KXMAX+kx) = temp_c(kx,j,i) + ct7(kx) &
      -dti_2dxi* &
      ( vx_c(kx,j,i)-abs(vx_c(kx,j,i))) &
      *insq_g11_gx(j,i) &
      + (vx_c(kx,j,i-1)-abs(vx_c(kx,j,i-1))) &
      *insq_g11_gx(j,i-1) &
      *insq_g11_gx(j,i-1) &
      -dti_2deta* &
      ( vy_c(kx,j,i)-abs(vy_c(kx,j,i))) &
      *insq_g22_gy(j,i) &
      + (vy_c(kx,j,i-1)-abs(vy_c(kx,j,i-1))) &
      *insq_g22_gy(j,i-1) &
      *insq_g22_gy(j,i-1) &
  #elif ADV_HOR==2
    lgs_b(KXMAX+kx) = temp_c(kx,j,i) + ct7(kx) &
      -dti_dxi*(ftx_c_r(kx)-ftx_c_l(kx)) &
      -dti_deta*(fity_c_r(kx)-fity_c_l(kx))
  #endif
end do
kx=KXMAX
lgs_a0(KXMAX+kx) = 0.0d0
lgs_a1(KXMAX+kx) = 1.0d0
lgs_b(KXMAX+kx) = temp_s(j,i)
...

```

“Simulation Code for POLythermal Ice Sheets”

→ three-dimensional,
dynamic/thermodynamic,
prognostic,
large-scale ice sheet model
(written in Fortran 90).

Timeline

- 1993: 2-D flow-line version of SICOPOLIS applied to the Greenlandic EGIG line.
- 1994: First operational 3-D version of SICOPOLIS for the Greenland ice sheet.
- 1995: Version for the Antarctic ice sheet.
- 1996: EISMINT Phase 1 experiments.
- 1997: Version for the entire northern hemisphere.
- 1998: Version for the north-polar ice cap of Mars.
- 2000: EISMINT Phase 2 simplified-geometry experiments.

Timeline

2001: “Grand Unification”:

All versions included in a single program

→ SICOPOLIS V1.0.

2002: Module for the Fennoscandian ice sheet.

2004: Spatially variable geothermal heat flux implemented.

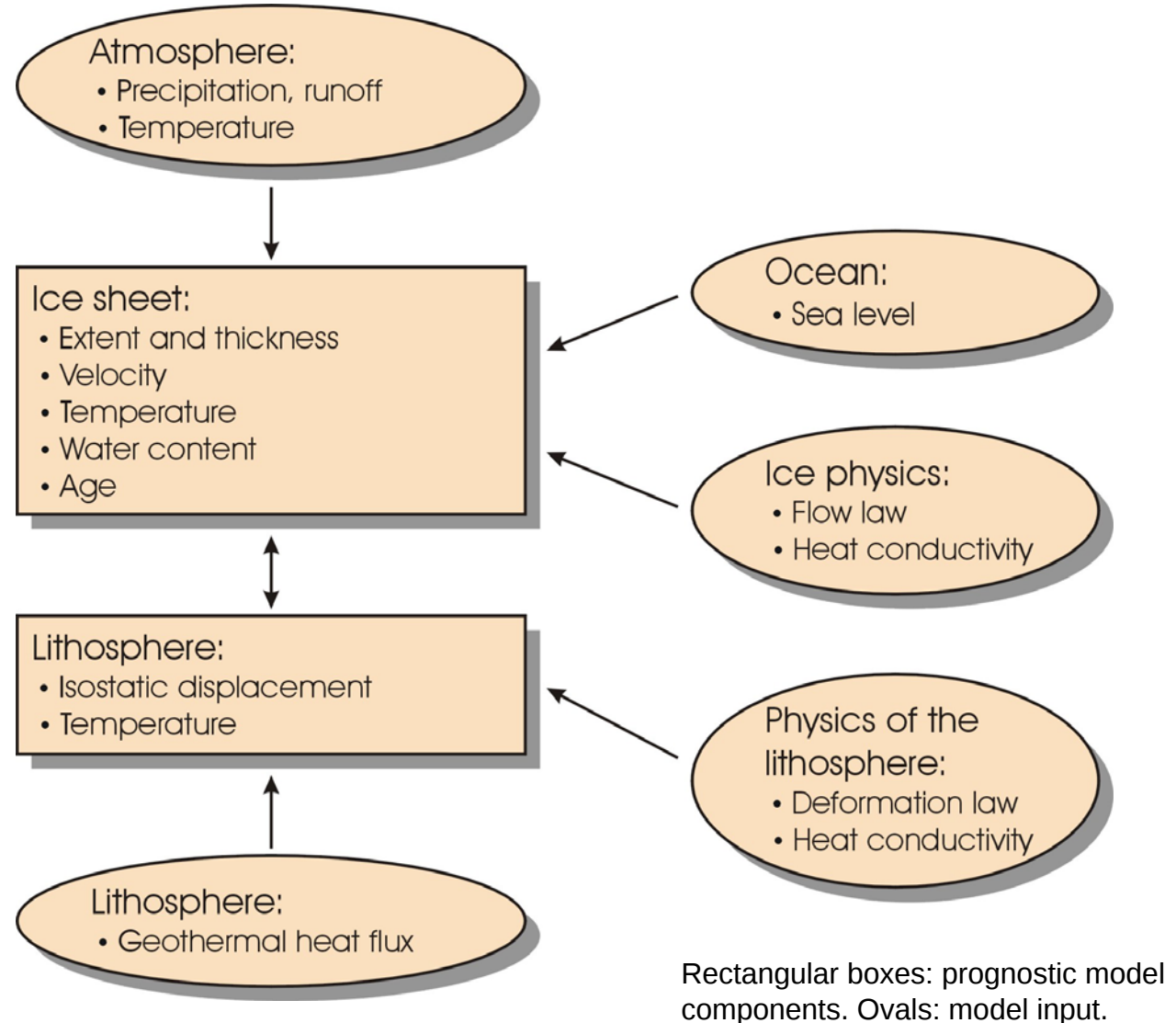
2005: Module for the south-polar ice cap of Mars.

2006: ISMIP HEINO experiments.

2007: Implementation of a simple treatment for the north-east ice stream of the Greenland ice sheet (NEGIS)

→ SICOPOLIS V2.8, current version.

Overview



Field equations (SIA)

- Non-linear viscous flow law (Glen):

$$D = EA(T', \omega) f(\sigma) \mathbf{t}^D, \quad f(\sigma) = \sigma^{n-1}, \quad n = 3$$

- Stresses:

$$p = \rho g(h - z), \quad (t_{xz}, t_{yz}) = -p \nabla h, \quad \sigma = \sqrt{t_{xz}^2 + t_{yz}^2}$$

- Horizontal velocity:

$$\mathbf{v}_h = \mathbf{v}_b - \left(2(\rho g)^n |\nabla h|^{n-1} \int_b^z A(T', \omega) (h - z')^n dz' \right) \times \nabla h$$

- Ice thickness equation:

$$\frac{\partial H}{\partial t} = -\nabla \cdot \mathbf{q} + a_s - a_b \quad \Rightarrow \quad \frac{\partial h}{\partial t} = \nabla \cdot (D \nabla h) + a_s - a_b + \frac{\partial b}{\partial t}$$

Field equations (SIA)

- Temperature equation (cold ice):

$$\frac{\partial T}{\partial t} + \mathbf{v} \cdot \text{grad } T = \frac{1}{\rho c} \frac{\partial}{\partial z} \left(\kappa \frac{\partial T}{\partial z} \right) + \frac{2}{\rho c} E A(T') \sigma^{n+1}$$

- Water-content equation (temperate ice):

$$\frac{\partial \omega}{\partial t} + \mathbf{v} \cdot \text{grad } \omega = \frac{2}{\rho L} E A(\omega) \sigma^{n+1} - D(\omega) + \text{CCC}$$

- Age:

$$\frac{\partial A}{\partial t} + \mathbf{v} \cdot \text{grad } A = 1$$

Field equations (lithosphere)

- Temperature equation:

$$\frac{\partial T}{\partial t} + \frac{\partial b}{\partial t} \frac{\partial T}{\partial z} = \frac{\kappa_r}{\rho_r c_r} \frac{\partial^2 T}{\partial z^2}$$

- Isostatic bedrock adjustment:

$$\text{LLRA: } \frac{\partial b}{\partial t} = -\frac{1}{\tau_{\text{iso}}} \left(b - \left(b_0 - \frac{\rho}{\rho_a} H \right) \right)$$

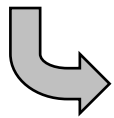
ELRA: Elastic thin-plate equation + relaxing asthenosphere

Boundary and transition conditions

- Free surface:
Surface temperature, surface mass balance (external forcing).
- Cold-temperate transition surface (CTS):
Continuity of temperature, no-slip,
energy balance ($\rightarrow$ Stefan-type matching condition).
- Ice base:
Continuity of temperature,
energy balance ($\rightarrow$ basal melting),
Weertman-type basal sliding.
- Lithosphere base:
Geothermal heat flux.

Boundary and transition conditions

- Margin:
Sea level surrounding the ice sheet.



Two options:

- Ice thickness set to zero at the coast.
- Marine-ice parameterization:
Ice can spread into the sea as long as
sea-bed elevation $\geq$ threshold value z_{mar} .

Causes sometimes problems... ☹

Orthogonal coordinates on the Earth's surface

- Contravariant coordinates x^1, x^2 on a sphere of radius R_e .
- Covariant metric tensor:

$$g = \begin{pmatrix} g_{11} & 0 \\ 0 & g_{22} \end{pmatrix}$$

- All model equations are re-formulated in the general coordinates x^1, x^2 .

Orthogonal coordinates on the Earth's surface

- Options:

Cartesian coordinates in the stereographic plane:

$$x^1 = x, \quad x^2 = y,$$

$$g_{11} = g_{22} = \frac{1}{K^2 \left(1 + \frac{x^2 + y^2}{(2R_e K)^2} \right)^2}, \quad K = \cos^2 \frac{\theta_0}{2}$$

standard parallel (in co-latitude)

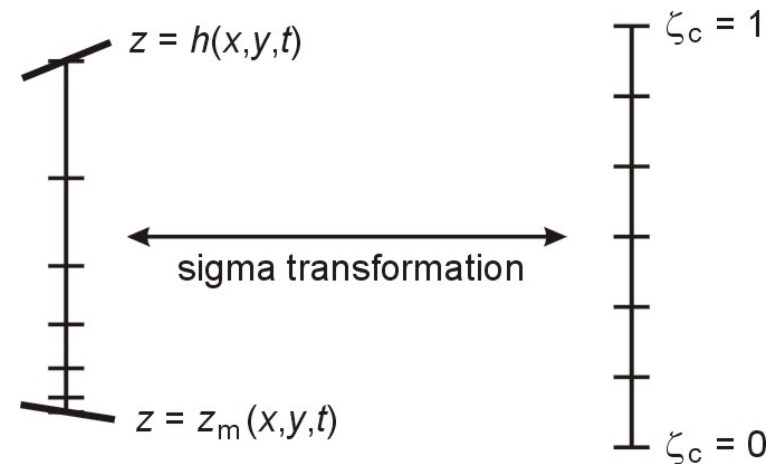
Geographical coordinates λ (longitude), φ (latitude):

$$x^1 = \lambda, \quad x^2 = \varphi, \quad g_{11} = R_e^2 \cos^2 \varphi, \quad g_{22} = R_e^2$$

Sigma transformation

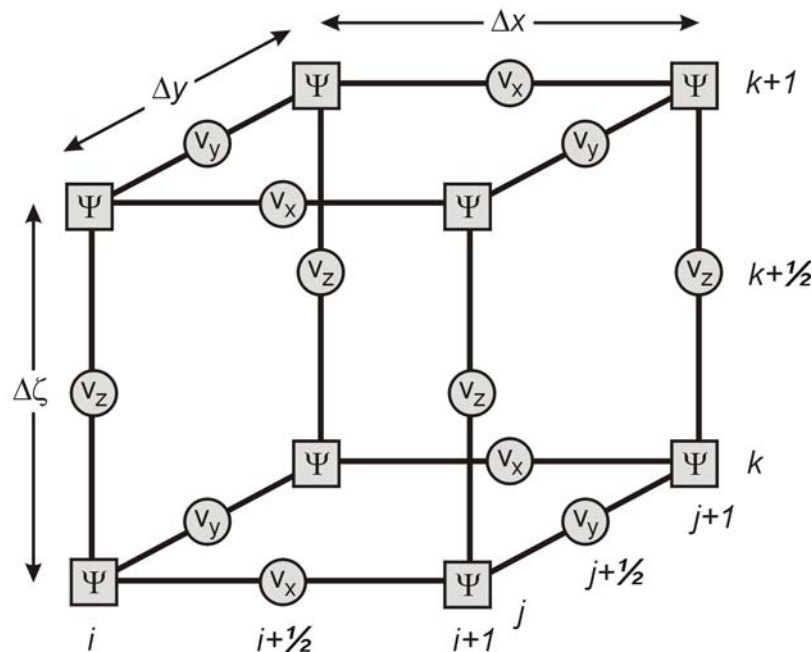
- Vertical ice columns mapped on $[0,1]$ intervals.
- Separate mappings for cold-ice layer, temperate-ice layer, lithosphere (rock) layer
→ vertical coordinates ζ_c , ζ_t , ζ_r .

- Cold-ice layer:
Densification of grid points
close to the base
→ parameter a .



Numerical solution technique

- Finite difference (FD) method.
- Staggered grid (Arakawa-C grid):



- Velocities (v_x, v_y, v_z) and volume fluxes (q_x, q_y) are defined in between grid points.
- Other field quantities (Ψ) are defined on grid points.

Numerical solution technique

- 2nd-order central differences for diffusive terms.
- 1st-order upstreaming for advective terms.
- Time-stepping (ice thickness equation):
 - Time-step Δt (same for velocity and isostasy).
 - **Over-implicit** in the linear part, explicit in the non-linear part.
- Time-stepping (temperature, water content and age):
 - Time-step $\tilde{\Delta t}$ (integer multiple of Δt).
 - Implicit in the vertical, explicit in the horizontal derivatives.

Output files

- `<name>.log`:
Lists the main specifications of simulation `<name>`.
- `<name>.ser`:
Time-series file which contains global parameters.
 - Time, t
 - Surface-temperature anomaly, D_{Ts} , or glacial index, $glac_ind$ (forcing)
 - Sea level, z_{sl} (forcing)
 - Maximum ice thickness, H_{max}
 - Maximum ice elevation, zs_{max}
 - Ice volume, V_g
 - Volume of the temperate ice, V_t
 - Freshwater production due to melting and calving, V_{fw}
 - Sea-level equivalent of ice volume, z_{sle}
 - Ice area, A_{ib}
 - Area covered by temperate ice, A_{tb}
 - Water drainage due to basal melting, V_{bm}
 - Water drainage from the temperate layer, V_{tld}
 - Maximum thickness of the temperate layer, H_{t_max}
 - Maximum surface velocity, vs_{max}

Output files

- `<name>.core`:

Time-series file which contains parameters for selected locations `xx`.

- Time, `t`
- Surface-temperature anomaly, `D_Ts`, or glacial index, `glac_ind` (forcing)
- Sea level, `z_sl` (forcing)
- Thickness, `H_xx`
- Surface velocity, `v_xx`
- Basal temperature, `T_xx`
- Basal frictional heating, `Rb_xx`

For the Greenland ice sheet, these data are written for six locations:

GRIP (`xx=GR`), **GISP2** (`xx=G2`), **Dye 3** (`xx=D3`),
Camp Century (`xx=CC`), **NorthGRIP** (`xx=NG`), **NEEM** (`xx=N1`).

- `<name>01.erg`, `<name>02.erg`,:

Complete set of fields for selected time-slices (≤ 20).

Further features

- + Thoroughly commented source code (in English).
- + Many options: polythermal mode on/off, etc.
- + No additional libraries required.
- + Very fast due to over-implicit ice-thickness solver (10 km resolution for Greenland no problem on PC).
- o No graphical user interface (GUI).
- No ice shelves.
- No adaptive time-stepping.
- No professional software management.

Acknowledgements

- Koli Hutter, Reinhard Calov, Imke Hansen, Roland Warner, Bernd Mügge, Sascha Knell, Thomas Zwinger, Ryoji Takahama, Shoko Otsu ...

... for contributions to the development of the theory and the computer model.

Thanks for your interest!



Ralf Greve