

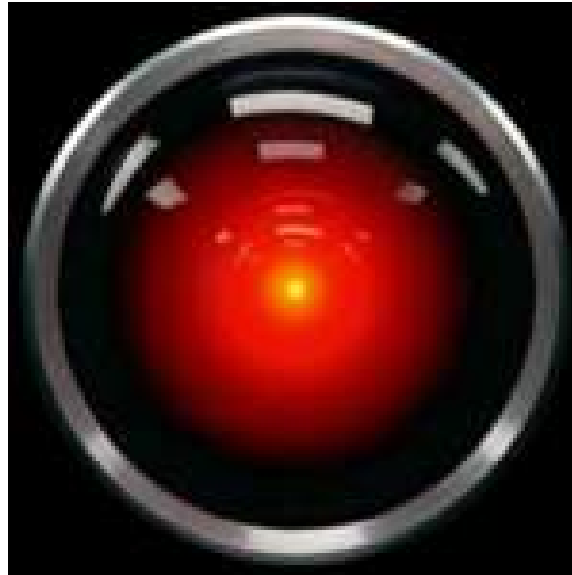


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[Instructions for use](#)

Ice-sheet model SICOPOLIS



HAL 9000's iconic camera eye



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SICOPOLIS

```

...
kc=KGMAX
kco=0
lgs_a0(kc) = ccb2
lgs_a1(kc) = -(ccb1+ccb2)
lgs_a2(kc) = ccb1
lgs_b(kc) = ccb3+ccb4
do kc=1, KGMAX-1
  lgs_a0(KGMAX+kc) = -0.5d0*(ct1(kc)-ct2(kc)-ct3(kc)-ct4(kc)) &
    -ct5(kc)*ct6(kc-1)
  lgs_a1(KGMAX+kc) = 1.0d0*(ct1(kc)+ct6(kc-1)
    -ct5(kc)*ct6(kc)
  lgs_a2(KGMAX+kc) = 0.5d0*(ct1(kc)-ct2(kc)-ct3(kc)-ct4(kc)) &
    -ct5(kc)*ct6(kc)
  #if ADV_FOR=1
    lgs_b(KGMAX+kc) = temp_c(kc,j,i) + ct7(kc) &
      -dt_2ax1 *
      ( vx_c(kc,j,i)-abs(vx_c(kc,j,i))) &
      *(temp_c(kc,j,i+1)-temp_c(kc,j,i)) &
      +insq_g11_sgx(j,i) &
      +vx_c(kc,j,i-1)+abs(vx_c(kc,j,i-1))) &
      *(temp_c(kc,j,i)-temp_c(kc,j,i-1)) &
      *insq_g11_sgx(j,i-1) ) &
      -dt_2aeta *
      ( vy_c(kc,j,i)-abs(vy_c(kc,j,i))) &
      *(temp_c(kc,j+1,i)-temp_c(kc,j,i)) &
      +insq_g22_sgy(j,i) &
      +vy_c(kc,j-1,i)+abs(vy_c(kc,j-1,i))) &
      *(temp_c(kc,j,i)-temp_c(kc,j-1,i)) &
      *insq_g22_sgy(j-1,i) )
  #elif ADV_FOR=2
    lgs_b(KGMAX+kc) = temp_c(kc,j,i) + ct7(kc) &
      -dt_dx1 * (dt_x_c_r(kc)-ftx_c_1(kc)) &
      -dt_v_delta*(fty_c_r(kc)-fty_c_1(kc))
  #endif
end do
kc=KGMAX
lgs_a0(KGMAX+kc) = 0.0d0
lgs_a1(KGMAX+kc) = 1.0d0
lgs_b(KGMAX+kc) = 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.

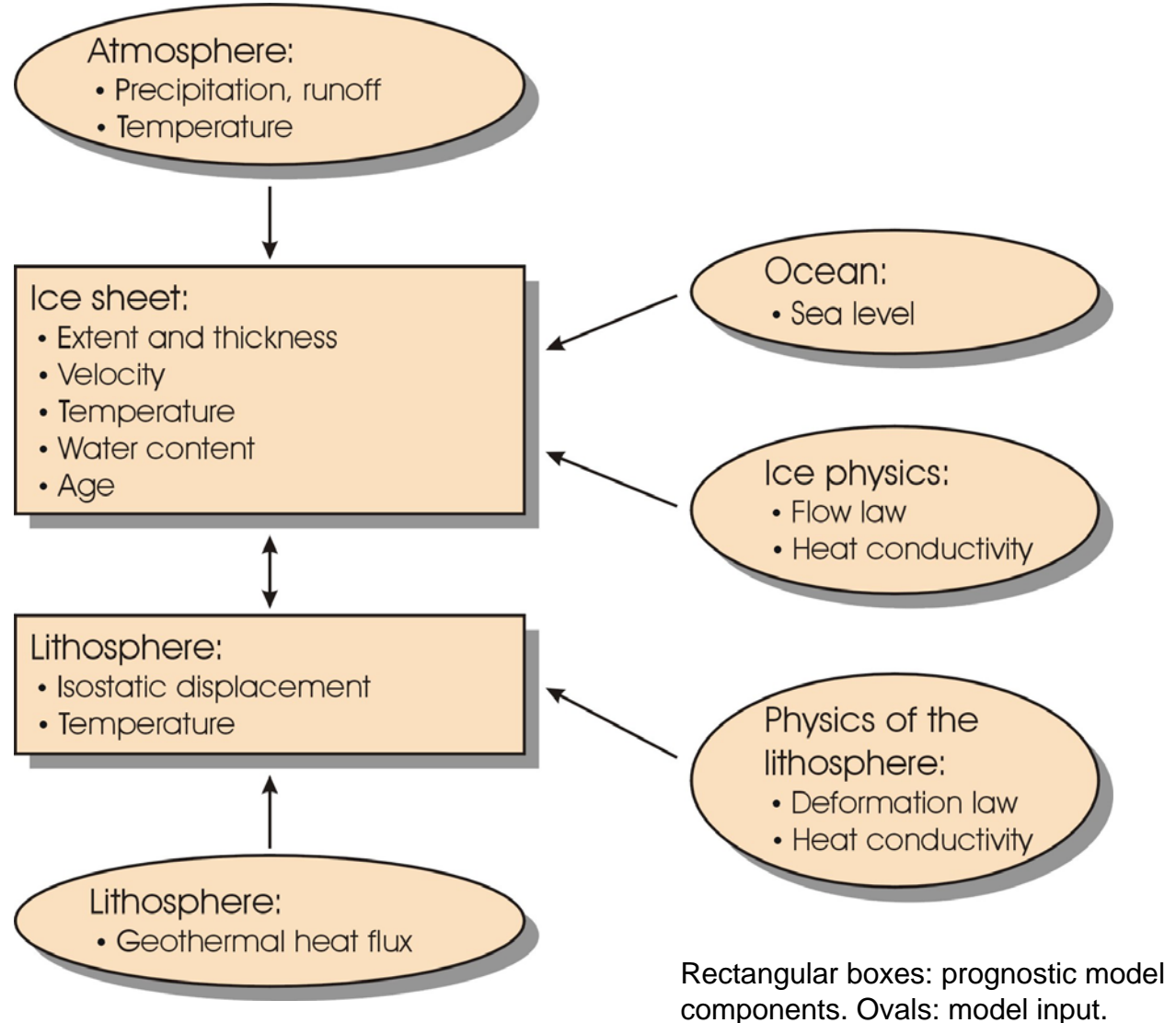
2005: Module for the south-polar ice cap of Mars.

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):

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

- 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:

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

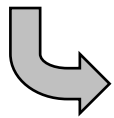
ELRA: Elastic thin-plate equation + relaxing asthenosphere

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 (→ Stefan-type matching condition).
- Ice base:
Continuity of temperature, energy balance (→ 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)

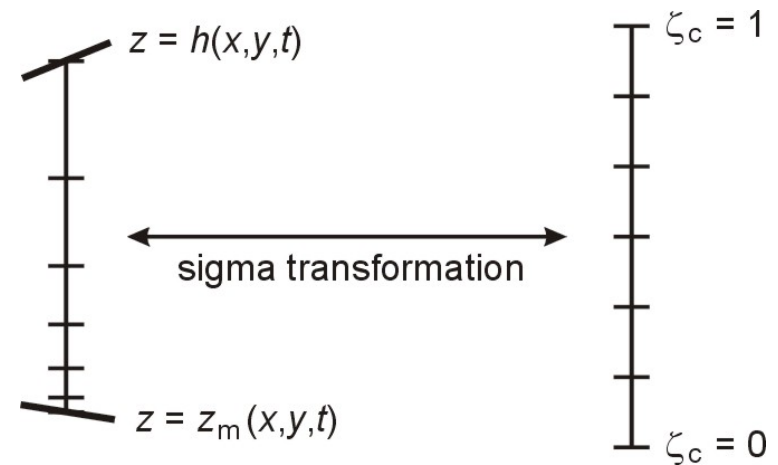
Geographical coordinates λ (longitude), φ (latitude):

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

Sigma transformation

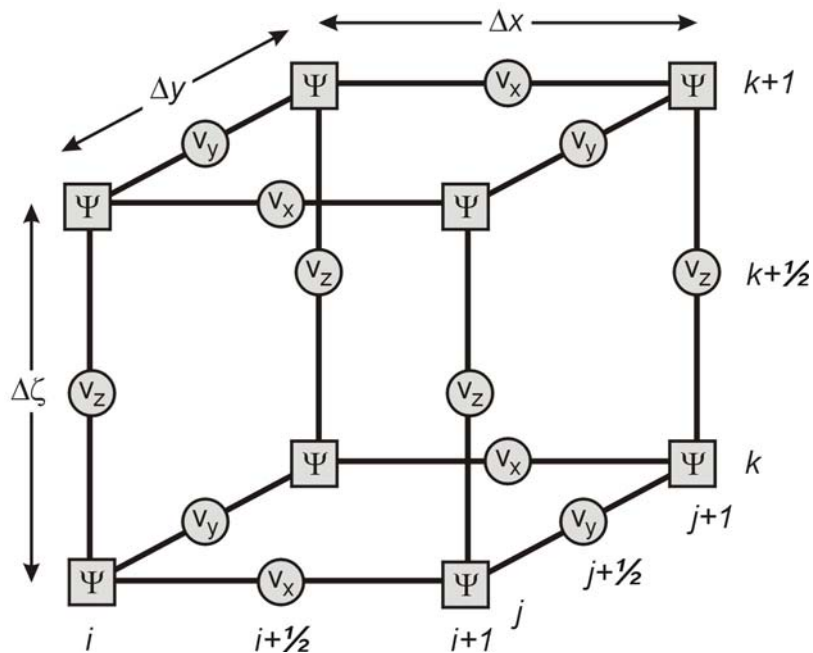
- Vertical ice columns mapped on $[0,1]$ intervals.
- Separate mappings for cold-ice layer, temperate-ice layer, lithosphere (rock) layer
→ vertical coordinates $\zeta_c, \zeta_t, \zeta_r$.

- 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.

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Thanks for your interest!

 Ralf Greve