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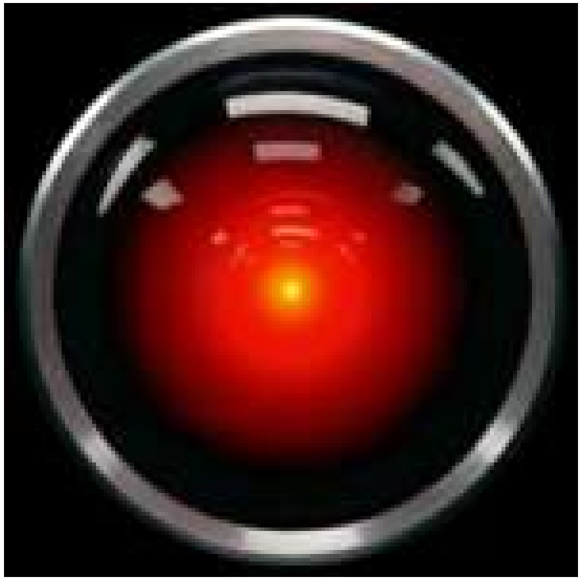
Ice-sheet model SICOPOLIS



HAL 9000's iconic camera eye

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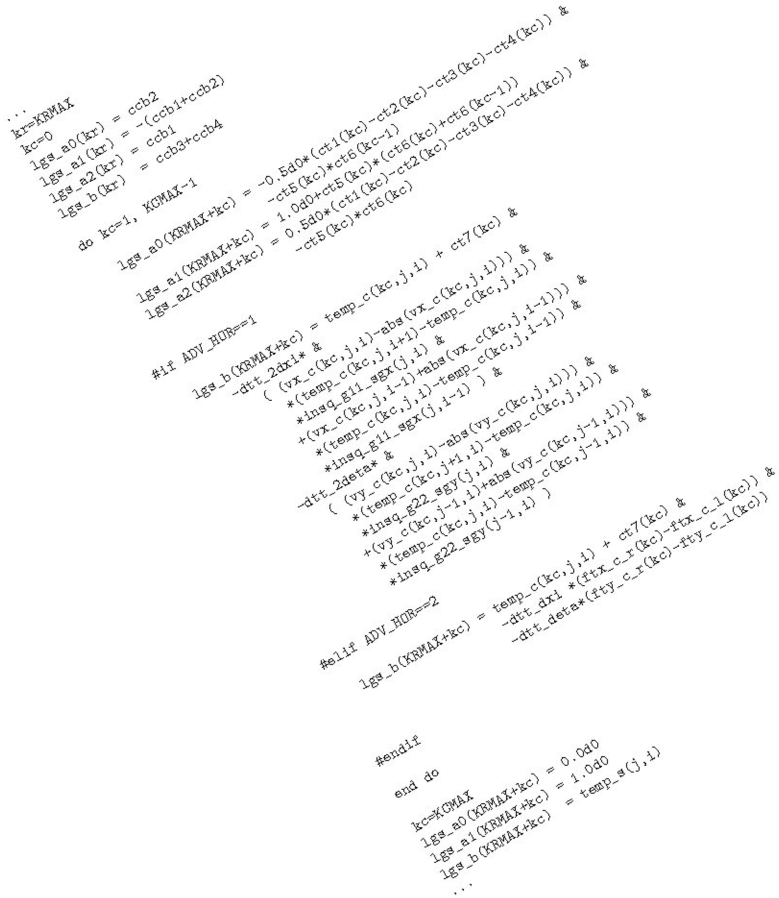
SICOPOLIS



"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
$\rightarrow$ SICOPOLIS V1.0.

2002: Module for the Fennoscandian ice sheet.

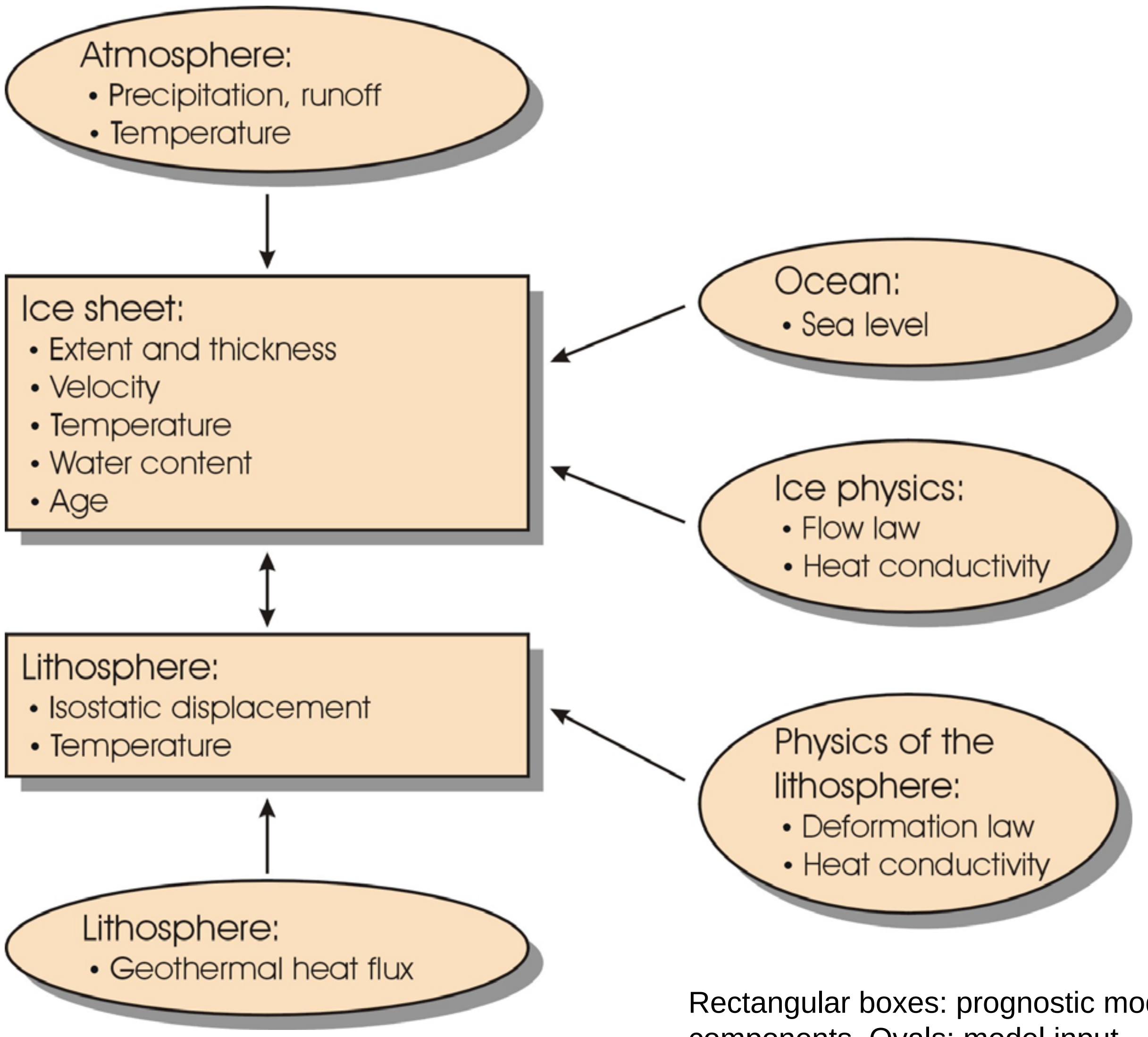
2004: Spatially variable geothermal heat flux implemented.

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)
$\rightarrow$ SICOPOLIS V2.8, current version.

Overview



Rectangular boxes: prognostic model components. Ovals: model input.

Field equations (SIA)

- Non-linear viscous flow law (Glen):

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

- 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:

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

- Ice thickness equation:

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

Field equations (SIA)

- Temperature equation (cold ice):

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

- Water-content equation (temperate ice):

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

- Age:

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

Field equations (lithosphere)

- Temperature equation:

$$\frac{\partial T}{\partial t} + \frac{\partial b}{\partial t}\frac{\partial T}{\partial z} = \frac{\kappa_\mathrm{r}}{\rho_\mathrm{r} c_\mathrm{r}}\frac{\partial^2 T}{\partial z^2}$$

- Isostatic bedrock adjustment:

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

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 ≥ 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:

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

- 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:

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

$$g_{11} = g_{22} = \frac{1}{K^2 \left(1 + \frac{x^2+y^2}{(2R_\mathrm{e}K)^2}\right)^2}, \qquad K = \cos^2\frac{\theta_0}{2}$$

standard parallel (in co-latitude)

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

$$x^1 = \lambda, \quad x^2 = \varphi, \qquad g_{11} = R_\mathrm{e}^2 \cos^2\varphi, \quad g_{22} = R_\mathrm{e}^2$$

Sigma transformation

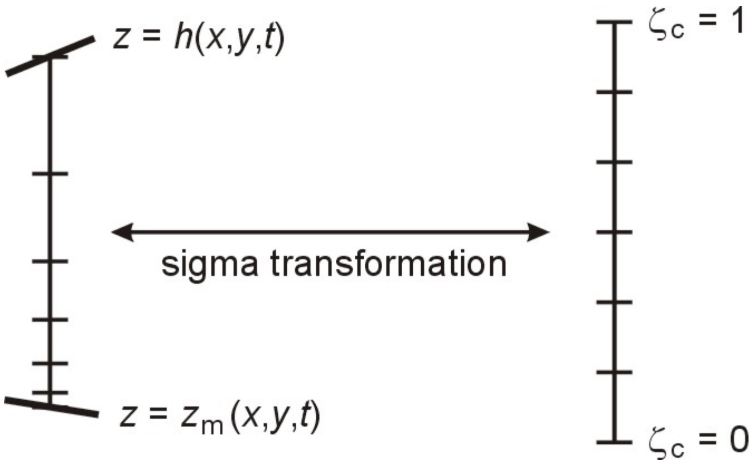
- Vertical ice columns mapped on [0,1] intervals.

- Separate mappings for cold-ice layer, temperate-ice layer, lithosphere (rock) layer

  $\rightarrow$ vertical coordinates ζ_c, ζ_t, ζ_r.

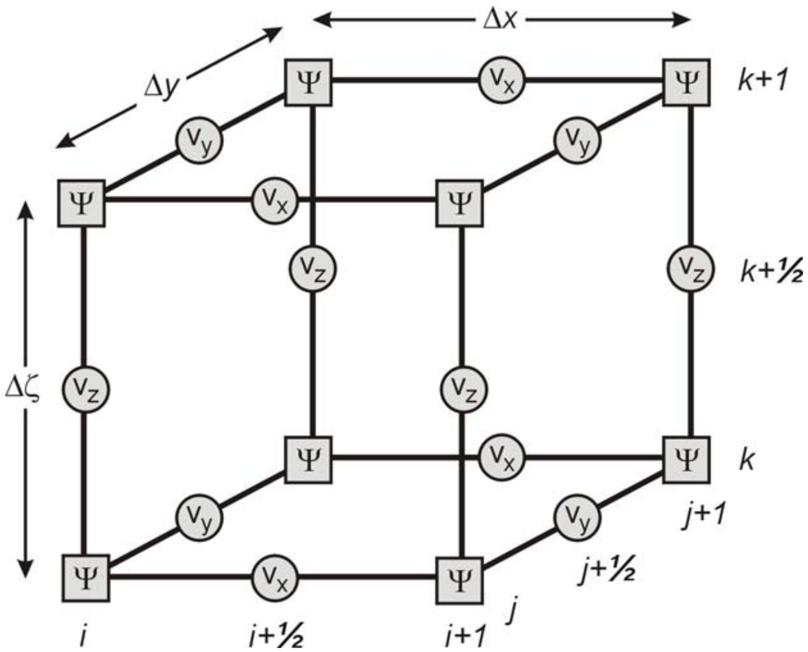
- Cold-ice layer:
  Densification of grid points close to the base

  $\rightarrow$ 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 $\widetilde{\Delta t}$ (integer multiple of Δt).
  - Implicit in the vertical, explicit in the horizontal derivatives.

Output files

- <rname>.log:
  Lists the main specifications of simulation <rname>.

- <rname>.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, Aib
  - Area covered by temperate ice, Atb
  - 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

- <rname>.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).

- <rname>01.erg, <rname>02.erg, …:
  Complete set of fields for selected time-slices ($\leq$ 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

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Thanks for your interest!

Ralf Greve