A Regional Coupled Model System to Examine Ocean-Atmosphere-Sea Ice, Ice Sheet and Permafrost Interactions in the Arctic

HIRHAM5 – HYCOM – CICE – PISM – GIPL – MIKE-SHE

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Motivation

• Arctic particularities (+ a bit Denmark-centric)
  – Atmosphere, Ocean, Cryosphere, Sub-surface
• Better representation of regional processes
• Limited abilities in parameterizing local processes
  – Permafrost
  – Glaciers
  – Ice sheets
  – Fjord circulation
  – Ground water
The model system

PISM: Parallel Ice Sheet Model (UAF)

HIRHAM5 MIKE SHE (DHI)

GIPL: permafrost model (UAF)

PISM: Parallel Ice Sheet Model (UAF)

Ocean / sea ice models: HYCOM–CICE (coupled for North Atlantic)
Regional Climate Model: HIRHAM5

• Combination of HIRLAM dynamical scheme with ECHAM5/& (+ add on) physics
  – CORDEX type and 5.5km horizontal resolution
  – 31 vertical levels in atmosphere
  – Time step of 120s/90s

• For Arctic
  – 5 snow/soil layers down to 10 m w.e.
  – Surface scheme calculates SMB with a surface energy balance scheme with retention and refreezing in snow pack
HIRHAM – MIKE-SHE

Coupled hydrological and climate model

- OpenMI coupling
- MIKE SHE
- WINDOWS - LINUX Communication link
- HIRHAM
- OpenMI
HIRHAM – MIKE-SHE

Input

Uncoupled mode MIKE SHE
Observation data

Windows workstation

Coupled mode MIKE SHE

Simulation

OpenMI – Linux proxy

Coupled exchange
PRECEP, RH, V, Rg, Ta & Ps
LE & Ts

One-way exchange
PRECEP, RH, V, Rg, Ta & Ps

Output

Uncoupled (MSDI)

Coupled one-way (MSDI)

Coupled two-way (TI/CV)

Uncoupled (HUV)

Linux HPC

HIRHAM

Coupled two-way (TI/CV)

PRECIP (mm) Precipitation
RH (%) Rel. humidity
V (m/s) Wind speed
Rg (W/m²) Global rad.
Ta (Deg. C.) Air temp.
Ps (hpa.) Surface pres.

Ts (Deg. C.) Surface temp.
LE (W/m²) Latent heat flux
H (W/m²) Sensible heat flux
G (W/m²) Soil heat flux
Q (m³/s) Discharge
**Root mean square error**

Distribution of the difference (coupled subtracted from uncoupled) in RMSE levels for a 365 day summation period.

Traditional Coupling

20 km resolution
Daily coupling
2006-2007 with 1 year spinup

Atmosphere
HIRHAM

Sea surface temperature

Wind, temperature, radiation, humidity, precipitation

Sea ice concentration

Ocean
HYCOM

Freshwater, heat and momentum

Sea ice
CICE
Ocean model: Hycom

- 3D currents (including tides), salinities and temperatures, sea surface height
- Fully coupled with sea ice model
- Operational setup: 10 km Arctic and North Atlantic, 29 vertical layers
- Setup for atm. coupling: 20 km Arctic
- High resolution setups for Godthåbsfjord (Greenland)
Sea Ice model: CICE

- Ice concentration, thickness, velocities, temperature, etc.
- Hibler-type elastic-viscous-plastic ice model
- Each grid cell has 5 ice thickness categories with 4 vertical layers for each, plus surface snow
- Fully coupled with ocean model, same resolution (10 or 20 km)
- For climate simulations: runs freely with a stable ice cover for several years
Experiments

- Era Interim
  - Hirham stand-alone
  - Hycom – CICE stand-alone

- Coupled
  - Hirham
  - Hycom – CICE
Sea ice concentration

HIRHAM forcing gives better results in Summer than ERA-Interim

Winter in coupled model is comparable

Greenland at 5 km resolution

- Resolution important to resolve fjords and ablation area
- Energy balance well represented
- Runoff very sensitive to albedo
Snowfall + Rain

Standard ECHAM5 subsurface

Snow, ice and water mass fractions

Snow
Ice
Water
(max 2% of snow mass)

Snowfall

Melt + rain

Runoff

Ice (-10°C)
Ice Sheet Modelling

- Forcing PISM ice sheet model with RCM output
- Surface elevation feedback
- Calving and ocean forcing neglected currently (but we’re working on it)
- Feedbacks between ocean and ice sheet (and atmosphere) may be important on longer timescales

Aðalgeirsdóttir et al., 2014
Calving in PISM
Full crevasses-depth criterion

• Nick et al, 2010

\[ d_S + d_B = H \]
**Driving Force**
- HIRHAM (Regional Climate Model)
- EC-EARTH (Global Climate Model)
- Offline mode (Polar Portal)

**STEP 1**
Initializing (Driving model, if applicable)

**STEP 2 (THE BIG LOOP)**
Boundary conditions from model or file (offline)
- Access the needed fields
- Take feedback into account (Remapping)

**STEP 3 (FINALIZE)**
End of model
- Write Restart file of driving model

**GIPL World**
- Static 3D field set up
- NetCDF input/output

**STEP 1 (STATIC)**
Initializing Permafrost
- Geometry
- Soil characteristics
- Read initial or former restart state

**STEP 2 (THE BIG LOOP)**
Read actual driving forces
- Distribute 2D forcing fields from “Driving force” to individual columns
- Prepare remapping of permafrost into the “Driving Force” (Feedback)

**STEP 3**
Write (NetCDF)
- Restart/State file, diagnostics, stations

**GIPL Column**
- GIPL2 dedicated permafrost model

**STEP 1**
Initial columns

**STEP 2 (THE BIG LOOP)**
Permafrost calculation in an independent / separated column

**STEP 3**

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**“Column world”:** essentially the original GIPL model.

**“Driving force”:** model (e.g. HIRHAM) or climatology, one-way or interactive

In the **“GIPL world”**, these join in a 3D setup; including model setup, reading / initializing / restart files / write out the results in netCDF.
### Temperature at 1 m depth, 5 km run

<table>
<thead>
<tr>
<th>Year Range</th>
<th>Temperature [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1980 - 1999</td>
<td>&lt; -12</td>
</tr>
<tr>
<td>2046 - 2065</td>
<td>-12 .... -8</td>
</tr>
<tr>
<td>2080 - 2099</td>
<td>-8 .... -5</td>
</tr>
</tbody>
</table>

### Active layer thickness, 5 km run

<table>
<thead>
<tr>
<th>Year Range</th>
<th>Active layer depth [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1980 - 1999</td>
<td>Seasonal freezing</td>
</tr>
<tr>
<td>2046 - 2065</td>
<td>0.01 .... 0.25</td>
</tr>
<tr>
<td>2080 - 2099</td>
<td>0.25 .... 0.5</td>
</tr>
</tbody>
</table>

Danen et al. 2011
Summary

- HIRHAM – MIKE-SHE proof of concept works. Coupling improves model performance
- HIRHAM-HYCOM-CICE model system reproduces observed Arctic regional climate and sea ice concentration on seasonal to inter-annual timescales
- Ice sheet dynamics can be studied (resolution issues)
- The local characteristics of Greenland fjords with calving glaciers can be represented
- The role of permafrost characteristics can be assessed
- More complete feedback mechanisms can now be assessed.
Future Work

- Climate service for an Arctic community
- Longer simulation
- Past climate and future projections
- International collaboration/model intercomparison exercises (e.g. CORDEX, ISMIP6)
- Further model developments
  - Code harmonisation between different model elements
  - Spectral nudging (?)
- Ice sheet feedbacks and influences
  - Meltwater fluxes around Greenland from ice sheet + Arctic rivers
- Refine/improve coupling methods to increase process efficiency
- .......