Modelling and simulation of sea ice dynamics
Part I: Context and objectives

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with
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TEN SIGNS OF A WARMING WORLD

Satellite images show that the area covered by sea ice in the Arctic at the end of the summer is getting smaller. Ice-free shipping routes and newly established access to oil and gas increase the risk of damage to this sensitive environment, and habitat for marine animals is threatened.

Global Sea Level

Ocean heat content

Air temperature over land

Air temperature over ocean

Sea surface temperature

Satellite sensors on ships and buoys show that the temperature of the surface of the ocean is rising. Warming surface waters can increase the destructive potential of tropical cyclones and hurricanes.

Humidity

Measurements from weather stations over land and water show increasing humidity—more water vapor in the air. The air feels stickier when it’s hot, and air conditioner use has to work harder for us to feel comfortable.

Temperature of the lower atmosphere

Measurements from satellites show that air temperatures at the lowest layer of the atmosphere—where we live—continue to rise. Heat waves get longer, and extreme weather events like floods, droughts, and wildfires become more frequent.

Snow

Historical paintings show that snowfall was much greater 50 years ago. Weather stations on land show that average air temperature in the lower atmosphere is rising. Consequently, we have an increase in the number of heat wave events, and the area affected by drought.

Glaciers

Satellite images show the area of land covered by snow during spring in the Northern Hemisphere is getting smaller. Snow is melting, and glaciers are receding. This is affecting river systems and the ecosystems that rely on them.

Climate change will have consequences for the Earth system and human lives. Explore further information and the data sets that support each of these statements at www.climate.noaa.gov/warmingworld
Arctic sea ice

- Small thickness (~meter) + Large extent (10^6 km²) = Large variability
- Thermodynamic processes (freeze/melt)
- Dynamic processes (drift/deformation)

Strong coupling

March extent ~15 10^6km²
Sept. extent ~ 5 10^6km²
Role of sea ice in the climate system

- Sea ice controls air – sea exchanges of heat and momentum (winter)

ATMOSPHERE
$T^\circ \ll 0$

Sea ice

OCEAN, $T \sim -1.8^\circ C$

= 50%

0.5% of open water

Highly non-linear dependence!!
Role of sea ice in the climate system

- Sea ice is also a summertime insulator:

\[
\text{Albedo} = \frac{\text{reflected}}{\text{incident}}
\]

- Snow / thick ice: high albedo
  - 90% reflected
  - 10% incident

- Ocean / thin ice: low albedo
  - 30% reflected
  - 70% incident

Accelerated sea ice melt
And water warming
Concentration and extent

- 50% in 42 years for the September ice extent
- 10% in 42 years for the winter ice extent (March)

Source: NSIDC
Concentration and extent

2012 September minimum extent
Sea ice thickness

Source: Lindsay and Schweiger, 2015

From various sources:
- Submarine upward-looking sonars
- Satellite and airborne lidars
- Airborne electro-magnetic measurements

- 65% in 37 years for ice thickness
- 85% in 37 years for september sea ice
Arctic warming

**ARCTIC WARMING**

Air-temperature data from 2000 to 2014 show that parts of the Arctic are now 3 °C warmer as compared to the baseline.
The albedo feedback

- Higher temperatures
- Increase of absorbed sunlight (summer)
- Albedo feedback
- Darker surface = Lower albedo
- More melting (snow, sea ice, ..)

More melting leads to a darker surface, which results in a lower albedo. This lower albedo increases the temperature, leading to more melting and a cycle.
Arctic sea ice thinning 4 times faster than forecast
Septembre 2003-Mai 2004

Date: 20030928
Trajectories of passive tracers (analogy with turbulence)
Drift acceleration

+ 9.0% (±1.9%) per decade for the average ice velocity

(Rampal et al., JGR, 2009)
“Proxy” of the strain-rate:

\[
\dot{\varepsilon}_{\text{disp}} = \frac{\left(\langle \Delta r^2 \rangle - \langle \Delta r \rangle^2 \right)^{1/2}}{L \times t}
\]
Increasing strain rates

(Rampal et al., JGR, 2009)

+ 50% (±10%) per decade for the average ice deformation rate!
Drift acceleration

- No trend on modelled sea ice speed
- Neglect an increasing sea ice export

(Rampal et al., JGR, 2009)
Drift acceleration: the cause?

The result of a more fractured/fragmented, and so weaker sea ice cover?
Sea ice mechanics: A multi-scale problem

- Space (m)
- Floe aggregate
- Individual floe
- Sea ice cover

Time: seconds, days, months

Space (m): $10^0$, $10^1$, $10^2$, $10^4$, $10^5$, $10^6$
How to model such multi-scale complexity?
Sea ice dynamics
(in operational, regional and coupled climate models)

Sea ice considered as a deformable continuum
(a « fluid mechanics » approach)

Cauchy’s equation of momentum

\[
\rho h \left[ \frac{\partial V}{\partial t} + (V \cdot \nabla)V + f k \times V \right] = \nabla \cdot (h \sigma) + \tau_a + \tau_w
\]

- thickness
- Coriolis
- Wind forcing
- Oceanic drag

Constitutive relationship (rheology)

Sea ice internal stress
• Constitutive relationship (rheology):

\[ \sigma = \eta \mathbf{K} : \dot{\varepsilon}_v \quad \sigma = E \mathbf{K} : \varepsilon_E \]

COMPRESSIBLE MATERIAL

adimensional stiffness matrix

\[ \mathbf{K} = \mathbf{K}(\nu) \]

Poisson’s ratio: \( 0 \leq \nu < 0.5 \)
Coupling with damage mechanics

\[ \eta = \eta(d) \]
\[ E = E(d) \]
\[ \lambda = \lambda(d) \]

Fractured, damaged zones:
- \( E \rightarrow 0 \)
- \( \eta \rightarrow 0 \)
- \( \lambda \rightarrow 0 \)

large, permanent deformations

Viscous-like relaxation of elastic stresses

Undamaged pack ice:
- \( E = E^0 \)
- \( \eta \rightarrow \infty \)
- \( \lambda \rightarrow \infty \)

small, elastic deformations

Long-range elastic interactions
Waves/ice interactions in the Marginal Ice Zone
Merci !