Using Remote-sensed Sea Ice Thickness, Extent and Speed Observations to Optimise a Sea Ice Model

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Motivation

- **Rothrock et al., (JGR, 2003)** illustrated the significant differences, in both means and anomalies, between model simulations of recent Arctic ice thickness
- Reasons for differences not well understood, but there is both parameter and forcing uncertainty
- How can we reduce this uncertainty and increase our confidence in conjectures based on model output?
Reducing Parameter Uncertainty in Sea Ice Models

- Use the Los Alamos sea ice model, CICE, and force it with ERA-40 & POLES data
- Optimise and validate the model using a comprehensive range of sea ice observations:
  - Sea ice velocity, 1994-2001 (SSM/I + buoy + AVHRR, NSIDC)
  - Sea ice extent, 1994-2001 (SSM/I, NSIDC)

We used this model and forcing to reduce uncertainty surrounding sea ice model parameters
Satellite Altimetry - Measurement Principle

\[ h = \frac{ct}{2} \]
Co-incident ATSR imagery reveals the origin of **Diffuse** and **Specular** echoes over sea ice:

- Diffuse echoes originate from ice floes
- Specular echoes originate from leads
- Gaps are caused by Complex echoes which are excluded
Freeboard to Thickness Conversion

- Conversion assumes reflection from the ice/snow interface
- Conversion to thickness uses climatology of snow depth/densities
  \( h_i = f \frac{\rho_w}{(\rho_w - \rho_i)} + \frac{h_s \rho_s}{(\rho_w - \rho_i)} \) (Warren et al., J. Climate 1999)
ERS Altimeter Ice Thickness Validation
Sea Ice Thickness Change

Ice Thickness - Summer Melt

Sea Ice Thickness Change

Melt Season Length (Smith, GRL, 1998)

Laxon et al., Nature, 2003
Parameter Space

We explored the model’s multi-dimensional parameter space to find the best fit to the observational data

- 3D parameter space
- Uncertainty surrounds correct values to use
- Space includes commonly-used values
- 168 model runs needed to optimise model

![Diagram showing parameter space with axes labeled:
- Ice strength, $P^*$
- Albedo, $\alpha_{ice}$
- Air drag coefficient, $C_{air}$

Values:
- $P^*$: 0.62, 0.54, 100 (kPa)
- $\alpha_{ice}$: 0.0003, 0.54
- $C_{air}$: 0.0016, 2.5]
Arctic Basin Ice Thickness

\[ \{ \alpha_{\text{ice}}, C_{\text{air}}, P^* \} = \{0.56, 0.0006, 5 \text{ kPa} \} \]

*Miller et al., J. Climate, submitted*
Arctic Basin Ice Extent

\[ \{\alpha_{\text{ice}}, C_{\text{air}}, P^*\} = \{0.56, 0.0006, 5 \text{ kPa}\} \]

Miller et al., J. Climate, submitted
Arctic Basin Ice Speeds

$\{\alpha_{\text{ice}}, C_{air}, P^*\} = \{0.56, 0.0006, 5 \text{ kPa}\}$

Miller et al., J. Climate, submitted
Validation With ULS Draft Data

Rothrock et al., 2003, JGR, 108(C3), 3083

87 97 Year

R = 0.98
RMS difference = 0.28m
Spatial Draft Discrepancy

Rothrock et al., JGR, 2003, 108(C3), 3083

Figure 9. Modeled minus observed mean draft (m) along cruise tracks from 1987 to 1997.

Model - ULS Observed Draft (m)
Improved Spatial Distribution

*Rothrock et al.*, JGR, 2003, 108(C3), 3083

Model - ULS Observed Draft (m)

CICE, $e = \sqrt{.5}$

Figure 9. Modeled minus observed mean draft (m) along cruise tracks from 1987 to 1997.
Zonal and Interannual Variability

Zonal Draft Averages

Cruise Averages

- Observed

\[ e = 2 \]

\[ e = \sqrt{0.5} \]

Miller et al., GRL, submitted
Model vs ERS Mean Winter Ice Thickness

$e = 2$

$e = \sqrt{5}$

Model - Satellite Thickness (m)
Satellite Altimeter Missions 1993 -
IceSat vs Envisat RA-2
March 2003

[Courtesy J. Zwally]

[Courtesy Andrew Ridout, CPOM]
The Future: Combining Radar/Laser Altimetry
Summary

• Remote-sensed sea ice data are vital for the optimisation and validation of sea ice models, and for reducing parameter uncertainty
• We have optimised CICE using remote-sensed thickness, extent and speeds, as well as ULS draft data
• Combining radar and laser data has the potential to significantly reduce uncertainties in snow loading
• Comparisons with submarine data suggest that our satellite thickness errors are considerably less than discrepancies between different model simulations
• These is still much work to do to fully understand these uncertainties. In particular, CryoSat will be a particular focus for a $15m validation campaign, post-launch (land ice and sea ice)
• www.esa.int/esaLP/cryosat.html
Summer 2005?

www.esa.int/esaLP/cryosat.html
Repeat Profile Analysis

- Up to 60 repeat profiles are analysed along each of the 501 orbit tracks.
- Ocean returns are used to construct a mean sea surface profile.
- Residual height profiles are used to determine ice freeboard.

\[ \Delta h = h - \bar{h} \]
Altimeter Elevation Profile

- **Sea level**
- **Sea ice freeboard**
Comparison of Submarine and Altimeter Thickness PDF
Combining Radar/Laser Altimetry

\[ \begin{array}{c}
\text{snow} & \rho_s \\
\text{ice} & \rho_i \\
\text{water} & \rho_w \\
\end{array} \]
Conceptual Experiment Design

Example: Level 2 Sea ice geometric and penetration model error

• Assess practicality and identify missing capability e.g. ASIRAS.

• Identify and contact important groups and planning time-scales e.g. Alfred Wegener Institute; 2-3 year planning horizon for polar activity.

• Identify practical locations e.g. Arctic Ocean N. and W. of Greenland is accessible and gives access to strong ice concentration variations.

• Identify experimental complexity and novelty and assess need for pre-launch trials e.g. LARA (2002) and CryoVEx (2003) campaigns.

• Identify and implement requirements on ground-segment capability.
Arctic Basin Ice Thickness Since 1980

Annual mean Arctic sea ice thickness has been in decline since the mid-1980s.
Ice Thickness Anomalies 1993-2003

Thickness Anomaly (Metres)

>40cm thinning in one year
Regional Ice Thickness Anomalies
1993-2003

Thickness Anomaly (Metres)

Year


All
West
East

Ice Thickness (m)

2.0  2.5  3.0  3.5  4.0  4.5  5.0
Sources of Uncertainty

Level 1b Processor

Level 2 Processor

Level 3 Processor

Level 1b data

Level 2 & 1b error

Independent L1b comparison

Imperfect Retrieval Models

Level 2 data

Level 2 & 1b error

Independent L2 comparison

Theory

Level 3/4 data

Level 3/4 & 2 & 1b errors

Independent L3/4 comparison

Imperfect Sampling

Imperfect System

Sources of Uncertainty