Improving Met Office seasonal predictions of Arctic sea ice using assimilation of CryoSat-2 sea ice thickness

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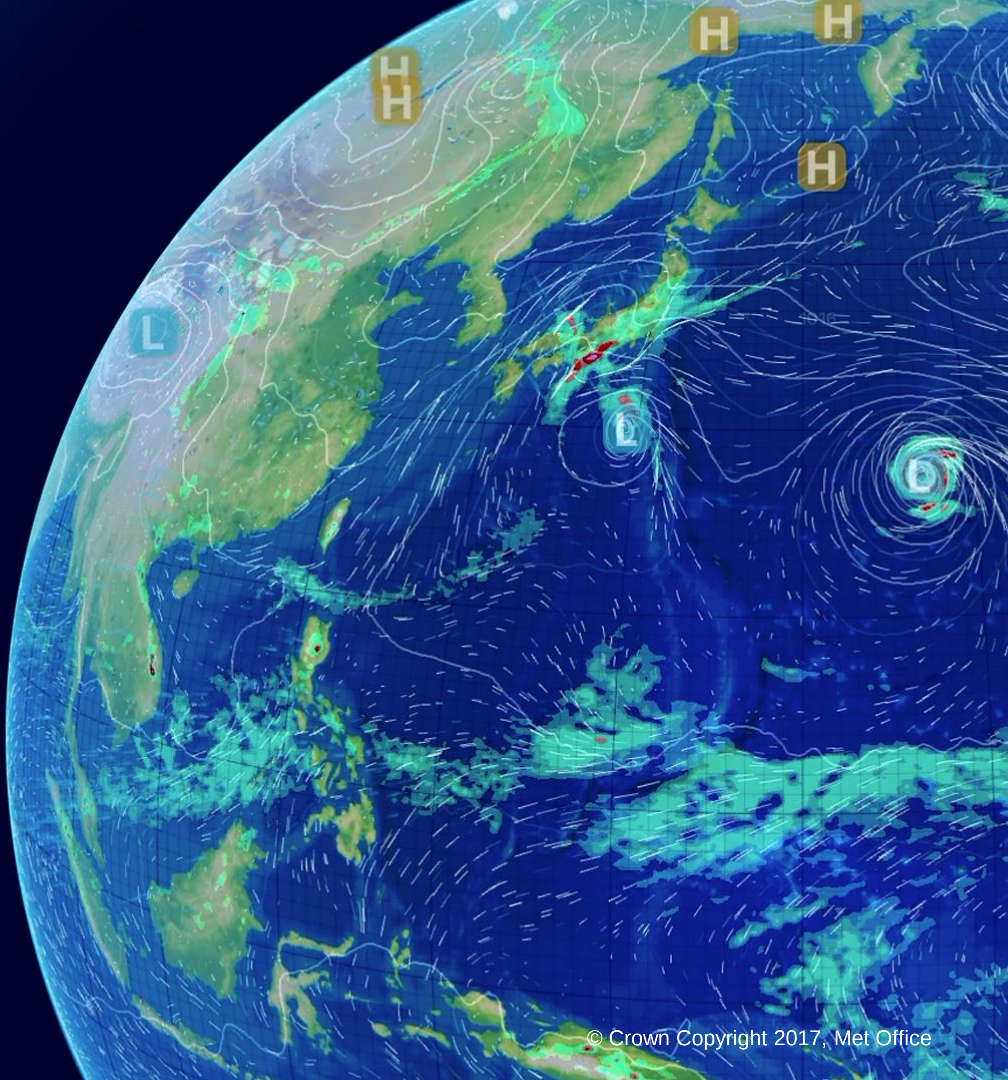
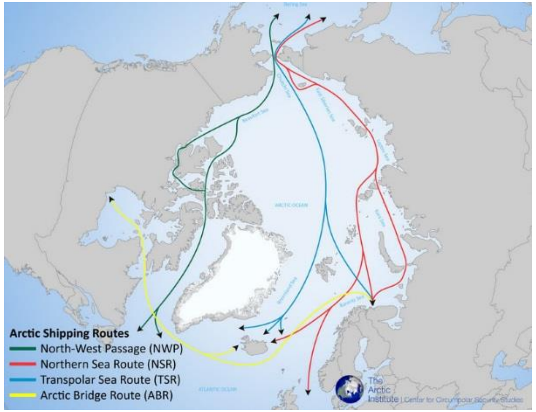


Why forecast Arctic sea ice?

- Access to the Arctic Ocean
  - Commercial shipping, tourism, fishing, oil & mineral extraction
  - Community resupply, subsistence hunting & fishing



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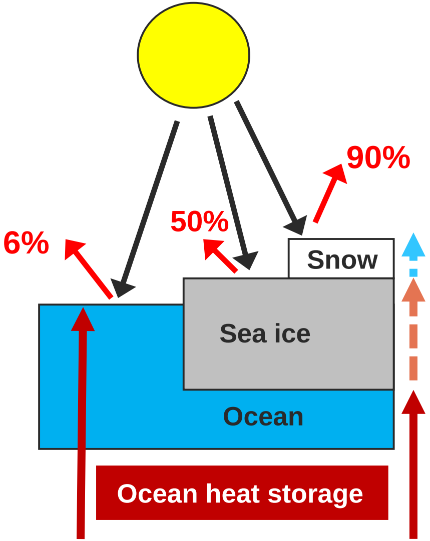
Why forecast Arctic sea ice?

- Access to the Arctic Ocean
  - Commercial shipping, tourism, fishing, oil & mineral extraction
  - Community resupply, subsistence hunting & fishing

- Impact on ocean/atmosphere:
  - *Summer*: sea ice (& snow) reflects Sun's radiation
  - *Winter*: sea ice (& snow) insulates ocean from cold atmosphere



Predicting Arctic summer sea ice cover

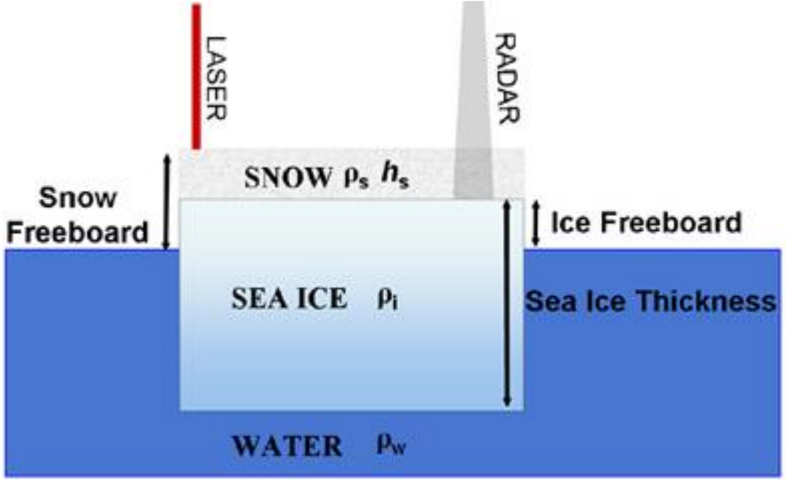
- September 2007 record-low sea ice extent sparked interest in Arctic summer sea ice forecasting
- Sea Ice Outlook (SIO) established in 2008 to focus predictions of basin-wide Arctic extent
- Met Office (GloSea) contributing to SIO since 2010
    - Considered an experimental forecast; bias correction applied
- **Skill shows room for improvement (for all models)**
    - **Coupled models barely beat trend or anomaly persistence forecasts**
    - **Hindcasts perform better than actual forecasts**
    - **Perfect models suggest models should be more skilful**

Motivation for sea ice thickness initialisation

- Blanchard-Wrigglesworth and Bitz (2014):
  - **Sea ice thickness anomalies in GCMs have timescale of between 6 and 20 months**
- Holland et al. (2011); Kauker et al. (2009):
  - **Knowledge of winter ice thickness can provide predictive capability for summer ice extent**
- Perfect model studies (Day et al., 2014):
  - **Correct initialisation of thickness can lead to improved seasonal forecasts**
- Collow et al. (2015); Blanchard-Wrigglesworth et al. (2017):
  - **Sea ice seasonal forecasts are sensitive to changes in thickness initial conditions.**

Sea ice thickness measurements

- Satellite measurements available from:
  - Radar altimetry (CryoSat-2, AltiKa, Envisat, ERS)
    "ice freeboard"
  - Laser altimetry (ICESat, ICESat2)
    "snow freeboard"
  - Microwave brightness temperatures (SMOS)
    "total thickness" (ice+snow)



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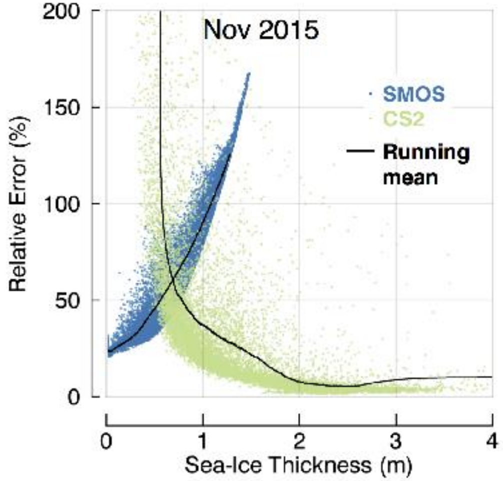
    “total thickness” (ice+snow)

Ricker et al. (2017)



CryoSat-2 for thick ice	[> 1.0 m]
SMOS for thin ice	[< 0.5 m]

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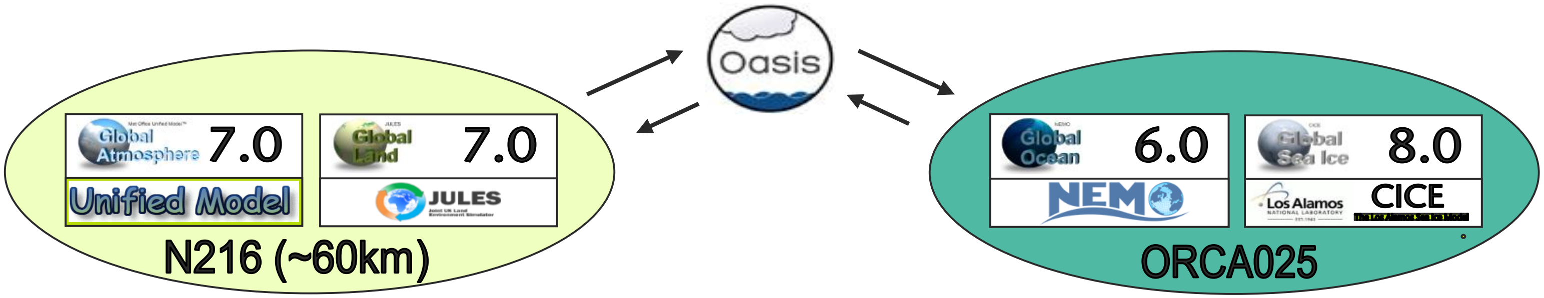
Met Office Global Seasonal Forecast System (GloSea)



- Ensemble prediction system
- Monthly (60 days) & seasonal (210 days) forecasts
- **NEMO** ocean model; **CICE** sea ice model
- Experimental Arctic sea ice forecasts

- Initialised from FOAM operational ocean/sea ice analysis assimilating:
  - **SIC +** SLA, SST, T & S profiles
  - **No Sea ice thickness** (yet)

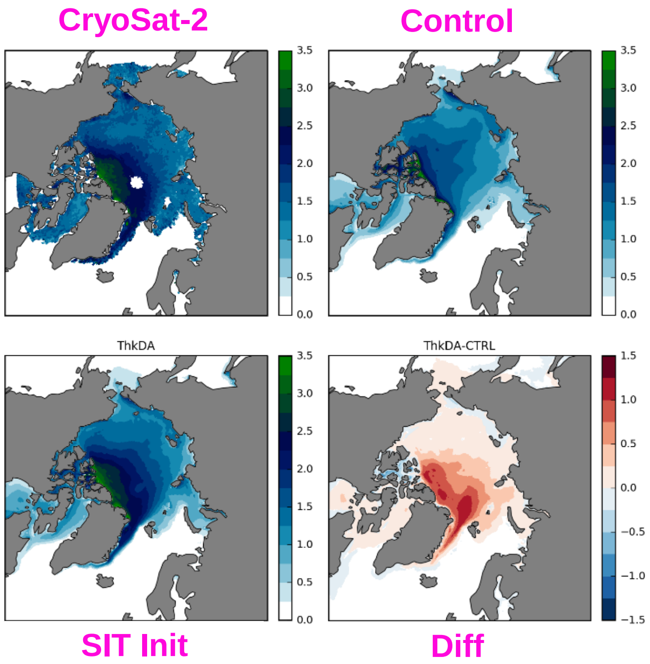
Motivating questions:

- How will initialisation of spring thickness affect GloSea seasonal forecasts of Arctic summer sea ice cover?

- Is there a relationship between spring thickness errors and summer extent errors?

[Blockley and Peterson (2018)]

Sea ice thickness assimilation: proof of concept



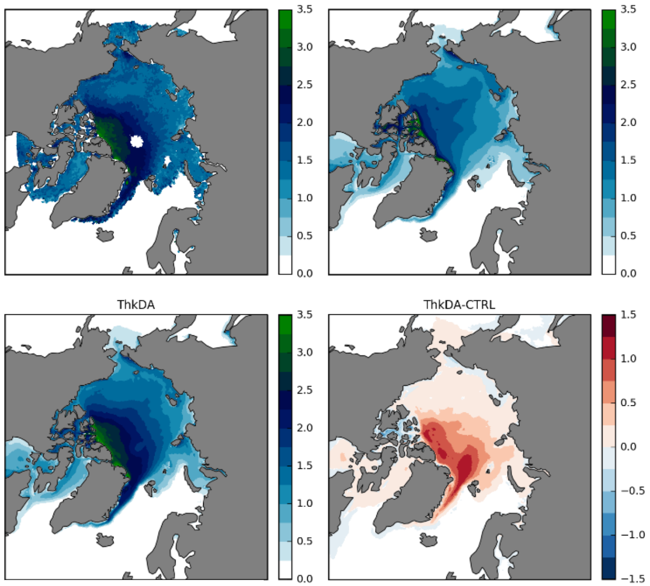
Oct-Apr mean

- Including CryoSat-2 sea ice thickness within FOAM reanalysis (GloSea hindcast IC's):
  - Using full thickness estimates from CPOM
  - Full assimilation of existing quantities:
    - SIC; SST; SLA; T&S profiles
  - QC of data
  - 2010-2015
- Nudging SIT in sea ice model (CICE):
  - Using monthly thickness data
  - Similar to climatological relaxation
  - Difference with grid-cell mean thickness
  - Increments applied using a 5-day relaxation timescale

[Blockley and Peterson (2018)]

Sea ice thickness assimilation: proof of concept

CryoSat-2 Control

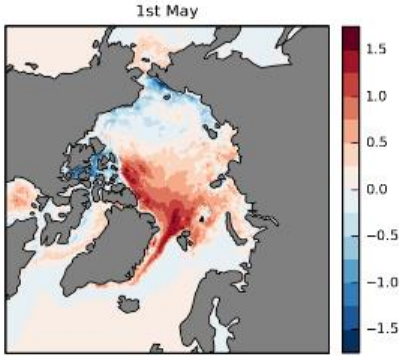


SIT Init Diff

<- Modified winter thickness distribution:

- Overall increase in thickness (& hence volume)
- Particularly in the Atlantic sector

- End winter IC changes:
  - Thickening: Atlantic sector & marginal seas
  - Thinning: Beaufort, Chukchi, East Siberian Seas



Oct-Apr mean

[Blockley and Peterson (2018)]

What is the impact on GloSea seasonal forecasts?

- GloSea 5-month re-forecasts: May -> September
    - 3 start dates: 25-04, 01-05, 09-05
    - 8 ensemble members each
    - => lagged ensemble with **24 forecasts per year** of September-mean from spring
    - 5 years: **2011 – 2015**
    - => **total 120** seasonal forecasts

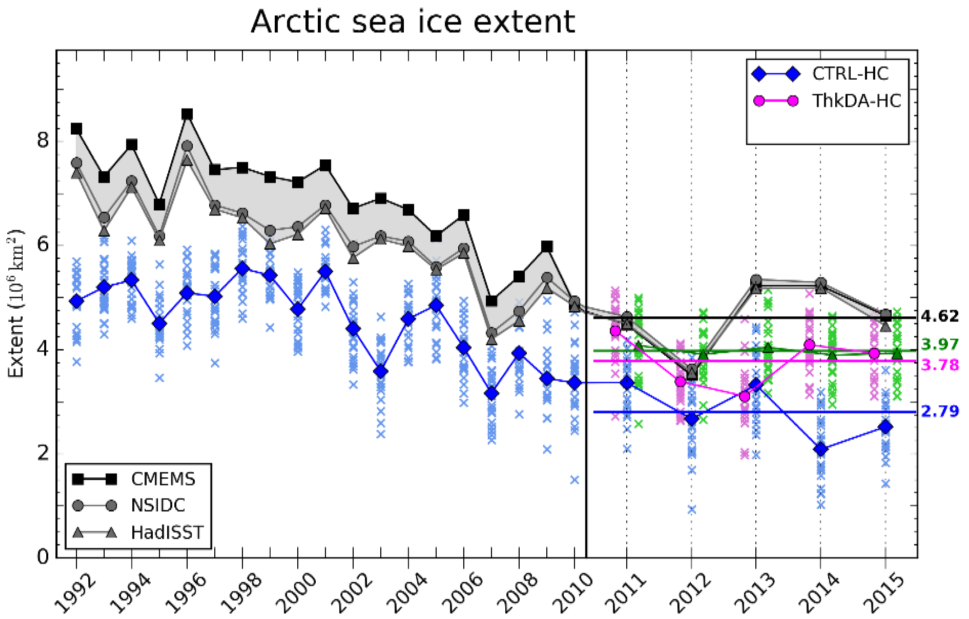
- [Using prototype GC3 GloSea version]

[Blockley and Peterson (2018)]

Arctic extent comparison

- General increase in extent
  - => reduction in low bias

- Ensemble distribution each year significantly different at 1% level (except 2013)



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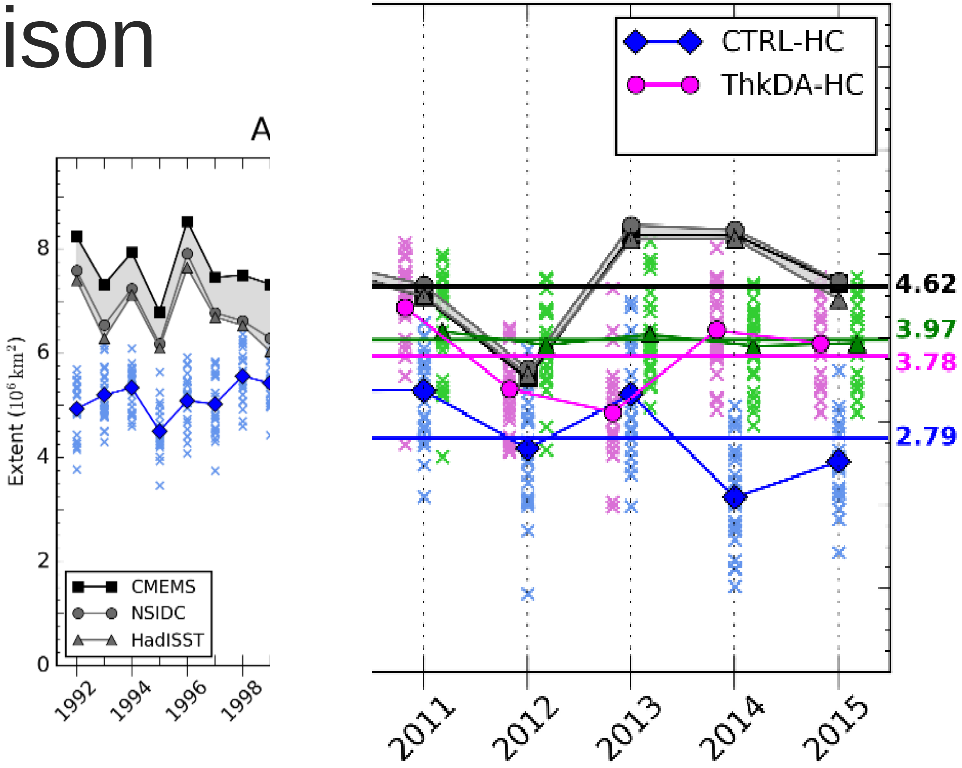

[Blockley and Peterson (2018)]

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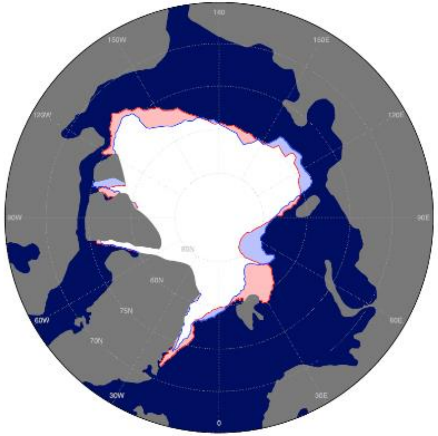
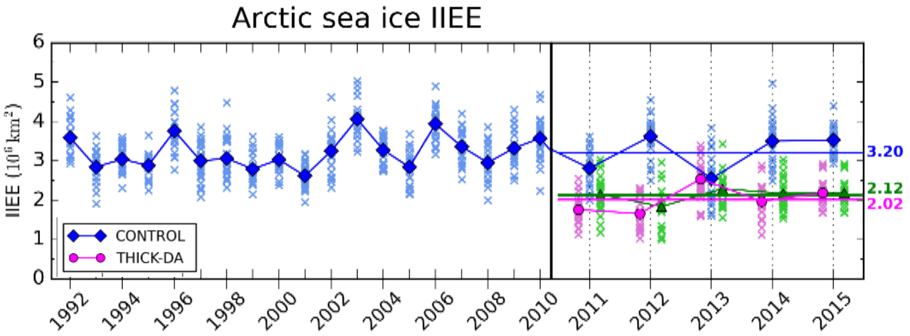
Integrated Ice Edge Error (IIEE)



- Using IIEE of Goessling et al. (2016)
  - Integral of all areas where model and observations disagree
    (sum of red and blue areas)

- General reduction in ice edge error
  - 37% lower IIEE for 5-year total

- Each year ensemble distribution significantly different at 1% level (except 2013)



Sea ice edge improvements

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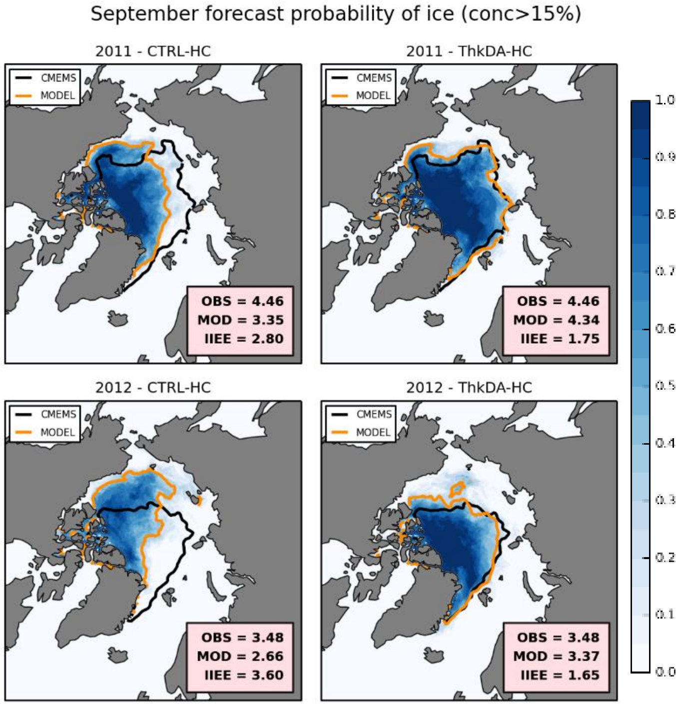
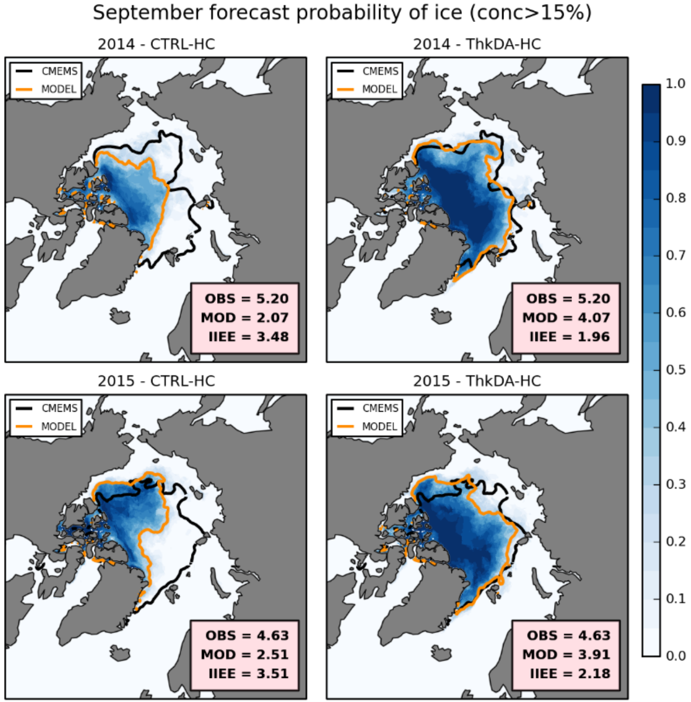
2011, 2012 & 2014, 2015



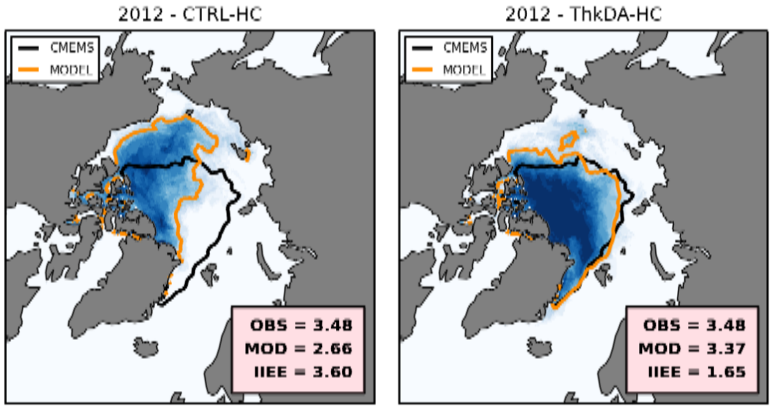


Control **ThkDA** **Control** **ThkDA**

[Blockley and Peterson (2018)]

Summary: sea ice thickness initialisation

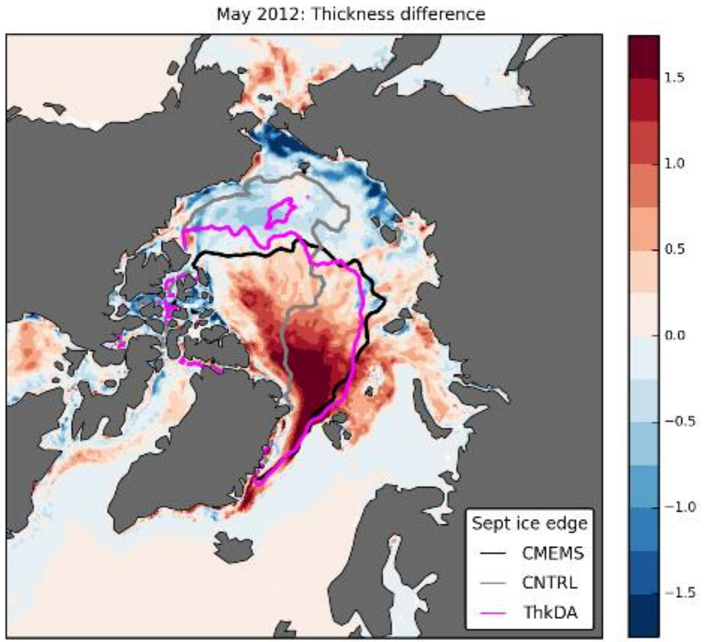
- Sea ice thickness initialisation in GloSea shows promise:
  - Potentially large impact on sea ice forecast evolution & predictability
  - Particularly the ice edge in the Atlantic sector
- Model persistently too thin in Atlantic sector and too thick in Pacific sector



[Blockley and Peterson (2018)]

Relationship between thickness and extent errors

- Example : 2012
- Clear alignment between:
  - May ice thickness changes (shading)
  - September ice edge location errors (lines)
    - **Black = Obs**
    - **Grey = GloSea Control**
    - **Pink = Thickness Initialised**
- Dipole pattern exists for all 5 years (2011-2015) to some extent



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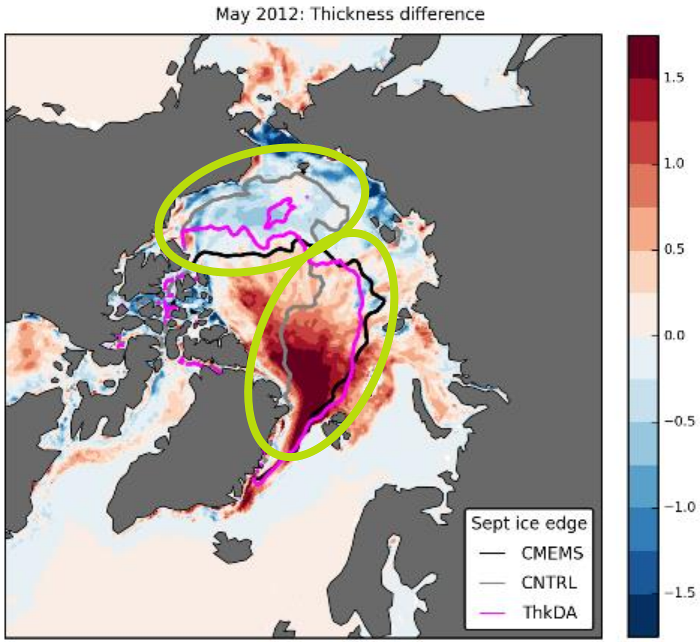

Additional questions:

- What is the relative importance of fixing persistent thickness distribution bias vs. correct initialisation?
  - Does the correct year matter?
  - Or does the model's thickness climatology?

- A further GloSea experiment was performed
  - Using 2015 sea ice initial conditions for 2011-2014
  - [As above but also 2015 ocean – not shown]

[Blockley and Peterson (2018)]

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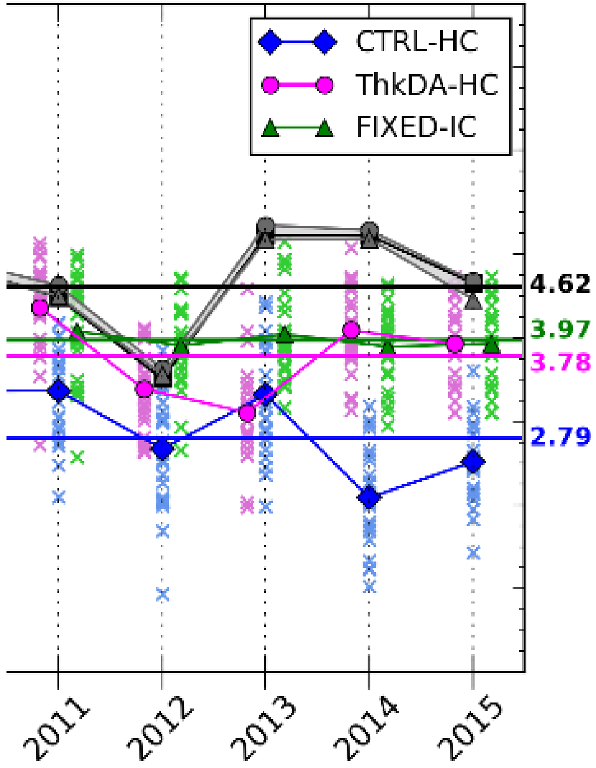
Using 2015 sea ice each year

- FIXED-IC run (green line) surprisingly level:
  - Ensemble large enough to account for atmospheric variability
  - Initial ice volume controls final extent/cover
  - Ocean less important
- FIXED-IC not significantly different from THICK-DA
  - 5-year time series too short



Summary

- Arctic sea ice thickness at end of winter exerts a strong control on eventual September minimum extent
  - => Improving winter thickness will improve summer forecasts
  - => Thickness initialisation can improve summer forecasts
- However DA cannot fix everything
- Fixing persistent model biases will also improve predictive skill

[Blockley and Peterson (2018)]

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The end

Thank you for your attention

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Improving Met Office seasonal predictions of Arctic sea ice using assimilation of CryoSat-2 thickness

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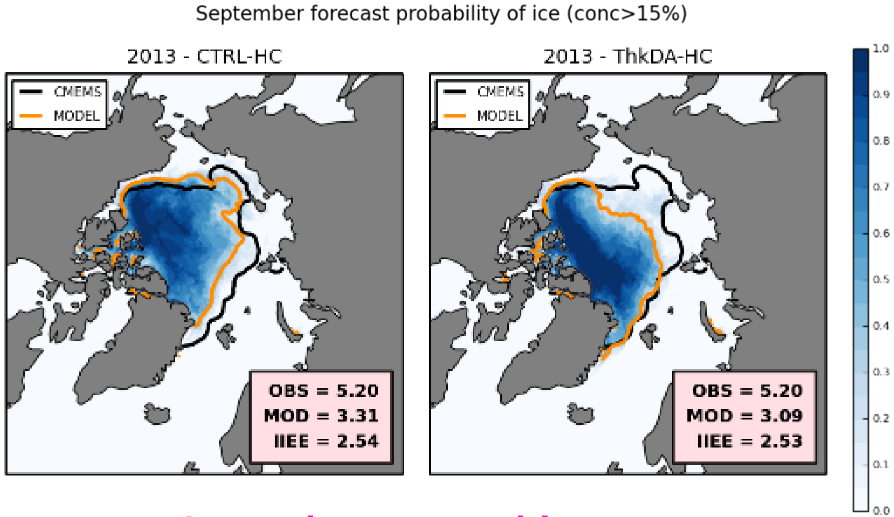
Abstract. Interest in seasonal predictions of Arctic sea ice has been increasing in recent years owing, primarily, to the sharp reduction in Arctic sea-ice cover observed over the last few decades, a decline that is projected to continue. The prospect of increased human industrial activity in the region, as well as scientific interest in the predictability of sea ice, provides important motivation for understanding, and improving, the skill of Arctic predictions. Several operational forecasting centres now routinely produce seasonal predictions of sea-ice cover using coupled atmosphere–ocean–sea-ice models. Although assimilation of sea-ice concentration into these systems is commonplace, sea-ice thickness observations, being much less mature, are typically not assimi-

1 Introduction and motivation

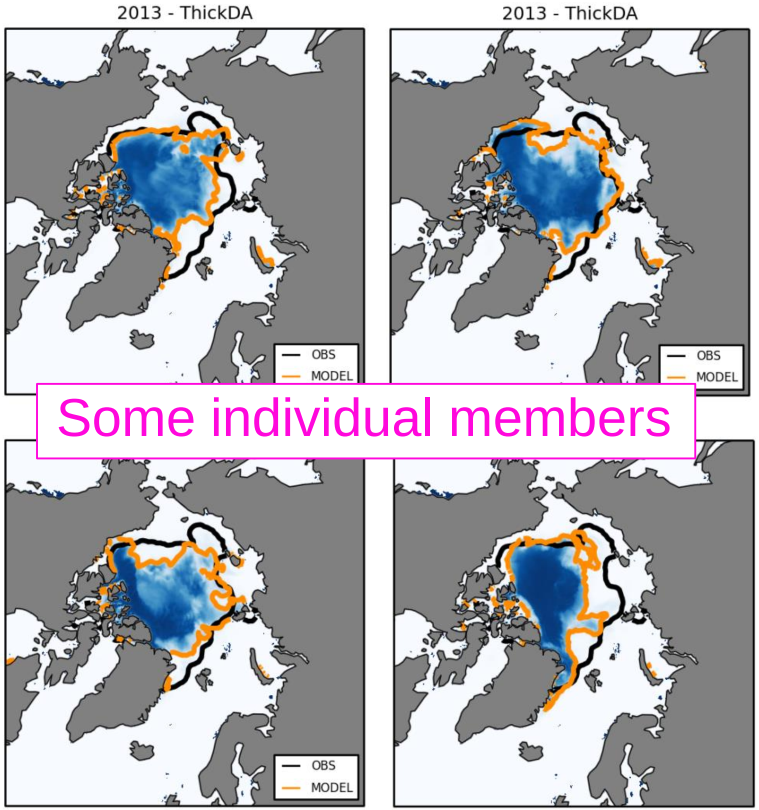
Arctic sea ice is one of the most rapidly, and visibly, changing components of the global climate system. The past few

2013: The ‘black sheep’…



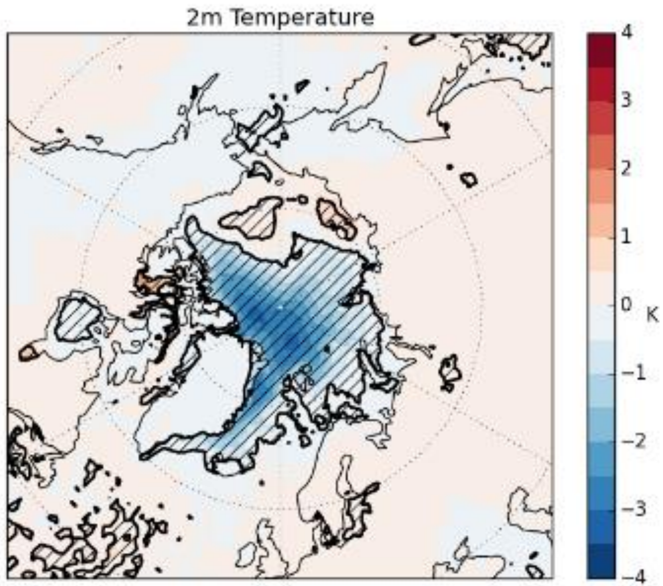
Control

ThkDA

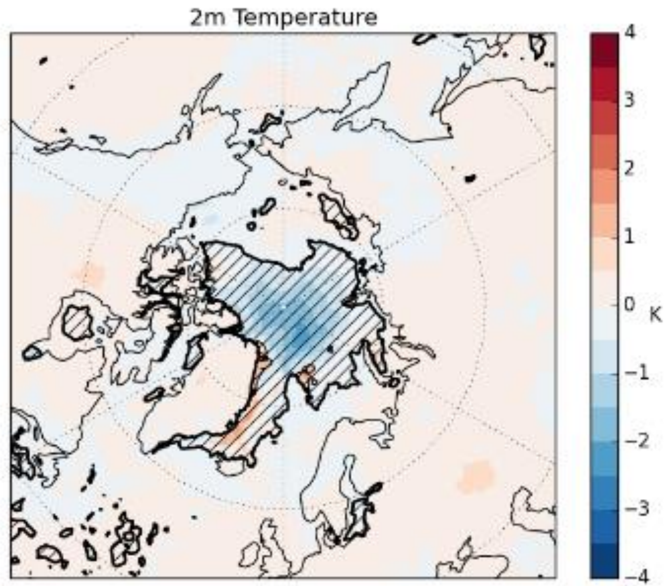


Some individual members

Local Atmospheric Impact : T2m



Average difference for all ensemble members 2011-15



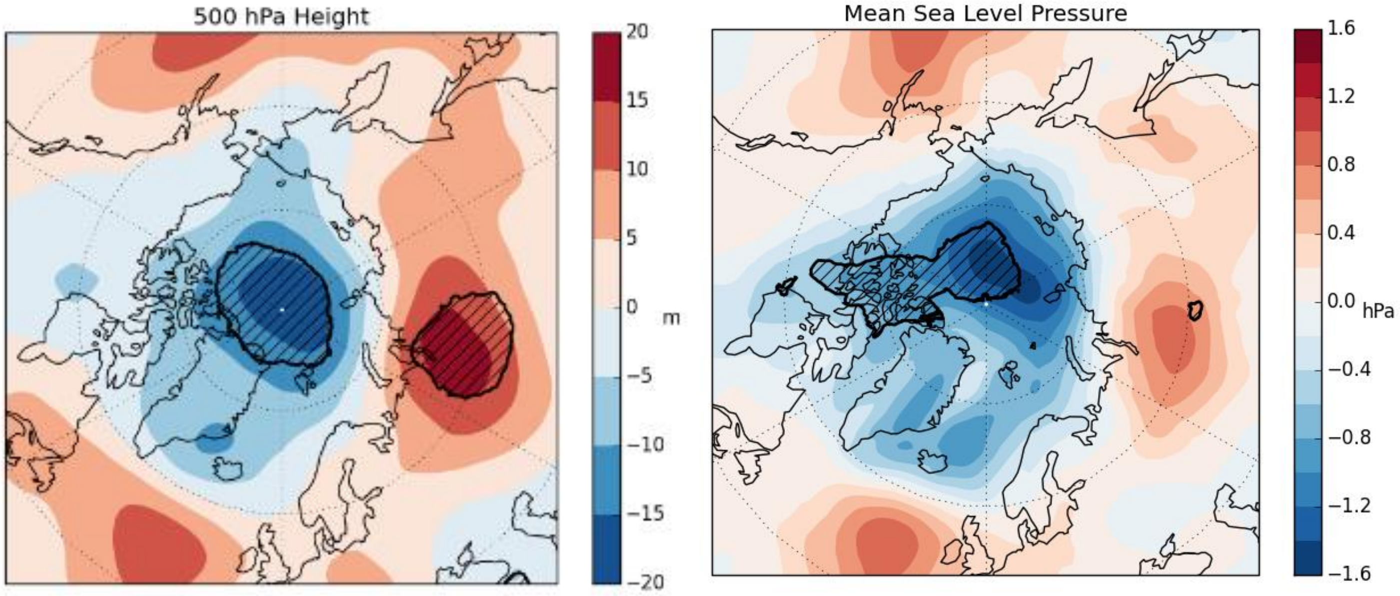
Average difference in RMSE over all ensemble members 2011-15 (vs ERA-Interim)

- Reduced near-surface temperature over Arctic Ocean
- Reduced temperature errors over Arctic Ocean
- Increased error south of Fram Strait
    - too much sea ice export?

Black contours/hatching where differences significant at 95% level

[Blockley and Peterson (2018)]

Wider impact : Z500 & MSLP Difference

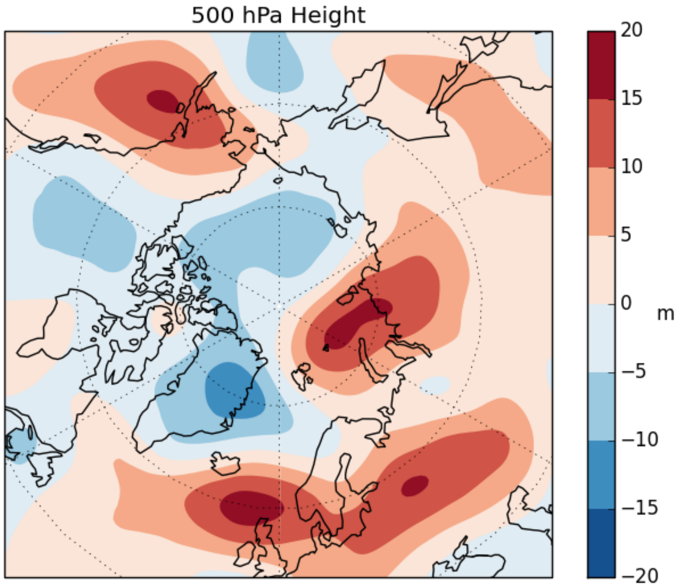


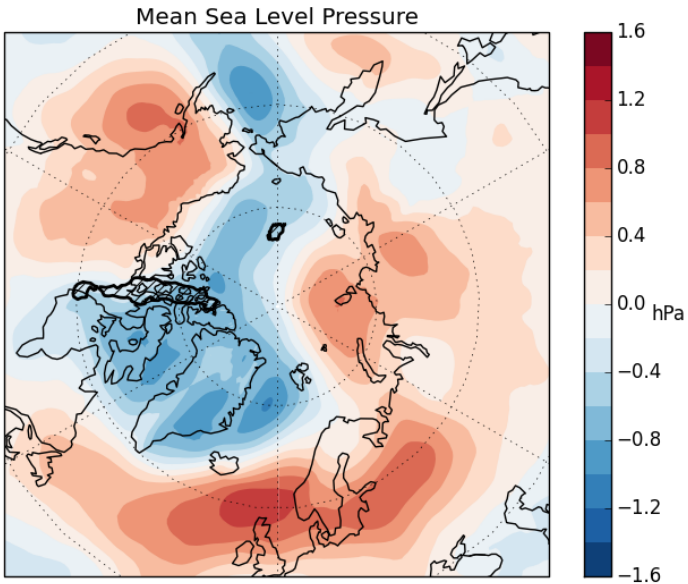
- Recall we have increased SIC
- Mostly north of Svalbard
- Reduction over Arctic Ocean
- Increase over Siberia

Average difference for all ensemble members 2011-15

Black contours/hatching where differences significant at 95% level

Wider impact : Z500 & MSLP Error





- Improved over Arctic Ocean and within Canadian Archipelago
- Degraded over mid-latitudes
- Mostly not significant

Average difference in RMSE over all ensemble members 2011-15 (truth is ERAi)

Black contours/hatching where differences significant at 95% level

[Blockley and Peterson (2018)]

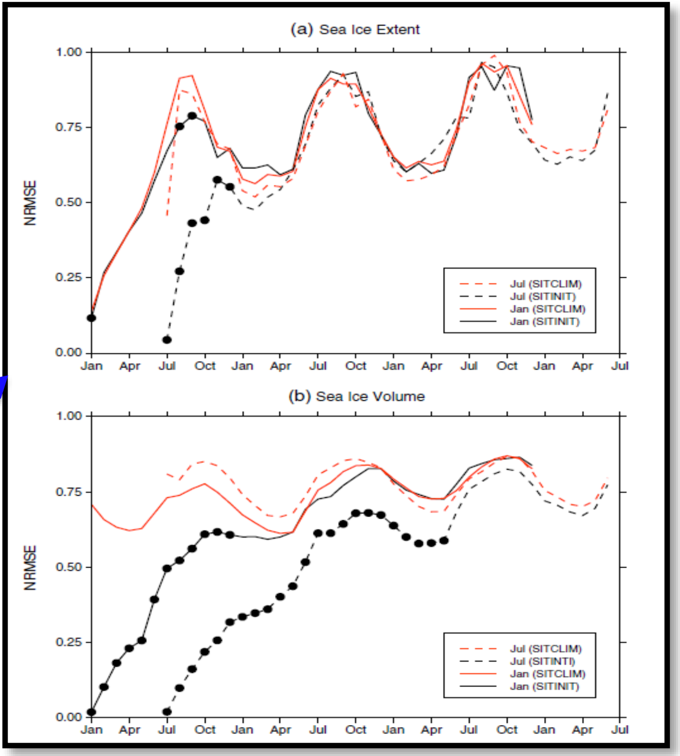
SIT assimilation: next steps

- Development of SIT assimilation within FOAM ocean-sea ice analysis
- Development of SIT assimilation in NEMOVAR 3D-Var (alongside SIC)
- EU-SEDNA project: “Safe maritime operations under extreme conditions: the Arctic case”
  - Prescription of observational errors (instrument, algorithm, & representativeness errors)
  - Methods to represent appropriate model background errors
  - Using raw (L2) satellite tracks, from as many observational platforms as possible (including CS2 and SMOS)
  - Information being spread through the model using spatial and inter-variable error correlations

Potential importance of ice thickness

- Perfect model study:
  - Day et al. (2014) using HadGEM1 perturbed ensemble
  - Initialisation of **sea ice thickness important** for monthly-seasonal forecast skill

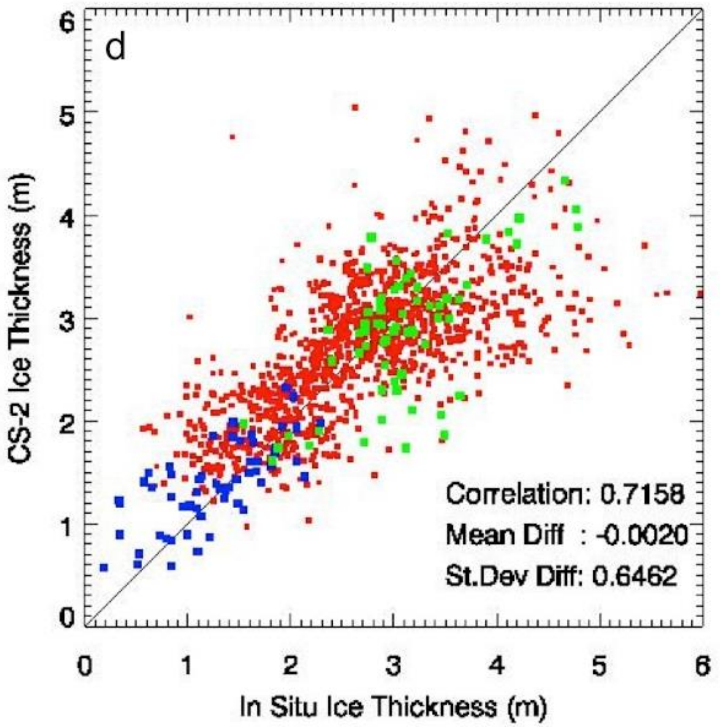
- Normal model initialisation
- SIT initialised with model climatology
- Dots show significant diffs



CPOM thickness QC

- Require the following:
  - thickness above 1m
  - thickness below 7.0m (to avoid outliers)
  - at least 10 altimeter points contributing towards the data point
  - maximum standard deviation of 2m amongst contributing data points
  - maximum COG distance 15km
    - as per CPOM suggestion (Andy Ridout)
    - to avoid smearing at ice edge

Sea ice thickness validation



Tilling et al. (2018)

IceBridge, CryoVEx } Airborne (seasonal)

Buoy data } Fixed (year-round)

- Validation of CryoSat-2 sea ice thickness from 2010-2017
- Average difference between CryoSat-2 and *in situ* thickness is 2mm (no significant bias overall)
- Standard deviations of the differences are comparable to accuracy of each instrument (13cm for CryoSat-2)