Variable atmospheric and oceanic drag over Arctic sea ice

Over Arctic sea ice, pressure ridges, floe and melt pond edges all introduce discrete obstructions to the flow of air or water past the ice, and are a source of form drag. In current climate models form drag is only accounted for by tuning the air-ice and ice-ocean drag coefficients, i.e. by effectively altering the roughness length in a surface drag parameterization. The existing approach of skin drag parameter tuning is poorly constrained by observations and fails to describe correctly the physics associated with the air-ice and ocean-ice drag. Here we combine recent theoretical developments to deduce the total neutral form drag coefficients from properties of the ice cover such as ice concentration, vertical extent and area of the ridges, freeboard and floe draft, and size of floes and melt ponds. We incorporate the drag coefficients into the CICE sea ice model and show the influence of the new drag parameterization on the motion and state of the ice cover, with the most noticeable being a depletion of sea ice over the west boundary of the Arctic Ocean and over the Beaufort Sea. The new parameterization allows the drag coefficients to be coupled to the sea ice state and therefore to evolve spatially and temporally. We find that the range of values predicted for the drag coefficients agree with the range of values measured in several regions of the Arctic. Finally we discuss the implications of the new form drag formulation for the spin-up or spin-down of the Arctic Ocean.

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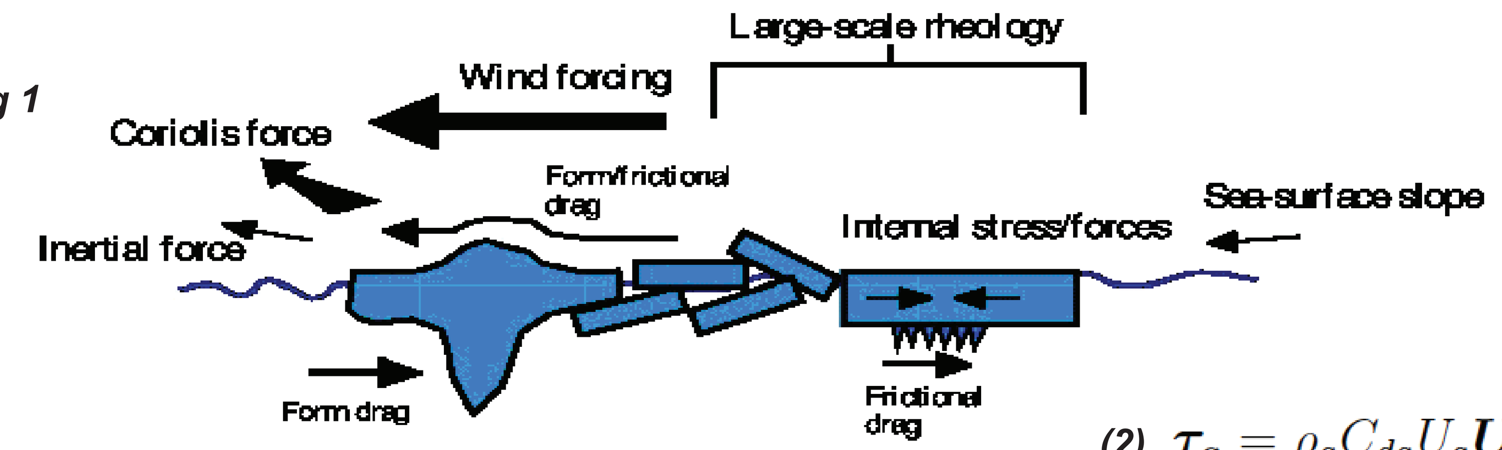
The new drag parameterization

Importance of form drag in the momentum equation

Fig 1



$$(1)\quad m\frac{D\boldsymbol{u}}{Dt} = \boldsymbol{\tau_a} + \boldsymbol{\tau_w} + \boldsymbol{\nabla}\cdot\boldsymbol{\sigma} - mf_c\boldsymbol{k}\times\boldsymbol{u} - mg\boldsymbol{\nabla}H$$

$$(2)\quad \boldsymbol{\tau_a} = \rho_a C_{da} U_a \boldsymbol{U_a}$$

$$(3)\quad \boldsymbol{\tau_w} = \rho_w C_{dw} U_w e^{i\boldsymbol{\theta_w}} \boldsymbol{U_w}$$

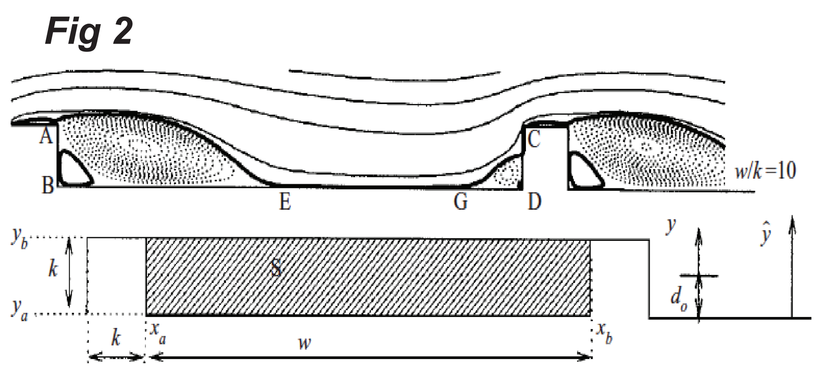
The first three terms on the r.h.s. dominate the momentum balance in typical Arctic sea ice conditions and determine the ice drift throughout the Arctic basin.

General expression of form drag coefficient over randomly oriented obstacles

Earlier theory (review in *Lupkes2012*) based on wind tunnel experiments and direct numerical simulations (Leonardi2003) can be summarized in the general expression,

$$(4)\quad C_d = \frac{NcS_c^2 gLH}{2S_T}\left[\frac{\ln(H/z_0)}{\ln(10/z_0)}\right]^2$$

Fig 2



where *N* discrete obstacles of height, *H*, and transverse length, *L*, are distributed randomly on a domain of surface, S_T. *c* is the coefficient of resistance of an individual obstacle, z_0 is a roughness length and *g* is a geometrical factor that depends on the shape of the obstacles. Finally, S_c, is a sheltering function for the obstacle considered and will be a function of the typical distance between obstacles, *D*, and the height, *H*.

The three main contributions to form drag

Current General Circulation Models (GCMs) only account for a constant neutral drag coefficient over sea ice both for the atmosphere and the ocean.

In the new approach we identify three main contribution to form drag from 1) ridges and keels, from 2) the freeboard and draft at the floe edges and from 3) the melt pond edges.

$$(5)\quad C_{da} = C_{dar} + C_{daf} + C_{dap} + C_{das} \qquad (6)\quad C_{dw} = C_{dwk} + C_{dwf} + C_{dws}$$

Fig 3

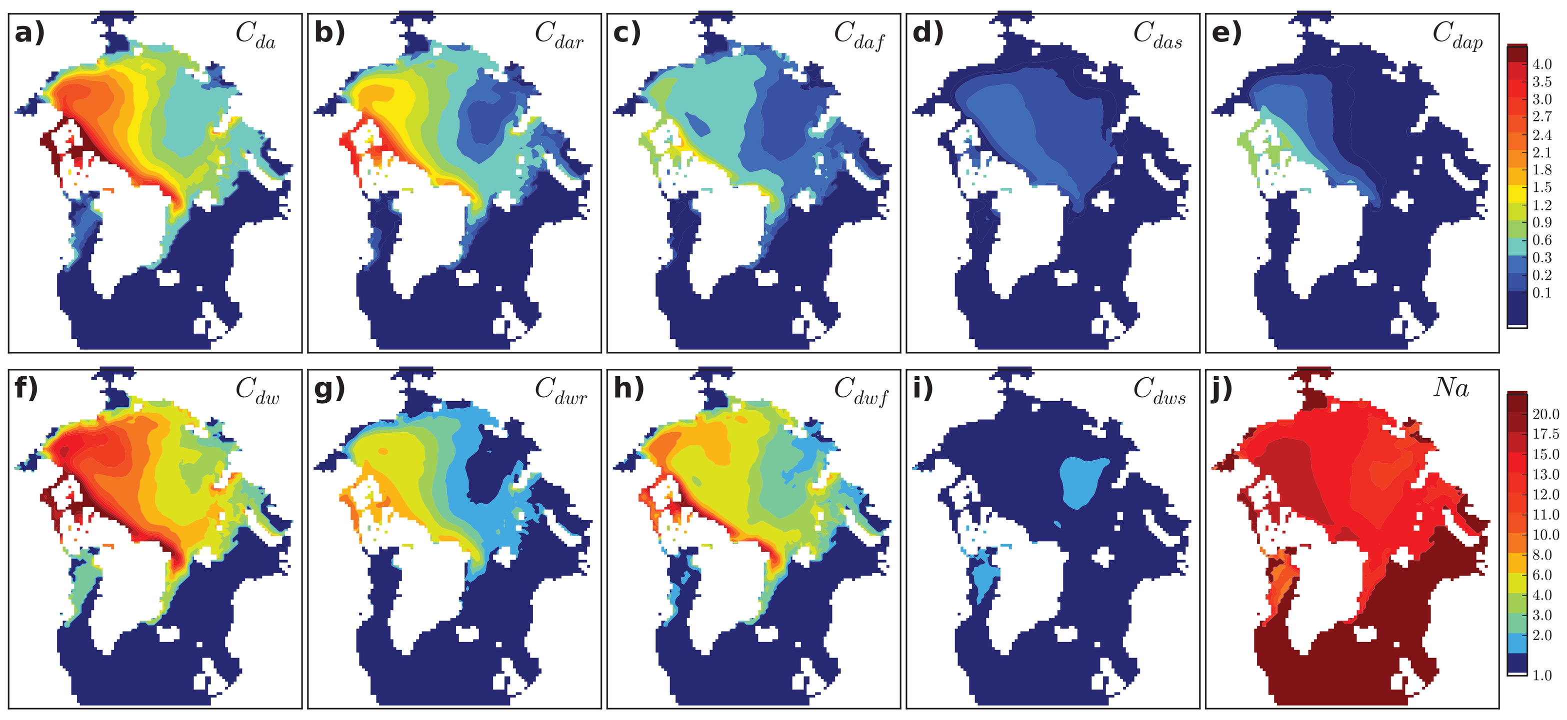
Winter pack ice — Melt season — Summer ice cover or MIZ

Variable drag coefficients (in time and space)

New neutral drag coefficients and main contributions. September average over 1990-2012 period

The model is able to reproduce a realistic spatial distribution of neutral drag coefficients for both the atmosphere and the ocean. The form drag associated to ridges/keels dominates in the central pack ice while the floe edge form drag dominates in the MIZ and during summer.

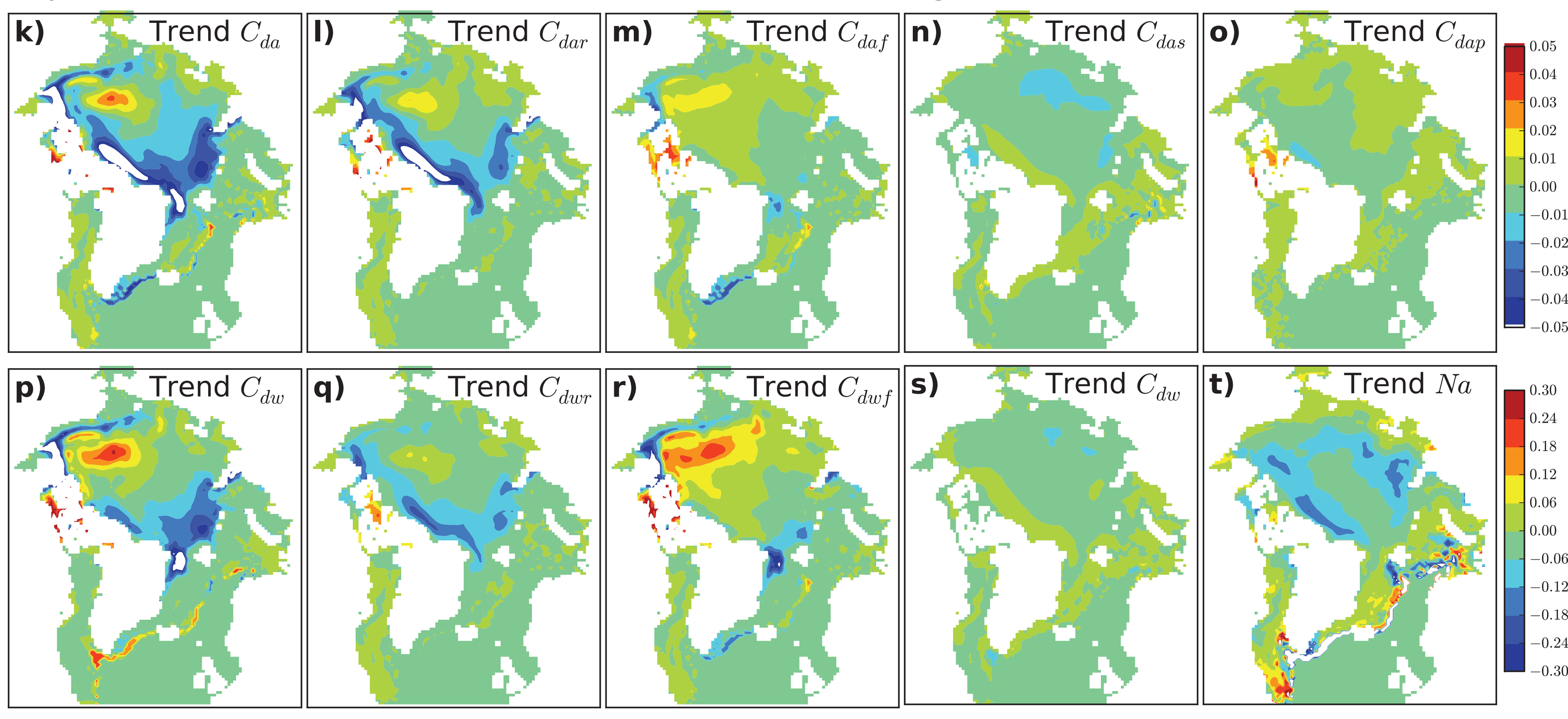
Fig 7



Trend of the same drag coefficients over the same time period (units in /year)

The trends in the drag contributions show that there is a large increase in the model in the summer values. This is mainly due to the increase of the contribution from floe edge and is associated to the decline of sea ice.

Fig 8



Seasonal dependence of the drag coefficients

The model captures the observed summer increase of the drag that we attribute to the floe edges contribution and to a smaller degree to the melt ponds. The summer maximum is more accute in the oceanic drag coefficient.

Fig9

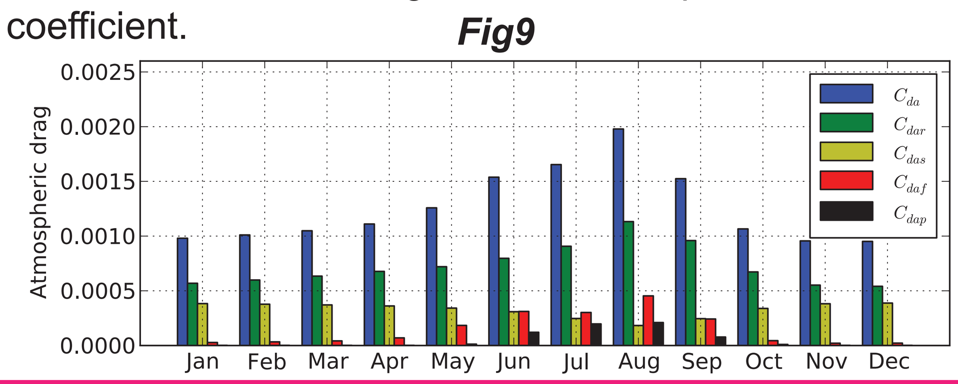
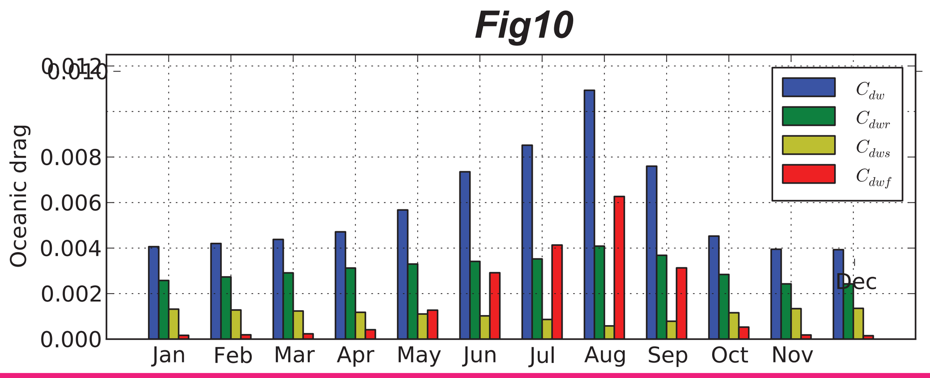


Fig10

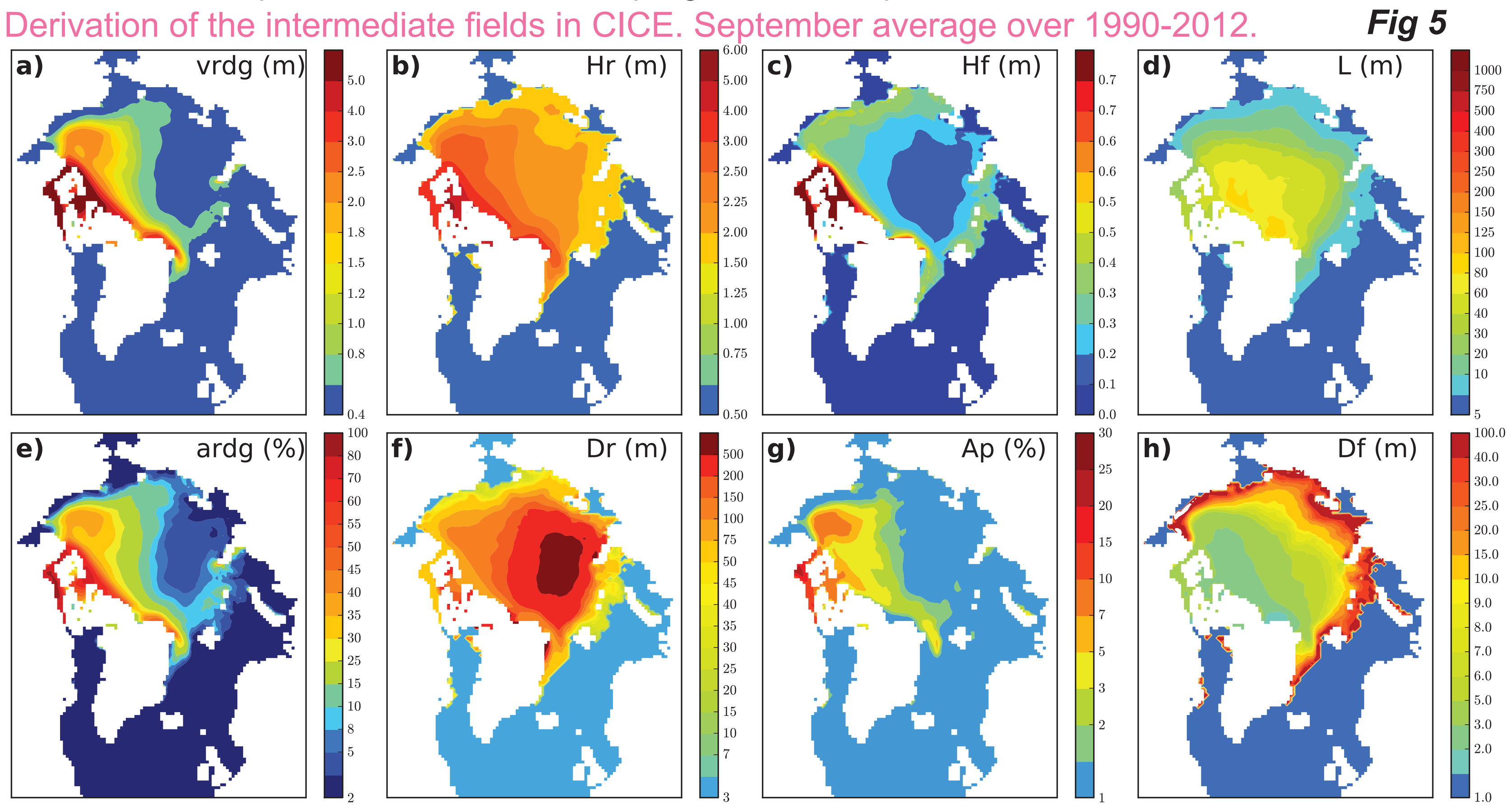


Intermediate variables in CICE - Validation

The CICE setup

- CICE version 4.1 in stand alone mode - Atmospheric forcing from NCEP_Reanalysis2
- Mixed layer temperature and salinity restoring towards monthly means from MYO-WP4-PUM-GLOBAL-REANALYSIS-PHYS-001-004
- CICE has ice thickness redistribution scheme with realistic ice thickness distribution, multiple ice categories and provides volume (vrdg) and area (ardg) of ridged ice tracers
- We have developed state of the art with prognostic meld pond scheme

Derivation of the intermediate fields in CICE. September average over 1990-2012. *Fig 5*



Validation against remote sensing observations - NASA Icebridge airborne project

Fig 5

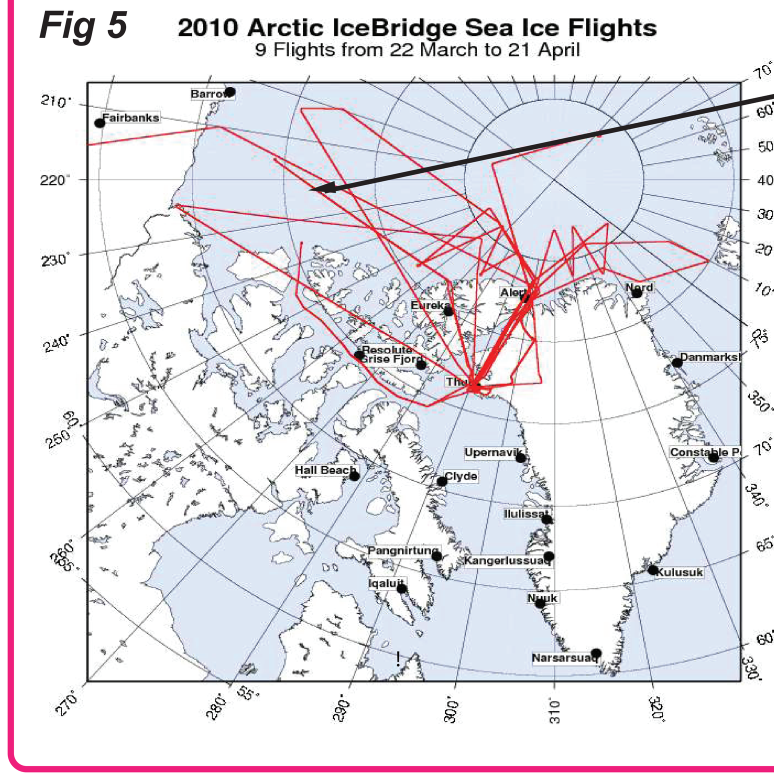
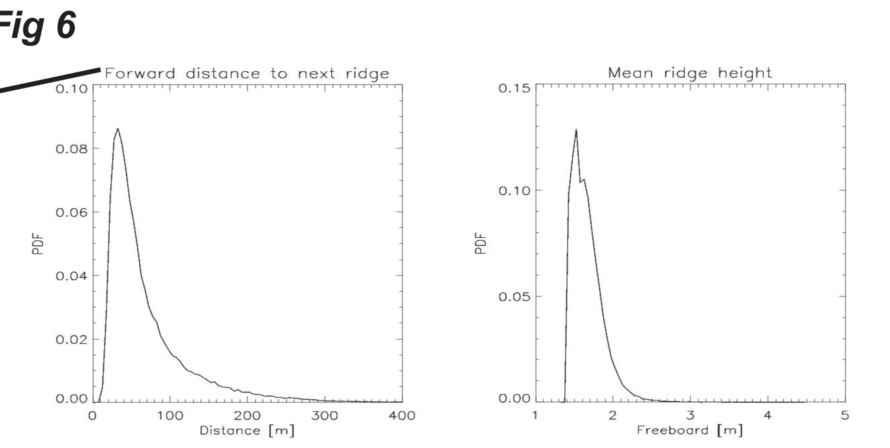


Fig 6



Icebridge offers an extended coverage of Arctic (and Antarctic) sea ice with sub-meter resolution.

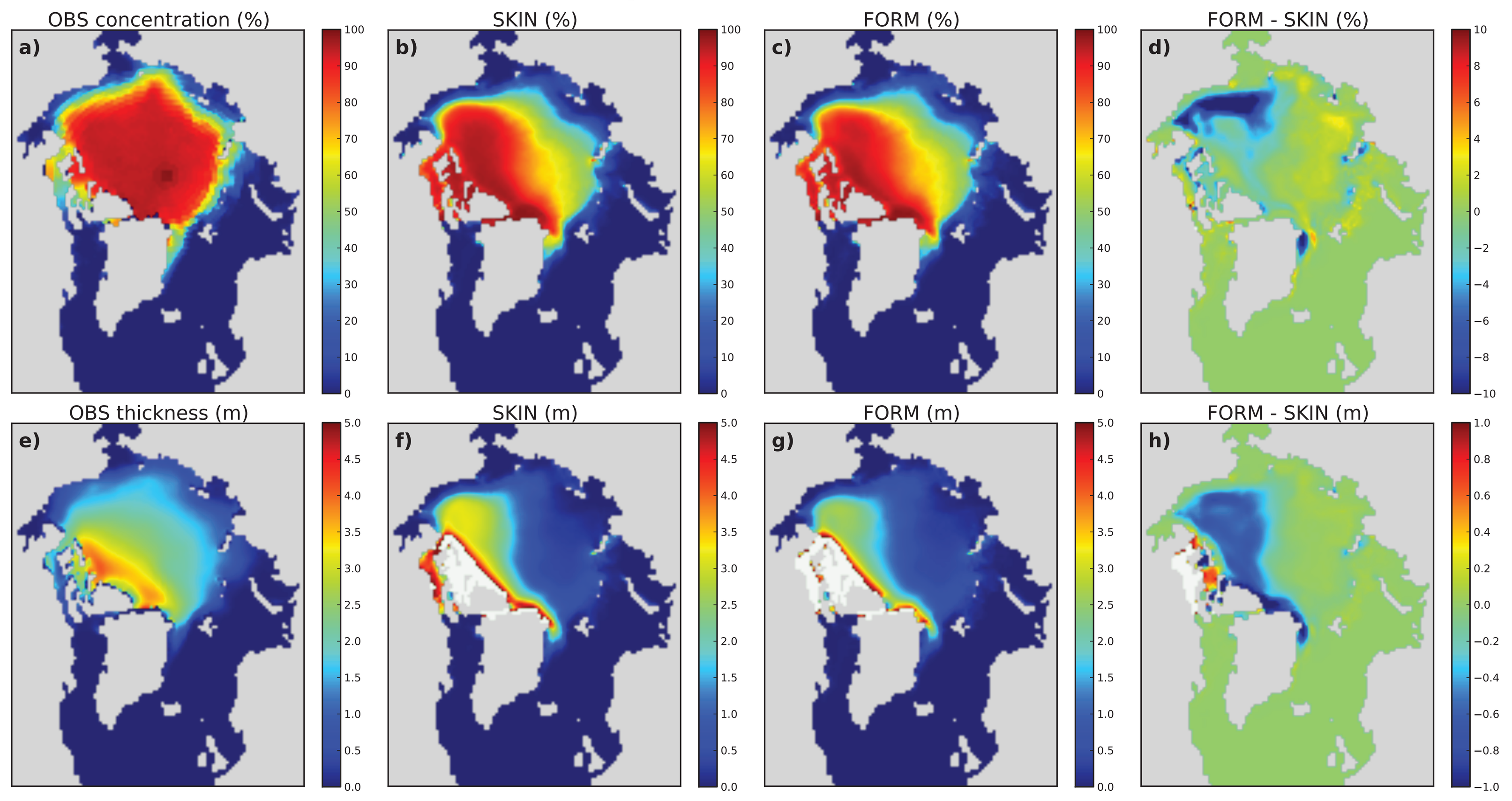
- Mainly the west part of the Arctic ocean (Fig 5), covering first year ice, multiyear ice and the MIZ.
- Coverage from 2009 to 2013, from March to June.

Impact on Arctic sea ice and on Arctic Ocean

Comparing model runs with constant (SKIN) and variable (FORM) drag coefficients with observations (OBS)

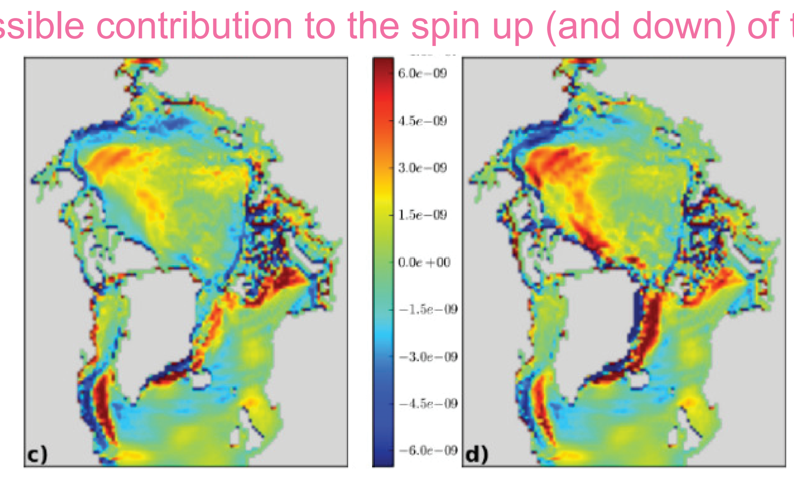
The variable drag coefficients accounting for form drag result in a depletion of sea ice over most of the west portion of the Arctic basin. This is the result of the combined effect of modified ice transport, ridging and heat fluxes associated with the variable drag coefficients. Most noticeable is the contribution from the heavily ridged regions north of Greenland and the Canadian Archipelago where the large transfer coefficients result in increased heat fluxes that lead to more ice being melted in the summer months.

Fig11



A possible contribution to the spin up (and down) of the Arctic Ocean

Fig12



We find that in the run accounting for form drag the increase in the curl of the oceanic stress is significant over the Beaufort Sea area (also over the Fram Strait) and could help explain the observed increased momentum transfer in this region.
This enhanced trend in the curl of the oceanic stress could help explain the observed spin up in recent years observed in the Beaufort Sea and the associated accumulation of fresh water through Ekman pumping.

Conclusion

A new parameterisation of the ice/ocean and ice/atmosphere momentum transfer is implemented in CICE and accounts for form drag from ridges/keels, form drag from floe edges, melt pond edges and reduced skin drag due to a sheltering effect.

The new physics introduced in the sea ice component, CICE, has the potential to improve the hindcast and forecast of the Arctic sea ice properties while also producing more realistic forcing of the Arctic Ocean (brine release, fresh water fluxes, Ocean spin up and down) when implemented in future generation GCMs.