IS-ENES3 Deliverable D8.1

NEMO sea ice model code

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ABSTRACT

In 2017 members of the newly formed NEMO Sea Ice Working Group (SIWG) agreed to work together to develop a unified sea ice model within the NEMO framework, bringing sea ice fully within the NEMO consortium, and bringing together the developers and users of the several different sea ice models that were previously used with NEMO (CICE, GELATO, LIM2, LIM3). This new fully integrated NEMO sea ice model is to be known as the "**Sea Ice modelling Integrated Initiative (SI3)**".
Development of the new SI3 code, and integration within the NEMO repository, has been supported by the IS-ENES3 project. This deliverable report provides details of the availability of SI3 code within the NEMO repository and describes some of the code improvements, both technical and scientific, that are included in the latest version of the model (NEMO v4.2).

Dissemination Level		
PU	Public	X
CO	Confidential, only for the partners of the IS-ENES3 project	

Revision table			
Version	**Date**	**Name**	**Comments**
Release for review	13/09/2021	E. Blockley, M. Vancoppenolle	
Final version	22/09/2021	E. Blockley, M. Vancoppenolle	Updates following review by C. Rousset, D. Iovino, S. Valcke, S. Morellon

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Executive Summary

The new NEMO sea ice model, known as the "Sea Ice modelling Integrated Initiative (SI3)", is now available in the NEMO trunk. This new SI3 code is:

- available within the NEMO repository alongside the NEMO ocean code
- the only sea ice model available with NEMO
- fully compliant with NEMO coding & design standards
- fully integrated with the NEMO ocean components, making use of centralised NEMO infrastructure as much as possible (e.g. for grid setup, diagnostic output, mpi libraries, etc.)

A preliminary version of SI3 was available at NEMO 4.0, which included several improvements (inc. bug fixes) relative to the older LIM3 model and made prior to the start of IS-ENES3. An updated version of the SI3 sea ice model will be available within the NEMO 4.2 release, comprising several improvements that have been supported from within IS-ENES3, including:

- improvements to code modularity, robustness, conservation and optimization
- additional sea ice rheology options such as the adaptive EVP (aEVP) and elastic anisotropic plastic (EAP) schemes
- new melt-pond modelling schemes, including both simple "level ice" and more complicated "topographic" options
- implementation of the 'conductivity coupling' scheme to allow SI3 to be included within the HadGEM & UKESM coupled models
- a new radiation parameterization with improved representation of light transfer through snow and sea ice

1. Introduction to the Sea Ice modelling Integrated Initiative (SI^3)

At the inception of NEMO as a pan-European ocean modelling framework, the sea ice was not considered fully within the scope of the consortium. Over the years several sea ice models have been used along with the ocean component of NEMO – including the LIM2 and LIM3 models, the Los Alamos sea ice model CICE, and the Météo-France/CNRM GELATO model. Prior to the release of NEMO version 4.0, use of the different sea ice models was undertaken with varying degrees of integration: whilst the LIM codes were provided through the NEMO subversion repository, only an interface to CICE was included within the NEMO Surface Boundary Condition (SBC) modules, and for GELATO an ad-hoc interface was maintained separately at Météo-France/CNRM.

In 2017 members of the newly formed NEMO Sea Ice Working Group (SIWG) agreed to work together to develop a unified sea ice model within the NEMO framework, bringing sea ice fully within the NEMO consortium, and bringing together former developers and users of the CICE, GELATO, and LIM, models. The new fully integrated NEMO sea ice model is to be known as the "Sea Ice modelling Integrated Initiative (SI3)".

Development of the new SI3 code, and integration within the NEMO repository, has been supported by the IS-ENES3 project. This deliverable report provides details of the availability of SI3 code within the NEMO repository and describes some of the code improvements, both technical and scientific, that are included in the latest version of the model.

2. Provision of SI^3 through the NEMO code repository

The SI3 model code is available for users to source directly through the NEMO subversion code repository at https://forge.ipsl.jussieu.fr/nemo/browser/NEMO/. Within the "src" source code directory, the SI3 code sits in an 'ICE' directory alongside the NEMO ocean code in 'OCE'. Within the 'ICE' directory all SI3 module names are prefixed with "ice", SI3 is named in all headers and building of the model is controlled with the "key_si3" CPP key. SI3 is released under the NEMO "CeCILL" licence and is the only sea ice model available within the NEMO repository. This is illustrated in Figure 1, which shows screenshots of the NEMO trac system at the 4.2 beta release (revision 15005).

As SI3 was initially branched from the LIM3 sea ice model, the code is fully compliant with NEMO coding standards and utilises all the relevant centralised NEMO infrastructure (XIOS diagnostics, grid specification/setup, AGRIF regional enhancement, MPI parallelisation, StandAlone Surface (SAS) module, etc.).

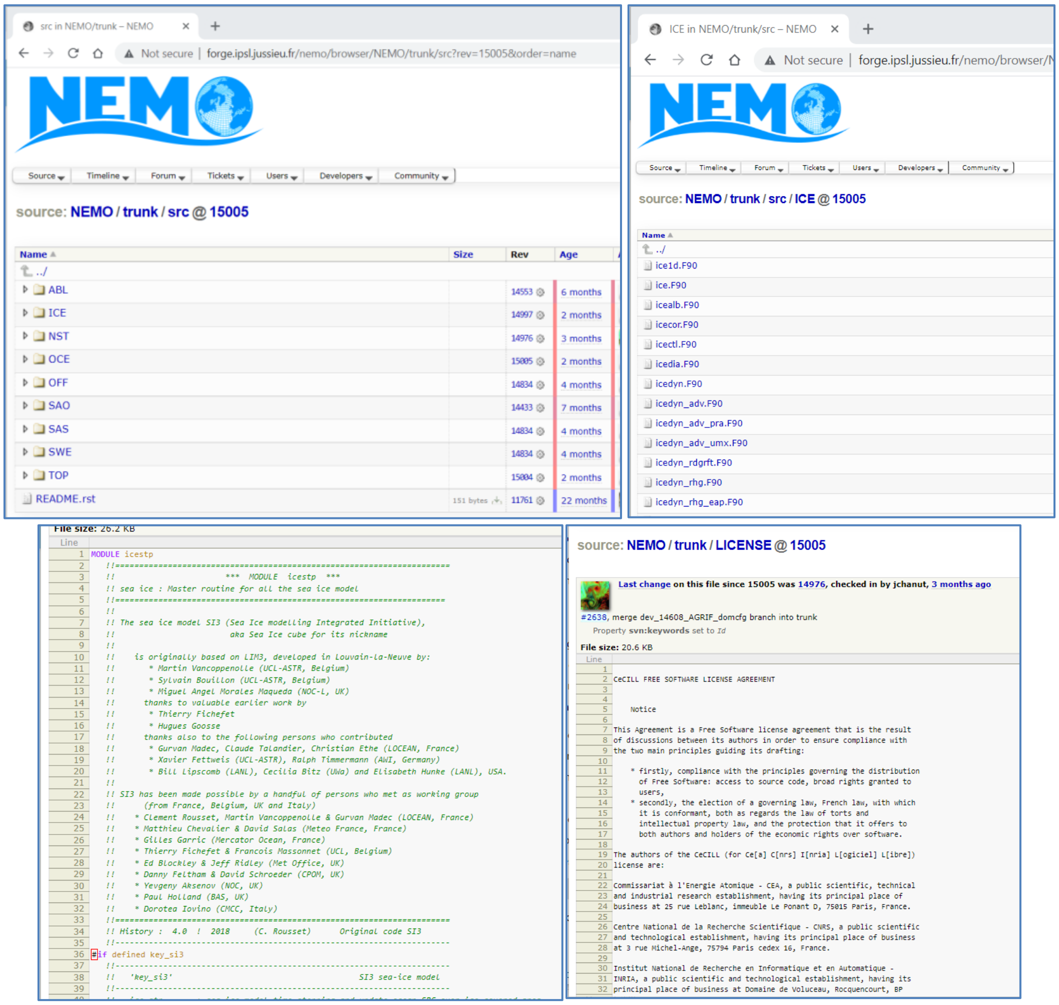

***Figure 1**: Screenshots from the trunk of the NEMO code repository at the 4.2 beta release (revision 15005) (https://forge.ipsl.jussieu.fr/nemo/browser/NEMO/trunk/?rev=15005): (upper-left) trunk source directory, "src", showing "ICE" folder; (upper-right) SI3 code modules within the 'ICE' folder; (lower-left) header of the SI3 time-stepping module (icestp.F90); (lower-right) CeCILL licence for the NEMO code (including SI3).*

3. SI^3 code developments included in the NEMO 4.2 beta release

Several improvements have been made to the SI3 model code for the NEMO 4.2 beta release. We document the key changes in this section and, where relevant, highlight which IS-ENES3 partner institutions were involved in the task. The first incarnation of SI3, that was released with NEMO 4.0, also included several updates to the code relative to the parent LIM3 model from which SI3 was branched. These updates include parameterisations for the modelling of land-fast ice and lateral ice melting, several bug fixes, and a new higher order sea ice advection scheme (UM5). Additionally, several preliminary technical changes were implemented to allow the larger developments made at NEMO 4.2 (and detailed below). However, we do not provide further details of these updates in this deliverable report because they were made prior to the start of the IS-ENES3 project.

3.1 Improving modularity and robustness of the code [CNRS-IPSL]

Prior to the development of SI3 there were interfaces to 3 different sea ice models in the NEMO code - CICE, LIM2, LIM3 (plus the ad-hoc GELATO interface maintained at CNRM). The SI3 merger has reduced the number of required sea ice model interfaces and has enabled a series of simplifications to be made to the NEMO/SI3 code. A simpler code is usually better because of improved readability and easier maintenance. One very first simplification was to remove the level of subroutine call for the sea ice model choice, such that now the main sea ice routine (ice_stp) is now called directly from the NEMO surface module (sbcmod.F). The different physical sea ice processes were also better grouped in the model subroutines, giving a further level of simplification. Most physical processes can now be switched on and off using the namelist, which allows compilation-free tests to be performed. A large effort has also been done on MPI performance/efficiency. SI3 scales better than LIM3 and the number of MPI communications required is about 3 times smaller in SI3 than in LIM3.

The ice-atmosphere interface module (in sbccpl.F) was also greatly simplified: many options warranting compatibility with the 3 original ice models were removed. Furthermore, an emulator for the ice-atmosphere interface to be used in forced-atmosphere mode was added to the NEMO code (blk_ice_qcn in sbcblk.F90). This feature permits using the ice-atmosphere interface without running the full atmospheric model, adding new features to it and understanding the impact of technical choices on the simulated sea ice state in the absence of atmospheric feedbacks.

The code was reviewed by many of the NEMO consortium partners, now all using the same sea ice code, focussing more of the attention to the same code, which revealed, as hoped, a few problems. Among other issues, mass and heat conservation issues were raised. The latter can pose problems for long integration times, in particular in climate model simulations. In response to those issues, improved conservation diagnostics, in the form of short output text files and netcdf 2D diagnostics were implemented (ice_drift). These diagnostics monitor conservation within the ice model at global and local scales, and for sea ice only (in isolation from the ocean), which was not possible before. Using these tools, the SI3 conservation problems were fixed, reaching virtually 0 W/m2 conservation error in coupled mode.

3.2 Adaptive EVP (aEVP) sea ice rheology [CNRS-IPSL]

One key sea ice physical process is referred to as “rheology”. This points to the evaluation of the key term of the sea ice momentum equation, which calculates the horizontal drift of the sea ice, a key specificity of sea ice with many implications on sea ice distribution, ocean circulation and marine biogeochemistry and climate.

The SI3 model uses a standard approach to handle rheology, the Elastic-Viscous-Plastic (EVP) approach (Hunke and Dukowicz, 1997). The EVP rheology has recently been updated to improve numerical convergence and stability, key to resolve narrow but large-scale openings in the ice pack (leads). The so-called adaptive EVP approaches (aEVP) have been implemented in SI3 (ice_dyn_rhg_evp.F90). The use of aEVP (Kimmritz et al., 2016) in particular reduces the cost of the sea ice rheology by a factor of 5 compared with EVP. Hence at comparable cost aEVP gives more converged solutions for sea ice drift velocities, leading to much improved representation of the leads in the Arctic sea ice pack and of the ice attached to the coasts of the Russian shore and of the Canadian Arctic Archipelago (landfast sea ice).

3.3 EAP anisotropic sea ice rheology [EU-IMMERSE]

The representation of sea ice dynamics in most modern sea ice models are based on continuum models that make the basic assumption that model grid-cells are large enough to contain a representative sample of ice types, with a sufficiently large number of leads and ridges for there to be no preferred orientation. In such a situation, it is acceptable to use the isotropic theory, which forms the basis of the VP family of rheologies - such as (a)EVP used within SI3. However, for models being run at sufficiently fine resolution, grid cells can no longer contain a representative sample of ice types and the question then arises as to whether an isotropic sea ice rheology is appropriate.

The EAP rheology (Tsamados et al., 2013) was developed to explicitly account for the sub-grid scale anisotropy of the sea ice cover. This anisotropic sea ice rheology has been ported from the CICE5 model into SI3 as part of the EU-IMMERSE project (funded under grant agreement no 821926), which works in synergy with IS-ENES3 on the development of NEMO (including SI3).

3.4 Melt-pond parameterisations [Met Office/CNRS-IPSL/UREAD]

Surface melting of sea ice and snow can cause meltwater to pool on top of the sea ice. These melt ponds can have an impact on the surface energy and radiation budget of the sea ice because they are less reflective than the surrounding ice or snow (lower albedo). Two melt pond modelling schemes have been implemented in SI3 and are available at the 4.2 release - a simple “level ice” scheme, and a more complicated “topographic” scheme.

The ‘topographic’ melt-pond scheme of Flocco et al. (2013) was developed at CPOM, University of Reading, and has been previously incorporated within the CICE5 model. The scheme evolves a prognostic model of melt-pond area and thickness, using the sub-grid ice thickness information to determine the topography of the melt-ponds. Surface refreezing of melt-ponds, so-called “lids”, are included. Within IS-ENES3 the SI3 topographic pond scheme has been tested by the CPOM team at University of Reading who were responsible for developing the scheme originally. The simpler “level ice” scheme is based upon the concept of Holland et al. (2012). The volume of surface meltwater is evolved at each grid-box, with melt-pond area fraction and depth being determined using an empirical relationship. The level scheme therefore requires evolution of fewer additional model prognostic variables.

Within the IS-ENES3 project this level ice scheme has been further developed to include the impact of refreezing at the surface of the ponds as an additional option. These pond lids have been shown to have a considerable impact on the surface albedo of the sea ice in the early freeze-up season (Flocco et al., 2015).

3.5 JULES ‘conductivity’ coupling [Met Office/CNRS-IPSL]

When coupling the sea ice and atmosphere model components in a coupled model one has a choice to make about the location of the coupling interface. Given the physical reality that ice and atmospheric temperatures are intimately related, one would, ideally, solve implicitly for the whole ice and atmosphere column. However, in practice, the sea ice and atmosphere temperature profiles are treated separately, and an explicit interface must be placed between them.

The standard approach to coupling in NEMO/SI3, as is true for many ocean-sea ice models, is to place the ice-atmosphere interface above the sea ice and use “bulk formulae” to calculate the surface exchanges between the two components. Although this approach provides a good method for forcing the surface of the sea ice, it does not allow the atmospheric boundary-layer to respond rapidly to changes in the sea ice surface, or vice-versa. The JULES “conductivity” coupling method of West et al. (2016) aims to improve this situation by placing the atmosphere coupling interface just below the surface of the sea ice. This allows surface exchanges and near-surface temperatures to be computed together as part of the atmospheric boundary-layer calculations, leading to an improved representation of surface temperature fluxes (see Figure 2 below and West et al., 2016).

The “conductivity coupling” approach has been implemented in SI3, including being added as an option within the ice-atmosphere interface emulator described in (i) above. The coupling has been thoroughly tested within the Met Office’s HadGEM3 model. This has been required to facilitate the uptake of SI3 by the Met Office and wider UK climate modelling community (UKESM), but will also allow wider uptake of SI3 amongst members of the Met Office Unified Model Partnership (in particular Australia, New Zealand, South Korea).

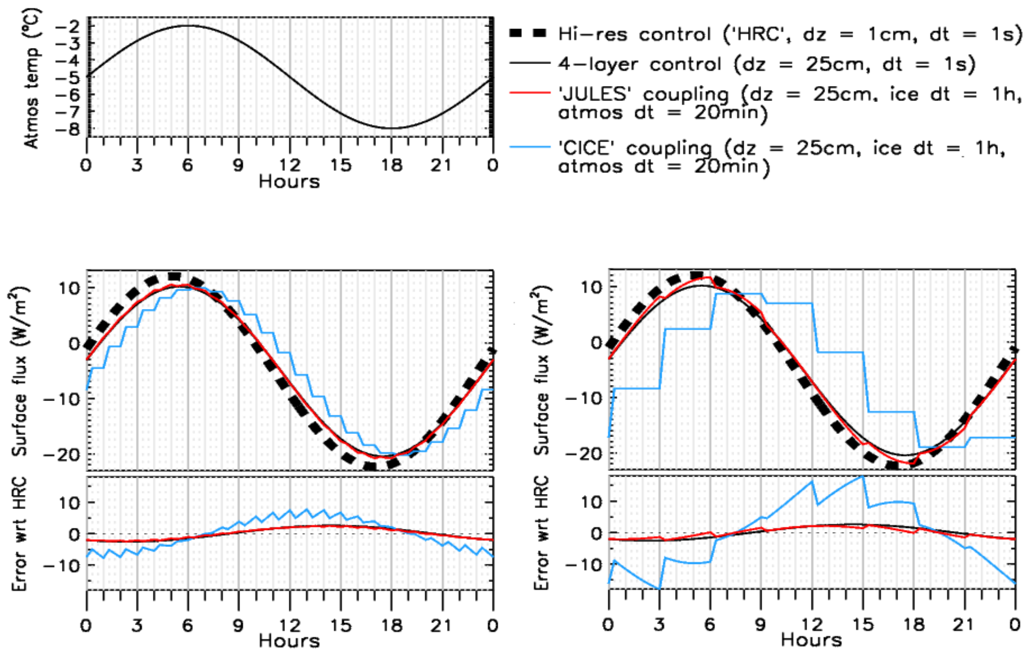

Figure 2*: Showing the impact of choice of coupling interface location using an imposed diurnal cycle of atmosphere temperature (upper-left) and run in an idealised 1D setup. Surface temperature fluxes and errors are shown for the JULES conductivity coupling (red lines) and for the standard coupling (blue lines) using both 1-hourly (lower-left) and 3-hourly (lower-right) coupling frequencies. The black lines represent the best possible implicit simulation, obtained using a model time-step and coupling frequency of 1s. (Adapted from West et al., 2016).*

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3.6 Radiation scheme improvements [CNRS-IPSL]

Radiative transfer in sea ice is a key process because it controls the light partitioning at the highly reflective sea ice interface, providing a physical basis to the so-called ice-albedo effect. Radiative transfer also drives the radiant energy reaching the surface ocean under the sea ice, controlling the heating rate of the surface ocean and the growth of phytoplankton under sea ice.

Under-ice optical observations run over the last decade provide means to evaluate the sea ice radiative transfer schemes for the first time. Such an evaluation, performed in part under the auspices of IS-ENES3, was performed by Lebrun (2019). This analysis has highlighted several areas in which the existing radiation scheme contained major oversimplifications, in particular regarding snow and melt ponds.

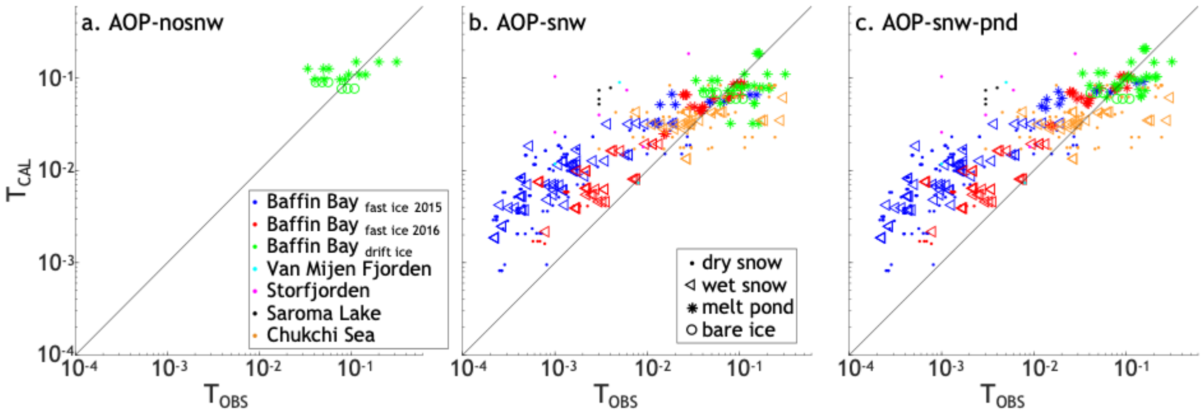

Figure 3: *(updated from Lebrun, 2019). Evaluation of the calculated (TCAL; y-axis) versus observed (TOBS; x-axis) sea ice transmittance for different surface types; from (a) the original SI3 radiation scheme, (b-c) modified SI3 radiation scheme with effects of snow and melt ponds. In (a) there are only green points, because transmission of radiation under snow is zero in the original SI3 scheme, hence all snow-covered points with T=0 are not visible on the plot due to the log-scale used.*

A revised parameterization for radiative transfer was formulated (see Lebrun, 2019 and Stroeve et al. 2021), including the effect of snow and melt ponds on light attenuation, successfully tested against observations and implemented into the SI3 code (Figure 3). The updated scheme still needs to be properly tested in realistic sea ice simulations, as first tests revealed surface melting is underestimated once the new scheme is activated. The evaluation procedure also raised issues in the partitioning of light in the upper ocean, still to be implemented in the code.

4. Conclusions

The NEMO repository now contains the new SI3 model code, which is included in the NEMO 4.2 “release candidate” (beta release) as the sole sea ice model in NEMO. SI3 is fully integrated with NEMO and fully compliant with NEMO coding standards. The new code is now simpler, more robust, and better optimized than LIM3 with a larger offering of parameterisations and represented physical processes.

Several key NEMO users, consisting of both operational forecasting and climate modelling centres, are already updating their systems to use SI3, including: CMCC, EC-Earth consortium, ECMWF, IPSL, Mercator Ocean, Met Office, Météo-France.

References

Flocco, D., Schröder, D., Feltham, D. L., and Hunke, E. C.: Impact of melt ponds on Arctic sea ice simulations from 1990 to 2007, J. Geophys. Res., 117, C09032, https://doi.org/10.1029/2012JC008195, 2012.

Flocco, D., Feltham, D. L., Bailey, E., and Schroeder, D., The refreezing of melt ponds on Arctic sea ice, J. Geophys. Res. Oceans, 120, 647– 659, https://doi.org/10.1002/2014JC010140, 2015.

Holland, M. M., D. A. Bailey, B. P. Briegleb, B. Light, and E. Hunke, Improved sea ice shortwave radiation physics in CCSM4: The impact of melt ponds and aerosols on Arctic sea ice, J. Clim., 25(5), 1413–1430, https://doi.org/10.1175/JCLI-D-11-00078.1, 2012.

Hunke, E. C., and Dukowicz, J. K. An elastic-viscous-plastic model for sea ice dynamics. Journal of Physical Oceanography, 27, 1849-1967, https://doi.org/10.1175/1520-0485(1997)027<1849:AEVPMF>2.0.CO;2, 1997.

Kimmritz, M., Danilov, S., Losch, M. The adaptive EVP method for solving the sea ice momentum equation, Ocean Modelling, 101, 59-67, https://doi.org/10.1016/j.ocemod.2016.03.004, 2016.

Lebrun, M. De l’interaction entre banquise, lumière et phytoplancton arctique. PhD thesis, Sorbonne Université, Paris, France, 2019.

Stroeve, J., Vancoppenolle, M., Veyssiere, G., Lebrun, M., Castellani, G., Babin, M., Karcher, M., Landy, J., Liston, G.E., and Wilkinson, J., A Multi-Sensor and Modeling Approach for Mapping Light Under Sea Ice During the Ice-Growth Season. Front. Mar. Sci. 7:592337, https://doi.org/10.3389/fmars.2020.592337, 2021.

Tsamados, M., D.L. Feltham, A.V. Wilchinsky, Impact of a new anisotropic rheology on simulations of arctic sea ice, J. Geophys. Res. Oceans, 107, 91-107, http://dx.doi.org/10.1029/2012JC007990, 2013.

West, A. E., McLaren, A. J., Hewitt, H. T., and Best, M. J.: The location of the thermodynamic atmosphere–ice interface in fully coupled models – a case study using JULES and CICE, Geosci. Model Dev., 9, 1125–1141, https://doi.org/10.5194/gmd-9-1125-2016, 2016.