LIM3, an advanced sea-ice model for climate simulation and operational oceanography

Martin Vancoppenolle[1], Thierry Fichefet[1], Hugues Goosse[1], Sylvain Bouillon[1], Chris König Beatty[1] and Miguel Angel Morales Maqueda[2].

[1] Institut d'Astronomie et de Géophysique G. Lemaître, Université Catholique de Louvain, Louvain-la-Neuve, Belgium.
[2] Proudman Oceanographic Laboratory, Liverpool, UK.
Contact : vancop@astr.ucl.ac.be
Web : http://www.astr.ucl.ac.be/index.php?page=vancop%23LIM

In this contribution, we briefly present the version 3 of the Louvain-la-Neuve Ice Model (LIM). The results of two 1970-2007 hindcasts performed with the ocean modelling system NEMO (Nucleus for European Modelling of the Ocean) – one using LIM2 and the other using LIM3 – are compared to available observations of ice concentration, thickness and mixed layer depth. LIM3 is found to significantly improve the simulation of sea ice characteristics compared to the earlier LIM2 version, making it a more appropriate and accurate tool not only in ice-ocean and climate simulations but also presumably for operational oceanography.

Introduction

Sea ice refers to all ice found at sea which has originated from the freezing of seawater. Sea ice, which covers 7 % of the World Ocean, is an important actor and a sensitive indicator of climate change, as witnessed by the spectacular sea ice historical minimum on September 16th, 2007, which shattered all previous records by more than one million square kilometers (NSIDC, 2007). In addition, salt and freshwater releases associated to the growth and melt of sea ice have a significant impact on the World Ocean circulation.

The Louvain-la-Neuve sea ice model (LIM) has been coupled to OPA (Ocean Parallélisé) almost 10 years ago, leading to significant successes in ice-ocean and climate simulations. Meanwhile, the development of LIM kept going on, leading to LIM3, a C-grid, dynamic-thermodynamic sea-ice model including the representation of the subgrid scale variations of ice thickness, enthalpy, salinity and age, which we describe in more detail in the next section. Then, the results of two 1970-2007 hindcasts performed with NEMO – one using LIM2 and the other using LIM3 – are compared to available observations of ice concentration, thickness and mixed layer depth.

Model description

LIM was originally a dynamic-thermodynamic sea ice model developed by Fichefet and Morales Maqueda (1997). LIM1 was subsequently coupled to the OPA model (Timmermann et al., 2005) and rewritten by Christian Ethé and Gurvan Madec at the LOCEAN laboratory, resulting in LIM2, the present sea ice component used in the reference version of the NEMO system. The newly developed LIM3 is based on this previous work and is included into the NEMO system.

LIM3 includes three major new developments (see Table 1 and Vancoppenolle et al., 2008). First, the C-grid elastic-viscous-plastic (EVP) rheology (Bouillon et al., 2008) replaces the classical former viscous-plastic (VP) formulation of Hibler (1979). Because it allows to drastically reduce the numerical viscous flow limit, using EVP gives a better solution of the

ice momentum equation. The C-grid allows the dynamical coupling to OPA (also in C-grid) in a much more natural way. EVP is explicit, which allows easier parallelization. Second, in order to account for unresolved variations in ice thickness, several thickness categories have been included into the model. Ice volume is redistributed among categories due to thermodynamic (growth and melt) and dynamic (opening, rafting and ridging) processes. Finally, a multi-layer halo-thermodynamic module (Vancoppenolle et al., 2007) replaces the former Semtner (1976) 3-layer model. This includes an explicit representation of brine entrapment and drainage, as well as the brine impact on sea ice growth and decay. LIM3 includes also several other features (e.g., age of sea ice, frazil ice formation in leads and polynyas) which are not detailed here.

Model component	LIM2	LIM3
Thermodynamics	Semtner 3-layer	Multilayer halo-thermodynamic
Dynamics	VP, B-grid	EVP, C-grid
Ice Thickness Distribution	2 levels (ice + open water). No redistribution.	6 levels (5 for ice + 1 for open water). Redistribution by opening, rafting, ridging, and ice growth/melt.

Table 1: Comparison of model components in LIM2 and LIM3

Model variables include the ice velocity vector (computed by the dynamical module), the ice area, volume, enthalpy, salt content and age content, as well as snow volume and enthalpy (computed by the ice thermodynamics and redistribution modules). In LIM3, the ice is represented as a series of minimum M=5 ice thickness categories. This means that all sea ice variables (except velocity) have a specific value for each of the thickness categories. In addition, in each thickness category, a series of N=5 vertical ice layers are used to resolve the heat diffusion equation. This number can decrease to 2 without deteriorating the results. The increase in CPU of the NEMO system using LIM3 is around 30 % compared to LIM2.

In the next section, we describe the results of a 1970-2007 hindcast simulation performed with NEMO, using alternatively LIM2 and LIM3, with default parameters[1], in the ORCA2 2°x 2° configuration, forced by the NCEP-NCAR surface air temperatures and winds and various meteorological climatologies. The years 1970-1978 are considered as model spinup. Though the model is global, we mostly focus the discussion on the Northern Hemisphere. For more information, notably on the Southern Hemisphere, we invite the reader to refer to Vancoppenolle et al. (2008) which will describe extensively the results of NEMO-LIM3.

Results

Ice state

The sea ice physical state as simulated by LIM3 is summarized in figure 1. Significantly different ice packs are found in the Northern and Southern Hemispheres. Arctic ice is on

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[1] We want to compare LIM2 and LIM3, each of them with its "best" set of parameters, in order to illustrate the transition from LIM2 to LIM3. The main parameters' values in LIM2 are, for the ice strength P^*=10000 N.m^{-1}, for the thickness of new ice h^0=0.5m, and for the melting bare ice albedo α_{su}=0.5. In LIM3, the default values of the main parameters are different: P^*=40000 N.m^{-1}, h^0=0.1m, and α_{su}=0.53. These values are closer to observations.

average older, thicker, less saline and has a deeper snow cover and a lower brine volume than its Antarctic counterpart.
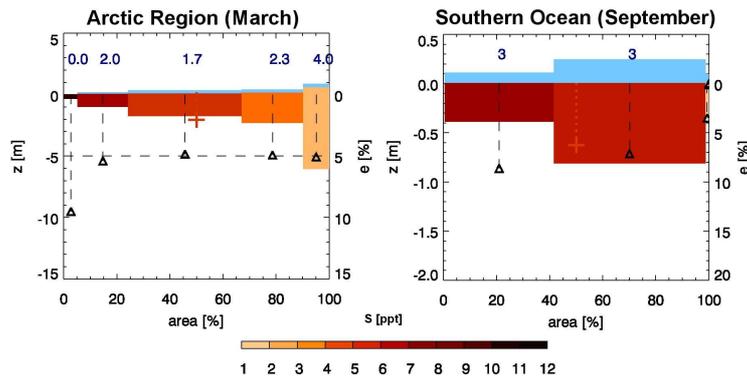
Fig. 1: Average winter sea ice physical state (1979-2006) for the Arctic (left) and the Antarctic (right). The ice concentration in each of the ice thickness categories is represented horizontally. The ice thickness (negative values) and snow depth (positive values) are shown vertically (m, left axis). Note the difference in scale in the two figures. The colors refer to the ice salinity (‰) in each category, the light blue corresponding to snow (fresh, S=0‰). The black triangles indicate the relative brine volume e (computed from temperature and salinity, %, right axis). The numbers on top refer to ice age (years in the Arctic, months in the Antarctic). The crosses indicate mean ice thickness. Note that in the SH, only the first two thickness categories are not empty.

The simulated sources and sinks of ice mass also differ from one hemisphere to the other. In the Arctic, bottom congelation domines in winter, whereas surface and bottom melt contribute equivalently in summer. In the Antarctic, in winter, bottom congelation, new ice formation in open water and snow ice formation contribute in similar amounts, while bottom melt largely domines in summer. This agrees with information inferred from in situ observations of ice and snow thicknesses and textural analysis of ice cores taken in situ.

Mean state

The sea ice mass balance is well characterized by the evolution of ice coverage and volume. Ice coverage is described by ice concentration (defined as the relative areal ice coverage in a given region). Ice concentration has been observed from space from 1979 on by passive microwave sensors onboard sattelites, which provides a good basis for model validation. The difference between simulated and observed Arctic sea ice extent averaged over 1979-2006 is -0.51 (0.71)$\times 10^6$ km² with LIM3 (LIM2). In winter, both models simulate very well the geographical distribution of ice concentration. In summer (see figure 2), LIM2 overestimates the ice coverage in the seasonal ice regions, in particular along the east coast of Greenland and along the Siberian shelf. In contrast, the LIM3 simulation is much more realistic. In LIM3, the ice-albedo feedback is governed by the behaviour of thin ice and can be characterized as follows. In early summer, thin ice in the marginal ice zones disappears quickly, which significantly reduces the ice concentration compared to LIM2 and promotes higher absorption of shortwave radiation in the ocean. This enhances the basal oceanic heat flux and hence bottom melt, leading to a decrease in ice thickness. Yet the LIM3 simulation is not perfect. Laptev and Beaufort Seas as well as Baffin Bay and Foxe Basin should be more frequently ice-free, and the ice concentration is underestimated in the Atlantic sector of the Arctic Ocean (i.e., between North Pole, Spitzbergen and Severnaya Zemlya).
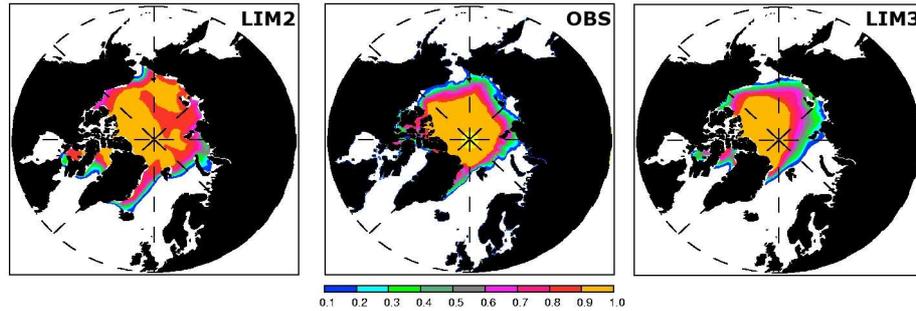
Fig. 2: Simulated September geographical distribution of ice concentration in the Arctic, simulated by LIM2 (left), as derived from passive microwave observations (Comiso, 2007, center), and simulated by LIM3 (right).

Ice volume is well described in terms of ice thickness. Comparison to data from upward-looking sonars (ULS) onboard submarines (see figure 3) reveal a mean 1976-2000 LIM3 (LIM2) – data difference of -0.55 ± 1.04 m (1.88 ± 0.97 m). The improvement is due to a combination of the improved ice dynamics, of the more realistic ice-albedo feedback, of the inclusion of thickness redistribution through rafting and ridging and of the time-varying ice salinity. Significant ice thickness biases remain in LIM3. Ice is too thick in the Beaufort Gyre and too thin in the Atlantic sector of the Arctic Ocean. Comparison with several other models showed that this pattern is typical of multicategory ice models and has been suggested to be due to an underestimated shear strength. Ongoing work is directed towards solving this problem.
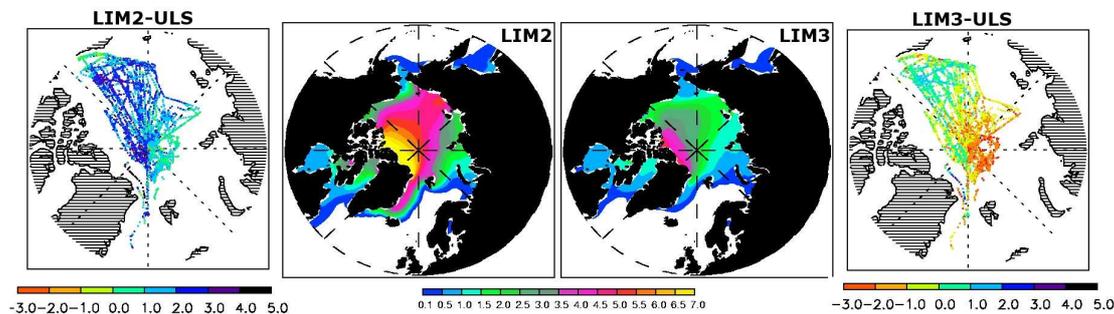
Fig. 3: Geographical distribution of January Arctic ice thickness (m). From left to right : difference LIM2 – ULS data, LIM2, LIM3 and difference LIM3 – ULS data. ULS data come from NSIDC (2006).

In the Southern Ocean, the simulations are reasonably good and quite comparable. The 1979-2006 average difference between the annual mean simulated and observed global hemispheric areas is -1.20×10^6 km^2 (-1.12×10^6 km^2) with LIM3 (LIM2). The winter ice extent is well simulated, but in summer the ice disappears excessively. The geographical distribution of ice thickness is well represented, though the ice is slightly too thin in both models.

Variability

Associated with the better mean seasonal cycle, the simulation of interannual variability is also improved. In the Arctic (see figure 4, left panel), the correlation between the simulated and observed monthly mean anomalies of ice area is 0.52 in LIM2 and 0.74 in LIM3. LIM3's better representation of the ice-albedo feedback makes it more efficient to simulate the September minimum of extent, the interannual variations and the long-term trend. In addition, the spatial distribution of anomalies is also much better captured with LIM3, as illustrated by the simulation of the recent 2007 minimum of extent (see figure 4), which reached a record

value of 4.28×10^6 km^2 (NSIDC, 2007). LIM3 simulates a pattern close to observations and slightly underestimates the summer 2007 ice extent (3.66×10^6 km^2). LIM2 does not manage to melt enough ice and significantly overestimates the ice extent (5.85×10^6 km^2). In the Southern Ocean, LIM2 and LIM3 models yield a similar correlation between the simulated and observed monthly mean anomalies of ice area (0.65). There is no significant long-term trend.
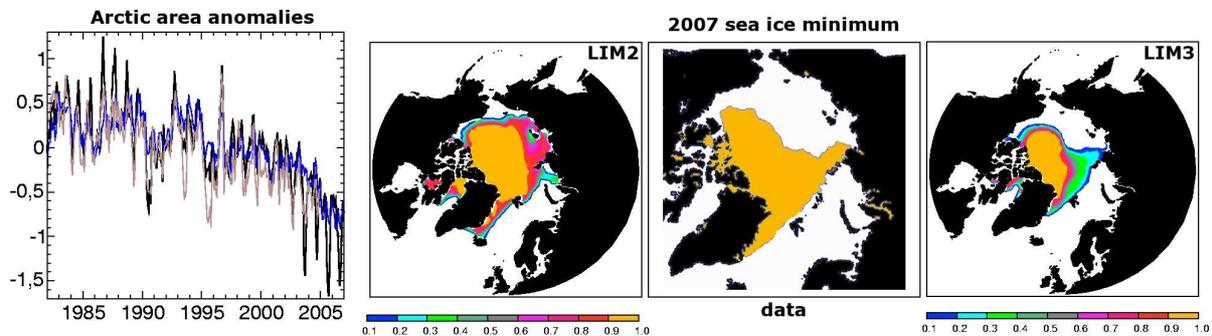
Fig. 4: (left) Monthly mean anomalies (i.e., differences of monthly means from the mean 1979-2006 seasonal cycle) of sea ice area (10^6 km^2) in the Northern Hemisphere as simulated by LIM3 (black), by LIM2 (blue) and as derived from passive microwave observations (brown). (right) The maps show, from left to right, first, the September 2007 distribution of ice concentration in the Arctic as simulated by LIM2; second, the September 2007 ice covered-area taken from NSIDC website (www.nsidc.org); and finally, simulation with LIM3.

Obviously, the sensitivities of LIM2 and LIM3 to a change in external forcing are different. This is also true for a change in internal parameters. For example, for a diminution of the albedo of melting ice from 0.53 to 0.50, the response of LIM2 is stronger. In the Arctic basin, the difference in thickness due to such a change in albedo is between -0.5 and -0.2 m with LIM2 (-0.3 and -0.1 m with LIM3).

Impact on the ocean

Briefly, we show that the response of the ocean to the change in sea ice model is important. This is particularly the case in the North Atlantic (see figure 5), where the role of sea ice inflow domines the buoyancy forcing. Compared to LIM2, LIM3 has a more realistic, smaller ice volume export through Fram Strait and an associated reduced freshwater transport to the North Atlantic. In turn, the frequency of deep convection increases in LIM3 compared to LIM2, which leads to a more realistic distribution of convection sites, in particular in the Labrador Sea.
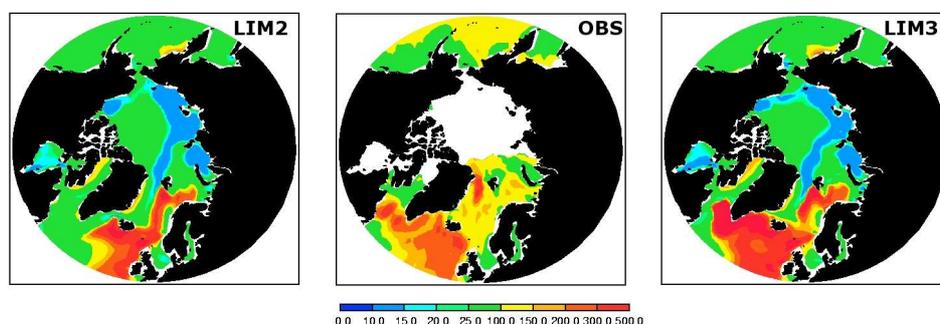
Fig. 5: Average seasonal maximum (1979-2006) mixed layer depth as simulated by LIM2 (left), as derived from observations based on a 0.2°C temperature criterion (de Boyer Montégut et al., 2004) and as simulated by LIM3 (right) with the corresponding density criterion ($\Delta\rho=0.03$ kg.m^{-3}).

Conclusion and perspectives

In this letter, we presented the new LIM3 sea ice model and reviewed the results of a 1970-2007 hindcast simulation performed with NEMO using LIM2 / LIM3. The results show that NEMO-LIM3 produces mean sea ice coverage and thickness fields that compare significantly better to available observations. In addition, variability and trends in ice coverage, as well as patterns of anomalies are also better captured. This suggests that the inclusion of LIM3 would affect and probably improve the results of climate projections in coupled GCMs. Finally, the improved sea ice field also results in a better distribution of the convection sites in the North Atlantic. In conclusion, LIM3 is certainly a more accurate tool for ice-ocean and climate simulations as well as for operational oceanography. Further development, calibration and use of NEMO-LIM will continue during the next few years in Louvain-la-Neuve.

Acknowledgments

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