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Cryosphere-hydrosphere interactions: Numerical modeling using the Regional Ocean Modeling System (ROMS) at different scales(*)

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Summary. — Conveyor belt circulation controls global climate through heat and water fluxes with atmosphere and from tropical to polar regions and vice versa. This circulation, commonly referred to as thermohaline circulation (THC), seems to have millennium time scale and nowadays—a non-glacial period—appears to be as rather stable. However, concern is raised by the buildup of CO_2 and other greenhouse gases in the atmosphere (IPCC, *Third assessment report: Climate Change 2001. A contribution of working group I, II and III to the Third Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge Univ. Press, UK) 2001, `http://www.ipcc.ch`) as these may affect the THC conveyor paths. Since it is widely recognized that dense-water formation sites act as primary sources in strengthening quasi-stable THC paths (Stommel H., *Tellus*, **13** (1961) 224), in order to simulate properly the consequences of such scenarios a better understanding of these oceanic processes is needed. To successfully model these processes, air-sea-ice–integrated modelling approaches are often required. Here we focus on two polar regions using the Regional Ocean Modeling System (ROMS). In the first region investigated, the North Atlantic-Arctic, where open-ocean deep convection and open-sea ice formation and dispersion under the intense air-sea interactions are the major engines, we use a new version of the coupled hydrodynamic-ice ROMS model. The second area belongs to the Antarctica region inside the Southern Ocean, where brine rejections during ice formation inside shelf seas origin dense water that, flowing along the continental slope, overflow becoming eventually abyssal waters. Results show how nowadays integrated-modelling tasks have become more and more feasible and effective; numerical simulations dealing with large computational domains or challenging different climate scenarios can be run on multi-processors platforms and on systems like LINUX clusters, made of the same hardware as PCs, and codes have been accordingly modified.

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This relevant numerical help coming from the computer science can now allow scientists to devote larger attention in the efforts of understanding the deep mechanisms of such complex processes.

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1. – Introduction

The Earth climate is regulated by a large number of complex interactions among atmosphere, oceans, ice regions, land and forests areas. All these subsystems constitute an interlinked ensemble that regulates itself through strong non-linear feedbacks, and the overall Earth system behaves as a single, deeply integrated one. In this perspective the role of oceans is of paramount importance, since they not only store heat through their high specific thermal capacity but move fresh water or, more generally, induce salinity anomalies, all around the world [1]. Despite their recognized importance, the links between global change and ocean general circulation have not been yet completely understood: several authors, indeed, stressed the possibility that climate warming may interfere with —and possibly reverse— regional [2] but also global thermohaline circulation [3, 4]. The THC of the global ocean is the major mechanism through which the oceans contribute to control the global radiation budget, and eventually also major climatic changes [1, 5]. The classical view of this circulation suggests that during winter of either polar hemisphere, both open-ocean deep convection and dense-water formation via sea-ice formation in marginal seas produce dense, cold, saline waters that flow toward the equator and slowly upwell. Therefore, the densest waters "ventilating" the world ocean abyss are produced in the Northern and Southern extremes. The THC convection part is driven by the buoyancy loss in the open ocean caused by cooling [6] and by densification due to salt release during sea-ice formation or sub-ice shelf accretion. In the Southern Ocean along Antarctic continental shelf break regions, dense plumes are formed and then slide down the continental slope all around the Antarctic coast [7]. Major sites are the Weddel and the Ross seas, where Antarctic Bottom Water (AABW) is formed by mixing and entrainment during these cascade events. The understanding of their interactions and feedbacks on the global THC through the Antarctic Circumpolar Current (ACC) are crucial scientific issues to address in order to understand the physical and biogeochemical aspects of the global climate variability.

Another relevant aspect for the global climate is the formation and dispersion processes of the marine ice, since these are directly influencing the ocean-atmosphere moisture flux, both in the Antarctic and in the Arctic regions.

The effects of changes in the THC in these extreme regions—due to high non-linear feedback mechanisms—are largely unknown [8] and are likely to generate concern for the environment in future scenarios [9]; with the aim of better understanding global climate evolution and narrowing uncertainties on predictions, modeling tools are becoming more and more adopted by the international scientific community [10].

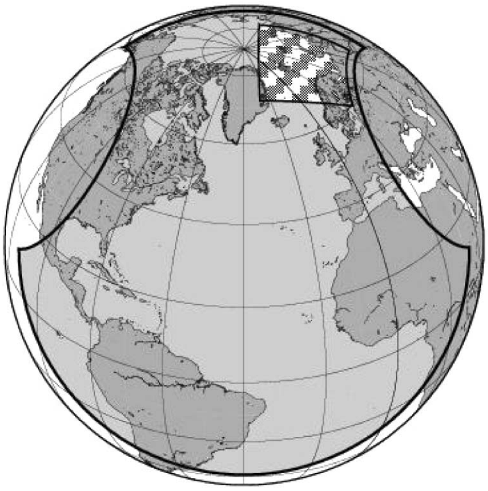

Fig. 1. – The large grey area is the domain of the large-area model used to force and initialize the Barents model (striped area).

The paper is organized as follows: sect. **2** presents a brief outline of the numerical tools employed, as well as the description of the experiments carried out; results and discussions are given in sect. **3**, while conclusions are drawn in sect. **4**.

2. – Model outline and numerical experiments

The Regional Ocean Modeling System is a free-surface, hydrostatic, primitive equation ocean model adopting stretched, terrain-following coordinates in the vertical and orthogonal curvilinear coordinates in the horizontal [10]. It is a finite-difference model including a variety of high-order advection schemes (the default one for the horizontal advection being a third-order upwind based), accurate pressure gradient algorithms, several subgrid-scale parameterizations (among which the Generic Length Scale approach, see [11]), and complex ice, bottom boundary layer, biological and sediment modules.

The model allows for a detailed choice among several numerical schemes and parameterizations and an efficient C-preprocessing system that activates the various physical and numerical options is available. ROMS (see `http://marine.rutgers.edu/po/index.php?model=roms`, accessed May 2005) is written in FORTRAN 90 and can be run under several platforms among which LINUX systems. The code works both in serial and parallel computers, using shared-memory (OpenMP, OMP) and distributed-memory (MPI) paradigms coexisting in the same code. The entire input and output data structure of the model is via NetCDF, which facilitates the interchange of data between computers, user community, and other independent post-processing analysis software.

2˙1. *The Barents Sea.* – A dynamic-thermodynamic sea ice model has been ported to ROMS 2.1 and applied to study the ice variability in the Barents-Kara Seas region, thus originating a coupled ice-ocean model to examine the implications of global warming scenarios produced by the Bergen Climate Model [12] on the Barents Sea region. The region was modeled by means of a nesting with a larger-area model to receive appropriate boundary conditions (see fig. 1). Before embarking on downscaling of future scenarios, it

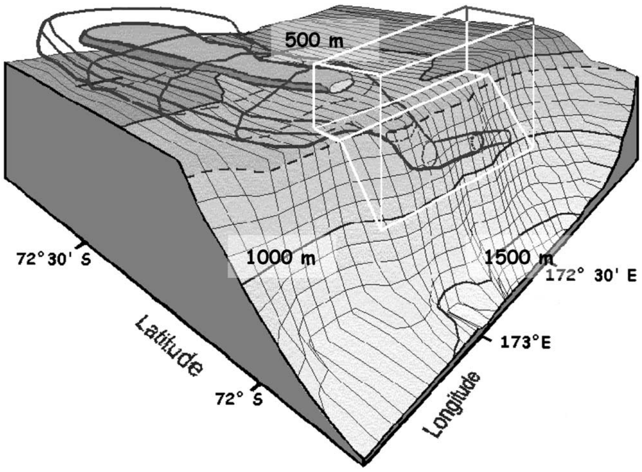

Fig. 2. – Bathymetry of the Ross Sea region with schematic representation of a cascading tongue (contour lines every 100 m). The white lines indicate the idealized topography setup adopted in this study.

is desirable to ensure that the regional model can reproduce the variability in present-day climate. ROMS was tested for this purpose by first conducting a hindcast for the period 1990-2002 using NCEP/NCAR reanalysis [13] atmospheric forcing data (results shown are the first year ones). Results were validated using available observations.

The model includes the ice-dynamics based upon the Elastic-Viscous-Plastic (EVP) rheology [14, 15]; the EVP scheme is based on a time-splitting approach whereby short elastic time steps are used to regularize the solution when the ice exhibits nearly rigid behavior. Because the time discretization uses explicit time-stepping, the ice dynamics are readily parallelizable and thus computationally efficient under both OpenMP and MPI.

The ice thermodynamics are based upon those of [16] and [17]. Main features include: two ice layers and a single snow layer; molecular sub-layers under ice, which provide improved freezing and melting rates; surface melt ponds included in the ice thermodynamics; forcing by short and long-wave radiation, sensible and latent heat flux.

The numerical model set-up consists of a grid 317 by 262 (horizontal resolution of 7.8 to 10.5 km, average of 9.3 km) and 32 levels in the vertical, generating an $O(850\ \mathrm{MB})$ problem. The adopted time step is 450 seconds. The tidal forcing acting as a boundary condition was obtained from AOTIM (Arctic Ocean Tidal Inverse Model [18]), while a coarse model was used for providing initialization and boundary forcing the regional one (50 km resolution in Nordic seas/Arctic).

2˙2. *Downslope processes in the Ross Sea (Antarctica).* – In the Ross Sea region (see fig. 2) recent observations have highlighted the presence of downslope processes [19]. In some localized regions of the continental slope the dense waters overflow the shelf break reaching velocities up to 1 m/s very close to the bottom. This process presents major relevance since it influences shelf sea exchanges, deep ocean "ventilation" and carbon and organic matter export in the abyssal regions. An attempt to model this bottom boundary layer dynamic in the continental shelf using an idealized set-up is presented

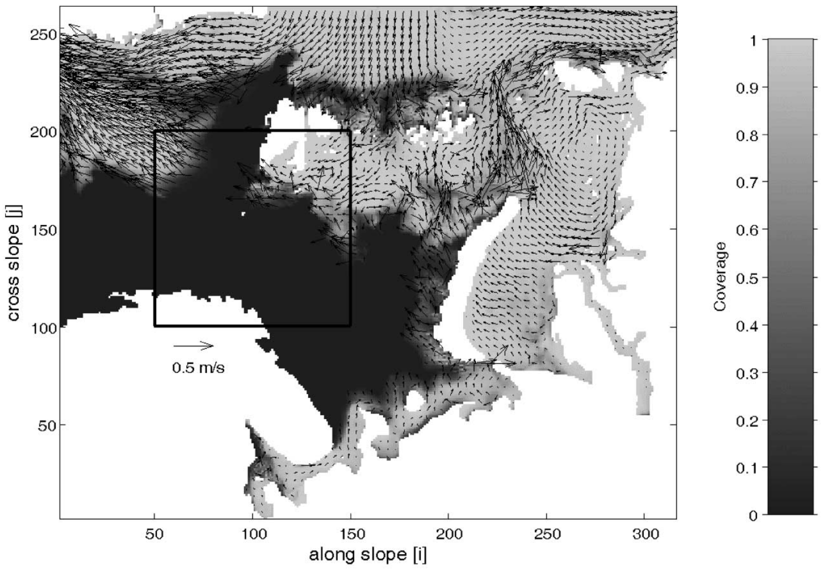

Fig. 3. – Simulated daily mean ice concentration and ice drift for March 20, 1993. The rectangle denotes the region shown in fig. 2. Every sixteenth ice drift vector is plotted.

here (see also [20]), in order to capture the main processes of the forced Ekman drainage (induced by the current present at the top of the shelf), and of the cascading process (induced by the downslope flux).

The numerical domain employed consists of 31 by 31 points having 1.5 km resolution, and the bathymetry profile ranges from 500 to 1500 m depth. Though being idealized, fig. 2 confirms that this topographic setup is realistic. The vertical resolution adopted (33 "sigma" levels) allows to have a bottom boundary layer resolution of 1 m at the southern edge (500 m) up to 3 m at the northern one (1500 m deep).

The code is using a state-of-the-art turbulence closure parameterization based on the Generic Length Scale approach [11], set-up in order to work as a "k-ε". This feature is taking particularly well care of strong vertical gradients typical of the cascading processes without being too much diffusive; as suggested by [10], no additional horizontal viscosity is specified besides the numerical one induced by the upstream third-order scheme used in the present experiment. For this $O(10\ \text{MB})$ problem a time step of 60 seconds (integrated 8640 times) was adopted.

3. – Results and discussion

3˙1. *The Barents Sea.* – Sample results for daily mean sea ice concentration and drift in the Barents region are shown in fig. 3.

Ocean surface temperature and velocity for the same time in a portion of the model domain near the Atlantic entrance to the Barents Sea are shown in fig. 4. While the current ≈ 9 km resolution is not eddy-resolving, the higher-order numerics of the new ROMS ice-ocean model in the Arctic still capture both mesoscale variability of the Atlantic inflow to the Barents and the full marginal ice zone dynamics as well. Namely, there is a good agreement between modeled/observed ice thickness and horizontal distribution.

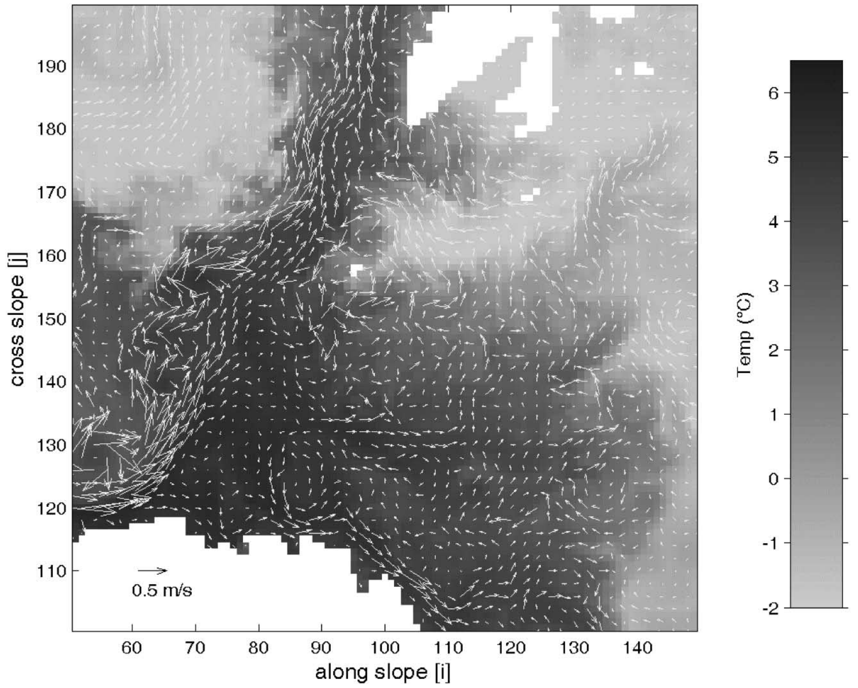

Fig. 4. – Simulated daily mean sea surface temperature and velocity for March 20, 1993 for the sub-region outlined in fig. 4. Every fourth velocity vector is plotted.

Using MPI with 36 processors on a SGI Origin 3800, one year of simulation took 40 hours of elapsed computing time, and the computational performance of ROMS was found to scale linearly with the number of processors.

3·2. *Downslope processes in the Ross Sea (Antarctica).* – In the Ross Sea region, the modeled behavior is supported by evidence of data acquired during CLIMA [2] and ANSLOPE sea-truth campaigns [19]. Particularly, besides presenting a good qualitative agreement with the generally accepted shape of the descending plume in the cascading process (see fig. 5), characteristic modeled velocities close to the bottom have values comparable to those reported by [18]. Model results, though preliminary, also helped depicting that the related spatial/temporal scales are small. Figure 6 presents the evolution of the last "sigma" level (*i.e.* the level of variable depth closest to the sea bottom), from which it is evident that the scale of the plume spans a few cells, therefore suggesting that future *in situ* measurements will have to be carried out at adequate resolution.

The run was tested on different platforms such as MS laptops representing the state-of-the-art in the period 2001-2004([1]) and a LINUX WS([2]). The performances for this idealized but realistic $O(10\ \mathrm{MB})$ problem resulted ranged from $17'11''$ (Laptop, Intel®

([1]) All under cygwin© and using the same Compaq Visual Fortran Standard Edition 6.6.0© compiler options.
([2]) Using Red Hat distribution, kernel 2.4.18, and Intel© Fortran compiler 7.1

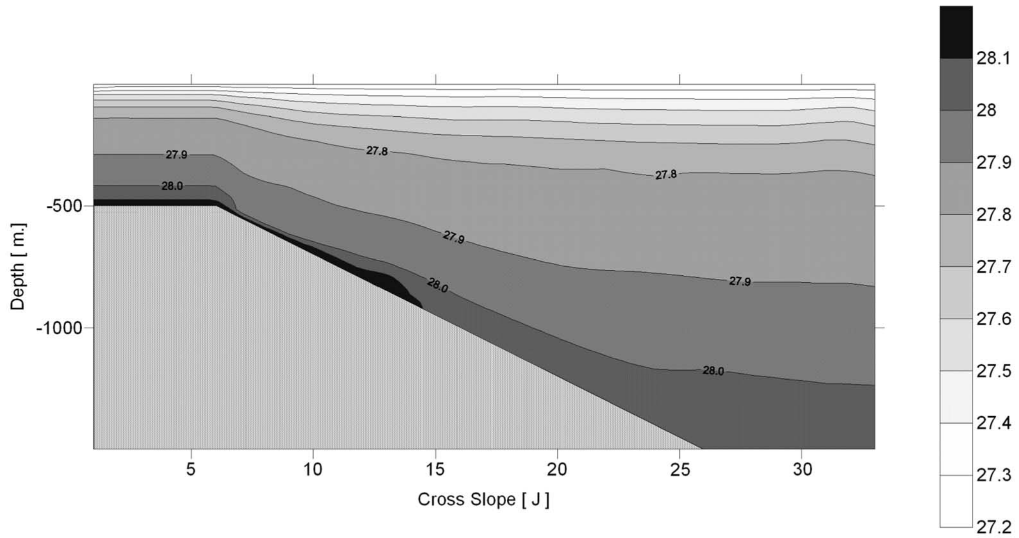

Fig. 5. – Cross-section of the density field (kg/m^3) in the Ross Sea downslope experiment. The cascading plume is visible, as well as the deformation induced by the Ekman drainage entrainment.

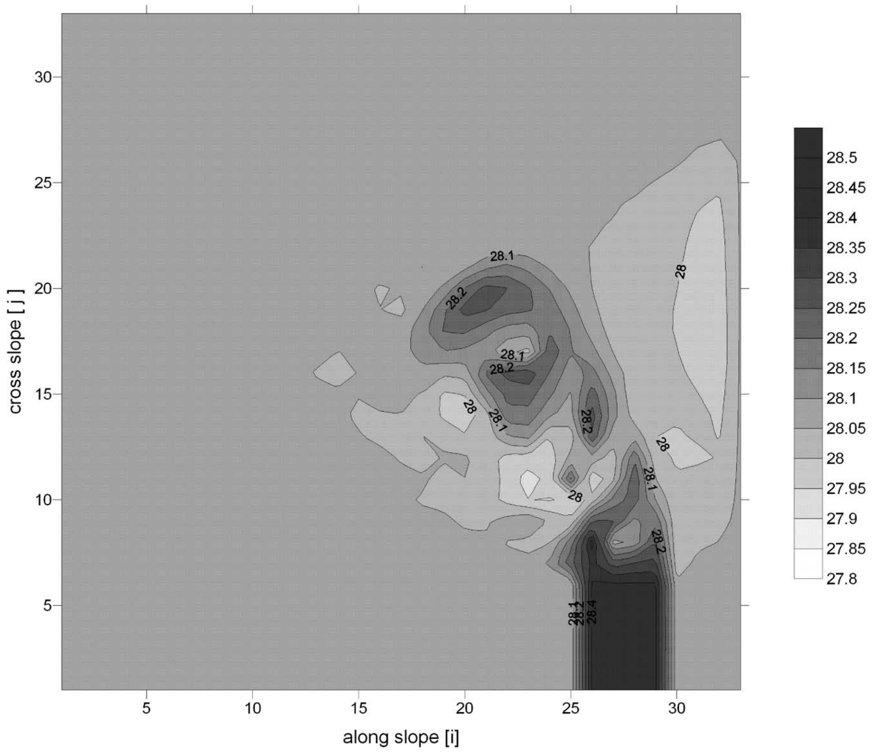

Fig. 6. – Horizontal view of the bottom level density field (kg/m^3) in the Antarctica downslope experiment.

Pentium® III, 1 GHz, 368 MB RAM), to 4′10″ (Laptop, Intel® Pentium®4, 1.7 GHz, 256 MB RAM) and 2′10″ (WS, Intel® Itanium® dual processors, OpenMP parallel shared-memory, each processor at 1.3 GHz and 2 GB RAM).

It is worthy to say that the larger percentage of elapsed time was spent by the model in solving the vertical mixing parameterizations (*e.g.*, the Pentium® 4 used for this task 35% of the elapsed time).

4. – Conclusions

Recent advances in the computer performances now enable oceanographers to proceed in the direction of integrated numerical simulations of high interest for climate change issues. Among these, we should here remind the possibility of resourcing to cheap computers that can be used in clusters, allowing higher-resolution, long-term integrations and ensemble runs, and the development of new tools and standards that facilitate web-based collaborations with large data sets such as those produced by numerical ocean models (*e.g.* using OpenDAP©, ROMS NetCDF output files can be placed on a web server and users can use a simple Matlab© command to extract just the desired output from the remote web site into a local session, avoiding file format conversion and saving network bandwidth).

Nevertheless, since the complexity and the non-linearity of these processes naturally bring a large degree of uncertainty, scientists should devote efforts in trying to improve the understanding of the processes links rather than simply pursuing higher resolution or extremely complex simulations, reminding that "simple" models that are nevertheless sufficiently developed, besides being numerically less expensive, provide a fundamental help in exploring processes that will be later on parameterized in larger runs.

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