Impact of fine atmospheric scales on ocean eddies and deep convection in the Subpolar Northern Atlantic

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Abstract. In this study we examine the sensitivity of the high-resolution regional ocean model solution to the atmospheric forcing of low (70 km - LoRes) and high (14 km - HiRes) spatial resolutions over the North Atlantic. To force the regional set up of NEMO ocean general circulation model (OGCM) we use the North Atlantic Atmospheric Downscaling (NAAD) product, which is the result of the Weather Research and Forecasting (WRF) atmospheric GCM with ERA-Interim as a boundary condition. Increase of the of the resolution of the atmospheric forcing and thus, representation of the surface turbulent heat and radiative fluxes in HiRes and LoRes atmospheric forcing, cause the 1.5˚ negative difference between sea surface temperature and -0.15 PSU in sea water salinity over the whole domain. The output of the OGCM forced by the high-resolution atmosphere is almost equal to the observational datasets. More intensive turbulent heat loss from the ocean surface and ventilation processes result in lower ocean heat content in the upper ocean (0-700 m) and at intermediate depth (700-1500 m) when the model is forced by HiRes. HiRes-driven experiment shows more intense coastal currents and less intensive large-scale currents. Ventilation processes are sensitive to the mesoscale atmospheric events representation: HiRes experiment provides deeper by 100 m mixed layer depths and its later in time deepening and restratification.

1. Introduction
Convective processes in the Northern Atlantic play a critical role in the variability of the Atlantic Meridional Overturning Circulation (AMOC) - a key climate phenomenon that largely determines the impact of the ocean on the global climate [1-3]. Convection in the sub polar latitudes links the upper and lower limbs of the AMOC – a general northward flow in the upper 1000 m and a compensating southward flow in the deep ocean. At first glance, the convection process may appear simple: in the northern latitudes surface waters experience cooling due to the air-sea interaction processes and becoming denser, start to sink to depths of several hundred meters, forming the North Atlantic Intermediate waters. After being mixed with Arctic waters advected over the sills of the Nordic Seas, these waters form the lower limb of the AMOC.

However, this is a seeming simplicity. First, because the response of the ocean to the atmospheric diabatic cooling is strongly modulated by the inner ocean variability, especially represented by mesoscale and sub-mesoscale circulation structures. Second, air-sea exchanges affecting densification of the surface waters and forcing their sinking are highly variable in time and space. Intensive mesoscale atmospheric phenomena are strongly localized and poorly quantified, mostly because of the questionable ability of modern atmospheric reanalyses to represent them. Thus, the North Atlantic convective processes are the result of interactions between large- and mesoscale structures in the ocean and between ocean and atmosphere exchanges at meso-, synoptic and large scales.
Importantly, many characteristics of the convection in the sub polar North Atlantic sites are hardly observable. Full depth hydrographic surveys, undertaken typically annually [4-6] provide space-time integrated measures of the volume of intermediate waters formed during the preceding winter. Some studies tracked the pathways of Labrador Sea water using different observations at different oceanic cross-sections. Moreover, these observations, documenting inter-annual variability of the mixed-layer depth (MLD), cannot hint on the physical mechanisms responsible for forming particular convective events in different years.

In this respect ocean high-resolution modelling is an invaluable tool to supplement observational data and to provide insights on the mechanisms behind convection. However, modelling efforts in these regions require extremely high spatial resolution in order to fully resolve mesoscale ocean processes, while existing model configuration with such resolution are still very few. Concerning the space-time scales of convection, it is also very important to drive these very high-resolution simulations with high-resolution atmospheric boundary conditions.

The problems highlighted above motivate the choice of methods used in this study in order to address the mechanisms to provide a physical description of the convection processes in the Northern Atlantic that is coherent across this variety of scales. The main goal of this study is to build and validate against the observations a regional high-resolution ocean model configuration, which will provide insights on convection mechanisms, long-term variability, and response to the high-resolution atmospheric forcing.

2. Data and method

We developed for this study an original regional configuration of the ocean and sea-ice general circulation model NEMOv3.6 [7]. Referred to as NNATL12, this configuration covers the subpolar gyre of the North Atlantic (Fig. 2) with a resolution of 1/12° (approximately 4.5 km in these high latitudes) and 75 vertical z-levels with higher density in the upper ocean. The domain has three open ocean boundaries in the north, south and west (Hudson Bay) where flow properties are driven by monthly mean temperature, salinity, velocity and sea-ice data obtained from the GLORYS2v4 ocean reanalysis [8].

In order to investigate the impact of the atmospheric forcing resolution on the ocean eddies characteristics and convection processes, the model is driven by three atmospheric datasets. The widely used Drakkar Forcing Set version 5.2 [9] and constructed from a combination of ERA40 and ERA-Interim reanalysis [10] was used at the stage of configuration setup. Two particular model experiments, discussed in this study are forced with the new atmospheric North Atlantic Atmospheric Downscaling [11] dataset produced by IORAS based on a downscaling of ERA Interim with the Weather Research and Forecasting (WRF) model. The horizontal resolution of these datasets is 0.7˚ and 0.12˚ (hereafter LoRes and HiRes datasets respectively).

A large number of simulations were performed to reach the present configuration setup (so-called MP14) that tested details of the configuration geometry, open boundary conditions, numerical schemes and physical process parameterisations. Decisions were made by comparing the model solution with the new generation of high-resolution reanalysis at 1/12° GLORYS12 produced by the Copernicus Marine Environment Monitoring Service [12], satellite observations, and repeated full depth hydrographic sections.

In order to investigate the sensitivity of the ocean mean state and variability, mesoscale activity and deep convection characteristics to the mesoscale resolving atmospheric forcing, two numerical experiments based on MP14 were conducted, driven respectively by the LoRes and HiRes dynamical downscaling (referred to as LR14 and HR14 respectively). Each experiment covers period from 1992 to 2015, and the ocean three-dimensional fields are stored every day.

3. Results

Significant differences in the representation of the heat fluxes (turbulent and radiation) at the ocean surface in LoRes and HiRes forcing datasets result in large differences in the ocean state as simulated by the corresponding ocean model experiments.
Domain-averaged sea surface temperature (SST) in summer is sustainably lower by 1 to 1.5°C in HR14 than in LR14, in better agreement with ESA CCI SST observational dataset (Fig.2, http://www.esa-sst-cci.org). HR14 run shows the exact same temperature trend as the observations.

![Graph showing SST seasonal variability and trend](image)

**Figure 1.** Domain-averaged SST (°C) seasonal variability and trend as simulated by HR14 (orange line), LR14 (purple line), and as in ESA CCI SST observational dataset (green line).

The spatial distribution of the differences SST and salinity (SSS) averaged over the whole run period (1992-2015) is shown in Figure 4. SST in HR14 is 1 to 1.5°C lower than in LR14 (Fig. 2a) everywhere except in the vicinity of Greenland coast, where a positive difference is caused by a smaller mean sea-ice concentration (no figure shown).

![Image showing SST and SSS differences](image)

**Figure 2.** Long term mean (1992-2015) difference between HR14 and LR14 for (a) surface temperature (°C) and (b) salinity (no unit). Blue color indicates that HR14 is cooler or fresher.

The pattern of the differences in mean SSS (Fig. 2b) is the result of various causes acting separately from each other. The large scale slightly negative signal (-0.15) seen over most of the domain is caused by increased precipitation in HiRes NAAD (not shown), and less intensive precipitations in HiRes could well contribute in conjunction to greater coastal winds to the positive differences north of Iceland and south of British Isles. The high positive difference (0.5 to 1) near the East Greenland coast is caused by lower ice concentration, as in this area sea-ice is typically advected along the coast from higher latitudes. Baffin and Saint-Laurent Bays positive biases are at least partially caused by higher wind speed seen in coastal area simulated in HR14 (no figure shown).
Figure 3. Ocean heat content in the upper 0-700 m (upper panel) and intermediate 700-1500 m ocean (lower panel) for the whole period excluding spin-up (1997-2015).

Cumulative effect of more intensive turbulent heat loss from the ocean surface (no fig. shown) and more precise cloudiness and radiative fluxes representation in HiRes NAAD resulted in lower net heat income during summer time in HR14. Consequently, this simulation represents lower ocean heat content in the upper ocean (0-700 m layer, fig. 3, upper panel). Ocean heat content at intermediate depth (700-1500 m) in HR14 is slightly lower than in LR14 (Fig. 3, lower panel), which could be linked to a more intensive ventilation of this layer due to deep convection processes.

Comparison of surface currents in HR14 and LR14 revealed some differences in main surface currents characteristics (Fig. 4). While the shallow coastal currents show a robust intensification of speed (up to 20%) in HR14 (see for example East Greenland Coastal Current and the Norwegian Atlantic Current). This reflects the sensitivity of the model to the higher coastal wind speeds seen in the HiRes dataset. On the contrary, the large scale currents that occupies greater depth (e.g. the Irminger Current, or the Labrador Current) are slightly weaker at the surface. An intensification of the southern branch of the NAC is suggested by the dipole structure in the south-central part of domain(40°W-20°W;50°-53°N), which means that the high-resolution wind characteristics have an impact on the NAC path.
High-resolution forcing also has an impact on mesoscale eddy activity, differences in EKE between the two runs exhibiting patterns similar to those seen in the mean currents.

Several differences in thermodynamical characteristics of the ocean caused by high-resolution atmospheric forcing and mesoscale eddy activity, such as surface heat balance, ice conditions lead to significant differences in the representation of deep convection process. Here we examine the characteristics of the MLD as a product of convection processes. Maximum mean and variability of March MLD in HR14 is located in the eastern Labrador Sea and below 60˚N, in good agreement with observations (Fig. 5a). March MLD in HR14 is deeper than in LR14 (by 100 meters) over a large part of the domain (Fig. 5b), especially at the sea-ice edge, where HR14 reproduces less icy conditions. However, HR14 MLD is shallower in the region of the Labrador Sea where maximum convection occurs, so the stirring induced by the high-resolution forcing may reduce the maximum convection depth.

![Figure 5](image1.png)

**Figure 5.** March mixed layer depth (a) period mean as simulated by HR14 and (b) mean difference between HR14 and LR14. Red color indicates a deeper MLD in HR14.

Daily climatologies of the winter time mixed layer depth in the Labrador and Irminger Seas (Fig. 6) shows that the mixed layer deepens slower in HR14, but remains deeper in the second part of winter (March-April). This is seen on the mean and variability.

![Figure 6](image2.png)

**Figure 6.** Mixed layer depth daily climatology (thick lines) and variability (vertical thin lines) from January to April regionally averaged over (a) Labrador Sea and (b) Irminger Sea.
Conclusion
We found a significant sensitivity of the surface temperature and salinity fields, and ocean heat content simulated by the regional ocean model to the high-resolution of the atmospheric forcing. We revealed that the amplitude of ocean surface currents, sea-ice cover and eddy properties are sensitive to the high-resolution wind representation. Differences due to the high-resolution atmospheric forcing may sometimes extend almost all over the domain, as for mixed layer depth and SST. Dynamical causes of this sensitivity are still to be examined.

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