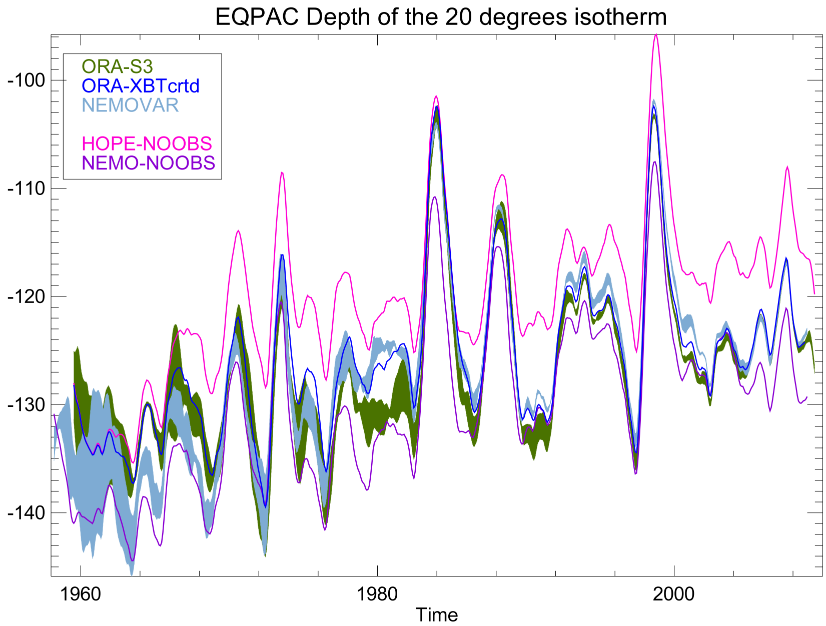
The NEMOVAR-COMBINE ocean re-analysis



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The NEMOVAR-COMBINE ocean re-analysis

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This document describes the main features of the ocean re-analysis system produced at ECMWF for the FP7 COMBINE project. It is the first ocean re-analysis produced with the NEMOVAR data assimilation system with output made available to the research community. Only temperature and salinity are assimilated in this system, which we call NEMOVAR-COMBINE. The climate variability of NEMOVAR-COMBINE is compared with that of the previous ocean re-analysis system ORAS3, and both similarities and discrepancies are discussed.

1 INTRODUCTION

A new ocean re-analysis, based on NEMOVAR (Mogensen et al. 2009, Weaver et al. 2005), has been developed at ECMWF. This new re-analysis is a deliverable for the FP7 COMBINE project http://www.combine-project.eu/ and it will be used for initialization of decadal forecasts by the EC-EARTH consortium. A selection of data from NEMOVAR-COMBINE is publicly available at http://icdc.zmaw.de/easy_init_ocean.html?&L=1, spanning the period 1958-2008. We refer to this product as NEMOVAR-COMBINE to distinguish it from the product generated with the ECMWF S4 operational ocean re-analysis system (NEMOVAR-ORAS4, Mogensen et al. (2011), in preparation).

This document describes the basic features of NEMOVAR-COMBINE, and summarizes the differences with respect to the previous operational ocean re-analysis (ORAS3, Balmaseda et al. 2008a). Far from being an exhaustive study, this report documents the variability of selected aspects of the ocean climate as represented by two ocean data assimilation systems (NEMOVAR-COMBINE and ORAS3). The specific topics discussed are the variability and trends of the Equatorial Pacific thermocline, the ocean heat content, the vertical penetration of the warming and the Atlantic Meridional Overturning Circulation (AMOC). The impact on the results of different aspects of a data assimilation system (ocean model, forcing fields, ocean observations, and assimilation method) is discussed.

2 NEMOVAR-COMBINE

NEMOVAR is a variational data assimilation system for the NEMO ocean model (Madec et al. 2008). It is based on the multivariate variational data assimilation system OPAVAR, described in Weaver et al. (2005) and Daget et al. (2009). The NEMOVAR system has been used at ECMWF to produce a 3D-Var ocean re-analysis for the period 1959-2008, using the ORCA1 configuration (http://www.noc.soton.ac.uk/nemo/). ORCA1 has a horizontal resolution of 1 degree (with equatorial refinement), and 42 levels in the vertical, 15 of which are in the upper 200 m. The ocean model is based on NEMO v3.0, with local modifications.

The NEMOVAR re-analysis assimilates profiles of temperature and salinity from a version of the quality controlled EN3_v2a data set, which contains corrections to the XBTs as in Table 1 of Wijffels et al. (2008) (http://hadobs.metoffice.com/en3/data/download.html), and called EN3_v2a_xbtc in Table 1. Multivariate relationships are imposed between temperature and salinity in order to approximately preserve the vertical water mass properties, and between density, sea surface height and ocean currents by imposing geostrophy and preserving a level of no motion, as described in Weaver et al. (2005). The assimilation cycle is 10 days, and is based on 3D-Var-FGAT with inner and outer loops as described in Mogensen et al. (2009), where the assimilation increment is applied using an incremental analysis update (Bloom et al. 1996)

In order to control the mean state, a bias correction algorithm is used, which consists of an a-priori offline seasonal term and online terms, acting on temperature, salinity and pressure gradient (Balmaseda et al. 2007a). The a-priori offline term has been estimated using the period 2000-2008, which has better observation coverage thanks to the advent of Argo. This is a way of extrapolating the Argo information into the past. Both the pressure and density corrections are applied as a function of latitude: the density correction (temperature and salinity) are minimum at the equator, increasing with latitude with the square of the Coriolis parameter; the pressure correction is largest at the equator and declining to zero with similar functional form. A 3D weak relaxation (20 years time scale) to the temperature and salinity climatological data set from the WOA05 (Locamini et al. 2006; Antonov et al. 2006) is also used in addition to the bias correction.

The first guess is given by the NEMO model forced by ERA40 fluxes from 1957 until 1988 and by ERA-Interim thereafter. The ERA40 fluxes are from the original ERA-40 product (Uppala et al. 2005) except for the precipitation field, which has been corrected as in Troccoli and Kalberg 2004). The re-analysis consists of 5 ensemble members, created by perturbing the wind stress as in ORAS3, but also the ocean initial conditions at the beginning of the run, and the observation coverage. As in ORAS3, the model SST is strongly relaxed (3 days timescale) to NOAA OI_v2 (Reynolds et al. 2002) after 1982, and to the ERA40 SST prior to that date.

Mogensen et al. (2011) provide a more thorough description of the NEMOVAR system (quality control and thinning of observations, specification of observation and background error covariances and other details), as well as details of the differences between NEMOVAR-COMBINE and NEMOVAR-ORS4. For now, it suffices to say that the main differences between these two NEMOVAR based systems resides in the treatment of observations near the coast, vertical thinning of observations, the latitudinal dependence of the bias terms, and the assimilation of altimeter data (both anomalies and global trends).

2.1 Description of the experiments

The main differences between ORAS3 and NEMOVAR-COMBINE are illustrated in Table 1. Differences include the ocean model, the data assimilation system, forcing fluxes, the version of the in-situ data and the ensemble generation strategy. The treatment of the mean state is also slightly different: in ORAS3 there is no latitudinal dependence of the pressure and density bias terms, the relaxation to WOA05 is 10 years instead of 20 years and the offline bias was estimated from the long-term climatology instead of from the Argo period.

NAME	MODEL/ASSIM	FORCING	Assimilated Observations	Comments
ORAS3	HOPE/OI	ERA40 (-2002) NWP OPS	EN2(-2004)/GTS ALTIMETER	Uncorrected XBTs. SOLO/FSI Argo included, as well as other drifting floats 5 ensemble members
ORA-XBTc	HOPE/OI	ERA40 (-2002) NWP OPS	EN2_xbtc(2007)/GTS ALTIMETER	As ORAS3, but with XBT corrected. No SOLO/FSI
HOPE-NOOBS	HOPE	ERA40 (-2002) NWP OPS	NONE	
NEMO-NOOBS	NEMO	ERA40 (-1989) ERA-INTERIM	NONE	
NEMOVAR-COMBINE	NEMO/3D-Var	ERA40 (-1989) ERA-INTERIM	EN3_v2a_xbtc No altimeter yet	XBT corrected. No SOLO/FSI Argo floats + Other Blacklists on Argo 5 ensemble members

Table 1: Summary of experiments dissused here, illustrating the changes from the current ORAS3 operational system to NEMOVAR-COMBINE. Differences in the ensemble generation strategy and bias correction scheme are not given in the table, but are described in the main text.

In order to investigate the impact of the XBT corrections on the climate variability, an experiment similar to ORAS3, but with the corrected XBTs was conducted. We refer to this experiment as ORA-XBTc in what follows. To assess the impact of the assimilation in the ORAS3 and NEMOVAR-COMBINE, two additional experiments with NEMO and HOPE respectively are conducted, where no data are assimilated but everything else is as in their respective reanalysis. We refer to those as NEMO-NOOBS an HOPE-NOOBS. These two experiments differ not only in the ocean model, but also in the spin up, the control of the mean state and forcing fluxes. For instance, ORAS3 and HOPE-NOOBS use ERA40/OPS fluxes (this is to say, ERA40 until 2002 and operational NWP fluxes thereafter), while NEMOVAR-COMBINE and NEMO-NOOBS use ERA40 until 1989 and ERA-INTERIM thereafter (ERA40/INTERIM). The differences in the forcing fluxes (ERA40/OPS versus ERA40/INTERIM) are discussed in Balmaseda and Mogensen (2010) from an ocean perspective. The most relevant changes affecting the ocean variability are related to the improved wind stress variability in ERA-INTERIM, which improves the interannual variability of the ocean everywhere, but especially in the Equatorial and South Atlantic. The global fresh water balance in ERA-INTERIM is also improved with respect to ERA-40.

3 RESULTS

3.1 Variability of the equatorial thermocline

Figure 1 shows the time evolution of the depth of the 20 degree isotherm (D20) in the Equatorial Pacific (5°N-5°S, 130°E-80°W), as represented by the various experiments in Table 1. This variable is a proxy for the depth of the thermocline. The shaded areas are for the ensemble of re-analyses in NEMOVAR-COMBINE (blue) and ORAS3 (green). The blue line is for ORA-XBTc, which follows closely ORAS3, except for the 1975-1985, where the XBT corrected version produces a shallower thermocline than ORAS3. The ocean-only simulations HOPE-NOOBS (pink) and NEMO-NOOBS (violet) are the outliers: the thermocline is too shallow in HOPE and slightly too deep in NEMO. The data assimilation, in both NEMOVAR-COMBINE and ORAS3, constrains the solution by reducing the uncertainty coming from the models and forcing fields.

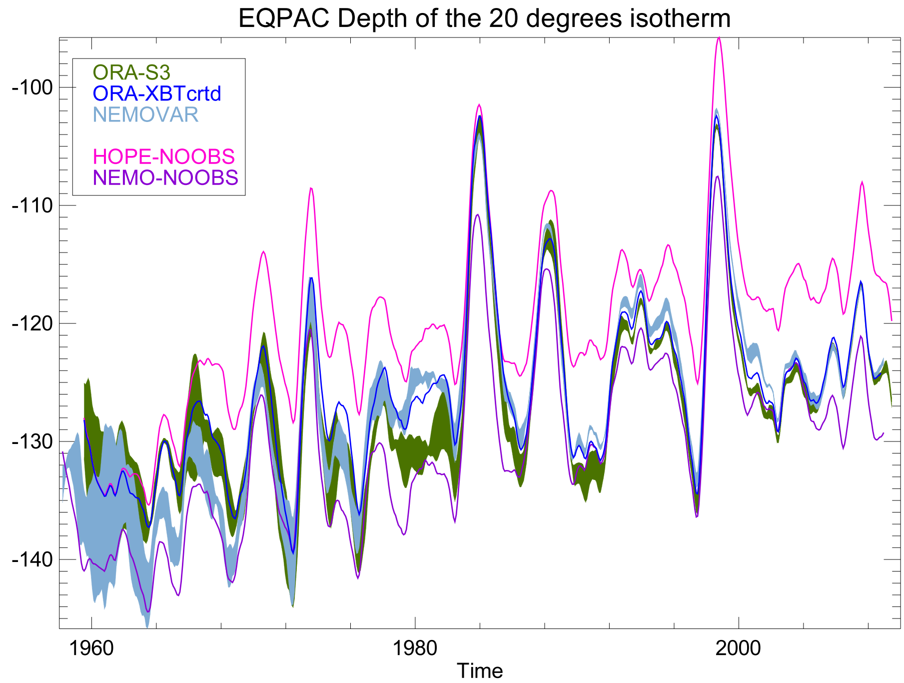

Figure 1: Depth (m) of the thermocline in the Equatorial Pacific as represented by the different experiments in Table 1. The shaded curves represent the ensemble spread among the different ensemble members, indicative of the estimated uncertainty

All the experiments exhibit a pronounced shallowing trend (~30 m in the last 50 years). This shallowing of the equatorial thermocline has been discussed by Balmaseda et al. (2008b) as indicative of changes in the wind stress, which induce an enhanced heat export by intensification of the equatorial meridional circulation. Corre et al. (2010) identify the shallowing trend of the equatorial thermocline in several ocean re-analysis products, and attribute its fingerprint to global warming.

The uncertainty in the re-analyses decreases with time, as the number of ocean observations increases. In the later years, not only the ensemble spread is clearly reduced, but it is also commensurable of the uncertainty in the analysis. This is not the case in the earlier years, where in spite of both re-analyses showing larger spread, it is not enough to cover the differences between reanalyses.

3.2 Upper ocean heat content

Figure 2 shows the time evolution of the global upper ocean heat content in ORAS3 (green shades), NEMOVAR-COMBINE (blue shades) and NEMO-NOOBS (violet). The data have been filtered with a 12-month running mean, and the mean state has been removed, to facilitate the comparison of the variability. The observation-based reconstruction of Domingues et al. (2008) (D08 in what follows), which uses XBT corrected as in Table 1 of Wijffels et al. (2008), is shown in black (yearly values).

The effect of the XBT correction is clearly visible in this variable. In ORAS3 the XBTs were not corrected, which caused the spurious signals in the 70's and sharp warming post-1995. These signals are not in D08, nor in NEMOVAR-COMBINE and the ocean-only simulations (for presentation reasons only NEMO-NOOBS is shown in the figure). The ORAS3 variability is also contaminated by the faulty SOLO/FSI sensors in Argo floats (Lyman et al. 2006) and lack of manual blacklisting in Argo. In ORAS3, the combination of XBT errors and SOLO-FSI errors created a heat content peak in 2003 and a large drop post 2003.

NEMOVAR-COMBINE is affected neither by the SOLO-FSI nor by the XBT problem. Therefore, it does not show the peaks in the 70's or 2003, and it seems to be in good agreement with D08. The impact of data assimilation, visible as the differences between NEMOVAR-COMBINE and NEMO-NOOBS, are more pronounced after the second half of the 90's: in NEMO-NOOBS the heat content continues to increase quite monotonically after 1995, while it declines in NEMOVAR-COMBINE after 1998, with a local minimum around 2000, and the warming trend seems to stabilize after 2003. The post 2003 differences may be related to the vertical penetration of the warming, as discussed below.

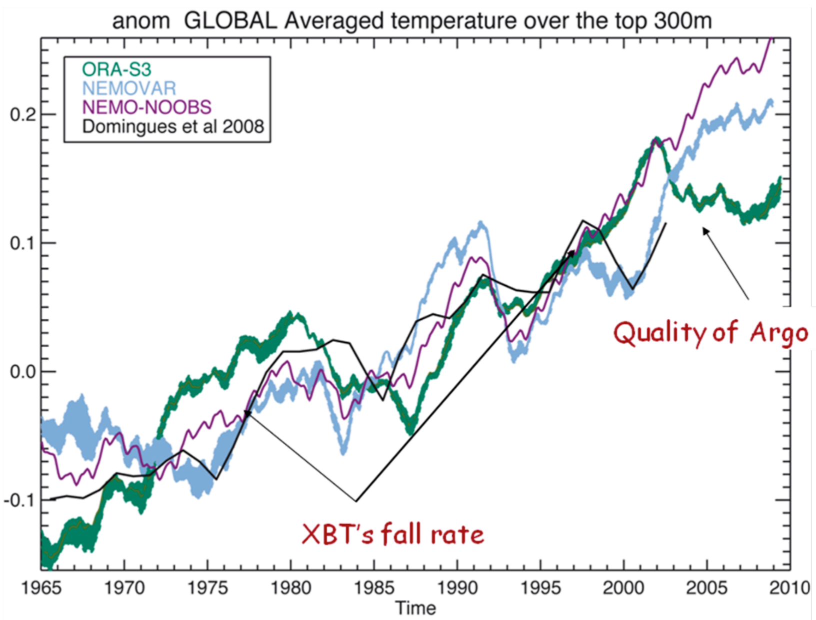

Figure 2: Time evolution of the upper-300 m averaged temperature (T300) anomalies from ORAS3, NEMOVAR-COMBINE and NEMO-NOBS. Also shown is the observational estimate of Domingues et al. (2008). Anomalies (in K) have been computed with respect to the 1965-2000 climatology.

3.3 Vertical penetration of warming

Figure 3 shows a time-depth section of the globally-averaged temperature anomalies from NEMO-NOOBS (left) and NEMOVAR-COMBINE (right). Both the ocean-only simulation and the ocean data assimilation show the existence of a nonlinear trend, with quite a pronounced warming after the 90's. The data assimilation has a marked impact in the vertical penetration of the warming. As seen before, the upper ocean warming is stronger in NEMO-NOOBS than in NEMOVAR-COMBINE, but the warming penetrates deeper in the latter. The time evolution is also different: while the warming in NEMO-NOOBS is monotonic after the second part of the 90's, it decreases in NEMOVAR-COMBINE during the late 90's, and then suddenly increases after 2000. The advent of Argo as a global observing system may be responsible for these differences, as the depth/time pattern of the difference suggests. Observing system experiments should be conducted to assess the sensitivities and robustness of these warming signals.

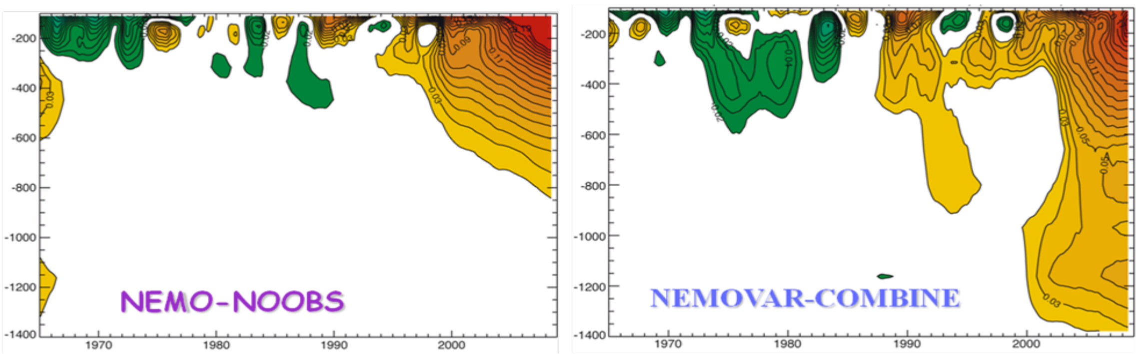

Figure 3: Time evolution of globally averaged temperature anomalies from NEMO-NOOBS and NEMOVAR-COMBINE. The warming reaches deeper in NEMOVAR-COMBINE. Anomalies have been computed with respect to the 1965-2000 climatology. Contour interval is 0.01 K.

3.4 Atlantic Meridional Overturning Circulation

Time series of the Atlantic Meridional Overturning Circulation at 26^{o}N are shown in Figure 4. Shown are the unperturbed ensemble member of ORAS3 (green), HOPE-NOOBS (pink), NEMOVAR-COMBINE (blue) and NEMO-NOOBS (violet). The impact of assimilation in ORAS3 was documented in Balmaseda et al. (2007b), showing that ocean data assimilation improved the mean state of the MOC, by increasing it with respect to the control simulation (HOPE-NOOBS). However, the impact of data assimilation in NEMOVAR-COMBINE is the opposite, since it reduces the amplitude of the overturning. Contrary to the results shown in Figure 1, where data assimilation was effective in constraining the uncertainty due to ocean model and forcing fluxes in the thermal field, the impact of assimilation in the MOC increases the uncertainty. The reasons for this are not well understood. Preliminary experiments indicate that the value of the MOC in the assimilation is very sensitive to the treatment of the ocean observations near bathymetry. Experiments also showed that the MOC in the free ocean-only simulation depends very much on the spin up, whose memory can last up to 20 years, the surface relaxation to SST, and the 3D temperature and salinity bias correction. Without the 3D bias corrections, the value of the MOC in this version of NEMO is substantially reduced. It is also interesting to notice that the NEMO simulations show a sharp decline in the MOC after 1995, which continues during the 00's, while the HOPE simulations do not show such a maintained low value. It is not easy to assert which representation is more realistic.

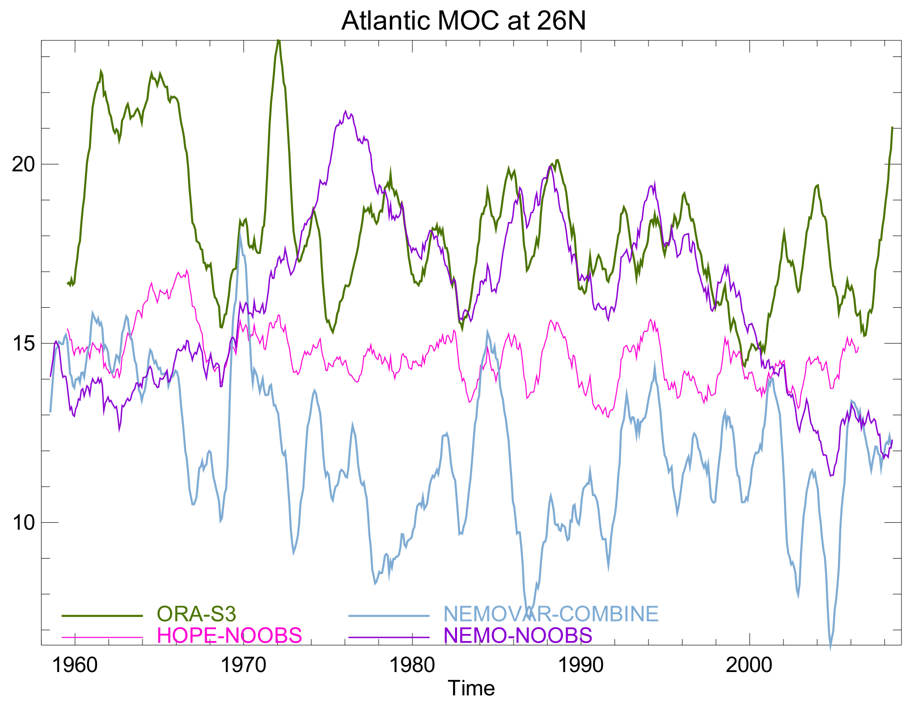

Figure 4: Atlantic Meridional Overturning Circulation at 26°N as represented by ORAS3 (green), HOPE-NOOBS (pink), NEMOVAR (blue) and NEMO-NOOBS (violet). The assimilation of ocean data has different impacts in ORAS3 and in NEMOVAR-COMBINE, and increases the uncertainty arising from different ocean models and forcing fluxes. Units are Sv.

4 SUMMARY

A new ocean reanalysis, based on NEMOVAR, has been produced at ECMWF. This reanalysis, which we called NEMOVAR-COMBINE, assimilates temperature and salinity data only, and it is the first milestone before the next ocean re-analysis using NEMOVAR is implemented operationally at ECMWF, replacing the current one (ORAS3). NEMOVAR-COMBINE is a deliverable for the FP7-COMBINE project, and it will be used to initialize the decadal forecasts using EC-EARTH. A subset of data from NEMOVAR-COMBINE is also publicly available.

Some aspects of the climate variability of ORAS3 and NEMOVAR-COMBINE have been discussed. It is shown that both re-analyses show a consistent shallowing trend of the thermocline in the Equatorial Pacific, a feature also noticeable in ocean-only simulations. The decadal variability in the upper ocean heat content differs between the two re-analyses, and these differences are largely attributed to the quality of the observations assimilated, in particular the errors in the XBTs and the SOLO/FSI Argo floats that affected ORAS3 variability. Results show that the assimilation of ocean data is effective in constraining the upper thermal field, reducing the uncertainty arising from ocean models and forcing fluxes. However, it does not constrain the ocean circulation. For instance, the difference in the

AMOC at 26^{o}N between NEMOVAR-COMBINE and ORAS3 is larger than the differences between the HOPE and NEMO ocean-only simulations. NEMOVAR-COMBINE weakens the values of the AMOC with respect to NEMO-NOOBS, while ORAS3 strengthens the AMOC with respect to that of HOPE-NOOBS. The AMOC in NEMOVAR-COMBINE is weaker than in ORAS3.

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