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Analysis of a 44-year hindcast for the Mediterranean Sea: comparison with altimetry and in situ observations

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SUMMARY: We study the interannual and seasonal variability in the Mediterranean Sea over the period 1958-2004 by comparing a numerical simulation (the 1/4º ORCA-R025 G70 model run, 'ORCA' hereafter) with altimetry and the MEDAR temperature and salinity database. The model is forced by the ERA40 atmospheric forcing and has a salinity restoring term applied at surface. Comparing temperature between ORCA and MEDAR shows good interannual variability agreement (correlations of ~0.8 in the western Mediterranean and ~0.5 in the eastern Mediterranean) at surface layers (0-150 m), but slightly higher mean values in the model (0.08-0.16°C). The salinity analysis shows that the surface salinity restoring term has obliterated most of the interannual variability. Mean surface salinities are slightly lower in the model (~0.3), replicated in deeper layers to a lesser degree, and could mean that the restoring term applies insufficient evaporation to compensate for a weak atmospheric forcing (ERA40) water loss flux. The sea level analysis comparing sea surface height (SSH) and steric height from ORCA and sea level anomalies from altimetry (1993-2004) shows good correlations (~0.8) in the interannual variability and annual cycle. However, the model's SSH overestimates (~15 mm/yr) observed positive altimetric trends (~3-4 mm/yr). In an attempt to identify the source of this overestimation, a water budget calculation was performed between the horizontal and vertical water fluxes in the Mediterranean Sea. Horizontal transport through the main straits shows appropriate values when compared to observations. Thus, the cause of the exaggerated SSH trend is probably a water flux imbalance. By improving surface salinity restoring and atmospheric forcing, the ORCA simulations can provide very promising tools for studies of interannual variability in the Mediterranean Sea.

Keywords: sea level, altimetry, temperature, salinity, modelling, Mediterranean Sea.

RESUMEN: Evaluación de un retroanálisis de 44 años para el mar Mediterráneo: comparación con altimetría y observaciones in situ. – Estudiamos la variabilidad estacional e interanual en el mar Mediterráneo durante el periodo 1958-2004, comparando una simulación numérica (la simulación de 1/4º ORCA-R025 G70, 'ORCA' de ahora en adelante) con datos de altimetría, y temperatura y salinidad (MEDAR). El modelo utiliza el forzamiento atmosférico ERA40 y tiene aplicado un término de relajación a la salinidad en superficie. La comparación de temperatura entre ORCA y MEDAR muestra un buen acuerdo de la variabilidad interanual (correlación ~0.8 en el Mediterráneo Occidental (WMED), ~0.5 en el Mediterráneo Oriental (EMED)) en las capas superficiales (0-150 m), pero con valores medios ligeramente superiores en el modelo (0.08-0.16ºC). El análisis de salinidad muestra que la mayor parte de la variabilidad en superficie ha sido destruida por el término de relajación. Las salinidades medias en superficie son ligeramente inferiores en el modelo (~0.3), lo cual se repite en capas más profundas pero en menor grado. Esto podría significar que el término de relajación no aplica suficiente evaporación para compensar un débil flujo de pérdida de agua en el forzamiento atmosférico (ERA 40). El análisis de altura de nivel del mar (SSH) y altura estérica (SH) del modelo ORCA y anomalía del nivel del mar proveniente de la altimetría (1993-2004) muestra buenas correlaciones (~0.8) en la variabilidad interanual y ciclo estacional. Sin embargo la SSH del modelo sobreestima (~15 mm/año) la tendencia positiva observada por la altimetría (~3-4 mm/año). En un intento de identificar el origen de esta sobreestimación, se hizo un cálculo de balance de masas entre los flujos horizontales y verticales (E-P-R) que entran al mar Mediterráneo. Los flujos horizontales a través de los principales estrechos muestran valores adecuados cuando se comparan con observaciones. Por lo tanto, la exagerada tendencia en SSH del modelo es probablemente debido a un desequilibrio entre la E-P-R (evaporación, precipitación y aporte fluvial). Mejorando el término de relajación de salinidad y el forzamiento atmosférico, las simulaciones ORCA pueden proporcionar unas herramientas muy prometedoras para estudios de variabilidad interanual en el mar Mediterráneo.

Palabras clave: nivel del mar, altimetría, temperatura, salinidad, modelos numéricos, mar Mediterráneo.

INTRODUCTION

The ocean plays a fundamental role in the slow evolution of climate on our planet (Molines *et al.*, 2006). Until recently, our comprehension of the oceans' variability has been limited by the lack of historical observations. Over the last few decades, the quality of oceanic observations has greatly increased, especially since the World Ocean Circulation Experiment and more recently with the advent of spatial oceanography and the ARGO programme.

These datasets have highlighted the complexity and ubiquity of the oceans' variability over a wide range of space and time scales comprised of many interlinked processes. Despite significant progress, observational datasets remain too short, too superficial (satellites) or too dispersed in time and space (drifters, CTD cruises, etc) to allow detailed studies of the above physical processes across their full range of scales (Penduff *et al.*, 2006). In order to study the relative importance of each of the mechanisms playing a role in ocean variability (external forcing or internal ocean variability), it is crucial to complement all the information from observations (both in situ and remote sensing) with data from numerical modelling studies, which have been steadily improving over the last decade.

In the context of ocean variability and climate change studies, the Mediterranean Sea, where this study is centred, is considered a "miniature ocean" (Bethoux and Gentili, 1999), a kind of ideal, accessible, reduced-scale ocean laboratory where many phenomena present in many different regions of the global ocean can be studied at a smaller scale: deep convection (MEDOC Group, 1970; Leaman and Schott, 1991), shelf-slope exchanges (Bethoux and Gentili, 1999), thermohaline circulation and water mass interaction (Wüst, 1961), mesoscale and submesoscale dynamics (Robinson *et al.*, 2001), etc. Due to its reduced size and scale (Robinson *et al.* [2001] gives a value of 10-14 km for the internal Rossby Radius of Deformation, four times smaller than the typical value in the open ocean) and complex topography, accurate representation of this observed variability of the Mediterranean Sea circulation is a challenging problem in numerical ocean modelling.

Several numerical modelling efforts have been focused on the Mediterranean Sea using different resolutions and forcings to reproduce and understand the Mediterranean general circulation and its variability. Some examples include the work by Alvarez *et al.* (1994), Beckers *et al.* (2002), Roussenov *et al.* (1995), Wu and Haines (1998) and Zavatarelli and Mellor (1995) using coarse resolution models (20-25 km); and Demirov and Pinardi (2002), Fernández *et al.* (2005), Herbaut *et al.* (1997), Horton *et al.* (1997), Korres *et al.* (2000) and Pinardi *et al.* (1997) using higher resolution models (<15 km). More recent studies by Somot *et al.* (2006) and Herrmann *et al.* (2008) used a combination of eddy permitting (1/8º) and eddy resolving (3 km grid) models, and Tonani *et al.* (2008) used the (1/16º) EU-MFSTEP operational model.

However, most of these modelling studies have usually covered short periods of time that are insufficient for longer-term studies. More recently, with numerical models creating 40-50 year hindcasts, research focusing on climatic scales has emerged, allowing the study of decadal and interannual variability.

Many of these recent studies focus on a small number of ocean parameters, which in conjunction provide a large amount of information about the climatic state of the ocean. This is the case of sea level, which is influenced by many forcing parameters of the ocean such as circulation changes, water properties and atmospheric forcing. In addition, both altimetry data and ocean models have become mature enough to be used for medium-term studies. The other main parameters analyzed are the temperature and salinity properties of the ocean's water masses. Examples include the work by Tsimplis and Rixen (2002), who studied the effects of temperature and salinity on Mediterranean sea level using the MEDAR database, and Tsimplis *et al.* (2008), who analysed sea-level behaviour by comparing tide gauge measurements with steric sea level from 2D and 3D (ORCA R025-G70 global) models as well as hydrographic (T and S) data. Very recently, Tsimplis *et al.* (2009) performed a sea-level analysis using altimetry, hydrographic data (MEDAR) and 2D and 3D regional models.

However, in this study we look at the subject with a different approach, studying the interannual and seasonal variability in the Mediterranean Sea by performing a model assessment of the global ORCA-R025 G70 simulation, and comparing it with altimetry and the MEDAR (temperature and salinity) observational database. We also analyze the prognostic sea surface height (SSH) from the models, which has not been done before, and try to identify the drift problems common in the SSH of most models. Also, using a global model (with suitably resolved straits) reduces certain issues related to boundary conditions. We analyze the model's output using a series of techniques, attempting to identify its strengths, and especially its weaknesses, in order to improve future simulations.

DATA AND METHODS

The ORCA-R025 G70 simulation

In this study we use the ORCA-R025 G70 numerical simulation (hereafter ORCA) developed by the DRAKKAR group (Barnier *et al.*, 2006) aiming at the study of ocean variability under realistic atmospheric conditions (from ECMWF/ERA40 (Simmons and Gibson, 2000)) over the last half century (1958-2004). The model simulates the evolution of temperature, salinity, velocity, sea surface height (SSH), sea-ice characteristics, and oceanic concentrations of tracers (CFC^{11} and C^{14}) (Barnier *et al.*, 2007).

The ORCA simulation uses a global configuration of NEMO (Madec, 2008) implemented on a 1/4° resolution grid (eddy-permitting but not eddy-resolving). Effective resolution gets finer with increasing latitudes (in this case ~27.75 km at the equator, ~21.8 km in the Mediterranean and ~13.8 at 60°N/S). Grid, masking and initial conditions are inherited from the global configuration of the MERCATOR Ocean operational oceanography centre, with 1442×1021 grid points and 46 vertical levels. Vertical grid spacing is finer near the surface (6m) and increases with depth to 250 m in the deep abyssal plains (maximum depth is 5844 m). Bathymetry is derived from the 2-min resolution Etopo2 bathymetry file of the NOAA National Geophysical Data Centre (also referred to as the 'Levitus climatology'). Some smoothing is applied when the bathymetry is added to the model. In a few key areas the modelling team performed some hand editing of the bathymetry (including the Gibraltar Strait which was widened to allow a suitable flow given the coarse resolution of the model). Initial conditions for temperature and salinity were derived from the NODC World Ocean Atlas data set for middle and low latitudes. For the Mediterranean, initial conditions were derived from the MEDAR climatology (more details can be found in Barnier *et al.* [2006]).

Forcing

With regard to forcing, one of the great difficulties of "forced" oceanic modelling is the balance of atmospheric fluxes. The uncertainties in air temperature, humidity, winds, rainfall and air-sea fluxes are so great that when one integrates the global heat and freshwater fluxes, there is usually a huge imbalance that drives an unacceptable drift in the ocean model. The forcing applied in this model run is a combination of the ERA40 reanalysis (wind, temperature and atmospheric humidity) and CORE (downward shortwave and long wave radiation forcing) as well as precipitation derived from direct satellite measurements for the last few decades (prior to satellite measurements, the CMAP climatological monthly mean precipitation was used). River runoff is provided by MERCATOR Ocean and applied as extra rainfall at the approximate location (closest grid point) where the river meets the ocean. Thanks to the adjustments made in the flux forcing (use of a hybrid forcing between CORE and ERA40) the global thermohaline circulation is maintained within measured values. However, the mean global ocean sea level increases 25 cm during the entire simulation (Barnier *et al.*, 2007; Molines *et al.*, 2006).

Due to an imbalance in the freshwater fluxes, a salinity relaxation is made at the surface using, in the Mediterranean Sea, the MEDAR climatology (Rixen *et al.*, 2005), with a characteristic relaxation time of 12 days (model run time). This relaxation is applied as evaporation if the model is less salty than the reference, and as rainfall if the model is saltier than the reference. This avoids a significant drift in surface salinity.

Prognosis of sea surface height

The NEMO code uses the Boussinesq approximation (the model conserves volume rather than mass) and the Free Surface Formulation calculates sea surface height as a prognostic variable given by the equation:

$$\partial\eta/\partial t = -D + P - E \qquad (1)$$

where

$$\mathrm{D} = \nabla[(H + \eta)\ \bar{U}_h] \qquad (2)$$

where the P–E component is the net downward water flux, also including the river runoff and the sea surface salinity restoring term. H is the depth of the sea floor, η is the height of the sea surface and $\bar{U}_h$ is the vertically integrated flow (for more details on the model characteristics, please refer to the model's manual: Madec [2008]).

Altimetry

For this study we use 12 years (Jan 1993-Dec 2004) of gridded altimetric fields combining several altimeter missions (Topex/Poseidon (T/P), Jason-1, ERS1/2, ENVISAT). These data are delivered by the AVISO web server: http://www.aviso.oceanobs.com. The processing of altimetric data goes as follows. Sea surface height measurements are geophysically corrected (tides, wet and dry troposphere, ionosphere) with the atmospheric correction applied in order to minimize aliasing effects. The along-track data are resampled every 7 km using cubic splines and the sea level anomalies (SLA) are computed by removing a 7-year mean SSH corresponding to the 1993-1999 period. The mean profile contains the geoid signal and the mean dynamic topography over the averaging period. Measurement noise is reduced by applying Lanczos cut-off and median filters. The mapping method to produce gridded SLA fields from along-track data is detailed in Le Traon *et al.* (1998). It has been applied in many studies (e.g. Ducet *et al.*, 2000) and was recently improved in Le Traon *et al.* (2003). Maps of the gridded data are calculated every week on a 1/4° grid. The data used in this study is filtered with a 30 day running filter and sub-sampled for monthly temporal resolution in order to have the same resolution as the model output.

MEDAR

In an effort to provide an integrated picture of temperature and salinity in the Mediterranean, the MEDAR Group (2002) built a new database interpolating 291,209 T and 124,264 S quality checked profiles onto a 0.2×0.2° horizontal grid and 25 standard vertical levels (Rixen *et al.*, 2005). The MEDAR dataset contains yearly data for the period 1945-2002. The data interpolation was obtained using the variational inverse method. The correlation length calibration and the signal-to-noise ratio were obtained by generalized cross validation.

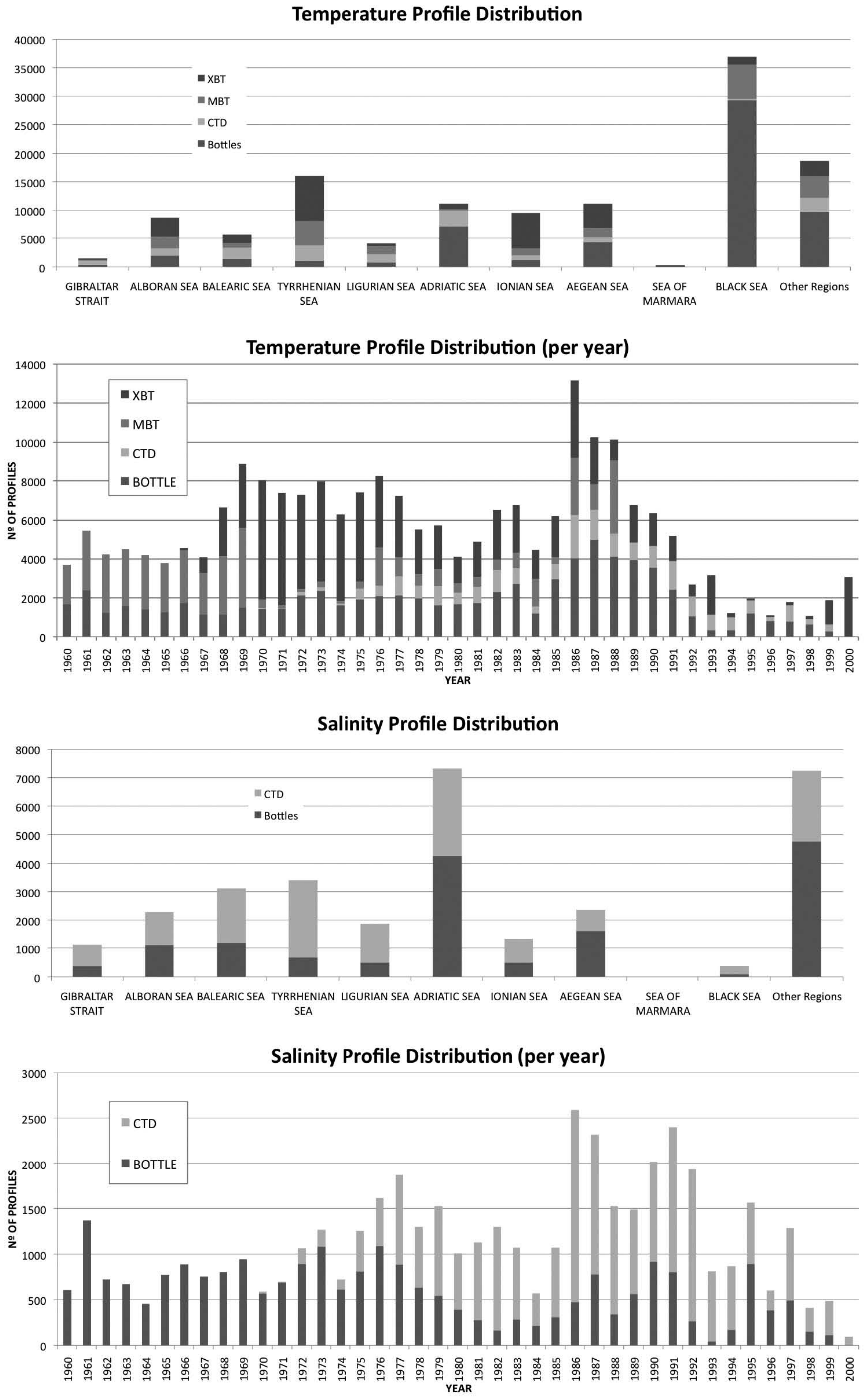


FIG. 1. – MEDAR spatial and temporal profile distribution.

It is important to note that although the database is available for a long period, the number of profiles at the beginning, and especially in the WMED prior to the 1970s, is low (see Fig. 1). In addition, sampling of the Mediterranean is biased towards the areas of deep and intermediate water formation, whereas areas near the African coasts have not been sampled adequately. Moreover the data are also seasonally biased (Tsimplis and Rixen, 2002) as most measurements have been taken during the spring and summer periods. This can lead to significant interpolation errors.

There is a separate product, the MEDAR climatology, which is comprised of monthly averages without interannual variability. That is to say, one average for every January, every February, and so on. This climatology is also used in this study to look at the seasonal cycle of the steric signal.

Methods

The intercomparison between the ORCA data and satellite altimetry data is based on several parameters computed from gridded data such as mean sea level, variance, trends and the annual and semi-annual cycles. The latter were obtained by fitting two harmonic functions using a least squares method:

$$y(t) = A_a \cos \frac{2\pi}{365.25} t - \phi_a + A_{sa} \cos \frac{2\pi}{182.63} t - \phi_{sa} \qquad (3)$$

where A_a and ϕ_a are the amplitude and phase of the annual cycle, and A_{sa} and ϕ_{sa} are the amplitude and phase of the semi-annual cycle (Pascual *et al*., 2008).

Temperature and salinity were separated into basins and layers according to Rixen *et al*. (2005). Trends and correlations were calculated for every layer.

The steric component of sea level (steric height, the expansion/contraction of the water column due to changes in temperature and salinity) was computed for each grid point of the model as the vertical integration from surface to a chosen reference level (H, the full depth in this case) of the specific volume anomaly (α) (with respect to the specific volume at 35 psu and 0ºC) caused by changes in potential temperature (T) and salinity (S):

$$Steric\ Height = 1/g \int_{-H}^{0} \alpha\, dx \qquad (4)$$

Water transport into the Mediterranean was calculated through its main straits in order to get an estimate of the mass balance of the model in the Mediterranean Sea. Transport through the Strait of Gibraltar was calculated by integrating the zonal velocities provided by the ORCA model at a north-south transect centred at 5.45°W. Positive values were considered as transport of Atlantic waters into the Mediterranean Sea, and negative values were considered as Mediterranean waters flowing out into the Atlantic. For the Black Sea, the same process was followed with a north-south transect through the Turkish Straits centred at 28°E. It is worth noting that, due to the model's resolution, both straits had to be widened to two grid points ~40 km at Mediterranean latitudes. A restoring was applied towards the Levitus climatology (T and S) at the Gibraltar Strait exit, in the Gulf of Cadiz. This restoring increases from 200 to 400 m, then remains constant to the bottom. Since it only affects the Mediterranean outflow, its effects are not felt directly within the Mediterranean Sea.

RESULTS AND DISCUSSION

ORCA vs. MEDAR

Temperature

In order to better understand the time evolution and vertical distribution of temperature in the Mediterranean, the study area was separated into basins and vertical layers (Fig. 2) identical to those used by Rixen *et al*. (2005). This allows a better comparison between the model and observations.

For these comparisons, the model data were filtered out with a 1-year running average in order to remove the intra-annual variability not resolved by MEDAR.

The surface layer (top 150 m) shows good agreement between the model and observations, with correlations of 0.8 in the western Mediterranean (WMED) and 0.5-0.6 in the eastern Mediterranean (EMED), and is capable of reproducing signals such as the temperature anomaly around 1990-95. Tsimplis and Rixen (2002) relate this temperature fluctuation with the East Mediterranean Transient (EMT). However, the model is slightly warmer, between 0.08 and 0.16ºC, than the observational data, which may be related to the underestimation of total winter period heat loss (Herrmann *et al.*, 2008) caused by the low resolution of ERA40.

Trend values for both ORCA and MEDAR show a positive trend in the WMED (0.51±0.28°C/100 yr and 0.81±0.29°C/100 yr respectively), and coincide in sign with other studies by Tsimplis and Rixen (2002), Rixen *et al. (*2005) and Salat and Pascual (2006). The EMED shows a strong negative trend for the second half of the 20th century in MEDAR (-1.21±0.33°C/100 yr) but no significant trend in ORCA, also coinciding with the studies referenced above. However, these trends are usually difficult to detect reliably because surface layers are subjected to seasonal and high-frequency variability, where the noise superimposed on mean climatological values or trends is very large (Vargas-Yáñez *et al.,* 2009).

Intermediate layers (150-600 m), which are dominated by the Levantine Intermediate Water, show a clear trend difference in the WMED with warming in ORCA (0.67±0.12°C/100 yr) and cooling in MEDAR (-0.33±0.13°C/100 yr). In contrast, the EMED shows essentially no trend in ORCA and a stronger cooling in MEDAR (-0.96±0.14°C/100 yr). Vargas-Yáñez *et al.* (2009) provide a compilation of studies such as those by Bethoux and Gentili (1999) (1959-1997, for the Ligurian Sea) and Sparnocchia *et al.* (1994) (1950-1987, for the Ligurian Sea and Sicily Strait), obtaining similar trends to ORCA, but these studies may not be directly comparable due to the trends' strong dependence on area, depth range and period of study. Other results by Krahmann and Schott (1998) and Rixen *et al.* (2005) describe the period as having decadal variability but no discernible trend. Trends in intermediate layers still do not agree even between observations.

Taking away the trend from the model's data reveals that the variability is actually well reproduced in both basins (de-trended correlations of 0.57 in WMED and 0.75 in EMED). The MEDAR data show a considerable drop in temperature around the 1979-1983 period in both basins; this drop is well represented by the model in the WMED (de-trended) but not in the EMED, where the model shows a more modest drop.

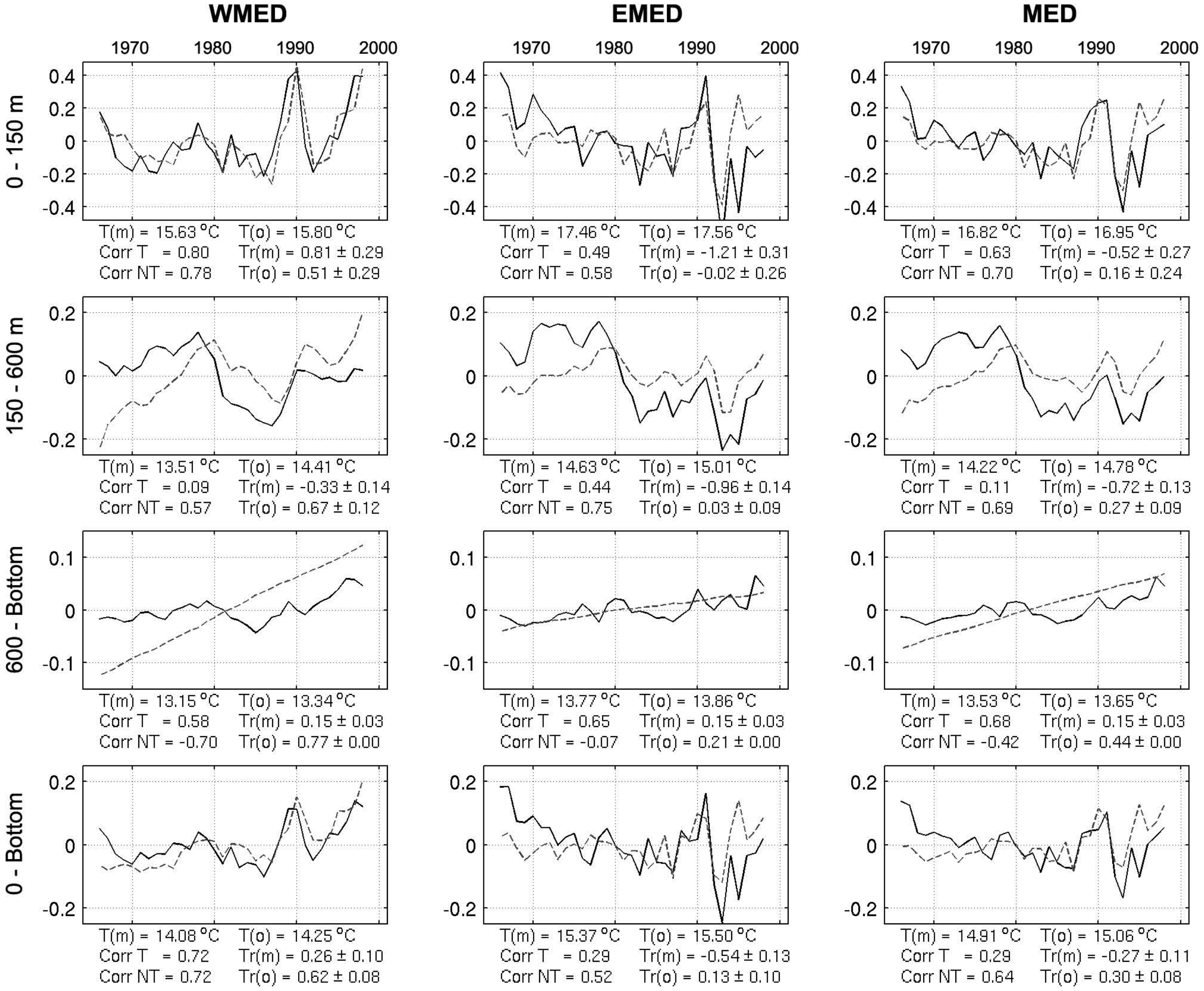


FIG. 2. – ORCA **(o)** (dashed-line) and MEDAR **(m)** (solid-line) temperature time-series divided into basins and layers (1965-1998). **T** refers to the mean temperature. **Corr T** refers to the correlation of the time-series with their respective trends. **Corr NT** refers to the de-trended correlation values. **Tr** refers to the trend value.

Deep layers (600 m) show a large temperature trend difference in the WMED. Here, ORCA shows no interannual variability and severely overestimates the trend at 0.77±0.00°C/100 yr, five times higher than the trend observed in MEDAR (0.15±0.04°C/100 yr). Other deep layer temperature studies (Bethoux and Gentili, 1996; Bethoux *et al.,* 1998; Bethoux and Gentili, 1999; Krahmann and Schott, 1998; and Tsimplis and Baker, 2000) have generally found lower temperature trends (between 0.16 and 0.36°C/100 yr) than those obtained by ORCA. Relevant work by Rixen *et al.* (2005) is not compared here since the MEDAR data used in this study is essentially the same. A possible reason for the exaggerated warming trends in the deep layers of the model could be related to the resolution of the atmospheric forcing. Most deep-water formation events in the Mediterranean occur during short cold and strong events over relatively small areas. With an atmospheric forcing resolution of 125 km, these events are not allowed to develop. Therefore deep layers are not replenished with cold, dense waters and eventually heat up by diffusion. In fact, calculating the heat flux from the ERA40 atmospheric forcing reveals that the Mediterranean Sea is gaining heat at a rate of 3.88 W/m^2, whereas the established observational-based heat flux coming in through the Strait of Gibraltar is of ~5 W/m^2 (so the same amount should be lost by the atmosphere to maintain a state of equilibrium).

Salinity

The salinity analysis shows that the correlations between ORCA and MEDAR are indeed much lower (Fig. 3) than those of temperature.

At all layers, the interannual variability has been almost obliterated by the sea surface salinity restoring term. Data for the WMED display very low or even negative correlations at all depth levels, with large differences in the interannual variability of both datasets. The EMED shows statistically significant positive cor-

TABLE 1. – ORCA and MEDAR temperature statistics related to Figure 1. Correlation values that are significant to 99% are in bold.

Depth range	Basin	Tmean (medr) ºC	Tmean (orca) ºC	Correlation (with trend)	Correlation (no trend)	Trend (medar) ºC/100yr	Trend (orca) ºC/100yr
0-150 m	WMED	15.63	15.80	**0.80**	**0.78**	0.81±0.29	0.51±0.28
	EMED	17.46	17.56	**0.49**	**0.58**	-1.21±0.33	-0.02±0.25
	MED	16.82	16.95	**0.63**	**0.70**	-0.52±0.27	0.16±0.24
150-600 m	WMED	13.51	14.41	0.09	**0.57**	-0.33±0.13	0.67±0.12
	EMED	14.63	15.01	**0.44**	**0.75**	-0.96±0.14	0.03±0.10
	MED	14.22	14.78	0.11	**0.69**	-0.72±0.12	0.27±0.09
600-Bottom	WMED	13.15	13.34	**0.58**	-0.70	0.15±0.04	0.77±0.00
	EMED	13.77	13.86	**0.65**	-0.07	0.15±0.03	0.21±0.00
	MED	13.53	13.65	**0.68**	-0.42	0.15±0.03	0.44±0.00
0-max	WMED	14.08	14.25	**0.72**	**0.72**	0.26±0.10	0.62±0.08
	EMED	15.37	15.50	**0.29**	**0.52**	-0.54±0.14	0.13±0.10
	MED	14.91	15.06	**0.29**	**0.64**	-0.27±0.11	0.30±0.08

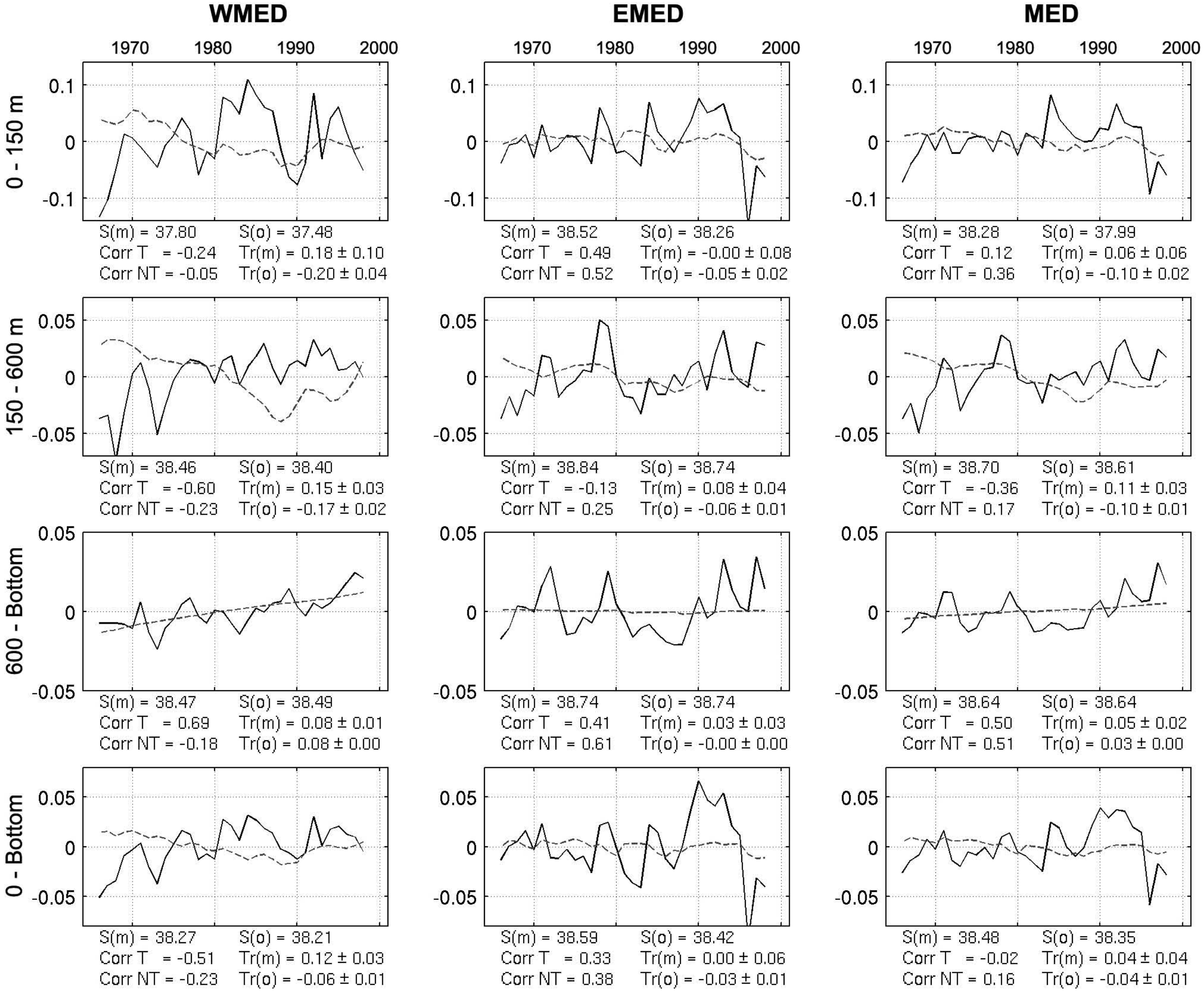


FIG. 3. – ORCA **(o)** (dashed-line) and MEDAR **(m)** (solid-line) salinity timeseries divided into basins and layers (1965-1998). **S** refers to the mean temperature. **Corr T** refers to the correlation of the time-series with their respective trends. **Corr NT** refers to the de-trended correlation values. **Tr** refers to the trend value.

Table 2. – ORCA and MEDAR salinity statistics related to Figure 2. Correlation values that are significant to 99% are in bold.

Depth range	Basin	Smean (medr)	Smean (orca)	Correlation (with trend)	Correlation (no trend)	Trend (medar) psu/100yr	Trend (orca) psu/100yr
0-150 m	WMED	37.80	37.48	-0.24	-0.05	0.18±0.10	-0.17±0.02
	EMED	38.52	38.26	**0.49**	**0.52**	-0.00±0.08	-0.05±0.02
	MED	38.28	37.99	0.12	**0.36**	0.06±0.06	-0.10±0.02
150-600 m	WMED	38.46	38.40	-0.60	-0.23	0.15±0.03	-0.17±0.02
	EMED	38.84	38.74	-0.13	**0.25**	0.08±0.04	-0.06±0.01
	MED	38.70	38.61	-0.36	0.17	0.11±0.03	-0.10±0.01
600-Bottom	WMED	38.47	38.49	**0.69**	-0.18	0.08±0.01	0.08±0.00
	EMED	38.74	38.74	**0.41**	**0.61**	0.03±0.03	-0.00±0.00
	MED	38.64	38.64	**0.50**	**0.51**	0.05±0.02	0.03±0.00
0-max	WMED	38.27	38.21	-0.51	-0.23	0.12±0.03	-0.06±0.01
	EMED	38.59	38.42	**0.33**	**0.38**	0.00±0.06	-0.03±0.01
	MED	38.48	38.35	-0.02	0.16	0.04±0.04	-0.04±0.01

relations at all depths (except the intermediate layer) but the interannual variability from the model is much lower than the MEDAR database. It is worth noting that the mean surface salinity for the entire Mediterranean basin is significantly lower in ORCA than in MEDAR (~0.3 psu); this is replicated in intermediate and deep layers to a lesser degree. Therefore the salinity restoring term still applies insufficient evaporation to compensate for the weak ERA40 water loss flux (Hermann *et al.,* 2008; Josey, 2003; and Mariotti *et al.,* 2002).

However, one must also be cautious regarding the MEDAR dataset because its quality depends directly on the amount and distribution of real data (Fig. 1), and there are less than half as many salinity profiles as temperature ones as well as a heavy northern bias.

Seasonal steric signal

As opposed to ORCA, the MEDAR data is only available in annual time steps for the second half of the 20th century. This does not allow for the representation of the seasonal cycle. However, there is a monthly MEDAR climatology (monthly averages without interannual variability) for this period, which can be used to determine the differences and similarities of the steric signal for both ORCA and MEDAR. The steric height is the component of sea level driven by the expansion/contraction due to changes in temperature and salinity. Figure 4 shows the computed steric height for the Mediterranean basin from the climatological data (from the surface to the full depth). Amplitudes coincide perfectly (~5-6 cm), and phases are very similar with only very minor differences. The most notable result is the absolute height difference between the two datasets, with ORCA being an average of 14.33 centimetres higher than MEDAR. This is because the mean salinity for the entire Mediterranean basin is significantly lower in ORCA than in MEDAR, while temperature is slightly higher. A simple test of adding a bias of 0.13 to the salinity (which is the mean difference observed for the whole Mediterranean integrated from the surface to the sea floor in Fig. 3) made the absolute steric height of MEDAR change by ~17 cm. Halosteric and thermosteric sensitivity analysis shows that about 85% of the steric signal is due to temperature (amplitude of ~8-10 cm) and 15% due to salinity (amplitude of ~2 cm) (not shown).

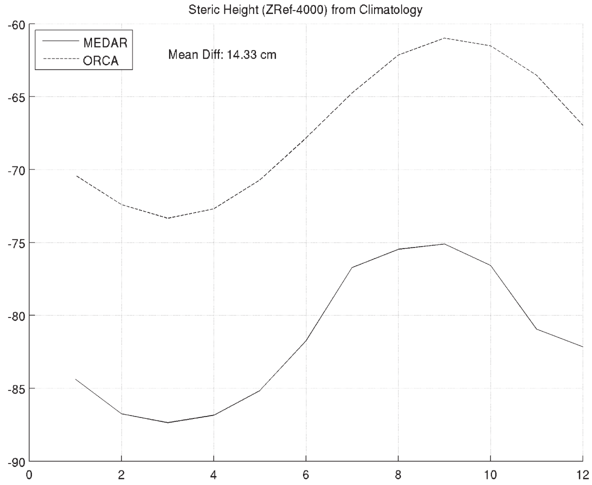


Fig. 4. – ORCA (dashed-line) and MEDAR (solid-line) climatology of steric height calculated from a reference depth level of 4000 m.

ORCA vs. altimetry

In addition to temperature and salinity, the sea surface height performance of the model was also analyzed and compared to Altimetry data. Since the altimetry dataset is only available from 1993, only the period 1993-2004 was analyzed in this section. This analysis was also performed on the computed steric height of the model.

Mean sea level

We look at the time evolution of the sea surface height variables over the Mediterranean and its two main basins, the EMED and WMED basins. Figure 5

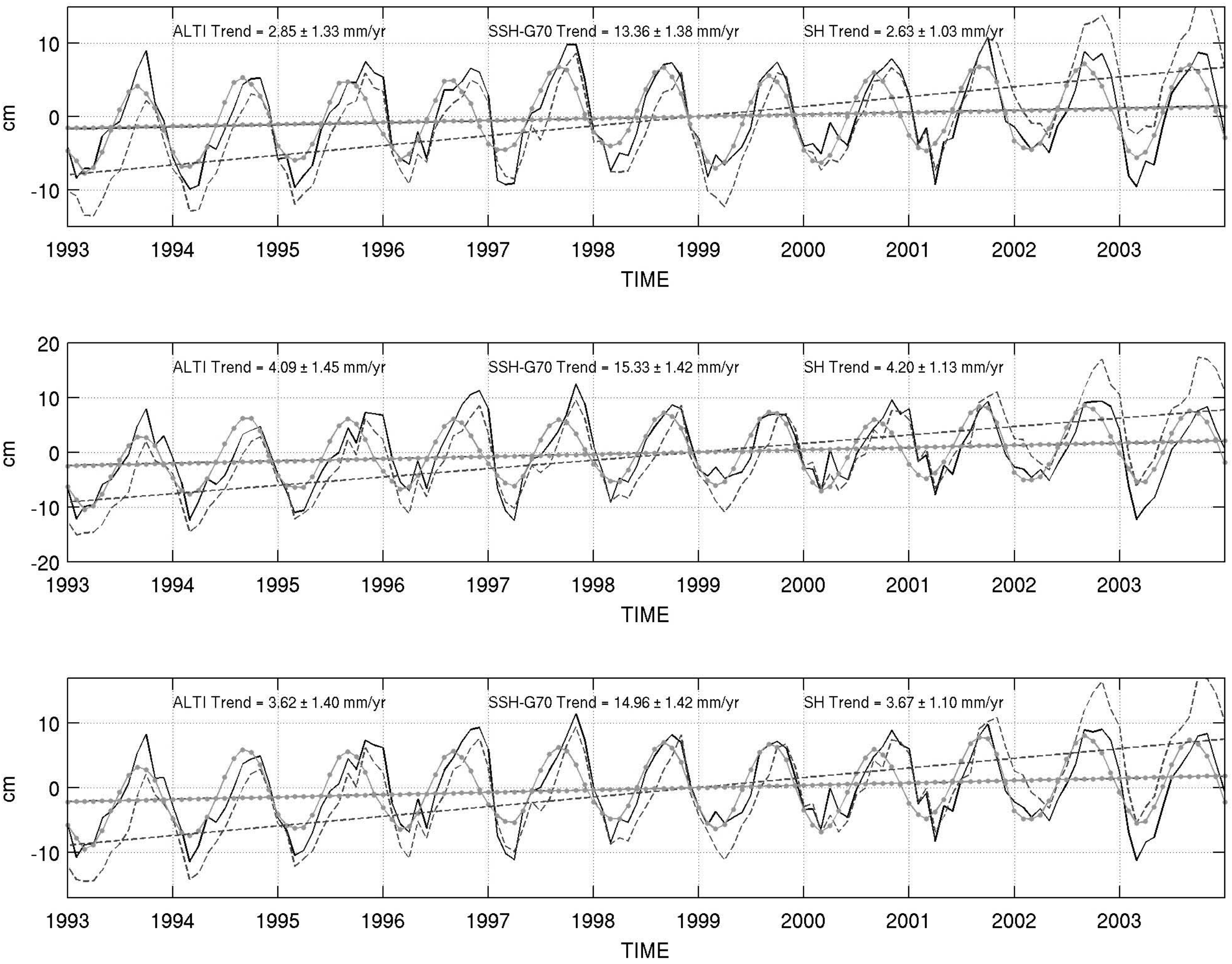


Fig. 5. – Timeseries of ORCA sea surface height (SSH, grey dashed-line), steric height (SH, light-grey line-dot) and altimetry (ALTI, solid black line) for the WMED (top), EMED (middle) and whole Mediterranean (bottom).

shows the Mediterranean basins' mean anomaly timeseries for the model's SSH (grey dashed-line), steric height (light-grey line-dot) and altimetry (solid black line) for the period 1993-2004, where the main component of this signal is clearly due to the seasonal cycle.

From these results, it is clear that the model is perfectly capable of accurately reproducing the phase and amplitude of the seasonal cycle with very good comparison between the model's SSH and the altimetry (which in theory are observing the same processes), with correlations of ~0.8 (0.89 with the signals detrended). A clear example of this is the sea level signal linked with the 1996 negative North Atlantic Oscillation (Woolfe *et al.,* 2003), which according to Tsimplis *et al.* (2008) is the strongest signal of the last four decades (particularly in the WMED). When computing the model's steric height, the specific volume anomaly was integrated from the surface to the full depth of the model.

Figure 5 shows that the steric component accounts for about half of the total sea level signal. The computed steric height of the model shows an annual cycle amplitude of ~5 cm, and the full SSH signal as diagnosed by the model of ~10 cm. These values coincide with the altimetry data and are confirmed by Bouzinac *et al.* (2003) and Larnicol *et al.* (1995).

A notable limitation of the model is its ability to reproduce long-term SSH trends. With an average trend of 14.95±1.52 mm/year for the whole Mediterranean, the model overestimates 4-5 times the trend observed by altimetry (3.6±1.54 mm/year). The trend is higher in the EMED than in the WMED, but this coincides with the altimetry. A surprising result is that the steric height computed from the model's temperature and salinity data does not display the same exaggerated trend. Moreover, the trend is almost identical to the altimetry trend (3.66±1.16 mm/year). However, the fact that the steric height's trend coincides with the altimetry should be interpreted with caution due to the discrepancies observed in the temperature trends between ORCA and MEDAR (especially at intermediate and deep layers, Fig. 2).

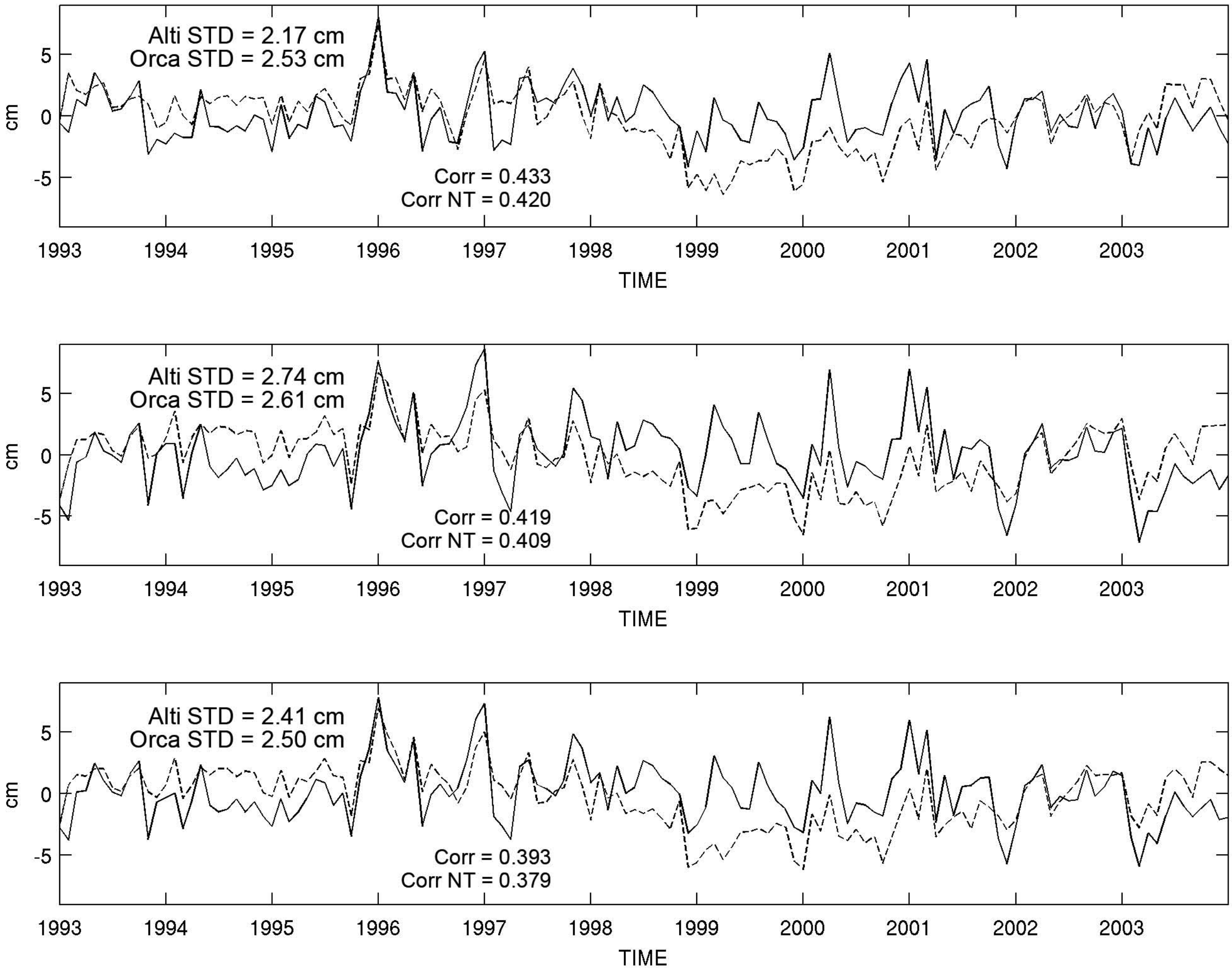


FIG. 6. – Time-series (with the seasonal cycle and trends removed) of ORCA sea surface height (dashed-line) and altimetry (solid-line) for the WMED (top), EMED (middle) and whole Mediterranean (bottom). STD refers to the standard deviation values for each time-series. 'Corr' and 'Corr NT' refer to correlation and de-trended correlation respectively.

The spatial distribution of trends (not shown) for SSH and altimetry confirms that the model's trend overestimation is a global feature of the model (in the Mediterranean 8-18 mm/year, average 14.95 mm/year), whereas altimetry displays areas of both positive and negative trends (-16 to +10 mm/year, average 3.6 mm/year).

These data calculated using basin averages are useful to provide a general idea of the basin's behaviour but may not be truly representative of many areas within the basins themselves. These must therefore be analyzed with caution. Tsimplis and Rixen (2002) found that given the strong spatial variability of the trends, a basin average could not be used to realistically assess its behaviour (consequently, further studies will include smaller, sub-basin scales). As an example, altimetry in the EMED shows a strong sea level drop in the northern Ionian basin (~10 mm/yr) and the opposite in the Levantine basin (~14-18 mm/yr). Up to now, no numerical study has been able to reproduce this sea level drop in the northern Ionian basin, instead showing an intense sea level rise over the EMED with similar values to the altimetry trend in the Levantine basin (Tsimplis *et al.,* 2008).

In order to study the interannual variability of the signals, the seasonal cycle and trend are removed. Examining Figure 6 shows that most of the peaks in the model coincide with those in the altimetry data despite some differences in the intensities. Altimetry generally appears to show a more intense interannual variability than SSH but standard deviation calculations revealed that the model and the altimetry show similar values over the period studied. Interestingly, the model shows a lower frequency ~4 year signal, with a positive trend from 1993 to 1996, a negative one from 1996 to 2000, and a positive one again from 2000 to 2004.

Variance

Figure 7 shows the variance maps for the 1993-2004 period of the model's SSH, the steric height and satellite altimetry. Comparing the model's SSH and

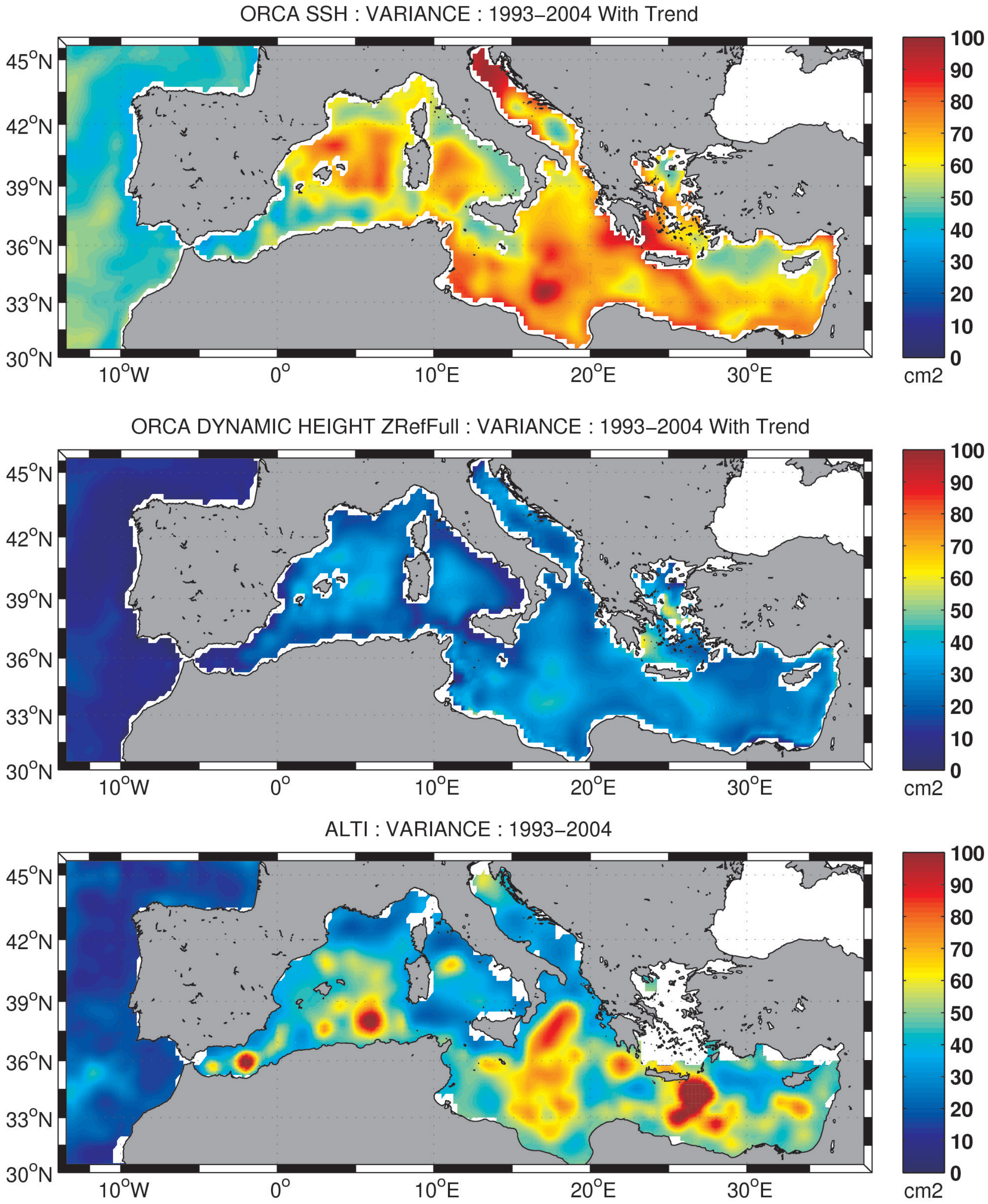
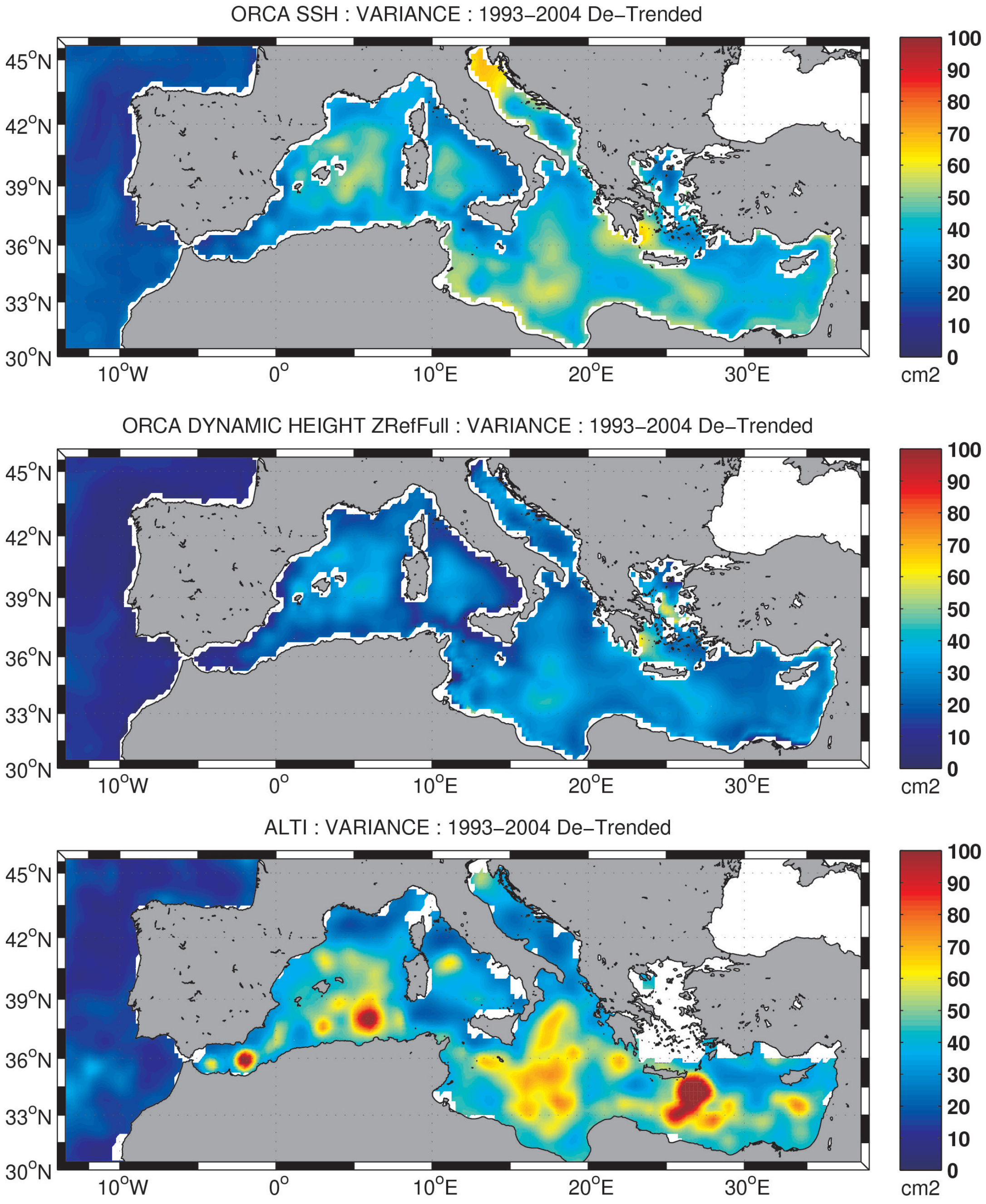


FIG. 7. – ORCA steric height (top), ORCA sea surface height (middle), and altimetry (bottom) variance maps for the 1993-2004 period.

computed steric height shows a large difference between them, with steric height variability showing a much lower overall intensity than the SSH.

This large difference is caused by the exaggerated positive trend identified in the analysis of mean sea level. Removing this trend from the variance (Fig. 8) for all three figures shows little change in the steric height and altimetry but a significant reduction in the SSH variance, bringing the ratios much closer to the expected values. Comparing the de-trended SSH map with altimetry reveals that the model is not capable of resolving the intense mesoscale features which are detected by the altimetry; however, ignoring this fact (that was expected given the model's spatial resolution), the average variance values of both SSH and altimetry are quite similar.


ORCA SSH : VARIANCE : 1993–2004 De–Trended

ORCA DYNAMIC HEIGHT ZRefFull : VARIANCE : 1993–2004 De–Trended

ALTI : VARIANCE : 1993–2004 De–Trended

FIG. 8. – ORCA steric height (top), ORCA sea surface height (middle) and altimetry (bottom) de-trended variance maps for the 1993-2004 period.

Annual amplitude

As seen in Figure 5, the amplitude of the seasonal cycle is very well reproduced. Both datasets display an amplitude of around 10 cm. Looking at the spatial distribution of the amplitude (Fig. 9) shows that both ORCA and Altimetry have similar distributions of high and low amplitude features. Altimetry exhibits a more intense structure but this is most likely due to its higher resolution. From the spatial distribution maps, it can be confirmed that the model does not have sufficient resolution to accurately reproduce the mesoscale activity in the Alboran Sea and the Algerian Current.

Transports

Strait of Gibraltar

Many studies have focused on the Strait of Gibraltar as it is the only point of contact between the Mediterranean and the open ocean, through which the water balance in the Mediterranean is maintained.

The correct representation of this transport is crucial for a model to work properly within the Mediterranean. Figure 10 shows transport through the Strait of Gibraltar calculated from the ORCA horizontal velocity fields. The transport values obtained by ORCA are 1.076±0.078 Sv of inflow and 1.008±0.089 Sv of outflow, with a net inflow of 0.067±0.064 Sv (for the period 1993-2004). Flow variability displayed by the model is quite low compared to the observational studies since the model data used is comprised of monthly averages and the observations contain higher frequency variability.

Astraldi *et al.* (1999) provide a summary table of different transport estimates by a variety of authors up to 1999. In many cases the estimated transports are derived from heat, salt and water budgets for the Mediterranean Sea. The large uncertainty regarding this transport is mainly due to the lack of long-term direct measurements, the complexity of the horizontal and vertical profile of the strait, and the presence of strong tidal currents (Tsimplis and Bryden, 2000; Gomis *et al.,* 2006).

To date, no observational studies have been carried out for long enough to calculate a long-term mean. Most estimates are based on short mooring deployments (less than one year) and short cruises, and most studies assume a certain vertical and horizontal uniformity of the inflow/outflow. The longest study is by Candela (2001), who performed 2 years of continuous current profile measurements from October 1994 to October 1996 at a mid-sill location on Gibraltar's main sill, as well as two hydrographic cruises. The results from this study give a mean inflow of 1.01 Sv, outflow of 0.97 Sv and a mean inflow of 0.04 Sv. Other studies include that of Tsimplis and Bryden (2000), who estimated a mean inflow of 0.789 Sv, an outflow of 0.634 Sv and a net inflow of 0.156±0.696 Sv from 23 January to 23 April 1997. Also, García Lafuente *et al.* (2002) estimated a mean inflow of 0.724 Sv, an outflow of 0.741 Sv and a net outflow of 0.018±0.502 Sv from 16 October 1997 to 27 March 1998. Transport values obtained by ORCA are close to those estimated by Candela (2001), but show a more intense inflow/outflow than those of Tsimplis and Bryden (2000) and García Lafuente *et al.* (2002). However, given the general uncertainty, these values do enter well within the generally accepted transport values for the Strait of Gibraltar.

Black Sea

The water volume contribution from the Black Sea is also important to complete the freshwater budget of the Mediterranean. The calculated transport values for the model are 0.019±0.021 Sv into the Mediterranean

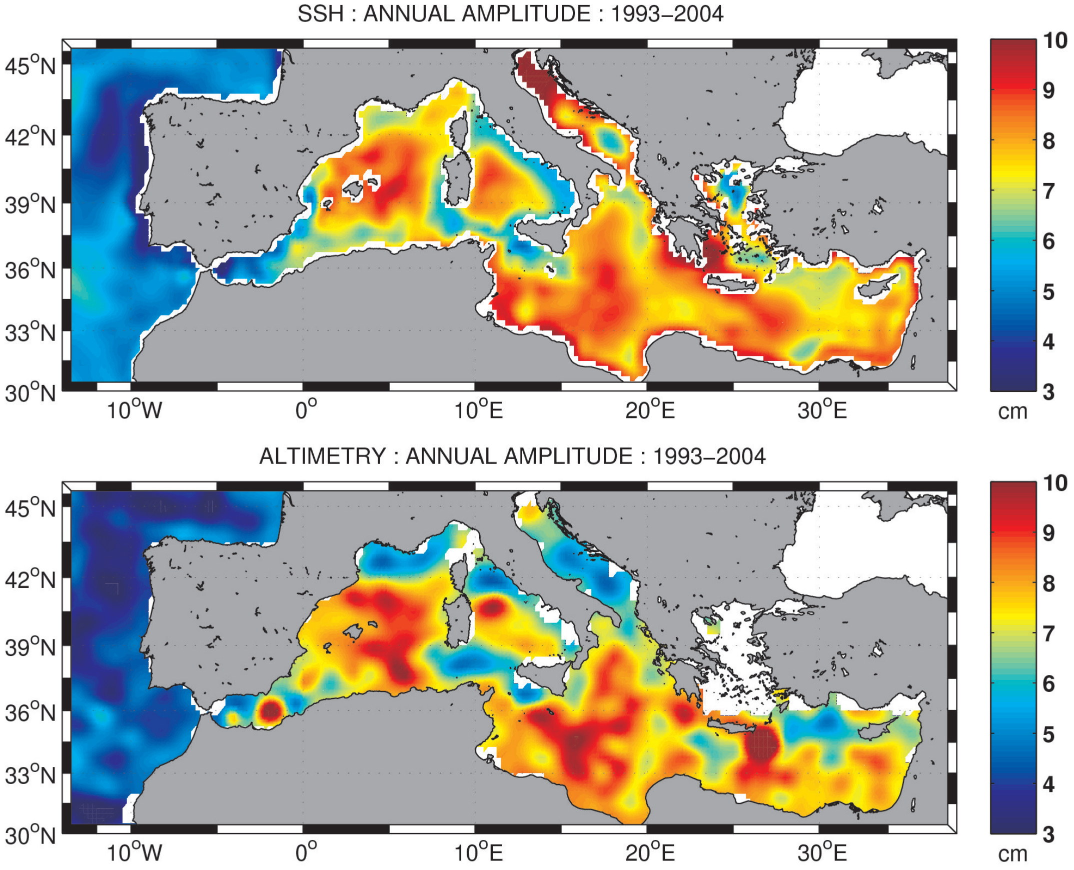


FIG. 9. – ORCA SSH and altimetry annual amplitude maps for 1993-2004.

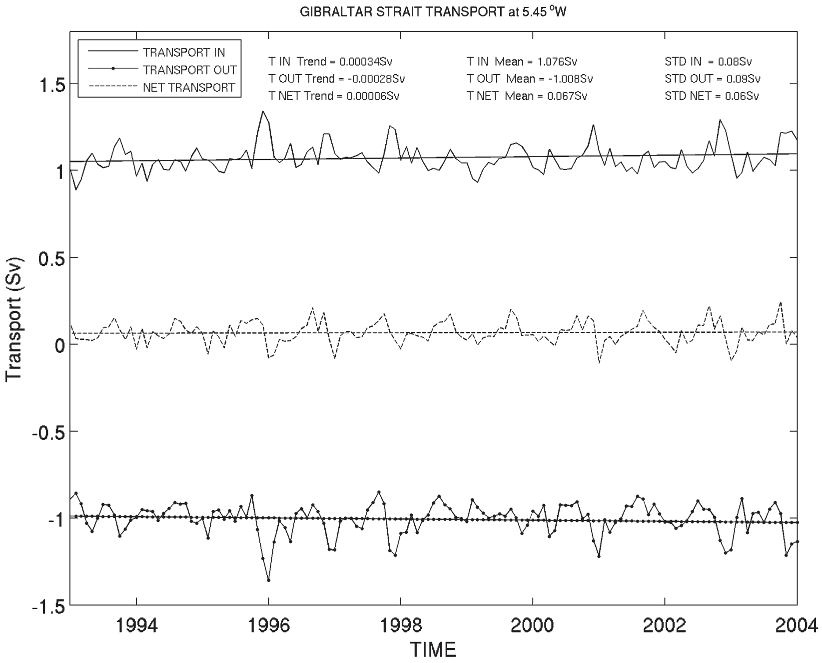


FIG. 10. – Transport through the Strait of Gibraltar.

Sea. As opposed to the Strait of Gibraltar, very few studies have looked at the water transport from the Black Sea into the Mediterranean Sea. Mass balance estimates by Unluata *et al.* (1990) and Özsoy and Unluata (1998) yielded a net vertically averaged transport of 0.0095 Sv, and Peneva *et al.* (2001) used sea level anomaly from Topex/Poseidon to calculate a net transport of 0.016±0.0057 Sv. These values are within the same order of magnitude as those obtained from ORCA, given the margin of error. This is a remarkable result for a 1/4° global model, especially given the complexity of the Turkish Straits system. Nevertheless, the error associated with this transport is probably an important source of error for the freshwater balance calculation (see next Section).

Freshwater balance of the Mediterranean

As seen during the mean sea level analysis, the SSH calculated by the model shows a significant positive trend. In an attempt to identify the possible source of this trend, a water budget calculation was made for the Mediterranean Sea. The water budget is the balance between the water coming into the Mediterranean through its main straits, the Strait of Gibraltar and the Turkish Straits (connecting the Mediterranean Sea to the Black Sea), and the net downward/upward water flux (precipitation minus the evaporation plus the river run-off; P–E+R).

Transport calculations provided mean transport values into the Mediterranean Sea for the Strait of Gibraltar and the Turkish Straits of 0.0674 Sv and 0.0189 Sv respectively. The net sea level change due to horizontal water transports was obtained by dividing the total volume of water entering the Mediterranean Sea by its area (giving a net trend of water inflow of 1.083 10^3±51.7 mm/yr). From this term, the net downward water flux, which includes the salinity restoring term, was subtracted (1.0291 10^3±32.5 mm/yr), giving a total net positive sea level change trend for the Mediterranean Sea of 54 mm/yr with an associated error of 44 mm/yr (calculated by a bootstrap method). These trend values, taking into account the associated error, fall within the trends observed for the model's SSH in the mean sea level analysis (around 15 mm/yr). The salinity restoring term applied to the model increases evaporation in the NDWF by an equivalent of 8.06±4.1 mm/yr, but this is insufficient to compensate for the low evaporation rate of the atmospheric forcing, resulting in an imbalance between the horizontal and vertical water fluxes.

Given that the water transport into the Mediterranean Sea is within the range of values obtained in the literature (although transport through the Turkish Straits can show significant error and make a contribution to the sea level trend), the positive trend observed in the model's SSH is probably related to an imbalance of the water and heat fluxes of the model.

CONCLUSIONS

This study has focused on the interannual and seasonal variability in the Mediterranean Sea by performing a model assessment of the ORCA-R025 G70 Simulation and comparing it with altimetry and the MEDAR (temperature and salinity) observational database. When comparing the ORCA outputs with the MEDAR database we found that the mean surface temperature values and the surface layer (0-150 m) over the 1962-2001 period were quite accurately represented with regard to temperature (de-trended correlations of 0.7), but the sea surface salinity restoring term applied to the model eliminates most of the interannual variability (de-trended correlations of 0.36). Mean temperatures for this layer are slightly higher in the model (0.08-0.16°C), very probably related to the atmospheric forcing's (ERA40) known underestimation of the total heat loss (-3.88 W/m^2 for ORCA in the Mediterranean as opposed to the well established observation based value of ~5 W/m^2 inferred from heat transport at Gibraltar, meaning that the Mediterranean is gaining heat. However, this result is actually within the range of other observational and modelling studies. Ruiz *et al.* [2008] put together a table [Table 2] of the different heat flux studies and the values range between -11 W/m^2 and 29 W/m^2). Intermediate (150-600 m) and deep (600 m- bottom) layers show a clear positive trend that was not seen in MEDAR. This is possibly due to the atmospheric forcing's resolution, which prevents the formation of deep water resulting in cold, dense waters not reaching the deep ocean, which eventually heated up through diffusion. Our results have shown that the mean surface salinity for the entire Mediterranean basin is significantly lower in ORCA than in MEDAR (~0.3), which is replicated in intermediate and deep layers to a lesser degree and could be a consequence of a weak sea surface salinity restoring, without sufficient evaporation to compensate for a weak ERA40 water loss flux.

The evaluation of ORCA with regard to sea level (in terms of both absolute sea surface height (SSH) and its steric component) has revealed that the model reproduces the large-scale interannual variability reasonably well, as well as the seasonal cycle when compared to the altimetry data. However, the model presents an unrealistic SSH positive trend (~15 mm/year). Given that the water transport into the Mediterranean is within the range of values obtained in the literature (although transport through the Turkish Straits can show significant error and make a contribution to the sea level trend), the positive trend observed in the model's SSH is probably related to an imbalance of the water budget of the model (E-P-R).

As expected with this model‘s 1/4º resolution, which is eddy-permitting but not eddy-resolving, the model is incapable of correctly reproducing most mesoscale features. This is especially notable in the Alboran Sea and Algerian Current, where the model is unable to reproduce the gyres and eddies that are formed in these regions.

Besides the mesoscale and sea level trends, this global ocean model behaves well in the Mediterranean Sea, taking into account its relatively low resolution for the dynamic features of this semi-enclosed sea. With a few key issues (such as surface salinity restoring and atmospheric forcing) that, once identified, can be improved, the ORCA ocean model can provide a very promising tool for the study of the Mediterranean seasonal cycle and inter- annual variability characteristics.

Future work will expand on the knowledge acquired during the model assessment and incorporate analysis of new model runs from the ORCA series. These new and improved simulations cover a longer time period (up to 2007), have improved the atmospheric forcing (requiring a weaker salinity restoring) and have increased the number of vertical levels.

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