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Inter-comparing five forecast operational systems in the North Atlantic and Mediterranean basins: The MERSEA-strand1 methodology

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Abstract

The methodology to achieve a real time inter-comparison of five state-of-the-art operational forecast systems for the North Atlantic and Mediterranean basins is presented. All systems provide analysis and near real-time prediction of the three-dimensional ocean through Opendap servers. A standard set of diagnostics called metrics, is described. Definition and examples of metrics are given. An inter-comparison of the five systems is conducted over a 1 year period using those metrics. It is shown that the methodology developed allows a successful inter-comparison. It has been adopted by the GODAE community. It is also shown that the systems are consistent with the current knowledge of the ocean circulation and climatologies. Systems are deficient in the representation of specific water masses characteristics as Mode waters. Data assimilation of vertical profiles of temperature and salinity solve such deficiencies. Metrics also allow a monitoring of the system's North Atlantic overturning stream function and will allow detecting any changes in the coming year system's thermohaline circulation.

Keywords: MERSEA; GODAE; Metrics; Inter-comparison; North Atlantic; Mediterranean Sea

1. Introduction

The Global Data Assimilation Experiment GODAE gathers the international ocean modeling and data assimilation communities around global ocean high resolution forecast systems. GODAE will soon demonstrate the real time production of global ocean products. At the European level, the Marine Environment and Security for the European Area (MERSEA, 2004–2008) project, aims at creating in 2008 the Global Monitoring for Environment and Security (GMES) forecast system (Ryder and Stel, 2002). The initiating MERSEA-strand1 (2003–2004) project (Johannessen et al., 2003b) already inter-compared, on a near real time basis, 5 existing forecast systems for the North Atlantic and Mediterranean basins. The MERSEA project develops websites (http://www.mersea.eu.org and http://strand1.mersea.eu.org) where you will find complementary information.

The forecast systems involved in the inter-comparison exercise are the following: FOAM from United Kingdom, MERCATOR from France, MFS from Italy, TOPAZ from Norway. The HYCOM-US from USA also joined as part of the GODAE contribution. This is the first generation of ocean forecasting systems which need to be assessed in order to converge towards more

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accurate systems. To allow a fair inter-comparison, a common methodology is set up using “metrics”. Metrics are mathematical definitions of chosen diagnostics agreed on and adopted by all teams involved in the project. Standardized output fields and diagnostics are distributed via OPeNDAP servers and can be visualized through a Live Access Server (LAS) or with DODS clients (see http://www.opendap.org). Metrics definition aims at systematically assessing the quality, consistency and performance of each system.

FOAM, HYCOM-US, MERCATOR, MFS and TOPAZ systems differ in many ways, for example in the horizontal and vertical resolution used. When system’s outputs differ, it is difficult to pinpoint exactly why, as individual approaches and objectives are multiple. The inter-comparison exercise involves comparing whole systems, not just various data assimilation methods in the same ocean model configuration for example. The main objective of the inter-comparison exercise is to show the strengths and weaknesses of each system according to the specificity and strategy adopted, as well as to provide guidance for improving future operational systems. The goal of this paper is to document the methodology developed, mainly based on the definition of a standard set of metrics.

This paper is organized as follows. Section 2 describes the FOAM, HYCOM-US, MERCATOR, MFS and TOPAZ operational systems used in this paper. Sections 3 and 4 give the definition of metrics for the North Atlantic and Mediterranean basins. Sections 5, 6 and 7 show results of the use of metrics during the inter-comparison exercise in the North Atlantic Ocean and the Mediterranean Sea. Section 8 concludes on main insights from this inter-comparison exercise and its associated methodology.

2. Configuration of the five operational systems

The five forecast systems used in the inter-comparison exercise for the North Atlantic and Mediterranean basin are described below.

The FOAM system has been previously described in Bell et al. (2000). It is based on the Bryan–Cox code developed for the Hadley Center’s coupled model HadCM3 (Gordon et al., 2000). A rigid-lid is used with a formulation which avoids the Killworth instability (Bell et al., 2000, appendix A). It includes a thermodynamic and simple advective sea-ice model. A global version of the FOAM system run each day on a grid with 1° spacing in the horizontal and 20 levels in the vertical. The North Atlantic model (from about 10° N to 70° N) with a 1/9° (12 km) grid and 20 vertical levels is nested within the global model. There is no relaxation to Mediterranean Water Outflow in the North Atlantic model. The nesting is one-way and based on the Flow Relaxation Scheme (Davies, 1983). The bathymetries in the two models in this nesting region are prescribed to be as similar as possible. The bathymetry of the 1/9° model is based on the DBDB2 2″ bathymetry. A separate model with a standard latitude–longitude 1/9° grid-spacing and 20 levels covers the Mediterranean and Black Sea. A 1Sv exchange flow through the Gibraltar straits is imposed. Spin up is 5 months long. Mixed layer parameterization is based on Kraus Turner model. Foam system is forced by six hourly NWP-Met office forcing with a flux formula. A weak relaxation to Levitus sea surface salinity and sea surface temperature is applied at the surface. River runoff is not included. Assimilation method by Lorenc et al. (1991) and Bell et al. (2000) is used. This scheme is a sub-optimal iterative approach to 3-D variational assimilation which allows different groups of observations to be assimilated with relatively few restrictions on the specification of the forecast error covariance. A modified form of the Cooper and Haines (1996) scheme is used as described by Hines (2001). Data assimilation is stopped in coastal areas along isobaths 300 m towards the coast. Along track Jason1/ERS2-Envisat/GFO sea level anomaly is assimilated once a week, as well as 2.5° gridded sea surface temperature from ARGO, along with Thermal profiles above 1000 m before Dec 18 2003. Temperature and Salinity profiles are assimilated at all depths since Dec18 2003. Gridded sea-ice concentration from CMC is also assimilated. In the North Atlantic, the mean sea surface height used in the assimilation process comes from a previous run with Singh and Kelly (1997) climatology in the Gulf Stream region. In the Mediterranean Sea, FOAM uses a mean sea surface height based on a 1 year run with sea surface temperature and temperature profiles assimilation (this is a temporary solution pending access to a more suitable mean sea surface height).

The HYCOM-US system is based on the HYCOM 2.1 hybrid coordinates ocean model with a free surface and (Rho,S) prognostic variables (Bleck, 2002). The hybrid coordinate is one that is isopycnal in the open, stratified ocean, but that makes a dynamically smooth transition (via the layered continuity equation) to a terrain-following coordinate in shallow coastal regions, and to pressure coordinates in the mixed layer and/or unstratified seas. Spin-up is 15 years long. Mixed layer is ruled by KPP mixing (Large et al., 1994). HYCOM-US has a 1/12° horizontal resolution (6.5 km), with 26 vertical hybrid layers. The top layer is always 3 m thick, except in shallow water where the top 15 layers can act like sigma levels. The geographical domain covers the Atlantic and the Mediterranean basin from 28° S to 70° N and 98° W to 36° E. Parameterization of the entrainment of Mediterranean Water is applied at the strait of Gibraltar to better represent Mediterranean Outflow Water. Buffer zones are 3° wide with relaxation to monthly climatological Levitus temperature and salinity. Bathymetry is a quality controlled version of ETOPO 2.5. Three hourly Navy Operational Global Atmospheric Prediction System (NOGAPS) forcing are used with a bulk formula for heat forcing. Freshwater fluxes include a combination of evaporation minus precipitation ($E-P$) and a relaxation to Levitus sea surface salinity. Monthly River runoff is included. Data assimilation is by Optimal Interpolation and vertical projection via Cooper and Haines scheme (1996). Data assimilation is stopped in coastal areas along isobaths 300 m towards the coast. Maps of MODAS (obtained via the NAVOCEANO Altimeter Data Fusion Center) sea level anomaly are assimilated once a week. A relaxation to MODAS sea surface temperature is also applied. HYCOM-US uses a mean sea surface height field based on a previous 1/12° MICOM free run with perpetual ECMWF forcing.

The MERCATOR system has been documented in Drillet et al. (2005). It provides analysis and real-time prediction of three-dimensional ocean conditions in the North Atlantic and Mediterranean basin at high resolution. It produces forecasts up to 7 days ahead. The MERCATOR ocean grid has a 1/15° (5–7 km) horizontal resolution with 43 vertical levels with layer thicknesses from 6 m at the surface to 200 m at the bottom of the Mediterranean basin and 300 m at the bottom of the Atlantic Ocean. The bathymetry is processed from the Smith and Sandwell (1997) data base. The ocean code is based on the 8.1 version of the OPA *z*-coordinates code (Madec et al., 1998), with a rigid lid. It includes diagnostic ice model, i.e. atmospheric fluxes are set to zero and there is a relaxation to freezing temperature and sea surface salinity in the case of sea ice. Mixed layer dynamic is ruled by the TKE turbulent closure scheme (Blanke and Delecluse, 1993). Geographical domain covers the Atlantic and the Mediterranean basins from 10° N to 70° N, with gradual buffer zones in the 65–70° N and 10–15° N latitude bands, where relaxation to Reynaud et al. (1998) seasonal climatology occurs. A relaxation to seasonal Medatlas (2002) climatology is also applied below 500 m in the Gulf of Cadiz to better represent Mediterranean Outflow Water. Momentum and heat forcing are daily ECMWF forcing. A weak relaxation to daily Reynolds sea surface temperature (Reynolds and Smith, 1994) and seasonal Reynaud et al. (1998) sea surface salinity is applied at the surface. River runoff are monthly and from UNESCO GRDB. A 2 weeks spin-up was performed before switching to assimilative operational model. Data assimilation method is a reduced order optimal called SOFA (Sub Optimal Filtering of Altimetry) (De Mey and Benkiran, 2001). The baroclinic component is corrected applying a lifting–lowering method similar to Cooper and Haines method (1996). Data assimilation is stopped in coastal areas along isobaths 500 m towards the coast. Sea level anomaly from Jason1/Envisat/GFO is assimilated along track, once a week. The mean sea surface height used during the assimilation process is based on gravity, altimetry and in-situ observations (Rio and Hernandez, 2004) in the Atlantic ocean. In the Mediterranean basin, the mean sea surface height is built up from several previous numerical simulations.

The MFS system components have been implemented during the EU funded MFSPP project (IV FP-1998–2001) while the system is now being upgraded through the ongoing MFSTEP (VFP-2003–2006) project. Full information about MFSPP can be found in the special volume of Annales Geophysicae dedicated to MFSPP (Volume 21, 2003). It is based on the Modular Ocean Model code MOM 1.0 *z*-coordinates ocean model with a rigid lid. MFS ocean system has a 1/8° horizontal resolution with 31 vertical levels. It produces daily forecasts up to 10 days ahead. Vertical mixing is considered to be constant and convective adjustment is used to rapidly mix the waters. The input data for bathymetry have been taken from the 1/60° US Geological Survey gridded bathymetry. Spin-up initial state is built up from a 7 years long run with perpetual climatological forcing, followed up by a 2.5 years run with six hourly ECMWF forcing. Transport through Gibraltar strait is parameterized thanks to a 3°×3° Atlantic box that expands 3° west of Gibraltar to dump the outflow and impose the inflow, with surface forcing switched off and temperature and salinity relaxed to annual mean climatology. MFS system is forced by six hourly ECMWF forcing with a bulk formulae for momentum and heat. Surface salinity is relaxed to monthly mean climatology and no freshwater water river runoff is added. Assimilation method is the SOFA (Sub Optimal Filtering of Altimetry) optimal interpolation method (De Mey and Benkiran, 2001). Along track sea level anomaly from Jason1/ERS2-Envisat/GFO is assimilated once a week sea surface temperature weekly mean maps at 1/8°×1/8° resolution special analysis, as well as vertical temperature profiles to 500 m depth are also assimilated (Demirov et al., 2003). The multivariate error covariance vertical EOF are different for the sea level anomaly and the thermal profile assimilation, thus optimizing the information content in the different data sets. Data assimilation is stopped in coastal areas along isobaths 1000 m towards the coast. Mean sea surface height used in the assimilation process is coming from a previous run with 1993–1999 forcing.

The TOPAZ system (Bertino and Evensen, 2002) is being developed and maintained by the Nansen Environmental and Remote Sensing Centre in Bergen, Norway. The TOPAZ operational system was developed in the EU-funded TOPAZ project, which is a continuation of the lessons learned in an earlier EU project, DIADEM (Brusdal et al., 2003). It is based on the HYCOM hybrid coordinates ocean model version 1.0 (Bleck, 2002) with a free surface with bathymetry taken from ETOPO5. It advects ocean temperature and salinity, while density is diagnosed. It includes a complete dynamic and thermodynamic ice model. The sea-ice model uses the EVP rheology (Hunke and Dukowicz, 1997) and a thermodynamic formulation by Drange and Simonsen (1996). The sea-ice model includes a snow layer, and has a varying surface albedo, depending on the surface substance and on melting/freezing conditions. Spin-up initial state is coming from a 27 years low resolution simulation. The model uses the KPP scheme (Large et al., 1994) to specify surface boundary layer and interior diapycnal mixing. Topaz system horizontal resolution ranges from 20 to 30 km, with 22 vertical hybrid layers. The geographical domain covers the Arctic Ocean to the southern ocean at 60° S and does not include the Mediterranean basin. Presently there is no boundary relaxation or transport prescribed at the edges of the physical domain (South Atlantic, Bering Strait, Gibraltar and Kattegat). Six hourly ECMWF forcing are used, with bulk formula for momentum and heat. Bulk formulae have different parameterizations depending on the marine interface

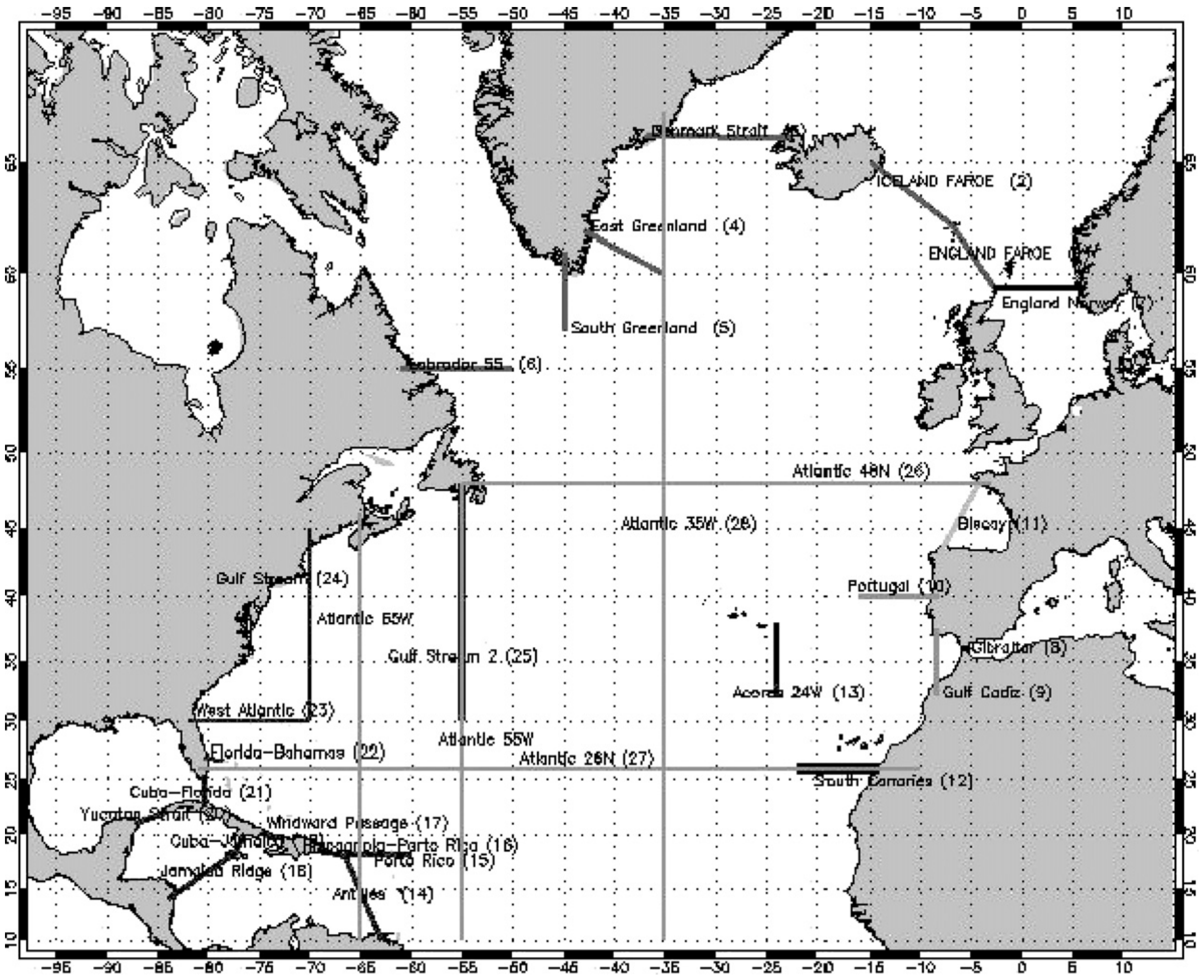

Fig. 1. Class2 sections in the North Atlantic ocean.

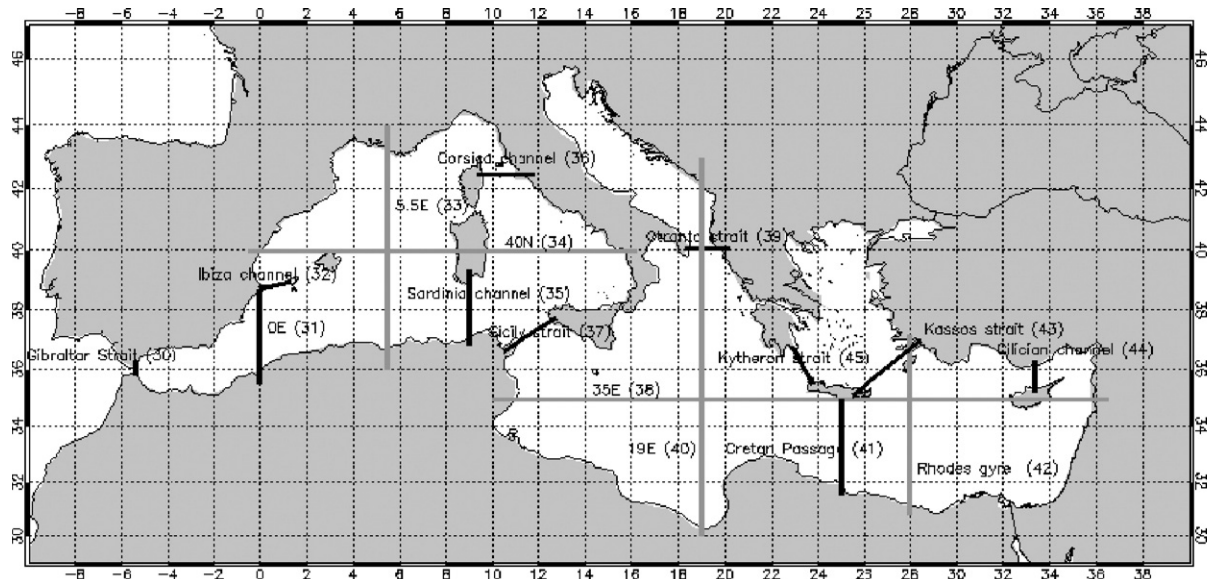

Fig. 2. Class2 sections in the Mediterranean Sea.

(snow/ice or ocean). Freshwater fluxes are prescribed from the Legates and Wilmott (1990) precipitation climatology in addition to a weak relaxation to Levitus sea surface salinity. River runoff is not included. Data assimilation is done by the Ensemble Kalman filter method (Evensen, 1994) which uses an ensemble of model states to calculate statistics for the analysis. The assimilation also affects both the sea-ice and ocean model, which is important for the assimilation of sea-ice concentration (Lisæter et al., 2003). Data assimilation is stopped in coastal areas along isobaths 300 m towards the coast. Maps of sea level anomaly from SALTO-DUACS are assimilated once a week. Sea surface temperature from CLS AVHRR, as well as maps of sea-ice concentration (Svendsen et al., 1983). The mean sea surface height used during the assimilation process is the one from a previous OCCAM run in the Atlantic Ocean.

3. Definition of a common grid and work environment

An inter-comparison exercise requires equivalent quantities extracted out of the different systems for the same geographic locations. It also requires for example the computation of the difference of a given quantity from 2 different systems. As all the systems use different vertical coordinates with different vertical resolution, as they all cover different geographical domains with different horizontal resolution, a common horizontal and vertical grid called the *MERSEA grid* has been defined over a given geographical domain. All the systems interpolate their outputs on the MERSEA grid with a horizontal resolution of 1/8° and a vertical resolution with 8 vertical levels (at 5, 30, 50, 100, 200, 500, 1000 and 2000 m) in the Mediterranean basin and 12 (at 5, 30, 50, 100, 200, 400, 700, 1000, 1500, 2000, 2500 and 3000 m) in the North Atlantic. The common geographical domain extends from 10° N to 68° N for the North Atlantic and covers the whole Mediterranean Sea excluding the Black Sea from 6° W eastward. Outputs fields with a common Netcdf format are delivered through each system's *OPeNDAP server* which URL addresses follow (Password and user name are available upon request):

http://www.nerc-essc.ac.uk:9090/thredds/dodsC/ for FOAM
http://hycom.rsmas.miami.edu/thredds/dodsC/ for HYCOM-US
http://user:password@opendap2.mercator-ocean.fr/dodsC/ for MERCATOR
http://thredds.sincem.unibo.it:8080/thredds/dodsC/ for MFS
http://topaz.nersc.no/thredds/catalog.html for TOPAZ

The inter-comparison exercise runs over a 1 year period from June 1st, 2003 to June 1st, 2004. The inter-comparison exercise for the North Atlantic Ocean will consider FOAM, HYCOM-US, MERCATOR and TOPAZ systems when the Mediterranean exercise will compare FOAM, MERCATOR and MFS systems.

4. Definition of metrics

In order to compare the same exact quantities from each system, a standard set of diagnostics, called metrics, is defined. Such metrics definition aims at systematically assessing the quality, consistency and performance of each system (Le Provost, 2002), whereby:

- 'Consistency' means that operational systems outputs have to be consistent with the current knowledge of the ocean circulation and climatologies.
- 'Quality' means that operational systems outputs have to be in agreement with independent observations (i.e. not assimilated).
- 'Performance' means that metrics should quantify the capacity of each system to provide accurate short term forecast.

Following those criteria, the metric is sorted into different classes: Class1, 2, 3 and 4 which allow testing of the consistency and quality of the systems. Definitions for the North Atlantic and Mediterranean basins are summarized below. Complementary metrics are currently being defined in the context of GODAE for the Pacific Ocean (Masa Kamachi, personal communication), the Arctic and Antarctic Oceans with metrics for the ice (Gilles Garric, personal communication) and the Indian and Southern Oceans (Peter Oke and Gary Brassington, personal communication). Class1 to 3 diagnostics are provided on a real time basis by all teams through their OPeNDAP server for the daily mean (or snapshots for HYCOM-US) best estimates fields (the best estimate corresponds to the best field that each system can produce, i.e. a hindcast or nowcast), as well as for the sixth day forecast.

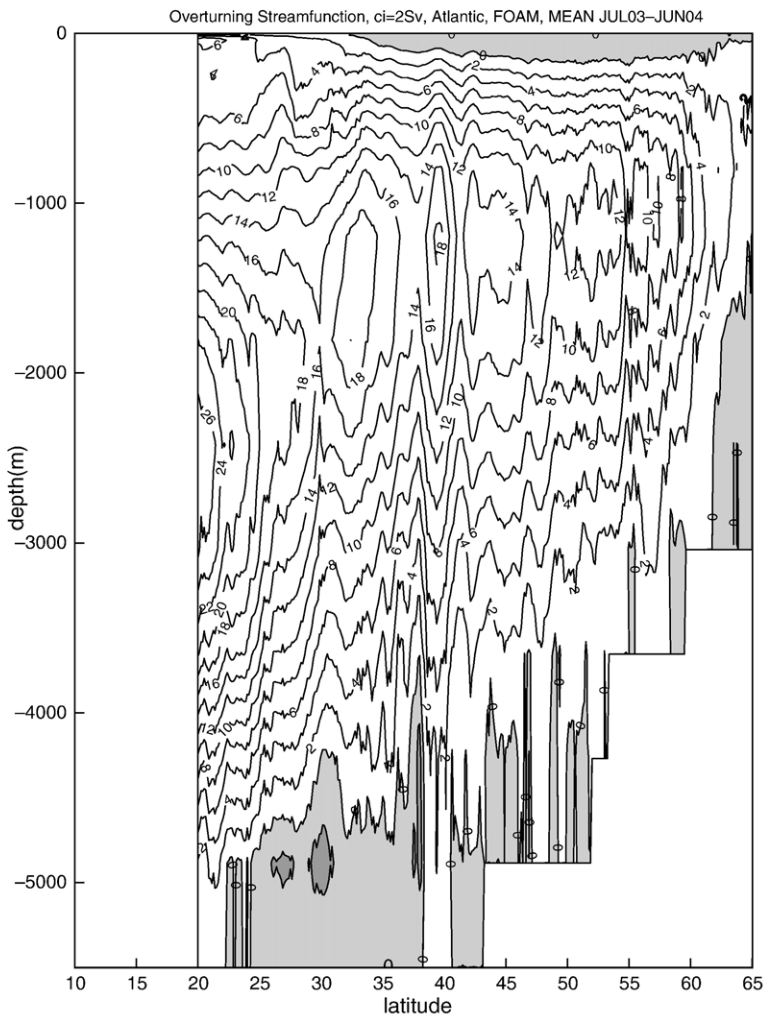

Fig. 3. Class3 annual mean Overturning Streamfunction (Sv) in the North Atlantic in FOAM.

Class1 diagnostics gathers 2-D and 3-D fields interpolated on the MERSEA grid. Two dimensions fields are the zonal and meridional wind stress (Pa), the total net heat flux including relaxation term (W/m^2), the freshwater flux including relaxation term (kg/m^2/s), the barotropic streamfunction (Sverdrup = 10^{6}m^3/s), the mixed layer depth (m). Two kinds of mixed layer depth diagnostics are provided in the Atlantic basin: the mixed layer depth as a function of the potential temperature referenced to the surface with a 1 °C criteria, and the mixed layer depth as a function of the potential density referenced to the surface with a 0.05 kg/m^3 criteria. In the Mediterranean Sea, the mixed layer depth as a function of potential density referenced to the surface with a 0.011 kg/m^3 criteria, is provided. Other 2-D Class1 diagnostics are the sea level anomaly (m) and the mean sea surface height (m) used as a reference during the assimilation procedure. Three dimensions fields are potential temperature (°C), salinity (psu), zonal and meridional velocity fields (m/s). Moreover, the potential temperature (°C) and salinity (psu) fields from Reynaud et al. (1998) and Levitus (1998) climatologies in the Atlantic and from Medatlas (2002) climatology in the Mediterranean basin are provided as a reference.

Class2 diagnostics are potential temperature (°C), salinity (psu), zonal and meridional velocity fields (m/s)

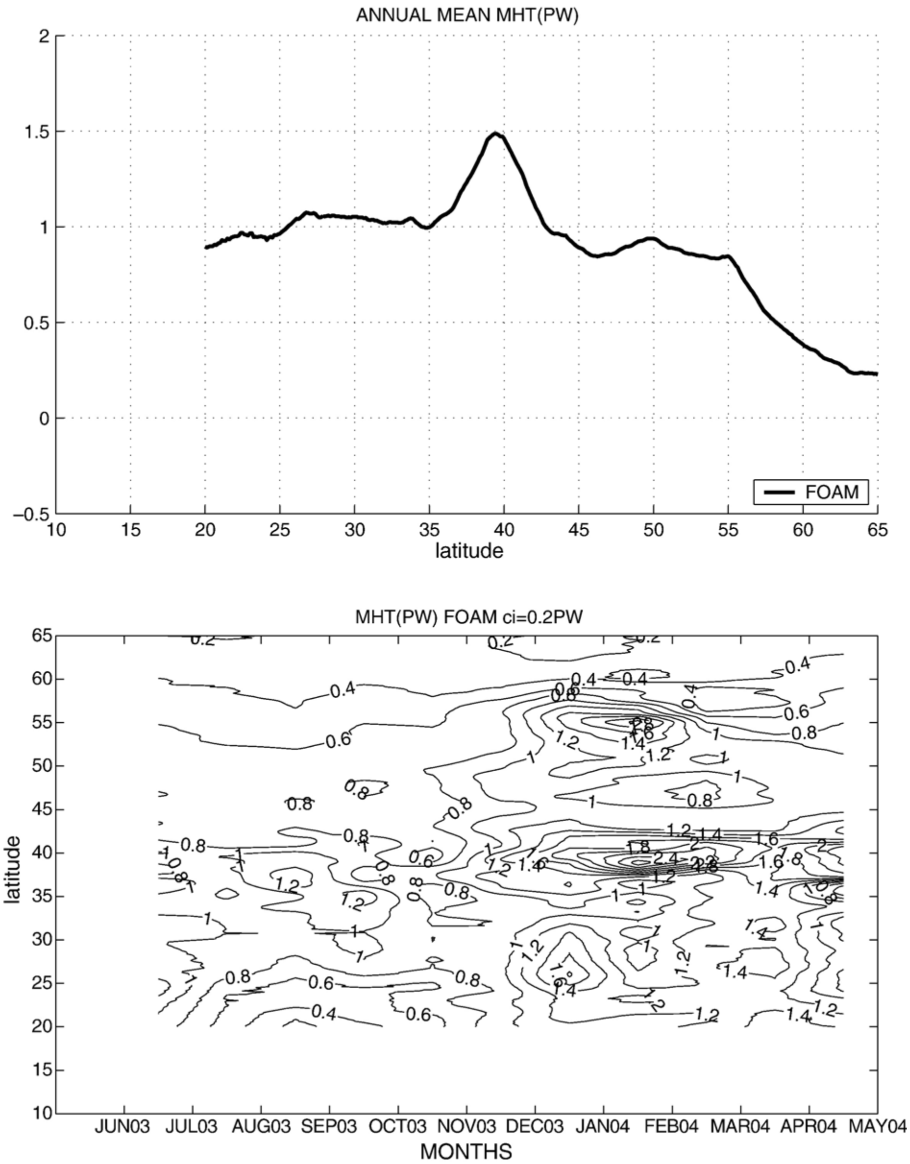

Fig. 4. Class3 annual mean North Atlantic Meridional Heat Transport (pW) (top panel) and its seasonal cycle (bottom panel) in FOAM.

interpolated on high 10 km resolution vertical sections (Figs. 1 and 2) and at moorings locations. Some of the chosen tracks coincide with oceanographic cruises or ship of opportunity tracks.

Class3 diagnostics are integrated quantities (integration done on the original grid) such as daily volume transport (in Sv) through chosen sections (Figs. 1 and 2). Depending on the section considered, one has to provide the total volume transport or the volume transport per defined potential temperature classes or density classes. Class3 diagnostics also include meridional heat transport ($PW = 10^{15}W$) and overturning streamfunction ($10^6 m^3/s$) as a function of latitude and depth (m) or potential temperature (°C) or potential density (kg/m^3).

Class4 metrics are the root mean square statistics in the model and observation space to assess data assimilation performance and forecast skill. They are not available for this paper and will not be further discussed.

5. Examples of Class3 metrics

In this section, we give examples of metrics, starting with the Class3 as it includes two of the most important diagnostics, i.e. the overturning streamfunction and the meridional heat transport. Class3 metrics provide test on the consistency and quality of the systems. Next two sections will provide examples for Class1 and 2 metrics.

Modifications of the ocean model resulting from the data assimilation process are not necessarily dynamically consistent with such a model, usually implying sinks or sources of heat and freshwater. Operational systems are thus usually not heat conservative and could be drifting away from realistic temperature and salinity characteristics. The overturning streamfunction characterizes the thermohaline circulation established in response to external forcings (winds, heat and freshwater fluxes) and to the water masses conservation taking place in the buffer zones. The large scale overturning is

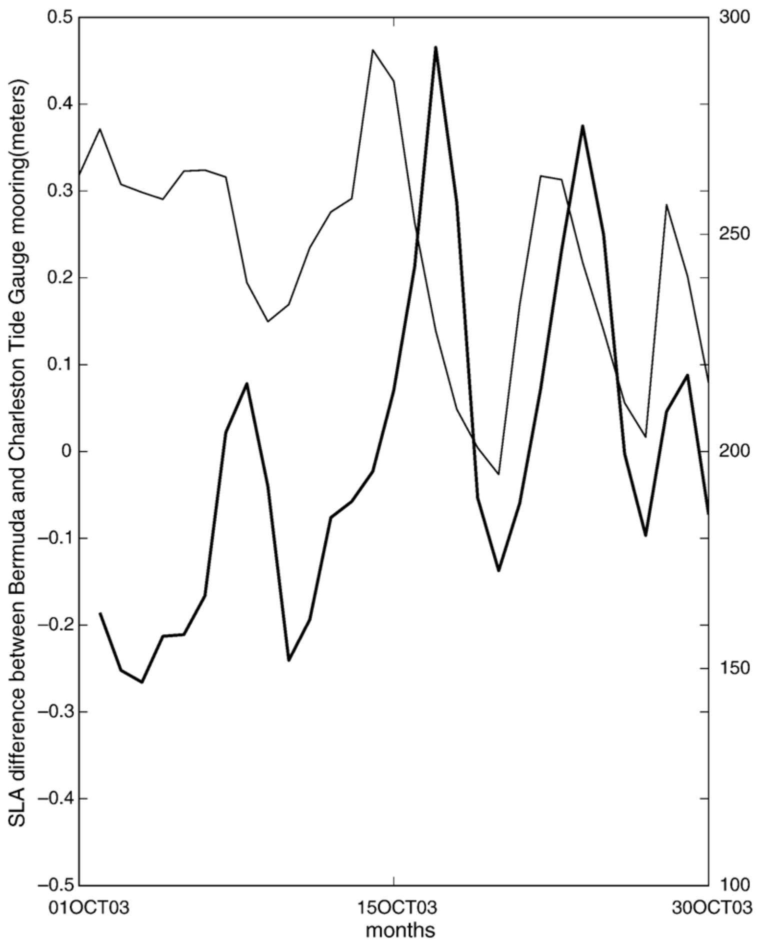

Fig. 5. Class3 Volume transports (Sv) across Section 23 in MERCATOR (scale on the right *Y* axis, units = Sverdrup) correlated with tide gauge Sea Level Anomaly difference between Bermuda and Charleston stations (scale on the left *Y* axis, units = meters) in October 2003.

not directly observable, but an annual mean maximum overturning from 16 to 20 Sv between 30° N and 40° N in the depth range 1000 m to 1500 m seems consistent with the estimates of the corresponding heat transport. Models usually exhibit a deep reverse cell which is traditionally attributed to the penetration of Antarctic Bottom Water in the North Atlantic. The meridional heat transport is strongly linked to the overturning cell and mostly reflects the North Atlantic Deep Water overturning cell behaviour: the stronger the North Atlantic Deep Water cell, the stronger the northward heat transport. The canonical value is 1.2+/−0.3 PW at 24° N, computed from direct oceanographic observations by Hall and Bryden (1982) and Macdonald and Wunsch (1996). The seasonal cycle of the heat transport usually experiences a weakening or a reverse of the northward heat transport around 8° N during boreal summer (Philander and Pacanowski, 1986a,b). The overturning streamfunction and meridional heat transport Class3 diagnostics provide a significant index of the thermodynamic behaviour of the model.

In the FOAM system, the annual mean overturning cell as well as the annual mean and seasonal heat transport are shown in (Figs. 3 and 4) respectively. Meridional heat transport and overturning cell between 10 and 20° N is not available in FOAM because of the boundary layer located between 10–20° N. FOAM overturning streamfuction displays a realistic 18Sv maximum for the North Atlantic Deep Water cell in the 1000–2000 m depth range centred at 32° N as well as a realistic Antarctic Bottom Water. An unrealistic feature is seen in the 20–28° N latitude range with a strong

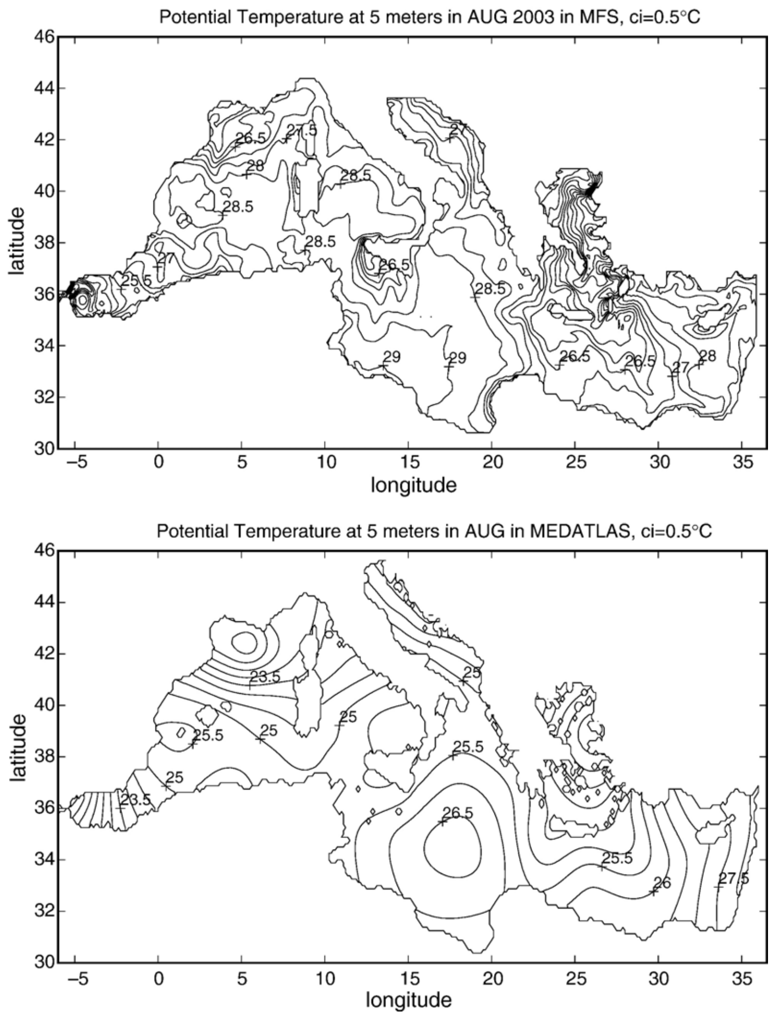

Fig. 6. Class1 August 2003 mean surface potential temperature in the Mediterranean Sea (°C) in MFS (top panel) and Medatlas climatology (2002) (bottom panel).

positive cell of 26 Sv due to the 10–20°N boundary layer. The annual mean heat transport lay within observed range (Mcdonald and Wunsch, 1996) with 1 PW at 24° N. We notice a weakening of the heat transport on a seasonal scale during boreal summer at 20° N (Philander and Pacanowski, 1986a,b; Böning and Herrmann, 1994) due to the weakening of the trade winds. Anomalous strong overturning cell and heat transport are seen at 38° N and 55° N due to erroneous vertical salinity profiles assimilated. Local modifications of the ocean model resulting from assimilation of wrong salinity profiles are shown not to be dynamically consistent with such a model, and imply internal sinks or sources of heat. The quality control before assimilation of vertical profiles has since then been improved in the FOAM system and now avoid assimilating such erroneous vertical profiles. We have here an example on the difficulty to perform an efficient quality control on the data being assimilated, and an example of the consequences such assimilation of wrong salinity profiles can have.

Volume transports through particular sections, part of the Class3 metrics, are major indicators of the realism of the outputs of a system. For example, the water flowing through the Florida Strait comes from the different Caribbean straits through the Yucatan Channel: the Windward Passage between Cuba and Haiti, the Canal de la Mona, between Hispaniola and Puerto Rico, and the many different passage of the Leeward Islands and the Windward Islands. The knowledge of the flow distribution through these passages appears as a significant test for the North Atlantic model simulations (Böning et al., 1991; Maltrub et al., 1998). Tide gauge sea level anomaly time series from the University of Hawaii Sea Level Center (Fast Mode data base) (Kilonsky et al., 1999) can also be used to validate the realism of operational forecast system. We consider here 2 tide gauge moorings, the Bermuda and Charleston stations, located respectively at (32.37° N–64.7° W) and (32.78° N–79.93° W). An Inverse barometer contribution to the sea level gauge sea level anomaly is removed. The inverse barometer contribution is determined using daily maps from the MOG2-D model (Carrere and Lyard, 2003). The tide gauge hourly values were detided using a 3 day Demerliac filter. In Fig. 5, we compare the volume transport variability across the zonal section at 30°N (see Fig. 1 for the track location of Section 23) in October 2003 from the MERCATOR system to sea level anomaly differences from tide gauge moorings. The sea level anomaly difference between the Bermuda and Charleston stations (respectively located at the eastern and western extremity of Section 23 track) is proportional to the geostrophic volume transport across those 2 stations (Fig. 5, bold solid line). It is highly correlated to the volume transport computed from Section 23 from the MERCATOR system (Fig. 5, solid line) during the month of October 2003, although with a few days lag, showing the realism of the variability of the MERCATOR system in this area.

6. Examples of Class1 metrics

In this section, we provide examples of Class1 metrics which allow to test the consistency and quality of the

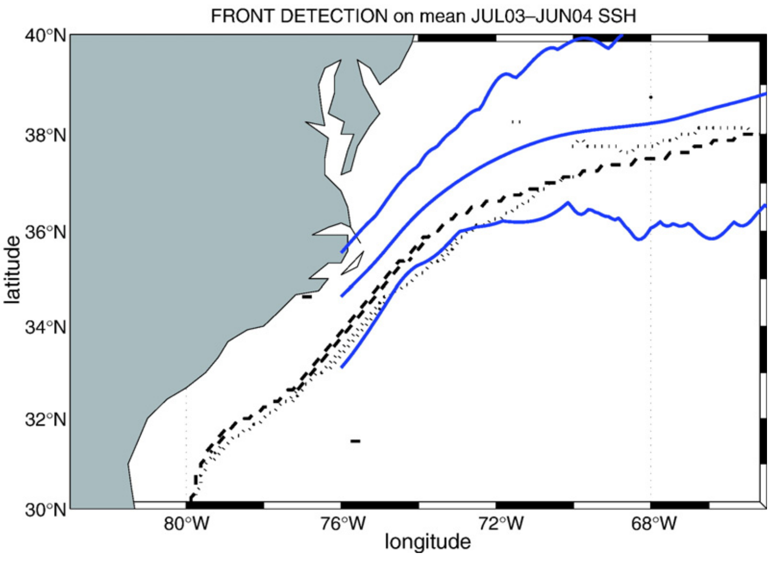

Fig. 7. Class1 Gulf Stream Path computed from the annual mean sea surface height (SSH) in HYCOM-US (black dashed line), MERCATOR (black dotted line) using Le Provost and Bremond (2003) algorithm, and from observations (bold black lines for the mean, north and south envelope).

systems. We provide a few examples of Class1 metrics chosen as the most illustrative. This is not an exhaustive list and many other diagnostics could be shown.

Monthly mean values of the best estimates Class1 fields have been computed at all depths in the North Atlantic and Mediterranean Sea. The comparison of the monthly mean Class1 fields with available climatologies put in light problems in the various systems. Such tests have been used in recent inter-comparison experiments such as DYNAMO (Meincke et al., 2001) and DAMEE (Chassignet and Malanotte-Rizzoli, 2000). We would like to point out here the role of Class1 metrics in showing specific problems in a given system on a real time basis and in triggering off fast reaction and correction of the problem by the system team. We give here two examples. For instance, Fig. 6 shows the mean AUGUST 2003 potential temperature at 5 m in the Mediterranean basin in MFS system and Medatlas (2002) climatology. One can note the warmer than climatology surface Mediterranean temperature during the heat wave event last summer 2003 up to 29 °C in the Ionian Sea. Noticing that such warming was less clear in the MERCATOR system (not shown), the MERCATOR team has since then modified the vertical diffusivity of its Mediterranean system in order to allow a stronger vertical stratification in case of large summer heating. Another example takes place in the North Atlantic basin in the FOAM system at 2000 m depth where anomalous salinity were found and were originating from assimilation of wrong salinity vertical profiles.

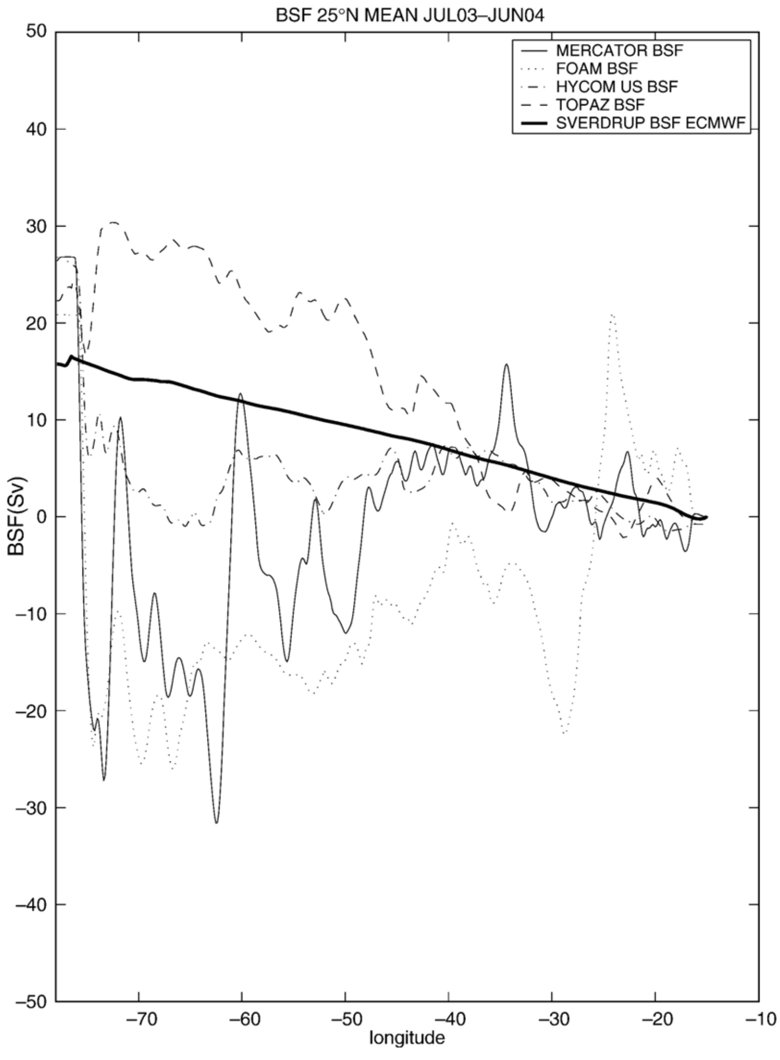

Fig. 8. Class1 annual mean Barotropic Streamfunction (Sv) and Sverdrup Barotropic Streamfunction (Sv) (bold solid line) at 25° N in the North Atlantic in the FOAM (dotted line), HYCOM-US (dashed dotted line), MERCATOR (light solid line) and TOPAZ (dashed line) systems.

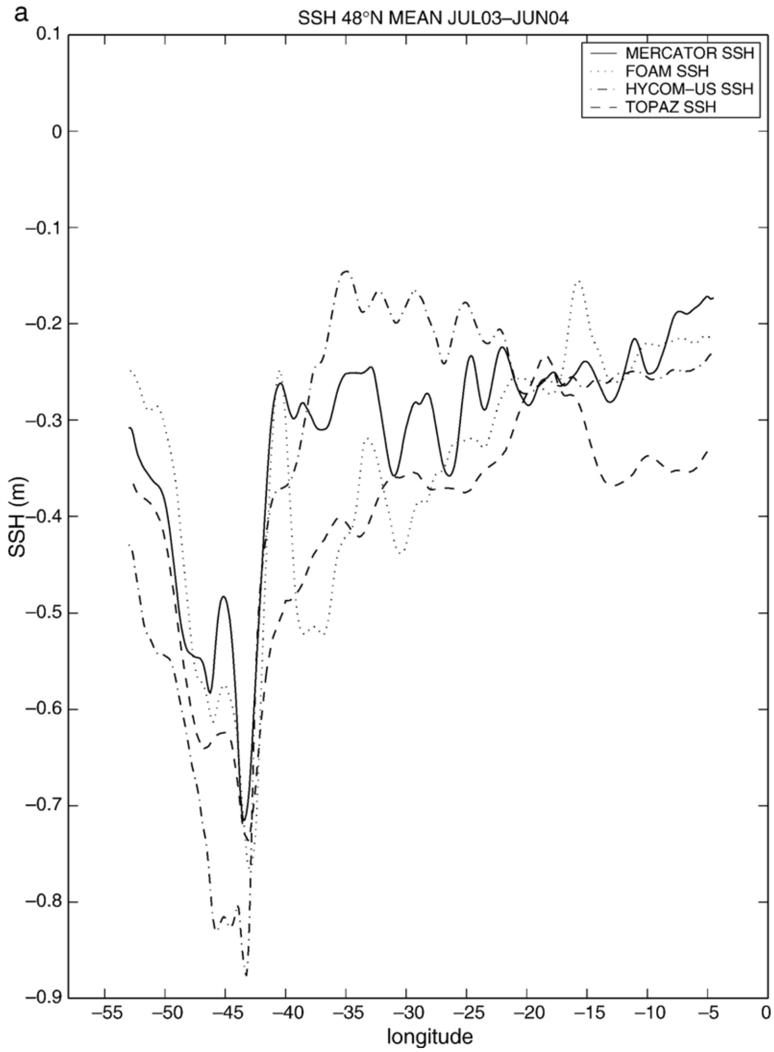

Fig. 9. Class1 annual mean sea surface height (SSH) (meter) (top panel) and mean sea surface height (MSSH) (meter) (bottom panel) at 48° N in the North Atlantic in the FOAM (dotted line), HYCOM-US (dashed dotted line), MERCATOR (solid line) and TOPAZ (dashed line) systems.

At 3000 and 2000 m depth in the North Atlantic and Mediterranean basins respectively, monthly mean potential temperature and salinity characteristics in system with long spin-up as HYCOM-US, MFS and TOPAZ have drifted away from realistic initial climatological conditions whereas simulations with shorter spin-up as in MERCATOR and FOAM, display deep water masses closer from climatology (not shown). The drift in temperature and salinity at depth because of long spin-up is a well known problem. The choice of the spin-up length is always a compromise between avoiding such a drift, and achieving a stable state for the ocean.

Another diagnostic that can be derived from Class1 metrics is the major currents fronts. The position and characteristic of the major ocean currents are well known from compilation of in situ data and remote sensing observations. Among others are the Gulf Stream, the Gulf Stream extension, the North Atlantic drift, the Azores front, the Brazil current, and many slope currents on the North Atlantic continental shelves. The position of such fronts, not directly accessible from satellite altimetry because of large uncertainties in the knowledge of the geoid at the oceanic scales (Johannessen et al., 2003a), can be deduced from each system's numerical mean sea surface height using Le Provost and Bremond (2003) algorithm. The latter allows one to compute and display front location associated to geostrophic currents. True current position deduced from observations can also be displayed for further inter-comparison. An example for the path of the

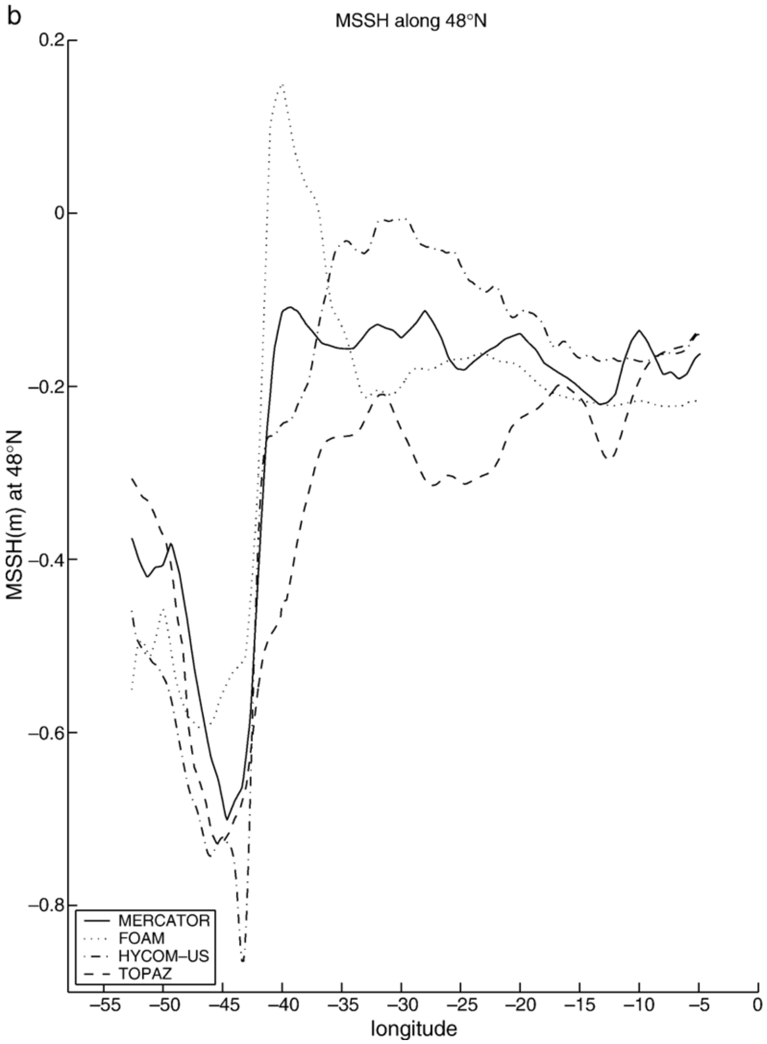

Fig. 9 (*continued*).

Gulf Stream in the HYCOM-US and MERCATOR systems is shown in Fig. 7. The Class1 daily best estimate sea surface height fields have been averaged over the period June 1st 2003–May 31st 2004. Using this annual mean sea surface height fields, the Gulf Stream front location has been computed using the Le Provost and Bremond (2003) algorithm. It can be compared with its mean true position deduced from observations. Both MERCATOR and HYCOM-US front are located too south compared to the mean front deduced from observations, MERCATOR front being the more south one. MERCATOR front is overshooting around 70° W–37° N whereas HYCOM-US front has a more realistic behaviour in this area.

The barotropic streamfunction, also part of the Class1 metrics, characterizes the wind-driven circulation established in response to wind forcing. One year mean flat-bottom Sverdrup barotropic streamfunction has also been computed for each system using the provided Class1 wind stress fields. At 25° N, it is commonly assumed that the vertically integrated transport is governed by a flat-bottom Sverdrup balance at least in the eastern basin. A zonal section at 25° N (Fig. 8) shows that all the models, except FOAM, are following the Sverdrup equilibrium in the eastern basin from 15° W to 45° W. This is not the case in the western basin. The DYNAMO (Willebrand et al., 2001, their Fig. 15) 5 years mean numerical simulations without data assimilation at this latitude showed better agreement in the western basin within models. In the present study, a 1 year mean barotropic streamfunction might not be a long enough mean to compare to the Sverdrup

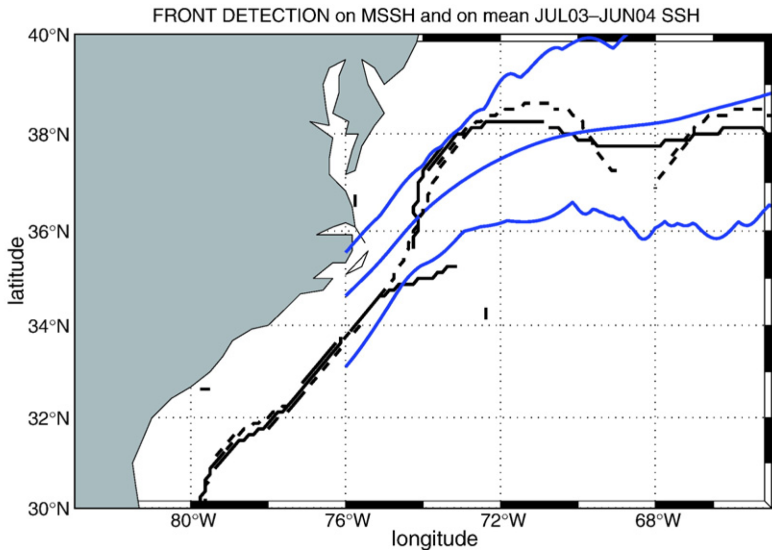

Fig. 10. Class1 Gulf Stream Path computed from the annual mean sea surface height (SSH) (solid black line) and from mean sea surface height used a reference for data assimilation (MSSH) (dashed black line) in TOPAZ using Le Provost and Bremond (2003) algorithm, and from observations (bold black lines for the mean, north and south envelope).

barotropic streamfunction. The HYCOM-US and TOPAZ systems both have a positive barotropic streamfunction in the ocean interior, whereas FOAM has a negative barotropic streamfunction and MERCATOR oscillates between negative and positive values. We notice here that the well defined subtropical and subpolar gyre structure commonly seen in numerical simulation without data assimilation in the North Atlantic (Willebrand et al., 2001) usually fades away in numerical simulation with data assimilation. This needs to be further investigated.

The mean sea surface height used as a reference for the data assimilation process is also provided by each system as a Class1 field. Each system is using different mean sea surface height fields which are described in Section 2. Differences in the mean sea

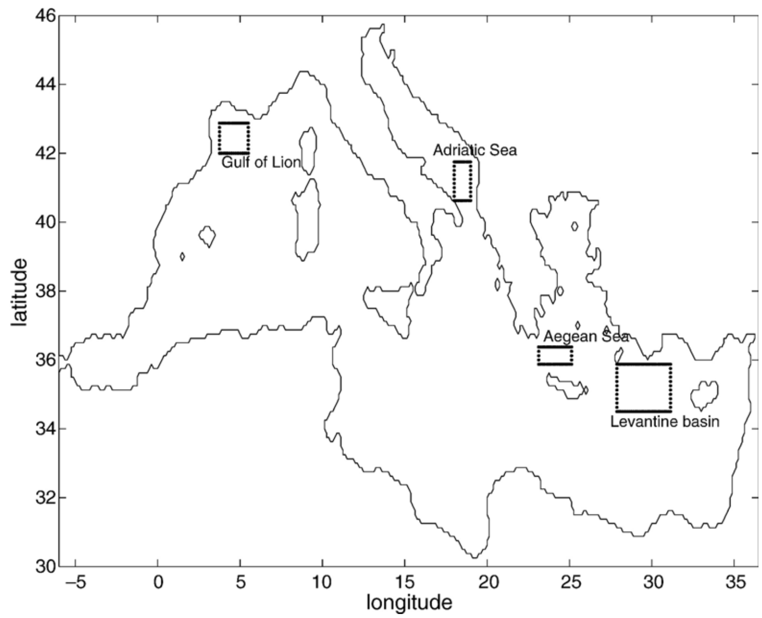

Fig. 11. Four regions chosen for Mixed Layer Depth average in the Mediterranean basin.

surface height fields between the systems can be large is some areas (not shown) and have major influences on the system behaviour (Birol et al., 2004). More generally, there is a strong need for a precise mean sea surface height field in the open ocean and near the shelves and the GOCE mission (Johannessen et al.,

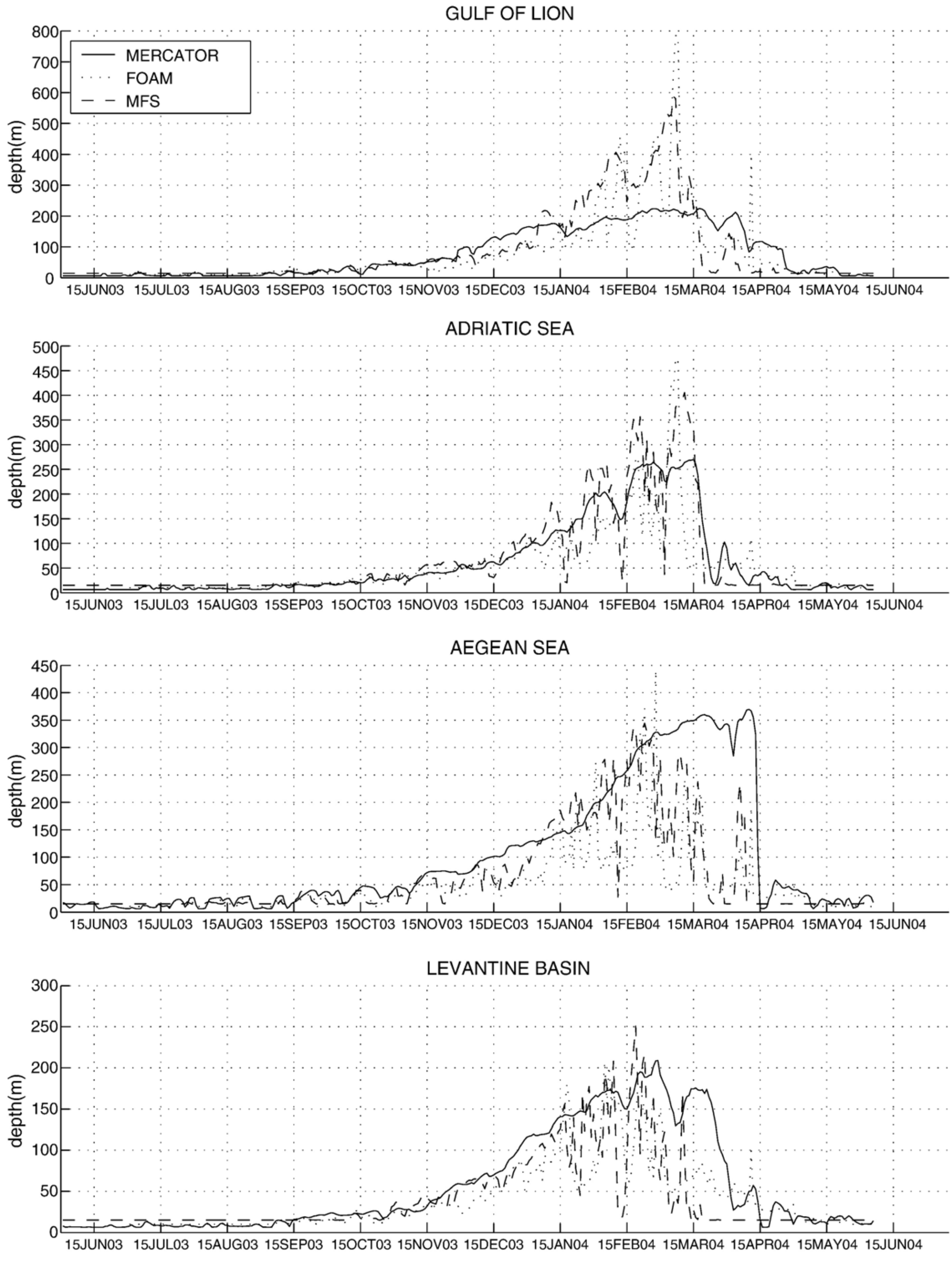

Fig. 12. Class1 Mixed Layer Depth (metres) in the 4 regions (from top to bottom panels: Gulf of Lion, Adratic Sea, Aegean Sea and Levantine Basin) as a function of time in the Mediterranean Sea in the FOAM (dotted line), MERCATOR (solid line) and MFS (dashed line) systems.

2003a) planned for launch in 2006 should bring improvement in this matter.

Class1 metrics also include sea surface height. A zonal section at 48° N of the 1 year mean sea surface height (Fig. 9 top panel) shows in all the systems a realistic North Atlantic Current located at 42° W. FOAM, HYCOM-US and MERCATOR systems show a steep 50 cm sea surface height increase (Fig. 9 top panel) within 200 km around 42° W associated with the North Atlantic Current northward flow, whereas a weaker 30 cm sea surface height increase takes place in the coarser resolution TOPAZ system. All sea surface height increase are weaker than the one seen in the Singh and Kelly (1997) climatology, thus implying in all systems a reduced recirculation on the eastern flank east of 40° W. All four models have a similar sea surface height decrease around 50° W associated with the Labrador Current, although weaker in the MERCATOR sea surface height. A similar figure from the Dynamo project (Willebrand et al., 2001, their Fig. 13) also showed a realistic North Atlantic drift current located at 42° W in all systems except the *Z*-coordinates one which was performing rather poorly in this area. The FOAM and MERCATOR *Z*-coordinates systems with data assimilation both perform well here. This is most likely due to the correct information given from the mean sea surface height (Fig. 9 bottom panel) used as a reference during the assimilation procedure. Killworth et al. (2001) indeed showed that the mean flow of an eddy-permitting model, and especially the North Atlantic Current flow location, can be altered by assimilation of sea surface height variability, providing that the right information about the mean sea surface height is included.

Another example is given in the TOPAZ system where the Gulf Stream path (Fig. 10, dashed line) from the mean sea surface height, computed with the Le Provost and Bremond (2003) algorithm, is overshooting. The same behaviour is noticed in the Gulf Stream path deduced from the 1 year mean TOPAZ sea surface height Class1 field (Fig. 10, solid line). The assimilation of surface height variability in the coarse horizontal resolution TOPAZ system is not able to correct the path of the Gulf Stream, as the information given in the mean sea surface height field used as a reference during assimilation process is incorrect.

Mixed layer depth diagnostics are also part of the Class1 metrics. To illustrate the seasonal cycle of the mixed layer depth in the Mediterranean basin, four regions are chosen: The Gulf of Lion, Adriatic, Aegean Sea and Levantine regions (Fig. 11). In all four regions,

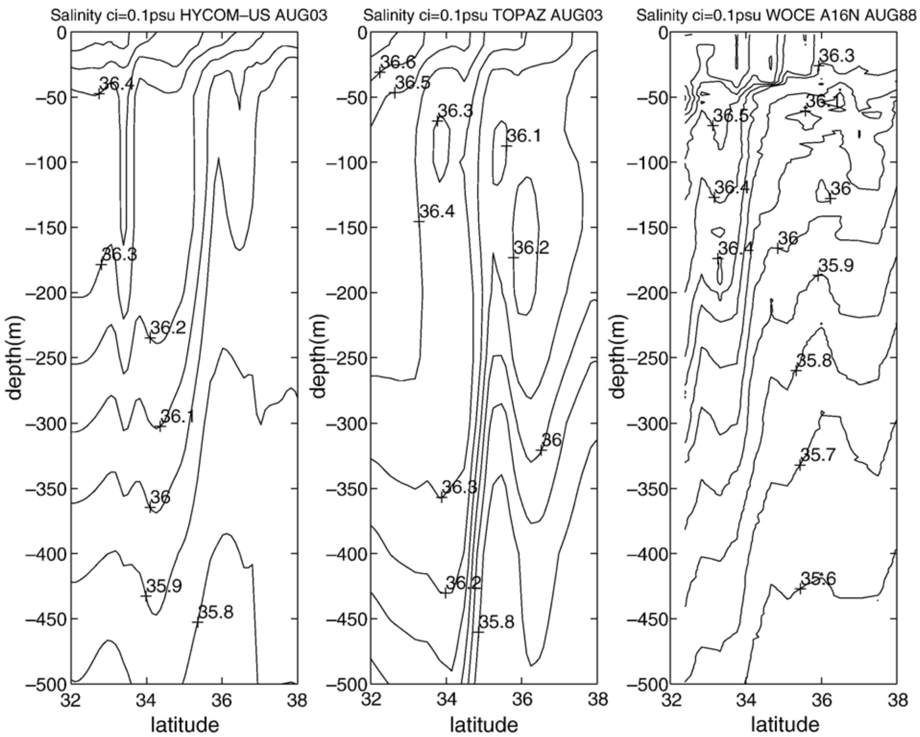

Fig. 13. Class2 Azores salinity (psu) vertical section (Section13 at 24° W) in HYCOM-US in August 2003 (left panel), TOPAZ in August 2003 (middle panel), and WOCE in August 1988 (right panel).

mixed layer depth are shallow during boreal summer and reach their maximum during late boreal winter (Fig. 12). No matter which mixing parameterization the system uses, no matter which forcing fields they use (some using fields from ECMWF, other using NWP-UK-Met-office, some using bulk formulae for heat and/or momentum, some other not), all systems display the same mixed layer seasonal cycle, which reflects the maturity in tuning such mixing parameterization.

7. Examples of Class2 metrics

In this section, we provide a non-exhaustive list of Class2 metrics.

The first vertical Class2 section considered is the Azores section at 24° W (Fig. 1). We compare, when possible, Class2 to historical WOCE synoptic sections. The WOCE program gathered in situ data during the 90 s, time period not synchronous with the MERSEA-strand1 exercise. Nevertheless, the comparison between WOCE and Class2 sections brings relevant insights on the systems water masses characteristics. A WOCE section (A16N, July 23–August 27 1988) (WOCE, 2002) at 20° W close from the 24° W Class2 section in the Azores region, shows Madeira Mode Water (Fig. 13). It is formed north of Madeira in the 16–18 °C range and is indicated by a summer thermostad at 70–150 m depth (Siedler et al., 1987). WOCE salinity section shows such a volume of Madeira Mode Water in the 36.2–36.5 psu salinity range, in the 75–250 m depth interval, as well as HYCOM-US and TOPAZ sections (Fig. 13). MERCATOR and FOAM systems do not show such volume of Madeira Mode Water (not shown). This results from the better ability of the HYCOM-US and TOPAZ Hybrid coordinates ocean models against *Z*-coordinates models for MERCATOR and FOAM at representing water masses characteristics.

This is not true everywhere as seen on the second Class2 section considered along 26° N (Figs. 1 and 14). The Subtropical Under Water (O'Connor et al., 1998) is not well represented in any of the systems. Two WOCE sections at 26° N in 1992 and 1998 (WOCE, 2002) (only one shown) show Subtropical Under Water in the western part of the basin in the longitude range 80° W–50° W, at depths 100 to 300 m, characterized by a salinity maximum up to 36.9 psu. The Subtropical Under Water are a component of the Central Water formed by subduction within the subtropical gyre and are characterized by a high salinity maximum. MERCATOR, TOPAZ, FOAM (without ARGO salinity profiles assimilation, i.e. before December 18 2003) and HYCOM-US systems do not represent well the Subtropical Under Water salinity maximum. FOAM system is assimilating ARGO temperature and salinity profiles at all depths since December 18 2003. FOAM was only assimilating temperature profiles above 1000 m before this date. When looking in the FOAM system at the same 26° N salinity section on December 15 2003 and on December 20 2003 (i.e. before and after the assimilation of ARGO salinity profiles) (Fig. 14), we notice a clear improvement at representing the salinity maximum of the Subtropical Under Water thanks to assimilation of ARGO salinity profiles. ARGO salinity profiles available in the area and period considered (26° N–80° W to 50° W in September 2003) in the depth range 100–300 m are really few (not shown), but sufficient to improve the salinity characteristic from FOAM of 0.2 psu, thus bringing FOAM system closer to observations. Fox and Haines (2003) also showed that

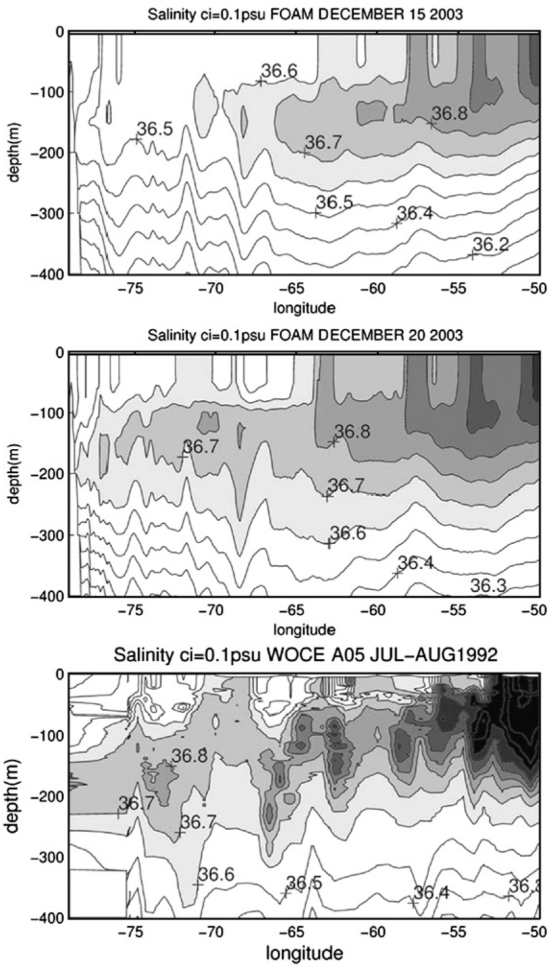

Fig. 14. Class2 salinity (psu) vertical section (Section27 at 26° N) in FOAM on December 15 2003 (top panel), in FOAM on December 20 2003 (middle panel), and WOCE in July–August 1992 (bottom panel).

assimilation of vertical profiles was helping models resolve mode water characteristics. They showed that during a 5 year assimilation experiment with the global OCCAM model, the impact of temperature profile assimilation over the North Atlantic region is largely to compensate for poor air–sea heat fluxes in maintaining water masses such as 18 °C mode waters.

WOCE sections across Denmark Strait (WOCE, 2002) show very cold (down to −1 °C) and fresh (down to 30.5 psu) in the western part of the section associated with the East Greenland Current flowing southward. None of the FOAM, HYCOM-US, MERCATOR, TOPAZ systems are able to display observed water masses characteristics through this section (not shown). They are all warmer and saltier than observations. FOAM and TOPAZ systems have a sea-ice model and assimilate sea-ice concentration, which does not allow here a realistic representation of water masses characteristics in the northern seas. MERCATOR and HYCOM-US systems have a boundary layer where a relaxation to climatology occurs just north of the Denmark Strait section. Relaxation frequency applied and climatology used for relaxation do not enable to simulate realistic temperature and salinity through

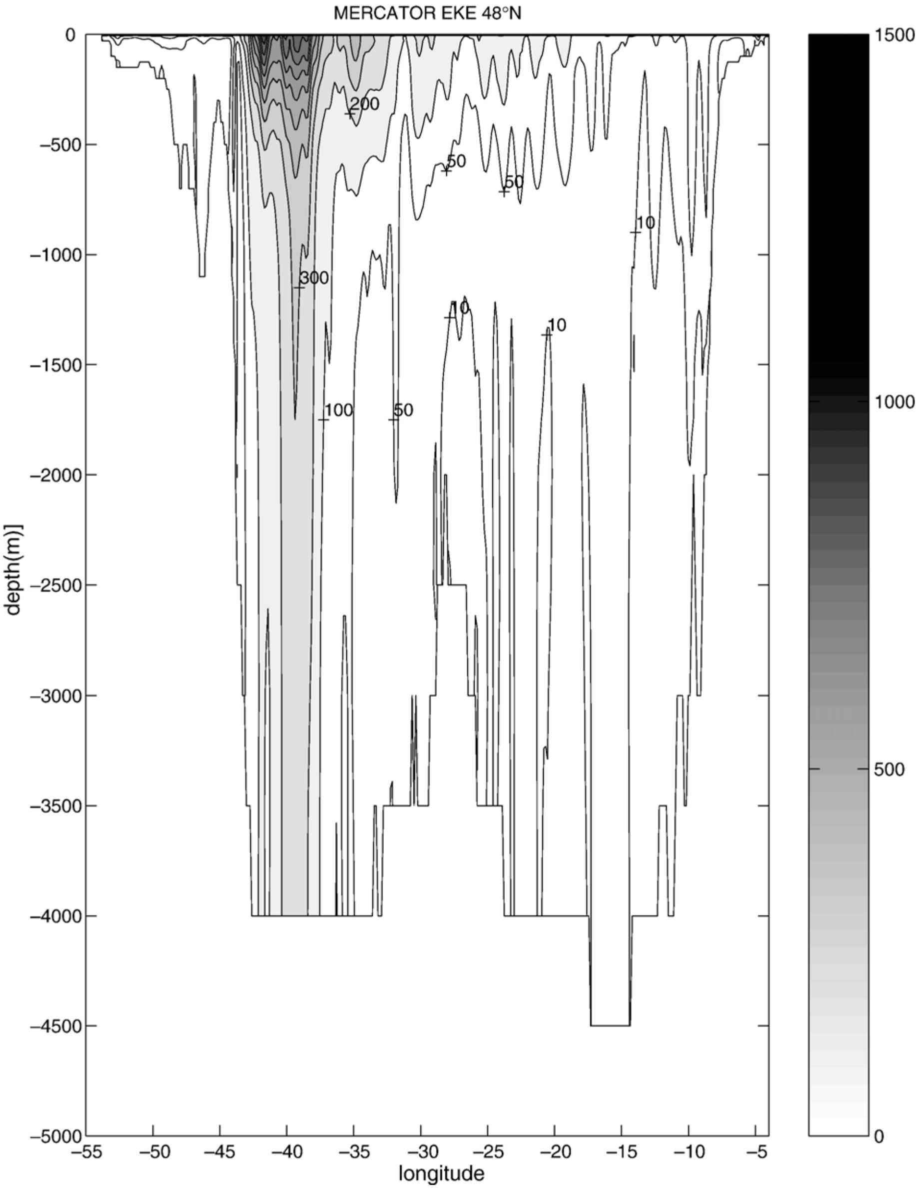

Fig. 15. Eddy Kinetic Energy (cm^2/s^2) at 48° N (Section26) in the MERCATOR system.

Denmark Strait section. This will be further investigated during the MERSEA IP project including the Arctic region.

Another derived Class2 diagnostic is the eddy kinetic energy which can be computed for instance along the 48° N zonal section in the MERCATOR system (Fig. 15) and compared to eddy kinetic energy observations from Colin de Verdière et al. (1989) (Their Fig. 9). In the eastern basin, the MERCATOR eddy kinetic energy is in agreement with observations which show an intensified variability above the main thermocline (100 cm^2/s^2 near the surface, 10 cm^2/s^2 at 1500 m), but a very low variability at depth (below 5 cm^2/s^2). Over the ridge, the variability is greatly reduced both in the observations and in the MERCATOR system. West of the Mid Atlantic Ridge in the longitude range 35° W–27° W, the MERCATOR eddy kinetic energy is in agreement with observations with show the maximum variability ranges from 350 cm^2/s^2 near the surface to 40 cm^2/s^2 in the deep ocean. West of 35° W, observations are no longer available and MERCATOR display a maximum eddy kinetic energy at the surface up to 1000 cm^2/s^2 around 40° W which propagates at depths with eddy kinetic energy up to 200 cm^2/s^2 at 4000 m. The HYCOM-US and FOAM systems also display high eddy kinetic energy magnitude (from 100 to 200 cm^2/s^2) at 4000 m around longitude 40° W.

Class2 metrics also bring information on the vertical structure of currents, and for example the North Atlantic Deep Water below the Gulf Stream. To a large extent, the southward branch of the thermohaline circulation occurs through narrow western boundary current. Observations

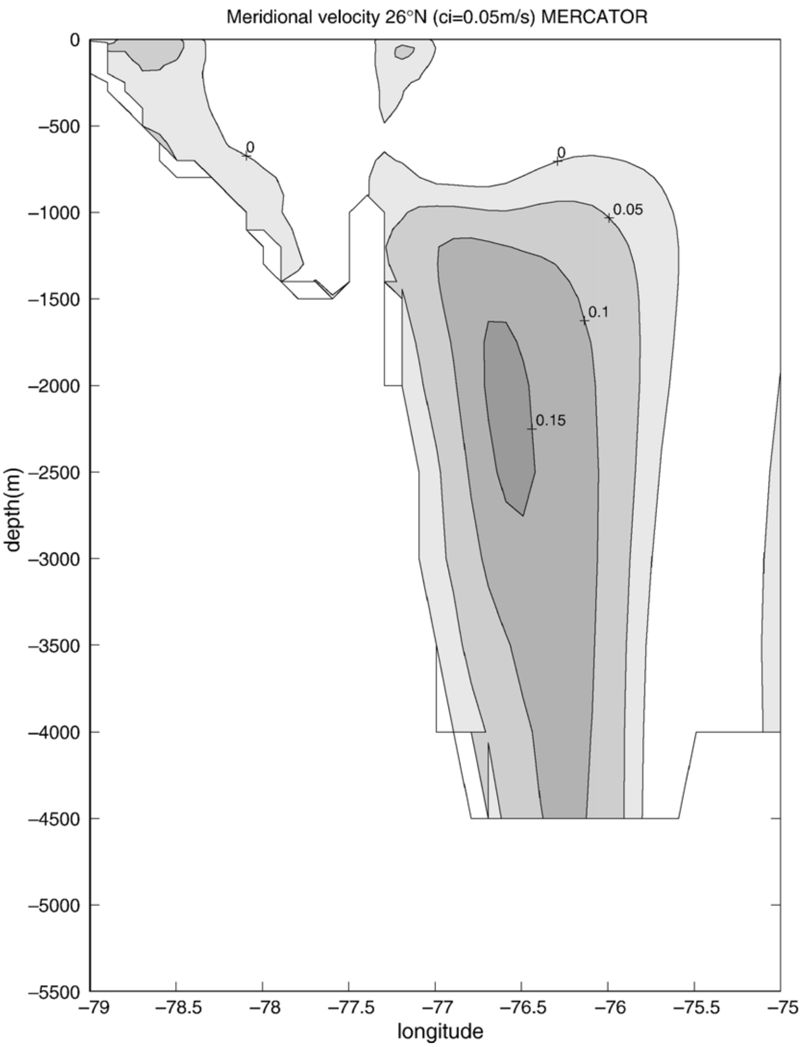

Fig. 16. Class2 annual mean meridional velocity (m/s) vertical section (section at 26° N) in MERCATOR.

by Lee, Johns, Zantopp and Fillenbaum (1996) show that there is a deep western boundary current within less than 50 km of the continental shelf, that reaches maximum velocities of 15 cm/s below 2000 m depth. Vertical sections of the meridional velocity at 27° N obtained in the DYNAMO experiments (Willebrand et al., 2001, their Fig. 7) showed a clear deep western boundary current core within 100 km of the coast in the 3 models considered. The same section is shown here in the MERCATOR system (Fig. 16) and shows a well defined deep western boundary current core with maximum southward velocities reaching 15 cm/s in agreement with observations.

8. Discussion and conclusion

The delivery of the forecast system's outputs through OPeNDAP servers has been convenient for the inter-comparison exercise as fields are easily available remotely in near real time in a common standard format.

Class1, 2 and 3 metrics are a set of standard diagnostics which have been agreed and applied in 5 forecast systems. They allow to assess the consistency (i.e. whether the system is consistent with current knowledge of the ocean) as well as quality (i.e. whether the system compares well to independant observations) of each operational system.

Class1 metrics diagnostics, both in the Mediterranean and Atlantic basins, raised the question of the simulation spin-up length as long spin-up end up with deep water masses characteristics that have drifted away from realistic initial conditions. Class1 diagnostics also showed large differences between mean sea surface height used by the systems as a reference in the assimilation process, using mean sea surface height either diagnosed from in-situ observations or from numerical sea surface height. There is a strong need for a precise mean sea surface height in the open ocean and near the shelves. GOCE mission should partly solve the problem. Class1 diagnostics also showed a similar seasonal cycle of the mixed layer depth in the systems, each using different mixed layer parameterisation.

Class2 diagnostics pointed out that models fail at representing well Central Water as the Subtropical Under Water characterized by high salinity properties, because models fail at representing the air–sea fluxes which maintain the Mode Water formation. All models are able to resolve well such water masses as soon as they assimilate temperature and salinity Argo profiles. Assimilation of temperature and salinity profiles is thus a key feature to help systems better represent water masses characteristics at all depths, especially in the upper 2000 m where most of the Argo profiles are available. There is a need for more temperature and salinity Argo profiles, in order to have a better horizontal and vertical coverage of the Atlantic, Mediterranean and global ocean basins. So far, only FOAM and MFS systems are assimilating vertical Argo profiles (FOAM is assimilating temperature and salinity profiles, and MFS is assimilating temperature profiles only). MERCATOR, in another system than the one involved in the MERSEA-Strand1 inter-comparison exercise, is running a 1/15° system with assimilation of temperature and salinity Argo profiles. Improvement in data assimilation techniques are needed for a better use of all observation data. Class2 metrics will be used to monitor and identify systematic differences and tendencies relative to observations, as the MERSEA project is working on distributing real time data sets such as a 3-D objective analysis of temperature and salinity, high resolution sea surface temperature, ocean color data and sea-ice data among others.

Class3 metrics provide a significant index of the thermodynamic behaviour of the systems. An example of Class3 is given with the FOAM system where an overall realistic overturning streamfunction and meridional heat transport are shown. The monitoring of the overturning stream function and the meridional heat transport in the forecast systems in the North Atlantic will be pursued during the next decade and will allow to detect changes in the thermohaline circulation, in parallel with the deployment of observing array in the North Atlantic to investigate rapid climate change (Srokosz, 2004; Bryden et al., 2005).

The definition and use of a common set of metrics have allowed a systematic and fast inter-comparison of operational systems, enabled to detect problems on a near real time basis and triggered fast correction of the problem as well as upgrade of the system. The inter-comparison exercise is being pursued during the European MERSEA Integrated Project (2004–2008). The methodology allows a continuous and comprehensive assessment of the performances of each system including all components as the observing system, the modeling, assimilation and product distribution components. It has also been adopted by the GODAE partners, who are defining more metrics adapted to the global Ocean. The next challenge is now to define synthetic climate indexes which will be largely used by the end-users community as for example fisheries.

Acknowledgments

This work is dedicated to CLP who passed away in February 2004. CLP initiated the metrics definition and the inter-comparison exercise. This work benefited fully from his large scientific and human experiences. MERSEA-strand1 is a research project supported by the European commission under the Fifth Framework Programme and contributing to the implementation of the ”Sustainable Marine Ecosystem” within the Energy, Environment and Sustainable Development programme (contract number EVK3-JY-2002-00089). The authors are grateful to Mike Bell, Adrian Hines, Keith Haines, Chunlei Liu and David Storkey from FOAM team, to Eric Chassignet, Harley Hulburt, Ashwanth Srinivasan, Alan Wallcraft, Ole Martin Smedstad from HYCOM-US team, to Pierre Bahurel, Eric Dombrowsky, Pierre-Yves Le Traon, Lucas Nouel, Gaetan Vinay, Eric Greiner and Romain Bourdalle from MERCATOR team, to Mario Adani and Nadia Pinardi from MFS team, to Knut Lisaeter, Laurent Bertino, Johnny Johannessen from TOPAZ team for providing their data on their OPeNDAP server and useful comments. We also acknowledge Frederique Blanc and Tony Jolibois from CLS for keeping the Live Access Server and MERSEA-strand1 web site working. Finally, we also wish to thank two anonymous reviewers for their useful comments and suggestions.

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