Incremental Analysis Update Implementation into a Sequential Ocean Data Assimilation System

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ABSTRACT

This study deals with the enhancement of a sequential assimilation method applied to an ocean general circulation model (OGCM). A major drawback of sequential assimilation methods is the time discontinuity of the solution resulting from intermittent corrections of the model state. The data analysis step can induce shocks in the model restart phase, causing spurious high-frequency oscillations and data rejection. A method called Incremental Analysis Update (IAU) is now recognized to efficiently tackle these problems.

In the present work, an IAU-type method is implemented into an intermittent data assimilation system using a low-rank Kalman filter [Singular Evolutive Extended Kalman (SEEK)] in the case of an OGCM with a 1/3° North Atlantic grid. A 1-yr (1993) experiment has been conducted for different setups in order to evaluate the impact of the IAU scheme. Results from all of the different tests are compared with a specific interest in high-frequency output behaviors and solution consistency. The improvements brought up by the IAU implementation, such as the disappearance of spurious high-frequency oscillations and the time continuity of the solution, are shown. An overall assessment of the impact of this new approach on the assimilated runs is discussed. Advantages and drawbacks of the IAU method are pointed out.

1. Introduction

Data assimilation aims at combining a physical model with observations to provide an analyzed state closer to reality. Because of the large size systems to be solved and the nonlinearity of the ocean dynamics, as well as the spatially and temporally sparse observations available, complex assimilation methods are required. To produce the best possible forecast, the models have to be initialized with the most accurate ocean state available. Because of the chaotic nature of ocean dynamics, current models cannot predict the ocean state further than a certain time range. For this reason, models need to be intermittently reinitialized by correcting the forecast with recent observations. This can be done by using statistical approaches and choosing optimality criteria based on error minimization. Among the possible data assimilation methods, the optimal statistical estimation theory, and more precisely the Kalman filtering approach, is appropriate to supply a solution of the best linear unbiased estimation. Such sequential filtering methods have been extensively studied and used for several years in the context of nonlinear ocean dynamics (Evensen 1994; Burgers et al. 1998). When operating high-resolution models routinely for operational oceanography applications, adapted assimilation methods are required. Several studies have been performed on the simplification of the estimation error statistics, in order to make feasible the computation needed for a conventional Kalman filter with nonlinear models (Fukumori and Malanotte-Rizzoli 1995; Pham et al. 1998).

A significant drawback of sequential methods is the discontinuity between the forecast and the analysis estimates. This discontinuity is recognized as a major problem; because of the suboptimal processing, it can introduce a shock in the model restart stage, causing spurious high-frequency oscillations and possibly leading to data rejection. The transient waves introduced by the analysis step can be considered the result of imperfectly corrected ocean states due to physically unbalanced error covariances.

To solve these problems, Bloom et al. (1996) have proposed a method called Incremental Analysis Update (IAU), consisting of incorporating the analysis increment in a gradual manner. This method has been frequently used in atmospheric general circulation

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models since. In comparison, this method has only been implemented quite recently for ocean general circulation models (OGCMs), and very few studies have been done on its impact. The purpose of this work is to implement and assess a chosen IAU method into a data assimilation system for an OGCM.

This work is organized as follows. The second section provides information on the IAU principles and reviews acknowledged impacts of the various methods. The third section details the model configuration, the assimilation system, and IAU implementation characteristics used for the present study. Section 4 defines the experiments conducted while section 5 shows the relevant results obtained. Finally, major improvements needed as well as downsides of the method are discussed in section 6.

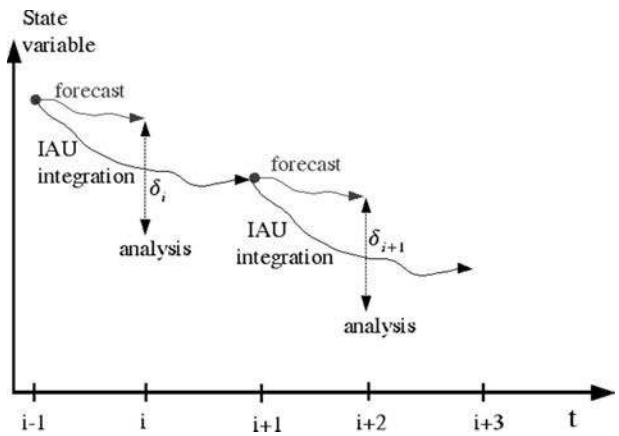

FIG. 1. IAU method from Bloom et al. (1996); δ represents the increment.

2. IAU methods

Numerous IAU methods are currently used in atmospheric and ocean circulation models. To choose an adapted algorithm for the present study, an overview of the different approach is done in the following subsections.

a. Atmospheric general circulation models (AGCMs)

The IAU principles were initially designed for intermittent data assimilation systems in atmospheric circulation models to reduce analysis-induced initial shocks in the model forecast. Bloom et al. (1996) were the first to introduce the IAU concept in the data assimilation system within the Goddard Earth Observing Satellite (GEOS). The basic principle of IAU is to incorporate an increment calculated from the analysis in the model integration as a forcing term. As mentioned by Bloom et al. (1996), the IAU method has the properties of a low-pass time filter and can then help in reducing high-frequency oscillations often observed at the restart of the model after the analysis step. A schematic overview of the IAU method as described by Bloom et al. (1996) is shown in Fig. 1. In the particular case of Bloom et al. (1996), the assimilation process is restarted 3 h before the analysis step, and the model is integrated forward for 6 h with the IAU forcing. At the end of the IAU forcing run, the model performs a free run for a period of 3 h, providing the first guess for the next analysis. In this configuration, the IAU increment is constant through the IAU forcing time window.

The IAU procedure is widely used in atmospheric models and mainly in a similar way to Bloom et al.'s description (Schubert et al. 1993; Zhu et al. 2003; DeWeaver and Nigam 1997). This method has been acknowledged to feature several advantages in the model integration process. As mentioned by Bloom et al. (1996), it acts like a continuous assimilation method (cf. Fig. 1). It also controls imbalances introduced by the analysis step (Zhu et al. 2003). It suppresses gravity waves due to assimilation updates, minimizing spurious adjustment processes (DeWeaver and Nigam 1997). In a recent work by Polavarapu et al. (2004), comparisons between IAU and other assimilation techniques such as Incremental Digital Filtering (IDF) are made, leading to several interesting points. They state that the IAU response does not only depend on the wave frequency but also on the model dynamics; therefore, the wave growth rate is of influence too. Polavarapu et al. (2004) also concluded that the IAU could damp slower waves too much when a constant increment is applied. The IAU principle also leads to an increase of 50% in the model integration time for Bloom et al.'s method.

b. Ocean general circulation models (OGCMs)

Compared to its use in atmospheric models, the IAU procedure has only been implemented into ocean circulation models quite recently. The main goals when applying IAU are globally the same as the ones previously described for atmospheric models. However, different methods have been developed and applied to OGCMs, although the overall principles remain similar. Carton et al. (2000) have adapted a technique very close to Bloom et al.'s method for a free surface OGCM. The main difference stands in the duration of the model forecast and the IAU forcing time window, due to the different time scales of the ocean dynamics. According to Carton et al. (2000), this method has advantages of both acting like a continuous assimilation method and suppressing gravity waves induced by the analysis update process. Moreover, Carton et al. (2000) also stated that because of this continuous correction of the forecast, the effect of the bias was reduced on the analysis. On the other hand, the cost of this technique is a 50% increase in integration time over that of a usual 10-day intermittent assimilation scheme.

Huang et al. (2002) developed a different IAU method, computationally more economical than Bloom et al.'s version. For this study, the model used is a version of the Geophysical Fluid Dynamics Laboratory (GFDL) Modular Ocean Model (Pacanowski et al. 1993), and the assimilation system is the Ocean Data Assimilation (ODA) system (Derber and Rosati 1989). With this ODA configuration, the temperature correction is inserted into the model for 12 h. At the end of these 12-h runs, a temperature increment is calculated and applied at every time step for the next 12 h. This persistent method was developed by Rosati et al. (1995). Huang et al. (2002) also tested a modified strategy: a temperature increment is calculated from an analysis done after 1 h of model prediction. This increment is divided by the number of time steps in a day (24 in this case) and converted into a 24-h time tendency. This tendency will then be added to the model temperature field at each time step, including the one from which the increment has been derived for a 24-h forecast. According to Huang et al. (2002), such a method still preserves model internal fluctuations while damping analysis-induced high-frequency signals. By further studying some results obtained with this new methodology, they also claimed that a nonassimilated variable such as the velocity could give closer agreement with observational data than the former strategy from Rosati et al. (1995) would do. It is important to note that the determination of a nonassimilated variable is dependent on the dynamical coupling between variables; hence its quality can reveal how the observational and dynamical data are balanced in the assimilation scheme.

In Alves et al. (2004), the temperature observations are assimilated into the ocean model as it is integrated. Every 10 days, an analysis is done using observations 5 days before and after the analyzed time. An increment is calculated from the difference between the analyzed and the forecast state. This increment is then added to the temperature field integration for the subsequent 10 days. The model state obtained is then used for the next analysis step. The major difference with other methods is that the incremental integration is continuous, as no model forecast without IAU is performed. A procedure similar to Alves et al. (2004) is used in Weaver et al. (2003) in their three-dimensional variational assimilation system developed for the Océan Parallélisé (OPA) model. Again, their analysis produces an increment for the temperature field only and this increment is applied as a constant forcing through the time window.

c. Discussion

From a review on relevant work using IAU, several key ideas can be pointed out. In the case of AGCMs, the IAU methods used remain strongly similar to the one proposed by Bloom et al. (1996). In the case of OGCMs, different variants have been developed from Bloom et al.'s original method, mainly because of the specific characteristics of ocean dynamics and time-scale dynamics. When used for OGCMs, differences between the IAU methodologies used in Carton et al. (2000), Huang et al. (2002), and Alves et al. (2004) mainly stand in the increment calculation and the choice of its time-window application. No definitive conclusions can be drawn on the choice of the variables to be corrected, but all the methodologies include a correction on the temperature field T and most of them on the salinity field S. In some cases, the incremental correction is systematic (no more forecast of the model without IAU forcing), and in other configurations, the correction is only applied during a defined time window (as in Bloom et al. 1996).

However, whatever the method, all authors agree on the benefits of the IAU implementation. It offers the advantage of a continuous assimilation method while providing a reduction of analysis-induced oscillations. Other acknowledged impacts, such as a reduction of the model bias (Carton et al. 2000), appear to remain specific to the configuration used. On the other hand, it is important to note that IAU implementation will always increase the computing time depending on which scheme is used.

It appears that the choice of a specific method remains open, as numerous IAU methods are currently used. The original IAU method used for the present study can be considered an adaptation of Bloom et al.'s method modified to allow comparison between the forecast, the analyzed, and the IAU cast states (cf. section 3).

3. Model configuration and data assimilation schemes

This section focuses on the model configuration and the assimilation process used for both the intermittent scheme and the continuous scheme with the IAU method.

a. Model configuration

The model is OPA 8.1 (Madec et al. 1998), a primitive equation model using the hydrostatic approximation and the rigid-lid condition. Prognostic variables are the three-dimensional velocity field and the thermohaline variables. The state vector includes the zonal velocity *U*, the meridional velocity *V*, the temperature field *T*, the salinity field *S*, and the barotropic streamfunction (BSF). The distribution of variables is a three-dimensional Arakawa-C-type grid using prescribed *z* levels. Vertical mixing of momentum, temperature, and salinity is computed according to the turbulent kinetic energy (TKE) closure model (Blanke and Delecluse 1993). The grid configuration features a model domain covering the North Atlantic basin from 20°S to 70°N and from 98.5°W to 20°E with a horizontal resolution of 1/3° × 1/3° cos(latitude). The resolution is therefore eddy permitting. The vertical discretization is done on 43 geopotential levels, with a grid spacing increasing from 12 m at the surface to 200 m below the depth of 1500 m. The atmospheric forcing fields of heat, freshwater, and momentum are derived from the reanalyses of the European Centre for Medium-Range Weather Forecasts (ECMWF) 6-h forecasts of the 1979–93 period. The model surface temperature is relaxed toward weekly Reynolds SST data.

b. Data assimilation scheme

For the assimilation of observation data into the model state, the analysis scheme used is a reduced-rank Kalman filter derived from the Singular Evolutive Extended Kalman (SEEK) methodology (Pham et al. 1998). This sequential method has been developed in several theoretical studies (Brasseur et al. 1999) and successfully applied to various oceanographic situations (Testut et al. 2003; Brankart et al. 2003).

As any other Kalman filter, the SEEK filter requires a parameterization of the error covariance on the various sources of information: initial condition ($\mathbf{P}°$), observations ($\mathbf{R}$), and model ($\mathbf{Q}$), all of which needed to be specifically adapted for each experiment. In the theoretical Kalman filter, it is assumed that a correction is computed and applied to the model state each time a new observation is available. However, in the SEEK configuration, as in most applications, and in practically all ocean basin–scale operational systems currently running, the time is divided in a number of equal periods or assimilation windows. For each assimilation window, all collected innovations are gathered for the analysis and the model correction to be made at the end of this time window. The justification for such a suboptimal scheme is that having more observations for each statistical analysis, the solution is less sensitive to approximation in the parameterization of the various error covariance matrices ($\mathbf{P}°$, $\mathbf{R}$, $\mathbf{Q}$). Therefore, the optimal assimilation window is a compromise between the minimization of the model drift between two successive analyses and the minimization of spurious effects due to inadequate error parameterization. This problem is obviously amplified by the lack of observations, which is a constant preoccupation in ocean assimilation systems, usually underconstrained by the observations. The consequence of this situation is that the correction applied to the model can often be nonnegligible with respect to the controlled signal. This leads to two kinds of problems: (i) significant time discontinuity of the solution and (ii) spurious high-frequency oscillations, if no adequate initialization procedure is applied. The purpose of this study is precisely to correct these problems by applying an IAU scheme. However, despite these potential problems, such a data assimilation method has been demonstrated to produce satisfying results, providing obvious improvements to the forecast fields when compared to reality (Testut et al. 2003).

In the present study, the overall analysis process is similar to the one explained in Testut et al. (2003). The estimation vector, containing the variables on which statistical analysis is done, includes the zonal velocity *U*, the meridional velocity *V*, the temperature field *T*, the salinity field *S*, and the sea surface height (SSH). The control vector contains the following variables used to constrain the model: *U*, *V*, *T*, and *S*. The data assimilated are the SST, the SSH, and the sea surface salinity (SSS). The SSH dataset consists of a combination of Ocean Topography Experiment (TOPEX)/Poseidon (T/P) and European Remote Sensing (ERS) altimeters along-track data for the period December 1992–December 1993.

The SST dataset consists of Advanced Very High Resolution Radiometer (AVHRR) observations gathered in the National Aeronautics and Space Administration (NASA) pathfinder project remapped at a 1/4° resolution with a time periodicity of 10 days. The SSS dataset is derived from the Levitus monthly climatology (Levitus et al. 1998). Therefore, the statistical analysis simultaneously uses all available observations from all sources (SST, SSS, and SSH).

It is worth noting that in order to compute the model equivalent to the SSS Levitus climatology, a low-pass filter is included in the observation operator for the sea surface salinity. Assimilating the SSS as well as the SST is required in order to better control the mixed layer density.

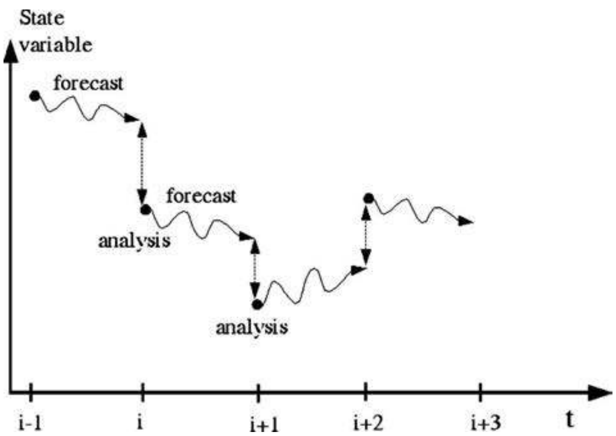

FIG. 2. Intermittent data assimilation system.

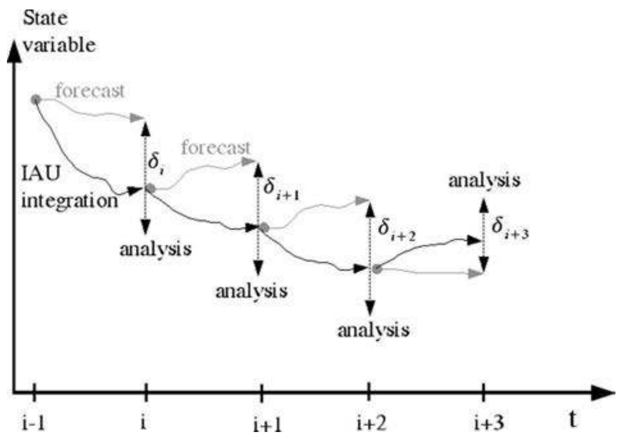

FIG. 3. Continuous assimilation method with the IAU scheme used for the present study; δ represents the increment.

c. *Intermittent data assimilation method*

So far, the SEEK filter has been used within an intermittent data assimilation configuration, producing satisfying results (Testut et al. 2003) but also leading to problems previously discussed. This scheme has been used in this study for comparison with the continuous assimilation scheme with IAU implemented (section 3d); therefore, it appears important to briefly restate its principle. Figure 2 gives a schematic view of such an intermittent assimilation system.

The method can be described as follows: a forecast is done from time i to $i + 1$, then an analysis is performed at time $i + 1$ using the SEEK filter. The analyzed state obtained is then used as the initial condition for the next forecast from time $1 + 1$ to $i + 2$.

d. *Continuous data assimilation method: IAU*

As said previously, an original IAU method has been chosen using information provided by the various approaches cited in section 2. All the tests and results presented in this study were done using the algorithm illustrated by Fig. 3. The method can be described as follows: a model forecast is done from time i to $i + 1$ and an analysis is performed at time $i + 1$. Again, the analysis stage is similar to the one performed in the intermittent assimilation scheme previously described. An increment is calculated on the temperature and salinity fields by taking the difference between the analyzed and the forecast fields. Then the model is run again from time i to $i + 1$ but with the increments applied to the corresponding fields. During the model IAU integration, the additional forcing term imposed on the model salinity and temperature fields at each time step is a fraction of the increment. In the present case, as in most IAU methodologies, this forcing term is the increment divided by the duration of the assimilation cycle Δt_c [cf. Eqs. (1) and (2)]. Hence, this value is constant during the IAU integration and the time-integrated quantity of this value over the IAU forcing time window is the increment. The ocean state obtained at $i + 1$ will then provide the initial conditions for the next model forecast. This particular method was chosen because it offers the possibility to compare the forecast, the analyzed, and the IAU corrected states at the same time and also because it allows coherent comparisons with the intermittent data assimilation system. However, compared to the method from Bloom et al. (1996), that only increases the CPU time by 50%; the present method leads to an increase in the integration time of the model by 100%.

During the IAU integration, the increments δT_{IAU} and δS_{IAU} are applied as shown in Eqs. (1) and (2):

$$\frac{\partial T}{\partial t} = -\boldsymbol{\nabla} \cdot (T\mathbf{U}) + D^T + \lambda(t)\delta T_{\mathrm{IAU}}, \quad \text{and} \tag{1}$$

$$\frac{\partial S}{\partial t} = -\boldsymbol{\nabla} \cdot (S\mathbf{U}) + D^S + \lambda(t)\delta S_{\mathrm{IAU}}, \tag{2}$$

with $\mathbf{U}$ representing the vector velocity, D^T and D^S representing the parameterizations of subgrid-scale physics for temperature and salinity, respectively, including the surface forcing terms, and $\lambda(t)$ representing a parameter such that

$$\int_0^{\Delta t_c} \lambda(t)\, dt = 1, \tag{3}$$

where Δt_c represents the duration of the assimilation cycle. In the present case, $\lambda(t)$ is chosen to be constant:

$$\lambda(t) = \frac{1}{\Delta t_c}. \tag{4}$$

Since the control vector in the IAU configuration is (T, S), it is different from the control vector of the intermittent assimilated scheme presented in section 3c. Again, the incremental update value applied to T and S for a given grid point is constant through the IAU forcing assimilation cycle. Polavarapu et al. (2004) stated that applying a constant value for the IAU increment might damp slower waves too much; it is, however, the method most often used.

We stress that the incremental analysis update technique is different from the nudging method (Bloom et al. 1996). The nudging technique blends data with the model by adding a Newtonian relaxation term to the prognostic model equation. This nudging term is typically a function of distance between the model variables and the observations. In addition to that, the nudging method does not take into account the model and the observations errors. The IAU term is different from the nudging technique, as it does not involve the current value of the considered variable (here T, S) so that the filtering effect of the nudging method on the model dynamics is avoided in the IAU method. Moreover, the IAU correction term can be applied to any model state variable and not only to the observed ones, as a multivariate statistical analysis of the observations is performed previously, consistently with the Kalman filter error statistics.

It is important to note that the incremental correction could be applied to other variables such as the horizontal velocities U, V. Such tests have not been performed in the present study. The choice of the corrected variables remains a difficult issue. However, most of the studies with OGCMs, presented in section 2b, were conducted with corrections applied to T and S. The choice of a correction on (T, S) in the present study was not only influenced by the reviewed work but also by the fact that testing the correction effects of the incremental correction appeared to be more convenient and fair for a few variables.

4. The conducted experiments

Numerical experiments have been conducted using the model configuration, the assimilation method, and the IAU technique described in section 3. This study features results from three different configurations run over the same time period: a free model run, a run with intermittent data assimilation, and a continuous assimilated run with implemented IAU. From now on, for reading convenience, the model run including the IAU method and the assimilation process will be named "IAU run," the free model run will be named "FREE run," and the model run with the intermittent (INT) assimilation method will be named "INT run." The experiments have been conducted for a period of 1 yr, starting 4 December 1992 and ending 5 December 1993.

TABLE 1. High-frequency point characteristics.

Point No.	Lat °N	Lon °W	Mooring
1	18	34	yes
2	26	29	yes
3	33	22	yes
4	26	79	yes
5	35.5	66.3	no
6	60	30	no

All of the state vector fields are saved every day. Six grid points have also been selected, for which high-frequency outputs (every time step) are done for the temperature and the SSH. The time step of the model being 40 min, the temperature and SSH evolution of the model at the selected grid points will then be produced 36 times per day. These points have been selected to correspond to areas of interesting ocean activity. Four of these points also correspond to locations of real moorings taken from the World Ocean Circulation Experiment (WOCE) database (ACM25/26 campaigns in 1993) that were operational during the same period, providing an independent dataset of temperature values. Table 1 is a summary of the points' characteristics while Fig. 4 shows the point locations in the North Atlantic basin.

Concerning the data assimilation characteristics, an analysis was performed every 3 days for the intermittent and the IAU-implemented experiments. Therefore, according to Fig. 3, in the IAU configuration the model performs a forecast from day 0 to day 3, then an analysis is done at day 3. The increments are calculated from the difference between the forecast and the analyzed states at day 3, then a model integration with incremental forcing is done from day 0 to day 3. This ocean state obtained at day 3 is further used as the initial state for the model forecast from day 3 to day 6, and so on. For the INT run, an analysis was also performed every 3 days (cf. Fig. 2), providing the initial state for the next 3 days of the model forecast.

For the three different experiments, the model has been initialized from an ocean state obtained after 8 yr of free run spinup, starting from rest in 1985. Such a period was proven to be sufficient enough for dynamical consistency and climatological fitting (Testut et al. 2003).

5. Results

The results section is organized as follows. A general validation of the IAU solution is done in section 5a as

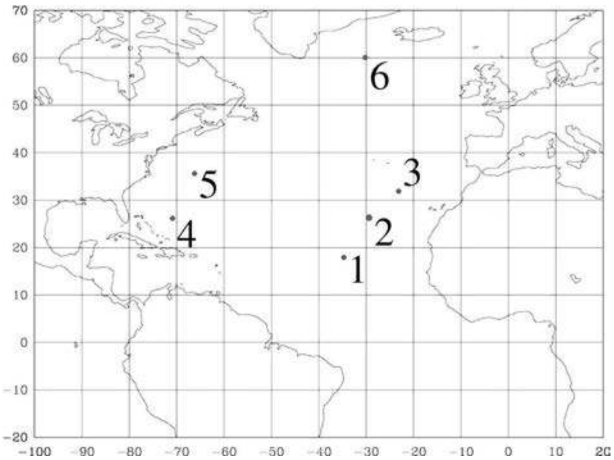

FIG. 4. Gridpoint locations for the high-frequency outputs.

a prior assessment of the method. Then in section 5b, the solution is further studied in terms of result improvements and realistic forecast. In section 5c, the IAU solution is considered in the context of its high-frequency properties, such as the damping of spurious oscillations. In the final section 5d, the eddy kinetic energy (EKE) production is studied as an additional diagnostic.

Among the results presented below, all of the time mean quantities have been calculated for a period starting 4 December 1992 and ending 5 December 1993.

a. Solution consistency

1) Averaged SST and SSH field comparisons

The averaged SSH field for the entire Atlantic basin for the three different runs is shown in Fig. 5. The averaged SST for the Atlantic basin for the three different runs and the Levitus et al. (1998) climatology is shown in Fig. 6.

In Fig. 6, the IAU and INT runs show the improvement brought by data assimilation, as the SST fields from these two experiments are closer to the Levitus et al. (1998) climatology than the FREE run is. Figures 5 and 6 demonstrate that the assimilated variables in the INT and IAU runs are of similar enhancement compared to the FREE run.

2) Gulf Stream structure modification

Vertical meridional sections of the time-averaged zonal velocity U in the Gulf Stream region is shown in Fig. 7 from the surface to a depth of 2000 m for the 3 types of runs. As discussed in Testut et al. (2003), the section from the INT run clearly demonstrates that the data assimilation has consistently modified the three-dimensional structure of the flow when compared to the result from the FREE run. For the INT run, the zonal velocity is stronger, featuring a jet located at a more realistic latitude. It turns out that the overall flow characteristics of the IAU run are quite similar to the INT run. However, a few differences between the INT and IAU runs can be noticed. The IAU run seems to have slightly weakened strong gradients, such as the one located at latitude 37°N from the surface to a depth of 500 m. This effect is not so surprising, as the IAU filtering method is apparently leading to more balanced ocean states [cf. section 5c(2)] and might therefore act as a spatial smoothing filter on the solution. The strong jet velocities reach deeper layers for the INT run than for the IAU run.

b. Assessment of the modified solution

1) RMS difference with the assimilated data

To validate the method, it is also important to study the overall performance of the IAU implementation in terms of root-mean-square (RMS) differences between the assimilated observations and the IAU integration. Figure 8 shows the RMS obtained for the SST over the entire North Atlantic basin for the FREE, the INT, and the IAU runs for a year.

From Fig. 8, it appears that the RMS in the analysis in INT mode is systematically smaller than the RMS in the IAU integration. However, the RMS trajectory of the forecast in IAU mode is of similar amplitude compared to the RMS in the INT forecast. When the RMS obtained for the SSH over the entire basin is plotted (Fig. 9), results are quite different. In a similar way to the RMS of the SST, the RMS in the INT analysis is smaller than the RMS in the IAU integration, but the RMS in the forecast in IAU is systematically larger than the INT one. Such an outcome is difficult to diagnose, as no direct correction is applied to the variable SSH. However, the analysis step is strongly influenced by the SSH data; therefore, the increment itself incorporates information from the assimilated SSH data. Despite getting larger for some cases, the overall RMS scoring of the IAU run remains satisfactory compared to the RMS calculated from the INT run.

2) Spatial averaged field evolution

If a Gulf Stream region is defined as shown in Fig. 10, spatially averaged fields can be calculated and their daily evolution can be studied, as all the runs were also set to output the state vector fields every day. Figure 11

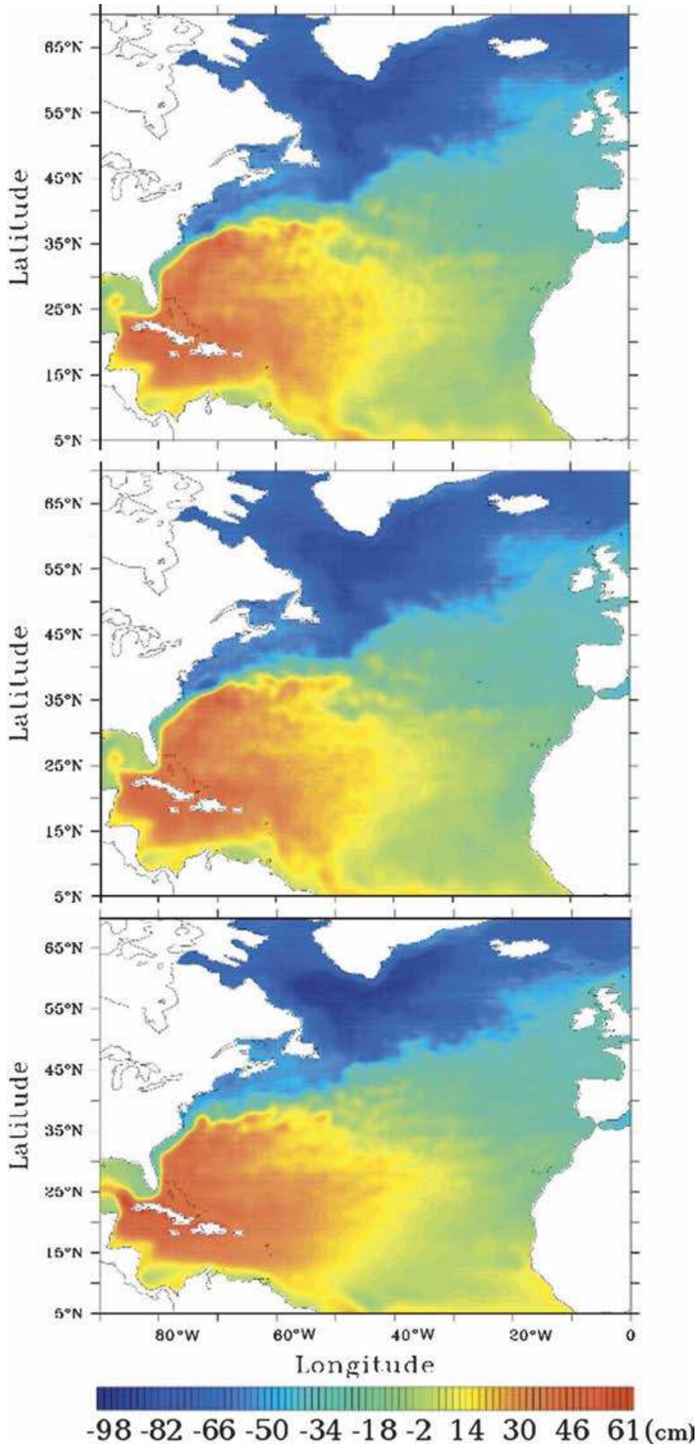

FIG. 5. Mean SSH for the December 1992–December 1993 period: (top) IAU, (middle) INT, and (bottom) FREE runs.

shows the evolution for a given period of the spatially averaged zonal velocity at the sea surface while Figs. 12 and 13 are for depths of 55 and 452 m, respectively. At the sea surface, the averaged velocity from the FREE, the INT, and the IAU runs is nearly always superposed with few overshoots from the IAU or INT run. Figure 11 only shows a given period, but if the entire year is considered, equivalent results are obtained. The simi-

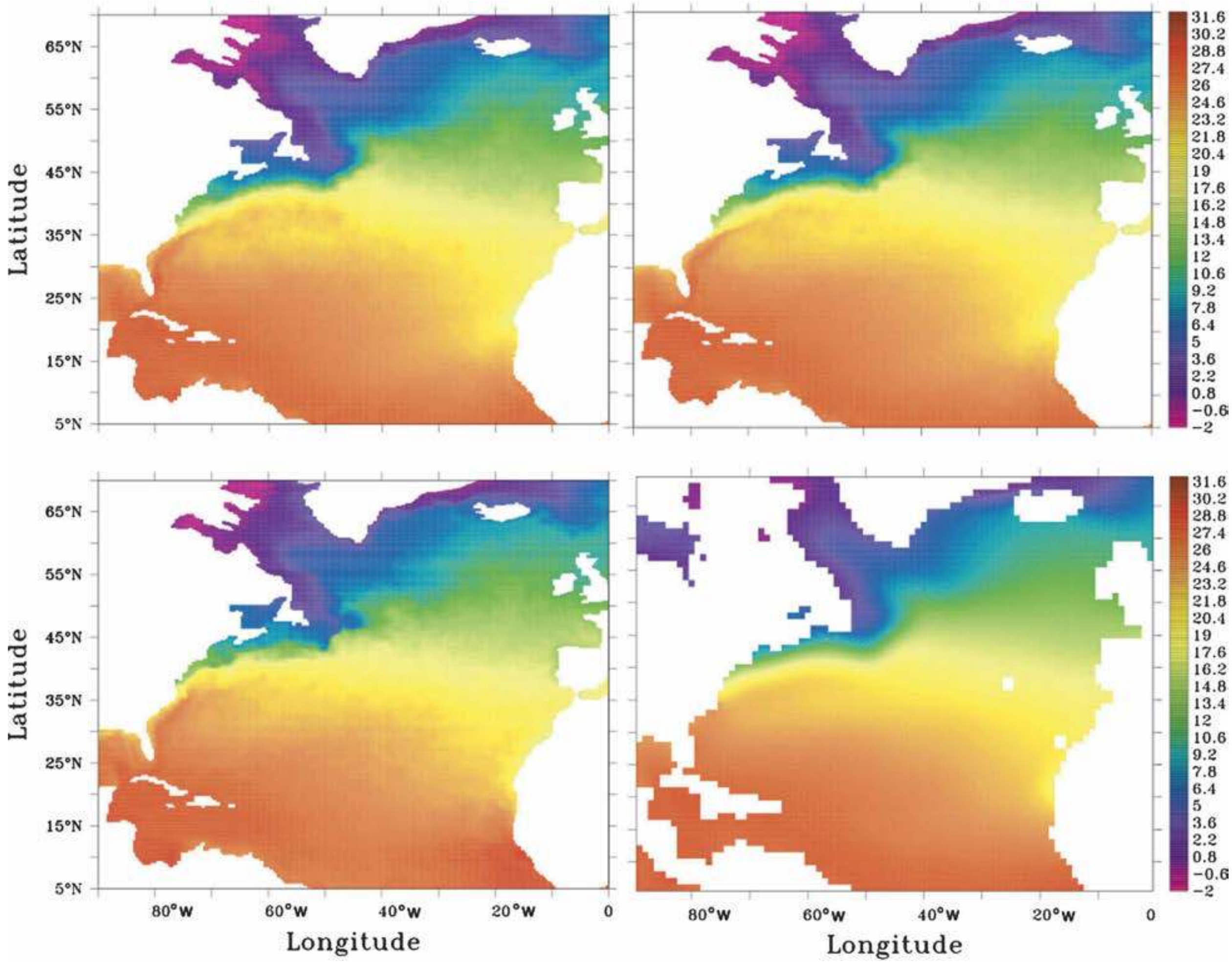

FIG. 6. Mean SST: (top left) IAU run, (top right) INT run, (bottom right) FREE run, and (bottom left) Levitus et al. (1998) climatology.

larity noticed for the three runs in Fig. 11 probably comes from the fact that the surface currents are mainly driven by the wind. At a depth of 55 m (Fig. 12), the agreement remains good between the runs, despite the large-amplitude oscillations of the INT run. At a depth of 452 m (Fig. 13), from the end of May 1993, the INT and IAU trajectories drift away from the FREE run, with the INT run still featuring large-amplitude oscilla-

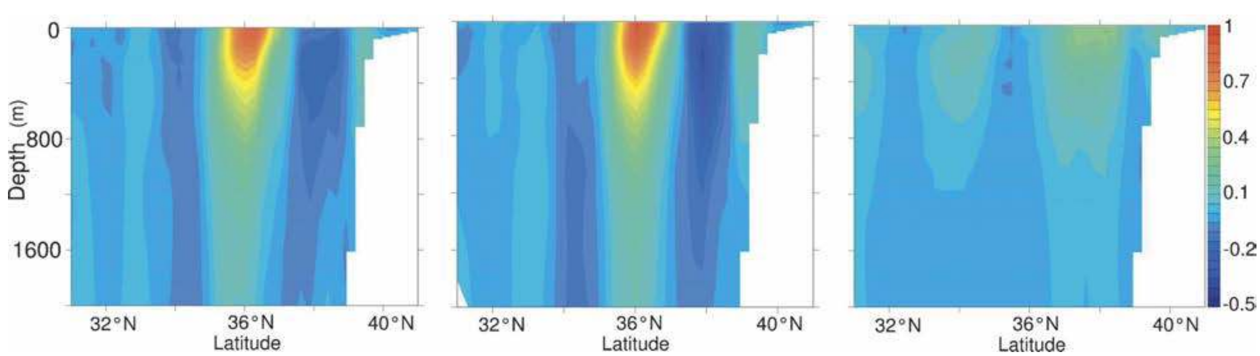

FIG. 7. Mean zonal velocity U (m s^{-1}) for a meridional section in the Gulf Stream region (at 72°W): (left) IAU, (middle) INT, and (right) FREE runs.

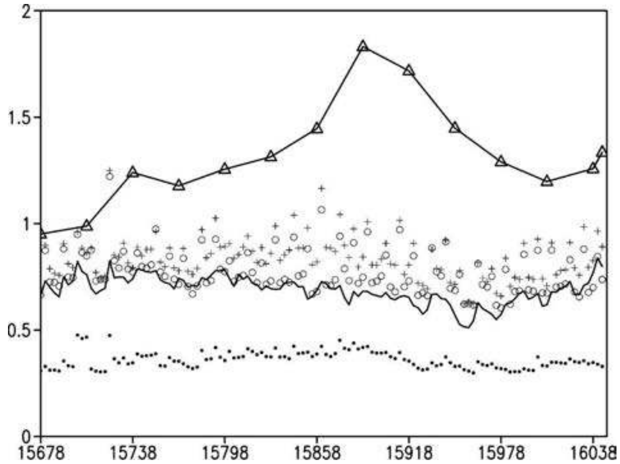

FIG. 8. RMS differences with the assimilated data for the SST (°C) (entire basin) for the period from Julian day 15678 (4 Dec 1992) to 16038 (29 Nov 1993): △ symbols represent FREE run, black circles represent analysis in INT mode, open circles represent forecast in INT mode, solid line represents IAU integration mode, and plus signs represent forecast in IAU mode.

tions. The differences between the FREE run and the assimilated IAU and INT runs in Fig. 13 show that deeper currents are likely to be more influenced by data assimilation than surface currents are (Fig. 11). In the present case, the Gulf Stream characteristics are significantly modified in the deep layers.

An additional remark can be made on the velocities plotted for a depth of 55 m (Fig. 12). For a period running from December 1992 to April 1993 (around Julian day 15798), the FREE run exhibits large-amplitude oscillations, satisfyingly reproduced in the IAU run. Then for a period of 6 months (approximately until early October 1993, around Julian day 15978), the

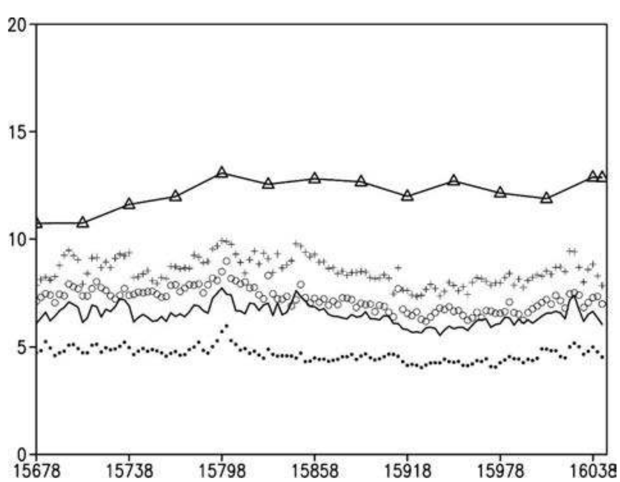

FIG. 9. Same as in Fig. 8, but for SSH (cm). The x axis is the time in Julian days.

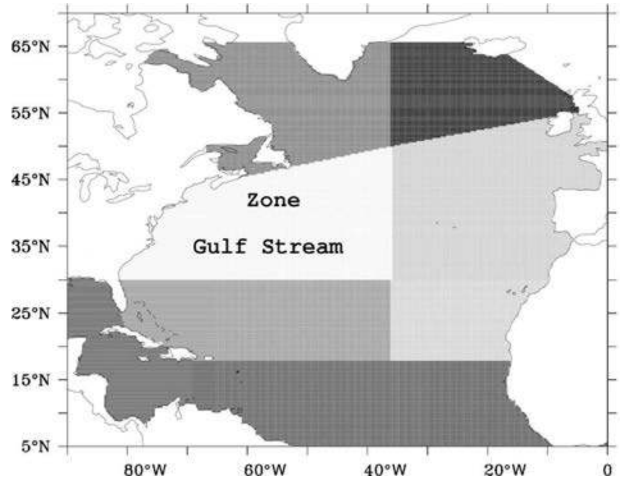

FIG. 10. Gulf Stream zone used for spatially averaged calculations.

FREE run oscillation amplitudes significantly weaken and so do the oscillations in the IAU trajectory, but extensive amplitude oscillations are still present for the INT run. As soon as the FREE run large-amplitude oscillations restart at the end of year 1993, the IAU trajectory includes similar oscillations again. Such a result confirms that the overall signal when featuring significantly large-amplitude waves does not seem to be filtered out by the IAU method. On the other hand, the spurious oscillations included in the INT run are clearly damped by the IAU method. In this case, the periodicity of the FREE run oscillations is about 4 days, being

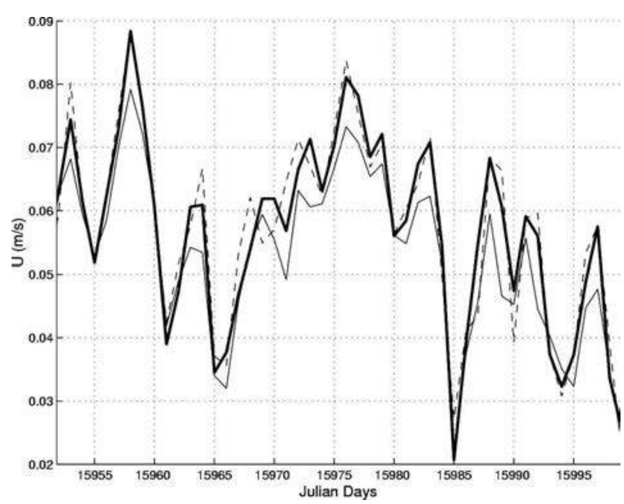

FIG. 11. Daily evolution of the spatially averaged zonal velocity U in the Gulf Stream zone at the sea surface (model level 1) for the period from Julian day 15951 (3 Sep 1993) to 15998 (20 Oct 1993): thin line represents FREE run, dashed line represents INT run, and thick line represents IAU run.

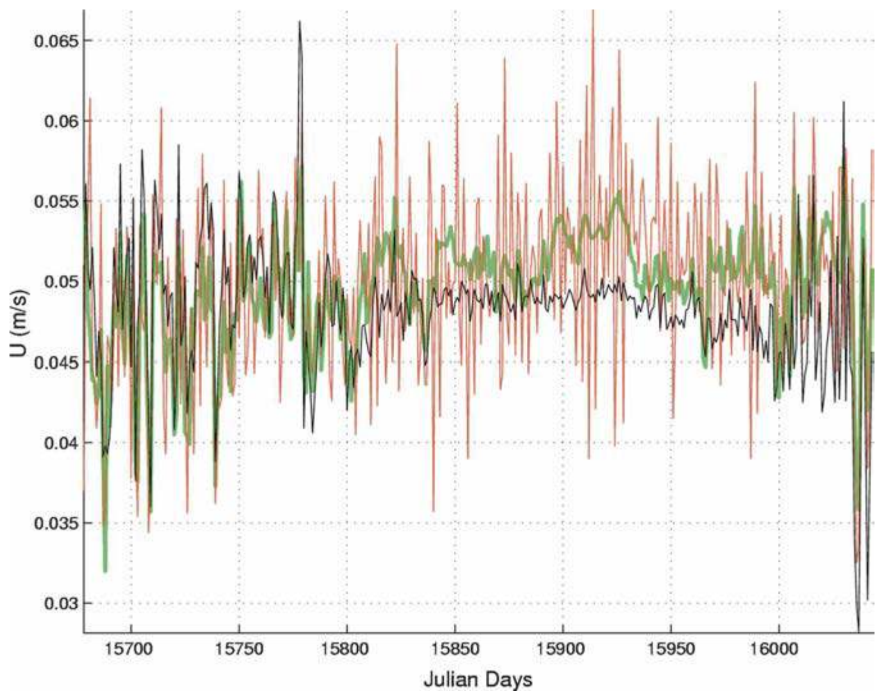

FIG. 12. Same as in Fig. 11, but at a 55-m depth (model depth level 5) from Julian day 15678 (4 Dec 1992) to 16038 (5 Dec 1993): black line represents FREE run, red line represents INT run, and green line represents IAU run.

quite close to the main periodicity of the INT oscillations, estimated as nearly 3 days. It turns out that the frequency of the oscillations might be less important than the model dynamics from the IAU impact point of view, as the oscillations are not screened out when they are apparently part of the model dynamics, and the oscillations simply vanish when they seem to be part of a spurious effect, despite being of a similar order of periodicity in this case.

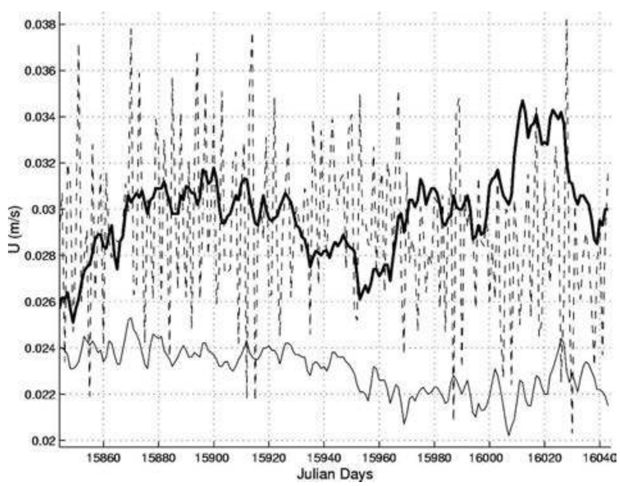

FIG. 13. Same as in Fig. 11, but at a depth of 452 m (model level 16) from Julian day 15844 (19 May 1993) to 16044 (5 Dec 1993).

3) Comparisons with independent moorings data

In terms of the realistic representation of ocean dynamics, a more accurate assessment can be performed by comparing the IAU results to high-frequency data recorded on moorings. Some grid points selected for high-frequency monitoring have also been chosen to correspond to mooring locations (cf. Table 1, section 4.). These moorings were deployed during the WOCE ACM25/26 campaigns in 1993. Unfortunately, these moorings did not provide data for the entire period considered in this study, but comparisons were still possible for a few months for the temperature. The acquisition period of the instruments was 15 min. The original signal being very noisy, the mooring data used in the present study have been filtered by a running average with a filtering window of 12 h. Figure 14 shows such a comparison for grid point 2 located in the Azores Current zone (cf. Fig. 4). From Fig. 14, the IAU trajectory of the SST is in good agreement with the mooring data but remains obviously closer to the assimilated SST. It appears that the assimilated data can be very different from the mooring data; hence, no close agreement can be expected. It can be noted that for all comparisons made with moorings data (not shown in this work), the assimilated data were systematically underestimated when compared to the mooring datasets.

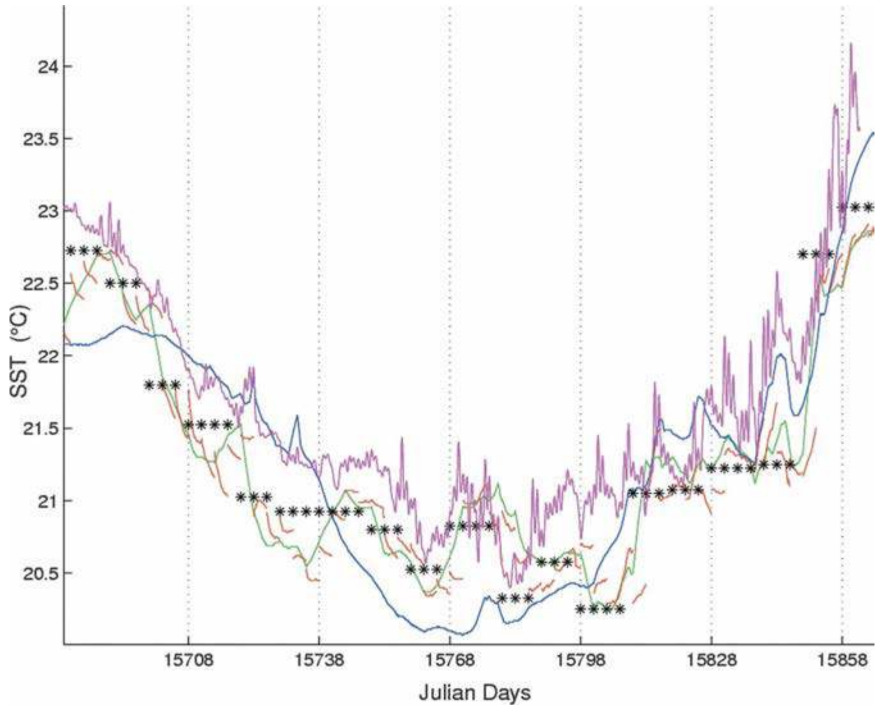

FIG. 14. SST at grid point 2 from Julian day 15678 (4 Dec 1992) to 15862 (6 Jun 1993): blue line represents FREE run, red line represents INT run, green line represents IAU run, asterisks represent assimilated data, and pink line represents independent data from WOCE moorings.

However, any conclusion from this type of comparison must be considered cautiously, as the behavior of the solution at one grid point cannot be directly extrapolated to a larger ocean zone.

c. *High-frequency behavior of the modified solution*

1) Oscillation filtering

As pointed out in section 2, spurious oscillations can be introduced in the variable trajectories when the model restarts after the analysis step, mainly due to the suboptimal processing of the intermittent approach leading to unbalanced mass fields. When the model output for a few selected grid points (cf. section 4) is considered, it is shown that at least for the output variables (temperature and SSH), high-frequency oscillations are a common feature of the INT run, but when the IAU run is considered, these oscillations are indeed strongly damped or completely missing.

Figure 15 shows the SSH evolution for the considered year for the INT run and the IAU run at grid point 3, located in the Portugal Current area. Despite not having a trajectory that is always similar to the INT one, the IAU trajectory does not feature the high-frequency oscillations clearly noticeable for the INT run. This kind of oscillation has been noticed for all of the variables studied at single grid points. The periodicity of these oscillations could not be clearly identified, varying from one point to another as well as from one vari-

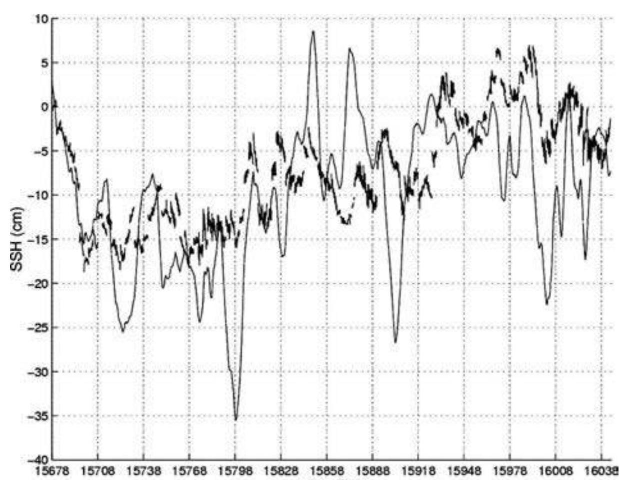

FIG. 15. High-frequency evolution of the SSH (cm) for grid point 3 during a year: thick line represents INT run and thin line represents IAU run.

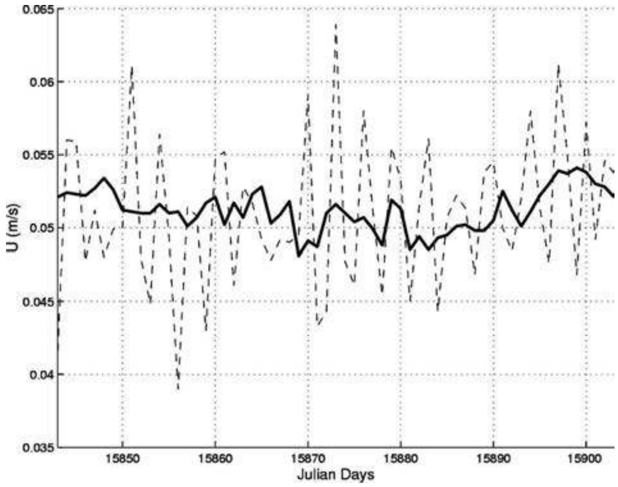

FIG. 16. Same as in Fig. 12, but from Julian day 15843 (18 May 1993) to 15903 (17 Jul 1993): dashed line represents INT run and solid line represents IAU run.

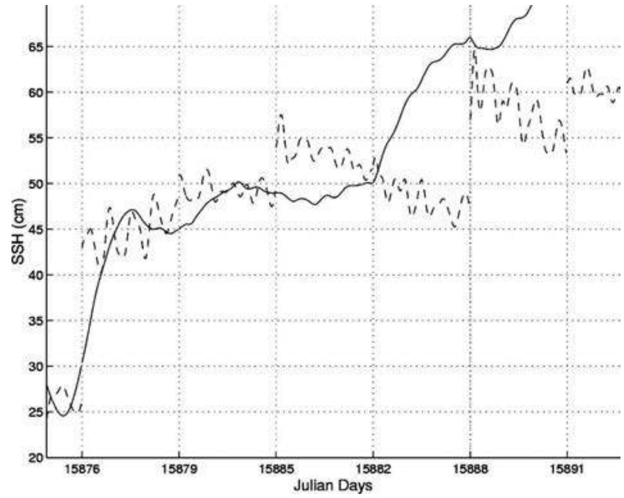

FIG. 17. High-frequency evolution of the SSH (cm) for grid point 5 from Julian day 15876 (20 Jun 1993) to 15891 (5 Jul 1993): dashed line represents INT run and solid line represents IAU run.

able to another. The estimated periods of oscillations fluctuate between 12 h and nearly 3 days. Figure 16 is an example of the daily evolution of the zonal velocity U at a depth of 55 m when a spatial average is calculated for the Gulf Stream zone defined in Fig. 10 for the case of the IAU and INT runs. Despite considering a spatial average over a large region, spurious oscillations are still noticeable for the INT run, while they clearly appear to be strongly damped for the IAU run. The period of the spurious large-amplitude oscillations is different from that of the single grid points (Fig. 15) and can be identified here as nearly 3 days, corresponding to an assimilation cycle length.

Along with the oscillation filtering properties of the IAU, when a few assimilation cycles are considered, the continuous aspect of the IAU run solution appears obvious compared to the INT run, as shown in Fig. 17.

2) OSCILLATION DURATION

Additional tests have been performed to study the persistence of the oscillations shown in the previous subsection. To do so, the ocean states obtained after 9 months of experiments in the case of the INT run and the IAU run have been selected. Two free model forecasts have been done starting from these two different states. If the temperature trajectory for isolated grid points is considered, results show that the oscillations existing in the INT run can last more than 12 days, as illustrated in Fig. 18. In a similar way, if the SSH trajectory is studied, oscillations can last over an entire month for the case of a free run restarted from an ocean state obtained with intermittent assimilation. From these results, it turns out that a free model run started from an ocean state obtained after several months of IAU integration does not feature any oscillations, when a free run started from an ocean state obtained after a similar period but with intermittent assimilation will exhibit spurious oscillations lasting several weeks. Then it appears that the ocean states obtained after several months of IAU integration are more balanced. This feature could be valuable for operational forecasting,

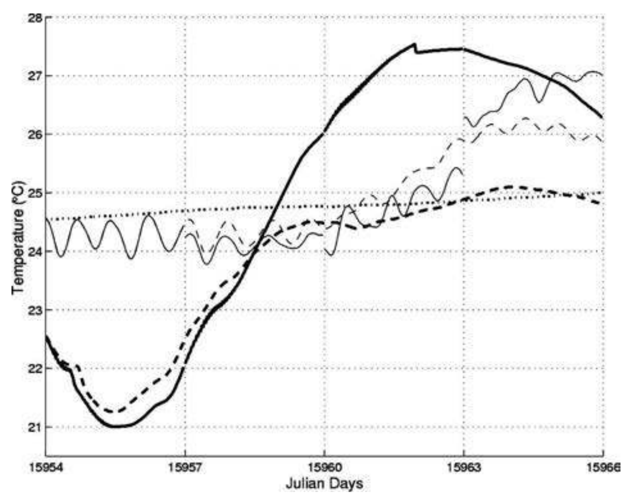

FIG. 18. High-frequency evolution of the temperature T (°C) for grid point 5 (Gulf Stream region) at a depth of 55 m from Julian day 15954 (6 Sep 1993) to 15966 (18 Sep 1993): dots represent FREE run, solid line represents INT run, thick line represents IAU run, thin dashed line represents FREE run started from an INT-obtained state, and thick dashed line represents FREE run started from an IAU-obtained state.

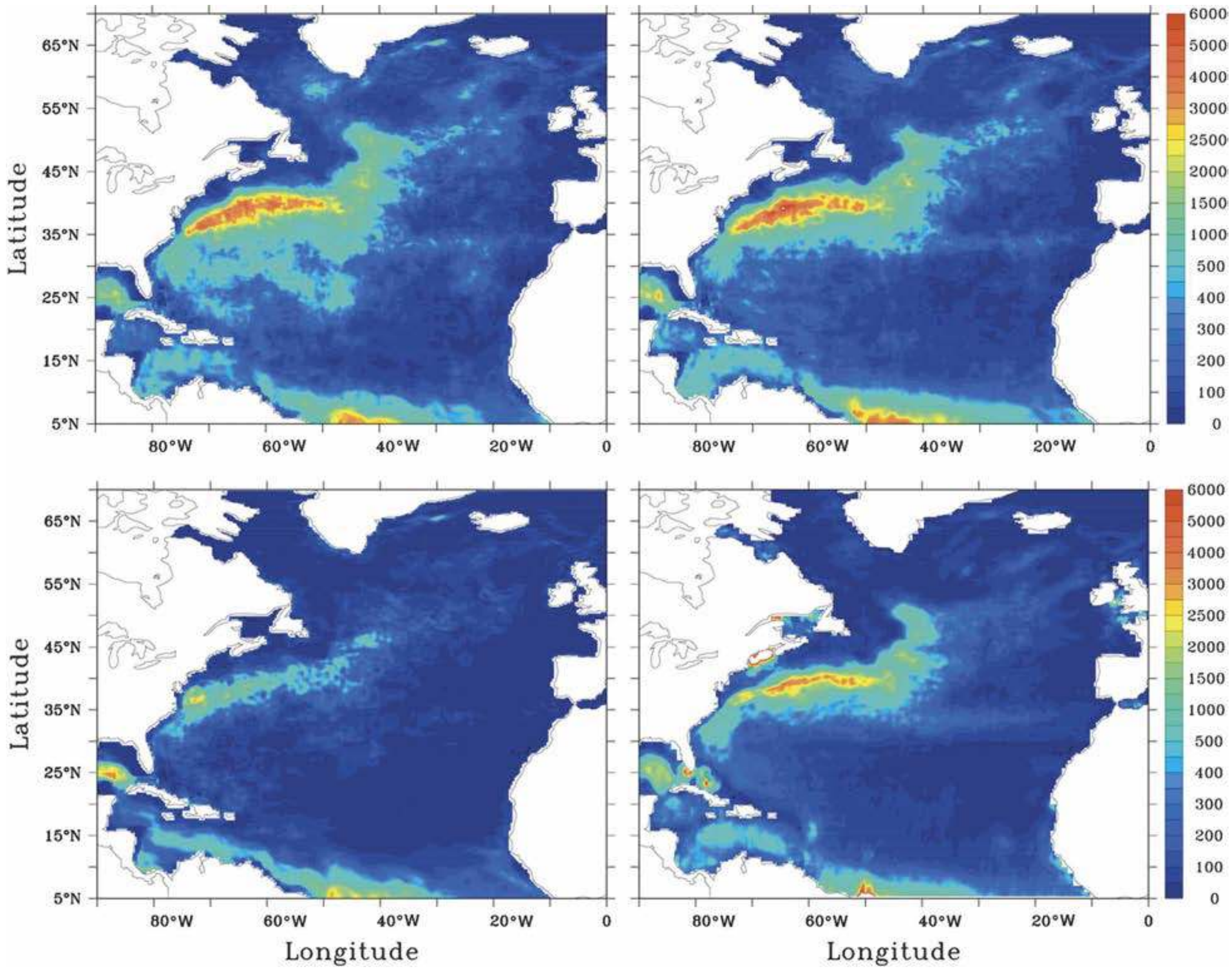

FIG. 19. EKE ($cm^2\ s^{-2}$) calculated for year 1993 at the sea surface: (top left) IAU run, (top right) INT run, (bottom right) FREE run, and (bottom left) observations from TOPEX/Poseidon/ERS for the period 1992–97.

where getting a model trajectory free of oscillations can be of major importance.

d. Additional diagnostic: The EKE distribution

EKE is a diagnostic quantity characterizing the eddy dynamics and the turbulent activity of the basin. The EKE is calculated over the usual period for the IAU, the INT, and the FREE runs and compared to the EKE calculated from TOPEX/Poseidon and ERS observations for the period 1992–97 (Ducet et al. 2000). As shown in Fig. 19, results from the INT and IAU runs are in good agreement with Ducet et al.'s (2000) calculations, despite values that are globally larger in the Gulf Stream region. However, as mentioned by Ducet et al. (2000), the method used to evaluate the EKE from satellite observations might also underestimate the reality in high-energy regions such as the Gulf Stream. The IAU run features stronger values of EKE in the Azores Current than in the INT case, being closer to the results from Ducet at al. (2000) for this region. The EKE calculated from the IAU run is consistent, with values generally weaker than the INT run and featuring wider patches of values from 500 to 1000 $cm^2\ s^{-2}$, especially for the subregion of the Gulf Stream with an extension to the Azores Current region. It appears that large-scale structures noticed in the INT run are still present in the IAU run. It is also worth noting that the spurious oscillations of the velocity observed for the INT run do not deteriorate the EKE solution as could be expected.

6. Conclusions and perspectives

A review of past and present work on the IAU methodologies for AGCMs and OGCMs showed that the algorithm itself is not unique but that two key ideas on the IAU impact could be confirmed, whatever the method. First, the IAU method efficiently suppresses spurious oscillations often existing in intermittent data assimilation systems, and second, it acts like a continuous assimilation method.

The choice, implementation, and assessment of the specific IAU method led to several results and discussions.

The IAU technique takes out efficiently spurious oscillations existing in the case of the intermittent data assimilation system used. Additional tests starting from an ocean state obtained after several months of IAU integration showed that the ocean fields were more balanced than for a similar experiment started from an ocean state obtained after several months of intermittent data assimilation. For these specific experiments, no oscillations were seen in the case of an IAU restarted state while oscillations could last for a month in the case of an intermittent restarted state. In addition to that, it appears that the IAU tends to weaken strong gradients, which might be explained by the stabilizing effect of the incremental approach. The IAU also seems to act like a spatial smoothing filter.

The overall solution does not appear to be inadequately modified compared to a solution with or without intermittent data assimilation. Flow structures enhanced by intermittent data assimilation usually remain of equivalent improvement in the IAU configuration. No particular diagnostic quantity, such as the eddy kinetic energy, turned out to be invalid for the IAU results.

Variables not controlled by the IAU increments, such as the horizontal velocities, behave in a satisfying manner. With regard to IAU performance in terms of RMS and comparison with independent data, it appears that any improvement in the data assimilation method will also benefit the efficiency of an IAU implemented system. The continuity of the solution is inherent to the IAU method. However, the increase in computing time for an IAU implemented OGCM is inevitable because of the very nature of this method.

Generally speaking, this study demonstrated that the IAU technique has a lot to offer to operational systems in oceanography. One further development that could be achieved for the enhancement of the IAU performance is to impose a systematic incremental correction (no more free model forecast). It seems clear that the main advantages brought up by the IAU technique can be easily enhanced depending on the chosen targets of the forecasting system used. Further developments also need to be done in order to test this assimilation scheme with a free surface OGCM.

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