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Comparison of different assimilation schemes in a sequential Kalman filter assimilation system

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ABSTRACT

In this paper, four assimilation schemes, including an intermittent assimilation scheme (INT) and three incremental assimilation schemes (IAU 0, IAU 50 and IAU 100), are compared in the same assimilation experiments with a nonlinear ocean circulation model using the Ensemble Kalman Filter as assimilation method. The three IAU schemes differ from each other in the position of the increment update window that has the same size as the assimilation window. 0, 50 and 100 correspond to the degree of superposition of the increment update window on the current assimilation window. Twin experiments are performed. Firstly, the assimilation experiments are initialised on the same number of ensemble members and with analysis every 2 and 6 days respectively in order to investigate the behaviours of different assimilation schemes against the assimilation cycles with different mixing and adjustment processes. In addition to the constant increment update, weighting functions with time scales in accord with the observation decorrelation are also applied. Secondly, the assimilation experiments are performed with the same computational cost, thus different number of ensemble members for different assimilation schemes. The relevance of each assimilation scheme is evaluated through analyses on four control variables including the sea surface height, the temperature, the zonal and meridional velocities and two diagnostic variables, the vertical velocity and the vertical eddy diffusivity. The comparisons between these assimilation schemes are performed at both global and local scales. The advantages and shortcomings of each assimilation scheme are highlighted. According to the results obtained: with the same number of ensemble members, for the control variables, the difference between the four schemes exists essentially at local scale. At global scale, no large difference is observed. Thus, the model error reduction by the IAU schemes with respect to the INT scheme is not observed in these experiments. The IAU schemes outperform the INT scheme on one hand at level of vertical advection where the IAU schemes suppress to a large extent the spurious geostrophic adjustment analysis-induced oscillation, on the other hand at level of vertical diffusion where much smaller instability is induced by gradual increment update in the IAU schemes. The application of the time scale in accord with the observation decorrelation during increment update is beneficial to the instability reduction with the schemes IAU 0 and IAU 50. With the same computational cost, thus less ensemble members for the schemes IAU 50 and IAU 100, the reduced ensemble members degrade the performance of the schemes IAU 50 and IAU 100. Therefore, taken into account the analysis-induced oscillation and instability reduction, as well as the computational cost, the scheme IAU 0 is preferred.

1. Introduction

In recent years, data assimilation, addressing the problem of producing useful analyses and forecasts given imperfect dynamical models and observations, has shown increasing interest in the atmosphere and ocean science community.

One can distinguish intermittent data assimilation and continuous data assimilation. The intermittent assimilation allows observations to modify the model integration in an instantaneous way. Although this assimilation scheme has been applied extensively for a long time, it is known to introduce a shock in the model restart stage after the analysis, resulting in spurious high-frequency oscillations and possibly leading to data rejection (Bloom et al., 1996; Brasseur, 2006; Ourmières et al., 2006). On the contrary, the continuous assimilation aims to incorporate observations into an ongoing model integration. In this manner, it can reduce the spurious oscillations produced in the intermittent assimilation by keeping the mass and momentum fields in balance. However, a major difficulty with this strategy is that instantaneous data are usually patchy and sparse, which leads to the related problem of having an ocean circulation model respond properly to isolated

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sporadic forcing (Bloom et al., 1996). The incremental analysis update (IAU) is considered to combine aspects of the intermittent and continuous assimilation schemes.

The IAU scheme, consists of incorporating the analysis increment in a gradual manner, is originally proposed by Bloom et al. (1996). Since then, it has been frequently used in data assimilation with atmospheric general circulation model (DeWeaver and Nigam, 1997; Zhu et al., 2003). For data assimilation with ocean general circulation model (OGCM), it has only been implemented since 2000. Later, diverse varieties have been developed and implemented (Carton et al., 2000; Huang et al., 2002; Alves et al., 2004; Ourmières et al., 2006). The main difference between these IAU techniques lies on the time window of the increment application. Carton et al. (2000) used an adaptive technique very similar to the technique in Bloom et al. (1996) for a free surface OGCM (namely IAU 50 thereafter). In Huang et al. (2002) and Alves et al. (2004), the IAU techniques used are very similar (namely IAU 0 thereafter), but different from the technique proposed by Bloom et al. (1996). In their techniques, after the model integration, an increment is calculated at the end of each assimilation window and applied at every time step inside the next assimilation window. In Ourmières et al. (2006), another different technique is proposed and implemented (namely IAU 100 thereafter). The increment is calculated at the end of each assimilation window after the model integration, and then applied at every time step inside the current assimilation window by re-running the model. In all these works, satisfactory results have been obtained with different IAU assimilation schemes and the capacity of the IAU techniques to act like a continuous assimilation and to reduce the high frequency analysis-induced oscillations has been proven. Carton et al. (2000) stated that the IAU technique reduces also the model bias compared to the intermittent assimilation. Ourmières et al. (2006) thought this reduction of model bias appears to be specific to the configuration used, since no model bias reduction by the IAU scheme is observed in their experiments. However, in Ourmières et al. (2006), the control vector of assimilation in the IAU configuration is different from the control vector of the intermittent assimilation scheme, which can mislead the comparison between these two schemes. In Huang et al. (2002), the IAU scheme is also compared to an intermittent assimilation scheme different from the one commonly used in data assimilation, the relevance of the IAU scheme acting as a spatial smoothing filter on the solution is highlighted, and the model error reduction by the IAU scheme is only reported for the equatorial current, not for all the model variables. Nowadays, there is no comparison between these IAU assimilation schemes in the same experiment with the same control vector. It seems thus interesting to investigate the performance of these IAU schemes, as well as the intermittent assimilation scheme, in regard of model error reduction in the same experiment with the same control vector. Moreover, in the previous work (Carton et al., 2000; Huang et al., 2002; Ourmières et al., 2006), the analyses were mainly focused on the temperature, the zonal velocity, as well as the sea surface height. Analyses on other variables, such as the vertical velocity and the vertical eddy diffusivity are also of particular interest for comparisons between different assimilation schemes.

In this paper, three different IAU assimilation schemes (IAU 0, IAU 50 and IAU 100) and an intermittent assimilation scheme (INT) are compared in a twin experiment. The ocean circulation model is the SQB (square box) configuration of the NEMO model (Cosme et al., 2010). The square root analysis scheme of the Ensemble Kalman Filter (EnKF) (Evensen, 2007) is used as assimilation method. The assimilation experiments are firstly performed with the same number of ensemble members for all the assimilation schemes and analysis every 2 and 6 days respectively in order to investigate the behaviours of each assimilation scheme against different assimilation cycles with different mixing and adjustment processes. In addition to the constant increment update, time scales in accord with the observation decorrelation as used in Lozano et al. (1996), Lermusiaux (1999) and Haley et al. (2009) are also applied to the weighting function of the increment update. Since the computational cost constitutes one of the main limitations in data assimilation, it seems interesting to investigate the behaviours of these assimilation schemes with the same computational cost. Therefore, the assimilation experiments are also performed with the same computational cost, thus different number of ensemble members for different assimilation schemes. The comparisons between different assimilation schemes are realised at both global and local scales, and four control variables including the sea surface height, the temperature and the zonal and meridional velocities and two diagnostic variables, the vertical velocity and the vertical eddy diffusivity, are analysed, from which the advantages and shortcomings of each assimilation scheme are highlighted.

This paper is organised as follows: In Section 2, different assimilation schemes are illustrated in detail. The model description and the assimilation setups are given in Section 3. In Section 4, results obtained with different assimilation schemes in different experiments are discussed and the inter-comparisons are performed at different spatial and temporal scales. Finally, the conclusion is derived in Section 5.

2. Different assimilation schemes

This section is dedicated to the description of different assimilation schemes considered in this paper.

The intermittent assimilation scheme, denoted by "INT" hereafter, corresponds to the commonly used and familiar assimilation scheme in data assimilation community. With this scheme, the free model integration is performed inside each assimilation window, and at the end of the assimilation window, the analysis is done combining the model forecast and the observations around the analysis time. The analysed model state is then used to initialise the model integration in the subsequent assimilation window. Different from the IAU schemes, the model state correction in this scheme is instantaneous before the model integration for the subsequent assimilation window.

According to the increment update time window position, the existing IAU techniques can be grouped into 3 categories: namely IAU 0, IAU 50 and IAU 100.

In the scheme IAU 0 (Fig. 1(a)), at the end of each assimilation window, the analysis is done using observations around the analysis time. An increment is calculated from the difference between the analysed and the forecast model states. This increment is then added to the model integration for the subsequent assimilation window. Therefore, the model integration is always forward, there is no model integration repeat for each assimilation window. The assimilation schemes used in Huang et al. (2002) and Alves et al. (2004) correspond to this kind of scheme. Regarding the computation time, with the same number of ensemble members, this scheme is similar to the INT scheme, and more economical than the other two IAU schemes.

For the scheme IAU 50 (Fig. 1(b)), the increment update time window is located at half of the assimilation window length before and after the analysis time step. After the increment update, the model integration continues for a period of half of the assimilation window length, the model state obtained at the end of this model integration is used for the analysis at the subsequent step. This scheme corresponds to the scheme originally proposed by Bloom et al. (1996) and the adaptive version applied by Carton et al. (2000) later. Compared to the scheme IAU 0, inside each