

# Comparison of stochastic parameterizations in the framework of a coupled ocean-atmosphere model – Response to the 1st reviewer

Jonathan Demaeyer <sup>1</sup> and Stéphane Vannitsem <sup>1</sup>

<sup>1</sup>Institut Royal Météorologique de Belgique, Avenue Circulaire, 3, 1180 Brussels, Belgium

## 1 General comments

We thank the reviewer for his/her careful reading of the manuscript. We will first address the general comments and then address the proposed suggestions.

5 First, a comparison with a data-driven method would have been very interesting too. It could be easily done in the framework of the software code given as supplementary material. However, we wanted that the article remained focused on *first principle* methods and their technical details.

Secondly, the reviewer indicates that the consideration of the case  $\varepsilon = \delta = 1$  only is another drawback of the study. We wanted to focus on the methods derivation within the ocean-atmosphere model, and their performance in its original form. The extension to other values has been done in Demaeyer and Vannitsem (2018) with a simpler system. It can of course be  
10 reproduced here but it is left for future works.

## 2 Modifications

We now address the proposed suggestions:

- p.2 l.22: over which → on which

**Answer:** Ok.

15

- 
- p.2 footnote: over which → on which

**Answer:** Ok.

- 
- p.3 l.5: mode → modes

20

**Answer:** Ok.

---

– p.4 l.20: “It results”: what does “it” refer to? Please clarify.

**Answer:** Indeed, the procedure was not correctly explained. We have modified the text according to:

5

*By recasting these expansions into the partial differential equations of the model, one obtains a set of ODEs for its coefficients  $\mathbf{Z} = (\{\psi_{a,i}\}, \{\theta_{a,i}\}, \{\psi_{o,j}\}, \{\theta_{o,j}\})_{i \in \{1, \dots, n_a\}, j \in \{1, \dots, n_o\}}$ :*

---

– p.6 eq.17: there is an  $\varepsilon$  and  $\varepsilon^2$  missing in the second and third term on the RHS

**Answer:** Ok.

---

10

– p.7 l.5: Vanden-Eijnden

**Answer:** Ok.

---

– p.7 l.10: In term  $\rightarrow$  In terms

**Answer:** Ok.

---

15

– p.7 eq.23-24: note that in homogenization theory  $F_X$  and  $F_Y$  can also depend on both  $\mathbf{X}$  and  $\mathbf{Y}$

**Answer:** We have added this comment as footnote in the text:

*Note that in homogenization theory  $F_X$  and  $F_Y$  can also depend on both  $\mathbf{X}$  and  $\mathbf{Y}$ , a possibility that was not considered here in order to effectively compare the MTV and WL parameterizations.*

---

20

– p.8 eq.32-33: The choice of decomposition is arbitrary without information of the size of different terms in the dynamical equation. If you agree, please insert a comment (here or elsewhere) that other decompositions may improve or decrease the performance. Could you also comment why you consider the assumptions of a time-scale separation or weak coupling to be valid in the current system?

25

**Answer:** We have change this section according to:

*This decomposition can be chosen arbitrarily since the only requirement is that  $F_X$  depends solely on  $\mathbf{X}$ . However, in the following (and in the provided code), we will consider that the resolved-unresolved components form a coupled system, with “maximal” uncoupled dynamics. In this view for both parameterizations, the decomposition of the  $\mathbf{X}$  component is the same:*

$$F_X(\mathbf{X}) = \mathbf{H}^X + \mathbf{L}^{XX} \cdot \mathbf{X} + \mathbf{B}^{XXX} : \mathbf{X} \otimes \mathbf{X}$$

*and*

$$\Psi_X(\mathbf{X}, \mathbf{Y}) = \mathbf{L}^{XY} \cdot \mathbf{Y} + \mathbf{B}^{XXY} : \mathbf{X} \otimes \mathbf{Y} + \mathbf{B}^{YYX} : \mathbf{Y} \otimes \mathbf{X}.$$

*This choice was also considered in Franzke et al. (2005), dealing with the MTV parameterization. It is worth noting that other decompositions may improve or decrease the performance of the parameterization.*

In addition, we do not assume that the resolved-unresolved components decomposition possesses a weak coupling or a timescale separation since these can be set arbitrarily by the user of the code. If the decomposition is for instance a resolved ocean and an unresolved atmosphere, then a timescale separation exists (weak-coupling is less obvious due to the temperature scheme). On the other hand, for all the cases considered in the result section, the decomposition is made in the atmosphere, where no weak-coupling or timescale separation (spectral gap) is found.

So the assumptions are valid depending on the “experiment” which is made. We have developed the parameterizations based on these assumptions, but then one can “push” these methods over their limits, in order to see if they would satisfy more difficult applications, like the parameterization of some atmospheric large scales. This is what we have tried to do.

- 
- p.9 1.4-10: Either method should work as long as the fast dynamics has an ergodic invariant measure (with some extra assumptions). Please comment on the reason for choosing two different decompositions for the two methods.

**Answer:** We have modified this section according to:

The definition of  $F_Y$  and  $\Psi_Y$  is also arbitrary, but it is of particular importance since it is the measure of the system whose tendencies are given by  $F_Y(\mathbf{Y})$  over which the averages are performed (De-maeyer and Vannitsem, 2018). A requirement is thus that the dynamics  $\dot{\mathbf{Y}} = F_Y(\mathbf{Y})$  has an ergodic invariant measure. In the framework of the WL method, it is natural to consider the measure of the intrinsic  $\mathbf{Y}$ -dynamics as:

$$F_Y(\mathbf{Y}) = \mathbf{H}^Y + \mathbf{L}^{YY} \cdot \mathbf{Y} + \mathbf{B}^{YYY} : \mathbf{Y} \otimes \mathbf{Y}$$

to perform the averaging.

In the framework of the MTV method, the measure of the  $O(1/\delta^2)$  singular system  $\dot{\mathbf{Y}} = F_Y(\mathbf{Y})$  is used for the averaging and it is usually assumed that the quadratic  $\mathbf{Y}$ -terms of the unresolved component tendencies represent the fastest timescale of the system (see Majda et al. (2001); Franzke et al. (2005)):

$$F_Y(\mathbf{Y}) = \mathbf{B}^{YYY} : \mathbf{Y} \otimes \mathbf{Y}.$$

and those are the ones over which the averaging has to be done.

In both cases, the others terms belong then to  $\Psi_Y$ .

It is interesting to note that there is no a priori justification for one or the other assumption. For both parameterization methods, the decomposition of the unresolved dynamics could be based on Eq. (34) or on Eq. (35). The code provided as supplementary materials allows to select the  $F_Y$ -dynamics as either Eq. (34) or Eq. (35).

The MTV and WL parameterizations described above are presented in more details in the appendices A and B, respectively.

We have chosen the dynamics of Eq. (34) to test the case with maximal uncoupled resolved-unresolved components. The test with Eq. (35) can easily be done with the code provided. In addition, it has already been used in Franzke et al. (2005).

5 Following the reviewer comment, we have also noticed that the line 2 p. 10 :

*The  $F_Y(\mathbf{Y}) = (F_{Y,a}(\mathbf{Y}), F_{Y,o}(\mathbf{Y}))$  function can be specified by either Eq. (35) or (34) (only (34) for the WL parameterization).*

should be modified. The text inside the parenthesis should be removed since the dynamics (35) could also be used to perform the WL parameterization. The code should allow this dynamics to be used by this parameterization, it will be changed in a future version.

10

- p.9 l.13-14: “we consider these two different assumptions”: this is contradictory to p.10 l.27: “we will here consider only the dynamics of (34)”.

**Answer:** Indeed, there is a contradiction. It has been solved by removing the sentence “we consider these two different assumptions...” (p.9 l.13-14).

5

---

- p.10 l.1: please add a few words explaining the problem of “dead” scales

**Answer:** We have decided to remove the expression “*dead*” scales which we have in fact not found in the literature. In place we have written :

10

[...] *or to increase the small-scale variability to address the problem of scales that are passively slaved and whose variability comes uniquely from their interactions with others.*

---

- p.13 l.6: setting → settings

**Answer:** Ok.

---

15

- p.30 l.12: “We will also assume...”: this is not an extra assumption if you already consider a Gaussian Ornstein-Uhlenbeck process.

**Answer:** Indeed, we have thus modified and moved this sentence just after equation (A1):

*This dynamics thus generates Gaussian distributions, such that the odd-order moments vanish and that the even-order moments are related to the second-order one.*

---

20

- p.30 eq. A5 and A7: the  $1/\delta^2$  factors here should be 1

**Answer:** These factors in front of the time integrals are correct. This is due to the fact that we use the  $1/\delta^2$  scaled dynamics Eq. (A2) to compute the average. Therefore, as stated p.31 line 1-2, the integrals over the lagtime  $s$  is of order  $\delta^2$  and the r.h.s. of Eq. (A5) and (A7) are of order 1. The integrals are of order  $\delta^2$  since the exponential decorrelation of the scaled dynamics (A2) are scaled accordingly. In addition, the integrated correlation matrices  $\Sigma$  and  $\Sigma_2$  are also  $O(\delta^2)$  matrices, as stated p. 34 line 4.

25

In principle, the unscaled dynamics  $\dot{Y} = F_Y(Y)$  corresponding to the  $\mathcal{L}_1$  operator should be used to compute the average. But here, the need for a code that allows to compute both the MTV and WL parameterization, with the

same initialization files, led to this particular formulation. The text of the appendix try to stay close to how the code performs the computation of the parameterization.

To clarify this for the reader, we added the following footnote p.31 on line 2 :

5

*It is due to the fact that we use directly the measure  $\tilde{\rho}_Y$  of the  $O(1/\delta^2)$  dynamics (A2) to performs the averaging, and not the measure of the dynamics  $\dot{Y} = F_Y(Y)$ .*

---

– p.31 l.17: the backward KE describes the evolution of expectation values, not densities

**Answer:** To our knowledge, the backward Kolmogorov equation:

$$-\frac{\partial}{\partial t}p(x,t) = b(x,t) \frac{\partial}{\partial x}p(x,t) + \frac{1}{2} \Sigma(x,t) \frac{\partial^2}{\partial x^2}p(x,t)$$

10

describes the evolution of the probability density  $p(x,t)$  with a final condition  $p(x,s) = u_s(x)$  with  $t < s$ . But it is true that the Feynman-Kac formula allows for its interpretation in terms of the expectation of the final condition  $u_s(x)$  over all paths starting from  $x$  at time  $t$ , see for instance Pavliotis (2014). In that sense, the probability density of a SDE is always an expectation over paths, the transition probability giving the “weight” (measure) of each path. Therefore both formulations are correct and we stick with the word “density” but we add “probability” in front for the sake of clarity. See also Gardiner (2009) and Risken (1996).

---

15

– p.3p.32 l.5-6: incomplete sentence

**Answer:** Has been completed by adding the word “vanishes” at the end.

---

20

– p.32 footnote: Additional to the diagonality, one needs assumption A4 of Majda et al. (2001)

**Answer:** A diagonal matrix  $\mathbf{A}$  in Eq. (A1) implies that assumptions A4 is fulfilled, due to the following property of the quadratic terms in quasi-geostrophic systems:

$$\frac{\partial}{\partial Y_i} B_{i j k}^{Y Y Y} Y_j Y_k = 0 \quad \forall j, k \quad . \quad (1)$$

25

Indeed, if  $\mathbf{A}$  is diagonal then the multidimensional Ornstein-Uhlenbeck process is made of uncorrelated one-dimensional Ornstein-Uhlenbeck processes, and thus:

$$\left\langle B_{i j k}^{Y Y Y} Y_j Y_k \right\rangle = 0 \quad \forall i, j, k \quad (2)$$

which is precisely the assumption A4. In other words, in this case the covariance matrix of the multidimensional O-U process is also diagonal and with the special property (1), it implies that the assumption A4 is fulfilled.

To explain this better in the article, we removed the footnote and modified the text according to:

*The first solvability conditions is obviously satisfied but the the second one is not necessarily satisfied since*

$$\mathbb{P}\mathcal{L}_2\rho_0 = \left( \mathbf{B}^{XY Y} : \left\langle \mathbf{Y} \otimes \mathbf{Y} \right\rangle_{\tilde{\rho}_Y} \right) \cdot \partial_{\mathbf{X}}\rho_0 = \left( \mathbf{B}^{XY Y} : \boldsymbol{\sigma}_Y \right) \cdot \partial_{\mathbf{X}}\rho_0$$

where  $\mathbb{P}$  is the expectation with respect to the measure of the process (A1) and  $\boldsymbol{\sigma}_Y$  is its covariance matrix. If the matrix  $\mathbf{A}$  in Eq. (A1) is considered to be diagonal, as in Majda et al. (2001) and in Franzke et al. (2005), then it is satisfied. Indeed, in this case  $\boldsymbol{\sigma}_Y$  is diagonal and  $\mathbb{P}\mathcal{L}_2\rho_0 = 0$  due to the following property of the quadratic terms in the model:

$$\frac{\partial}{\partial Y_i} B_i^{Y Y Y} Y_j Y_k = 0 \quad .$$

However, here we do consider the general case:  $\mathbf{A}$  is not diagonal and thus we can have  $\mathbb{P}\mathcal{L}_2\rho_0 \neq 0$ . It then indicates that  $1/\delta$  effects have to be taken into account in the parameterization.

5 – p.34 eqs A34: check the factors  $1/\delta^2$

**Answer:** As stated above, the “integrated” correlation matrices  $\boldsymbol{\Sigma}$  and  $\boldsymbol{\Sigma}^2$  are of order  $\delta^2$ , therefore these factors are correct.

10 – p.36 l. 11-12: Have any tests been performed to conclude that the process can be approximated with an Ornstein-Uhlenbeck?

**Answer:** No other tests than a rapid evaluation of the PDFs of the processes and a check of the fast exponential decorrelation properties have been done. In general, the PDFs looked Gaussian. Since then, we have computed the standardized third and fourth moments which show that indeed the statistics of the unresolved processes

$$\dot{\mathbf{Y}} = F_Y(\mathbf{Y})$$

15 is nearly Gaussian for every case that we considered. We comment now on that at the end of the introduction of section 4:

*In each case, we have also checked the statistics of the dynamics (34) and have concluded that it is nearly Gaussian.*

However, as stated in the conclusion, the parameterization methods could be extended to deal with the non-Gaussian case.

20 We thank again the reviewer for his/her suggestions.

## References

- Demaeyer, J. and Vannitsem, S.: Stochastic Parameterization of Subgrid-Scale Processes: A Review of Recent Physically Based Approaches, in: *Advances in Nonlinear Geosciences*, pp. 55–85, Springer, 2018.
- 5 Franzke, C., Majda, A. J., and Vanden-Eijnden, E.: Low-order stochastic mode reduction for a realistic barotropic model climate, *Journal of the atmospheric sciences*, 62, 1722–1745, 2005.
- Gardiner, C. W.: *Handbook of stochastic methods*, Springer Berlin, fourth edn., 2009.
- Majda, A. J., Timofeyev, I., and Vanden Eijnden, E.: A mathematical framework for stochastic climate models, *Communications on Pure and Applied Mathematics*, 54, 891–974, 2001.
- 10 Pavliotis, G. A.: *Stochastic processes and applications: Diffusion processes, the Fokker-Planck and Langevin equations*, vol. 60, Springer, 2014.
- Risken, H.: Fokker-planck equation, in: *The Fokker-Planck Equation*, pp. 63–95, Springer, 1996.



# Comparison of stochastic parameterizations in the framework of a coupled ocean-atmosphere model – Response to the 2nd reviewer

Jonathan Demayer<sup>1</sup> and Stéphane Vannitsem<sup>1</sup>

<sup>1</sup>Institut Royal Météorologique de Belgique, Avenue Circulaire, 3, 1180 Brussels, Belgium

We thank the reviewer for his/her comments on the manuscript and address his/her proposed suggestions:

1. The correlation plots (Figs. 4, 6 and 9) do not seem to be autocorrelations but autocovariances since the value at lag 0 is not 1. I think it would be easier to compare if the authors plot the autocorrelation function.

**Answer:** Depending on the background, “autocovariance” can mean “autocorrelation”. In this case, what the reviewer denotes as “autocorrelation” would be called “normalized autocorrelation”. Besides these terminology issues, we believe that the “autocovariances” are more complete because they they illustrate both the time scale and variability properties of the variable.

- 
2. There are a few recent review papers on stochastic modeling. Including them in the introduction would make it more informative: Berner, Judith, et al. "Stochastic parameterization: Toward a new view of weather and climate models." *Bulletin of the American Meteorological Society* 98.3 (2017): 565-588.  
Franzke, Christian LE, et al. "Stochastic climate theory and modeling." *Wiley Interdisciplinary Reviews: Climate Change* 6.1 (2015): 63-78.

**Answer:** We agree on this point, they have been added in the introduction.

- 
3. In the introduction the authors seem to distinguish between stochastic parameterizations and backscatter schemes. Backscatter schemes can also be stochastic so can be similar. I also think stochastic parameterizations are implicitly also based on the idea to “backscatter” energy from the unresolved scales into the resolved.

**Answer:** Our point was not to distinguish the backscatter methods as being non-stochastic but that these methods are based on specific turbulence closure models which are different from the other non-specific method proposed. We have however restated in the text that we have stochastic version of these methods in mind:

*They provide promising alternatives to other **stochastic** methods such as the ones based on the reinjection of energy from the unresolved scale through backscatter schemes (Frederiksen and Davies (1997); Frederiksen (1999), see also Frederiksen et al. (2017) for a recent review) or on empirical stochastic modeling methods based on autoregressive processes (Arnold et al., 2013).*

Of course, every stochastic methods can also be seen as a kind of backscatter scheme, since it introduces energy onto the large scales, coming in principle from the unresolved small-scales.

---

4. Page 2, footnote 2: I do not understand the meaning here.

5 **Answer:** This footnote just enumerate a few of the underlying hypothesis used to develop parameterization methods. For more clarity, we have incorporated this footnote in the text.

---

5. MAOOAM should be defined at first use.

**Answer:**

10 Ok.

---

6. Are “weak coupling” and “time scale separation” equivalent in a mathematical sense? How would one measure weak coupling in the real atmos-ocean system? For me weak coupling is rather opaque concept whereas time-scale separation is more tangible (at least I know how to estimate this from real data). Some comments on this would be appreciated.

15 **Answer:**

This is a very interesting question. While in some setting, a kind of equivalency can be made between time-scale separation and weak coupling (see Wouters et al. (2016)). On more general ground, such equivalence is far from trivial, and research could certainly be done in this direction.

20 Weak coupling is difficult to measure in data, and should rather be assessed by a proper modeling of the components of a system (dimensionalization). We agree that time-scale separation is easier to assess by computing the decorrelation time in data. We now comment at the end of Section 3.2 in the paper about that:

*In some particular cases, it is possible to establish an equivalence between these two assumptions (Wouters et al., 2016). However, in general, the relation between the two is far from trivial. Time-scale separation is easy to assess, by considering the decorrelation times in the output data of the model. On the other hand, weak-coupling is difficult to measure in data, and appears in general as a small coupling parameter resulting from the proper modeling of the components of a system.*

---

25 7. In the “seamless MTV” procedure of Franzke et al. (2005) we generalized MTV and do not need to assume an Ornstein-Uhlenbeck process any longer but just one stochastic process with Gaussian statistics.

**Answer:** Once the formula have been obtained with an Ornstein-Uhlenbeck process, they can easily be reused in seamless way, considering Gaussian statistic. This is the kind of approach that have been taken in the article, considering the odd-moments of the  $Y$ -dynamics to be zero. We comment on Appendix Section A2 about this:

*The formulas presented here are valid for an Ornstein-Uhlenbeck process, but as stated above, the covariance and correlations of the dynamics (A2) can be used directly as well, provided that the right assumptions are fulfilled. In the present work, we have always used the statistic of Eq. (A2) to compute the tensors.*

5

---

8. In Eqs. 36-39 are the coupling and time-scale separation parameters included. Which values have been used for the experiments?

**Answer:** Yes, and as stated on page 10 line 22-25:

*In addition, the parameters  $\delta$  and  $\varepsilon$  appearing in Eqs. (36)-(39) will be set to 1, meaning that we consider the natural timescale separations and coupling strengths of the model. Nevertheless, the study of the impact of these parameters is important (Demaeyer and Vannitsem, 2018) and should be carried out in forthcoming works.*

10

---

9. (and 10.) In my work I use a split integration scheme: Runge-Kutta 4th order for the deterministic part and Euler-Maruyama for the stochastic part. Such a split scheme might solve parts of your numerical problems.

In MTV the cubic terms are nonlinear damping. This has been shown in Majda, Andrew J., Christian Franzke, and Daan Crommelin. "Normal forms for reduced stochastic climate models." Proceedings of the National Academy of Sciences 106.10 (2009): 3649-3653. Peavoy, Daniel, Christian LE Franzke, and Gareth O. Roberts. "Systematic physics constrained parameter estimation of stochastic differential equations." Computational Statistics & Data Analysis 83 (2015): 182-199. Perhaps one can also ensure that the cubic term in WL is negative definite then the system should be stable.

15

20

**Answer:**

Since the instability takes place in the deterministic integral part of the integro-differential equation, in the cubic terms, we do not think that it would solve the problem. In fact, with the same configuration and the same cubic terms, the MTV method does not diverge, showing that it is the nature of the WL equation which is a problem (integro-differential equation).

25

In addition, we think that the appellation "cubic terms" is more directly identifiable by the reader, but we mention now in the text:

*These cubic terms are nonlinear dampings, as shown in Majda et al. (2009) and Peavoy et al. (2015).*

We thank again the reviewer for his/her suggestions.

## References

- Arnold, H., Moroz, I., and Palmer, T.: Stochastic parametrizations and model uncertainty in the Lorenz'96 system, *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, 371, 20110479, 2013.
- Demeyer, J. and Vannitsem, S.: Stochastic Parameterization of Subgrid-Scale Processes: A Review of Recent Physically Based Approaches, in: *Advances in Nonlinear Geosciences*, pp. 55–85, Springer, 2018.
- Frederiksen, J., Kitsios, V., Okane, T., and Zidikheri, M.: Stochastic subgrid modelling for geophysical and three-dimensional turbulence, in: *Nonlinear and Stochastic Climate Dynamics*, edited by Franzke, C. and O’Kane, T., pp. 241–275, Cambridge University Press, 2017.
- Frederiksen, J. S.: Subgrid-scale parameterizations of eddy-topographic force, eddy viscosity, and stochastic backscatter for flow over topography, *Journal of the atmospheric sciences*, 56, 1481–1494, 1999.
- 10 Frederiksen, J. S. and Davies, A. G.: Eddy viscosity and stochastic backscatter parameterizations on the sphere for atmospheric circulation models, *Journal of the atmospheric sciences*, 54, 2475–2492, 1997.
- Majda, A. J., Franzke, C., and Crommelin, D.: Normal forms for reduced stochastic climate models, *Proceedings of the National Academy of Sciences*, 106, 3649–3653, 2009.
- Peavoy, D., Franzke, C. L., and Roberts, G. O.: Systematic physics constrained parameter estimation of stochastic differential equations, *Computational Statistics & Data Analysis*, 83, 182–199, 2015.
- 15 Wouters, J., Dolaptchiev, S. I., Lucarini, V., and Achatz, U.: Parameterization of stochastic multiscale triads, *Nonlinear Processes in Geophysics*, 23, 435–445, 2016.

# Comparison of stochastic parameterizations in the framework of a coupled ocean-atmosphere model – Response to the 3rd reviewer

Jonathan Demayer <sup>1</sup> and Stéphane Vannitsem <sup>1</sup>

<sup>1</sup>Institut Royal Météorologique de Belgique, Avenue Circulaire, 3, 1180 Brussels, Belgium

We thank the reviewer for his/her comment. We have taken the liberty of breaking down the few points he/she addresses as follow:

1.1 At the beginning of Section 3.1.2 the authors state that “These methods are applicable for parameterization purposes if the problem can be cast into a backward Kolmogorov equation.” This is not a correct statement: Every dynamical system (deterministic or stochastic) can be cast into a backward Kolmogorov equation. Casting a nonlinear dynamical system into the linear backward Kolmogorov equation (or alternatively the linear Fokker-Planck equation) allows for the machinery of perturbation theory of linear systems to derive explicit formulae for the homogenized equations. The authors may want to reference here the monograph “Multiscale Methods: Averaging and Homogenization” by Pavliotis and Stuart.

10 **Answer:** We agree with the referee and have modified the statement as:

*These methods are applicable for parameterization purposes if the problem can be cast into a [linear backward Kolmogorov equation \(Pavliotis and Stuart, 2008\)](#).*

---

1.2 Furthermore, the authors provide references for the mathematical justification of MTV (including Papanicolaou). These are references if the underlying dynamical system is stochastic; for the applicability of the MTV procedure for deterministic systems, the references are Melbourne and Stuart (2011), Nonlinearity 24, pp 1361, Gottwald and Melbourne (2013), Proc. Roy. Soc. A 469, pp 2013020 and Kelly and Melbourne (2017), Journal of Functional Analysis 10, pp 4063.

**Answer:** We agree and have added the references:

*This approach is based on the singular perturbation methods that were developed for the analysis of the linear Boltzmann equation in an asymptotic limit (Grad, 1969; Ellis and Pinsky, 1975; Papanicolaou, 1976; Majda et al., 2001) and it has been applied to deterministic systems as well (Melbourne and Stuart, 2011; Kelly and Melbourne, 2017).*

---

20 1.3 The choice of notation with  $\rho$  for the backward Kolmogorov equation which propagates expectation values, is odd.  $\rho$  is usually reserved for densities. I also found the backward in time integration with the expectation value being defined at

the final time cumbersome; why not have a positive sign on the left hand side of (25) and (26), and have the expectation value equal to  $f(\mathbf{X})$  at  $t = 0$ ? Also, the generator  $\mathcal{L}$  is not defined when it is introduced.

**Answer:** Please see our answer to the 1st referee. For the choice of the backward integration, we align with the MTV derivation in Majda et al. (2001). We have modified the first sentence where the operators appear as:

*In this setting, the backward Kolmogorov equation reads (Majda et al., 2001):*

$$-\frac{\partial \rho^\delta}{\partial s} = \left[ \frac{1}{\delta^2} \mathcal{L}_1 + \frac{1}{\delta} \mathcal{L}_2 + \mathcal{L}_3 \right] \rho^\delta$$

where the *probability density*  $\rho^\delta(s, \mathbf{X}, \mathbf{Y}|t)$  is defined with the final value problem  $f(\mathbf{X})$ :

$\rho^\delta(t, \mathbf{X}, \mathbf{Y}|t) = f(\mathbf{X})$ . The *density*  $\rho^\delta$  can be expanded in term of  $\delta$  and inserted in Eq. (25). The zeroth order of this equation  $\rho^0$  can be shown to be independent of  $\mathbf{Y}$  and its evolution given by a closed, averaged backward Kolmogorov equation (Kurtz, 1973):

$$-\frac{\partial \rho^0}{\partial s} = \bar{\mathcal{L}} \rho^0.$$

*The precise definition of the operators  $\mathcal{L}_i$  and  $\bar{\mathcal{L}}$  acting on the densities is given in Appendix A.*

2. In the case when the unresolved scales consist of the wavenumber 2 atmospheric variables, the authors found that the WL approach leads to unstable dynamics. I am surprised by that. The authors relate this to a cubic form. Can the authors comment on which assumption of WL is being violated by this choice of unresolved variables? Are higher-order corrections needed?

**Answer:**

The weak-coupling assumption is violated in the atmosphere when  $\varepsilon$  is set to 1 as we have done for every experiment in the article. This might be a reason and a simple way (but computationally expensive) to check this is to repeat the experiment with smaller values of  $\varepsilon$  until the instability disappears. Higher-order corrections might solve the problem but are quite tedious to compute. What we find the most intriguing is the fact that the MTV method is stable, but not the WL one, leading us to suspect that the method is sensitive to the accuracy of the memory term  $M_3$  integration.

3. There are a few typos in the text:

Eqn (24): missing full stop.

Above (42): let -> left

**Answer:**

Thanks.

We thank again the reviewer for his/her suggestions.

## References

- Ellis, R. S. and Pinsky, M. A.: The first and second fluid approximations to the linearized Boltzmann equation, *J. Math. Pures Appl*, 54, 125–156, 1975.
- Grad, H.: Singular and nonuniform limits of solutions of the Boltzmann equation, *Transport theory*, 1, 269–308, 1969.
- 5 Kelly, D. and Melbourne, I.: Deterministic homogenization for fast–slow systems with chaotic noise, *Journal of Functional Analysis*, 272, 4063–4102, 2017.
- Kurtz, T. G.: A limit theorem for perturbed operator semigroups with applications to random evolutions, *Journal of Functional Analysis*, 12, 55–67, 1973.
- Majda, A. J., Timofeyev, I., and Vanden Eijnden, E.: A mathematical framework for stochastic climate models, *Communications on Pure and*
- 10 *Applied Mathematics*, 54, 891–974, 2001.
- Melbourne, I. and Stuart, A.: A note on diffusion limits of chaotic skew-product flows, *Nonlinearity*, 24, 1361, 2011.
- Papanicolaou, G. C.: Some probabilistic problems and methods in singular perturbations, *Journal of Mathematics*, 6, 1976.
- Pavliotis, G. and Stuart, A.: *Multiscale methods: averaging and homogenization*, Springer Science & Business Media, 2008.



# Comparison of stochastic parameterizations in the framework of a coupled ocean-atmosphere model

Jonathan Demaeyer <sup>1</sup> and Stéphane Vannitsem <sup>1</sup>

<sup>1</sup>Institut Royal Météorologique de Belgique, Avenue Circulaire, 3, 1180 Brussels, Belgium

*Correspondence to:* svn@meteo.be

**Abstract.** A new framework is proposed for the evaluation of stochastic subgrid-scale parameterizations in the context of [the Modular Arbitrary-Order Ocean-Atmosphere Model \(MAOOAM\)](#), a coupled ocean-atmosphere model of intermediate complexity. Two physically-based parameterizations are investigated, the first one based on the singular perturbation of Markov operator, also known as homogenization. The second one is a recently proposed parameterization based on the Ruelle's response theory. The two parameterization are implemented in a rigorous way, assuming however that the unresolved scale relevant statistics are Gaussian. They are extensively tested for a low-order version known to exhibit low-frequency variability, and some preliminary results are obtained for an intermediate-order version. Several different configurations of the resolved-unresolved scale separations are then considered. Both parameterizations show remarkable performances in correcting the impact of model errors, being even able to change the modality of the probability distributions. Their respective limitations are also discussed.

# 1 Introduction

Climate models are not perfect, as they cannot encompass the whole world in their description. Model inaccuracies, also called *model errors*, are therefore always present (Trevisan and Palatella, 2011). One specific type of model error is associated with spatial (or spectral) resolution of the model equations. A stochastic parameterization is a method that allows to represent the effect of unresolved processes into models. It is a modification, or a closure, of the time-evolution equations for the *resolved variables* that take into account this effect. A typical way to include the impact of these scales is to run a high-resolution models and to perform a statistical analysis to obtain the information needed to compute a closure of the equations such that the truncated model is statistically close to the high-resolution model. These methods are crucial for climate modeling, since the models need to remain as low-resolution as possible, in order to be able to generate runs for very long times. In this case, the stochastic parameterization should allow for improving the variability and other statistical properties of the climate models at a lower computational cost.

Recently, a revival of interest in stochastic parameterization methods for climate systems has occurred, due to the availability of new mathematical methods to perform the reduction of ordinary differential equations (ODEs) systems. Either based on the conditional averaging (Kifer, 2001; Arnold, 2001; Arnold et al., 2003), on the singular perturbation theory of Markov processes (Majda et al., 2001) (MTV), on the conditional Markov chain (Crommelin and Vanden-Eijnden, 2008) or on the Ruelle’s response theory (Wouters and Lucarini, 2012) and non-Markovian reduced stochastic equations (Chekroun et al., 2014, 2015). These methods have all in common a rigorous mathematical framework. They provide promising alternatives to other [stochastic](#) methods such as the ones based on the reinjection of energy from the unresolved scale through backscatter schemes ([Frederiksen and Davies \(1997\)](#); [Frederiksen \(1999\)](#), see also [Frederiksen et al. \(2017\) for a recent review](#)) ([Frederiksen and Davi](#) on empirical stochastic modeling methods based on autoregressive processes (Arnold et al., 2013). [For a comprehensive review on this matter, we invite the reader to consider the references Franzke et al. \(2015\), Frederiksen et al. \(2017\) and Berner et al. \(2017\).](#)

The usual way to test the effectiveness of a parameterization method is to consider a well-known climate low-resolution model [over-on](#) which other methods have already been tested. For instance, several methods cited above have been tested on the Lorenz’96 model (Lorenz, 1996), see e.g. Crommelin and Vanden-Eijnden (2008); Arnold et al. (2013); Abramov (2015) and Vissio and Lucarini (2016). These approaches have also been tested in more realistic models of intermediate complexity that possess a wide range of scales and possibly a lack of timescale separation<sup>1</sup>, like for instance the evaluation of the MTV parameterization on barotropic and baroclinic models (Franzke et al., 2005; Franzke and Majda, 2006). Due to the blooming of parameterization methods developed with different statistical or dynamical hypothesis <sup>2</sup>([i.e. weak coupling hypothesis, large scale separation, ...](#)), new comparisons are called for.

In this work, we investigate two parameterizations in the context of the MAOOAM ocean-atmosphere coupled model (De Cruz et al., 2016), used as a paradigm for multiscale systems. It is a two-layer baroclinic atmospheric model coupled to a shallow water ocean. It has been shown to exhibit multiple timescales including a low-frequency variability which is realistic for the

---

<sup>1</sup>Timescale separation, or the existence of a *spectral gap*, is a crucial ingredient [over-on](#) which numerous parameterization methods rely.

<sup>2</sup>[i.e. weak coupling hypothesis, large scale separation, ...](#)

midlatitude O-A system (Vannitsem et al., 2015). It possesses also a wide range of behaviors depending on the chosen operating resolution (De Cruz et al., 2016). As such, it forms a nice framework for testing parameterization methods on ocean-atmosphere related problems.

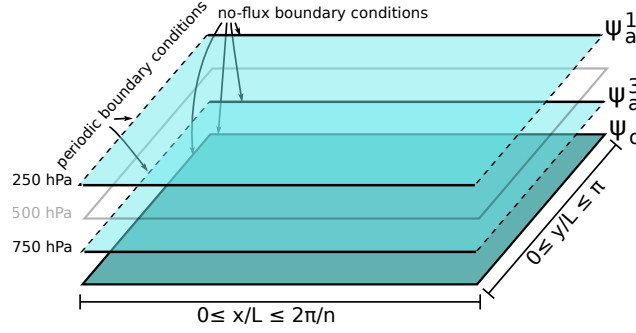
The particular problem of the atmospheric impact on the ocean could be addressed in this context as in Arnold et al. (2003) and Vannitsem (2014). It is an elegant problem, with a nice timescale separation, and which dates back to the work of Hasselmann (Hasselmann, 1976). However, in the present framework, other arbitrary decompositions of the model are possible, to address other questions. For instance, one may ask the question of the influence of the fast atmospheric processes on the slower atmospheric ~~mode~~modes as well as on the very slow ocean. This problem was already addressed by the authors in Demaeyer and Vannitsem (2017) for a particular decomposition of the atmospheric modes based on the existence of an underlying invariant manifold. The parameterization considered was the one proposed by Wouters and Lucarini (Wouters and Lucarini, 2012), and for this specific invariant-manifold configuration, the stochastic parameterization is greatly simplified. Here, we extend this study by considering also the MTV parameterization (Franzke et al., 2005) with different arbitrary configurations. This in particular allows us to study different cases with or without multiplicative noise.

This paper is organized as follow: in Section 2, we introduce briefly the MAOOAM model and its time-evolution equations. In Section 3, we review the parameterization methods we have applied to MAOOAM, and detail the model decompositions into resolved and unresolved components. The results obtained with these parameterizations, with different configurations, are presented in Section 4. Finally, the conclusions are provided in Section 5 and new work avenues are proposed.

## 2 The MAOOAM model

The Modular Arbitrary-Order Ocean-Atmosphere Model is a coupled ocean-atmosphere model for midlatitudes. It is composed of a two-layer atmosphere over a shallow-water ocean layer on a  $\beta$ -plane (De Cruz et al., 2016). The ocean is considered as a closed basin with no-flux boundary conditions, while the atmosphere is defined in a channel, periodic in the zonal direction and with free-slip boundary conditions along the meridional boundaries. The model incorporates both a frictional coupling (momentum transfer) and an energy balance scheme which accounts for radiative and heat fluxes transfers between the ocean and the atmosphere. This model is developed as a basic representation of the processes at play between the ocean and the atmosphere, and to emphasize their impact on the midlatitude climate and weather. In particular, it has been shown to display a prominent *low-frequency variability* (LFV) in a 36-dimensions model version (Vannitsem et al., 2015).

The dynamical fields of the model include the atmospheric barotropic streamfunction  $\psi_a$  and temperature anomaly  $T_a = 2\frac{f_0}{R}\theta_a$  (with  $f_0$  the Coriolis parameter at midlatitude and  $R$  the Earth radius) at 500hPa, as well as the oceanic streamfunction  $\psi_o$  and temperature anomaly  $T_o$ . In order to compute the time evolution of these fields, they are expanded in Fourier series



**Figure 1.** MAOOAM model schematic representation.

with a set of functions satisfying the aforementioned boundary conditions:

$$F_P^A(x', y') = \sqrt{2} \cos(Py') \quad (1)$$

$$F_{M,P}^K(x', y') = 2 \cos(Mnx') \sin(Py') \quad (2)$$

$$F_{H,P}^L(x', y') = 2 \sin(Hnx') \sin(Py') \quad (3)$$

5 for the atmosphere and

$$\phi_{H_o, P_o}(x', y') = 2 \sin\left(\frac{H_o n}{2} x'\right) \sin(P_o y') \quad (4)$$

for the ocean, with integer values of  $M$ ,  $H$ ,  $P$ ,  $H_o$ , and  $P_o$  and where  $x' = x/L$  and  $y' = y/L$  are the non-dimensional coordinates on the  $\beta$ -plane. These functions are then reordered as specified in De Cruz et al. (2016) and the fields are expanded as follow:

$$10 \quad \psi_a(x', y', t) = \sum_{i=1}^{n_a} \psi_{a,i}(t) F_i(x', y'), \quad (5)$$

$$T_a(x', y', t) = 2 \frac{f_0}{R} \sum_{i=1}^{n_a} \theta_{a,i}(t) F_i(x', y'),$$

$$\psi_o(x', y', t) = \sum_{j=1}^{n_o} \psi_{o,j}(t) (\phi_j(x', y') - \overline{\phi_j}), \quad (6)$$

$$T_o(x', y', t) = \sum_{j=1}^{n_o} \theta_{o,j}(t) \phi_j(x', y'). \quad (7)$$

with

$$15 \quad \overline{\phi_j} = \frac{n}{2\pi^2} \int_0^\pi \int_0^{\frac{2\pi}{n}} \phi_j(x', y') dx' dy', \quad (8)$$

a term that allows for mass conservation in the ocean, but does not play any role in the dynamics.

It results into By recasting these expansions into the partial differential equations of the model, one obtains a set of ODEs for the its coefficients  $\mathbf{Z} = (\{\psi_{a,i}\}, \{\theta_{a,i}\}, \{\psi_{o,j}\}, \{\theta_{o,j}\})_{i \in \{1, \dots, n_a\}, j \in \{1, \dots, n_o\}}$  of the expansion:

$$\dot{Z}_i = H_i + \sum_{j=1}^N L_{ij} Z_j + \sum_{j,k=1}^N B_{ijk} Z_j Z_k \quad (9)$$

where  $N = 2n_a + 2n_o$  is the total number of coefficients. This model includes thus forcings, linear interactions and dissipations, as well as quadratic interactions representing the advection terms. Note that the full model equations of MAOOAM include quartic terms for the temperature fields, but those terms have been linearized around equilibrium temperatures (Vannitsem et al., 2015).

### 3 Model decompositions and parameterizations

Now let us consider a more general system of ordinary differential equations (ODEs):

$$\dot{\mathbf{Z}} = T(\mathbf{Z}) \quad (10)$$

where  $\mathbf{Z} \in \mathbb{R}^N$  represents the set of variables of a given model. A parameterization of the model supposes first to define a decomposition of this set of variables into two different subsets  $\mathbf{Z} = (\mathbf{X}, \mathbf{Y})$ , with  $\mathbf{X} \in \mathbb{R}^{N_X}$  and  $\mathbf{Y} \in \mathbb{R}^{N_Y}$ . In general, this decomposition is made such that the subsets  $\mathbf{X}$  and  $\mathbf{Y}$  have strongly differing *response times*:  $\tau_Y \ll \tau_X$  (Arnold et al., 2003). However, we will assume here that this constraint is not necessarily met, allowing for a more arbitrary split of the system variables. System (10) can then be expressed as:

$$\begin{cases} \dot{\mathbf{X}} = F(\mathbf{X}, \mathbf{Y}) \\ \dot{\mathbf{Y}} = H(\mathbf{X}, \mathbf{Y}) \end{cases} \quad (11)$$

The timescale of the  $\mathbf{X}$  sub-system is typically (but not always) much longer than the one of the  $\mathbf{Y}$  sub-system, and it is sometimes materialized by a parameter  $\delta = \tau_Y / \tau_X \ll 1$  in front of the time derivative  $\dot{\mathbf{Y}}$ . The  $\mathbf{X}$  and the  $\mathbf{Y}$  variables represent respectively the resolved and the unresolved components of the system. A parameterization is a reduction of the system into a closed evolution equation for  $\mathbf{X}$  alone such that this reduced system approximates the resolved component (Arnold et al., 2003). The term ‘‘accurately’’ here can have several meanings, depending on the kind of problem to solve. For instance we can ask that the closed system for  $\mathbf{X}$  has statistics that are very close to the ones of the resolved component of system (11). We can also ask that the trajectories of the closed system remains as close as possible to the trajectories of the full system for long times, but this latter question will not be addressed in the present work.

More precisely a parameterization of the sub-system  $\mathbf{Y}$  is thus a relation  $\Xi$  between the two sub-systems:

$$\mathbf{Y} = \Xi(\mathbf{X}, t) \quad (12)$$

which allows to effectively close the equations for the sub-system  $\mathbf{X}$  while retaining the effect of the coupling to the  $\mathbf{Y}$  sub-system. Since the work of Hasselmann (1976), various stochastic parameterizations have been introduced (Demaeyer and

Vannitsem (2018) and Frederiksen et al. (2017) for reviews). They allow for a better representation of the variability of the processes and consider the relation (12) in a statistical sense. In this case, the aforementioned closed system for  $\mathbf{X}$  becomes a stochastic differential equation (SDE). If the system (11) is rewritten:

$$\begin{cases} \dot{\mathbf{X}} &= F_X(\mathbf{X}) + \Psi_X(\mathbf{X}, \mathbf{Y}) \\ \dot{\mathbf{Y}} &= F_Y(\mathbf{Y}) + \Psi_Y(\mathbf{X}, \mathbf{Y}) \end{cases}, \quad (13)$$

5 these SDEs are usually written:

$$\dot{\mathbf{X}} = F_X(\mathbf{X}) + G(\mathbf{X}, t) + \boldsymbol{\sigma}(\mathbf{X}) \cdot \boldsymbol{\xi}(t) \quad (14)$$

where the matrix  $\boldsymbol{\sigma}$ , the deterministic function  $G$  and the vector of random processes  $\boldsymbol{\xi}(t)$  have to be determined. We now detail in the rest of this section the two parameterizations that we will consider, namely the WL and the MTV approach.

### 3.1 Stochastic parameterizations

#### 10 3.1.1 The Wouters-Lucarini (WL) parameterization

The first one is based on the Ruelle's response theory (Ruelle, 1997, 2009) and is valid when the resolved and the unresolved components are weakly coupled. This method proposed by Wouters and Lucarini (2012) is connected to the Mori-Zwanzig formalism (Wouters and Lucarini, 2013). It has already been applied to stochastic triads (Wouters et al., 2016; Demaeyer and Vannitsem, 2018), to the Lorenz'96 model (Vissio and Lucarini, 2016) and to the MAOOAM model in the 36-variables  
15 configuration displaying LFV (Demaeyer and Vannitsem, 2017). It considers the following decomposition:

$$\dot{\mathbf{X}} = F_X(\mathbf{X}) + \varepsilon \Psi_X(\mathbf{X}, \mathbf{Y}) \quad (15)$$

$$\dot{\mathbf{Y}} = F_Y(\mathbf{Y}) + \varepsilon \Psi_Y(\mathbf{X}, \mathbf{Y}) \quad (16)$$

where  $\varepsilon$  is a small parameter accounting for the weak coupling and the functions  $F_X$  and  $F_Y$  account for all the terms involving only  $\mathbf{X}$  and  $\mathbf{Y}$ , respectively.

20 As said above, the parameterization is based on the Ruelle's response theory, which quantifies the contribution of the "perturbations"  $\Psi_X$  and  $\Psi_Y$  to the invariant measure  $\rho$  of the fully coupled system (13) as:

$$\rho = \rho_0 + \underline{\varepsilon} \delta_{\Psi} \rho^{(1)} + \underline{\varepsilon}^2 \delta_{\Psi, \Psi} \rho^{(2)} + O(\underline{\Psi} \varepsilon^3) \quad (17)$$

where  $\rho_0$  is the invariant measure of the uncoupled system. The two measures  $\rho$  and  $\rho_0$  are supposed to be existing, well-defined Sinai-Ruelle-Bowen (SRB) measures (Young, 2002). As a result of Eq. (17), the parameterization is based on three different  
25 terms having a response similar, up to order two, to the couplings  $\Psi_X$  and  $\Psi_Y$ :

$$\dot{\mathbf{X}} = F_X(\mathbf{X}) + \varepsilon M_1(\mathbf{X}) + \varepsilon^2 M_2(\mathbf{X}, t) + \varepsilon^2 M_3(\mathbf{X}, t) \quad (18)$$

where

$$M_1(\mathbf{X}) = \left\langle \Psi_X(\mathbf{X}, \mathbf{Y}) \right\rangle_{\rho_0, \mathbf{Y}} \quad (19)$$

is an averaging term.  $\rho_{0,Y}$  is the measure of the uncoupled system  $\dot{Y} = F_Y(Y)$ . The term  $M_2(\mathbf{X}, t)$  is a correlation term:

$$\left\langle M_2(\mathbf{X}(t), t) \otimes M_2(\mathbf{X}(t+s), t+s) \right\rangle = \left\langle \Psi'_X(\mathbf{X}, \mathbf{Y}) \otimes \Psi'_X(\phi_X^s(\mathbf{X}), \phi_Y^s(\mathbf{Y})) \right\rangle_{\rho_{0,Y}} \quad (20)$$

where  $\otimes$  is the outer product,  $\Psi'_X(\mathbf{X}, \mathbf{Y}) = \Psi_X(\mathbf{X}, \mathbf{Y}) - M_1(\mathbf{X})$  is the centered perturbation and  $\phi_X^s, \phi_Y^s$  are the flows of the uncoupled system  $\dot{X} = F_X(X)$  and  $\dot{Y} = F_Y(Y)$ . The  $M_3$  term is a memory term:

$$5 \quad M_3(\mathbf{X}, t) = \int_0^\infty ds h(\mathbf{X}(t-s), s). \quad (21)$$

involving the memory kernel

$$h(\mathbf{X}, s) = \left\langle \Psi_Y(\mathbf{X}, \mathbf{Y}) \cdot \partial_Y \Psi_X(\phi_X^s(\mathbf{X}), \phi_Y^s(\mathbf{Y})) \right\rangle_{\rho_{0,Y}} \quad (22)$$

All the averages are thus taken with  $\rho_{0,Y}$ , and the terms  $M_1, M_2$  and  $M_3$  are derived (Wouters and Lucarini, 2012) such that their responses up to order two match the response of the perturbations  $\Psi_X$  and  $\Psi_Y$ . Consequently, this ensures that for a *weak*  
 10 *coupling*, the response of the parameterization (18) on the observables will be approximately the same as the response of the full coupled system.

### 3.1.2 The **Majda-Timofeyev-Vanden-Eijnde** Majda-Timofeyev-Vanden-Eijnde (MTV) parameterization

This approach is based on the singular perturbation methods that were developed for the analysis of the linear Boltzmann equation in an asymptotic limit (Grad, 1969; Ellis and Pinsky, 1975; Papanicolaou, 1976; Majda et al., 2001) and it has been applied  
 15 to deterministic systems as well (Melbourne and Stuart, 2011; Kelly and Melbourne, 2017). These methods are applicable for parameterization purposes if the problem can be cast into a linear backward Kolmogorov equation (Pavliotis and Stuart, 2008). Additionally, the procedure, described in Majda et al. (2001), requires some assumptions on the timescales of the different terms of the system (13). In term-terms of the timescale separation parameter  $\delta = \tau_Y/\tau_X$ , the fast variability of the unresolved component  $\mathbf{Y}$  is considered of order  $O(\delta^{-2})$ , and the coupling terms are acting on an intermediary timescale of order  $O(\delta^{-1})$ :

$$20 \quad \dot{X} = F_X(X) + \frac{1}{\delta} \Psi_X(X, Y) \quad (23)$$

$$\dot{Y} = \frac{1}{\delta^2} F_Y(Y) + \frac{1}{\delta} \Psi_Y(X, Y). \quad (24)$$

The intrinsic dynamics  $F_X$  is thus the climate  $O(1)$  timescale which one is trying to improve with the parameterization<sup>2</sup>. The term  $F_Y$  is defined based on which terms are considered as part of the fast variability. It is then assumed that this fast variability can be modeled as an Ornstein-Uhlenbeck process. The Markovian nature of the process defined by Eqs. (23)-(24) and its  
 25 singular behavior in the limit of an infinite timescale separation ( $\delta \rightarrow 0$ ) allow then to apply the method. More specifically, the parameter  $\delta$  serves to distinguish terms with different timescales and is then used as a small perturbation parameter. In this

<sup>2</sup>Note that in homogenization theory  $F_X$  and  $F_Y$  can also depend on both  $X$  and  $Y$ , a possibility that was not considered here in order to effectively compare the MTV and WL parameterizations.

setting, the backward Kolmogorov equation reads (Majda et al., 2001):

$$-\frac{\partial \rho^\delta}{\partial s} = \left[ \frac{1}{\delta^2} \mathcal{L}_1 + \frac{1}{\delta} \mathcal{L}_2 + \mathcal{L}_3 \right] \rho^\delta \quad (25)$$

where the [function-probability density](#)  $\rho^\delta(s, \mathbf{X}, \mathbf{Y}|t)$  is defined with the final value problem  $f(\mathbf{X}): \rho^\delta(t, \mathbf{X}, \mathbf{Y}|t) = f(\mathbf{X})$ .

The [function-density](#)  $\rho^\delta$  can be expanded in term of  $\delta$  and inserted in Eq. (25). The zeroth order of this equation  $\rho^0$  can be shown to be independent of  $\mathbf{Y}$  and its evolution given by a closed, averaged backward Kolmogorov equation (Kurtz, 1973):

$$-\frac{\partial \rho^0}{\partial s} = \bar{\mathcal{L}} \rho^0. \quad (26)$$

[The precise definition of the operators  \$\mathcal{L}\_i\$  and  \$\bar{\mathcal{L}}\$  acting on the densities is given in Appendix A.](#) This [latter](#) equation is obtained in the limit  $\delta \rightarrow 0$  and gives the sought limiting, averaged process  $\mathbf{X}(t)$ . The parameterization obtained by this procedure is detailed in Franzke et al. (2005) and takes the form (14). As stated above, the parameterization itself depends on which terms of the unresolved component are considered as “fast”, and some assumptions should here be made. It is the subject of the next section.

### 3.2 Model decompositions

As MAOOAM is a model whose nonlinearities consist solely of quadratic terms, the decomposition of Eq. (9) into a resolved and an unresolved component can be done based on the constant, linear and quadratic terms of its tendencies, as in Majda et al. (2001) and Franzke et al. (2005) :

$$\dot{\mathbf{X}} = \mathbf{H}^X + \mathbf{L}^{XX} \cdot \mathbf{X} + \mathbf{L}^{XY} \cdot \mathbf{Y} + \mathbf{B}^{XXX} : \mathbf{X} \otimes \mathbf{X} + \mathbf{B}^{XXY} : \mathbf{X} \otimes \mathbf{Y} + \mathbf{B}^{XYX} : \mathbf{Y} \otimes \mathbf{X} + \mathbf{B}^{YYX} : \mathbf{Y} \otimes \mathbf{Y} \quad (27)$$

$$\dot{\mathbf{Y}} = \mathbf{H}^Y + \mathbf{L}^{YY} \cdot \mathbf{Y} + \mathbf{L}^{YX} \cdot \mathbf{X} + \mathbf{B}^{YXX} : \mathbf{X} \otimes \mathbf{X} + \mathbf{B}^{YXY} : \mathbf{X} \otimes \mathbf{Y} + \mathbf{B}^{YYX} : \mathbf{Y} \otimes \mathbf{X} + \mathbf{B}^{YYY} : \mathbf{Y} \otimes \mathbf{Y} \quad (28)$$

The vectors  $\mathbf{H}$  are the constant terms of the tendencies. The matrices  $\mathbf{L}$  give the linear dependencies through matrix-vector products:

$$\left( \mathbf{L}^{XX} \cdot \mathbf{X} \right)_i = \sum_{j=1}^{N_X} L_{ij}^{XX} X_j. \quad (29)$$

The symbol  $\otimes$  is the outer product and is used to define matrices and tensors, e.g.:

$$(\mathbf{X} \otimes \mathbf{X})_{ij} = X_i X_j \quad \text{and} \quad (\mathbf{X} \otimes \mathbf{X} \otimes \mathbf{X})_{ijk} = X_i X_j X_k \quad (30)$$

and “ $\cdot$ ” means an element-wise product with summation over the last and first two indices of its first and second arguments respectively<sup>3</sup>. For a rank-3 tensor and a matrix, it gives for example:

$$\left( \mathbf{B}^{XXX} : \mathbf{X} \otimes \mathbf{X} \right)_i = \sum_{j,k=1}^{N_X} B_{ijk}^{XXX} X_j X_k. \quad (31)$$

<sup>3</sup>For two matrices  $\mathbf{A}$  and  $\mathbf{B}$ , it is thus the Frobenius inner product :  $\mathbf{A} : \mathbf{B} = \text{Tr}(\mathbf{A}^\top \cdot \mathbf{B})$ .



As we have seen in Section 3.1, the two parameterization methods rely on a weak coupling between the components for the WL method and on a clear three-stages timescale separation for the MTV method. ~~Moreover, as we will see below, their decomposition of the equations (27)-(28) is not necessarily the same, depending on modeling choices~~ In some particular cases, it is possible to establish an equivalence between these two assumptions (Wouters et al., 2016). However, in general, the relation

5 between the two is far from trivial. Time-scale separation is easy to assess, by considering the decorrelation times in the output data of the model. On the other hand, weak-coupling is difficult to measure in data, and appears in general as a small coupling parameter resulting from the proper modeling of the components of a system.

### 3.2.1 Decomposition of the resolved component tendencies

~~For~~ This decomposition can be chosen arbitrarily since the only requirement is that  $F_X$  depends solely on  $X$ . However, in the

10 following (and in the provided code), we will consider that the resolved-unresolved components form a coupled system, with “maximal” uncoupled dynamics. In this view for both parameterizations, the decomposition of the  $X$  component is the same, and we have:

$$F_X(\mathbf{X}) = \mathbf{H}^X + \mathbf{L}^{XX} \cdot \mathbf{X} + \mathbf{B}^{XXX} : \mathbf{X} \otimes \mathbf{X} \quad (32)$$

and

$$15 \Psi_X(\mathbf{X}, \mathbf{Y}) = \mathbf{L}^{XY} \cdot \mathbf{Y} + \mathbf{B}^{XXY} : \mathbf{X} \otimes \mathbf{Y} + \mathbf{B}^{XYY} : \mathbf{Y} \otimes \mathbf{Y}. \quad (33)$$

This choice was also consider in Franzke et al. (2005), dealing with the MTV parameterization. It is worth noting that other decompositions may improve or decrease the performance of the parameterization.

### 3.2.2 Decompositions of the unresolved component tendencies

The definition of  $F_Y$  and  $\Psi_Y$  is ~~not necessarily the same for both~~ also arbitrary, but it is of particular importance since it

20 is the measure of the system whose tendencies are given by  $F_Y(\mathbf{Y})$  over which the averages are performed (Demaeyer and Vannitsem, 2018). ~~Indeed, in~~ A requirement is thus that the dynamics  $\dot{\mathbf{Y}} = F_Y(\mathbf{Y})$  has an ergodic invariant measure. In the framework of the WL method, it is always natural to consider the measure of the intrinsic  $\mathbf{Y}$ -dynamics as:

$$\equiv F_Y(\mathbf{Y}) = \mathbf{H}^Y + \mathbf{L}^{YY} \cdot \mathbf{Y} + \mathbf{B}^{YYY} : \mathbf{Y} \otimes \mathbf{Y} \quad (34)$$

~~that is used~~ to perform the averaging.

25 In the framework of the MTV method, the measure of the ~~singular system  $\dot{\mathbf{Y}} = \frac{1}{\delta^2} F_Y(\mathbf{Y})$~~  singular system  $\dot{\mathbf{Y}} = F_Y(\mathbf{Y})$  is used for the averaging and it is usually assumed that the quadratic  $\mathbf{Y}$ -terms of the unresolved component tendencies represent the fastest timescale of the system (see Majda et al. (2001); Franzke et al. (2005)):

$$F_Y(\mathbf{Y}) = \mathbf{B}^{YYY} : \mathbf{Y} \otimes \mathbf{Y}. \quad (35)$$

and those are the ones over which the averaging has to be done. ~~The~~

In both cases, the others terms<sup>4</sup> belong then to  $\Psi_Y$ .

It is interesting to note that there is no a priori justification for this one or the other assumption. For instance both parameterization methods, the decomposition of the unresolved dynamics could be based on the full intrinsic dynamics (as in the WL method) and Eq. (34) or on Eq. (35). The code provided as supplementary materials allows to select the  $F_Y$  would then be given by the expression (34) - We consider these two different assumptions for the MTV in the following dynamics as either Eq. (34) or Eq. (35).

The MTV and WL parameterizations described above are presented in more details in the appendices A and B, respectively.

### 3.2.3 Noisy model

To take into account model errors or the impact of smaller scales, the present implementation of MAOOAM allows for the addition of Gaussian white noise in each components: resolved and unresolved, for both the ocean and the atmosphere. It also includes the timescale separation parameter  $\delta$  of the MTV framework (see Eqs. (23) and (24)) and the coupling parameter  $\varepsilon$  of the WL framework (see Eqs. (15) and (16)). The full equation (11) then reads:

$$\dot{\mathbf{X}}_a = F_{X,a}(\mathbf{X}) + \mathbf{q}_{X,a} \cdot d\mathbf{W}_{X,a} + \frac{\varepsilon}{\delta} \Psi_{X,a}(\mathbf{X}, \mathbf{Y}) \quad (36)$$

$$\dot{\mathbf{X}}_o = F_{X,o}(\mathbf{X}) + \mathbf{q}_{X,o} \cdot d\mathbf{W}_{X,o} + \frac{\varepsilon}{\delta} \Psi_{X,o}(\mathbf{X}, \mathbf{Y}) \quad (37)$$

$$\dot{\mathbf{Y}}_a = \frac{1}{\delta^2} \left( F_{Y,a}(\mathbf{Y}) + \delta \mathbf{q}_{Y,a} \cdot d\mathbf{W}_{Y,a} \right) + \frac{\varepsilon}{\delta} \Psi_{Y,a}(\mathbf{X}, \mathbf{Y}) \quad (38)$$

$$\dot{\mathbf{Y}}_o = \frac{1}{\delta^2} \left( F_{Y,o}(\mathbf{Y}) + \delta \mathbf{q}_{Y,o} \cdot d\mathbf{W}_{Y,o} \right) + \frac{\varepsilon}{\delta} \Psi_{Y,o}(\mathbf{X}, \mathbf{Y}) \quad (39)$$

and the noise amplitude can hence be different for each components. The  $d\mathbf{W}$ 's vectors are standard Gaussian white noise vectors. In the framework of stochastic parameterization, the presence of noise is sometimes required to smooth the averaging measure (Colangeli and Lucarini, 2014) or to increase the small-scale variability to address the problem of “dead” scales scales that are passively slaved and whose variability comes uniquely from their interactions with others. The  $F_Y(\mathbf{Y}) = (F_{Y,a}(\mathbf{Y}), F_{Y,o}(\mathbf{Y}))$  function can be specified by either Eq. (35) or (34) (only (34) for the WL parameterization). This flexible setup allows for testing both parameterizations in the same framework, with or without additional noise. We now present the results obtained by applying them to the MAOOAM model.

## 4 Results

The relative performance and the interesting features of the parameterizations described in the previous section require to consider multiple versions and resolutions of the model. We thus shall consider in the following two different resolutions. The first one is the 36-variables model version considered in Vannitsem et al. (2015) for which the maximum values for  $M$ ,  $H$  and

<sup>4</sup>In Franzke et al. (2005), it is also assumed that the constant terms  $\mathbf{H}^X$  and  $\mathbf{H}^Y$  are of order  $\delta$ , making it a four timescales system. These constant terms can thus be neglected in the parameterization. We do not consider this assumption in the present work, and suppose instead that  $\mathbf{H}^X$  and  $\mathbf{H}^Y$  are of order one.

$P$  in Eqs. (1)-(3) is 2. It corresponds to a “ $2x-2y$ ” resolution for the atmosphere as referred to in De Cruz et al. (2016). For the ocean, the maximum values for  $H_o$  and  $P_o$  in Eq. (4) are respectively 2 and 4, and the resolution is therefore noted “ $2x-4y$ ” in the same notation system. The model version for this first case is thus noted “atm- $2x-2y$  oc- $2x-4y$ ” and we shall abbreviate it the acronym “VDDG” from the name of the authors in Vannitsem et al. (2015). The other resolution that we shall consider is “atm- $5x-5y$  oc- $5x-5y$ ” that can be abbreviated “ $5 \times 5$ ” since we include Fourier modes up to the wavenumber 5 in both the ocean and the atmosphere. In this latter model version, the model possesses 160 variables.

We shall also consider different sets of parameters for the model configuration. To control the results obtained with the code implementation provided as supplementary material, we will compare our results with those obtained in Demaeyer and Vannitsem (2017) with the first set of parameter defined therein. We will refer to this set of parameter DV2017. A second set of parameters from De Cruz et al. (2016) is also considered and will be denoted DDV2016. For both “DV2017” and “DDV2016”, MAOOAM has been shown to depict coupled ocean–atmosphere low-frequency (LFV) variability. In consequence, we will also consider a third parameter set where no LFV is present. The LFV has been removed by reducing by an order of magnitude the wind friction parameter  $d$  between the ocean and the atmosphere. The coupled-mode dynamics then disappears. This parameter set is referred as noLFV. In addition, the parameters  $\delta$  and  $\varepsilon$  appearing in Eqs. (36)-(39) will be set to 1, meaning that we consider the natural timescale separations and coupling strengths of the model. Nevertheless, the study of the impact of these parameters is important (Demaeyer and Vannitsem, 2018) and should be carried out in forthcoming works.

Finally, for a given resolution and a given parameter set, multiple different parameterization experiments can be designed, by using for example the unresolved dynamics (35) or (34) for the MTV parameterization. However, to simplify the study and to be able to compare both the MTV and the WL parameterizations, we will here consider only the dynamics of (34) to perform the averages. Another way of defining different parameterization experiments is by changing the resolved and unresolved components. We shall detail these different experiments and the results obtained in the following subsections. [In each case, we have also checked the statistics of the dynamics \(34\) and have concluded that it is nearly Gaussian.](#)

Unless otherwise specified, the subsequent results were obtained by considering long trajectories lasting  $2.8 \times 10^6$  days  $\simeq$  7680 years, generated with a timestep of 96.9 s, and after an equivalent transient time. Such long trajectories were needed to be able to sample sufficiently the long timescales present in the model ( $\simeq$  20-30 years).

Parameter	DV2017	DDV2016	noLFV
$\lambda$	20	15.06	20
$r$	$10^{-8}$	$10^{-7}$	$10^{-8}$
$d$	$7.5 \times 10^{-8}$	$1.1 \times 10^{-7}$	$10^{-9}$
$C_o$	280	310	350
$C_a$	70	103.3333	100
$k_d$	$4.128 \times 10^{-6}$	$2.972 \times 10^{-6}$	$4.128 \times 10^{-6}$
$k'_d$	$4.128 \times 10^{-6}$	$2.972 \times 10^{-6}$	$4.128 \times 10^{-6}$
$H$	500	136.5	500
$G_o$	$2.00 \times 10^8$	$5.46 \times 10^8$	$2.00 \times 10^8$
$G_a$	$10^7$	$10^7$	$10^7$
$q_{a,X}, q_{a,Y}$	$5 \times 10^{-4}$	$5 \times 10^{-4}$	$5 \times 10^{-4}$
$q_{o,X}, q_{o,Y}$	0	0	0

**Table 1.** The main parameters used in the parameterization experiments. For a description of the parameters, see De Cruz et al. (2016) and Demaeyer and Vannitsem (2017).

#### 4.1 The 36-variables VDDG model version

For this model version, the atmospheric Fourier modes are denoted:

$$\begin{aligned}
F_1(x', y') &= \sqrt{2} \cos(y'), \\
F_2(x', y') &= 2 \cos(nx') \sin(y'), \\
5 \quad F_3(x', y') &= 2 \sin(nx') \sin(y'), \\
F_4(x', y') &= \sqrt{2} \cos(2y'), \\
F_5(x', y') &= 2 \cos(nx') \sin(2y'), \\
F_6(x', y') &= 2 \sin(nx') \sin(2y'), \\
F_7(x', y') &= 2 \cos(2nx') \sin(y'), \\
10 \quad F_8(x', y') &= 2 \sin(2nx') \sin(y'), \\
F_9(x', y') &= 2 \cos(2nx') \sin(2y'), \\
F_{10}(x', y') &= 2 \sin(2nx') \sin(2y'),
\end{aligned} \tag{40}$$

and the oceanic ones:

$$\begin{aligned}
\phi_1(x', y') &= 2 \sin(nx'/2) \sin(y'), \\
\phi_2(x', y') &= 2 \sin(nx'/2) \sin(2y'), \\
\phi_3(x', y') &= 2 \sin(nx'/2) \sin(3y'), \\
5 \quad \phi_4(x', y') &= 2 \sin(nx'/2) \sin(4y'), \\
\phi_5(x', y') &= 2 \sin(nx') \sin(y'), \\
\phi_6(x', y') &= 2 \sin(nx') \sin(2y'), \\
\phi_7(x', y') &= 2 \sin(nx') \sin(3y'), \\
\phi_8(x', y') &= 2 \sin(nx') \sin(4y').
\end{aligned} \tag{41}$$

- 10 The associated Fourier coefficients  $\{\{\psi_{a,i}\}, \{\theta_{a,i}\}, \{\psi_{o,j}\}, \{\theta_{o,j}\}\}_{i \in \{1, \dots, 10\}, j \in \{1, \dots, 8\}}$  form the dynamical system variables. We now propose different partitions of these variables into different resolved and unresolved sets. We will detail, for each of these parameterization experiment, the results obtained for the different aforementioned parameter sets.

#### 4.1.1 Parameterization based on the invariant manifold

- We first consider a parameterization based on the presence in the VDDG model of [an a](#) genuine invariant manifold. As stated  
15 in [Demaeyer and Vannitsem \(2017\)](#), this manifold is due to the existence of a subset of the Fourier modes that is [let left](#) invariant by the Jacobian term of the partial differential equation of the system:

$$J(\psi, \phi) = \frac{\partial \psi}{\partial x} \frac{\partial \phi}{\partial y} - \frac{\partial \psi}{\partial y} \frac{\partial \phi}{\partial x}. \tag{42}$$

In the same spirit, we consider the atmospheric variables outside of this invariant manifold to be unresolved, all the other variables being resolved. The modes  $F_2, F_3, F_4, F_7$  and  $F_8$  are outside of this invariant set, and therefore the variables

- 20  $\psi_{a,2}, \psi_{a,3}, \psi_{a,4}, \psi_{a,7}, \psi_{a,8}, \theta_{a,2}, \theta_{a,3}, \theta_{a,4}, \theta_{a,7}, \theta_{a,8}$

- are considered as unresolved. Using the same parameterizations, parameters and methods as in [Demaeyer and Vannitsem \(2017\)](#), we should recover the same results with our current implementation<sup>5</sup>. This would thus provide a first mandatory check for the correctness of the current implementation. We show the results obtained on Fig. 2 for the ‘‘DV2017’’ parameter set, where the probability density functions (PDFs) of three important variables of the dynamics are displayed. These three variables are  
25  $\psi_{a,1}, \psi_{o,2}$  and  $\theta_{o,2}$ , and were shown in [Vannitsem and Ghil \(2017\)](#) to account for respectively 18%, 42% and 51% of the variability in some key reanalysis 2-dimensional fields over the North-Atlantic ocean. In [Vannitsem et al. \(2015\)](#), it was also shown that these three variables are dominant in the LFV pattern found in the VDDG model version of MAOOAM. In addition to the PDFs of the full coupled system (13) and of the uncoupled system  $\dot{X} = F_X(X)$ , the PDFs of the parameterizations are depicted on Fig. 2 with two different settings for the correlation and covariance matrices. Indeed, the two methods need the

<sup>5</sup>The code used in [Demaeyer and Vannitsem \(2017\)](#) is different than the implementation provided as supplementary materials with the present work.

specification of the correlation and covariance matrices of the unresolved dynamics (34). These are the matrices  $\sigma_Y$ ,  $\Sigma$  and tensor  $\Sigma_2$  for the MTV method (see Appendix A), and the matrices  $\sigma_Y$ ,  $\langle Y \otimes Y^s \rangle_{\rho_{0,Y}}$  and tensors  $\rho_{\partial Y}$ ,  $\rho_{Y\partial Y Y}$  for the WL method (see Appendix B). In the present case, with a parameterization based on the invariant manifold, the dynamics of the unresolved dynamics (34) is a multidimensional Ornstein-Uhlenbeck, for which the measure is well known and thus analytical expressions for the correlations can be provided to the code. This analytical solution is also used in Demaeyer and Vannitsem (2017) and is one of the [setting\\_settings](#) that we used to compute the parameterization. This setting is also compared with a setting using a numerical least-square regression method to obtain the correlation of variables of the system (34), assuming that these are of the simplified form

$$a \exp\left(-\frac{t}{\tau}\right) \cos(\omega t + k) \quad (43)$$

where  $t$  is the time lag and  $\tau$  is the decorrelation time. The results obtained for these two different settings of the correlation (analytical vs. numerical) are shown in Fig. 2 with “check” indicating the results obtained with the analytical expressions for the correlations. The latter expressions improve the correction of the dynamics for both the WL and the MTV methods and we recover the same results as in Demaeyer and Vannitsem (2017).<sup>6</sup> On the other hand, in the case where the correlations are specified by the results of the numerical analysis, the parameterizations perform less well, indicating that these methods can be very sensitive to a correct representation of the correlation structure of the unresolved dynamics.

Both the MTV and the WL methods correct better the oceanic variables whereas the atmospheric variables seem to display too different dynamical behavior between the coupled and uncoupled systems which are difficult to correct. As stated in Demaeyer and Vannitsem (2017), it may be due to the huge dimension of the unresolved system, with half of the atmospheric mode being parameterized. However, the decomposition based on the invariant manifold is an elegant one, based on deep properties of the advection operator (42). It leads to simplified coupling and is thus computationally advantageous. Within this framework, an adaptation based on the next order of both parameterization methods or the consideration of other parameterizations could lead to a very efficient correction for both the ocean and atmosphere.

As the present implementation allows for an arbitrary selection of the resolved-unresolved components, we shall now consider cases of the VDDG model version with different unresolved components.

#### 4.1.2 Parameterization of the wavenumber 2 atmospheric variables

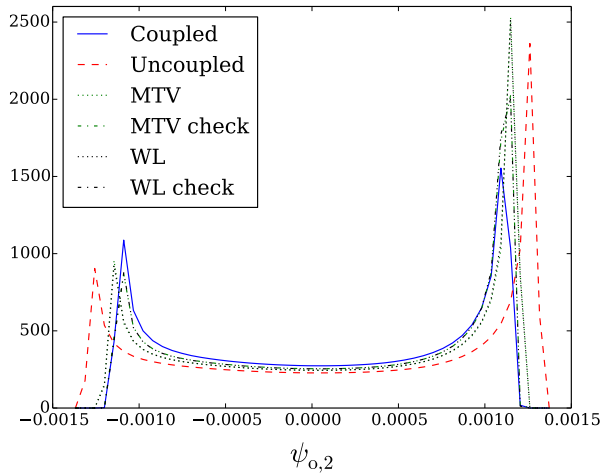
We consider now a smaller set of unresolved variables  $Y$ , composed of the two higher resolution modes of the model:

$$\begin{aligned} F_9(x', y') &= 2 \cos(2nx') \sin(2y') \\ F_{10}(x', y') &= 2 \sin(2nx') \sin(2y'). \end{aligned} \quad (44)$$

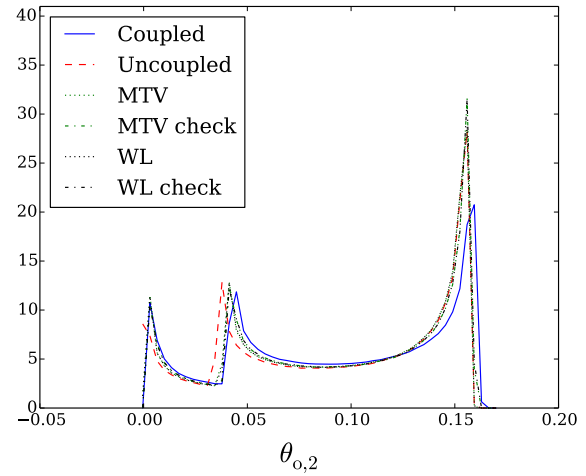
The unresolved variables  $Y$  are thus the following ones:  $\psi_{a,9}$ ,  $\psi_{a,10}$ ,  $\theta_{a,9}$  and  $\theta_{a,10}$ .

A first comment on the results obtained with that particular configuration is that the WL method seems to be unstable for all the parameter sets investigated. As stated in the Appendix section B4, the equation (18) is integrated with a

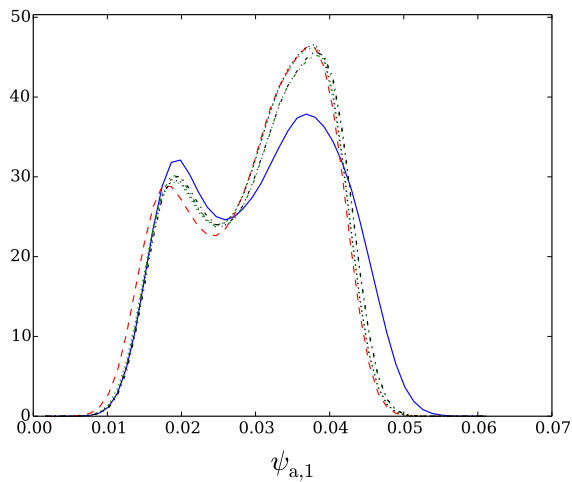
<sup>6</sup>In fact, for the present parameterization based on invariant manifold, the expression of both methods is very close and coincide for a infinite timescale separation.



(a)



(b)



(c)

**Figure 2.** Probability density functions (PDFs) of the dominant variables of the system dynamics with the invariant manifold decomposition for the  $X$  and  $Y$  components. The densities of the full coupled system (13) and of the uncoupled system are depicted for the “DV2017” parameter set, as well as the ones of the MTV and WL parameterizations and their verifications. The “check” label indicates that the correlations used for the parameterizations were analytical, while for the other they were obtained by numerical analysis.

Heun algorithm where the term  $M_3$  is considered constant during the corrector-predictor steps. As this could lead to instabilities, a *backward differentiation formulae* (BDF) designed for stiff integro-differential equations has been tested to integrate (18) (Lambert, 1991; Wolkenfelt, 1982), but the instabilities were still present, leading us to suspect a genuine instability in the parameterized system. Indeed, we found that it is the cubic term  $M(s)$  in the memory term  $M_3$  (see Eq. (B30)) which causes the divergence, in particular the interactions with the  $F_4$  mode. [These cubic terms are nonlinear dampings, as shown in Majda et al. \(2009\) and Peavoy et al. \(2015\).](#) On the contrary, the MTV parameterization is stable and performs well, despite having a similar cubic term. It indicates that the correlations induced by the memory term are a possible cause of the instability. More research effort to understand this stability issue is needed.

The quality of the solutions obtained with the MTV method alone, applied to the system with the three parameter sets of Table 1, is evaluated using the Kullback-Leibler divergence

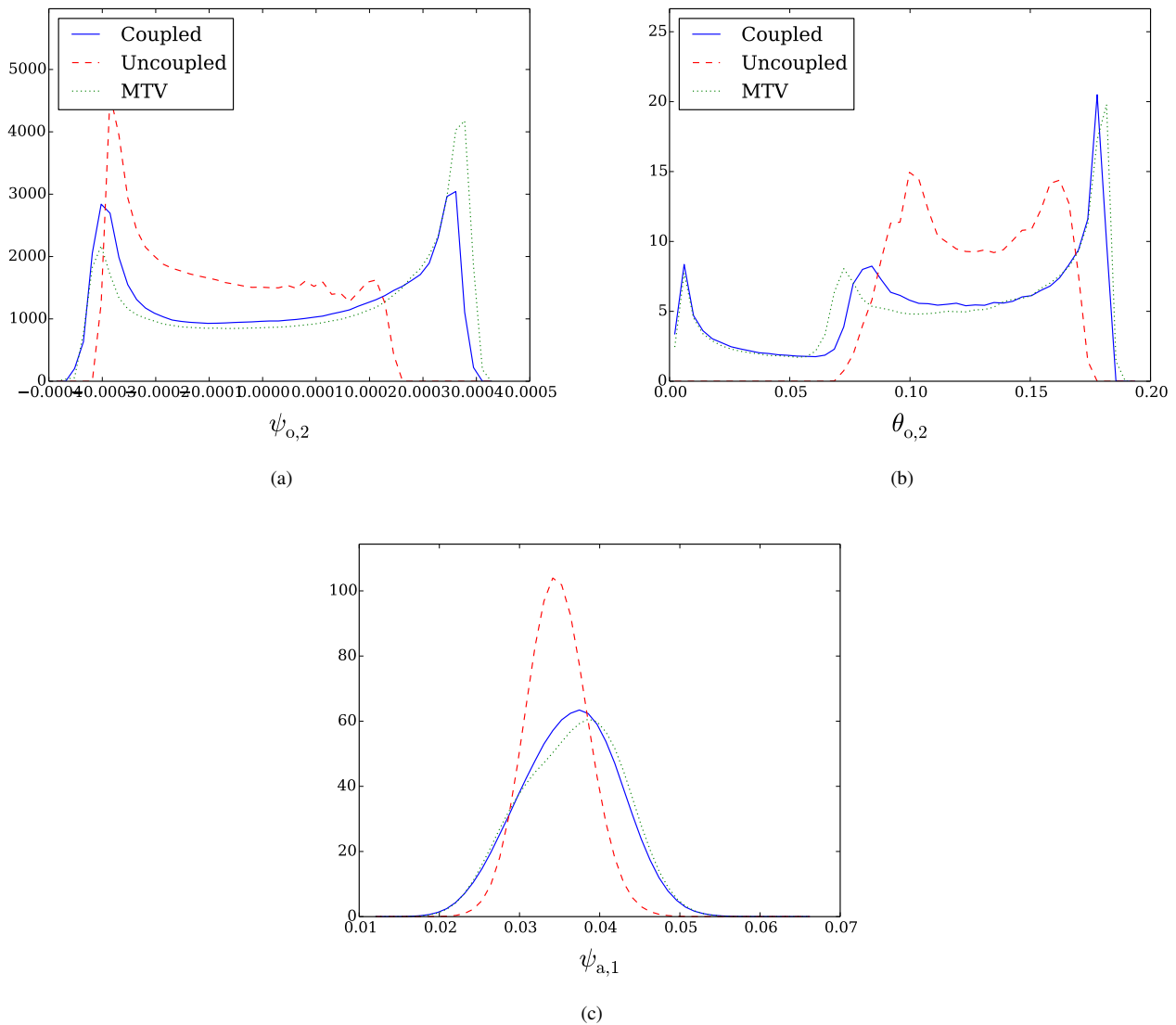
$$D_{\text{KL}}(p||q) = \int_{-\infty}^{\infty} dx \log \frac{p(x)}{q(x)} \quad (45)$$

between the distribution of  $p(x)$  the full coupled system and the distribution  $q(x)$  of the parameterized system that is tested. It is related to the information lost when this parameterization is used instead of the full system. The bigger the divergence, the greater is the amount of information lost. For clarity, we show only the divergence of the marginal distributions averaged by component. In every case and for every component, the MTV parameterization reduces dramatically the divergence and thus corrects well the models, making it clearly a better choice than the “Uncoupled” dynamics. These divergences are compiled in Table 2. It is worth noting that in the atmosphere, it is the barotropic component (the streamfunction) that gets better corrected, while on the contrary, in the ocean, it is the temperature field which benefits the most from the parameterization effects.

As depicted on Figs. 3 and 5, the PDFs of the three dominant variables selected show a neat correction, with a good representation of the LFV when it is present, and a correct shift of the dynamics and the temperature when no LFV occurs. In particular, one can notice on Fig. 3 a change of the distributions modality due to the parameterization. It raises the question about the mechanism of this rather drastic modification: Is it the noise that changes the dynamics or does the noise simply trigger and shift a bifurcation of the unresolved system, which then induces the change of modality? To give some insight about this latter possibility, we considered the “noLFV” parameter set and increased the ocean-atmosphere wind stress coupling parameter  $d$  to  $5 \times 10^{-9}$ . With this change of parameter, the system now lies nearby the Hopf bifurcation generating the long periodic orbit which forms the backbone of the LFV. In other words, the system does not exhibit a LFV but a small parameter perturbation could induce it. As seen on Fig. 7, the MTV parameterization then induces a LFV which is not present in both the resolved and the full system. In that case, the parameterization wrongfully “triggers” a bifurcation and thus leads to a false reduced dynamics. This interesting issue, also considered by recent works on the effect of the noise on models dynamics, will be further discussed in the conclusion of this paper (see Section 5).

The impact of the MTV parameterization on the correlation is also particularly important, as seen on Figs. 4 and 6, correcting the covariance (the value at the time lag  $t = 0$ ) and inducing or suppressing oscillations. It shows that the parameterization not only affects the attractors and the climatologies of the models, but also the temporal dynamics.

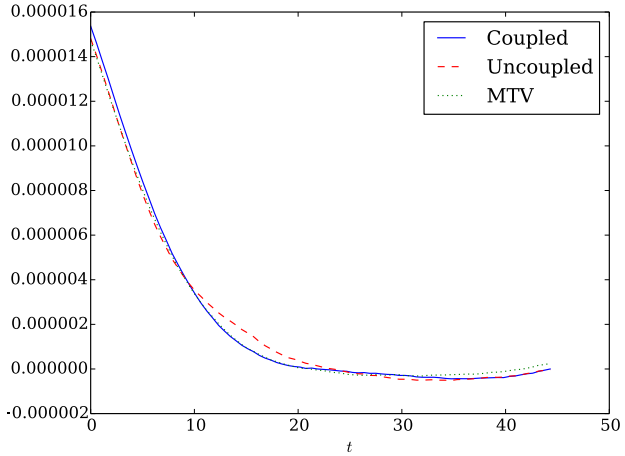




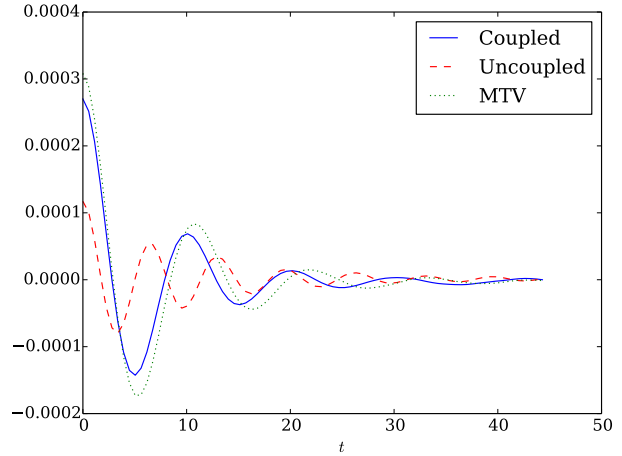
**Figure 3.** Probability density functions (PDFs) of the dominant variables of the system dynamics as in Fig. 2, but for the wavenumber 2 parameterization and with the parameter set “DDV2016”. The WL parameterization results are not shown as it is unstable and diverges.

Additional marginal PDF and autocorrelation function figures are available for each variable of the system in the supplementary material. The Kullback-Leibler divergences (45) are available as well.

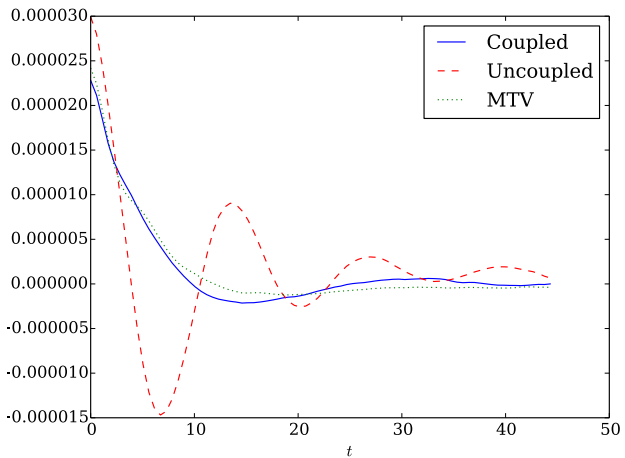
Since the WL parameterization does not work in the current case, we cannot properly compare both methods. To do so, we shall consider two other parameterization configurations in the following sections.



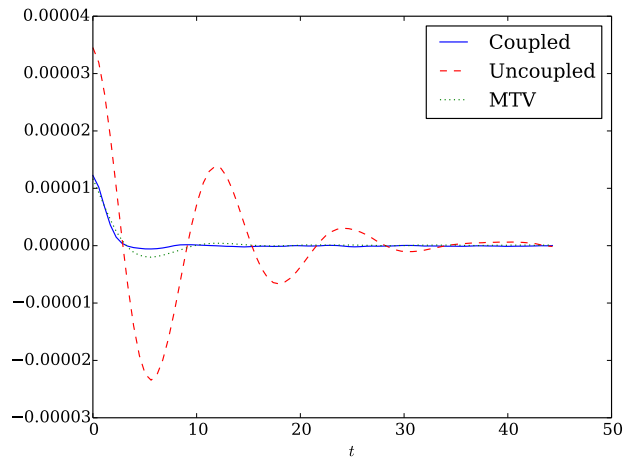
(a) Correlation function of  $\psi_{a,1}$ .



(b) Correlation function of  $\psi_{a,2}$ .

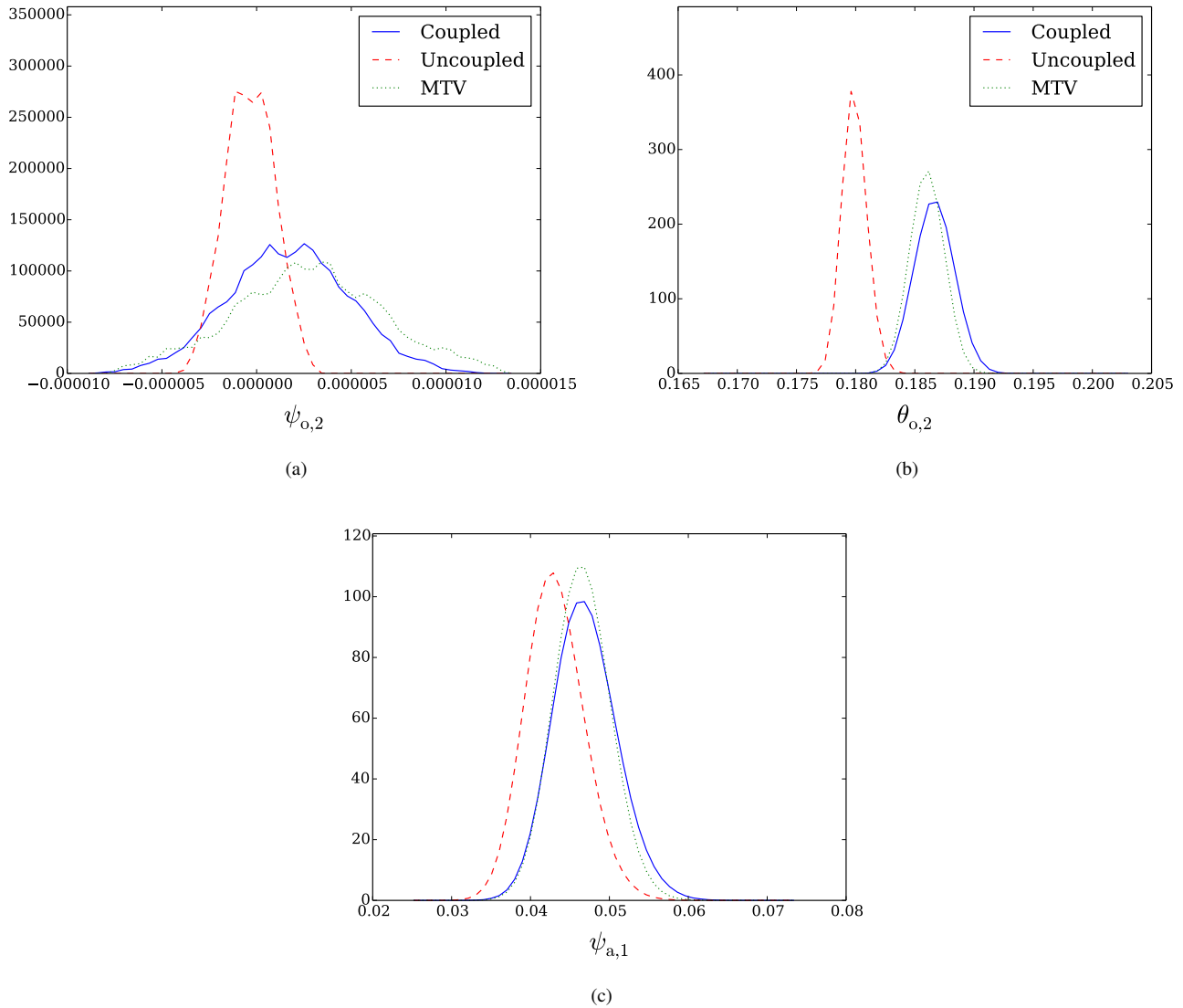


(c) Correlation function of  $\theta_{a,6}$ .

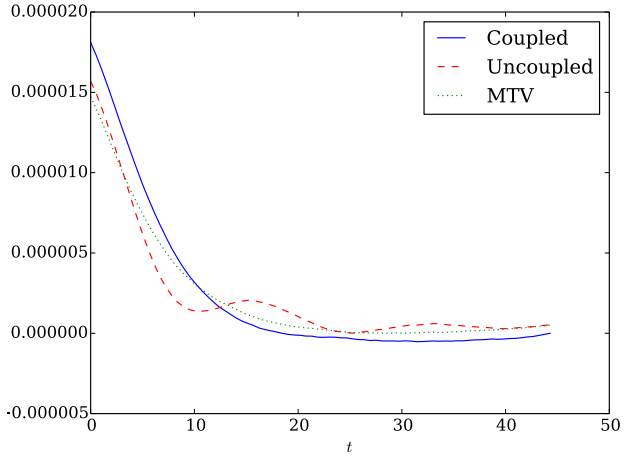


(d) Correlation function of  $\theta_{a,8}$ .

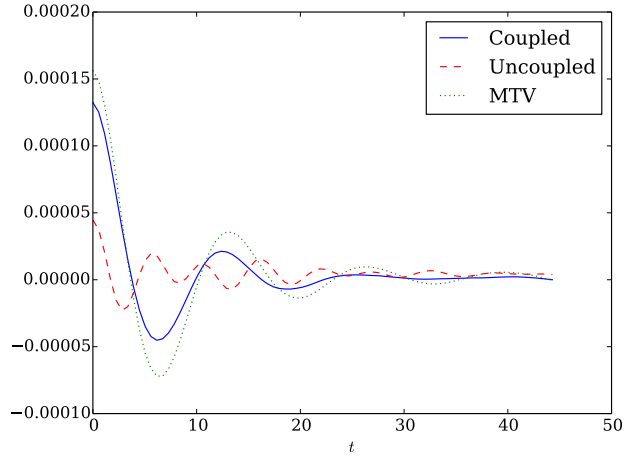
**Figure 4.** Correlation function of various variables for the wavenumber 2 parameterization and with the parameter set “DDV2016”. The correlation of the full coupled system (13), the uncoupled system and the MTV parameterizations are depicted as a function of the time lag  $t$ . The WL parameterization results are not shown as it is unstable and diverges.



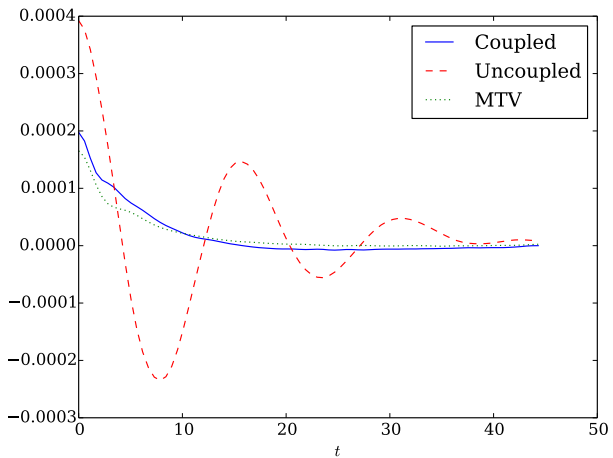
**Figure 5.** Probability density functions (PDFs) of the dominant variables of the system dynamics as in Fig. 2, but for the wavenumber 2 parameterization and with the parameter set “noLFV”. The WL parameterization results are not shown as it is unstable and diverges.



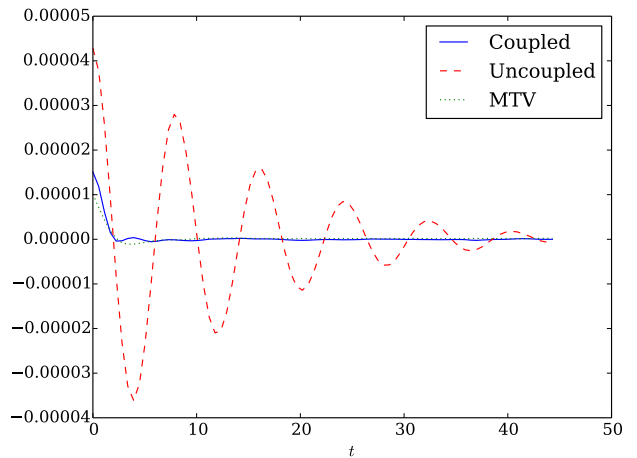
(a) Correlation function of  $\psi_{a,1}$ .



(b) Correlation function of  $\theta_{a,2}$ .

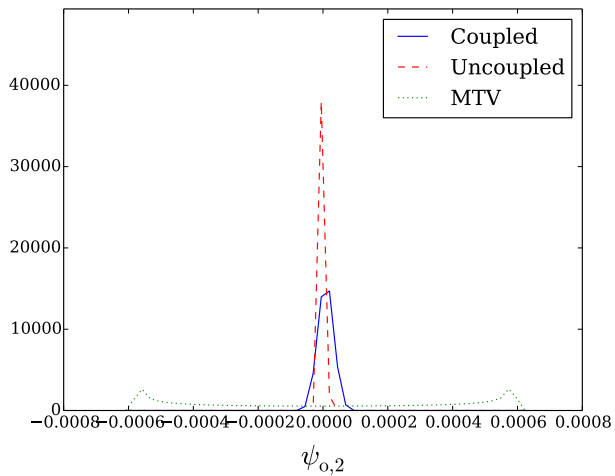


(c) Correlation function of  $\psi_{a,5}$ .

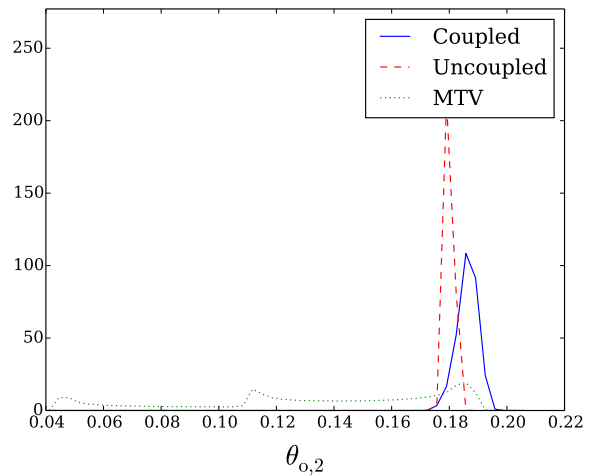


(d) Correlation function of  $\theta_{a,7}$ .

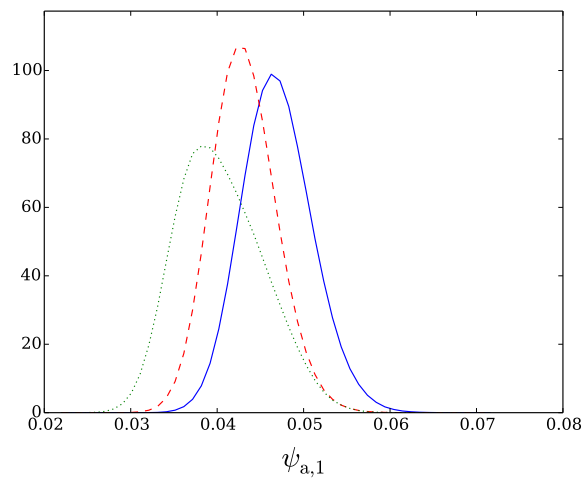
**Figure 6.** Correlation function of various variables for the wavenumber 2 parameterization and with the parameter set “noLFV”. The correlation of the full coupled system (13), the uncoupled system and the MTV parameterizations are depicted as a function of the time lag  $t$ . The WL parameterization results are not shown as it is unstable and diverges.



(a)



(b)



(c)

**Figure 7.** Probability density functions (PDFs) of the dominant variables of the system dynamics as in Fig. 2, but for the wavenumber 2 parameterization. It is shown for the parameter set “noLFV” but with the wind-stress parameter set to  $d = 0.5 \times 10^{-9}$  and for which the MTV parameterization depicts a false LFV.

	Barotropic atm.		Baroclinic atm.		Barotropic oc.		Temperature oc.	
	Uncoupled	MTV	Uncoupled	MTV	Uncoupled	MTV	Uncoupled	MTV
DDV2016	0.3343	0.0075	0.1643	0.0066	0.4592	0.0811	0.8148	0.0346
DV2017	0.0776	0.0022	0.0476	0.0031	0.1477	0.0822	0.1886	0.0379
noLFV	0.7415	0.0572	0.4113	0.0386	0.0875	0.0796	1.5815	0.2389

**Table 2.** Component averaged Kullback-Leibler divergence with respect to the distributions of the full coupled system, in the case of the wavenumber 2 atmospheric variables parameterization.

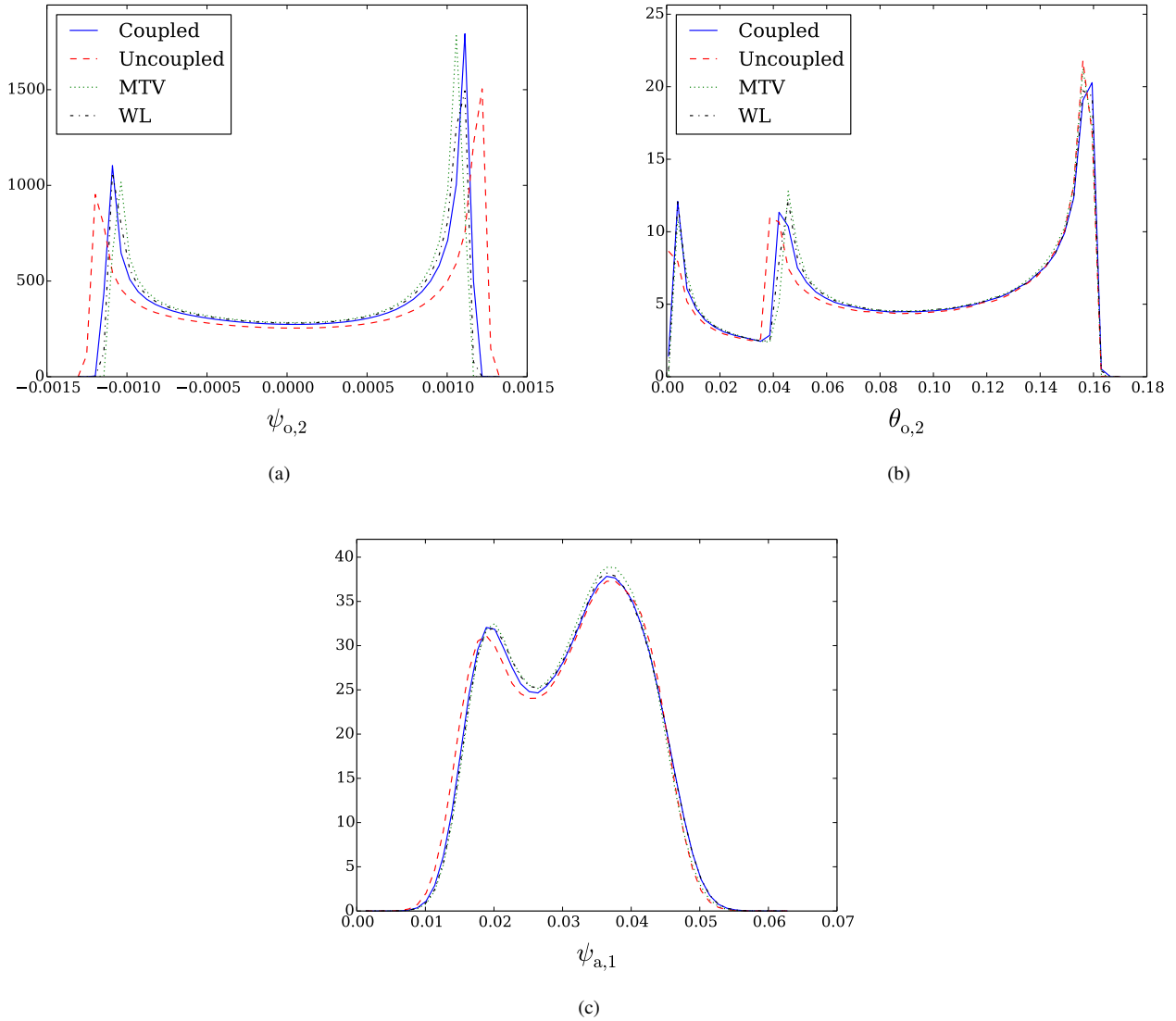
### 4.1.3 Parameterization of the wavenumber 2 atmospheric baroclinic variables

Let us now consider that only the two baroclinic variables  $\theta_{a,9}$  and  $\theta_{a,10}$  are unresolved. This particular case allows for the comparison of the WL and the MTV methods. Indeed, in this configuration, the destabilizing cubic interactions with the mode  $F_4$  are suppressed and the WL parameterization is now stable. The results are summarized in Table 3 where the Kullback-Leibler divergence (45) of the parameterizations marginal distributions with respect to the full coupled system ones are indicated. The divergence of the uncoupled system with respect to the full system is less pronounced than in the previous section. The uncoupled dynamics is thus not very different from the coupled one. Nevertheless:

- The parameterizations correct quite well the ocean components, except for the MTV parameterization of the baroclinic component in the noLFV case. The MTV parameterization is better in the DDV2016 case, and the WL one is better in the two other cases.
- The barotropic component of the atmosphere is only well corrected in the DV2017 case. Additionally, the MTV fails to correct also the baroclinic PDFs in the two other cases. In fact, the MTV method seems only to performs well in the DV2017 case. Looking to the divergence for every variables (see the supplementary material), we note that those under-performance are due to the incorrect representation of the small-scale wavenumber 2 barotropic variables, namely the  $\psi_{a,6}-\psi_{a,10}$  ( $\psi_{a,5}-\psi_{a,10}$ ) variables for the WL (MTV) method.

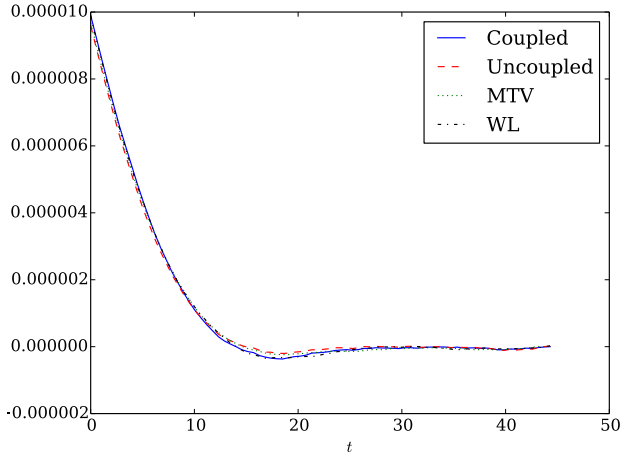
Interestingly, the PDFs of the dominant variables  $\psi_{a,1}$ ,  $\psi_{o,2}$  and  $\theta_{o,2}$  are well corrected as shown in Fig. 8 for the DV2017 case and slightly better corrected in Fig. 10 for the DDV2016 case. We remark that in general the WL parameterization is better at correcting the LFV than the MTV one, but the situation can be more complicated, like in Fig. 10(b), where the WL parameterization captures well one mode of the distribution, and the MTV parameterization captures well another mode.

Regarding the correlation functions, a first general comment is that in this configuration, the decorrelation time of the large scales (mode  $F_1$ ) does not appear to be significantly affected by the absence of the unresolved variables. On the other hand, the impact on the other modes is noticeable, and both parameterizations improve in general the correlations of the resolved variables. Finally, a general observation for all the parameter sets is the bad correction of the variables  $\psi_{a,9}$  and  $\psi_{a,10}$  (see Fig. 9(d)). This is not surprising since these variables are strongly coupled to the unresolved  $\theta_{a,9}$  and  $\theta_{a,10}$  variables, and have roughly the same decorrelation timescale. It also may explain the poor scores of the atmospheric zonal wavenumber 2 modes

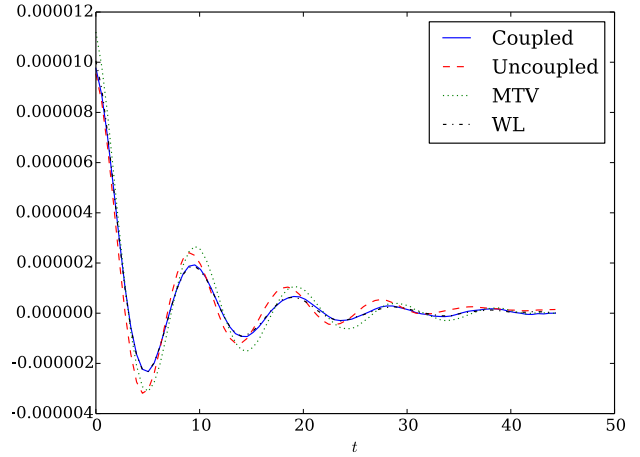


**Figure 8.** Probability density functions (PDFs) of the dominant variables of the system dynamics as in Fig. 2, but for the wavenumber 2 baroclinic parameterization and with the parameter set DV2017.

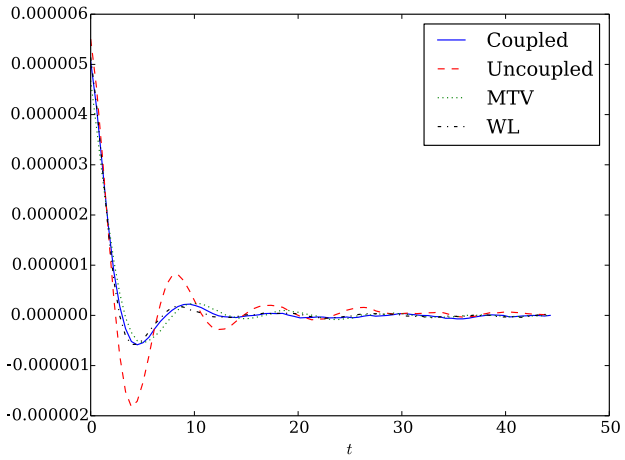
noted above. It implies that by parameterizing baroclinic variables at certain scales, one should not expect these methods to perform well for the barotropic variables at the same scale.



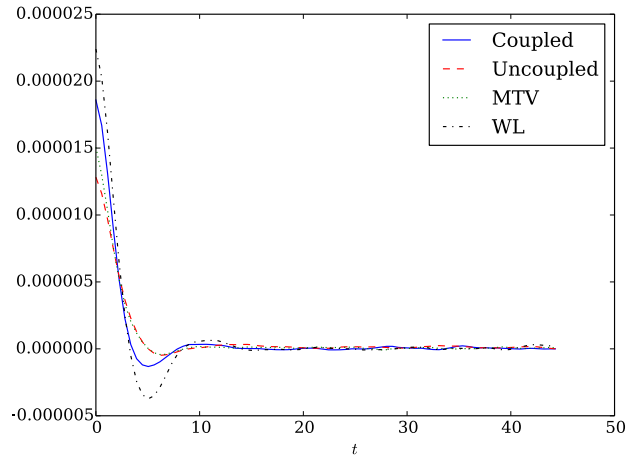
(a) Correlation function of  $\psi_{a,1}$ .



(b) Correlation function of  $\theta_{a,4}$ .



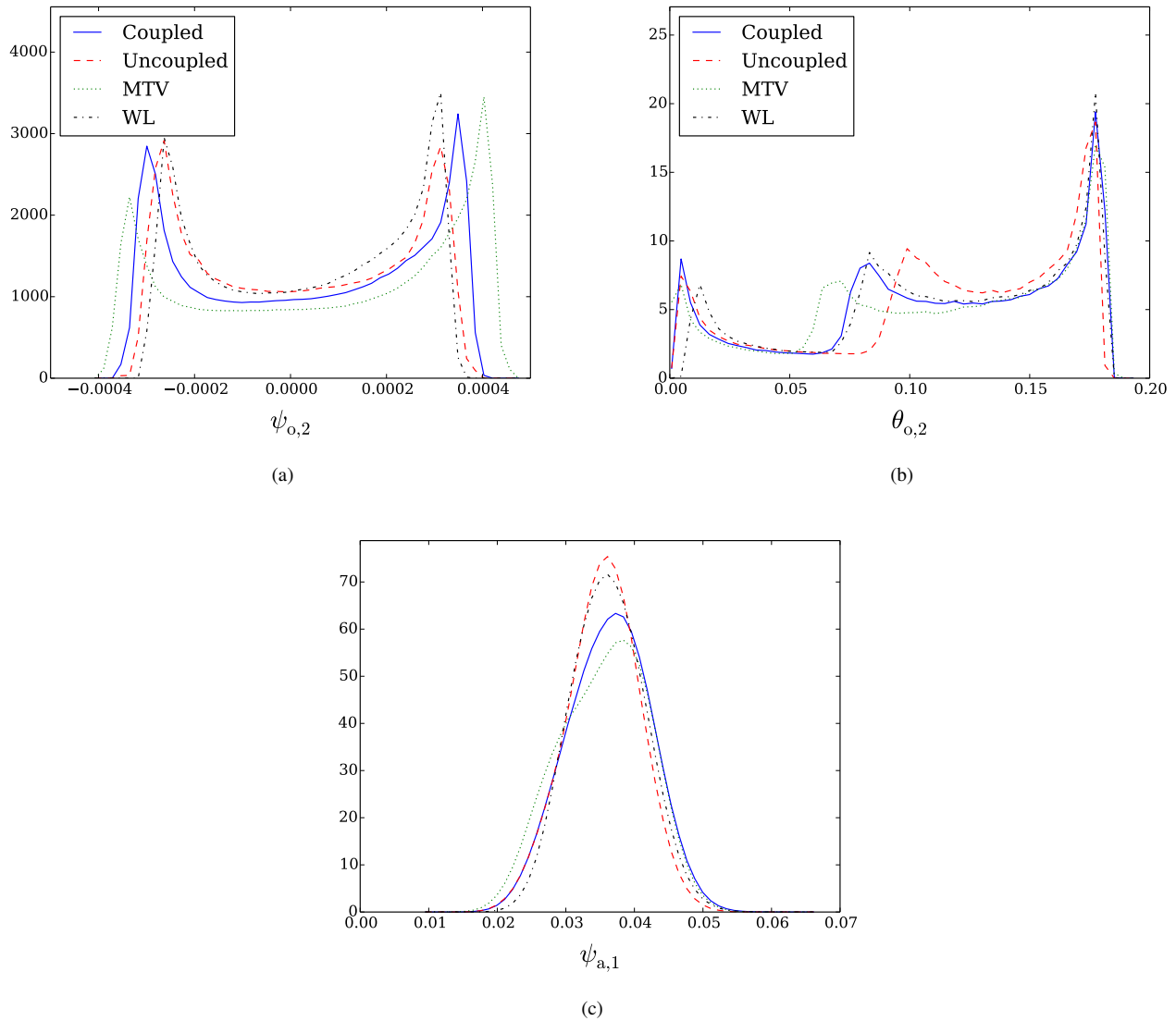
(c) Correlation function of  $\theta_{a,7}$ .



(d) Correlation function of  $\psi_{a,10}$ .

**Figure 9.** Correlation function of various variables for the wavenumber 2 parameterization and with the parameter set DV2017. The correlation of the full coupled system (13), the uncoupled system, the MTV and the WL parameterizations are depicted as a function of the time lag  $t$ .





**Figure 10.** Probability density functions (PDFs) of the dominant variables of the system dynamics as in Fig. 2, but for the wavenumber 2 baroclinic parameterization and with the parameter set DDV2016.

	Barotropic atm.			Baroclinic atm.			Barotropic oc.			Temperature oc.		
	Uncoupled	MTV	WL	Uncoupled	MTV	WL	Uncoupled	MTV	WL	Uncoupled	MTV	WL
DDV2016	0.0097	0.0352	0.0104	0.0104	0.0145	0.0032	0.1983	0.0932	0.1120	0.1191	0.0700	0.0930
DV2017	0.0110	0.0036	0.0016	0.0018	0.0013	0.0003	0.1312	0.0781	0.0227	0.1277	0.0152	0.0090
noLFV	0.0208	0.1070	0.0433	0.0233	0.0660	0.0174	0.1891	0.0597	0.0523	0.1041	0.3696	0.0998

**Table 3.** Component averaged Kuhlback-Leibler divergence with respect to the distributions of the full coupled system, in the case of the wavenumber 2 atmospheric baroclinic variables parameterization.

	Barotropic atm.			Baroclinic atm.			Barotropic oc.			Temperature oc.		
	Uncoupled	MTV	WL	Uncoupled	MTV	WL	Uncoupled	MTV	WL	Uncoupled	MTV	WL
DV2017	0.1409	0.0376	0.0087	0.1910	0.0252	0.0042	1.1779	0.1254	0.2035	1.4277	0.0613	0.1369
noLFV	0.6905	1.1874	0.3076	0.4360	1.0114	0.1578	0.0214	0.1337	0.2368	1.2016	1.1374	0.8179

**Table 4.** Component averaged Kuhlback-Leibler divergence with respect to the distributions of the full coupled system, in the case of the wavenumber 2 and  $F_4$  modes atmospheric parameterization.

#### 4.1.4 The parameterization of the atmospheric wavenumber 2 and $F_4$ modes

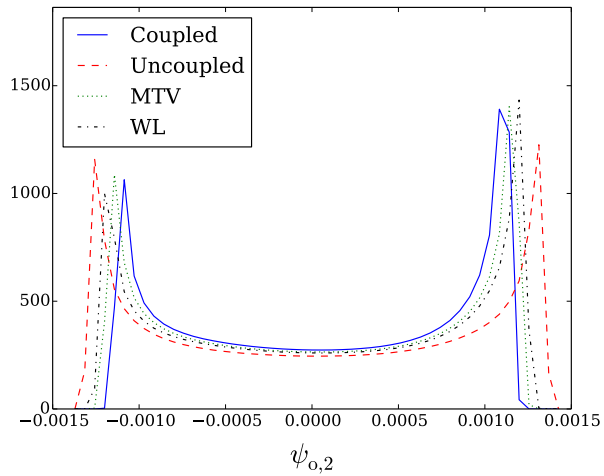
Another possibility to test the WL parameterization is to remove the aforementioned cubic interactions by considering that the wavenumber 2 modes and the meridional mode

$$F_4(x', y') = \sqrt{2} \cos(2y') \quad (46)$$

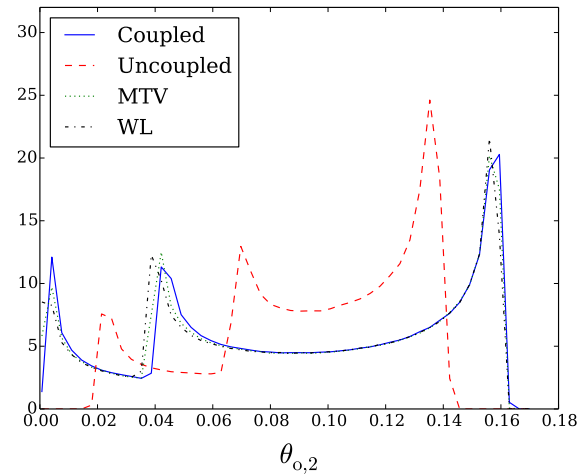
5 are unresolved. In this case the variables,  $\psi_{a,4}$ ,  $\theta_{a,4}$ ,  $\psi_{a,9}$ ,  $\psi_{a,10}$ ,  $\theta_{a,9}$  and  $\theta_{a,10}$  are considered as unresolved. The WL method is then stable and this configuration allows to compare both parameterizations.

The global averaged Kuhlback-Leibler divergence are given in Table 4 for two parameter sets. These results show a great disparity. For the DV2017 parameter set, the WL method does a better job at correcting the atmosphere while the MTV method corrects better the oceanic modes. Considering the other parameter set without a LFV, we notice that both methods have 10 troubles at improving the oceanic component. Note that with this particular wind stress reduced configuration, this component dynamics is less important since it can basically be modeled as an atmospheric fluctuations integrator (Hasselmann, 1976). The MTV method has also troubles at modeling the atmospheric dynamics correctly.

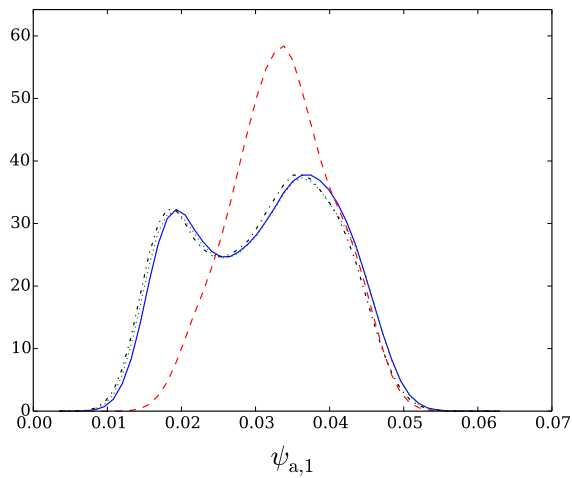
The PDFs of the three main variables (see Fig. 11) show that both parameterizations induce a change of modality for  $\psi_{a,1}$  and a good correction of the LFV. We note that the MTV method corrects better the LFV signal in the dominant oceanic modes 15  $\psi_{o,2}$  and  $\theta_{o,2}$  (as also shown in Table 4).



(a)



(b)



(c)

**Figure 11.** Probability density functions (PDFs) of the dominant variables of the system dynamics as in Fig. 2, but for the wavenumber 2 and  $F_4$  modes parameterization and with the parameter set “DV2017”.

## 4.2 The $5 \times 5$ model version

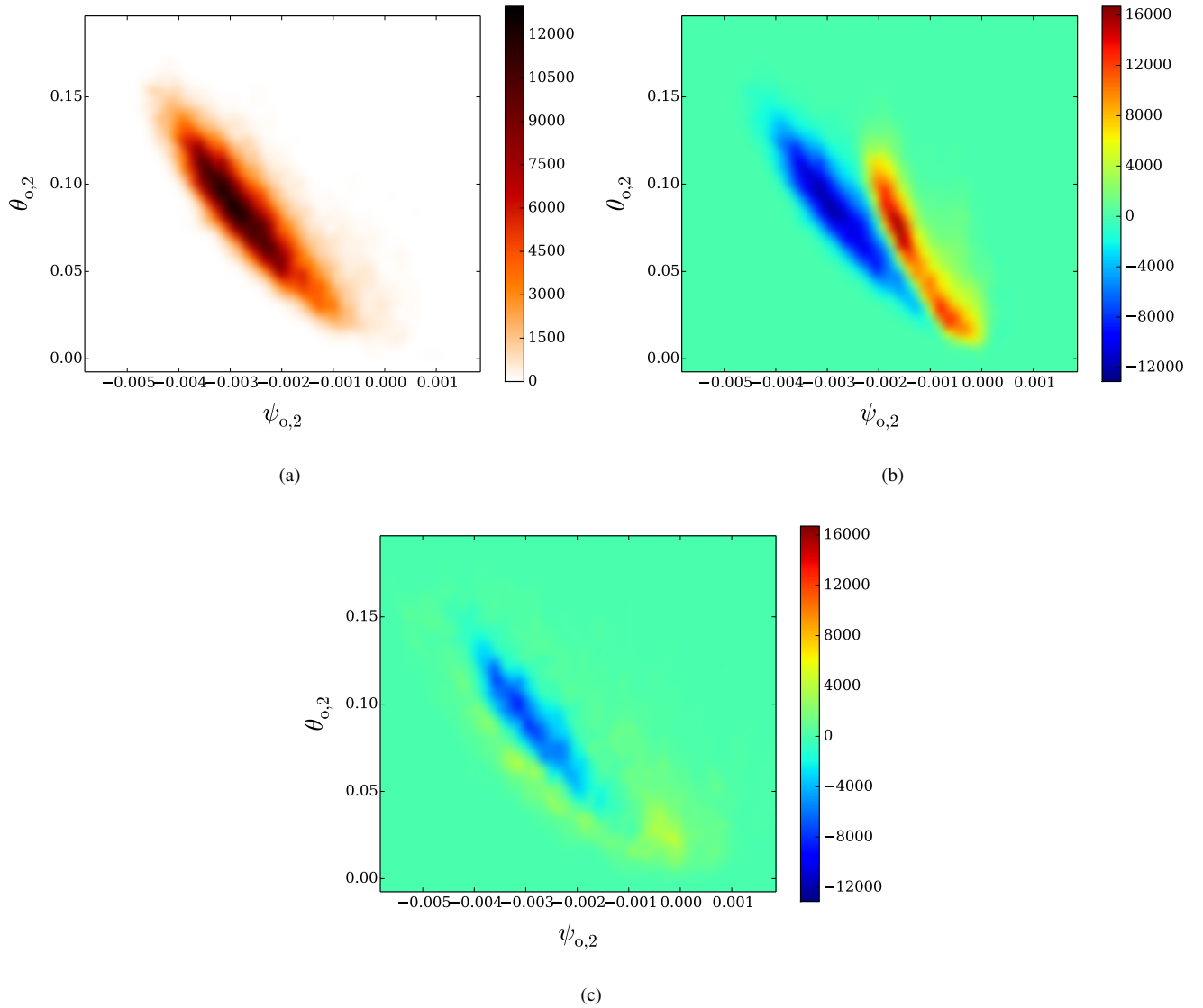
A higher-resolution test with the MTV method has also been performed by considering the  $5 \times 5$  resolution system discussed at section 4. In this version, the resolution goes up to wavenumber 5 in every spatial direction and in every component. We do a quite drastic reduction of the dimensionality of the system by considering every mode above the wavenumber 2 in the atmosphere as unresolved. Consequently, the uncoupled system is an “atm-2x-2y oc-5x-5y” model version. The result of the parameterization on the dominant  $\psi_{0,2}$  and  $\theta_{0,2}$  is shown on Fig. 12. The MTV method significantly corrects the 2D marginal distribution compared to the uncoupled model, as seen on the anomaly plots. Therefore, the oceanic section of the attractor of the MTV system is closer to the full coupled system than the uncoupled one. The atmosphere is not very well corrected by the parameterization. This could have multiple cause. First, the trajectory computed at this resolution is shorter (roughly one million days) and thus some long term equilibration of the dynamics might still take place. In this case, much longer computation might be undertaken. Secondly, the  $5 \times 5$  resolution represents a particular case, where the atmosphere’s Rhines scale is attained. At this scale, the dynamics is quite different from the higher or lower resolution model version De Cruz et al. (2016). If this has an influence on the parameterization performances, then it calls for even higher-resolution tests for confirmation. Finally, the parameterization may genuinely well correct the ocean while having trouble at improving the atmosphere representation, like for instance with the invariant manifold parameterization described in section 4.1.1 (see Fig. 2(c)).

## 5 Conclusions

In the present work, we have introduced a new framework to test different stochastic parameterization methods in the context of the ocean-atmosphere coupled model MAOOAM. We have implemented two methods: a homogenization method based on the singular perturbation of Markovian operator and known as MTV (Majda et al., 2001; Franzke et al., 2005), and a method based on the Ruelle’s response theory (Wouters and Lucarini, 2012) abbreviated WL. The code of the program is available as supplementary material, which allows for the future implementation of other parameterization methods in the context of a simplified ocean-atmosphere coupled model.

Within this framework, we have considered two different model resolutions and performed model reduction. We have performed several reductions in the case of a model version with 36 dimensions. We first parameterized atmospheric modes related to the existence of an invariant manifold present in the dynamics and the results previously obtained in Demaeyer and Vannitsem (2017) were recovered. In addition, we considered a more complex model reductions by parameterizing the atmospheric wavenumber 2 modes, for different model parameters. In most of the cases, the two methods performed well, correcting the marginal probability distributions and the autocorrelation functions of the model variables, even in the cases where a LFV is developing in the model. However, we have also found that the WL method shows instabilities, due to the cubic interactions therein. It indicates that the applicability of this method may crucially depend on the long-term correlations in the underlying system. The MTV method does not exhibit this kind of problem.

Additionally, we have found that these methods are able to change correctly the modality of the distributions in some cases. However, in some other cases, they can also trigger a LFV that is absent from the full system. This leads us to underline the



**Figure 12.** Parameterization of the  $5 \times 5$  model version with the MTV parameterization: (a) Two-dimensional probability density function (PDF) of the full-coupled dynamics with respect to the two dominant oceanic modes. (b) Anomaly of the PDF of the uncoupled dynamics with respect to the full-coupled one. (c) Anomaly of the PDF of the MTV dynamics with respect to the full-coupled one.

profound impact that a stochastic parameterization, and noise in general, can have on models. For instance, Kwasniok (2014) has shown that the noise can influence the persistence of dynamical regimes and can thus have a non-trivial impact on the PDFs, whose origin is the modification of the dynamical structures by the noise. In the present study as well, the perturbation of the dynamical structures by the noise is a very plausible explanation for the observed change of modality, and for the good performances of the parameterizations in general. However, if these perturbations can lead to a correct representation of the full dynamics, they can also generate regimes that are not originally present. This may happen near a sensitive bifurcation, as it is the case with a wrong LFV regime, which develops around a long-period periodic orbit (Vannitsem et al., 2015) arising through a Hopf bifurcation. If the main parameter (here for instance the wind stress parameter  $d$ ) is set close to this bifurcation, the noise may thus trigger it while it is not present in the full system (Horsthemke and Lefever, 1984).

10 The MTV parameterization has also been tested in a intermediate-order version of the model, showing that this parameterization reduces the anomaly of the PDF of the two dominant oceanic modes. The atmospheric modes are however less well corrected. In this case the number of modes that are removed is large and one can wonder whether reducing this number or increasing the resolution will help. More work needs to be done to assess the impact of the parameterizations on higher-order version of the models in the future.

15 The MTV method is simpler, less involved than the WL one, with no memory term estimations needed, and thus no integrals are being computed at every step. The memory term could however be Markovianized as in Wouters et al. (2016). The interest of the WL method is that it requires only a weak coupling between the resolved and the unresolved components, but no timescale separation between them, which is a desirable feature for a parameterization. Consequently, an improvement of the present framework would be to make the MTV method less dependent on the timescale separation. One way to do that is to consider the next order in  $\delta$ , the timescale separation parameter. This can be done effectively using the so-called *Edgeworth* expansion formalism, as shown by Wouters and Gottwald (2017). A next step would thus be to compute this expansion for the present coupled ocean-atmosphere system.

25 Finally, it would be interesting to consider that the unresolved dynamics used to perform the averaging may have non-Gaussian statistics. In the present work, as stated in Appendix A, the statistics of the neglected variables are assumed to come from a Gaussian. However, depending on the terms regrouped in this discarded part of the system, the statistics may well be non-Gaussian, and the resulting parameterization developed in this Appendix is then only an approximation. Indeed, unresolved variables with different linear damping terms can lead to such non-Gaussianity (see Sardeshmukh and Penland (2015)). An example of it is the MTV parameterization of the wavenumber 2 in the 36-variable system (see section 4.1.2), where the statistics are weakly non-Gaussian, because the linear damping of the baroclinic unresolved variables is not the same as the barotropic ones. But other configurations are concerned as well. Taking this into account could probably improve further the results obtained in the present study.

*Code availability.* The source code for MAOOAM v1.2 is available on GitHub at <http://github.com/Climdyn/MAOOAM>. The stochastic parameterization code is available in fortran in the `stoch` branch of this repository, in the `fortran` subdirectory. It is also provided as supplementary material to the present article.

## Appendix A: The MTV method

- 5 We now consider Eqs. (23)-(24) and assume that the dynamics induced by the order  $1/\delta^2$  term of the  $\mathbf{Y}$ -dynamics can be replaced by (or behaves like) a multidimensional Ornstein-Uhlenbeck process:

$$\dot{\mathbf{Y}} = \frac{1}{\delta^2} \mathbf{A} \cdot \mathbf{Y} + \frac{1}{\delta} \mathbf{B}_Y \cdot d\mathbf{W}_Y \quad (\text{A1})$$

- where  $\mathbf{W}_Y$  is a vector of independent Wiener processes. This [dynamics thus generates Gaussian distributions, such that the odd-order moments vanish and that the even-order moments are related to the second-order one](#). This assumption is described in Majda et al. (2001) as a *working assumption for stochastic modeling*. ~~This assumption~~ It is related to other underlying assumptions, i.e. that the dynamics of this singular term

$$\dot{\mathbf{Y}} = \frac{1}{\delta^2} F_Y(\mathbf{Y}) \quad (\text{A2})$$

- is ergodic and mixing with an integrable decay of correlation (Franzke et al., 2005). ~~We will also assume that this dynamics generates Gaussian distributions, such that the odd-order moments vanish and that the even-order moments are related to the second-order one.~~ In this case, the singular perturbation theory mentioned in section 3.1.2 gives the following result (see Papanicolaou (1976)) in the limit  $\delta \ll 1$  for the parameterization of the resolved component:

$$\dot{\mathbf{X}} = F_X(\mathbf{X}) + R(\mathbf{X}) + G(\mathbf{X}) + \sqrt{2} \boldsymbol{\sigma}(\mathbf{X}) \cdot d\mathbf{W} \quad (\text{A3})$$

where

$$R(\mathbf{X}) = \frac{1}{\delta} \left\langle \Psi_X(\mathbf{X}, \mathbf{Y}) \right\rangle_{\tilde{\rho}_Y} \quad (\text{A4})$$

$$20 \quad G(\mathbf{X}) = \frac{1}{\delta^2} \int_0^\infty ds \left\langle \Psi_Y(\mathbf{X}, \mathbf{Y}) \cdot \partial_Y \Psi_X(\mathbf{X}, \mathbf{Y}^s) \right\rangle_{\tilde{\rho}_Y} + \frac{1}{\delta^2} \int_0^\infty ds \left\langle \Psi_X(\mathbf{X}, \mathbf{Y}) \cdot \partial_X \Psi_X(\mathbf{X}, \mathbf{Y}^s) \right\rangle_{\tilde{\rho}_Y} \quad (\text{A5})$$

and

$$\boldsymbol{\sigma}^2(\mathbf{X}) = \mathbf{P}(\mathbf{X}) \quad (\text{A6})$$

with

$$\mathbf{P}(\mathbf{X}) = \frac{1}{\delta^2} \int_0^\infty ds \left\langle \bar{\Psi}_X(\mathbf{X}, \mathbf{Y}) \otimes \bar{\Psi}_X(\mathbf{X}, \mathbf{Y}^s) \right\rangle_{\tilde{\rho}_Y} \quad (\text{A7})$$

$$25 \quad \bar{\Psi}_X(\mathbf{X}, \mathbf{Y}) = \Psi_X(\mathbf{X}, \mathbf{Y}) - \left\langle \Psi_X(\mathbf{X}, \mathbf{Y}) \right\rangle_{\tilde{\rho}_Y} \quad (\text{A8})$$

and where  $\mathbf{W}$  is a vector of independent Wiener processes. Note that the terms  $G(\mathbf{X})$  and  $\mathbf{P}(\mathbf{X})$  are of order  $O(1)$ , since the integrals over the lagtime  $s$  in Eqs. (A5) and (A7) are of order<sup>7</sup>  $O(\delta^2)$ . On the other hand, the term  $R(\mathbf{X})$  is of order  $O(1/\delta)$  and identifies with the first term of the left-hand side of Eq. (A25) (see below).

The measure  $\tilde{\rho}_Y$  is the one of the system (A2) or the measure of the Ornstein-Uhlenbeck process (A1) replacing it. Similarly,  
 5  $\mathbf{Y}^s = \phi_Y^s(\mathbf{Y})$  is the result of the evolution of the flow  $\phi_Y^s$  of the system (A2) or the non-stationary solution of the Ornstein-Uhlenbeck process:

$$\mathbf{Y}^s = \exp(\mathbf{A}s/\delta^2) \cdot \mathbf{Y} + \frac{1}{\delta} \int_0^s \exp[\mathbf{A}(s-\tau)/\delta^2] \cdot \mathbf{B}_Y \cdot d\mathbf{W}_Y(\tau) \quad (\text{A9})$$

In section A1, we sketch the derivation of Eq. (A3), assuming that the  $\mathbf{Y}$ -dynamics is an Ornstein-Uhlenbeck process. Furthermore, if the  $\mathbf{Y}$ -dynamics is an Ornstein-Uhlenbeck process like (A1), the results (A3)-(A7) can also be expanded to give  
 10 formula in terms of the covariance and correlation matrices of this process. Therefore, assuming that the dynamics of system (A2) has Gaussian statistics, its measure can be used as  $\tilde{\rho}_Y$  and these formula for the process (A1) can then be applied directly using the covariance and correlation matrices of system (A2). It gives a way to practically implement the parameterization as we detail it in section A2.

### A1 Brief sketch of the parameterization derivation

15 As stated in Section 3.1, the MTV parameterization is based on the singular perturbation theory of Markovian operator. We follow the derivation proposed in Majda et al. (2001) and assume that the singular  $O(1/\delta^2)$  term is an Ornstein-Uhlenbeck process like (A1). The backward Kolmogorov equation for Eqs. (23)-(24) for the [probability](#) density  $\rho^\delta(s, \mathbf{X}, \mathbf{Y}|t)$ , where  $t$  is the final time, reads:

$$-\frac{\partial \rho^\delta}{\partial s} = \left[ \frac{1}{\delta^2} \mathcal{L}_1 + \frac{1}{\delta} \mathcal{L}_2 + \mathcal{L}_3 \right] \rho^\delta \quad (\text{A10})$$

20 with the final condition given by some function of  $\mathbf{X}$ :

$$\rho^\delta(t, \mathbf{X}, \mathbf{Y}|t) = f(\mathbf{X}).$$

The operator appearing in Eq. (A10) are given by:

$$\mathcal{L}_1 = \mathbf{Y}^\top \cdot \mathbf{A}^\top \cdot \partial_{\mathbf{Y}} + \frac{\delta}{2} \mathbf{B}_Y : \partial_{\mathbf{Y}} \otimes \partial_{\mathbf{Y}} \quad (\text{A11})$$

$$\begin{aligned} \mathcal{L}_2 = & \left( \mathbf{Y}^\top \cdot \mathbf{L}^{XX^\top} + \mathbf{B}^{XXY} : \mathbf{X} \otimes \mathbf{Y} + \mathbf{B}^{XY Y} : \mathbf{Y} \otimes \mathbf{Y} \right) \cdot \partial_{\mathbf{X}} \\ & + \left( \mathbf{X}^\top \cdot \mathbf{L}^{YX^\top} + \mathbf{Y}^\top \cdot \mathbf{L}^{YY^\top} + \mathbf{B}^{YXX} : \mathbf{X} \otimes \mathbf{X} + \mathbf{B}^{YXY} : \mathbf{X} \otimes \mathbf{Y} \right) \cdot \partial_{\mathbf{Y}} \end{aligned} \quad (\text{A12})$$

$$\mathcal{L}_3 = \left( \mathbf{H}^X + \mathbf{X}^\top \cdot \mathbf{L}^{XX^\top} + \mathbf{B}^{XXX} : \mathbf{X} \otimes \mathbf{X} \right) \cdot \partial_{\mathbf{X}} \quad (\text{A13})$$

---

<sup>7</sup>It is due to the fact that we use directly the measure  $\tilde{\rho}_Y$  of the  $O(1/\delta^2)$  dynamics (A2) to performs the averaging, and not the measure of the dynamics  $\dot{\mathbf{Y}} = F_Y(\mathbf{Y})$ .



where  $\mathsf{T}$  denotes the matrix transpose operation. Since  $\delta \ll 1$ , we can now perform an expansion procedure

$$\rho^\delta = \rho_0 + \delta \rho_1 + \delta^2 \rho_2 + \dots,$$

and recast it in Eq. (A10), equating term by term at each order, to get:

$$\mathcal{L}_1 \rho_0 = 0 \tag{A14}$$

$$5 \quad \mathcal{L}_1 \rho_1 = -\mathcal{L}_2 \rho_0 \tag{A15}$$

$$\mathcal{L}_1 \rho_2 = -\frac{\partial \rho_0}{\partial s} - \mathcal{L}_3 \rho_0 - \mathcal{L}_2 \rho_1 \tag{A16}$$

The solvability condition for these equations is that the right-hand side belong to the range of  $\mathcal{L}_1$  and thus that their average with respect to the invariant measure of (A1) vanishes. The first solvability conditions is obviously satisfied but the the second one is not necessarily satisfied <sup>8</sup> ~~since-~~

$$10 \quad \mathbb{P} \mathcal{L}_2 \rho_0 = \left( \mathbf{B}^{XYY} : \left\langle \mathbf{Y} \otimes \mathbf{Y} \right\rangle_{\tilde{\rho}_Y} \right) \cdot \partial_{\mathbf{X}} \rho_0 = \left( \mathbf{B}^{XYY} : \boldsymbol{\sigma}_Y \right) \cdot \partial_{\mathbf{X}} \rho_0$$

since

$$\mathbb{P} \mathcal{L}_2 \rho_0 = \left( \mathbf{B}^{XYY} : \left\langle \mathbf{Y} \otimes \mathbf{Y} \right\rangle_{\tilde{\rho}_Y} \right) \cdot \partial_{\mathbf{X}} \rho_0 = \left( \mathbf{B}^{XYY} : \boldsymbol{\sigma}_Y \right) \cdot \partial_{\mathbf{X}} \rho_0$$

where  $\mathbb{P}$  is the expectation with respect to the measure of the process (A1) and  $\boldsymbol{\sigma}_Y$  is its covariance matrix. ~~If the matrix  $\mathbf{A}$  in Eq. (A1) is considered to be diagonal, as in Majda et al. (2001) and in Franzke et al. (2005), then it is satisfied. Indeed, in~~

15 this case  $\boldsymbol{\sigma}_Y$  is diagonal and  $\mathbb{P} \mathcal{L}_2 \rho_0 = 0$  due to the following property of the quadratic terms in the model:

$$\frac{\partial}{\partial Y_i} B_{i j k}^{YYYY} Y_j Y_k = 0 \quad .$$

However, here we do consider the general case:  $\mathbf{A}$  is not diagonal and thus we can have  $\mathbb{P} \mathcal{L}_2 \rho_0 \neq 0$ . It then indicates that  $1/\delta$  effects have to be taken into account in the parameterization. This can be done by following the method to treat “fast-waves” effects described in Majda et al. (2001). From here we thus depart from the standard derivation, to include those  $1/\delta$  effects

20 in the parameterization. We need to assume that two timescales are present in the parameterization and consider them in the Kolmogorov equation (A10). Hence, we modify it explicitly by setting:

$$\frac{\partial}{\partial s} \rightarrow \frac{\partial}{\partial s} + \frac{1}{\delta} \frac{\partial}{\partial \tau}$$

and

$$\rho^\delta(s, \tau, \mathbf{X}, \mathbf{Y} | t) = \rho_0(s, \tau, \mathbf{X}, \mathbf{Y} | t) + \delta \rho_1(s, \tau, \mathbf{X}, \mathbf{Y} | t) + \delta^2 \rho_2(s, \tau, \mathbf{X}, \mathbf{Y} | t) .$$

<sup>8</sup>~~The second solvability condition is satisfied if  $\mathbf{A}$  in Eq. (A1) is diagonal, as it is the case in Majda et al. (2001) and Franzke et al. (2005). Here we do assume the general case.~~

Again, recasting this expansion in Eq. (A10) and equating term by term at each order, we obtain:

$$\mathcal{L}_1 \rho_0 = 0 \tag{A17}$$

$$\mathcal{L}_1 \rho_1 = -\mathcal{L}_2 \rho_0 - \frac{\partial \rho_0}{\partial \tau} \tag{A18}$$

$$\mathcal{L}_1 \rho_2 = -\frac{\partial \rho_0}{\partial s} - \frac{\partial \rho_1}{\partial \tau} - \mathcal{L}_3 \rho_0 - \mathcal{L}_2 \rho_1 \tag{A19}$$

- 5 The solvability condition of Eq. (A17) imposes that  $\mathbb{P} \mathcal{L}_1 \rho_0 = 0$ . Since  $\mathbb{P} \mathcal{L}_1 \rho_0 = \mathbb{P} \mathcal{L}_1 \mathbb{P} \rho_0 = 0$ , it means that  $\mathbb{P} \rho_0 = \rho_0$  and that  $\rho_0$  belongs to the null space of  $\mathcal{L}_1$ . As a result of the introduction of the  $1/\delta$  timescale in the equations, the second solvability condition  $\mathbb{P} \mathcal{L}_1 \rho_1 = 0$  is now tractable and gives

$$\frac{\partial \rho_0}{\partial \tau} = -\mathbb{P} \mathcal{L}_2 \mathbb{P} \rho_0 \tag{A20}$$

and thus

$$10 \quad \rho_1 = -\mathcal{L}_1^{-1} \left( \mathcal{L}_2 \rho_0 + \frac{\partial \rho_0}{\partial \tau} \right). \tag{A21}$$

These two equations gives together:

$$\rho_1 = -\mathcal{L}_1^{-1} (\mathcal{L}_2 \rho_0 - \mathbb{P} \mathcal{L}_2 \mathbb{P} \rho_0). \tag{A22}$$

Since  $\mathbb{P}$  commutes with  $\mathcal{L}_1^{-1}$  and since  $\mathbb{P} \mathbb{P} = \mathbb{P}$ , we thus have that  $\mathbb{P} \rho_1 = 0$  and  $\mathbb{P} \partial \rho_1 / \partial \tau = 0$ . The solvability condition of Eq. (A19) imposes that  $\mathbb{P} \mathcal{L}_1 \rho_2 = 0$  and thus

$$15 \quad -\mathbb{P} \frac{\partial \rho_0}{\partial s} = \mathbb{P} \frac{\partial \rho_1}{\partial \tau} + \mathbb{P} \mathcal{L}_3 \mathbb{P} \rho_0 + \mathbb{P} \mathcal{L}_2 \rho_1 \tag{A23}$$

which becomes, with Eq. (A22),

$$-\frac{\partial \rho_0}{\partial s} = \mathbb{P} \mathcal{L}_3 \mathbb{P} \rho_0 - \mathbb{P} \mathcal{L}_2 \mathcal{L}_1^{-1} (\mathcal{L}_2 - \mathbb{P} \mathcal{L}_2) \mathbb{P} \rho_0 \tag{A24}$$

Finally, grouping Eqs. (A20) and (A24) together gives:

$$-\left( \frac{\partial}{\partial s} + \frac{1}{\delta} \frac{\partial}{\partial \tau} \right) \rho_0 = \left[ \frac{1}{\delta} \mathbb{P} \mathcal{L}_2 \mathbb{P} + \mathbb{P} \mathcal{L}_3 \mathbb{P} - \mathbb{P} \mathcal{L}_2 \mathcal{L}_1^{-1} (\mathcal{L}_2 - \mathbb{P} \mathcal{L}_2) \mathbb{P} \right] \rho_0 \tag{A25}$$

- 20 which is the result that was obtain in Papanicolaou (1976). From here, the computation proceeds along the standard line described in Majda et al. (2001) and gives the result (A3).

## A2 Practical implementation

We will now derive explicitly the MTV parameterization for the system (27)-(28). For the time of the derivation, we will again assume that the  $\mathbf{Y}$ -dynamics is given by the process (A1), but we suppose that the final results apply as well with the measure,

- 25 covariance and correlation matrices of system (A2).

We consider first the case defined by Eq. (35) where the intrinsic dynamics is considered to be given by the quadratic terms of the tendencies alone. We define the matrix

$$\Sigma = \int_0^\infty ds \left\langle \mathbf{Y} \otimes \mathbf{Y}^s \right\rangle_{\tilde{\rho}_Y} \quad (\text{A26})$$

and note that

$$5 \int_0^\infty ds \left\langle \partial_{\mathbf{Y}} \otimes \mathbf{Y}^s \right\rangle_{\tilde{\rho}_Y} = \boldsymbol{\sigma}_Y^{-1} \cdot \Sigma \quad (\text{A27})$$

$$\left\langle \mathbf{Y} \otimes \partial_{\mathbf{Y}} \otimes \mathbf{Y}^s \right\rangle_{\tilde{\rho}_Y} = 0 \quad (\text{A28})$$

$$\left\langle \partial_{\mathbf{Y}} \otimes \mathbf{Y}^s \otimes \mathbf{Y}^s \right\rangle_{\tilde{\rho}_Y} = 0 \quad (\text{A29})$$

$$\int_0^\infty ds \left\langle Y_i \partial_{Y_j} Y_k^s Y_l^s \right\rangle_{\tilde{\rho}_Y} = \int_0^\infty ds \sum_{m=1}^{N_Y} \sigma_{jm}^{-1} \left( \left\langle Y_m Y_k^s \right\rangle_{\tilde{\rho}_Y} \left\langle Y_i Y_l^s \right\rangle_{\tilde{\rho}_Y} + \left\langle Y_m Y_l^s \right\rangle_{\tilde{\rho}_Y} \left\langle Y_i Y_k^s \right\rangle_{\tilde{\rho}_Y} \right) \quad (\text{A30})$$

since  $\left\langle \mathbf{Y}^s \right\rangle_{\tilde{\rho}_Y} = 0$  and where  $\boldsymbol{\sigma}_Y$  is the covariance matrix of the process (A1). These results can be explicitly obtained using the non-stationary solution (A9). We also define

$$\Sigma_2 = \int_0^\infty ds \left( \left\langle \mathbf{Y} \otimes \mathbf{Y}^s \right\rangle_{\tilde{\rho}_Y} \otimes \left\langle \mathbf{Y} \otimes \mathbf{Y}^s \right\rangle_{\tilde{\rho}_Y} \right) \quad (\text{A31})$$

which is thus a rank-4 tensor. Note that both  $\Sigma$  and  $\Sigma_2$  are  $O(\delta^2)$  objects. With those definitions, it can be shown that the parameterization (A3) becomes

$$\dot{\mathbf{X}} = F_X(\mathbf{X}) + R(\mathbf{X}) + G(\mathbf{X}) + \sqrt{2} \boldsymbol{\sigma}^{(1)}(\mathbf{X}) \cdot d\mathbf{W}^{(1)} + \sqrt{2} \boldsymbol{\sigma}^{(2)} \cdot d\mathbf{W}^{(2)} \quad (\text{A32})$$

15 with  $\left\langle d\mathbf{W}^{(1)}(t) \otimes d\mathbf{W}^{(2)}(t') \right\rangle = 0$  and

$$R(\mathbf{X}) = \frac{1}{\delta} \mathbf{H}^{(3)} \quad (\text{A33})$$

$$G(\mathbf{X}) = \frac{1}{\delta^2} \left[ \sum_{i=0}^2 \mathbf{H}^{(i)} + \left( \sum_{i=0}^3 \mathbf{L}^{(i)} \right) \cdot \mathbf{X} + \left( \mathbf{B}^{(1)} + \mathbf{B}^{(2)} \right) : \mathbf{X} \otimes \mathbf{X} + \mathbf{M} :: \mathbf{X} \otimes \mathbf{X} \otimes \mathbf{X} \right] \quad (\text{A34})$$

$$\boldsymbol{\sigma}^{(1)}(\mathbf{X}) \cdot \left[ \boldsymbol{\sigma}^{(1)}(\mathbf{X}) \right]^\top = \mathbf{P}_1(\mathbf{X}) = \frac{1}{\delta^2} \left[ \mathbf{Q}^{(1)} + \mathbf{U} \cdot \mathbf{X} + \mathbf{V} : \mathbf{X} \otimes \mathbf{X} \right] \quad (\text{A35})$$

$$\boldsymbol{\sigma}^{(2)} \cdot \left[ \boldsymbol{\sigma}^{(2)} \right]^\top = \mathbf{P}_2 = \frac{1}{\delta^2} \mathbf{Q}^{(2)} \quad (\text{A36})$$

20 The product “ $::$ ” is similar to the definition (31) but with a rank-4 tensor and three variables :

$$\mathbf{M} :: \mathbf{X} \otimes \mathbf{X} \otimes \mathbf{X} = \sum_{j,k,l=1}^{N_X} M_{ijkl} X_j X_k X_l. \quad (\text{A37})$$

All the products involved concern the last and the first indices of respectively their first and second arguments.  $\mathbf{M}$  and  $\mathbf{V}$  are rank-4 tensors,  $\mathbf{U}$  is a rank-3 tensor and the  $\mathbf{Q}^{(i)}$ 's are matrices. The  $\mathbf{H}^{(i)}$ 's are vectors, the  $\mathbf{L}^{(i)}$ 's are matrices and the  $\mathbf{B}^{(i)}$ 's

are rank-3 tensors. The formula of these quantities are given below:

$$H_i^{(0)} = \mathbf{L}_i^{XY} \cdot (\boldsymbol{\sigma}_Y^{-1} \cdot \boldsymbol{\Sigma})^\top \cdot \mathbf{H}^Y = \sum_{j,k,l=1}^{N_Y} L_{ij}^{XY} \Sigma_{jk}^\top (\sigma_Y^{-1})_{kl} H_l^Y \quad (\text{A38})$$

$$H_i^{(1)} = \mathbf{B}_i^{XXY} : (\mathbf{L}^{XY} \cdot \boldsymbol{\Sigma}) = \sum_{j=1}^{N_X} \sum_{k,l=1}^{N_Y} B_{ijk}^{XXY} L_{jl}^{XY} \Sigma_{lk} \quad (\text{A39})$$

$$H_i^{(2)} = \left( (\mathbf{B}_i^{XYY} + \mathbf{B}_i^{XYY}^\top) \otimes \mathbf{L}^{YY} \right) \times (\boldsymbol{\sigma}_Y^{-1} \cdot \boldsymbol{\Sigma}_2) = \sum_{j,k,l,m,n=1}^{N_Y} \left( B_{ijk}^{XYY} + B_{ikj}^{XYY} \right) L_{lm}^{YY} (\sigma_Y^{-1})_{jn} (\Sigma_2)_{nlkm} \quad (\text{A40})$$

$$5 \quad H_i^{(3)} = \mathbf{B}_i^{XYY} : \boldsymbol{\sigma}_Y = \sum_{j,k=1}^{N_Y} B_{ijk}^{XYY} (\sigma_Y)_{jk} \quad (\text{A41})$$

$$L_{ij}^{(0)} = \mathbf{B}_{ij}^{XXY} \cdot (\boldsymbol{\sigma}_Y^{-1} \cdot \boldsymbol{\Sigma})^\top \cdot \mathbf{H}^Y = \sum_{k,l,m=1}^{N_Y} B_{ijk}^{XXY} \Sigma_{kl}^\top (\sigma_Y^{-1})_{lm} H_m^Y \quad (\text{A42})$$

$$L_{ij}^{(1)} = \mathbf{L}_i^{XY} \cdot (\boldsymbol{\sigma}_Y^{-1} \cdot \boldsymbol{\Sigma})^\top \cdot \mathbf{L}_j^{YX} = \sum_{k,l,m=1}^{N_Y} L_{ik}^{XY} \Sigma_{kl}^\top (\sigma_Y^{-1})_{lm} L_{mj}^{YX} \quad (\text{A43})$$

$$L_{ij}^{(2)} = \left( (\mathbf{B}_i^{XYY} + \mathbf{B}_i^{XYY}^\top) \otimes \mathbf{B}_j^{YXY} \right) \times (\boldsymbol{\sigma}_Y^{-1} \cdot \boldsymbol{\Sigma}_2) = \sum_{k,l,m,n,p=1}^{N_Y} \left( B_{ikl}^{XYY} + B_{ilk}^{XYY} \right) B_{mjn}^{YXY} (\sigma_Y^{-1})_{kp} (\Sigma_2)_{pmln} \quad (\text{A44})$$

$$L_{ij}^{(3)} = \mathbf{B}_i^{XXY} : (\mathbf{B}_j^{XXY} \cdot \boldsymbol{\Sigma}) = \sum_{k=1}^{N_X} \sum_{l,m=1}^{N_Y} B_{ikl}^{XXY} B_{kjm}^{XXY} \Sigma_{ml} \quad (\text{A45})$$

$$10 \quad B_{ijk}^{(1)} = \mathbf{L}_i^{XY} \cdot (\boldsymbol{\sigma}_Y^{-1} \cdot \boldsymbol{\Sigma})^\top \cdot \mathbf{B}_j^{YXX} = \sum_{l,m,n=1}^{N_Y} L_{il}^{XY} \Sigma_{lm}^\top (\sigma_Y^{-1})_{mn} B_{njk}^{YXX} \quad (\text{A46})$$

$$B_{ijk}^{(2)} = \mathbf{B}_i^{XXY} \cdot (\boldsymbol{\sigma}_Y^{-1} \cdot \boldsymbol{\Sigma})^\top \cdot \mathbf{L}_k^{YX} = \sum_{l,m,n=1}^{N_Y} B_{ijl}^{XXY} \Sigma_{lm}^\top (\sigma_Y^{-1})_{mn} L_{nk}^{YX} \quad (\text{A47})$$

$$M_{ijkl} = \mathbf{B}_i^{XXY} \cdot (\boldsymbol{\sigma}_Y^{-1} \cdot \boldsymbol{\Sigma})^\top \cdot \mathbf{B}_k^{YXX} = \sum_{m,n,p=1}^{N_Y} B_{ijm}^{XXY} \Sigma_{mn}^\top (\sigma_Y^{-1})_{np} B_{pkl}^{YXX} \quad (\text{A48})$$

$$Q_{ij}^{(1)} = \mathbf{L}_i^{XY} \cdot \boldsymbol{\Sigma} \cdot \mathbf{L}_j^{XY}^\top = \sum_{k,l=1}^{N_Y} L_{ik}^{XY} \Sigma_{kl} L_{jl}^{XY} \quad (\text{A49})$$

$$Q_{ij}^{(2)} = \left( \mathbf{B}_i^{XYY} \otimes (\mathbf{B}_j^{XYY} + \mathbf{B}_j^{XYY}^\top) \right) \times \boldsymbol{\Sigma}_2 = \sum_{k,l,m,n=1}^{N_Y} B_{ikl}^{XYY} \left( B_{jmn}^{XYY} + B_{jnm}^{XYY} \right) (\Sigma_2)_{kmln} \quad (\text{A50})$$

$$15 \quad U_{ijk} = \mathbf{L}_i^{XY} \cdot \boldsymbol{\Sigma} \cdot \mathbf{B}_j^{XXY} + \mathbf{B}_i^{XXY} \cdot \boldsymbol{\Sigma} \cdot \mathbf{L}_k^{XY} = \sum_{l,m=1}^{N_Y} L_{il}^{XY} \Sigma_{lm} B_{jkm}^{XXY} + \sum_{l,m=1}^{N_Y} B_{ijl}^{XXY} \Sigma_{lm} L_{km}^{XY} \quad (\text{A51})$$

$$V_{jikl} = \mathbf{B}_i^{XXY} \cdot \boldsymbol{\Sigma} \cdot \mathbf{B}_j^{XXY} = \sum_{m,n=1}^{N_Y} B_{ikm}^{XXY} \Sigma_{mn} B_{jln}^{XXY} \quad (\text{A52})$$

where  $\cdot$  is the product and summation over the last and the first indices of respectively its first and second arguments<sup>8</sup>. The product  $:$  is defined as in Eq. (31). The tensors whose indices are indicated define a lower rank tensor, for instance the rank-3 tensor  $\mathbf{B}_i^{X.XY}$  hence noted defines a matrix whose elements are  $B_{ij}^{X.XY}$ . The symbol  $\times$  then defines the following permuted product and summation of two given rank-4 tensors  $\mathbf{C}$  and  $\mathbf{D}$ :

$$5 \quad \mathbf{C} \times \mathbf{D} = \sum_{ijkl} C_{ijkl} D_{ikjl}. \quad (\text{A53})$$

With the notable exception of  $\mathbf{H}^{(0)}$ ,  $\mathbf{H}^{(3)}$  and  $\mathbf{L}^{(0)}$ , one can easily check that the formulation (A39)-(A52) gives back the formulas of the appendix in Franzke et al. (2005) when  $\sigma_Y$  is diagonal. It is these particular tensors that are implemented and computed by the code provided with the present article as supplementary material. They are computed using the covariance matrix  $\sigma_Y$  and the integrated correlation matrices  $\Sigma$  and  $\Sigma_2$  as input. The formulas presented here are valid for an Ornstein-  
 10 Uhlenbeck process, but as stated above, the covariance and correlations of the dynamics (A2) can be used directly as well, provided that the right assumptions are fulfilled. In the present work, we have always used the statistic of Eq. (A2) to compute the tensors. Once the tensors are available, the resulting tendencies are then computed at each timestep and Eq. (A3) can be integrated with one of the available integrators.

This solve the case when the singular perturbation  $O(1/\delta^2)$  term is given by Eq. (35). In the case where the  $O(1/\delta^2)$  term is  
 15 given by Eq. (34), i.e. the intrinsic dynamics, it is straightforward to show that the parameterization is exactly the same, except that  $\mathbf{H}^{(0)} = \mathbf{H}^{(2)} = \mathbf{L}^{(0)} = 0$ .

### A3 Technical details

The equation (A32) is integrated with a *stochastic Heun algorithm* described in Greiner et al. (1988) and which converges toward the Stratonovitch statistic (Hansen and Penland, 2006). In particular, the  $R(\mathbf{X})$  and  $G(\mathbf{X})$  terms and the  $\mathbf{P}_1(\mathbf{X})$  and  $\mathbf{P}_2$   
 20 matrix are computed by performing sparse-matrix products. The square root of the matrix  $\mathbf{P}_2$  is computed once at initialization with a *singular-value decomposition* (SVD) method to obtain the matrix  $\sigma^{(2)}$ . The square root of the state-dependent matrix  $\mathbf{P}_1(\mathbf{X})$  is computed each `mnuti` time<sup>9</sup> to obtain the matrix  $\sigma^{(1)}(\mathbf{X})$ , again with a SVD decomposition. In general, in the present work, we have set `mnuti` equal to the Heun algorithm timestep.

## Appendix B: The WL method

25 The Wouters-Lucarini method is considered with the decomposition (34) and consists of three terms (Wouters and Lucarini, 2012):

$$\dot{\mathbf{X}} = F_X(\mathbf{X}) + \varepsilon M_1(\mathbf{X}) + \varepsilon^2 M_2(\mathbf{X}, t) + \varepsilon^2 M_3(\mathbf{X}, t) \quad (\text{B1})$$

which we detail now in the following.

<sup>8</sup>Thus for vectors and matrices it is the standard product.

<sup>9</sup>The notation `mnuti` indicates a parameter of the code implementation, please read the code documentation for more information.

## B1 The $M_1$ term

This is the averaging term, which is defined as

$$M_1(\mathbf{X}) = \left\langle \Psi_X(\mathbf{X}, \mathbf{Y}) \right\rangle_{\rho_{0,Y}} \quad (\text{B2})$$

where  $\rho_{0,Y}$  is the measure of the unperturbed intrinsic dynamics (34). Since

$$5 \quad \Psi_X(\mathbf{X}, \mathbf{Y}) = \mathbf{L}^{XY} \cdot \mathbf{Y} + \mathbf{B}^{XXY} : \mathbf{X} \otimes \mathbf{Y} + \mathbf{B}^{XYY} : \mathbf{Y} \otimes \mathbf{Y} \quad (\text{B3})$$

we get the following result:

$$M_1(\mathbf{X}) = \mathbf{L}^{XY} \cdot \boldsymbol{\mu}_Y + \mathbf{B}^{XXY} : \mathbf{X} \otimes \boldsymbol{\mu}_Y + \mathbf{B}^{XYY} : \boldsymbol{\sigma}_Y \quad (\text{B4})$$

where  $\boldsymbol{\mu}_Y = \left\langle \mathbf{Y} \right\rangle_{\rho_{0,Y}}$  is the mean of the dynamics (34) and  $\boldsymbol{\sigma}_Y$  its covariance matrix. In the following, we shall assume that this dynamics is Gaussian, hence  $\boldsymbol{\mu}_Y = 0$  and we get

$$10 \quad M_1(\mathbf{X}) = \mathbf{B}^{XYY} : \boldsymbol{\sigma}_Y \quad (\text{B5})$$

## B2 The $M_2$ term

It is the correlation term, which here can be written as follow

$$M_2(\mathbf{X}, t) = \Psi'_{X,1}(\mathbf{X})^\top \cdot \mathbf{a}^{XY} \cdot \boldsymbol{\sigma}(t) . \quad (\text{B6})$$

Indeed, since  $\Psi'_X(\mathbf{X}, \mathbf{Y}) = \Psi_X(\mathbf{X}, \mathbf{Y}) - M_1(\mathbf{X})$ ,  $\Psi'_X$  can be decomposed as a product of Schauder basis function of  $\mathbf{X}$  and  $\mathbf{Y}$  (Wouters and Lucarini, 2012):

$$\Psi'_X(\mathbf{X}, \mathbf{Y}) = \sum_{i,j=1}^2 \Psi'_{X,1,i}(\mathbf{X}) \cdot a_{ij}^X \cdot \Psi'_{X,2,j}(\mathbf{Y}) \quad (\text{B7})$$

with the basis

$$\Psi'_{X,1,1}(\mathbf{X}) = 1 \quad (\text{B8})$$

$$\Psi'_{X,1,2}(\mathbf{X}) = \mathbf{X}^\top \quad (\text{B9})$$

20 and

$$\Psi'_{X,2,1}(\mathbf{Y}) = \mathbf{Y} - \boldsymbol{\mu}_Y \quad (\text{B10})$$

$$\Psi'_{X,2,2}(\mathbf{Y}) = \text{vec}(\mathbf{Y} \otimes \mathbf{Y} - \boldsymbol{\sigma}_Y) \quad (\text{B11})$$

The symbol *vec* denotes an operation stacking the columns of a matrix into a vector:

$$(\text{vec } \mathbf{A})_{I(i,j)} = A_{ij} \quad \text{with} \quad I(i,j) = \text{div}(j, n) + i \quad (\text{B12})$$

where  $\text{div}(a, b)$  is the integer division of  $a$  by  $b$  and  $n$  is the second dimension of  $\mathbf{A}$ . The vector  $\text{vec}(\mathbf{Y} \otimes \mathbf{Y} - \boldsymbol{\sigma}_Y)$  is thus a  $N_Y^2$  length vector. The object  $a_{ij}^X$  in Eq. (B7) can then be rewritten as a matrix:

$$\mathbf{a}^{XY} = \begin{bmatrix} \mathbf{L}^{XY} & \text{mat}(\mathbf{B}^{XYY}) \\ \mathbf{B}^{XXY} & 0 \end{bmatrix} \quad (\text{B13})$$

where we define

$$5 \quad \Psi'_{X,1,1}(\mathbf{X}) \cdot a_{1j}^X = 1 \cdot a_{1j}^X = a_{1j}^X = \left[ \mathbf{L}^{XY} \quad \text{mat}(\mathbf{B}^{XYY}) \right] \quad (\text{B14})$$

and

$$\mathbf{X}^\top \cdot \mathbf{B}^{XXY} \cdot \mathbf{Y} = \mathbf{B}^{XXY} : \mathbf{X} \otimes \mathbf{Y} \quad (\text{B15})$$

The symbol  $\text{mat}$  denotes an operation transforming rank-3 tensors into matrices, e.g.:

$$\left( \text{mat}(\mathbf{B}^{XYY}) \right)_{iJ(j,k)} = B_{i\bar{j}k}^{XYY} \quad \text{with} \quad J(j,k) = \text{div}(j, n) + k \quad (\text{B16})$$

10 where  $n = N_Y$  is the second dimension of  $\mathbf{B}^{XYY}$ . With this notation, we have thus for instance:

$$\text{mat}(\mathbf{B}^{XYY}) \cdot \text{vec}(\mathbf{Y} \otimes \mathbf{Y}) = \mathbf{B}^{XYY} : \mathbf{Y} \otimes \mathbf{Y} \quad (\text{B17})$$

Here  $\text{mat}(\mathbf{B}^{XYY})$  is thus a  $N_X \times N_Y^2$  matrix. The notation  $\text{vec}$  and  $\text{mat}$  introduced here are defined such that the expression (B7) can now be written in the compact form with matricial products:

$$\Psi'_X(\mathbf{X}, \mathbf{Y}) = \Psi'_{X,1}(\mathbf{X}) \cdot \mathbf{a}_{ij}^X \cdot \Psi'_{X,2}(\mathbf{Y}). \quad (\text{B18})$$

15 Now, the process  $\boldsymbol{\sigma}(t)$  appearing in Eq. (B6) has then to be constructed (see Wouters and Lucarini (2012)) such that

$$\left\langle \boldsymbol{\sigma}(t) \otimes \boldsymbol{\sigma}(t+s) \right\rangle = \mathbf{g}(s) \quad (\text{B19})$$

with

$$\mathbf{g}(s) = \left\langle \Psi'_{X,2}(\mathbf{Y}) \otimes \Psi'_{X,2}(\mathbf{Y}^s) \right\rangle_{\rho_{0,Y}} \quad (\text{B20})$$

$$= \left[ \begin{array}{cc} \left\langle (\mathbf{Y} - \boldsymbol{\mu}_Y) \otimes (\mathbf{Y}^s - \boldsymbol{\mu}_Y) \right\rangle_{\rho_{0,Y}} & \left\langle (\mathbf{Y} - \boldsymbol{\mu}_Y) \otimes \text{vec}(\mathbf{Y}^s \otimes \mathbf{Y}^s - \boldsymbol{\sigma}_Y) \right\rangle_{\rho_{0,Y}} \\ \left\langle \text{vec}(\mathbf{Y} \otimes \mathbf{Y} - \boldsymbol{\sigma}_Y) \otimes (\mathbf{Y}^s - \boldsymbol{\mu}_Y) \right\rangle_{\rho_{0,Y}} & \left\langle \text{vec}(\mathbf{Y} \otimes \mathbf{Y} - \boldsymbol{\sigma}_Y) \otimes \text{vec}(\mathbf{Y}^s \otimes \mathbf{Y}^s - \boldsymbol{\sigma}_Y) \right\rangle_{\rho_{0,Y}} \end{array} \right] \quad (\text{B21})$$

20 where  $\mathbf{Y}^s = \phi_Y^s(\mathbf{Y})$  is the result of the time-evolution of the flow of the uncoupled  $Y$ -dynamics given by system (34). Now if we assume that this latter dynamics is Gaussian, the non-diagonal entries in the matrix above vanish, and we can write

$$\boldsymbol{\sigma}(t) = \left[ \begin{array}{c} \boldsymbol{\sigma}_1(t) \\ \text{vec}(\boldsymbol{\sigma}_2(t)) \end{array} \right] \quad (\text{B22})$$



with

$$\left\langle \boldsymbol{\sigma}_1(t) \otimes \boldsymbol{\sigma}_1(t+s) \right\rangle = \left\langle \mathbf{Y} \otimes \mathbf{Y}^s \right\rangle_{\rho_0, \mathbf{Y}} - \boldsymbol{\mu}_Y \otimes \boldsymbol{\mu}_Y \quad (\text{B23})$$

$$\left\langle \boldsymbol{\sigma}_1(t) \otimes \text{vec}(\boldsymbol{\sigma}_2(t+s)) \right\rangle = 0 \quad (\text{B24})$$

$$\left\langle \text{vec}(\boldsymbol{\sigma}_2(t)) \otimes \text{vec}(\boldsymbol{\sigma}_2(t+s)) \right\rangle = \left\langle \text{vec}(\mathbf{Y} \otimes \mathbf{Y}) \otimes \text{vec}(\mathbf{Y}^s \otimes \mathbf{Y}^s) \right\rangle_{\rho_0, \mathbf{Y}} - \left\langle \text{vec}(\boldsymbol{\sigma}_Y) \otimes \text{vec}(\boldsymbol{\sigma}_Y) \right\rangle_{\rho_0, \mathbf{Y}}. \quad (\text{B25})$$

5 where  $\boldsymbol{\sigma}_2$  is a  $N_Y \times N_Y$  matrix of processes. The  $M_2$  term can thus be written:

$$M_2(\mathbf{X}, t) = \mathbf{L}^{XY} \cdot \boldsymbol{\sigma}_1(t) + \mathbf{B}^{XXY} : \mathbf{X} \otimes \boldsymbol{\sigma}_1(t) + \mathbf{B}^{XY Y} : \boldsymbol{\sigma}_2(t) \quad (\text{B26})$$

### B3 The $M_3$ term

It is the memory term which is defined as

$$M_3(\mathbf{X}, t) = \int_0^\infty ds h(\mathbf{X}(t-s), s) \quad (\text{B27})$$

10 with

$$h(\mathbf{X}, s) = \left\langle \Psi_Y(\mathbf{X}, \mathbf{Y})^\top \cdot \partial_Y \Psi_X(\mathbf{X}^s, \mathbf{Y}^s) \right\rangle_{\rho_0, \mathbf{Y}} \quad (\text{B28})$$

$$= \left\langle \left( \mathbf{L}^{YX} \cdot \mathbf{X} + \mathbf{B}^{YXX} : \mathbf{X} \otimes \mathbf{X} + \mathbf{B}^{YXY} : \mathbf{X} \otimes \mathbf{Y} \right)^\top \cdot \partial_Y \left( \mathbf{L}^{XY} \cdot \mathbf{Y} + \mathbf{B}^{XXY} : \mathbf{X}^s \otimes \mathbf{Y} + \mathbf{B}^{XY Y} : \mathbf{Y} \otimes \mathbf{Y} \right) \right\rangle_{\rho_0, \mathbf{Y}} \quad (\text{B29})$$

where  $\mathbf{X}^s = \phi_X^s(\mathbf{X})$  is the result of the time-evolution of the flow of the uncoupled  $\mathbf{X}$ -dynamics given by the system  $\dot{\mathbf{X}} =$

15  $F_X(\mathbf{X})$ . Detailing each term in this expression,  $M_3$  can be rewritten as

$$M_3(\mathbf{X}, t) = \int_0^\infty ds \left[ \left( \mathbf{L}^{(1)}(s) + \mathbf{L}^{(2)}(s) \right) \cdot \tilde{\mathbf{X}} + \mathbf{B}^{(1)}(s) : \tilde{\mathbf{X}} \otimes \tilde{\mathbf{X}} + \mathbf{B}^{(2)}(s) : \tilde{\mathbf{X}} \otimes \tilde{\mathbf{X}}^s + \mathbf{M}(s) : \tilde{\mathbf{X}} \otimes \tilde{\mathbf{X}} \otimes \tilde{\mathbf{X}}^s \right]_{\tilde{\mathbf{X}} = \mathbf{X}(t-s)} \quad (\text{B30})$$

with  $\tilde{\mathbf{X}}^s = \phi_{\mathbf{X}}^s(\mathbf{X}(t-s))$  and

$$L_{ij}^{(1)}(s) = \mathbf{L}_i^{XY} \cdot \boldsymbol{\rho}_{\partial Y}(s)^\top \cdot \mathbf{L}_j^{YX} = \sum_{k,l=1} L_{ik}^{XY} \rho_{\partial Y}(s)_{kl}^\top L_{lj}^{YX} \quad (\text{B31})$$

$$L_{ij}^{(2)}(s) = \mathbf{B}_j^{YXY}^\top : (\boldsymbol{\rho}_{Y\partial YY}(s) : \mathbf{B}_i^{XYY}) = \sum_{k,l,m,n=1}^{N_Y} B_{ljk}^{YXY} \rho_{Y\partial YY}(s)_{klmn} B_{imn}^{XYY} \quad (\text{B32})$$

$$B_{ijk}^{(1)}(s) = \mathbf{L}_i^{XY} \cdot \boldsymbol{\rho}_{\partial Y}(s)^\top \cdot \mathbf{B}_{jk}^{YXX} = \sum_{l,m=1}^{N_Y} L_{il}^{XY} \rho_{\partial Y}(s)_{ml} B_{mjk}^{YXX} \quad (\text{B33})$$

$$5 \quad B_{ijk}^{(2)}(s) = \mathbf{B}_{ij}^{XXY} \cdot \boldsymbol{\rho}_{\partial Y}(s)^\top \cdot \mathbf{L}_k^{YX} = \sum_{l,m=1}^{N_Y} B_{ijl}^{XXY} \rho_{\partial Y}(s)_{ml} L_{mk}^{YX} \quad (\text{B34})$$

$$M_{ijkl}(s) = \mathbf{B}_{ij}^{XXY} \cdot \boldsymbol{\rho}_{\partial Y}(s)^\top \cdot \mathbf{B}_{kl}^{YXX} = \sum_{m,n=1}^{N_Y} B_{ijm}^{XXY} \rho_{\partial Y}(s)_{nm} B_{nkl}^{YXX} \quad (\text{B35})$$

since

$$\left\langle \mathbf{Y} \otimes \partial \mathbf{Y} \otimes \mathbf{Y}^s \right\rangle_{\rho_{0,Y}} = 0 \quad (\text{B36})$$

$$\left\langle \partial \mathbf{Y} \otimes \mathbf{Y}^s \otimes \mathbf{Y}^s \right\rangle_{\rho_{0,Y}} = 0 \quad (\text{B37})$$

10 because the dynamics of (34) is assumed to be Gaussian and where

$$\boldsymbol{\rho}_{\partial Y} = \left\langle \partial \mathbf{Y} \otimes \mathbf{Y}^s \right\rangle_{\rho_{0,Y}} = \boldsymbol{\sigma}_Y^{-1} \cdot \left\langle \mathbf{Y} \otimes \mathbf{Y}^s \right\rangle_{\rho_{0,Y}} \quad (\text{B38})$$

$$\boldsymbol{\rho}_{Y\partial YY} = \left\langle \mathbf{Y} \otimes \partial \mathbf{Y} \otimes \mathbf{Y}^s \otimes \mathbf{Y}^s \right\rangle_{\rho_{0,Y}} \quad (\text{B39})$$

and the expression of this last definition can be inferred from Eq. (A30).

## B4 Technical details

15 The tendencies appearing in Eq. (B1) are computed according to the same Heun algorithm described in Sec. A3. A small difference with the latter here is that the term  $M_3$ , due to its computational cost, is computed every `muti` time<sup>10</sup> and remains constant in between. The term  $M_1$  is simply obtained by computing sparse-matrix products. The process  $\boldsymbol{\sigma}(t)$  of the term  $M_2$  is emulated by a Multidimensional  $n$ -th order Auto-Regressive process (MAR( $n$ )) described in Penny and Harrison (2007). The parameters and the order  $n$  of this process can be assessed for instance by using the variational Bayesian approach described in  
20 this article. The integrand of the term  $M_3$  is obtained by computing sparse-matrix products and integrating for each timestep the uncoupled  $\mathbf{X}$ -dynamics forward, to obtain  $\tilde{\mathbf{X}}^s$ . The integral is then performed with a simple trapezoidal rule with a time-step `muti` over a time interval which is set by the parameter `meml`. This interval should be set so that the absolute value of the integrand has sufficiently decreased at the end of it. In practice, it is sufficient to set `meml` proportional to the longest decorrelation time of the uncoupled  $\mathbf{Y}$ -dynamics.

<sup>10</sup>The notation `muti` indicates a parameter of the code implementation, please read the code documentation for more information.

*Competing interests.* Stéphane Vannitsem is a member of the editorial board of the journal. Jonathan Demaeyer declares that he has no conflict of interest.

*Acknowledgements.* The authors thank Lesley De Cruz for her authorization to use the Figure 1. [They thank also the reviewers for their help to increase the quality of the manuscript.](#) This work is supported by the Belgian Federal Science Policy Office under contracts

5 BR/121/A2/STOCHCLIM.

## References

- Abramov, R.: A simple stochastic parameterization for reduced models of multiscale dynamics, *Fluids*, 1, 2, 2015.
- Arnold, H., Moroz, I., and Palmer, T.: Stochastic parametrizations and model uncertainty in the Lorenz'96 system, *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, 371, 20110479, 2013.
- 5 Arnold, L.: Hasselmann's program revisited: The analysis of stochasticity in deterministic climate models, in: *Stochastic climate models*, pp. 141–157, Springer, 2001.
- Arnold, L., Imkeller, P., and Wu, Y.: Reduction of deterministic coupled atmosphere–ocean models to stochastic ocean models: a numerical case study of the Lorenz–Maas system, *Dynamical Systems*, 18, 295–350, 2003.
- Berner, J., Achatz, U., Batte, L., Bengtsson, L., Cámara, A. d. I., Christensen, H. M., Colangeli, M., Coleman, D. R., Crommelin, D.,  
10 Dolaptchiev, S. I., et al.: Stochastic parameterization: Toward a new view of weather and climate models, *Bulletin of the American Meteorological Society*, 98, 565–588, 2017.
- Chekroun, M. D., Liu, H., and Wang, S.: Stochastic parameterizing manifolds and non-Markovian reduced equations: stochastic manifolds for nonlinear SPDEs II, Springer, 2014.
- Chekroun, M. D., Liu, H., and Wang, S.: Approximation of Stochastic Invariant Manifolds: Stochastic Manifolds for Nonlinear SPDEs I,  
15 Springer, 2015.
- Colangeli, M. and Lucarini, V.: Elements of a unified framework for response formulae, *Journal of Statistical Mechanics: Theory and Experiment*, 2014, P01 002, 2014.
- Crommelin, D. and Vanden-Eijnden, E.: Subgrid-scale parameterization with conditional Markov chains, *Journal of the Atmospheric Sciences*, 65, 2661–2675, 2008.
- 20 De Cruz, L., Demaeyer, J., and Vannitsem, S.: The Modular Arbitrary-Order Ocean-Atmosphere Model: MAOOAM v1.0, *Geoscientific Model Development*, 9, 2793–2808, 2016.
- Demaeyer, J. and Vannitsem, S.: Stochastic parametrization of subgrid-scale processes in coupled ocean–atmosphere systems: benefits and limitations of response theory, *Quarterly Journal of the Royal Meteorological Society*, 143, 881–896, 2017.
- Demaeyer, J. and Vannitsem, S.: Stochastic Parameterization of Subgrid-Scale Processes: A Review of Recent Physically Based Approaches,  
25 in: *Advances in Nonlinear Geosciences*, pp. 55–85, Springer, 2018.
- Ellis, R. S. and Pinsky, M. A.: The first and second fluid approximations to the linearized Boltzmann equation, *J. Math. Pures Appl*, 54, 125–156, 1975.
- Franzke, C. and Majda, A. J.: Low-order stochastic mode reduction for a prototype atmospheric GCM, *Journal of the atmospheric sciences*, 63, 457–479, 2006.
- 30 Franzke, C., Majda, A. J., and Vanden-Eijnden, E.: Low-order stochastic mode reduction for a realistic barotropic model climate, *Journal of the atmospheric sciences*, 62, 1722–1745, 2005.
- Franzke, C. L., O’Kane, T. J., Berner, J., Williams, P. D., and Lucarini, V.: Stochastic climate theory and modeling, *Wiley Interdisciplinary Reviews: Climate Change*, 6, 63–78, 2015.
- Frederiksen, J., Kitsios, V., Okane, T., and Zidikheri, M.: Stochastic subgrid modelling for geophysical and three-dimensional turbulence, in: *Nonlinear and Stochastic Climate Dynamics*, edited by Franzke, C. and O’Kane, T., pp. 241–275, Cambridge University Press, 2017.
- 35 Frederiksen, J. S.: Subgrid-scale parameterizations of eddy-topographic force, eddy viscosity, and stochastic backscatter for flow over topography, *Journal of the atmospheric sciences*, 56, 1481–1494, 1999.

- Frederiksen, J. S. and Davies, A. G.: Eddy viscosity and stochastic backscatter parameterizations on the sphere for atmospheric circulation models, *Journal of the atmospheric sciences*, 54, 2475–2492, 1997.
- Grad, H.: Singular and nonuniform limits of solutions of the Boltzmann equation, *Transport theory*, 1, 269–308, 1969.
- Greiner, A., Strittmatter, W., and Honerkamp, J.: Numerical integration of stochastic differential equations, *Journal of Statistical Physics*, 51, 95–108, 1988.
- Hansen, J. A. and Penland, C.: Efficient approximate techniques for integrating stochastic differential equations, *Monthly weather review*, 134, 3006–3014, 2006.
- Hasselmann, K.: Stochastic climate models part I. Theory, *Tellus A*, 28, 1976.
- Horsthemke, W. and Lefever, R.: *Noise-induced transitions in physics, chemistry, and biology*, Springer, 1984.
- Kelly, D. and Melbourne, I.: Deterministic homogenization for fast–slow systems with chaotic noise, *Journal of Functional Analysis*, 272, 4063–4102, 2017.
- Kifer, Y.: Averaging and climate models, in: *Stochastic Climate Models*, pp. 171–188, Springer, 2001.
- Kurtz, T. G.: A limit theorem for perturbed operator semigroups with applications to random evolutions, *Journal of Functional Analysis*, 12, 55–67, 1973.
- Kwasniok, F.: Enhanced regime predictability in atmospheric low-order models due to stochastic forcing, *Phil. Trans. R. Soc. A*, 372, 20130 286, 2014.
- Lambert, J. D.: *Numerical methods for ordinary differential systems: the initial value problem*, John Wiley & Sons, Inc., 1991.
- Lorenz, E. N.: Predictability: A problem partly solved, in: *Proc. Seminar on predictability*, vol. 1, 1996.
- Majda, A. J., Timofeyev, I., and Vanden Eijnden, E.: A mathematical framework for stochastic climate models, *Communications on Pure and Applied Mathematics*, 54, 891–974, 2001.
- Majda, A. J., Franzke, C., and Crommelin, D.: Normal forms for reduced stochastic climate models, *Proceedings of the National Academy of Sciences*, 106, 3649–3653, 2009.
- Melbourne, I. and Stuart, A.: A note on diffusion limits of chaotic skew-product flows, *Nonlinearity*, 24, 1361, 2011.
- Papanicolaou, G. C.: Some probabilistic problems and methods in singular perturbations, *Journal of Mathematics*, 6, 1976.
- Pavliotis, G. and Stuart, A.: *Multiscale methods: averaging and homogenization*, Springer Science & Business Media, 2008.
- Peavoy, D., Franzke, C. L., and Roberts, G. O.: Systematic physics constrained parameter estimation of stochastic differential equations, *Computational Statistics & Data Analysis*, 83, 182–199, 2015.
- Penny, W. and Harrison, L.: Multivariate autoregressive models, *Statistical Parametric Mapping: The analysis of functional brain images*, pp. 534–540, 2007.
- Ruelle, D.: Differentiation of SRB states, *Communications in Mathematical Physics*, 187, 227–241, 1997.
- Ruelle, D.: A review of linear response theory for general differentiable dynamical systems, *Nonlinearity*, 22, 855, 2009.
- Sardeshmukh, P. D. and Penland, C.: Understanding the distinctively skewed and heavy tailed character of atmospheric and oceanic probability distributions, *Chaos: An Interdisciplinary Journal of Nonlinear Science*, 25, 036 410, 2015.
- Trevisan, A. and Palatella, L.: Chaos and weather forecasting: the role of the unstable subspace in predictability and state estimation problems, *International Journal of Bifurcation and Chaos*, 21, 3389–3415, 2011.
- Vannitsem, S.: Stochastic modelling and predictability: analysis of a low-order coupled ocean–atmosphere model, *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, 372, 20130 282, 2014.

- Vannitsem, S. and Ghil, M.: Evidence of coupling in ocean-atmosphere dynamics over the North Atlantic, *Geophysical Research Letters*, 44, 2016–2026, 2017.
- Vannitsem, S., Demaeyer, J., Cruz, L. D., and Ghil, M.: Low-frequency variability and heat transport in a low-order nonlinear coupled ocean–atmosphere model, *Physica D: Nonlinear Phenomena*, 309, 71–85, 2015.
- 5 Vissio, G. and Lucarini, V.: A proof of concept for scale-adaptive parameterizations: the case of the Lorenz’96 model, arXiv preprint arXiv:1612.07223, 2016.
- Wolkenfelt, P.: The construction of reducible quadrature rules for Volterra integral and integro-differential equations, *IMA Journal of Numerical Analysis*, 2, 131–152, 1982.
- Wouters, J. and Gottwald, G. A.: Edgeworth expansions for slow-fast systems and their application to model reduction for finite time scale  
10 separation, arXiv preprint arXiv:1708.06984, 2017.
- Wouters, J. and Lucarini, V.: Disentangling multi-level systems: averaging, correlations and memory, *Journal of Statistical Mechanics: Theory and Experiment*, 2012, P03 003, 2012.
- Wouters, J. and Lucarini, V.: Multi-level dynamical systems: Connecting the Ruelle response theory and the Mori-Zwanzig approach, *Journal of Statistical Physics*, 151, 850–860, 2013.
- 15 Wouters, J., Dolaptchiev, S. I., Lucarini, V., and Achatz, U.: Parameterization of stochastic multiscale triads, *Nonlinear Processes in Geophysics*, 23, 435–445, 2016.
- Young, L.-S.: What are SRB measures, and which dynamical systems have them?, *Journal of Statistical Physics*, 108, 733–754, 2002.