General Remarks

The manuscript has been thoroughly revised by fully taking into account the comments by the Editor, Peter Haynes, as well as by the two anonymous reviewers. Our responses originally posted to the ACPD Web site are appended below with only minor edit, because the revision follows our responses already provided. The line numbers are added systematically in the following, including in those individual responses, to refer exactly where these suggested modifications are made.

A major criticism common to all the comments received concerns readability. To improve the manuscript, a major re–structuring of the text has been performed at various places, most notably in the introduction and the final section. They should make the motivation and the goals clearer, while the main results of the work are presented in a more logical, sequential manner.

An outline of the analysis section (Sec. 3) has been added in the end of the first subsection (Sec. 3.1) so that readers can follow these rather detailed presentation of the complex results with an overall structure of the presentation in mind. This should substantially reduce the risk of readers getting lost in the details. Some general remarks are also inserted (L269, L297, L308–309, L315–317) throughout this section as a further guidance for readers.

In an effort to remove rather secondary details, Sec. 3.5.2 and the associated two figures (Figs. 9, 10) are removed in the revised manuscript.

For improving the overall clarity of the presentation, two tables are added that summarise the experiment categories and the individual forecast cases.

By following a request of Reviewer #2, some examples of the RMM analysis are also added in revision (new Fig. 3 with the original figures re–numbered).

The main weakness of the original manuscript was a lack of conclusions. In revision, both in the abstract and in the final section, we point out the following conclusions:

- A difficulty of emulating free dynamics in a global model without destroying a realistic background state necessary for supporting a free dynamics (L9–10, L399–404)
- Strong sensitivities of the MJO simulation on physics rather other than exclusively on convection parameterizations (L10–11, L449–453)
- The need for active contributions of theoretical studies that are more closely tied to the specific realisation of physics in global operational models (L6–9, L82–87, L454–461)

See also L94–96 in the introduction.

In the final section, the following points are further emphasized:

- Strong sensitivity of the MJO predictability on the initial condition (L421–429)
- Active interactions of MJOs with higher–latitude Rossby–wave activities (L441–448)

We hope that our revision is satisfactory for publication in ACP.

Individual Responses

Reply to Editor

We would like to thank the Editor for his considerate comments. We apologise again for the delay, partially this was due to Covid-19 as one of the authors had difficulties to access the relevant infrastructure and data. Having said this, we much appreciate the opportunity provided by the Editor to respond in full. We understand that it is not easy to give specific recommendations as an editor, when the main issue is in the presentation of difficult and unexpected results. We *do* believe that the results should be recorded to illustrate, for example, the contrast of friction formulations in operational models with those in idealised studies of the MJO. The latter are often based on a rather simple Rayleigh–friction formulation, taking a dichotomy of with or without. Unfortunately, existing theoretical models are too limited to explain corresponding MJO sensitivities simulated by operational models.

We agree that no simple theoretical interpretation of the results are possible from the present study. Originally, we started to explore a possibility of interpreting the MJO as a nonlinear free wave under active interactions with Rossby waves from and to higher latitudes. A main strategy has been to remove the constraints to the free dynamics in an operational model by selectively turning off the tendencies of different physical parametrisations (L37–40, L68–70 , L75–79, L87–89).

In spite of a substantial number of sensitivity experiments performed, it turns out to be difficult to draw firm conclusions. However, such a work should not simply be considered a failure. Here, we disagree with the Editor's comment that "the current state (of manuscript) is not useful", if what it means is a lack of positive results. Notably, in a recent comment in the journal Nature, Mehta (2019) argues why a negative result is crucial for a healthy progress of science.

It would be important to emphasise that our methodology is sound, and we have set out with a clear hypothesis as stated in the manuscript. More specifically, individual sensitivities of momentum diffusion are examined, with a hope of distilling specific impacts that either deteriorate or improve MJO forecasts. As it turns out, such an investigation is difficult, because other processes, that are not eliminated, compensate with a nonlinear response. We agree with the assessment that the results are complicated. However, it is unethical to simplify what we actually obtained. We further agree with the Editor and the Reviewers about the (lack of) presentation style of these complicated results. We have revised the manuscript to better present the unexpected complexity of the results (*e.g.*, L213–225). We also clearly state in revision that we do not find any clear-cut interpretations in terms of the nonlinear free-Rossby wave dynamics as we originally envisioned (L75–81, L389–404). Nevertheless, this is an important negative finding, that should inspire further experimental studies while avoiding repeating the same mistakes made here (L82–87, L454–461).

As recommended by Mehta (2019), the present manuscript will become a showcase that established researchers with a good background on the MJO fail to prove their hypothesis. It will further send a strong message to younger and aspiring scientists bombarded with success stories. It is our view that the Reviewers and the Editor read the present manuscript with 'success' in mind.

More specifically, in revision, we have realised that it is difficult to extract any firm conclusions for readers from the original manuscript for two related reasons. First, the basic nature of the present study is exploratory (L75). The main goal is an extensive sensitivity study of MJO forecasts on physics, that call for theoretical studies more closely tied to the actual physics of operational models (L75–86). Urgent needs for such a new type of theoretical studies are more explicitly emphasised in revision (L82–87, L449–461). Second, we have failed to state this actual main goal of the work in the original manuscript. The motivation of the study to investigate a possibility of interpreting MJO as a nonlinear free wave in operational models is wrongly stated as a main purpose (L2–3, L389–391). This has been corrected in revision so that readers will be better guided through the revised manuscript (L219–222, L391–397).

We still personally believe that the free nonlinear Rossby-wave theory remains a viable idea. However, clearly, we have failed to obtain any firm support to this theory by the present sensitivity study (L396–397). It simply demonstrates how hard it is to emulate free dynamics within a global forecast model without deteriorating the basic state of the model that so crucially depends on these physical parametrisations. This point has already been made in the original manuscript. However, we have failed to extend its implications (L399–420).

In contrast, we have obtained firm evidence for interactions of the MJO with extratropical waves by the present sensitivity study: the behaviour of the model is relatively insensitive to the choice of physics in representing this aspect of the MJO dynamics. This very point, that was failed to be remarked in the original manuscript, has been clearly be pointed out in revision (L223–225, L441–448).

The Editor suggests that finding sensitivities themselves do not constitute anything original. However, we disagree on this point in the context of MJO studies: these studies are strongly driven by a paradigm of MJO driven by convection, thus almost any global modelling studies of the MJO are also exclusively focused on sensitivities to convection parametrisation. A recent paper by Pilon et al (2016) and Jiang et al (2020) are a good example. The originality of the present paper is to explicitly point out that MJO forecasts do not sensitively depend on convection parametrisations only but also on other physics, especially the momentum dissipation processes (L20–36, L82–87, L449–453). Probably, pointing out this very simple fact is already a very important contribution of the present work. Unfortunately, we had failed to emphasise such a basic point in the original manuscript.

Respond to the Reviewer 1

Thank you for your comments posted on 3 March 2020.

I respond to those as follows:

<u>General Introductory Remarks:</u>

An explorative nature of the present manuscript is emphasised (L75). As well summarized as items 1) and 2) by the present Reviewer, the scientific questions of this study are well posed. We strongly believe that presented results are rich in implications (L20–36, L82–87, L449–453). However, as the present Reviewer suggests, we are short of developing full interpretations of the results. It is a major reason that we decided to submit the present manuscript to ACP, thus by going through the discussion session, we can obtain various useful feedback. Regardless of the amount of feedback we may receive, we also believe that the materials presented herein strongly invite for theoretical interpretations, that must further be developed (L6–9, L82–87, L449–461). Development of such theories must be a common effort of the community by placing these materials in public domain. This is the main reason that we believe that the present materials are worthwhile to publish in the present form. As stated in the current version, we believe it important to present those details of the model sensitivities so that the theoretical community will be aware of the real issues of the operational MJO modelling.

Major Comments:

1. We believe the difference of different simulations are already carefully described. If the Reviewer believes that further details are required, please be specific. The physical details of IFS are available on Web, and the Web address has been provided in the final version (L133–134). On more specifics,

i) The momentum dissipation is expected to suppress a "free dynamics", thus we expect that the MJO would also be enhanced by turning it off, if it is described as a free dynamics to some extent. This very basic point has been more explicitly stated in the final version (L37–40).

ii) However, the most fascinating aspect of the result is that the change of MJO behaviour is hardly monotonous by simply turning off various moment-dissipation terms (L4–6, L89–90). In other words, the role of momentum dissipation is highly nonlinear in the MJO dynamics, as already suggested in the manuscript. This point has also been more clearly stated in the final version . [The word "highly nonlinear" was not used in revision, because it sounds rather too strong, but the nonlinear response of the model to physics is much emphasised in revision (L87–88, L219–222, L392–394).]

iii) I agree that convection in Fig. 4(a) is stronger than that in Figs. 4(b) and (c). This point has been explicitly stated in the final version (L269–270, L276–277).

2. No ensemble run is considered in the present study. Every run is initiated with an initial condition for the operational standard run. Thus, the model is initialised by the most-likely state, and the resulting forecast is also the most-likely evolution under a given physical setting. We do not understand why an ensemble is important for the present purpose, because the most-likely evolution is the main result that we want to know, though ensemble information may provide supplementary information.

In the final version, the term "correlation analysis" has been replaced by "pattern correlation analysis", as suggested.

3. In Fig. 4(a), the most remarkable improvement is the clear-sky area behind MJO. A mechanism for this change is hard to identify, though the present Reviewer may like to speculate. Nevertheless, it does not prevent us from pointing out this most remarkable improvement. Convection associated with MJO is too strong with this setting (L269–270), and this is hardly considered an improvement as dramatic as the clear sky.

4. As already remarked in response to the item 1, the effect of turning off a physical process is hardly linear, but the MJO evolves in nonlinear manner in response. This is just

an example of such a nonlinear that turning off the convective friction leads to a sudden deterioration of the forecast towards the end of the forecast period. Data sampling may only artificially remove those nonlinearities that are actually present.

Minor Comments:

1. Against to what the present Reviewer suggests, there is no line for the CF in Fig. 4 (Fig. 5 after revision). In any case, such a line must be drawn somehow in a subjective manner, because the MJO is hardly a simple linear propagation process. In our opinion, it rather hinders us form more objectively see a change of the forecast by a change of physics (*cf.*, L216–222, L430–440).

2. This is a very good speculation to make: indeed, if the MJO is a free wave to a good extent, too strong convection will hinder a proper propagation tendency. This remark has been added in the final version (L276–277).

3. [Fig. 7(b) in revison] The y-axis here is correct. Note that the extended Mbb case is run for only 30 days, as stated in Sec. 2.3. The figure caption has been modified for a better clarity in the final version .

4. Thank you for pointing us errors in figures. These errors have been corrected in the final version.

5. "Emission of an anticyclonic Rossby-wave train from the Eastern Pacific towards higher latitudes" [The whole subsection containing this sentence has been removed in revision]

6. The verb "forecast" can be either "forecast" or "forecasted" in past participle form. According to whatis.techtarget.com: Although both are used, forecast is the preferred form.

7. Thank you for picking up a typo: "Wang et al. 2018" has been corrected to "Wang et al. 2019" in final form.

Respond to the Reviewer 2

We much appreciate the comments posted on 17 March 2020 by the present Reviewer. Our apologies for a delay of a response from our side, mostly due to a *confinement* of the first author during the epidemic.

Indeed, the present Reviewer provides us with a very good summary of the present study. We also much appreciate a positive evaluation, stating that "there may be many interesting results, especially that can help the world-best MJO forecast model to be even better.

Therefore, I agree with the authors that (from the reply to the reviewer's comment) this is a significant study." However, as the case with the first reviewer, the present Reviewer remarks that "it is very hard to follow" mostly due to "too complicated results".

Yes, the results are "very complicated" with very different behaviour sensitively depending on the choice of physics to be turned off. These are results that we even did not expect when we started this project. However, we are afraid that we must best present these complicated results as they are, because these are what we get. By reading through the original manuscript carefully, we realise that the main problem was in presenting our original motivation of the study as if the purpose of the paper itself. The real purpose here is to report these complicated results, which do not give any clear-cut interpretations in terms of the nonlinear free–Rossby wave dynamics as we originally envisioned (L75–87). The original manuscript was hard to read, because we presented the results without warning the readers properly. In the revised manuscript, we have made this point as clear (*e.g.*, L213–225). Furthermore, more interpretational remarks have been inserted into the analysis section so that readers may not be get lost in details (L269, L297, L308–309, L315–317).

We agree that, as a reviewer may react, it is very usual just to report all those details of model sensitivities as a scientific report. However, the first author, especially, points out that the very fact of never reporting those modelling sensitivities is a core reason for slow progress of global models, without much useful inputs from theoretical studies (L7–11, L75–86, L183–186, L397–398, L454–461). A commentary to Nature by Metha (2019) makes the merit on this type of publications clear.

For example, as already suggested in the original introduction, there are extensive studies in theoretical literature about whether the friction contributes to the MJO dynamics positively or negatively (L39–43). However, all these studies are based on a rather simple Rayleigh–friction formulation with a dichotomy of with or without friction (L84–85, L459–461). A very important message from the present study is that the effects of friction is hardly such a simple dichotomy. Rather the performance of MJO prediction sensitively depends on the choice of the exact friction term. This very fact is something to be reported to the theoretical community so that theoreticians can more positively contribute to understand these "complex" behaviours of MJO within global models (L80–87, L454–461).

Another important message to convey from the present study is a difficulty of emulating the free dynamics within an operational global model (L9–10, L399–404): if we totally turn off the dissipation terms as well as diabatic heating, as attempted in this study, the basic climatology, that is required to support a free nonlinear–wave dynamics, is also destroyed as a result, thus an expected free dynamics is no longer simulated. The significance of these lessons from the present study has been more clearly highlighted in revision (L399–404).

As for more specific issues:

1) Presentation of Figures: We decided to focus on the Hovmuller plot, because we find it the most succinct manner of presenting the MJO behaviour both in terms of convection and vorticity (rotational flows: L181–186). Under this configuration, "anticyclonic vortex pair symmetric to the equator" appears as a positive anomaly in a Hovmuller plot, as already remarked in Sec. 2.1. To make a point clearer, we have added a phrase "over the Indian Ocean" in revision. We will also change the phrase itself as "anticyclonic activity", because it is true that by Hovmuller plot only, it is not possible to tell, whether this is a vortex pair or not (L144). A reader would be able to identify a development of a positive stream–function anomaly along a MJO propagation easily in this manner.

2) Improvement of Hovmuller plots:

i) Though it would be possible to remove some redundant color bars from figures, presentation of figures would become less coherent as a result. For this reason, we opt not to perform this change.

ii) In Revision, "Hovmoeller of" has been removed from all the figure headings as suggested. Similar simplifications of the figure headings have also been applied to Figure 2.

iii) There was a problem with sub-labels in the original Figure 3. This has been corrected in final version.

iv) The values beyond a range of colour code is not shaded. This fact has been remarked in the revised caption of Figure 1 in such manner that the remark also applies to all the subsequent figures.

3) Results: For reducing the amount of results to be presented, Sec. 3.5.2 has been removed in revision, because it does not offer much. Nevertheless, the main message to be conveyed by the present paper is the very fact that none of the existing theories appears to explain the identified complex sensitivities. In this very respect, a number of cases is important to explicitly indicate a complex response of the model by selectively turning off the physics.

4) MJO event selection: A 'low–skill event' is selected in the present study, because by definition, it is more challenging to forecast (L139–142). As shown in Fig. 3, the performance of controls runs is rather poor. Thus, the question is: how can we improve it? As reported herein, we have certain successes. However, the change of the model performance is not

quite consistent in terms of change of contribution of friction (L216–221, L392–394). We believe that the latter is more important to emphasise rather than reporting some limited successes, which are only superficially good news (L222–223, L454–461).

By following a suggestion of the present Reviewer, some diagnostics based on RMM indices have been added in revision (new Fig. 3).

references:

Mehta, D., 2019; Highlight negative results to improve science. *Nature*. https://www.nature.com/articles/d41586-019-02960-3

Jiang, X., E. Maloney, and H. Su, 2020: Large-scale controls of propagation of the Madden-Julian Oscillation. *Clim. Atmos Sci*, **3**. https://doi.org/10.1038/s41612-020-00134-x

Sensitivities of the MJO Forecasts on Configurations of Physics in the ECMWF Global Model

Jun–Ichi Yano[1] and Nils P. Wedi[2]

[1]CNRM, Météo-France and CNRS, UMR 3589, 31057 Toulouse Cedex, France
[2]European Center for Medium–Range Weather Forecast, Reading, UK

Correspondence: Jun–Ichi Yano (jiy.gfder@gmail.com)

Abstract. Sensitivities of MJO forecasts to various different configurations of physics are examined with the ECMWF global model, IFS. The motivation of the study is to simulate the MJO as a nonlinear free wave under active interactions with Rossby waves from and to higher latitudes. To emulate free dynamics in IFS, various momentum dissipation terms ("friction") as well as diabatic heating are selectively turned off over the tropics for the range of the latitudes 20S-20N. The reduction of friction tends to improve the MJO forecasts, but hardly in any additive manner. A change of the forecast performance rather sensitively depends on the type of friction turned off. The behaviour is in contrast to many theoretical studies based on a rather simple Rayleigh–friction formulation under a dichotomy of with or without. By reporting the details of those physical sensitivities on the MJO forecast, the present study suggests a need for theoretical investigations that much more closely follow the actual operational formulations of physics. An important lesson to learn from the study is an inherent difficulty to emulate a free dynamics with an operational forecast model. The study also demonstrates the importance of other physical processes than convection for simulating the MJO in global forecast models.

1 Introduction

The Madden-Julian oscillation (MJO: Zhang 2005) is a prominent tropical variability that many global atmospheric models still have difficulties in simulating. In the case of the ECMWF Integrated Forecasting System (IFS), the forecast of the propagation of the pre-existing MJO has much improved in recent years (Vitart 2014), typically providing persistent MJO signals well beyond the medium-range forecast. However, the IFS still suffers from some difficulties, especially, in predicting the onset of MJOs. Needs for a capacity of extended MJO forecasts are becoming more important with increasing demand for extended forecasts up to a subseasonal range (3–4 weeks) and because the MJO is one of the most prominent and persistent tropical signals to be forecast over this time scale (*cf.*, Kim *et al.* 2018).

From an operational point of view, the MJO is typically considered physically forced in the sense that the physical parametrisation (or short 'physics' hereafter) in the models are the key for improving the simulation of the MJO, rather than a problem of the dynamical core (*e.g.*, Hirons *et al.* 2013a, b). The most crucial physical process to be considered is deep convection, that is typically parametrised as a subgrid-scale process in global models (Yano and Plant 2015). A majority of the existing theories for the MJO are based on a certain coupling of the large–scale dynamics with convection (*e.g.*, Hayashi 1970, Lindzen

1974, Emanuel 1987, Yano and Emanuel 1991, Majda and Stechmann 2009, Fuchs and Raymond 2017). For this reason, a general expectation is that simulations and forecasts of the MJO in the global models must be improved by improving the parametrization of deep convection (*cf.*, Jiang *et al.* 2015, 2020) as well as shallow convection (*cf.*, Pilon *et al.* 2015). For this reason, existing sensitivity studies on MJO simulations almost exclusively focus on convection parameterizations (*e.g.*, Hirons *et al.* 2013a, b, Pilon *et al.* 2015).

The present study examines the sensitivity of the MJO forecasts on physics from a different perspective proposed by Yano and Bonazzola (2009), Yano *et al.* (2009), Wedi and Smolarkiewicz (2010), Yano and Tribbia (2017), and Rostam and Zeitlin (2019), and Wang *et al.* (2019). According to their perspective, the tropical large–scale dynamics in general and the MJO specifically can be understood in terms of *free* Rossby–wave dynamics, in which model "physics" may still play a role, but secondary to the initiation and evolution. To investigate this possibility of the MJO as a free dynamics in the context of the operational global forecasts, we take the ECMWF global model (IFS) as a basic framework, and perform extensive physical sensitivity experiments.

To emulate a free dynamics within IFS, physical tendencies of some physical variables are selectively turned off so that the resulting sensitivities to the corresponding MJO forecasts can be examined. A key process to be turned off to emulate a free dynamics is the surface friction, or momentum dissipations more generally. This process has been expected to potentially play a crucial role in the MJO dynamics. A classical work by Chang (1977) makes this point by invoking the surface friction as a mechanism to slow down the propagation speed of the eastward-propagating free Kelvin wave to a degree comparable to that of the MJO. The frictional wave-CISK theories by Wang (1988) and Salby *et al.* (1994) also invoke frictional moisture convergence as a key ingredient in addition to deep convection for explaining the basic dynamics of the MJO. Along with the surface friction, diabatic heating is another key process to be turned off for achieving a free dynamics.

When physical forcings are turned off from a model, an alternative mechanism for generating MJOs must also be considered. In this respect, the present study also pays particular attention to a potential importance of the interactions of the MJO with the higher-latitude dynamics. Weickmann *et al.* (1985), Knutson and Weickmann (1987) suggest that the interactions with Rossby-wave trains from and to higher latitudes are intrinsic parts of the MJO dynamics. Hsu *et al.* (1990), Gustafson and Weare (2004), Ray and Zhang (2010), Ray and Li (2013), Zhao *et al.* (2013), and Wang *et al.* (2019) further suggest that Rossby-wave trains from the northern-hemisphere higher-latitudes trigger MJOs. For investigating this aspect of the MJO dynamics, in the following sensitivity study, we attempt to simulate the higher-latitude dynamics as properly as possible. In the following sensitivity experiments, a weighting of $\cos^6\phi$ with ϕ the latitude is adopted so that the effects of the applied sensitivity rapidly tail off above $ca.$, 20°. Hence, when a certain process is turned off over the tropics, the tendency due to this process is multiplied by $1-\cos^6\phi$.

Under this general strategy, four major categories of experiments are performed as listed in Table 1. These experiments are designed to address the following questions: 1) a possibility that the propagation of the MJO can be simulated even by turning off the diabatic heating due to convection; 2) a possibility that the MJO is induced by the Rossby-wave train arriving from higher latitudes, or more specifically from a European region towards the Indian Ocean.

Table 1. Four major categories of experiments

Category	Description
1	Control operational forecasts
2	OFF selected or total physical tendency for the momentum (due to shallow and deep convection and the vertical eddy diffusion)
3	OFF physical tendency for the temperature (entropy) (due to shallow and deep convection, radiation and cloud phase changes)
4	OFF all physical tendencies as above for both momentum and temperature

To address the question 1), we turn off all the diabatic heating in the heat equation (entropy budget) so that an adiabatic free dynamics regime is realised over the tropics. Here, it is crucial to turn off all the diabatic heating, because if the latent heating is turned off, but the radiative cooling tendency of the tropics is maintained, a steady state can only be maintained by turning the mean ascend (associated with moist convection) to a mean descent, that induces diabatic heating that balances the radiative cooling. We turn off the total diabatic heating so that the tendency for generating any vertical motion is suppressed, and a purely horizontal, quasi-nondivergent flow is realised. Additionally turning off the momentum dissipation is expected to further enhance a tendency for a free dynamics over the tropics. For this reason, this last set-up is referred to as a quasi-free (QF) forecast in the following.

To address the question 2), we turn off the non-conservative processes (*i.e.*, frictional dissipation in general) in the horizontal momentum equation, because we expect that the free Rossby–wave dynamics associated with MJO are enhanced by turning off the momentum dissipation. As a result, we also expect that Rossby-wave interactions between the tropics and the higher latitudes are enhanced. A claim of MJO as a free Rossby wave also contains another important general implication that the MJO can be principally understood in terms of nondivergent, rotational flows. Thus, an important question to be investigated is to what extent a non-divergent (rotational) component of the MJO is still maintained by this set-up. As schematically summarised by Madden and Julian (1972, see their Fig. 16), the MJO is usually considered being strongly associated with a divergent component of the tropical circulation.

An exploratory nature of the present investigation is emphasised. Unfortunately, our goal of emulating the free dynamics is not achieved in any obvious manner, without any systematically–identifiable trait in these sensitivity experiments. For example, the reduction of momentum–dissipation effects (“frictions”) in the model does not lead to a simple improvement or deterioration of the MJO forecast. The paper focuses on elucidating these complex sensitivities of the MJO forecasts on different configurations of the physics. Detailed descriptions of the results are presented throughout the text as objectively as possible, with the purpose of elucidating real operational issues in improving the MJO forecasts. That is where theoretical investigations are strongly needed to better understand the model behaviour.

For example, the role of friction in the MJO dynamics remains a key question since a pioneering study by Chang (1977). However, the majority of theoretical studies treat it simply as a Rayleigh friction (*cf.*, Sec. 4 of Yano *et al.* 2013 as a review of this line of theoretical studies). The present study, in turn, shows that the actual contribution of friction in an operational model is far more complex. Thus, a more serious effort to fill a gap between those idealised theoretical studies and operational problems is required.

However, there is a subtlety in turning off certain physics in a given model, because of their impact on the mean state and the nonlinearity of the system leading to various chain reactions and compensating behaviour with corresponding changes to MJO forecast skill. We find that a change of the results by turning off different physics hardly constitute simple additive processes, and it is likely also model specific. Previous studies have found significant changes in the energy cascade behaviour of the IFS model, controlled by certain physics or specific parts thereof (Malardel and Wedi 2016). A change of the tropical processes clearly influences the interactions of the tropical processes with those in higher latitudes. Subtle balances between higher latitudes and the tropics must therefore carefully be taken into account for a full interpretation of these sensitivity results.

The main contribution of the present study is to show that the MJO dynamics is not just a matter of its coupling with convection, but other physical processes, including friction, actively contributing in defining its dynamics. Another important, rather unintuitive result is a strong sensitivity of the MJO forecast on initial conditions. The following analysis is focused over the region of the Indian Ocean to the Western Pacific (90–180E), where main activities of the MJO are identified. Although the original study by Madden and Julian (1972) identifies the MJO as a global mode, as the analysis by Milliff and Madden (1996) shows, the continuous mode propagating eastwards beyond the Date Line is rather identified as a free Kelvin wave.

2 Forecast Cases

2.1 General Description of the Study Period: Association of the vorticity variability with the MJO

Wedi and Smolarkiewicz (2010), Yano and Tribbia (2017), and Rostam and Zeitlin (2019) propose that the MJO is basically understood in terms of a dipolar vortex (vortex pair) symmetric to the equator. According to their theory, this vortex structure must penetrate through the whole troposphere. However in data analysis, the lower troposphere tends to be too noisy for identifying the MJO signature in the rotational wind field (or vorticity) without a proper filtering or composite procedure (*cf.*, Wang *et al.* 2019). For this reason, we focus on the 150 hPa level rotational wind field in the following. For the reasons explained in Sec. 2.4 below, we take the stream function as the diagnostic field of choice for examining the vortex dynamics associated with the MJO.

To see a clear association of the rotational wind field with the convective variability of the MJO, we show in Fig. 1(a), (b) the time-longitude section averaged over 15S-15N for the outgoing longwave radiation (OLR) and the 150 hPa stream function (with the sign flipped for the southern hemisphere so that the anticyclonic vorticities are always treated as positive) for the four-month winter period (November 2016 – February 2017) from the ECMWF global analysis ("analysis" in short in the following), which is systematically adopted as an observational reference in the following. Here, data is plotted daily with the horizontal resolution of 2.5°. However, no filter is applied either in time or space. In the OLR field (Fig. 1(a)), three MJO events are identified over the Indian Ocean to the Western Pacific (90–180E) during this period: the two major ones in December and in January–February. Another weak MJO event is identified over December–January.

In association with these three MJO events, high anticyclonic activities (positive signals) over the Indian Ocean to the Western Pacific are identified (Fig. 1(b)), also propagating eastwards with a similar phase speed. According to Wedi, Smolarkiewicz, Yano, Tribbia, Rostam, and Zeitlin, based on a nonlinear *modon* solution, the MJO constitutes of anticyclonic vortex pair in the upper troposphere propagating eastwards. Thus, from point of view of their theory, these anticyclonic propagations are the key features to be simulated in association with the MJO. However, note that these propagating structures are not quite in phase, and for this reason, the absolute value for the pattern correlation between these two fields rarely exceeds 0.3.

2.2 Model description

The IFS version cycle 43r3 (operational during 11 July 2017 - 5 June 2018) is used for the forecast experiments with (unless otherwise stated) TCo639 (average grid spacing 18 km) and with 137 vertical levels. IFS is a spectral transform model solving part of the solution in spectral space, where prognostic variables are represented via spherical harmonic basis functions. To calculate nonlinear terms in the equations of motion, to perform the nonlinear (semi-Lagrangian) advection, and to calculate the contributions of all physics schemes in grid point columns, the model fields are transformed into a representation in grid-point space. A cubic octahedral (reduced) Gaussian grid is used for this purpose, denoted by 'TCo' and described in more detail in Wedi (2014) and Malardel *et al.* (2016), typically evincing a higher effective resolution. The model is stepped forward in time using a semi-implicit time discretization for the faster (wave) processes. The model includes a realistic topography, state-of-the-art descriptions of the diabatic forcing processes, including shallow and deep convection, turbulent diffusion, radiation and five categories for the water substance (vapour, liquid, rain, ice, snow). Full model documentation is available from: www.ecmwf.int/en/publications/ifs-documentation/.

2.3 Choice of the forecast cases

Two forecast cases are mainly considered. Both cover one of the most prominent MJO events during the northern winter 2016–2017. The MJO in concern here corresponds to a low–skill event (F. Vitart, personal communication, March 2018) under dichotomic categorisation of the MJO forecast difficulties introduced by Kim *et al.* (2016), which are more difficult than the average. Here, a low–skill event is chosen for our experiments for an obvious reason that it is more challenging to forecast. As going to be seen below, operational control forecasts perform rather poorly, thus a question to be posed is: how can we improve it? Sensitivity experiments are chosen, as discussed in introduction, with a hypothesis of the MJO as a nonlinear free–Rossby wave in mind. If this hypothesis is correct, we should obtain better forecasts by turning off selected physics.

The first forecast case (called "standard" in the following: Fig. 1(c), (d)) is initiated on 19 January 2017 and run for 20 days. At this initial condition, convection associated with MJO is already fairly well developed over the Indian Ocean (Fig. 1(c)), and the key question is whether the model can maintain this convective system and also propagate eastwards as observed. From a dynamical point of view, this is before the anticyclonic activity begins to develop over the Indian Ocean (Fig. 1(d)). Thus the key forecast question is whether the model can predict the onset of this activity.

The second cases (called "extended" in the following: Fig. 1(e), (f)) is initiated ten days earlier (9 January) than the standard case, and run for 40 days, except for the Mbb case (*cf.*, Table 2) runs for only 30 days. The initial condition corresponds towards the end of a previous MJO, and no mark of convective activity associated with the new MJO is yet to be seen over the Indian Ocean (Fig. 1(e)). Thus, a key operational challenge is to forecast the onset of convective variability associated with the MJO over the Indian Ocean. From a dynamical point of view, the vortex pair associated with the previous MJO is still well identified over the Western Pacific (Fig. 1(f)). Thus, another operational challenge is to forecast the continuous maintenance of this vortex pair, in association with a subsequent onset of another vortex pair over the Indian Ocean.

Finally, a single quasi-free forecast initiated on the 1 February 2017 is considered (QF). This is a moment that the vortex pair is fully developed over the given MJO event (Fig. 1(f)), although convection actually has already begun to fade out (Fig. 1(e)). Thus, this experiment examines whether it is possible to forecast the eastward propagation of this vortex pair even without convection. Table 2 describes the list of sensitivity experiments. As described in the Introduction, selective physics are turned off but only over the tropics, in the following experiments, by applying a factor, $1 - \cos^6 \phi$, on a physical term in concern with ϕ the latitude.

2.4 Analysis Procedure

2.4.1 OLR

We take the outgoing-longwave radiation (OLR) as a representative of the convective variability by following a standard approach in the literature. Here, however, special considerations are required with this variable, because within IFS, the longwave radiation (tagged as the "top net thermal radiation" J/m^2) is recorded as accumulated values. As a standard procedure at ECMWF, the emission rate is estimated from the accumulated values as a tendency over 24 hours. Since the outgoing longwave radiation is not one of the initialization fields, it is not included as an analysis field, either. As a result, "observational" OLR is, instead, estimated from the first 24-hour tendency of the operational daily forecasts. For this reason, even the initial 24-hour pattern correlation is noticeably less than the unity in the following presentations (Fig. 2(a) below). The OLR anomaly is defined as a deviation from the climatology. Here, the climatology is defined as an average over the years 1979–2009 for each given calendar day.

2.4.2 Vorticity field

For examining an association of MJO with the vorticity field, *or* rotational flow, we take the 150–hPa stream function. In preliminary analyses, we have also examined the vorticity field directly. However, this field turns out to be rather "noisy", being dominated by smaller scales over the tropical region with the forecast correlation typically lost more than 60 % over a single day. For this reason, we judge the vorticity field is rather an unreliable variable to diagnose over the tropics. The stream–function field is more robust, being obtained by applying an inverse-Laplacian to the vorticity, and by the nature of this inverse operator, this field is much smoother. We focus on the tropopause level (150 hPa), because as it turns out, at this level, a coherent rotational flow field associated with the MJO is much easier to identify than the lower levels (*cf.*, Wang *et al.* 2019).

Table 2. List of sensitivity experiments at TCo639 with 137 vertical levels: categories according to Table 1, the label used in the text, experiment description, and forecast cases (standard, extended).

Category	Label	Experiment description	Forecast Cases
1	CF	Control operational forecasts	standard, extended
2	Ma	OFF all the momentum dissipation (drag) tendencies in vertical eddy diffusion (including those in the boundary layer) and convection parametrization (shallow and deep)	standard
2	Mbe	OFF momentum dissipation tendencies due to vertical eddy diffusion only	standard
2	Mbb	OFF momentum dissipation tendencies due to vertical eddy diffusion (boundary layer below 800hPa)	standard, extended 30 days
2	Mbc	OFF momentum dissipation tendencies due to convection parametrisation (shallow and deep)	standard
2	Mbd	OFF momentum dissipation tendencies due to convection parametrisation (deep only)	standard
2	Mbs	OFF momentum dissipation tendencies due to convection parametrisation (shallow only)	standard, extended
2	Mbde	OFF momentum dissipation tendencies due to vertical eddy diffusion and convection parametrisation (deep only)	standard
2	Mbse	OFF momentum dissipation tendencies due to vertical eddy diffusion and convection parametrisation (shallow only)	standard
3	NQ	OFF physical tendency for the temperature (entropy) (due to shallow and deep convection, radiation and cloud phase changes)	standard
4	QF	OFF all physical tendencies as above for both momentum and temperature	standard, extended, 20 days from 1 February

2.4.3 Verification

In the following, the forecast performance is evaluated by inspecting time–longitude section of OLR and the stream function averaged over 15S–15N, considering the fact that the MJO is a longitudinally–propagating feature. When latitudinal interactions between MJO and extra–tropical Rossby waves are in concern, time–latitudinal sections are examined instead. In the present study, we emphasise an importance of the visual inspection of the forecast performance to compare it with the analysis. In the following, very specific descriptions of the forecast behaviours in comparison with the analysis or a control forecast will be presented, because we believe that these details are keys to understand the actual processes simulated by these forecasts.

As a basic point of reference, the correlation is computed between the analysis and a forecast over the longitudinal range of 0-180E between 15S and 15N. This correlation will be referred as a *pattern correlation* in the following. We adopt this measure, because it is a straight manner of comparing the two fields (analysis and forecast) over the tropics without imposing our prejudices of expectations.

Additionally, evolutions of forecasts in the phase space of the real–time multivariate MJO (RMM) index pair (Wheeler and Hendon 2004) are also presented for selective cases. Here, the RMM index pair is evaluated by projecting the anomaly field defined as a deviation from an average over a forecast period. Note that unlike the pattern–correlation analysis, the RMM measures a forecast skill in respect to a prescribed field pattern (*cf.*, Straub 2013).

3 Analysis Results

3.1 Summary of forecast experiments: the pattern–correlation analyses

The time series of pattern correlations between the forecasts and the analysis in Fig. 2 summarise the experiment results. The anomaly field is considered for the statistics of the OLR, whereas the zonal mean is taken out from the 150–hPa stream function. A first step of verifying the performance of the sensitivity experiments would be to examine how well the convective variability associated with the MJO is predicted by these experiments. The pattern correlations between the simulated OLR and the analysis are shown in Fig. 2(a). The same is shown in Fig. 2(b) for the rotational–wind field (150–hPa stream function). Fig. 2(c) is the same as Fig. 2(b), but focuses on the role of convective frictions (*cf.*, Sec. 3.3.2 below).

Fig. 2(a) additionally shows higher-resolution runs (orange and violets) with average grid-spacing of 5-6 km, for a reference. These do not perform any better than lower horizontal resolution simulations, thus are not considered further in the remainder of the paper.

As another summary for the forecast performances, Fig. 3 present RMM analyses for some selective cases. Here, (a) and (b), respectively, show the evolution trajectory of the analysis data on the RMM phase space over the standard and extended forecast periods. Evolution of the MJO is represented by a counter–clockwise movement of a trajectory in this phase space, with an initial point marked by a red circle, as seen in both frames. Note that although the extended forecast period contains the standard forecast period as a part, the two trajectories for the ERA5 analysis do not match exactly over the same period due to the different definitions of the anomaly used (defined relative to an average over a selected forecast period). These two trajectory patterns are to be compared with those of sensitivity experiments and control forecasts as a verification.

The remainder of this section proceeds as follows: morphological behaviours of the control forecasts are carefully described in the next subsection (Sec. 3.2), because they provide baselines for interpreting subsequent runs turning–off selected physics. The following two subsections (Secs. 3.3 and 3.4) look for improvements of MJO forecasts by removing momentum dissipations as well as diabatic heating effects, as would be expected from the free nonlinear Rossby–wave theory. As it turns out the performance of the MJO forecasts does not depend on these choices of physics in any consistent manner: less momentum friction does not necessarily lead to a further improved MJO forecast, but the skill and MJO propagation sensitively depends on the type of dissipation turned off. Effects are hardly additive, either, but clearly nonlinear interactions are going on between the physics. Thus, against the original motivation stated in the introduction, the main purpose of these two subsections becomes a report of these forecast sensitivities in more detail. Careful descriptions will also reveal that improvements of the MJO forecast is hardly a monotonic measure: certain aspects are improved, but often associated with deterioration of other aspects. Sec. 3.5 focuses on the model performance on simulating interactions between the MJO and higher–latitude Rossby–wave activities. Here, we rather find a consistent tendency that the model simulates those interactions features identified in the analysis relatively well, although some sensitivities inevitably emerge.

3.2 Control Forecasts (CFs)

This subsection first establishes basic behaviours of the control forecasts (CFs), because they are the base lines for defining a change in forecasts by turning off certain physical processes.

3.2.1 Standard 20–Day Control Forecast

With the standard 20-day control forecast (CF), the initial 0.7 pattern correlation of OLR with the analysis linearly decreases to 0.5 approximately at the end of the forecast (short black curve in Fig. 2(a)). Inspection of the time-longitude section (Fig. 4(a)) reveals that although the convective variability is persistent in the simulation, it is too stationary (lack of propagation), and as a result it loses a pattern correlation with the analysis with time (*cf.*, Fig. 1(c)).

The standard CF presents a rather high pattern correlation of the 150–hPa stream-function with the analysis above 0.8 for the first 16 days (long black curve in Fig. 2(b), (c)). However, this high pattern correlation turns out to be rather misleading, because a direct inspection of the time-longitude plot (Fig. 4(b)) reveals that the predicted stream–function signal is much weaker than analysis (Fig. 1(d)). Onset of the anticyclonic vorticity signal centered around 100E on 29 January is correctly predicted, leading to a high pattern correlation, but with a much weaker amplitude, and the signal suddenly dies out on 4 February associated with a sudden drop of the pattern correlation.

As expected from the description so far, the MJO signal as defined by RMM index (Fig. 3(c)) rapidly decays in the standard CF, and a forecast skill is totally lost in less than 10 days.

3.2.2 40–Day Extended Control Forecast

When the experiments are initialized 10 days earlier (9 January), the forecast is expected to be harder, because it corresponds to a final stage of the previous MJO, and a next MJO to be predicted is not yet initiated (*cf.*, Fig. 1(e)). The pattern correlation of OLR gradually decreases to 0.4 over 20 days with CF (black curve in Fig. 2(a)). However, from this point, the pattern–correlation value begins to gradually recover, and it exceeds that of the standard 20-day forecast on 2 February, and increases to above 0.6 by 4 February.

Some possible interpretations are inferred from the time-longitude section (Fig. 4(c)). The last phase of the previous MJO consists of a westward propagating cloud cluster over the Western Pacific, partially driven by the linear Rossby wave dynamics. In the extended CF, this westward propagating cloud cluster continues to propagate into the Indian Ocean although it dissipates out in analysis. The continuous westward propagation effectively simulates the initiation of the new MJO, as observed. The termination of this cloud cluster on 26 January coincides with an initiation of a new cloud cluster to its east side. The new cloud cluster is also more persistent than the observed counterpart, that in turn, contributes to a significant recovery of the pattern correlation. It is speculated that the persistence of this cloud cluster is helped by a persistent anticyclonic signal over the same region, successfully predicted albeit with a 4-day delay of onset (Fig. 4(d)). The simulation predicts an initiation of another convectively active phase on 11 February, as observed. However, this convective variability turns out to be more active and persistent than observed.

According to Fig. 3(d),the MJO signal defined by the RMM initially decays rapidly over the first 5 days. However, the forecast skill gradually recovers towards the end of the forecast by following a circle marked in the phase space (corresponding to a standard deviation of climatological RMM index pair).

3.3 Forecasts Sensitivities on Friction

Forecast performance sensitively changes by turning off some physical processes. We focus mostly on the standard 20–day forecasts first to elucidate various aspects, then briefly remark on the 40–day extended forecasts.

3.3.1 Momentum Dissipation

Performance of the forecasts for the MJO rotational field sensitively depends on the choice of momentum dissipation terms. This subsection discusses this overall aspect. The next subsection focuses more specifically on convective friction. A first case to be considered is when the total tendency for the momentum dissipations (both eddy diffusive and convective: Ma) is turned off. The time-longitude section (Fig. 5(a)) shows that the eastward propagation structure of convection is better simulated than by CF, apparently in support of a free nonlinear–wave theory. However, convection also becomes too strong compared to the analysis. More significantly, a clear-sky area (60-70E) behind the MJO convective variability seen in the last 8 days in the analysis, but absent in CF, is successfully predicted in this case. The RMM analysis (Fig. 3(e)) also shows that the Ma run evolves around a well–defined counter–clockwise circle with a large radius in the phase space.

Turning off the vertical–eddy momentum dissipation both totally (Mbe: Fig. 5(b)) and only in the boundary layer (BL, below 800 hPa: Mbb: blue curves in Fig. 2(a) and (b); Fig. 5(c)) leads to similar results. Inspection of their time-longitude plots show that the eastward propagation tendency is better simulated by these two cases (Mbe, Mbb) than when the momentum dissipation (drag) is totally turned off (Ma: Fig. 5(a)). Intensity of convection also reduces to a reasonable level, also presumably contributing to slow down the propagation (*cf.*, Seo *et al.* 2009).

Inspection of the time-longitude sections of the 150–hPa stream function for those cases reveal that the anticyclonic variability associated with the MJO event is better simulated by these cases than CF: the emission of the Rossby wave energy from west during 22–28 January is suggested as a major source *e.g.*, for initiating the anticyclonic signal associated with the MJO by the time-longitude plots (Fig. 6(a) for Ma). However, the wave structure to the west of the MJO anticyclone is exaggerated compared to the analysis: it may be interpreted as a westward propagation of a free Rossby wave. A similar feature in the rotational–wind field as in Ma is also identified with the Mbb (Fig. 6(b)), but in a more intermittent manner. The forecast performance of these cases for the 150–hPa stream function in terms of the pattern correlation is, however, not any better than the CF case as seen in Fig. 2(b).

3.3.2 Convective Friction

Turning off the convective friction tends to prolong the predictability of the MJO signal substantially as seen in the rotational wind field in Fig. 2(c) for the standard 20-day forecasts: a pattern correlation is typically maintained at a relatively high value ($ca.$, 0.8) until the end of the forecast, in contrast to a sudden drop of the pattern correlation with the CF (down to $ca.$, 0.4) over the last 4 days.

When the convective friction is totally turned off (Mbc: brown in Fig. 2(b)), the pattern correlation is occasionally higher than the CF case even during the first 16 days of the forecast. Inspection of the time-longitude section (Fig. 6(c)) shows that the predicted MJO signal in rotational–wind field is also comparable to the analysis (Fig. 1(d)). When only the shallow convective friction is turned off (Mbs: red in Fig. 2(b)), the pattern correlation remains higher during the last phase of the forecast than when the convective friction is totally turned off. Time-longitude section (Fig. 6(d)) reveals that in this case, the anticyclone signal over 100-120E persists throughout the experiment without a break over the period of 21-27 January as observed.

These tendencies may be interpreted as a support of a free nonlinear–wave theory. However, when only the deep convective friction is turned off (Mbd: blue in Fig. 2(c)), the forecast performance substantially deteriorates in the last phase. The deterioration is associated with an over-enhancement of the anticyclonic signal over the last phase (29 January to 8 February: Fig. 6(e)).

3.3.3 40–Day Extended Forecasts

With the extended forecast when the shallow with the extended forecast convective friction is turned off (long red in Fig. 2(b), Fig. 6(f): Mbs), the behaviour of the 150–hPa stream function is overall similar to that of the standard CF, except for some precursors for the anticyclonic signal leading to the new MJO event and a re-development of the anticyclonic variability towards the end of the forecast. When the boundary-layer friction further is turned off (30 days in blue, Fig. 2(b), Fig. 6(g): Mbb), the initial anticyclonic variability continues about 6 days longer than observed, and the second anticyclonic variability is also initiated 1-2 days later than observed. Its precursor, albeit weak, already has a good pattern correlation with the analysis.

These extended forecasts may be overall interpreted to suggest that turning off the momentum friction contributes to an improvement of the MJO forecast in general. However, a further removal of the momentum friction in the boundary layer (Mbde and Mbse, green and violate in Fig. 2(c), respectively) slightly reduces the forecast performance. When deep-convective and boundary-layer frictions are turned off (Fig. 6(h): Mbde), the second anticyclonic variability event is too strong, and too spread to the west. When shallow-convective and boundary-layer frictions are turned off (Fig. 6(i): Mbse), anticyclonic variabilities dramatically weaken. Especially, the second anticyclonic variability is too weak and too short: terminated 4 days before the end of the forecast.

Thus, less momentum friction does not positively contribute to the MJO forecast in any consistent manner. These modifications, rather, suggest that effects of turning off the momentum dissipation are not additive, suggesting that some nonlinear interactions are going on.

An initial phase of forecast of the rotational wind field (vorticity field) is easier when the experiment is initiated 10 days earlier than otherwise, because the initial condition corresponds to the maximum of the anticyclone signal (centered at 100-120E) associated with the previous MJO (Fig. 1(f)). A gradual decay of the pattern correlation (with this anticyclonic signal) over the next 4 days is reasonably predicted by CF (Fig. 4(d)), as well as the cases without shallow convective friction (Fig. 6(f), Fig. 7(a): Mbs) as well as without boundary-layer momentum dissipation (Fig. 6(g), Fig. 7(b): Mbb).

Further analysis suggests that the 40-day extended CF simulates the rotational field associated with a MJO rather for a wrong reason: a dipolar vortex structure, constituting an analogue to analytical nonlinear *modon* solution, as expected by a theory of Yano and Tribbia (2017), and Rostam and Zeitlin (2019), is formed by the northern-hemisphere anticyclone with a well–isolated cyclone further north rather than with a southern-hemisphere counterpart. The same interpretation also applies to the Mbs case.

3.4 Free–Dynamics Experiments

One of the reasons for our focus on the frictional terms in these sensitivity experiments is to test a possibility of interpreting the MJO as a free nonlinear Rossby wave as proposed by Wedi, Smolarkiewicz, Yano, Tribbia, Rostam, and Zeitlin. This subsection discusses this aspect by gradually turning–off more forcing and dissipation terms.

We first turn off diabatic heating totally (NQ) so that the vortex dynamics is no longer coupled with convection, against what the standard theories presume for the MJO. Without surprise, the pattern correlation steadily decreases with time approximately linearly to 0.2 towards the end of the forecast. The inspection of the time-longitude section of 150–hPa stream function (Fig. 8(a)) shows that the rotational wind field at this level decays fairly rapidly without diabatic heating, but leaving a small-amplitude wave field. It may be worthwhile to emphasise that the decay process of the anticyclonic signal from the previous MJO is fairly realistic in this forecast, though arguably slightly too fast. A subsequently-generated weak wave field may also be worthwhile to discuss: the cyclonic signal centered around 220-250E amplifies realistically as observed, then it leads to a westward propagation, presumably as a free linear Rossby waves, which turns into a anticyclonic signal around 170E and continues to propagate westward. On 31 January, the anticyclonic signal arrives 100E, that contributes to a significant recovery of the pattern correlation (*ca.*, 0.6 from *ca.*, 0.2 two days earlier). Those relatively positive evaluations of the NQ forecast is supported by the RMM analysis (Fig. 3(f)): it evolves around a well–defined counter–clockwise circle, albeit with a relatively small radius.

When the momentum friction is further turned off (QF) both in standard and extended forecasts cases, the OLR signal decays over the first few days (about four days): See Fig. 7(c) for the 40–day extended forecast. Though some pattern correlations persist beyond this point, that is achieved only by a very weak OLR signal predicted. With the standard forecast of QF (green curves in Fig. 2(a) and (b)), rather unintuitively (despite the lack of momentum dissipation), the westward propagating Rossby-wave signal decays much faster and the amplitude is weaker (Fig. 8(b)) than the case without turning off the momentum friction (NQ), say, by a factor of three. As a result, the pattern correlation with the analysis also becomes slightly smaller (by 0.1-0.2). A similar behaviouris also seen with an extended run (Fig. 8(c): QF).

A final experiment to test the idea of free MJO dynamics is initiated on 1 February 2017 (QF), when a vorticity pair associated with the MJO is already fully developed. Thus, this experiment examines whether it is possible to forecast the eastward propagation of this vortex pair even without convection. At this phase, convection is no longer very active. The quasi–free forecast of 150–hPa stream function for 20 days is shown in Fig. 8(d) along with the analysis (Fig. 8(e)). The result is rather disappointing in the sense that the vortex pair rapidly dissipates over the first few days. It suggests that the model is still not dissipation-less enough as we intend. Nevertheless, a rather surprising behaviour is an eastward propagation of the vortex pair as expected for nonlinear solitary Rossby waves, and opposite to a sense of propagation direction expected for linear Rossby waves. However, the propagation speed of this decaying vortex pair is much faster than that is found in the analysis.

3.5 Initiation of MJO by Intrusion of a Rossby-Wave Train?: Standard 20–Day Forecasts

Some studies (Hsu *et al.* 1990, Gustafson and Weare 2004, Ray and Zhang 2010, Ray and Li 2013, Zhao *et al.* 2013, Wang *et al.* 2019) suggest that an intrusion of a Rossby-wave train from the northern hemisphere to the tropical region can initiate a MJO.

The analysis of standard 20 day forecast period finds such an example over 20-27 January, as depicted in a time-latitude section for the 150–hPa stream function averaged over 20E–60E (Fig. 9(a)): a negative stream–function signal (cyclone) arrives from 80N to 30N by taking about 5 days. An inspection of this time-latitude section gives an impression that the arrival of this signal to 30N helps to re-vitalise and sustain longer the anticyclonic signal centred at 15N. Since its eastward extension is considered the MJO, it leads to an interpretation that the arrival of such a Rossby-wave train helps to initiate the anticyclonic variability (vortex pair) associated with the MJO.

However, the forecast experiments tend to not favour the above interpretation in terms of the Rossby–wave train. To see this point, the performance of the CF for the same period is, first, shown in Fig. 9(b): the arrival of the Rossby-wave train appears to enhance the anticyclone over the same longitudinal range centred at 15N to a degree more than in analysis. However, as a separate time-longitude section shows (Fig. 4(b)), the anti-cyclonic signal associated with MJO decreases faster than observed over the same period with CF.

Three additional experiments (NQ, QF, Ma) provide further insights (Figs. 9(c), (d), (e)): The first is a case with all the diabatic heating (radiation, convection, cloud physics) turned off (Fig. 9(c): NQ). The second case is with both diabatic heating and all the momentum dissipation (vertical eddy transport and convection) turned off (Fig. 9(d): QF). In both cases, the arrival of the Rossby-wave train with a cyclonic signal to the subtropics (30N) is well simulated, and the resulting cyclone signal along 30N is more persistent than in CF, and even more so than in the analysis. Presumably, the absence of the momentum dissipation helps to amplify the cyclone signal with time along 30N (QF), although it is less persistent than the case without turning off any momentum friction (NQ). In both cases, a further induction of the anticyclone signal along 15N, though identifiable, much weaker than the CF case, and it totally disappears after 3 February. Finally, when all the momentum friction is turned off, but the diabatic heating is maintained (Fig. 9(e): Ma), the cyclonic signal intruding into the subtropical region ($ca.$, 30N) from the higher latitudes becomes even weaker than in the analysis. The anticyclone anomaly is induced along 15N in a realistic manner without further amplification as with the CF case.

The predictions of the rotational field in standard 20–day forecasts are overall reasonable in patterns, but larger errors in amplitude. An impression is that the MJO dipole is less isolated than in the analysis, thus the internal (nonevanescent) wave structure leads to westward propagation (or stalled) rather than eastward.

4 Discussions

A main motivation for the present study has been to examine the extent that the MJO can be simulated with a relatively frictionless (physics unforced) setting, being consistent with the proposed free nonlinear Rossby–wave theory for the MJO by Wedi and Smolarkiewicz (2010), Yano and Tribbia (2017), Rostam and Zeitlin (2019), and Wang *et al.* (2019). The MJO forecast does indeed improve when the momentum dissipation is totally removed (Ma: *cf.*, Fig. 5(a))). However, the tendency is hardly consistent: the degree of forecast improvements sensitively depends on a choice of momentum–dissipation terms to be turned off. The effects are hardly additive, either, and clearly certain nonlinear interactions are going on. Most disappointingly, when all the dissipation and forcing terms both for the momentum and the entropy are turned off (QF), the features associated with MJO disappear rather rapidly. Thus, the present study does not support the proposed free nonlinear Rossby–wave theory in any consistent manner. Details on the forecast behaviour based on the choice of physical configurations of the model have been carefully documented to record the unexpected but nevertheless important impact on MJO forecast skill.

There are lessons to learn from the present sensitivity exercise, because after examining the forecast results closely, we have realised that it is not quite straightforward to simulate a free wave dynamics expected from the theory with a complex state-of-the-art global model, as originally intended. The failure to support a free nonlinear–wave theory of the MJO by the present study is mostly due to a failure of emulating the free dynamics with a global forecast model while maintaining a realistic mean state as detailed further below.

Discussions on some specific runs make this point clearer: with the quasi-free 40-day extended forecast (QF: Fig. 8(c)), the pre-existing anticyclonic variability over 100-150E persists almost as long as observed (7 days), albeit with weak amplitude. A weakly eastward tendency, being consistent with the nonlinear free-wave theory, may also be noticed in this simulation. In the standard 20-day forecast case, only a reminiscence of the anticyclone signature from the previous MJO event is found around 120E initially in analysis, and this feature disappears in less than two days (Fig. 1(d)). Note that no convective variability is found at the vicinity to this longitude at the initial time of this forecast period (Fig. 1(c)). The quasi-free forecast (QF) maintains anticyclonic variability longer than in the analysis albeit with a weaker amplitude (Fig. 8(b)).

We interpret these rather subtle results with the quasi–free (QF) forecasts experiments as a demonstration of the difficulties for realising a "realistic" free–dynamics experiment. The main problem with the QF forecasts in the present study is a fact that by practically turning off "all" the physical forcings, the basic state of the model also breaks down very rapidly, thus a proper background state that may support a free–dynamics MJO is also lost very rapidly. It also follows that a free MJO mode also dissipates out very rapidly. A more appropriate manner of performing free–dynamics experiments would be to maintain a background state with full physics in place, but to introduce quasi-free dynamics only to a perturbation component. The basic idea of this strategy may be understood in analogy with standard perturbation analyses. However, in the present case, perturbations must be treated in a fully nonlinear manner, to be consistent with our anticipation that the MJO is a fully nonlinear construct. Such a procedure is not straightforward, but may be considered with the emerging modelling infrastructure (Kühnlein *et al.* 2019).

The present study further suggests that the MJO predictability sensitively depends on the choice of the initial condition in a rather unintuitive manner, but being consistent with a clear distinction between high– and low–skill MJO events identified by Kim *et al.* (2016): longer forecasts from an earlier phase of the MJO may not be harder than a shorter one from a later phase. In the present study, the standard forecasts are initiated (on 19 January) from a pre-existing MJO, whereas 40–day extended forecasts are initiated 10 days earlier towards the end of the previous MJO event. Presumably, the latter is harder to forecast the MJO evolution, especially an onset of a new MJO. However, an inspection of the time-longitude section suggests a different picture: the longer 40-day extended forecasts tend to regenerate the MJO signal towards the end of the experiments, and the recover the forecast capacity. In some cases, their performance becomes even better than the shorter standard 20–day forecasts initiated 10 days later in terms of the pattern correlations of the OLR and the 150–hPa stream function.

As Nakazawa (1988) originally pointed out, the MJO typically constitutes a modulation of the westward-propagating cloud clusters of few-hundred km-scale. The 9 January, the initiation time of the 40-day extended forecasts, corresponds towards the end of the previous MJO event, and also a moment that the last cloud-cluster over the Western Pacific begins to propagate westwards, that marks the end of this MJO event. In the 40–day extended CF, this westward-propagating cloud cluster does not die out as observed, but continues to propagate westwards to the Indian Ocean, which marks an initiation of a new MJO under this experiment. Though the predicted new MJO weakens out at a middle, we note a recovery of the signal towards the end of the event. These initial condition sensitivities of the MJO forecasts point to a simple fact that an onset as well as evolution of a MJO should not be considered as an isolated event, but better interpreted as a part of chain of processes in the atmosphere. It also points to an importance of better understanding detailed processes associated with the MJO, in the present case, those of the westward–propagating cloud clusters. Standard MJO indices (*e.g.*, RMM) fail to depict those critical details (*cf.*, Straub 2013).

The present study has also elucidated active interactions of MJOs with higher–latitude Rossby–wave activities. Inspections of the latitude–time sections suggest that the performance of the MJO forecasts is, at least, partially helped by the successfully simulated interactions of the MJO with the higher-latitude Rossby waves (Rossby-wave trains). At the same time, the effects could also be deteriorating. For example, a stronger Rossby-wave train creates a more continuous wave train than observed over the Indian-Ocean and over the Maritime Continent, that may even destroy the isolation of the MJO dipole structure observed, leading to the westward dispersion of the original dipole. Extensive interactions between the MJO and the Rossby-wave trains revealed by the present study further suggest richer possibilities of processes contributing to the MJO dynamics. Overall, forecasts of these interactions are found to be rather robust and less sensitive to the physics than the MJO forecast skill itself.

The MJO forecast problem is often reduced to that of convection parameterizations (*e.g.*, Hirons *et al.* 2013a, b, Jiang *et al.* 2015, 2020, Pilon *et al.* 2015). However, improvement of the MJO forecast, along with the many other forecast issues, is not a matter of fixing a single physical scheme. Rather we need to examine a forecast model as a whole with its interacting physics for achieving this goal. The present model–sensitivity study has exposed the crucial importance of physical processes other than convection on maintaining a realistic tropical mean state and on MJO forecast skill.

The complex behaviour of the IFS model sensitively depending on the choice of physics turned off, as identified in the present study, should also be emphasised in its own right. For example, the role of momentum friction, in general, is not simply favourable or unfavourable for MJO forecasts. The behaviour sensitively depends on a precise type of momentum friction being turned off. In other words, the operational model behaviour is not decided by a dichotomy of with of without friction, as typically assumed in theoretical studies. By reporting the details of those physical sensitivities on the MJO forecast, the present study strongly suggests a need for theoretical investigations that are much more closely tied to the actual operational formulations of physical parametrisation and their impact on the mean circulation rather than merely modulating the (MJO) anomaly.

Author contributions. Forecast experiments were performed by NPW, and the graphic analyses were mostly performed by JIY. The manuscript was developed by closely analysing and discussing the results by the two authors

Competing interests. There is no competing interest with the present work.

Acknowledgements. Discussions with Peter Bechtold and Fredric Vitart are much appreciated. Fredric Vitart has also kindly provided us with a RMM plotting package. A bulk part of the work was performed when the first author was visiting ECMWF during February-March 2018.

References

Chang, C. P., 1977: Viscous internal gravity waves and low-frequency oscillations in the tropics. *J. Atmos. Sci.*, **34**, 901–910.

Emanuel, K. A., 1987: An air–sea interaction model of intraseasonal oscillations in the tropics, *J. Atmos. Sci.*, **44**, 2324–2340.

Fuchs, Ž., and D. J. Raymond, 2017: A simple model of intraseasonal oscillations. *J. Adv. Model. Earth. Syst.*, **9**, 1195–1211, doi:10.1002/2017MS000963.

Gustafson, W. I., Jr., and B. C. Weare, 2004: MM5 modeling of the Madden–Julian oscillation in the Indian West Pacific Oceans: Model description and control run results. *J. Climate*, **17**, 1320–1337.

Hayashi, Y., 1970: A theory of large-scale equatorial waves generated by condensation heat and accelerating the zonal wind. *J. Met. Soc. Japan*, **48**, 140–160.

Hirons L. C., P. Inness, F. Vitart, P. Bechtold, 2013a: Understanding advances in the simulation ofintraseasonal variability in the ECMWF model. Part I: The representation of the MJO. *Q. J. R. Meteorol. Soc.*, **139**, 1417–1426. DOI:10.1002/qj.2060

Hirons L. C., P. Inness, F. Vitart, P. Bechtold, 2013b: Understanding advances in the simulation ofintraseasonal variability in the ECMWF model. Part II: The application of process-based diagnostics. *Q. J. R. Meteorol. Soc.*, **139**, 1427–1444. DOI:10.1002/qj.2059

Hsu, H.–H., B. J. Hoskins, and F.–F. Jin, 1990: The 1985/86 intraseasonal oscillation and the role of the extratropics. *J. Atmos. Sci.*, **47**, 823–839.

Jiang, X., D. E. Waliser, P. K. Xavier, J. Petch, N. P. Klingaman, S. J. Woolnough, B. Guan, G. Bellon, T. Crueger, C. DeMott, C. Hannay, H. Lin, W. Hu, D. Kim, C.–L. Lappen, M.–M Lu, H.–Y. Ma, T. Miyakawa, J. A. Ridout, S. D. Schubert, J. Scinocca, K.–H. Seo, E. Shindo, X. Song, C. Stan, W.–L. Tseng, W. Wang, T. Wu, X. Wu, K. Wyser, G. J. Zhang, and H. Zhu, 2015: Vertical structure and physical processes of the Madden–Julian oscillation: Exploring key model physics in climate simulations. *J. Geophys. Res.*, **120**, 2014JD022375.

Jiang, X., E. Maloney, and H. Su, 2020: Large-scale controls of propagation of the Madden-Julian Oscillation. *Clim. Atmos Sci*, **3**. https://doi.org/10.1038/s41612-020-00134-x

Kim, H.-M., D. Kim, F. Vitart, V. E. Toma, J.-S. Kug, and P. J. Webster, 2016: MJO propagation across the Maritime Continent in the ECMWF Ensemble Prediction System. *J. Climate*, **29**, 3973–3988.

Kim, H., F. Vitart, and D. E. Waliser, 2018: Prediction of the Madden–Julian oscillation: A review. *J. Climate*, **31**, 9425–9443.

Knutson, T. R., and K. M. Weickmann, 1987: 30–60 day atmospheric oscillations: Composite life cycles of convection and circulation anomalies. *Mon. Wea. Rev.*, **115**, 1407–1436.

Kühnlein, C. and W. Deconinck, and R. Klein, and S. Malardel, and Z. P. Piotrowski, and P. K. Smolarkiewicz, and J. Szmelter, and N. P. Wedi, 2019: FVM 1.0: a nonhydrostatic finite-volume dynamical core for the IFS. *Geosci. Model Dev.*, **12**, 651–676.

Lindzen, R. S., 1974: Wave–CISK in the tropics. *J. Atmos. Sci.*, **31**, 156–179.

Madden, R. A., and P. R. Julian, 1972: Description of global–scale circulation cells in the tropics with a 40–50 day period. *J. Atmos. Sci.*, **29**, 1109–1123.

Majda, A. J., and S. N. Stechmann, 2009: The skeleton of tropical intraseasonal oscillations. *Proc. Natl. Acad. Sci.*, **106**, 8417–8422.

Malardel, S., and N. P. Wedi and W. Deconinck and M. Diamantakis and C. Kühnlein and G. Mozdzynski and M. Hamrud and P.K. Smolarkiewicz, 2016: A new grid for the IFS. *ECMWF Newsletter*, **146**, 23-28.

Malardel, S., and N. P. Wedi, 2016: How does subgrid-scale parametrization influence nonlinear spectral energy fluxes in global NWP models?. *J Geophys. Res*, **121**, 5395-5410.

Milliff, R. F., and R. A. Madden, 1996: The existence and vertical structure of fast, eastward-moving disturbances in the equatorial troposphere. *J. Atmos. Sci.*, **53**, 586–597.

Nakazawa, T., 1988: Tropical Super clusters within intraseasonal variations over the western Pacific. *J. Met. Soc. Japan*, **66**, 823–839.

Pilon, R., C. Zhang, and J. Dudhia, 2016: Roles of deep and shallow convection and microphysics in the MJO simulated by the Model for Prediction Across Scales, *J. Geophys. Res. Atmos.*, **121**, 10,575–10,600, doi:10.1002/2015JD024697.

Plant, R. S., and J.-I. Yano (Eds), 2015: *Parameterization of Atmospheric Convection*, Volumes I and II, World Scientific, Singapore, Imperial College Press, London.

Ray, P., and T. Li, 2013: Relative Roles of Circumnavigating Waves and Extratropics on the MJO and Its Relationship with the Mean State. *J. Atmos. Sci.*, **70**, 876–893.

Ray, P., and C. Zhang, 2010: A case study of the mechanics of extratropical influence on the initiation of the Madden–Julian oscillation. *J. Atmos. Sci.*, **67**, 515–528.

Rostami, M., and V. Zeitlin, 2019: Eastward–moving convection–enhanced modons in shallow water in the equatorial tangent plane featured *Phys. Fluids*, **31**, 021701

Salby, M. L., R. R. Garcia, and H. H. Hendon, 1994: Planetary-scale circulations in the presence of climatological and wave-induced heating. *J. Atmos. Sci.*, **51**, 2344–2367.

Seo, K., W. Wang, J. Gottschalck, Q. Zhang, J. E. Schemm, W. R. Higgins, and A. Kumar, 2009: Evaluation of MJO Forecast Skill from Several Statistical and Dynamical Forecast Models. *J. Climate*, **22**, 2372–2388, https://doi.org/10.1175/2008JCLI2421.1.

Straub, K. H., 2013: MJO initiation in the real–time multivariate MJO index. *J. Climate*, **26**, 1130–1151.

Vitart, F., 2014: Evolution of ECMWF sub–seasonal forecast skill scores. *Q. J. R. Meteorol. Soc.*, **140**, 1889–1899.

Wang, B., 1988: Dynamics of tropical low frequency waves: An analysis of the moist Kelvin wave. *J. Atmos. Sci.*, **45**, 2051-2065.

Wang, D., J.–I. Yano, and Y. Lin, 2019: Madden–Julian oscillations seen in the upper–troposphere vorticity field: Interactions with Rossby–wave trains. *J. Atmos. Sci.*, **76**, 1785–1807. https://journals.ametsoc.org/doi/abs/10.1175/JAS-D-18-0172.1

Wedi, N.P., 2014: Increasing horizontal resolution in NWP and climate simulations — illusion or panacea?. *Phil. Trans. R. Soc. A*, **372**, 20130289.

Wedi, N. P., and P. K. Smolarkiewicz, 2010: A nonlinear perspective on the dynamics of the MJO: Idealized large-eddy simulations. *J. Atmos. Sci.*, **67**, 1202—1217.

Weickmann, K. M., G.R. Lussky, and J. E. Kutzbach, 1985: Intraseasonal (30–60 day) fluctuations of outgoing longwave radiation and 250 mb streamfunction during northern winter. *Mon. Wea. Rev.*, **113**, 941–961.

Wheeler, M. C., and H. H. Hendon, 2004: An all–season real–time multivariate MJO index: Development of an index for monitoring and prediction. *Mon. Wea. Rev.*, **132**, 1917–1932.

Yano, J.-I., and K. A. Emanuel, 1991: An improved model of the equatorial troposphere and its coupling with the stratosphere, *J. Atmos. Sci.*, **48**, 377–389.

Yano, J.-I., and M. Bonazzola, 2009: Scale analysis for the large-scale tropical atmospheric dynamics, *J. Atmos. Sci.*, **66**, 159–172.

Yano, J.–I., and J. J. Tribbia, 2017: Tropical atmospheric Madden-Julian oscillation: Strongly–nonlinear free solitary Rossby wave? *J. Atmos. Sci.*, **74**, 3473–3489.

Yano, J.-I., S. Mulet, and M. Bonazzola, 2009: Large-scale tropical atmosphere: asymptotically non-divergent?, *Tellus*, **61A**, 417–427.

Yano J.-I., M. Bister, Z. Fuchs, L. Gerard, V. Phillips, S. Barkidija, and J. M. Piriou, 2013: Phenomenology of convection-parameterization closure. *Atmos. Phys. Chem.*, **13**, 4111–4131.

Zhang, C., 2005: Madden–Julian oscillation. *Rev. Geophys*, **43**, doi:10.1029/2004RG000158.

Zhao, C., T. Li, and T. Zhou, 2013: Precursor signals and processes associated with MJO initiation over the Tropical Indian Ocean. *J. Climate*, **26**, 291–307.

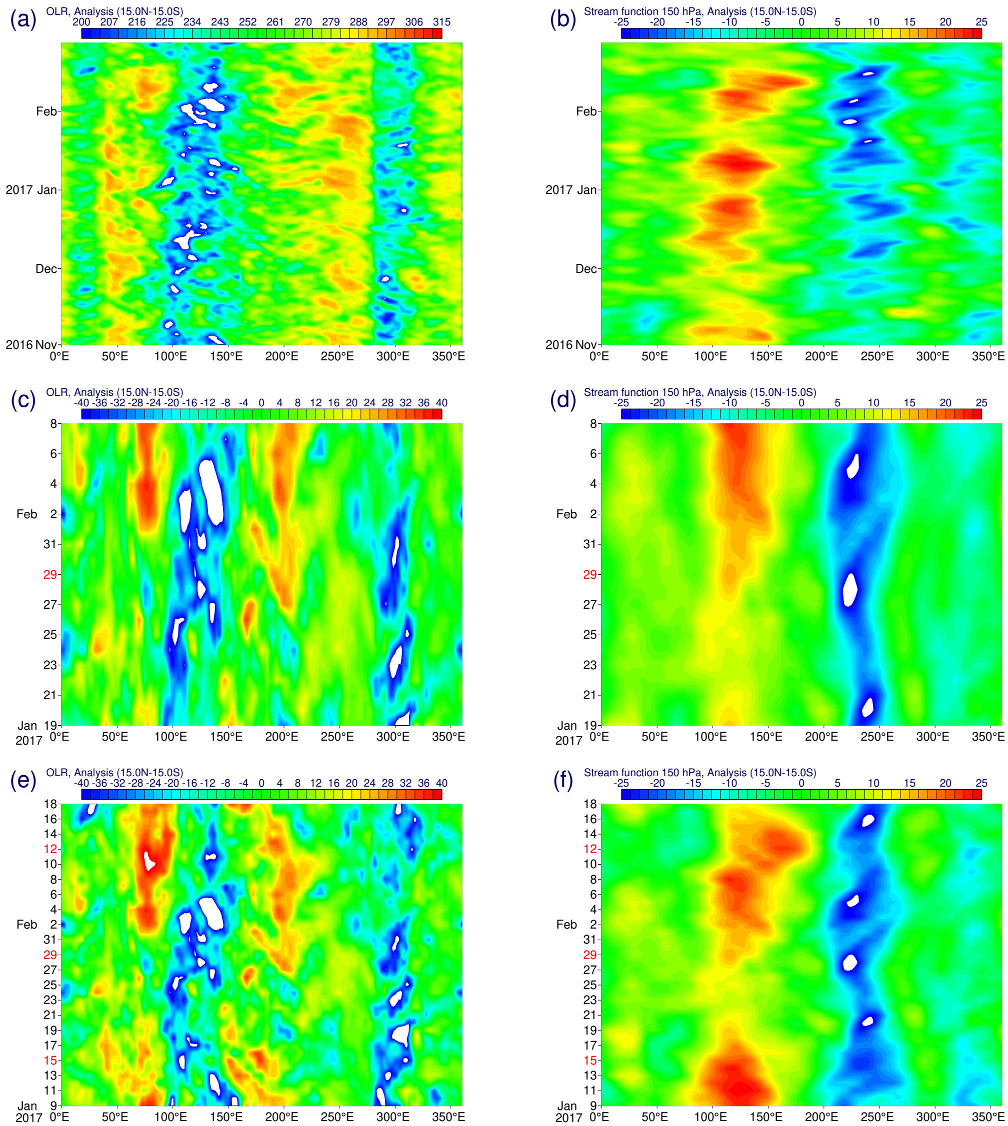

Figure 1. Time–Longitude sections averaged over 15S–15N for (a, c, e) OLR and (b, d, f) the stream function at 150hPa. Periods are for (a, b) four–month winter period of 2016–2017, (c, d) the standard 20–day forecast period, and (e, f) the 40–day extended forecast period. Anomaly fields are shown throughout here as well as in the following figures, except for the total OLR field shown in (a). Note that throughout the paper, values beyond a range of color code is not marked.

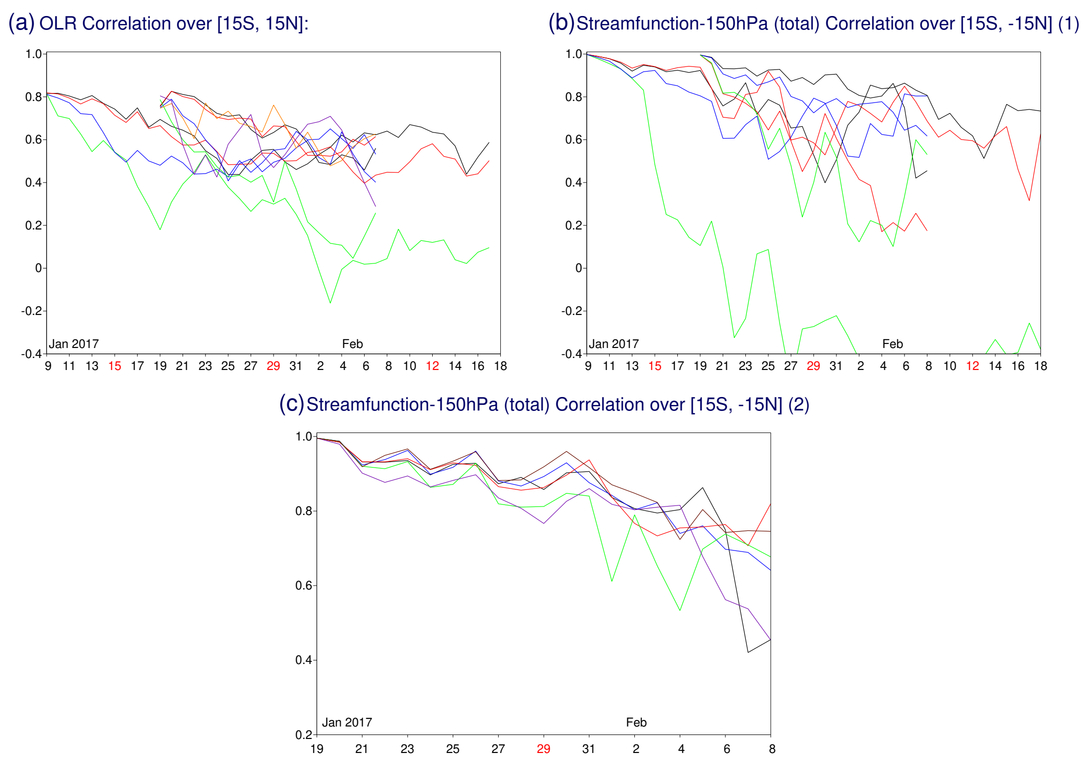

Figure 2. Time series of pattern correlations between the forecasts and the analysis over the longitudinal bands between 15S and 15N for (a) OLR and (b, c) the 150hPa-level stream function with CFs in black curves. The other cases shown in (a, b) are for Mbb (no BL momentum dissipation: blue), Mbs (no shallow convection: red), QF (no diabatic friction: green). In (a), also shown are higher resolution (5 km) runs with no convection parametrization (orange), and with no momentum dissipation (violet). Those in (c) are for experiments turning off momentum dissipation by: deep convection (blue: Mbd) shallow convection (red: Mbs), deep convection and the boundary layer (green: Mbde), shallow convection and the boundary layer (violet: Mbse), and convective friction (brown: Mbc)

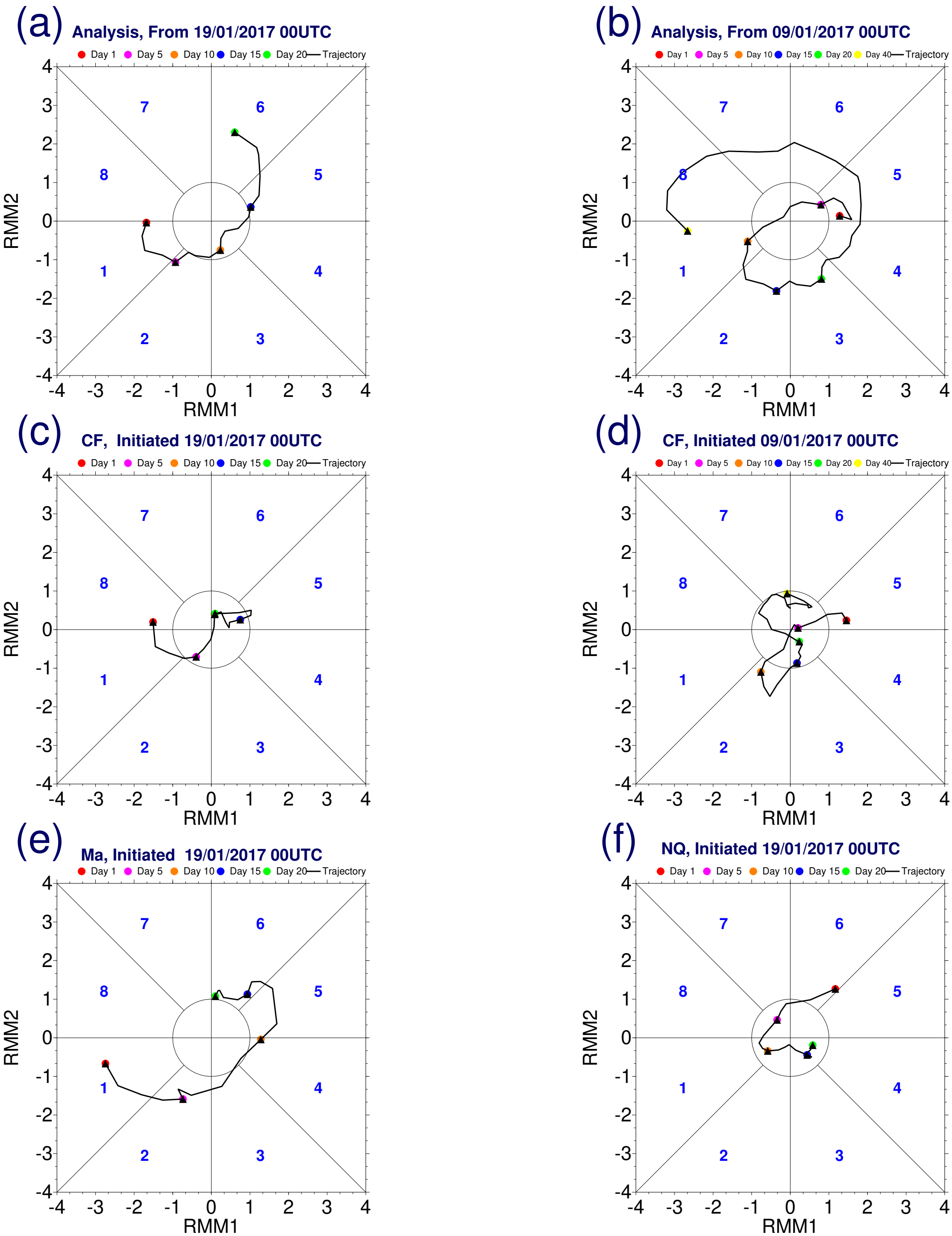

Figure 3. RMM analysis for the analysis (a, b), for control forecasts (c, d) for the standard (a, c) and the extended (b, d) forecast cases. Also Ma (e) and NQ (f) cases for the standard forecast.

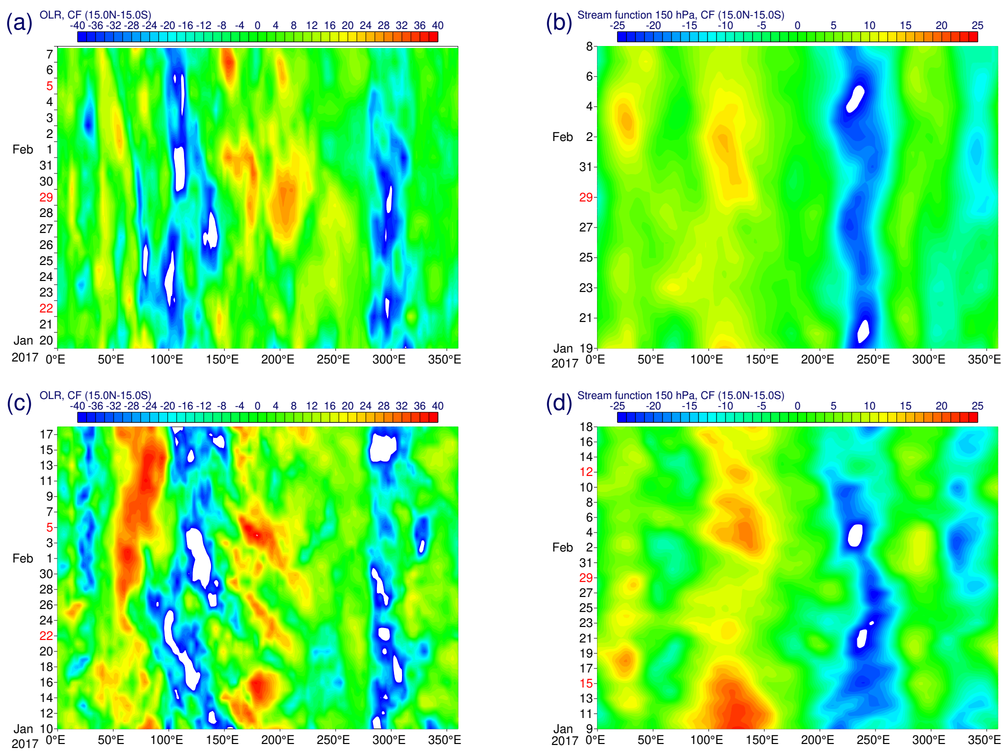

Figure 4. Time–Longitude sections averaged over 15S–15N of (a, c) OLR and (b, d) the 150hPa-level stream function for (a, b) the standard 20–day and (c, d) the 40–day extended CFs.

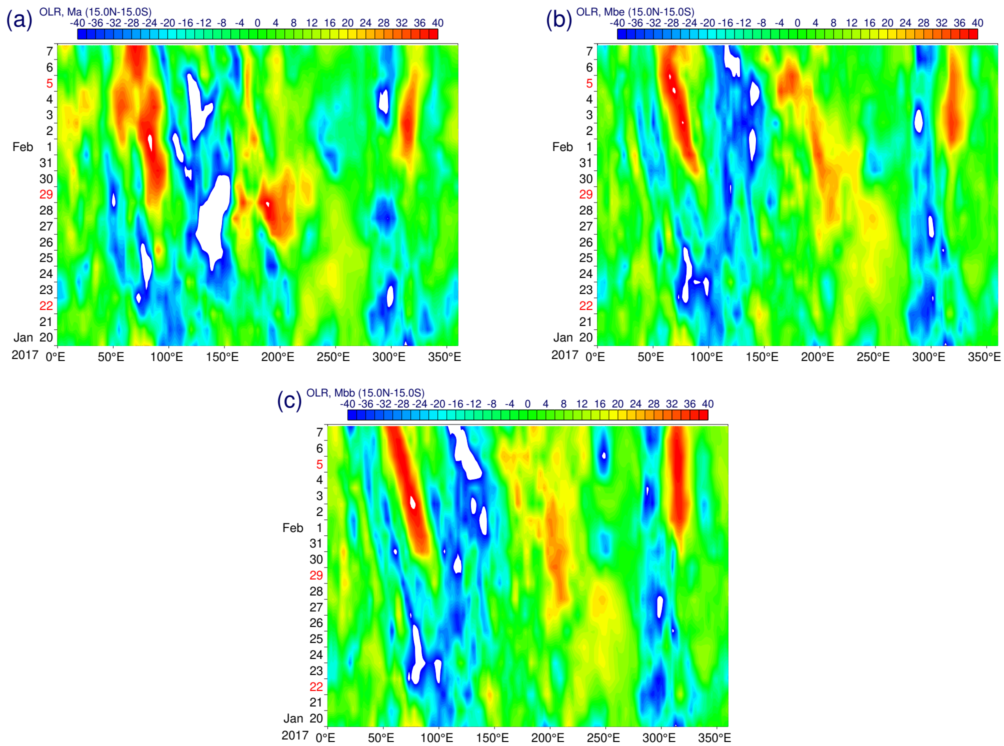

Figure 5. Time–longitude sections of OLR along the equator (15S–15N) with the the standard 20–day forecast cases: (a) Ma, (b) Mbe, and (c) Mbb.

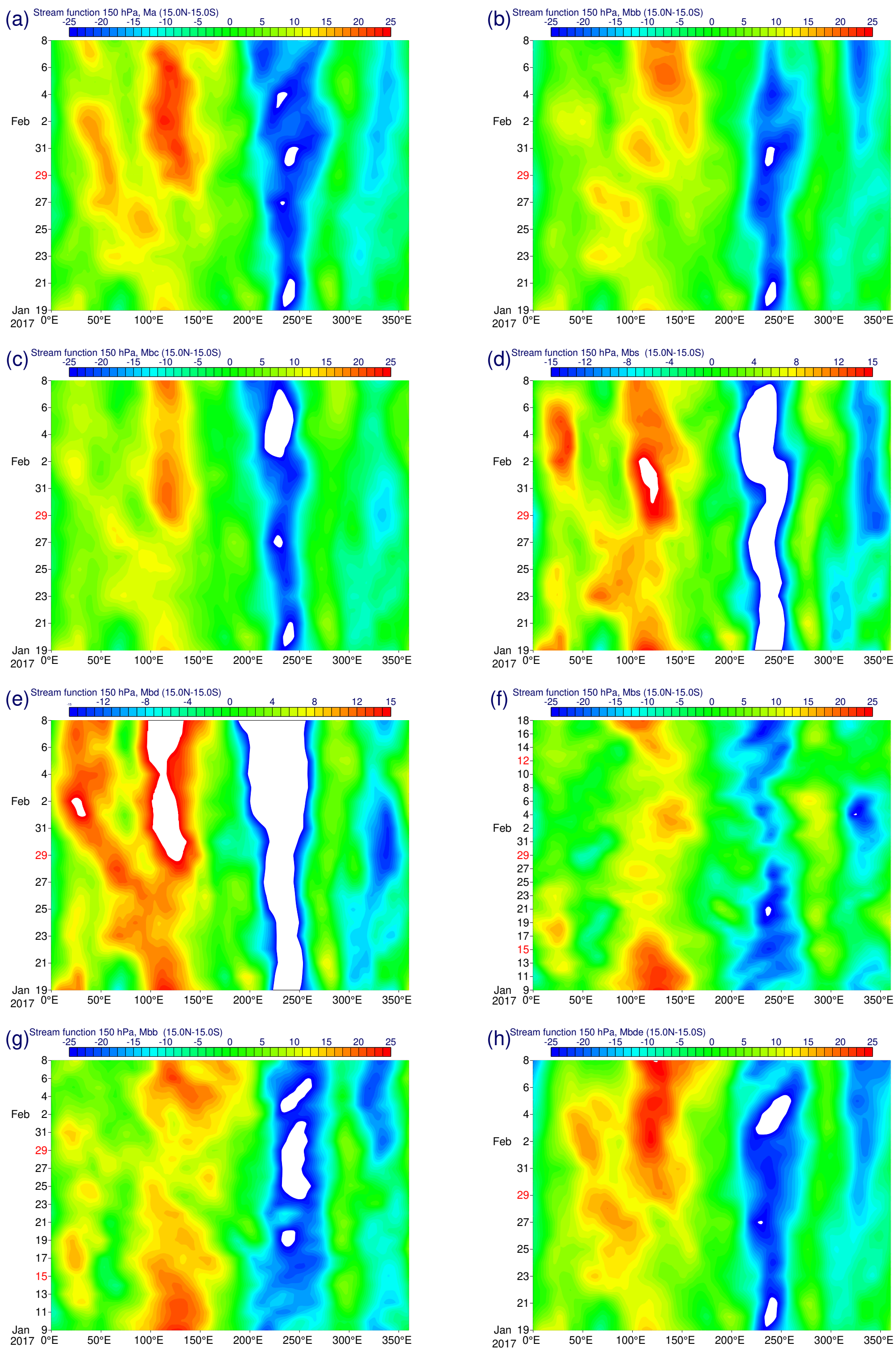

Figure 6. [See next page for the caption]

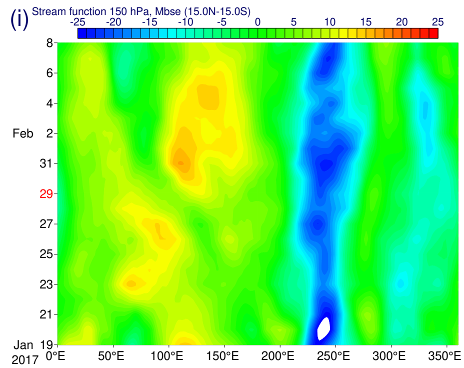

Figure. 5. Time–longitude sections of 150–hPa stream function along the equator (15S–15N) with the (a–e, h, i) standard 20–day and (f, g) extended forecast cases: (a) Ma, (b) Mbb, (c) Mbc, (d) Mbs, (e) Mbd, (f) Mbs, (g) Mbb, (h) Mbde, and (i) Mbse. Note that the Mbb case (g) exceptionally runs only for 30 days.

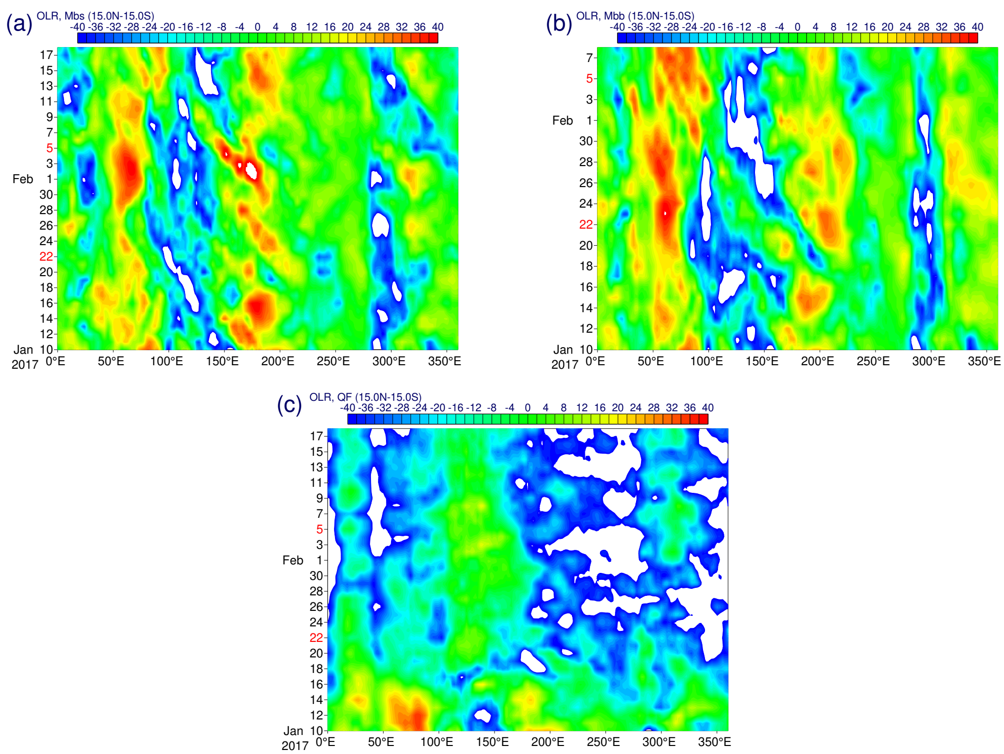

Figure 7. Time–longitude section of OLR along the equator (15S–15N) for the extended forecasts cases: (a) Mbs (40 days), (b) Mbb (30 days), and (c) QF (40 days).

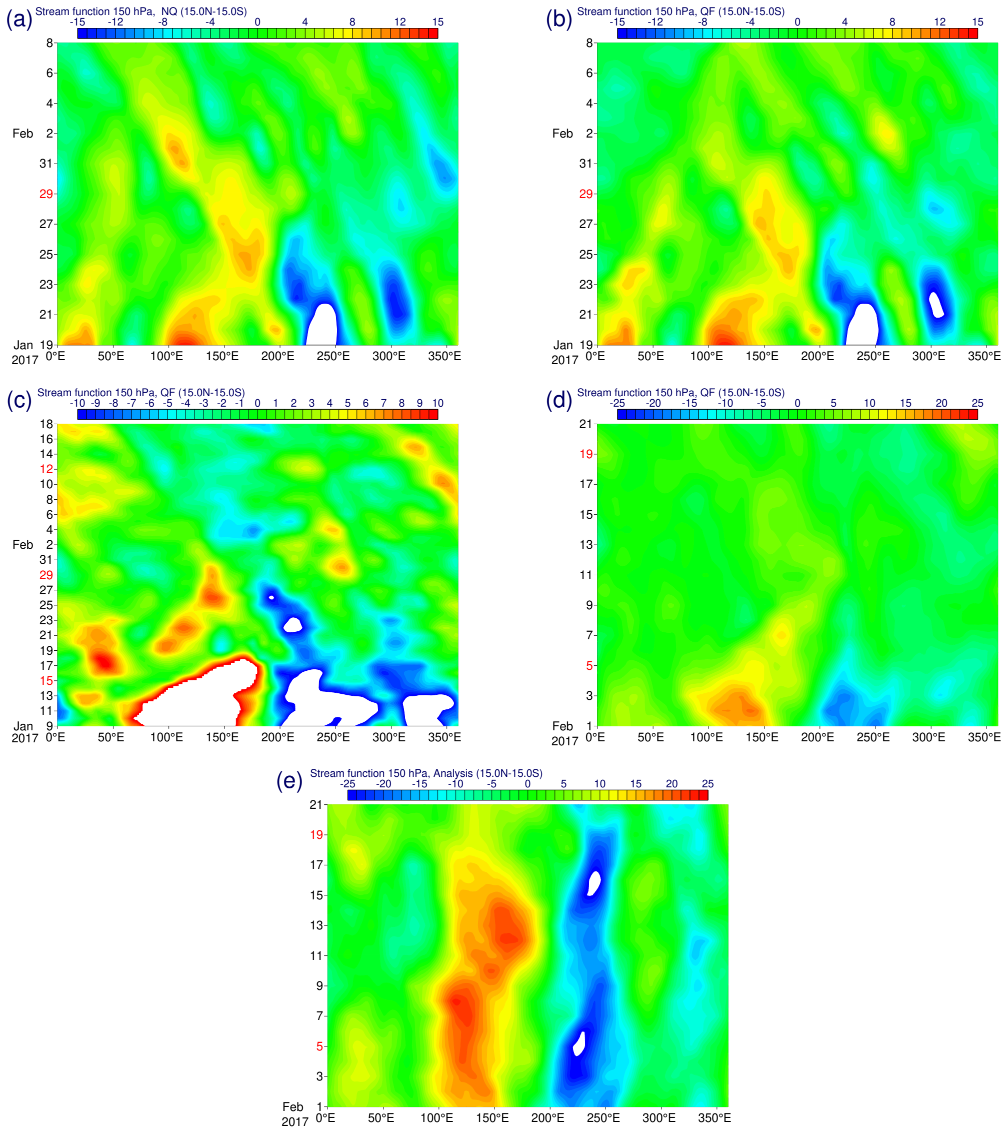

Figure 8. Time–longitude sections of 150–hPa stream function along the equator (15S–15N) with: (a) the standard NQ forecast, (b) the standard QF forecast, (c) the extended QF forecast, and (d) the 20–day QF forecast initiated on 1 February. Also shown in (e) is the analysis for the forecast period of (d).

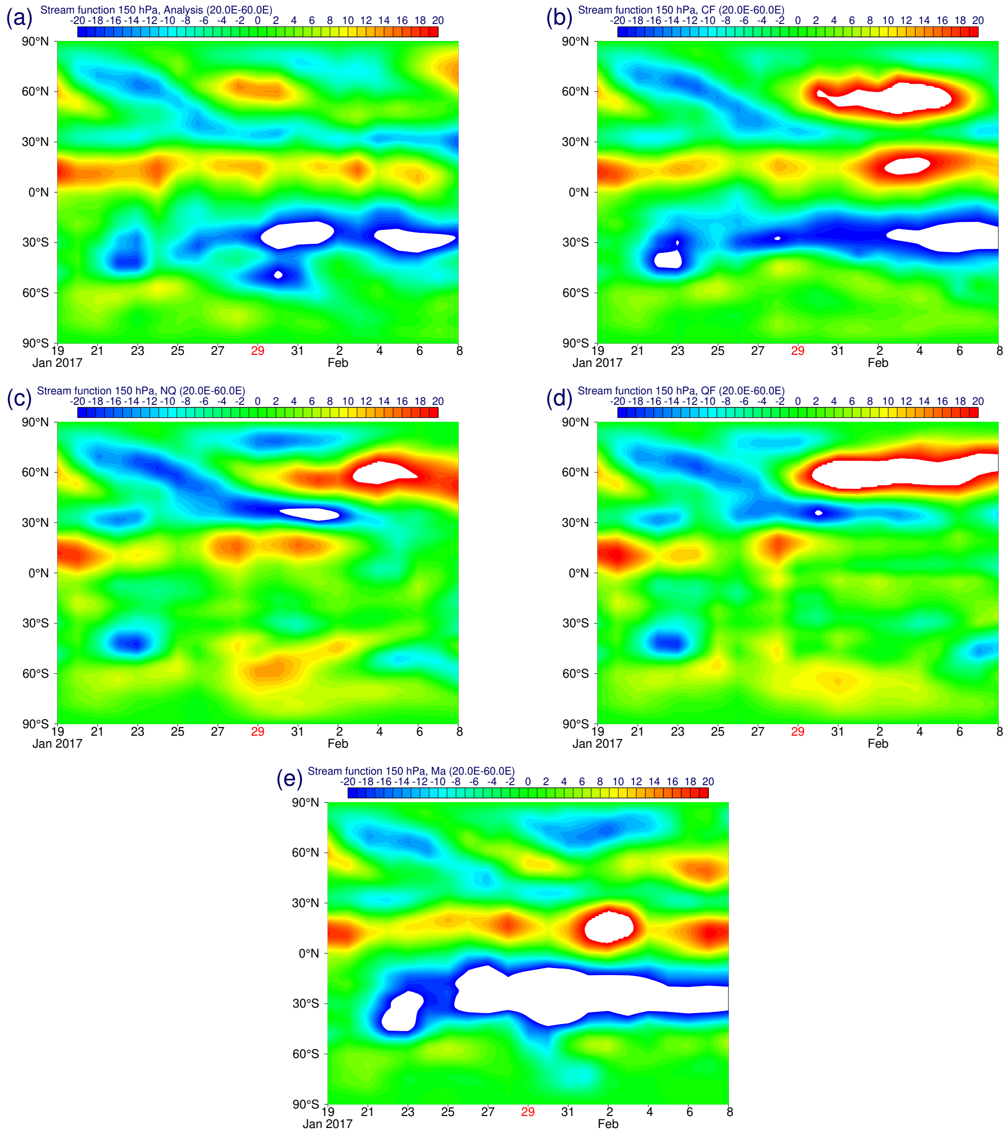

Figure 9. Time–latitude sections of 150–hPa stream function averaged over 20–60E: (a) the analysis for the standard 20–day forecast period, and standard 20–day forecasts with (b) CF, (c) NQ, (d) QF, and (e) Ma.