ECMWF Feature article

from Newsletter Number 126 – Winter 2010/11

METEOROLOGY

Simulation of the Madden-Julian Oscillation and its impact over Europe in ECMWF's monthly forecasts

www.ecmwf.int/en/about/news-centre/media-resources

doi:10.21957/we6q5m9r

This article appeared in the Meteorology section of ECMWF Newsletter No. 126 – Winter 2010/11, pp. 12–17.

Simulation of the Madden-Julian Oscillation and its impact over Europe in ECMWF's monthly forecasts

Frédéric Vitart, Franco Molteni

The Madden-Julian Oscillation (MJO) (*Madden & Julian*, 1971) is a tropical large-scale oscillation dominated by periods of 30–60 days and zonal wavenumber-1 propagating eastward. It is the main source of predictability in the tropics on time scales exceeding one week but less than a season. The maximum convective activity associated with the MJO occurs over the warm waters of the Indian Ocean and western Pacific where the MJO moves eastward at a relatively low speed (5 ms^{-1}) whereas in the western hemisphere the MJO is less well coupled to convection and propagates faster (15 ms^{-1}).

The MJO is not a regular oscillation. Instead it is episodic and its speed of propagation and duration vary from case to case. Also there is a strong seasonality, with more MJO events in winter and spring, and a strong interannual variability. This makes the prediction of the MJO a challenging task for NWP models.

The MJO has a large impact on the atmospheric circulation not only in the tropics, but also in the northern extratropics (see *Ferranti et al.*, 1990, for example). Several studies suggest that this impact is due to mid-latitude Rossby wave propagation. Since the MJO has a significant impact on the northern hemisphere weather, it is important for monthly forecasts to have skill not only in predicting the evolution of the MJO, but also in simulating the MJO teleconnections.

For a long time the IFS (Integrated Forecasting System) was not able to maintain the amplitude of an MJO event for more than a few days. Over the recent years, the representation of the MJO has improved dramatically (Figure 1), thanks mostly to changes in the model's physics introduced in Cy32r3 on 6 November 2007 (*Bechtold et al.*, 2008). Now the IFS is able to maintain the amplitude of the MJO for more than 30 days, which makes it possible to evaluate the teleconnections associated to the MJO in the model integrations.

This article describes the ability of the monthly extension of ECMWF's Ensemble Prediction System (EPS) to predict the MJO and its teleconnections in the sub-seasonal time range from a series of model hindcasts covering a 20-year period (1989–2008).

Experimental setup

A series of hindcasts has been performed for the 20-year period 1989 to 2008. The hindcasts start on the 15th of each month and are 46-days long to cover the next full calendar month. For each starting date, the hindcast consists of an ensemble of 15 members: a control and 14 perturbed forecasts. The version of the IFS used in this experiment is Cy32r3, which was operational from November 2007 until June 2008. As mentioned earlier, this version of the IFS showed a clear improvement in the representation of the MJO compared to previous versions.

The configuration of the hindcast is the same as the one used for operational monthly forecasts at ECMWF, except for the length of the forecasts (46 days instead of 32 days for the operational monthly forecasts) and the horizontal resolution. For the hindcasts:

- The IFS is first integrated for 10 days with a resolution of T399 (about 50 km resolution) and 62 vertical levels. The IFS is forced by persisted sea-surface temperature anomalies.
- At day 10, the horizontal resolution is lowered to T255 (about 80 km resolution) till the end of the forecast. The IFS is coupled to the HOPE oceanic general circulation model every 3 hours.

The initial conditions are taken from ERA-40 until 2001 and ECMWF operational analysis after 2001, and the ensemble perturbations are produced in the same way as in the operational monthly forecasts. More details about the model configuration can be found in *Vitart et al.* (2008).

doi:10.21957/we6q5m9r

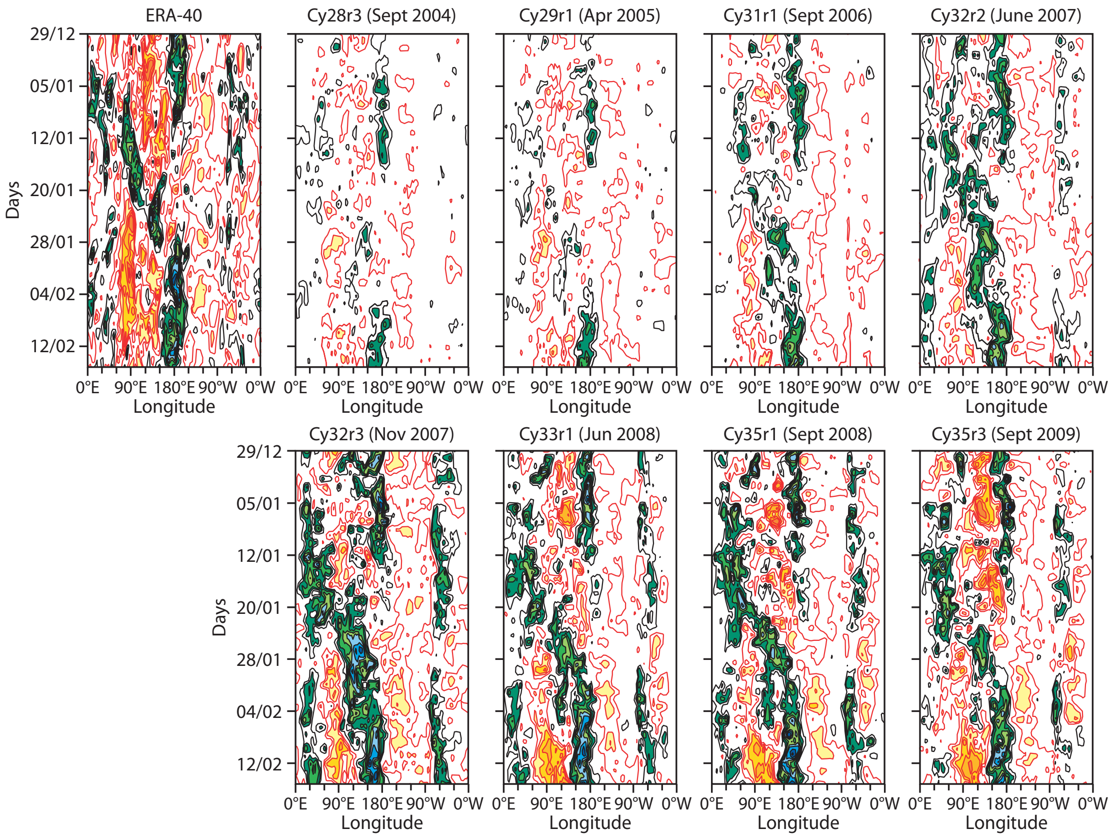

Figure 1 Hovmöller diagrams of the averaged outgoing long-wave radiation (OLR) between 10°S and 10°N from 29 December 1992 to 15 February 1993 as analysed by ERA-40 and obtained from daily forecasts with Cy28r3 to Cy35r3. Each forecast verifies at the 15-day lead time. Red shading denotes warm OLR anomalies (negative phase of the MJO) and blue shading cold anomalies (convectively active phase of the MJO).

MJO skill scores

The methodology for assessing the skill to predict the MJO follows *Gottschalck et al.* (2009). The Wheeler-Hendon Real-time Multivariate MJO (RMM) index (*Wheeler & Hendon*, 2004) has been applied to all the model hindcasts and to ERA-Interim over the period 1989–2008 to (a) evaluate the skill of the monthly forecasts in predicting MJO events and (b) produce composites for different phases of the MJO. The RMM index captures the MJO very well and is widely used to depict MJO activity.

The RMM index is calculated by projecting the forecasts or analysis onto the two dominant combined empirical orthogonal functions (EOFs) of outgoing longwave radiation (OLR), and zonal winds at 200 and 850 hPa averaged between 15°N and 15°S. It has been applied to daily anomalies relative to the 1989 - 2008 climate instead of the absolute value of the field, in order to remove the impact of seasonal cycle. In addition, a 120-day running mean has been subtracted to remove the variability associated with ENSO (El Niño-Southern Oscillation).

- The positive (negative) phase of EOF2 describes suppressed (enhanced) convection over the Indian Ocean and enhanced (suppressed) convection over the West Pacific.
- The positive (negative) phase of EOF1 describes enhanced (suppressed) convection over the maritime continent region.

Analysis and forecasts can be projected onto those two EOFs to describe the phase of the MJO in terms of time series of two principal components that vary mostly on the time scale of the MJO. The time series that form the index are referred to as the Real-time Multivariate MJO series 1 (RMM1) and series 2 (RMM2). These can be plotted as a succession of points in the two-dimensional phase space spanned by RMM1 and RMM2, in such a way that the MJO is described by a clockwise propagation in the phase space (Figure 2). The RMM1-RMM2 phase space can be divided into eight sections representing a specific phase of the MJO (see example in Figure 2).

doi:10.21957/we6q5m9r

- Phases 2 and 3 (negative EOF2) correspond to enhanced convection over the Indian Ocean.
- Phases 4 and 5 (positive EOF1) correspond to the MJO over the maritime continent.
- Phases 6 and 7 (positive EOF2) correspond to the MJO over the western Pacific.
- Phases 8 and 1 (negative EOF1) correspond to the active phase of the MJO in the western hemisphere.

Bivariate correlation and bivariate root mean square (RMS) error between the model and reanalysis RMM1 and RMM2 are used to evaluate the skill of the dynamical model in predicting the MJO. We consider that the forecast is skilful when the anomaly correlation is higher than 0.5. According to Figure 3a, the model ensemble mean has skill to predict the evolution of the MJO up to about day 23. RMM1 and RMM2 display similar correlations.

The model potential predictability is evaluated using the 'perfect model' assumption: an ensemble member is considered to be the 'truth' and the ensemble mean is validated against this ensemble member. According to Figure 3a, the model displays a potential predictability exceeding 45 days, which is far beyond the MJO predictability limit found by *Waliser et al.* (2003). Since the model has skill to predict the evolution of the MJO for only about 23 days, this result suggests that there is large scope for improvement of the skill score for the MJO forecasts.

Figure 3b shows that the bivariate RMS error of the ensemble mean reaches the RMS error obtained with climatology after day 30. It can also be seen that the ensemble spread is always smaller than the RMS error, which suggests that the ensemble spread is too small in this version of the IFS.

The results shown in Figure 3 indicate that the ECMWF model has useful skill up to at least day 20. However, the simulation of the MJO in this set of hindcasts suffers a few problems (see *Vitart & Molteni*, 2010 for more details): the propagation of the MJO is in general too slow compared to observations, and the simulated MJOs have often difficulties crossing the maritime continent. Statistically the percentage of MJO events which do not cross the maritime continent is higher in the model than in observations. In those cases, the convection can be locked over the maritime continent until the end of the 46-day forecast.

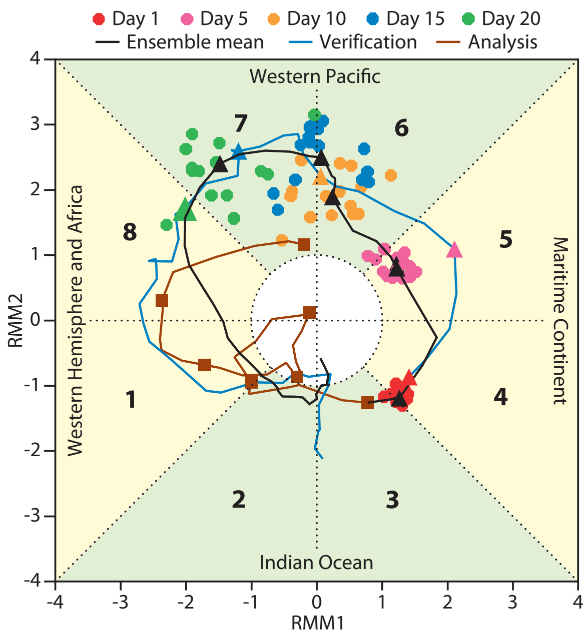

Figure 2 Projection of an observed MJO event (blue line) onto the RMM1-RMM2 phase space, for the period from 15 May 1997 to 16 June 1997. The brown line shows the observed MJO propagation during the 30 days preceding 15 May 1997. The black line represents the ensemble mean 32-day forecast starting on 15 May 1997. The points on the projection are separated by 5 days and correspond to individual ensemble member forecasts at days 1, 5, 10, 15 and 20. The coloured triangles correspond to the analysis at days 1, 5, 10, 15 and 20 for comparison with the forecast trajectories.

doi:10.21957/we6q5m9r

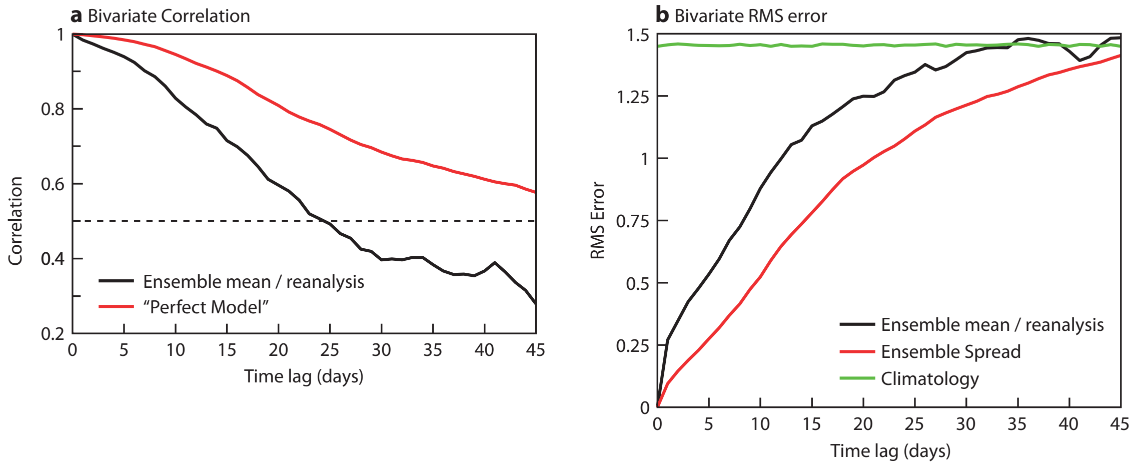

Figure 3 (a) Bivariate correlation and (b) bivariate RMS error between analysis and forecast RMM1 and RMM2 time series as a function of the forecast lead time for the period November to April 1989–2008 (black lines). In (a) the red line shows the bivariate correlation obtained by considering one ensemble member to be the truth (perfect model assumption). In (b) the green line shows the RMS error obtained with climatology and the red line represents the ensemble spread.

Impact of the MJO on Euro-Atlantic weather regimes

Using reanalysis data covering the period 1974–2007, *Cassou* (2008) showed that the impact of the MJO on European weather is the strongest about ten days after the MJO is in phase 3 or phase 6. The impact on the North Atlantic Oscillation (NAO) is as follows.

- The probability of a positive phase of the NAO is significantly increased about ten days after the MJO is in phase 3 (phase 3+10 days), and significantly reduced about ten days after the MJO is in phase 6 (phase 6+10 days).
- The probability of a negative phase of the NAO is reduced about ten days after the MJO is in phase 3 (phase 3+10 days), and increased about ten days after the MJO is in phase 6 (phase 6+10 days).

The impact of the MJO on two other Euro-Atlantic weather regimes, the Atlantic Ridge and Scandinavian blocking, is much weaker.

In the model simulations, the impact of the MJO on the frequency of a positive NAO, negative NAO, Atlantic Ridge and Scandinavian blocking has been evaluated. As in the reanalysis, the largest impact of the MJO in the model simulations is on the frequency of a positive NAO (Figure 4). In the model simulations, the probability of a positive NAO increases (decreases) during the days following an MJO event in phase 3 (phase 6). The amplitude of this impact (about 20% after 10 days) is smaller than in ERA-Interim (about 40% after 10 days).

Overall, the model displays a 10% decrease in the probability of a negative NAO (NAO–) in the 10-day period following an MJO event in phase 3 and a 12% increase in the 10-day period following an MJO event in phase 6 (Figure 4). The sign of this variation of NAO– probability is consistent with ERA-Interim and *Cassou* (2008). The model also simulates an impact of the MJO on the probability of an Atlantic Ridge with an overall decrease after an MJO in phase 3 (66% of ensemble members) and an increase following an MJO in phase 6 (75% of ensemble members). Overall this represents a decrease or an increase of about 10% in the probability of an Atlantic Ridge by day 10 following an MJO respectively in phase 3 or 6 (Figure 4).

Overall, the impact of the MJO on the weather regimes in the set of hindcasts is consistent with ERA-Interim, but the amplitude of the impact is smaller in the model than in ERA-Interim. This could be due to model errors or to a sampling issue with the reanalysis (20 years compared to the equivalent of 300 years of model simulations). For instance, *Vitart & Molteni* (2008) have shown that some ensemble members simulate an impact of the MJO on weather regimes similar to ERA-Interim.

Since the MJO simulated by the model has an impact on the Euro-Atlantic weather regimes, it is likely to impact the 2-metre temperature and precipitation anomalies over Europe. Consider the anomalies of 2-metre temperature at phase 3+10 days (Figure 5a) and phase 6+10 days (Figure 5b). In the days following an MJO in phase 3 (phase 6), the model tends to predict warmer (colder) 2-metre temperatures over Europe as in the reanalysis but with smaller amplitude. Over North America and North Africa, the 2-metre temperature anomalies following an MJO in phase 3 or 6 are generally consistent in the model and reanalysis, except over North America for phase 6, where the cold anomaly simulated by the model is not at the same place as in the reanalysis.

The monthly extension of the EPS also simulates an impact of the MJO on European precipitation consistent with reanalysis. Ten days after an MJO in phase 3 (phase 6), the model simulates wetter (dryer) conditions over North Europe and more (less) precipitation over southern Europe as in the reanalysis (not shown).

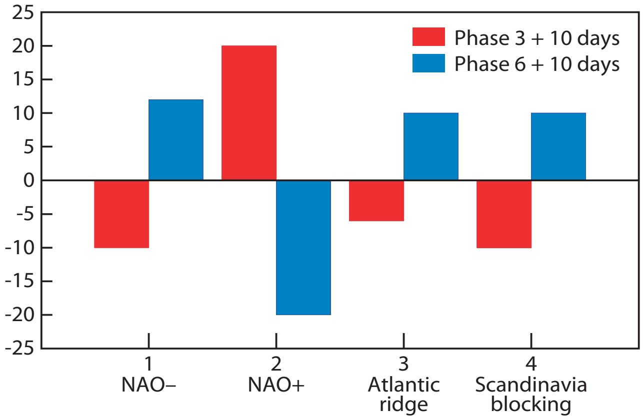

Figure 4 Variation of the percentage of days with NAO+, NAO–, Atlantic ridge or Scandinavian blocking 10 days after an MJO in Phase 3 (red bars) or Phase 6 (blue bars).

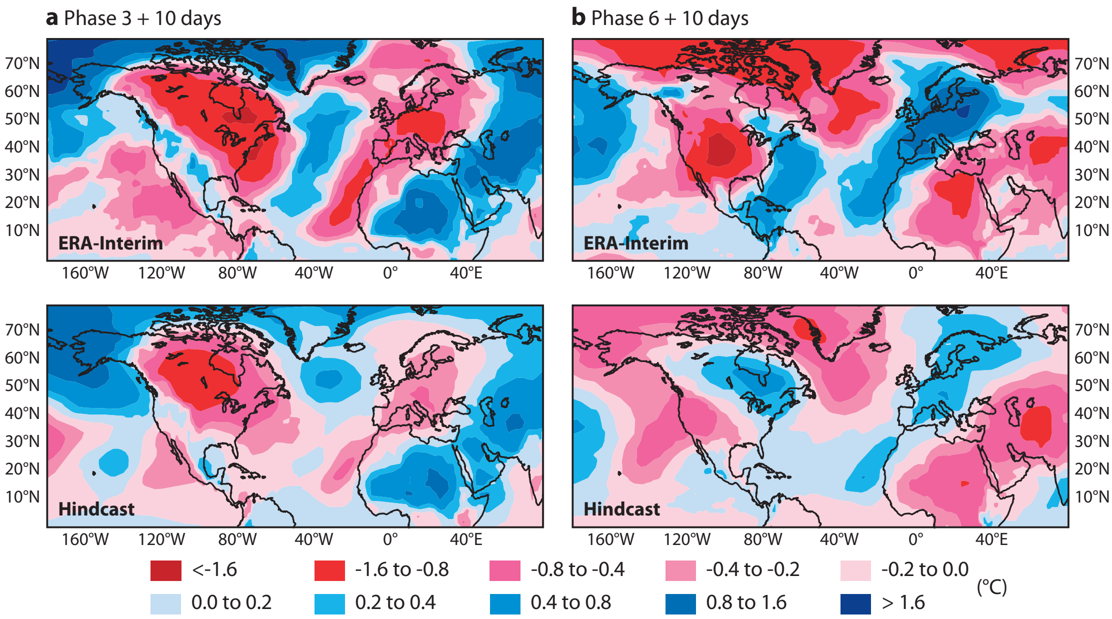

Figure 5 Composites of 2-metre temperature anomalies (a) 10 days after an MJO in phase 3 and (b) 10 days after an MJO in phase 6 in ERA-Interim (top panels) and in the hindcasts (bottom panels).

doi:10.21957/we6q5m9r

Impact of the MJO on monthly forecast probabilistic skill scores

The 120 15-member ensemble forecasts (all the forecasts starting on 15 October, November, December, January, February and March 1989–2008) have been classified as a function of the presence or not of an MJO event in the initial conditions. About 55% of the 120 cases have an MJO in the initial conditions (outside the central circle in Figure 2). This MJO event can be in any phase. Probabilistic skill scores computed for all the cases with an MJO event in the initial conditions are then compared to the probabilistic skill scores computed for all the cases with no MJO event in the initial conditions (inside the central circle in Figure 2). The probabilistic skill scores applied include the Relative Operating Characteristic (ROC) and Brier Skill Scores of the probability that 500 hPa geopotential height, 850 hPa temperature or total precipitation over the northern extratropics (north of 30°N) are in the upper or lower tercile, for the weekly periods days 5–11, 12–18, 19–25 and 26–32. For precipitation and temperature, only land points have been considered. The definition of the weekly periods (days 5–11, 12–18, 19–25 and 26–32) corresponds to the one used in the operational monthly forecast products provided by ECMWF.

The Brier Skill Scores for the probabilities to be in the upper tercile are shown in Figure 6. The results for the low tercile probabilities (not shown) are similar. The results obtained with the ROC scores (not shown) are also similar. According to Figure 6, the Brier Skill Scores are not affected by the presence of an MJO in the initial conditions for the day 5–11 forecasts, except for precipitation with statistically significantly higher skill scores when there is an MJO in the initial conditions. For days 12–18, the Brier Skill Scores are significantly higher when there is an MJO in the initial conditions. For instance, the presence of an MJO in the initial conditions more than doubles the Brier Skill Score of 500-hPa geopotential height at this time range. The difference is statistically significant within the 10% level of confidence using a 10,000 bootstrap re-sampling procedure.

The period of 19–25 days is a time range often considered as having very low predictability and reliability in the extratropics. Therefore it is interesting to notice that when there is an MJO event in the initial conditions, the forecasts over the northern extratropics have a positive Brier Skill Score for 500 hPa geopotential height and temperature at 850 hPa for days 19–25, suggesting that those probabilistic forecasts are likely to be useful at this time range. When there is no MJO in the initial conditions, the day 19–25 forecasts have very low ROC area (close to 0.5) and negative Brier Skill Score, indicating that those forecasts have low skill and are not reliable. This result is confirmed by the reliability diagrams (Figure 7) of the probability that 850-hPa temperature is in the upper tercile for northern extratropics and Europe.

Over Europe, the day 19–25 probabilistic forecasts display some reliability, with a reliability curve close to the diagonal, when there is an MJO in the initial conditions (red line in Figure 7). However, the probabilistic forecasts are unreliable (almost flat curve) when there is no MJO in the initial conditions (blue line in Figure 7). This result suggests that the MJO represents a major, if not the main, source of predictability in the northern extratropics at this time range. This also demonstrates that the skill at this time range is not always as low as previous studies suggested and forecasts at this time range can be potentially useful over the northern extratropics. From a practical point of view, this result also suggests that the users of ECMWF's monthly forecasts could use the presence of an MJO in the initial conditions to decide if the monthly forecasts of days 19–25 should be trusted or not.

For days 26–32, the presence of an MJO in the initial conditions also improves the probabilistic skill scores, but the probabilistic scores are very low, even with an MJO in the initial conditions.

doi:10.21957/we6q5m9r

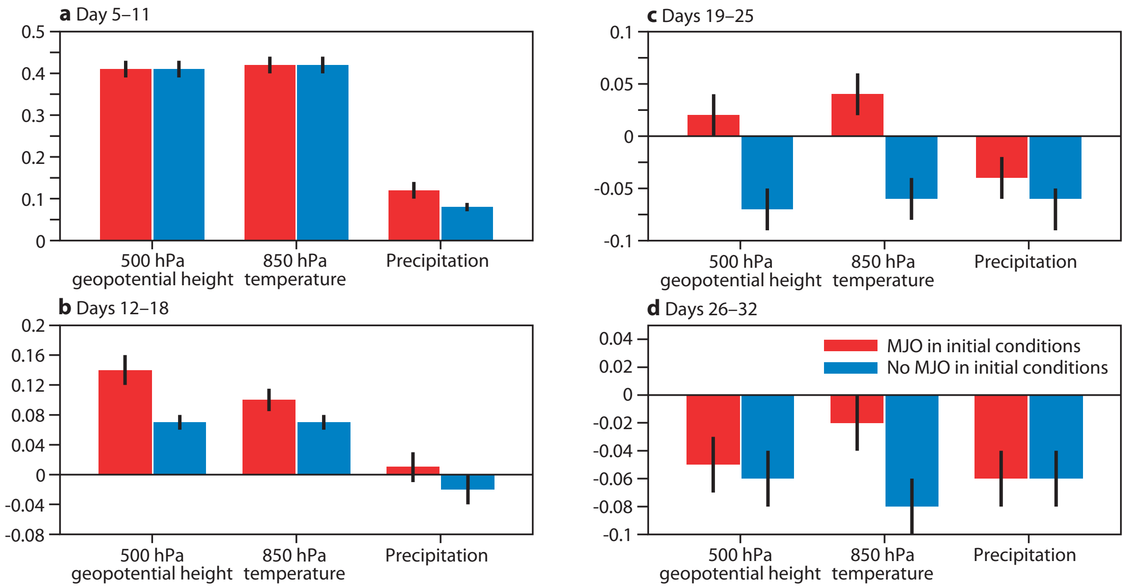

Figure 6 Brier Skill Scores of 500 hPa geopotential height, 850 hPa temperature and precipitation for days 5–11, 12–18, 19–25 and 26–32. The red bars show the scores obtained when there is an MJO in the initial conditions. The blue bars show the scores when there is no MJO in the initial conditions (amplitude of the MJO index less than 1 standard deviation). A 10,000 bootstrap re-sampling procedure has been applied to compute the 5% level of confidence (vertical black lines).

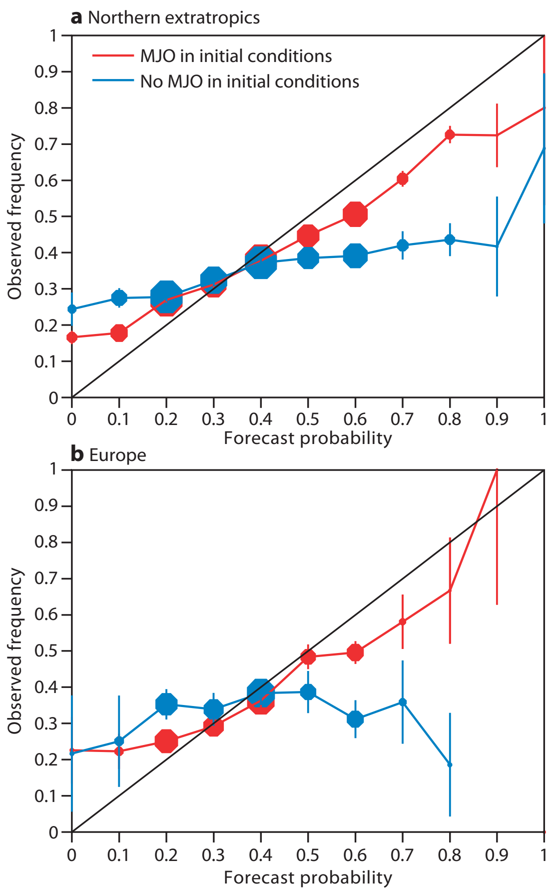

Figure 7 Reliability diagrams of the probability that the 850-hPa temperature is in the upper tercile for the days 19–25 for (a) northern extratropics and (b) Europe. The red (blue) curves represent the reliability diagram obtained with all the cases with an MJO (no MJO) in the initial conditions. The volume of the symbols is proportional to the number of cases in the probability bin. A 10,000 bootstrap re-sampling procedure has been applied to compute the 5% level of confidence (vertical lines). The numbers in the figures indicate the Brier Skill Scores. Only land points have been included in the calculation of the reliability diagram and the Brier Skill Scores.

doi:10.21957/we6q5m9r

Overall model performance and future developments

The ECMWF 46-day hindcasts show some notable skill in predicting the evolution of the MJO (about twenty days of predictability). However, the MJO simulated in this set of hindcasts tends to be too slow and has often difficulties crossing the maritime continent. Statistically, the percentage of MJO events which do not cross the maritime continent is higher in the model than in observations. Of all those problems, the too slow propagation of the MJO is probably the most serious issue for the ECMWF's current monthly forecasts, particularly for the longer time range (days 19–25 and 26–32). This problem and the difficulty of the MJO crossing the maritime continent may cause the forecast to be out of phase with observations after twenty days in some occasions.

In the extratropics, the model simulates an increase in the probability of a positive NAO following an MJO in phase 3 (enhanced convection over the eastern Indian Ocean) and a decrease following an MJO in phase 6 (suppressed convection over the eastern Indian Ocean). Overall, the model teleconnections in the extratropics are generally consistent with ERA-Interim, but they tend to be too weak over Europe.

The impact of the MJO on the extratropical forecast skill was investigated. Results show that the MJO has no significant impact for days 5–11, except for precipitation but has a positive impact for days 12–18, 19–25 and 26–32. This impact is statistically significant for days 12–18 and 19–25. The impact of the MJO is particularly important for days 19–25 with the model showing almost no skill at all when there is no MJO in the initial conditions, but the day 19–25 probabilistic forecasts become reliable and skilful when there is an MJO in the initial conditions. This suggests that it is possible to know *a priori* if a monthly forecast will be reliable or not. Those results also suggest that improvements in the representation of the MJO in the ECMWF model are likely to lead to improved monthly forecast skill.

Woolnough et al. (2007) have shown that coupling the atmospheric model to a high vertical resolution ocean mixed-layer model can impact the speed of the simulated MJO events through its impact on the diurnal cycle and intraseasonal variability of sea-surface temperature. Therefore coupling the IFS to a high vertical resolution ocean model, as in *Woolnough et al.* (2007), may help the atmospheric model to produce faster MJO events, which could lead to more realistic MJO teleconnections and enhanced skill in the extratropics

Further reading

Bechtold, **P.**, **M. Köhler**, **T. Jung**, **P. Doblas-Reyes**, **M. Leutbecher**, **M. Rodwell** & **F. Vitart**, 2008: Advances in simulating atmospheric variability with the ECMWF model: From synoptic to decadal time scales. *Q. J. R. Meteorol. Soc.*, **134,** 1337–1351.

Cassou, **C.**, 2008: Intraseasonal interaction between the Madden-Julian Oscillation and the North Atlantic Oscillation. *Nature*, doi:10.1038/nature07286.

Ferranti, **L.**, **T.N. Palmer**, **F. Molteni** & **E. Klinker**, 1990: Tropical-extratropical interaction associated with the 30–60 day oscillation and its impact on medium and extended range prediction. *J. Atmos. Sci.*, **125,** 2177–2199.

Gottschalk, **J.**, **M. Wheeler**, **K. Weickmann**, **F. Vitart**, **N. Savage**, **H. Hendon**, **H. Lin**, **M. Flatau**, **D. Waliser**, **K. Sperber**, **W. Higgins** & **A. Vintzileos**, 2009: Establishing and assessing operational model MJO forecasts: A project of the CLIVAR Madden-Julian Oscillation Working Group. *Bull. Am. Meteorol. Soc.*, **91,** 1247–1258.

Madden, **R.A.** & **P.R. Julian**, 1971: Detection of a 40–50 day oscillation in the zonal wind in the tropical Pacific. *J. Atmos. Sci.*, **5,** 702–708.

Vitart, **F.** & **F. Molteni**, 2010: Simulation of the MJO and its teleconnections in the ECMWF forecast system. *Q. J. R. Meteorol. Soc.*, **136,** 842–855.

Waliser, **D.E.**, **W. Stern** & **C. Jones**: 2003: Potential predictability of the Madden Julian Oscillation. *Bull. Am. Meteorol. Soc.*, **84,** 33–50.

Wheeler, **M.C.** & **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.

European Centre for Medium-Range Weather Forecasts, Shinfield Park, Reading, RG2 9AX, England