

Addressing model error through atmospheric stochastic physical parametrisations: Impact on the coupled ECMWF seasonal forecasting system

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Abstract

The finite resolution of general circulation models of the coupled atmosphere-ocean system and the effects of sub-grid scale variability present a major source of uncertainty in model simulations on all time scales. The European Centre for Medium-Range Weather Forecasts has been at the forefront of developing new approaches to account for these uncertainties. In particular, the stochastically perturbed physical tendency scheme and the stochastically perturbed backscatter algorithm for the atmosphere are now used routinely for global numerical weather prediction. The European Centre also performs long-range predictions of the coupled atmosphere-ocean climate system in operational forecast mode and the latest seasonal forecast System 4 has the stochastically perturbed tendency and backscatter schemes implemented in a similar way as for the medium range weather forecasts. Here we present results of the impact of these schemes in System 4 by contrasting the operational performance on seasonal time scales during the retrospective forecast period 1981-2010 with comparable simulations that do not account for the representation of model uncertainty. We find that the stochastic tendency perturbation schemes helped to reduce excessively strong convective activity especially over the maritime continent and the tropical Western Pacific leading to reduced biases of the outgoing longwave radiation, cloud cover, precipitation and near-surface winds. Positive impact was also found for the statistics of the Madden-Julian Oscillation showing an increase in the frequencies and amplitudes of Madden-Julian Oscillation events. Further, the errors of El Niño Southern Oscillation forecasts become smaller while increases in ensemble spread lead to a better calibrated system if the stochastic tendency is activated. The backscatter scheme has overall neutral impact. Finally, evidence for noise-activated regime transitions has been found in a cluster analysis of mid-latitude circulation regimes over the Pacific-North America region.

1 Introduction

The present paper is a contribution to the special themed issue of Philosophical Transactions A devoted to "Stochastic modelling and energy-efficient computing for weather and climate prediction". It describes and discusses results presented by the authors at a workshop in Oxford in March 2013¹. The Oxford workshop brought together meteorologists, physicists, mathematicians and computer scientists to report recent progress in the representation of inherent uncertainties in weather and climate models using stochastic approaches, and to discuss how innovative ideas of fast and energy-efficient approximate computing hardware could be used to improve simulations in probabilistic weather and climate models (Palmer, 2014).

The motivation for including stochastic approaches in our current generation of weather and climate models is clearly set out in a recent essay by Palmer (2012): Deterministic parameterisations in sophisticated weather and climate models are inconsistent with the implications of the scaling symmetries in the Navier-Stoke equations and the observed power-law behaviour in the atmosphere. These structures prevent a meaningful separation between resolved and unresolved scales. One important consequence of the power-law structure in the atmosphere is the upscale error propagation where errors at very small scales (very high horizontal model resolution) can grow and ultimately contaminate the accuracy of simulations at much larger scales in a finite time. Thus any parameterisation needs to take into account the representation of the sub-grid scale model uncertainty on the resolved scales.

¹ <https://www.maths.ox.ac.uk/groups/occam/events/stochastic-climate>

Successful applications of stochastic approaches in numerical weather prediction (NW) have evolved in the recent decade from the early attempts in the European Centre for Medium-Range Weather Forecasts (ECMWF) ensemble prediction system (Buizza et al., 1999) to operational schemes at several meteorological services around the world (e.g. Bowler et al., 2009; Charron et al., 2010). The currently operational medium-range ensemble prediction system at ECMWF includes two packages to represent model uncertainty, the Stochastically Perturbed Physical Tendencies (SPPT) scheme and the Stochastically Perturbed Back Scatter (SPBS) scheme. The SPPT scheme is based on the Buizza et al. (1999) scheme and applies stochastic perturbations in form of multiplicative noise to the diabatic (parameterised) part of the tendency equations of the prognostic variables (Palmer et al., 2009). The SPBS scheme aims at describing the mechanism of stochastic backscatter of kinetic energy from the near-truncation scales to the larger scales, as originally pioneered in Large Eddy Simulations (Berner et al., 2009). Both schemes were shown to not only improve the quality of numerical weather forecasts but also to reduce some systematic errors in these models (Palmer et al., 2009).

Apart from NWP, stochastic parameterisations have not been widely applied in general circulation models of the atmosphere or the coupled climate system. As a step towards reducing this gap between the use of these new stochastic approaches in weather and climate simulations, this study presents an analysis of the impact of these techniques on ECMWF's operational long-range predictions on seasonal time scales. Unlike conventional weather forecasts, seasonal predictions do not attempt to forecast the detailed day-to-day evolution of weather, because of the chaotic nature of the climate system. Rather, seasonal predictions provide estimates of forecast seasonal-means of the coming season. The physical basis for such estimates arises from the effect of predictable seasonal-timescale signals arising from the ocean, and to a lesser extent the land surface, on the atmosphere (Palmer and Anderson, 1994). The key paradigm for seasonal forecasting is the El Niño Southern Oscillation (ENSO), a coupled ocean-atmosphere phenomenon occurring primarily in the tropical Pacific and predictable six months and more ahead (Jin et al., 2008; Weisheimer et al., 2009).

ECMWF has been at the forefront of seasonal predictions for many years. Research on predictability on seasonal time scale in the early 1990s led to the implementation of the first ECMWF seasonal forecast system based on a global ocean-atmosphere coupled model in 1997, and a successful forecast of the major 1997-98 El Niño (Stockdale et al., 1998). The first coupled seasonal forecast System 1 was replaced by System 2 in 2001 and System 3 in March 2007. In November 2011 the latest seasonal forecasting System 4 started producing operational forecasts. As System 4 uses for its atmospheric component a version of ECMWF's model for NWP that includes the latest development of the SPPT and SPBS stochastic parameterisation schemes, it provides an ideal test bed for studying the impact of the perturbed tendency and backscatter scheme on seasonal climate forecasts. Positive results found in previous investigations with earlier non-operational versions of the ECMWF model using a cellular automaton pattern for the backscatter scheme (Berner et al., 2008) and comparing the stochastic model error approach to multi-model and perturbed physical parameter ensemble methodologies (Weisheimer et al., 2011) motivated the research described here. The results presented in this paper are based on System 4's retrospective seasonal forecasts by comparing them with a set of simulations without stochastic representations of model uncertainty.

Based on studies using simplified climate models with stochastic noise it was found that these perturbations can impact on the mean state of the system through noise-induced drift (e.g.

Sardeshmukh et al., 2003; Williams, 2012) and trigger noise-activated regime transitions (Molteni and Tibaldi, 1990). Suppose the system has a potential well structure with double minima, which would correspond to a bimodal non-Gaussian probability density function (pdf). While statistically the most frequent state of the system would be the one that corresponds to the absolute potential well minimum and the absolute maximum of the pdf, the system would also, though less frequently, visit the other quasi-stable mode if the forcing applied is strong enough to allow for it. Suppose a small stochastic forcing is now applied to the system. While most of the time it might be too weak to move the system out of its preferred state, some perturbations might be large enough to kick the system more often than normal to the other less frequent mode of variability. In a statistical sense, these noise-activated regime transitions will lead to changes in the mean state of the system and in the frequency of occurrence of the two modes of variability of the system.

In this study, we analyse the impact of stochastic perturbations on the long-term statistics and biases in the ECMWF coupled seasonal forecasting model. We find evidence for both noise-induced drift of the large tropical convective areas and noise-activated transitions between the preferred atmospheric circulation regimes over the extratropical North Pacific-North America region. The paper is structured as following. Section 2 described the seasonal forecasting System 4 that is used to study the impact of stochastic parameterisations. Section 3 discusses results of the change in the mean state looking at the individual contributions of the SPPT and SPBS schemes. The impact of these two schemes on the dominant tropical mode of intraseasonal variability, the Madden-Julian Oscillation (MJO), is the subject of Section 4. Tropical Pacific sea-surface temperature (SST) forecasts of ENSO are discussed in Section 5 while Section 6 shows how the impact of stochastic perturbations manifests itself in a cluster analysis of quasi-stationary circulation regimes over the Pacific North America region. A summary of the main results and some conclusions are presented in Section 7.

2 ECMWF's seasonal forecasting system 4

ECMWF's seasonal forecasting System 4 (Molteni et al., 2011) consists of an atmospheric and an oceanic model component to simulate the evolution of the global circulation in the atmosphere and in the oceans, based on the physical laws of fluid dynamics. The equations of motions and thermodynamics are solved numerically by discretising the atmosphere and the oceans vertically and horizontally. The atmospheric component of System 4 is version CY36R4 of ECMWF's state-of-the-art numerical weather prediction model IFS (Integrated Forecasting System). While the dynamical part of the model solves the equation of motion for adiabatic processes, many physical processes, e.g. related to phase changes of water and the formation of convection and clouds, operate on sub-grid scales and thus cannot be resolved explicitly by the finite coarse resolution of the atmospheric model grid. In the IFS model these unresolved diabatic processes are described through a set of deterministic physical parameterisation schemes.

As mentioned in the Introduction, two approaches to represent uncertainties in these physical parameterisations have recently been included in the IFS (Palmer et al., 2009) in the form of stochastic physical parameterisation schemes. In the Stochastically Perturbed Physical Tendency (SPPT) scheme the summed tendencies of the prognostic variables temperature, wind and humidity as passed on from the individual parameterisation schemes are perturbed with a multiplicative univariate Gaussian noise term. The perturbations vary smoothly following an AR-1 process in space and time with three distinct

spatio-temporal scales with characteristic lengths of 500, 1000 and 2000 km. The corresponding temporal scales (e-folding times) are 3 hours, 3 days and 30 days. The shortest scale is connected with the largest amplitude of the perturbations while the longest and slowest scale becomes active via small perturbations. The choice of the amplitude of the perturbations has been motivated by results from coarse-graining studies with cloud-resolving models (Shutts and Palmer, 2007; Palmer et al., 2009; Shutts and Callado Palleles, 2014). The parameter settings for SPPT used in System 4 are exactly the same as those used in ECMWF's operational medium-range weather forecasting system.

The second scheme, the Stochastically Perturbed Back Scatter (SPBS) scheme, describes a physical process missing in conventional parameterisation schemes: the upscale energy transfer from unbalanced motions associated with convection and gravity waves and from the balanced flow in the manner of two-dimensional (or quasi-geostrophic) turbulence. It is formulated in terms of a perturbed streamfunction forcing whose amplitude is modulated by the total dissipation rate (sum of numerical dissipation, dissipation due to orographic gravity wave drag and due to convection). The backscatter ratio, which determines the energy input rate in the streamfunction forcing depends on the horizontal model resolution and is set to 0.04 in the System 4 configuration. For detailed descriptions of these two schemes see Palmer et al. (2009), Shutts (2005), Berner et al. (2009) and Shutts and Callado Pallares (2014).

The atmospheric model IFS is run in horizontal spectral resolution T255, corresponding to a grid size of approx. 80km, and 91 vertical levels up to 0.01 hPa. The ocean model used in System 4 is NEMO (Nucleus for European Modelling of the Ocean) version 3.0., a state-of-the-art 3-dimensional general circulation model. The ocean model has 42 levels in the vertical and the grid boxes have an approx. length of 110 km (1°) with equatorial refinement. The atmosphere and the ocean are coupled using the OASIS3 coupler to interpolate between the oceanic and atmospheric grids with a coupling interval of 3 hours.

In order to achieve a robust estimate of the System 4 model performance, an extensive set of retrospective forecasts (re-forecasts) of the past has been generated and contrasted with verification data over that period. These re-forecasts form the basis of the analysis presented here. The System 4 re-forecasts were started every calendar month over the 30-year period 1981 - 2010 by emulating real forecast conditions when no observed information about the future is available at the beginning of the forecast. As discussed in the Introduction, seasonal forecasts must be probabilistic by nature. Thus the seasonal forecasts and re-forecasts produced by System 4 consist of ensembles of model integrations. For the operational forecasts, each month a forecast ensemble of 51 members is started using slightly different initial conditions in the atmosphere and ocean. Due to computational constraints, the default ensemble size of the re-forecasts is currently 15. However, for a subset of selected start months the re-forecast ensemble size was extended so that it matches the forecast ensemble size of 51. These extended hindcasts are available for February, May, August and November start dates over the 1981-2010 period.

The ensemble of initial conditions in the re-forecasts is generated through a combination of ocean and atmospheric re-analyses and perturbations to the surface wind and SST fields over the ocean (Molteni et al., 2011). Here the ORA-S4 NEMOVAR reanalysis (Balmaseda et al., 2013) provides five equally likely realisations of the three dimensional oceanic state at any given time during the re-forecast

period. ORA-S4 has been used to initialise the ocean in the S4 hind- and forecasts. The atmosphere in the re-forecasts is initialised using the ERA-Interim reanalysis (Dee et al., 2011) and ECMWF's operational configuration of singular vectors in the atmosphere. Each member of the ensemble has a different realisation of the stochastic representation of the sub-grid scale physical processes in the atmosphere using the SPPT and SPBS schemes.

Here we analyse 51 member ensemble re-forecasts initialised on the 1st of May and 1st of November 1981-2010. The standard forecast lead-time is 2-4 months corresponding to the boreal summer (June, July and August, JJA) and winter (December, January and February, DJF) seasons. For the MJO analysis in Section 4 forecast lead times of up to 6 months were considered and the re-forecasts initialised on the 1st of August 1981-2010 have also been used.

To distinguish clearly the impact of the stochastic physical parameterisation schemes on System 4, several control experiments have been performed with an identical set-up as in S4 with stochastic schemes switched off either separately or simultaneously. In the `stochphysOFF` experiment both the SPPT and the SPBS schemes were switched off. The experiment labelled `SPPT_ON` has the SPPT scheme activated but not the SPBS scheme. Similarly, the experiment labelled `SPBS_ON` only uses the SPBS scheme while the SPPT scheme is switched off.

3 Stochastic physical parameterisations and the mean state of the atmosphere

In this Section we describe the impact of the two stochastic physical parameterisation schemes SPPT and SPBS on the mean state and systematic errors of the atmosphere in S4. Stochastic perturbations have, through a process called noise-induced drift, the potential to change the mean state of a system (e.g. Sardeshmukh et al., 2003, and Williams, 2012). While the overall impact of the stochastic physics schemes on the mean atmospheric state is small, we find that the perturbed tendency scheme SPPT does have an impact in the convectively dominated tropical areas where it reduces some of the systematic errors of the coupled ECMWF system.

Figure 1a shows the net longwave radiation at the top of the atmosphere (Outgoing Longwave Radiation OLR) in DJF as a proxy for convection as estimated in ERA-Interim over the hindcast period 1981-2010. The areas of large convection over the Indonesian warm pool area, South America and Africa show relatively small values of OLR corresponding to relatively cold temperatures over these convectively dominated regions. The bias of the control experiment `stochphysOFF` (Fig. 1b) based on November start dates of the re-forecasts during the same period indicates that these are also the areas where the model underestimates the fluxes due to excessively strong convective activity. The biases are noticeably reduced in System 4 (Fig. 1c) where the stochastic physical parameterisation schemes are activated. The difference between `stochphysOFF` and S4 is displayed in Fig. 1d. It is the perturbed tendency scheme SPPT that leads to the reduced bias, as shown in figures 1e and 1f for the difference between the control experiments `stochphysOFF` and `SPPT_ON` or `SPBS_ON`.

Top LW 1981 – 2010 DJF

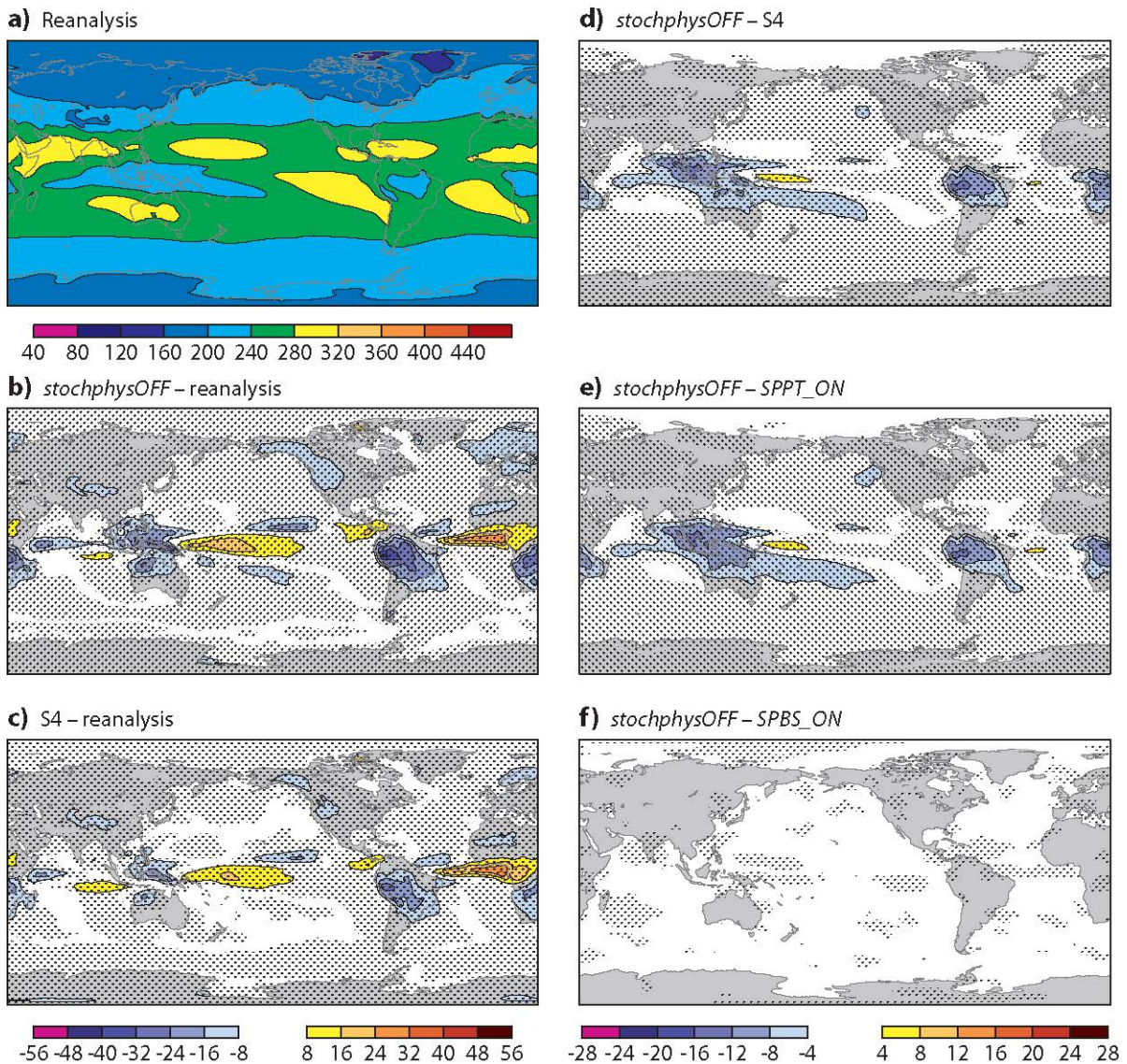


Figure 1: Top of the atmosphere net longwave radiation (Outgoing Longwave Radiation OLR) in W/m^2 in DJF. a) ERA Interim reanalysis, b) stochphysOFF – reanalysis, c) S4 – reanalysis, d) stochphysOFF – S4, e) stochphysOFF – SPPT ON, f) stochphysOFF – SPBS_ON. Significant differences at the 95% confidence level based on a two-sided t-test are hatched.

Similar conclusions can be drawn from the diagnostics of the total cloud cover in DJF over the three main tropical convection areas, see Fig. 2. The SPPT scheme (Fig. 2e) reduces the systematic over-estimation of cloud cover in the stochphysOFF control experiment (Fig. 2b), while the SPBS scheme (Fig. 2f) has no impact on the cloud cover. The overall combined effect of SPPT and SPBS is an improved mean cloud cover when compared with ERA-Interim (Fig. 2c).

TCC 1981 – 2010 DJF

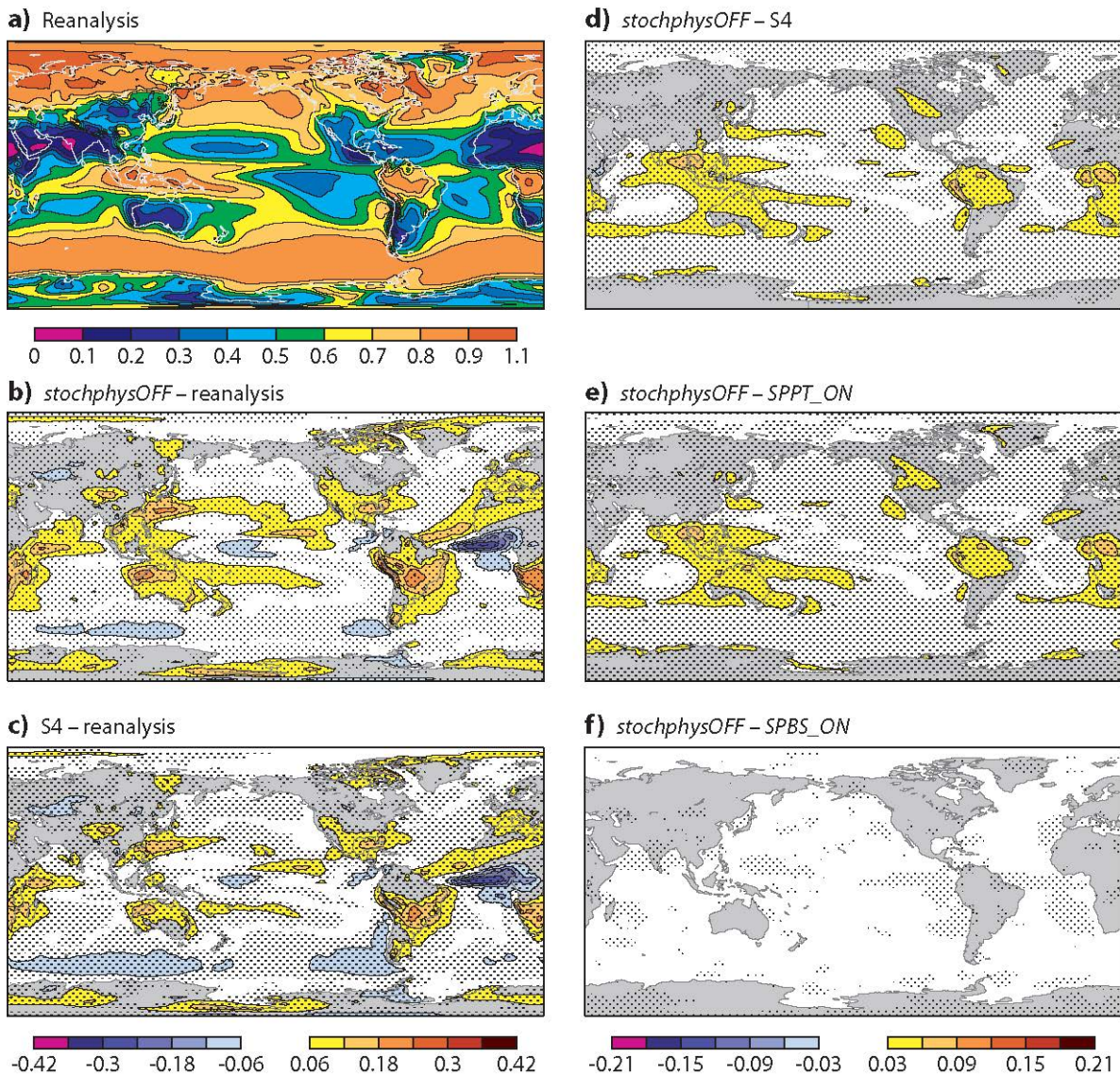


Figure 2: Total cloud cover in DJF. a) ERA Interim reanalysis, b) *stochphysOFF* –reanalysis, c) *S4* – reanalysis, d) *stochphysOFF* – *S4*, e) *stochphysOFF* – *SPPT_ON*, f) *stochphysOFF* – *SPBS_ON*. Significant differences at the 95% confidence level based on a two-sided *t*-test are hatched.

Convective activity is strongly coupled to precipitation and it is thus expected that the stochastic physical parameterisation schemes impact on the precipitation fields. Figure 3 demonstrate that the model in the control experiment *stochphysOFF* (Fig. 3b) produces excessive amounts of tropical precipitation in DJF, in particular over the warm pool and Western tropical Pacific. Here, the verification is done against GPCP precipitation data (Huffman et al., 1997; Adler et al., 2003) because the reanalysis estimates for tropical precipitation in ERA-Interim have non-negligible deficiencies (Dee et al., 2011). As for the longwave radiation at the top of the atmosphere and total cloud cover, the SPPT scheme (Fig. 3e) contributes the most to an overall reduction of that positive precipitation bias in System 4 (Fig. 3c and 3d).

The stochastic physical parameterisation schemes, and in particular the SPPT scheme, also have a positive impact on the seasonal-mean zonal wind climatology at 850 hPa in the tropics (Fig. 4). In the control experiment *stochphysOFF* without any representation of model error through stochastic parameterisations, the model has too strong easterly trade winds in the equatorial regions. This is especially true for the Western and central tropical Pacific. This overestimation of the easterlies is reduced when the stochastic physics schemes are implemented in S4 (Fig. 4c). Again, the SPPT scheme is the main reason for the improvement with SPBS having a nearly neutral impact.

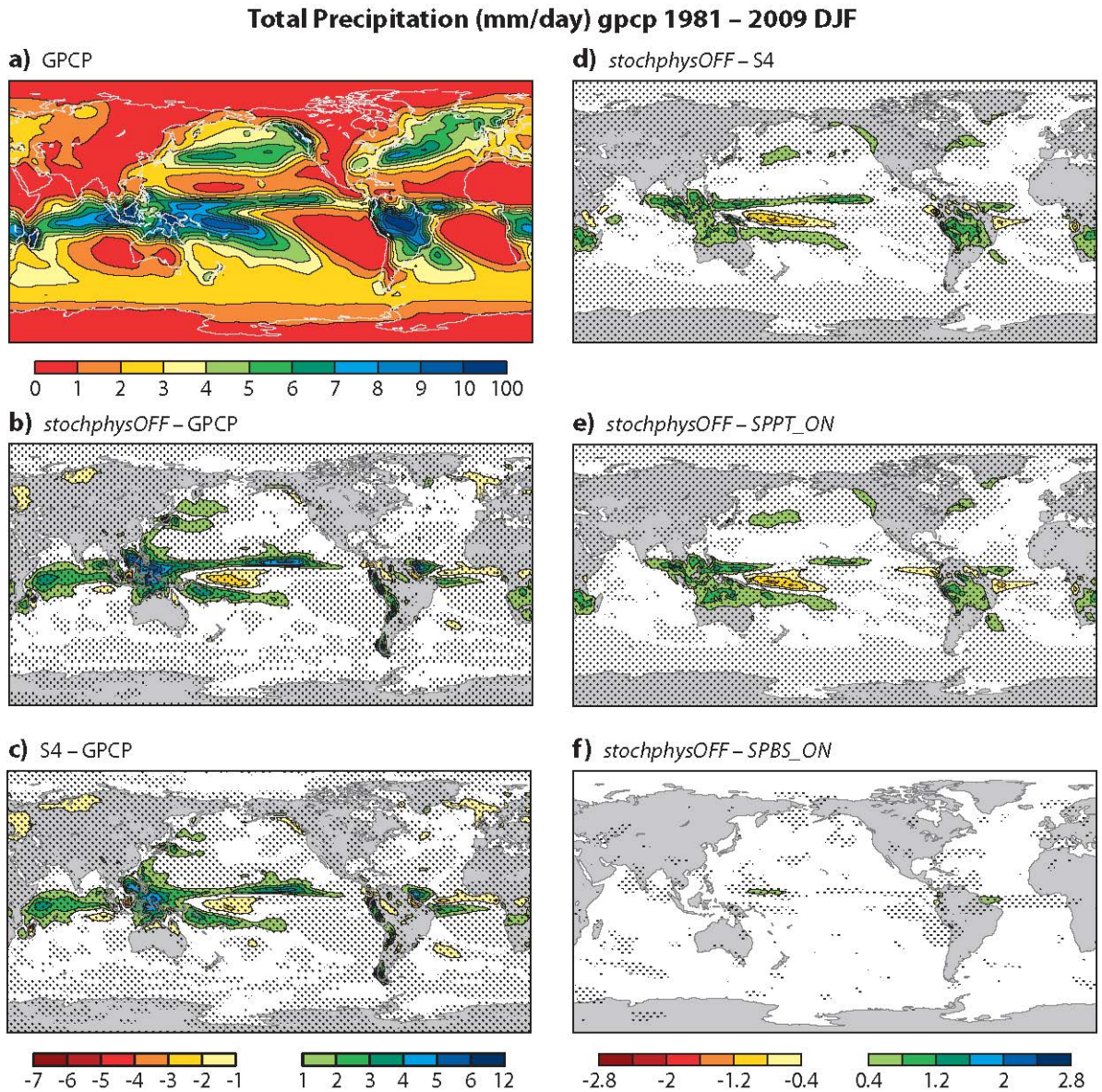
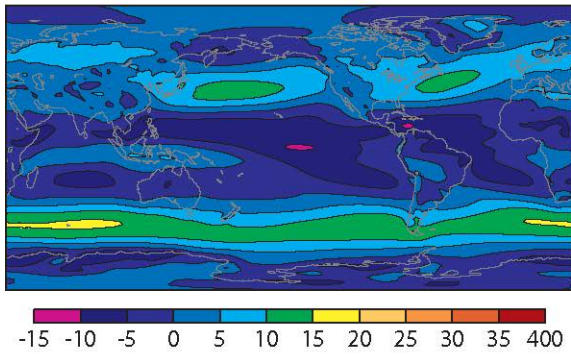
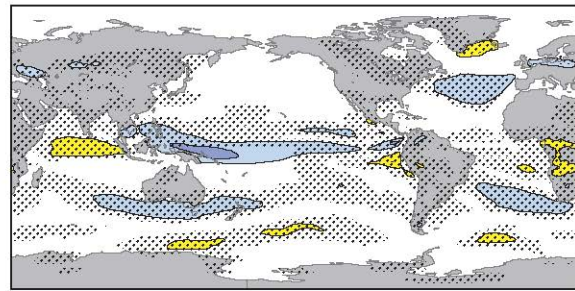
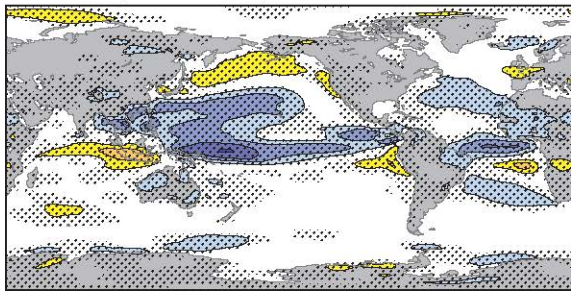
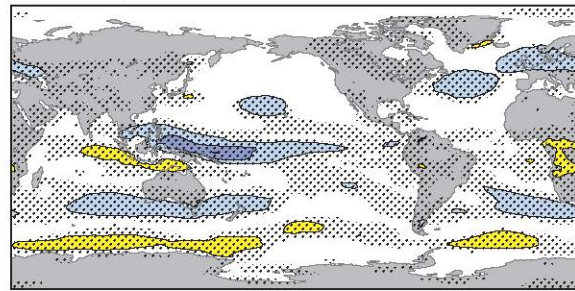


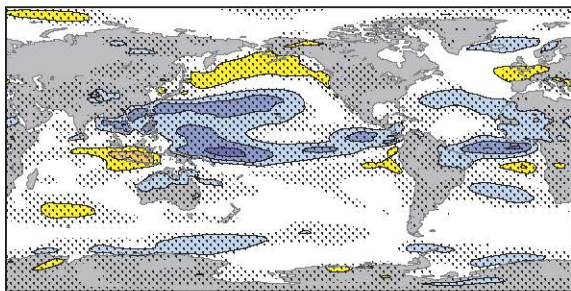
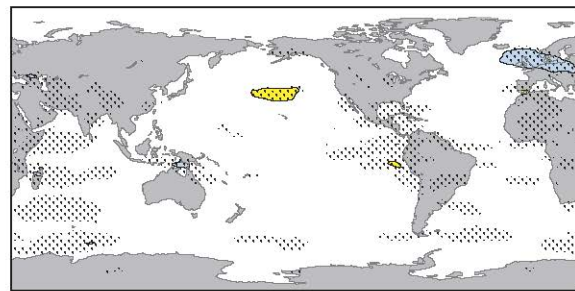
Figure 3: Total precipitation in mm/day in DJF. a) GPCP, b) *stochphysOFF* – GPCP, c) S4 – GPCP, d) *stochphysOFF* – S4, e) *stochphysOFF* – SPPT_ON, f) *stochphysOFF* – SPBS_ON. Significant differences at the 95% confidence level based on a two-sided t-test are hatched.

U850 1981 – 2010 DJF

a) Reanalysis

d) *stochphysOFF* – S4b) *stochphysOFF* – reanalysise) *stochphysOFF* – SPPT_ON

c) S4 – reanalysis

f) *stochphysOFF* – SPBS_ON

-7 -6 -5 -4 -3 -2 -1 1 2 3 4 5 6 7

-2.52 -1.8 -1.08 -0.36 0.36 1.08 1.8 2.52

Figure 4: Zonal wind at 850 hPa in m/s in DJF. a) ERA Interim reanalysis, b) *stochphysOFF* – reanalysis, c) S4 – reanalysis, d) *stochphysOFF* – S4, e) *stochphysOFF* – SPPT_ON, f) *stochphysOFF* – SPBS_ON. Significant differences at the 95% confidence level based on a two-sided *t*-test are hatched.

Summarising the findings discussed above, we conclude that the stochastic physical parameterisations have an overall positive impact on the DJF climatology of atmospheric fields (OLR, cloud cover, precipitation and near-surface wind) relevant for the large convectively active regions over the Indonesian warm pool/Western tropical Pacific area as well as over tropical South America and Africa. While the amplitude of the long-standing systematic errors for these quantities was not eliminated completely, the results from the stochastic schemes show a consistent improvement with a spatial projection onto the pattern of the coupled model bias. The reported model biases are already detectable during the first month of the simulations with a similar pattern and amplitude (not shown). Even though the emphasis in this section was on the DJF season, qualitatively similar conclusions hold also for the JJA season.

4 Impact on the statistics of the Madden-Julian Oscillation

The Madden-Julian Oscillation (MJO) is the dominant mode of intra-seasonal variability in the tropical atmosphere (e.g., Madden and Julian, 1971; Madden and Julian, 1994) linking the large-scale atmospheric circulation with organised tropical convection on a range of spatial scales such as mesoscale convective systems and convectively coupled waves. It is characterised by an eastward propagation of areas of enhanced and suppressed tropical rainfall mainly over the Indian and Pacific Oceans with a timescale of 30 to 60 days. The MJO has important links to the developments of the monsoon systems and El Niño events in the tropical Pacific (Zhang, 2005) as well as to extra-tropical predictability in the mid-latitudes (Cassou, 2008; Frederiksen and Lin, 2013).

Despite recent progress, understanding the dynamical mechanisms that lead to MJO events and realistically simulating the MJO in atmospheric circulation models remains a challenge for observational activities and modelling studies. New approaches like superparametrization (Grabowski, 2001), multcloud (Majda et al., 2007; Khouder et al., 2011; Peters et al., 2013) and multiscale models (Biello and Majda, 2005) are showing a promising capability to improve the simulation of the interaction between organised tropical convective processes. Another route of current research is the investigation of how air-sea coupling affects the MJO (Woolnough et al., 2000; Newman et al., 2009).

Thual et al. (2014) have suggested that stochastic parameterizations of unresolved synoptic processes in a minimal dynamical skeleton model of the MJO can account for some of the characteristic features of the MJO like the intermittent generation of MJO events and the organisation of MJO events into wave trains with growth and demise. While the role of stochasticity in forecasting the MJO using non-linear empirical prediction methods has recently been demonstrated by Kondrashov et al. (2013), it is not clear whether comprehensive general circulation models with stochastic parameterizations for the sub-grid scale (convective) variability can improve the representation of the MJO in such complex models.

In this Section we analyse the impact of the SPPT and SPBS stochastic parameterisation schemes on the statistics of simulating MJO events in the S4 re-forecasts. As the current predictability limit of the MJO in a recent version of the coupled ECMWF monthly forecasting system has been estimated to not reach more than 30 days (Vitart and Molteni, 2010; Vitart, 2014), we cannot expect skilful MJO forecasts beyond 1 month for individual events in the seasonal simulations. However, we can test how well the MJO is represented in S4 from a statistical point of view where we do not attempt to match individual MJO events in the reanalysis with events in the seasonal forecasts. Our focus here is on the frequency of occurrence of MJO events in the different stages of its propagation from West to East and on the amplitude distribution of the MJO events under the impact of the stochastic perturbation schemes.

The methodology for assessing the MJO follows Gottschalck et al. (2009). The Wheeler and Hendon Index (WHI, see Wheeler and Hendon, 2004) has been applied to all model forecasts and to ERA-Interim to evaluate how well the seasonal forecasting system can reproduce the distribution of MJO events. The multivariate WHI is calculated by projecting the forecasts or analysis on the two dominant combined Empirical Orthogonal Functions (EOFs) of OLR, zonal wind at 200 hPa and at 850 hPa averaged over the near-equatorial latitudes 15°N and 15°S. The index has been applied to daily anomalies relative to model climatology instead of the absolute value of the field, in order to remove

the impact of the annual cycle. In addition, a 120-day running mean has been subtracted to remove the variability associated with ENSO. The positive (negative) phase of EOF 1 describes enhanced (suppressed) convection over the Maritime Continent region. The positive (negative) phase of EOF 2 describes suppressed (enhanced) convection over the Indian Ocean and enhanced (suppressed) convection over the West Pacific. Analysis and forecasts are projected onto the two EOFs to describe the phase of the MJO in terms of two time series, the Real-Time Multivariate MJO series 1 (RMM1) and 2 (RMM2). The two time series can be plotted as a succession of points in the RMM1-RMM2 phase space (called Wheeler-Hendon diagram), in such a way that an evolving MJO event is described by a clockwise propagation in the phase space. The RMM1-RMM2 phase space can be divided into eight sections representing a specific phase of the MJO, see Fig. 5a-c. Phases 2 and 3 (negative EOF 2) 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 EOF 2) correspond to the MJO over the Western Pacific and phases 8 and 1 (negative EOF 1) correspond to the active phase of the MJO in the Western Hemisphere. Because of the loss of predictability of individual MJO events on seasonal time scales, we use the Wheeler-Hendon diagrams here to estimate the overall frequency of MJO events in each phase over the 30-year re-forecast period 1981-2010 for S4, stochphysOFF and ERA-Interim.

The Wheeler-Hendon diagrams of the model runs in Fig. 5 show daily data of the re-forecasts starting in May and ranging for 6 months over the 30 re-forecast years and for all 51 ensemble members in the two-dimensional phase space defined by RMM1 and RMM2. The diagram in Fig. 5a displays the data for the control experiment stochphysOFF and in Fig. 5b for S4. The corresponding data from the ERA-Interim reanalysis are shown for verification in Fig. 5c. Data points outside the unit circle are defined as MJO events where the amplitude of an MJO event is given by its distance from the origin of the diagram. Figure 5d summarises the relative frequencies of MJO events (amplitudes >1) in the 8 MJO phases for the control stochphysOFF experiment, for System 4 and for ERA-Interim as estimated from counting all data points in the Wheeler-Hendon diagrams. The ECMWF model has a pronounced bias in underestimating the frequency of MJO events for all phases. However, the stochastic physical parameterisations used in S4 increase the frequency of MJO events in each phase and thus reduce the negative bias. It is found (not shown) that this effect of the stochastic schemes increases with lead time from relatively little influence in the first month to a more pronounced impact at month 6. While the overall systematic underestimation of the number of MJO events in S4 remains a problem, the stochastic schemes show a consistent positive but small impact. These results were confirmed for the two other available start dates in August and November.

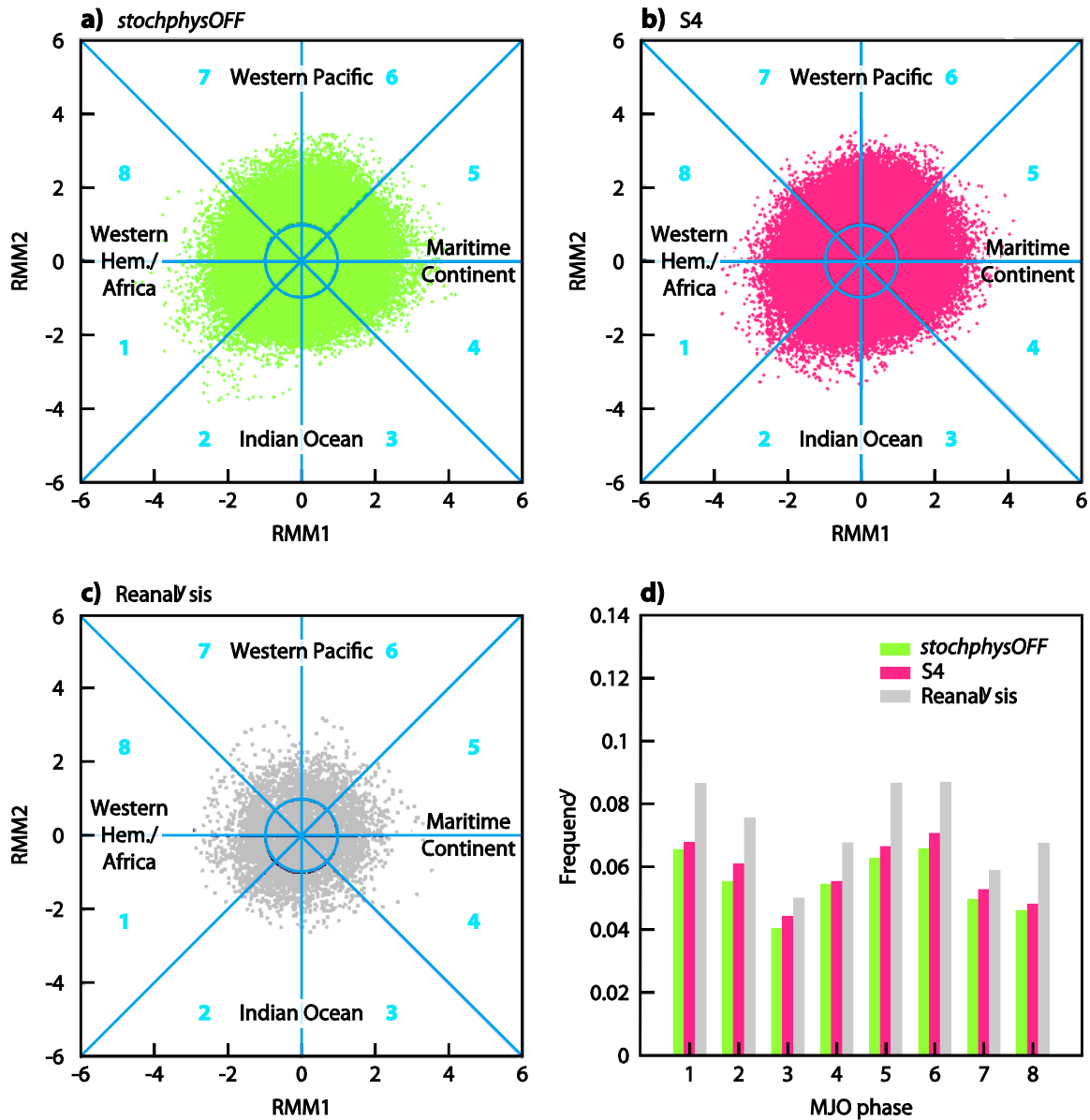


Figure 5: MJO frequencies. a) Wheeler-Hendon diagram for stochphysOFF. The dots show daily data over the 1981-2010 hindcast period for May start dates, forecast lead times up to 6 months and all ensemble members. b) As in a) but for S4. c) Similar to a) but for ERA Interim reanalysis. d) Relative frequencies of MJO events in each of the 8 MJO phases for the data in a) – c).

In order to answer the question what the impact of stochastic physics is on MJO events with different amplitudes, Fig. 6 quantifies the amplitude distributions for the stochphysOFF and S4 re-forecasts and compares them with the distribution of the ERA-Interim verification data. The model histograms in Fig. 6a and Fig. 6b are much smoother than the reanalysis histogram in Fig. 6c because of the larger overall sample size using 51 ensemble members. The data in all three histograms show a good fit to a Weibull distribution. A Kolmogorov-Smirnov test indicates that the three distributions are significantly (p-values < 0.01) different from each other.

The difference between the distributions in Fig. 6a and Fig. 6b is shown in the residual distribution in Fig. 6d. The seasonal re-forecasts without any representation of model uncertainty (stochphysOFF) generate more events with amplitudes smaller than 1 (not classified as MJO events). The impact of the stochastic physical parameterisation schemes manifests itself in an increase of the number of stronger MJO events with amplitudes larger than 1.

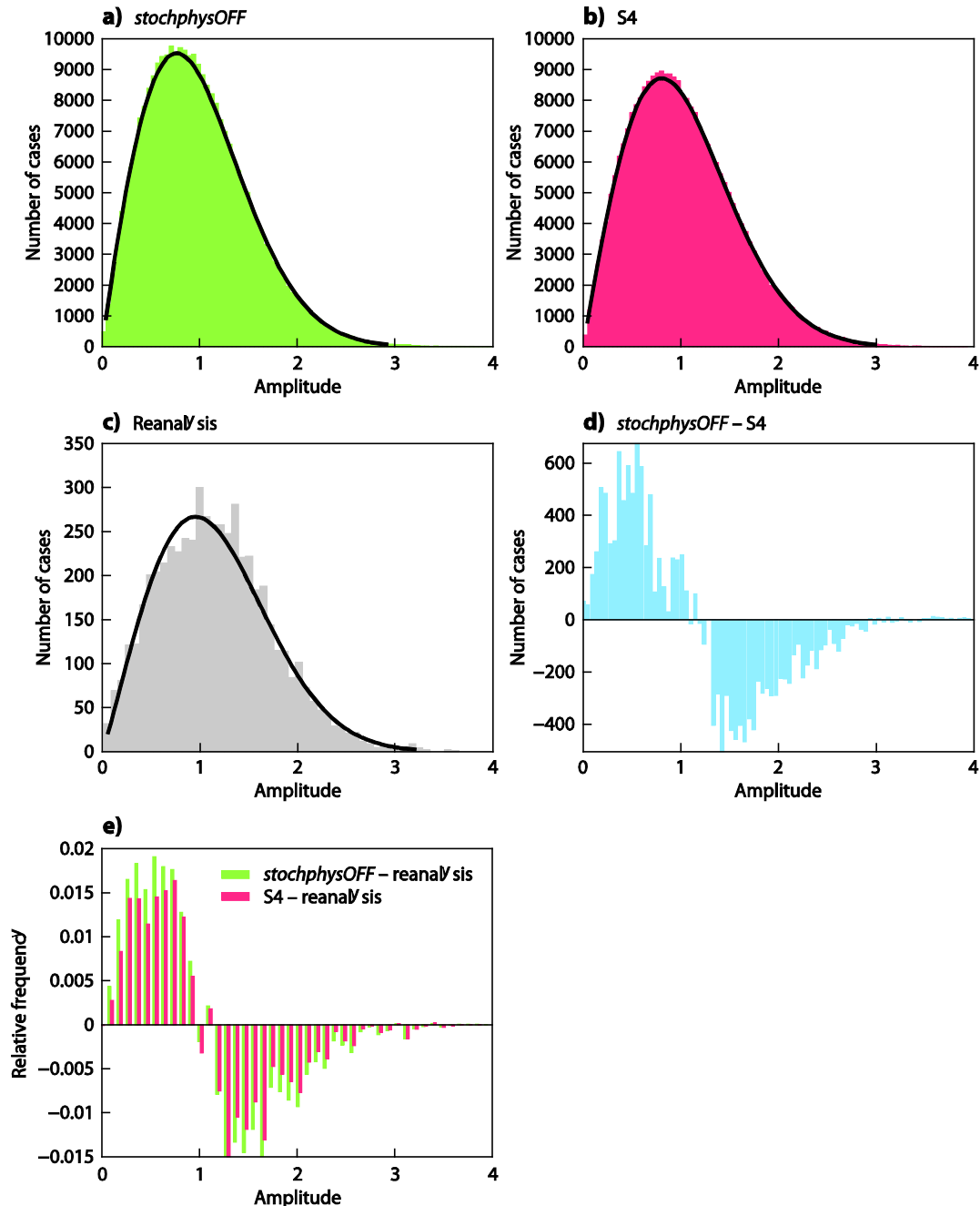


Figure 6: MJO amplitudes. a) Distribution of the MJO amplitudes from the Wheeler-Hendon diagram in Fig 5a for stochphysOFF. The fitted curve indicates a Weibull distribution. b) As in a) but for S4. c) Similar to a) but for ERA Interim reanalysis. d) Residual distribution for stochphysOFF minus S4. e) Residual distributions for stochphysOFF minus reanalysis (green) and S4 minus reanalysis (red).

This increase in the frequency of large-amplitude MJO events is an improvement in the model statistics of the MJO amplitude distribution. As shown in Fig. 6e, the frequency bias of S4 estimated as the binned difference between the histograms of ERA-Interim and S4 is for all amplitudes smaller than the frequency bias of stochphysOFF. It is clear that the stochastic physical parameterisations cannot eliminate completely the underestimation of MJO events when compared to ERA-Interim. However, the effect of introducing stochasticity reduces the underestimation consistently across the range of amplitudes.

What is the relative role of SPPT versus SPBS in the increased MJO activity? Figure 7a shows the residual distribution of MJO amplitudes between the SPBS_ON and SPPT_ON re-forecasts. Note that the SPPT_ON and SPBS_ON experiments have only been performed for November start dates and lead times of up to 4 months. The SPBS_ON experiment generates more events with amplitudes less than 1 (not classified as MJO events), while the SPPT_ON experiment increases the number of stronger amplitude MJO events. A comparison of the biases of the two experiments depending on amplitude (Fig. 7b) indicates that the SPPT_ON experiment develops for most cases a smaller bias (overestimation of weak events and underestimation of stronger events) than the SPBS_ON experiment.

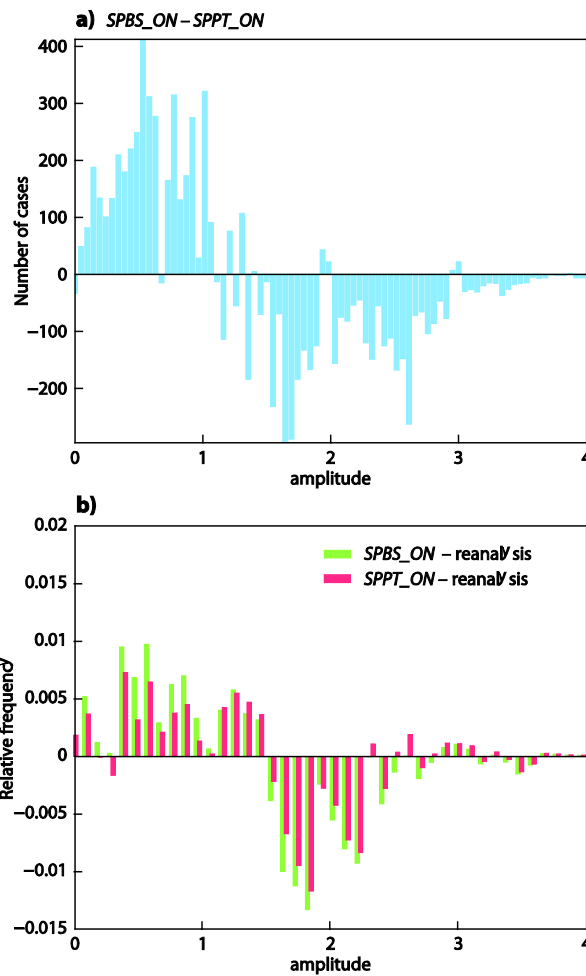


Figure 7: Impact of SPPT and SPBS on MJO amplitudes. a) Residual distribution for SPBS_ON minus SPPT_ON. b) Residual distributions for SPBS_ON minus reanalysis (green) and SPPT_ON minus reanalysis (red).

5 El Niño forecast quality

As demonstrated in Section 3, the stochastic parameterization schemes in System 4 reduce some of the systematic errors of the coupled ECMWF forecasting system. In particular, the perturbed tendency scheme SPPT had a positive impact over the Indonesian warm pool area and the Western tropical Pacific by weakening the convective activity, reducing excessive precipitation and decreasing the strength of the excessively strong near-equatorial winds in the Western and Central Pacific. In this Section we analyse how the representation of model uncertainty in System 4 and the related improvements of some of the systematic biases in these regions affect the forecast quality of ENSO on seasonal time scales.

In Figure 8a we show the evolution over forecast lead time up to 7 months of the root-mean squared error (RMSE) of the ensemble mean and ensemble spread (standard deviation) for SST forecasts in the Western tropical Pacific Niño4 area (160°E-150°W, 5°S-5°N) estimated from all available start dates 1st May, August and November over the re-forecast period 1981-2010. The solid red and blue lines show the RMSE and the dashed red and blue lines below the ensemble spread. The RMSE of a simple statistical persistence forecast is shown for comparison as the black dash-dotted line above the other lines. All red lines correspond to the System 4 hindcasts whereas the blue lines are from the experiment without stochastic parameterisations of model uncertainty *stochphysOFF*. The thin red lines around the RMSE of S4 indicate the sampling uncertainty in estimating the RMSE. As can be seen, S4 has a significantly lower RMSE than *stochphysOFF* for all lead times beyond 2 months. The improvement of S4 over *stochphysOFF* becomes larger for longer lead times. The spread in the S4 forecast ensemble is increased which together with the reduced RMSE leads to a better calibrated forecasting system. Qualitatively similar results were found when analysing individual start dates and for the SSTs in other parts of the equatorial Pacific.

The anomaly correlation coefficient for the Niño4 SSTs over lead-time is shown in Fig. 8b. Consistent with the findings for the RMSE, the correlation is improved when the stochastic physical parameterisation schemes are activated in S4.

For a subset of the re-forecasts (November start dates only over 1981-2010 for lead times up to 4 months) the individual contributions of the SPPT and SPBS stochastic perturbation schemes to the S4 performance were tested, see Fig. 8c. Here, the red lines correspond to S4, the green lines to the SPPT_ON experiment with only the stochastically perturbed physical tendency scheme being active, the blues line to the SPBS_ON experiment where only the backscatter scheme was activated and the orange lines showing the results from the *stochphysOFF* experiment with no representation of model uncertainty. It can be seen that the S4 and SPPT_ON re-forecasts are very similar in their magnitude of RMSE and spread evolution. In contrast, the SPBS_ON forecasts are very close to the control experiment *stochphysOFF*, both in terms of spread and error. This means that it is primarily the perturbed tendency scheme that generates a smaller RMSE and a larger spread of the ensemble compared to the control forecasts. The backscatter scheme by itself has only a very small impact.

The improvements due to the stochastic parameterisations in S4 in reducing both the RMSE and under-dispersiveness of ENSO forecasts may appear small. However, they are approximately of the same order as the effects of changing the physical parameterisation packages and model

configurations as occurs from one ECMWF seasonal forecast model version to the next (Molteni et al., 2011).

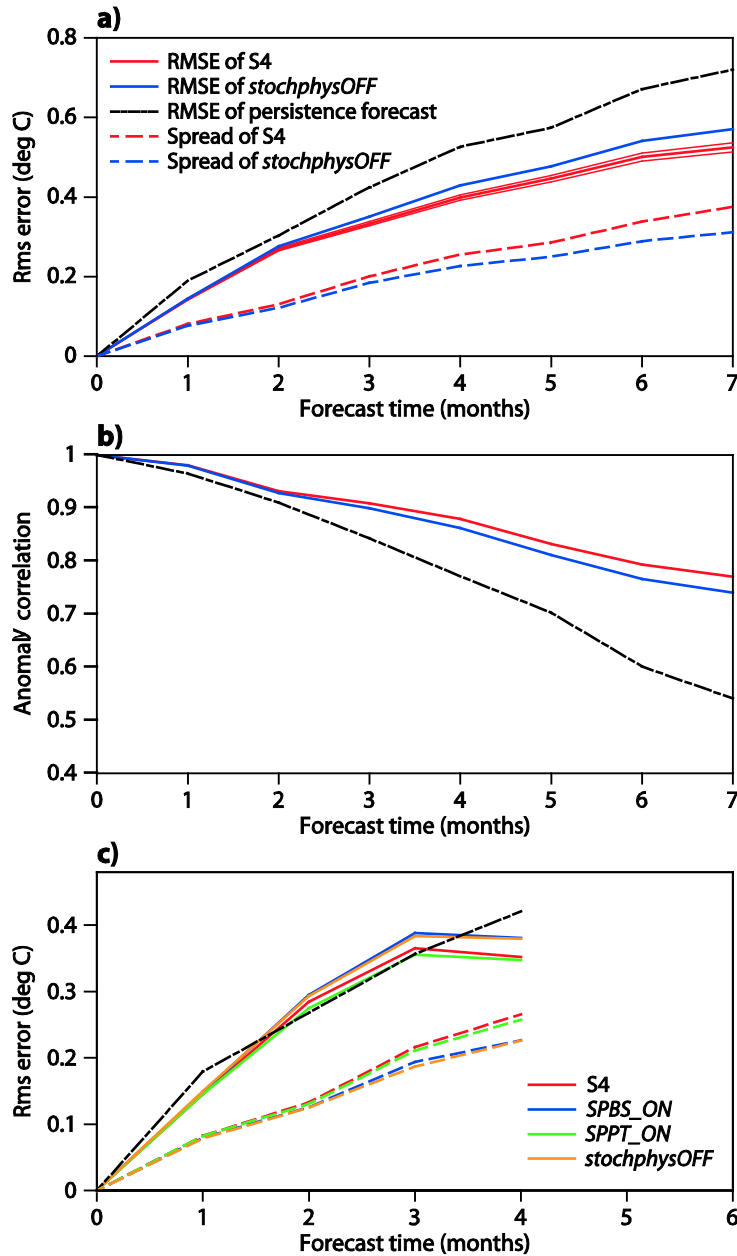


Figure 8: Forecast quality of SSTs in the Niño4 region. a) RMSE of ensemble mean (solid lines), ensemble spread (dashed line) and RMS of persistence (black dash-dotted line) as a function of forecast lead time for stochphysOFF (blue) and S4 (red). Thin red lines indicate error bars of S4 RMSE. Hindcast period: 1981-2010 May, Aug and Nov start dates. b) Anomaly correlation for stochphysOFF (blue), S4 (red) and persistence (black). c) As in a) but for S4 (red), SPPT_ON (green), SPBS_ON (blue) and stochphysOFF (orange). Hindcast period: 1981-2010 Nov start dates only.

The fact that the stochastic physical parameterisations in S4 improve the forecast quality of the tropical Pacific SSTs is in good agreement with the conclusions of Weisheimer et al. (2011) who compared the impact of stochastic parameterisations in seasonal forecasts of tropical Pacific SSTs with the multi-model and perturbed physical parameter approaches to account for model uncertainty.

6 Quasi-stationary circulation regimes over the Pacific-North America region

The notion of how stochastic perturbations have the potential to impact on the long-term statistics of multi-modal systems has been discussed in the Introduction. While Sections 3 and 4 focussed on analysing the impact of the operational stochastic physical parameterisations in ECMWF's seasonal forecasting system on the mean state and the statistics of the MJO, in this section we shall discuss how the stochastic perturbations in S4 affect the statistics of quasi-stationary circulation regimes over the Pacific North America region. A previous study by Jung et al. (2005) found that an earlier version of the back scatter scheme coupled to a cellular automaton, providing the spatial and temporal structure of the forcing, improved the frequency of occurrence of North Pacific weather regimes in atmospheric simulations with the ECMWF model driven by prescribed SSTs.

Atmospheric intraseasonal variability, especially in the extratropics during the cold season, is characterized by preferred large-scale flow patterns that appear repeatedly at certain geographical locations and persist beyond the typical lifetime of individual weather systems. These quasi-stationary flow patterns have non-Gaussian, or even non-modal characteristics and are called weather regimes (Reinhold and Pierrehumbert, 1982) or, more generally, circulation regimes (Straus et al., 2007). Circulation regimes can be associated with significant temperature and precipitation anomalies (Robertson and Ghil, 1999; Cassou et al., 2005). Several observation-based and model studies have shown that ENSO forcing affects the relative frequency of occurrence of circulation regimes (Corti et al., 1999; Straus et al., 2007). The ENSO forcing is particularly important for the Pacific North American (PNA) region, whose intraseasonal variability is directly linked to tropical Pacific SST anomalies (Wallace and Gutzler, 1981; Straus and Molteni, 2004).

The circulation clusters over the PNA region (140°E-80°W, 30°N-87.5°N) have been computed using daily data of geopotential height anomalies at 500 hPa during DJF for the re-forecast period 1981-2010 and applying the k-means clustering technique (Michelangeli et al., 1995; Straus and Molteni, 2004, Ferranti and Corti, 2011; Ferranti et al., 2014) in the phase space spanned by the first four EOFs to identify local density maxima. These EOFs explain about 50% of the total variance. We note that the spatial clustering patterns are very robust if the number of EOFs is increased. For the re-forecast simulations of S4 and *stochphysOFF*, the November start dates and all 51 ensemble members were used in the computation of the regimes.

Composite maps of the four circulation regimes of ERA-Interim (top row), System 4 (middle row) and *stochphysOFF* (bottom row) are shown in Fig. 9. Cluster 1 of the reanalysis data is, in agreement with other studies (Robertson and Ghil, 1999; Kimoto and Ghil, 1993; Cheng and Wallace, 1993, Straus et al., 2007), characterised by an eastward shift of the PNA pattern ("Pacific Trough"). The Pacific Trough is the most populated cluster in the period considered. It occurs on 28.6% of the days. The 30-year time series of the frequency of occurrence of the Pacific Trough cluster within each DJF season is

highly positively correlated ($r=0.7$) with the observed multivariate ENSO index (Wolter and Timlin, 2011) for the same period indicating the strong link of the variability in the tropical Pacific on the formation of the Pacific Trough flow regime. This is consistent with the results of Straus and Shukla (2002) who described the mid-latitude Rossby wave response pattern to ENSO-driven anomalous tropical heat sources as a PNA-like pattern that is similar but not identical to the PNA pattern of Wallace and Gutzler (1981).

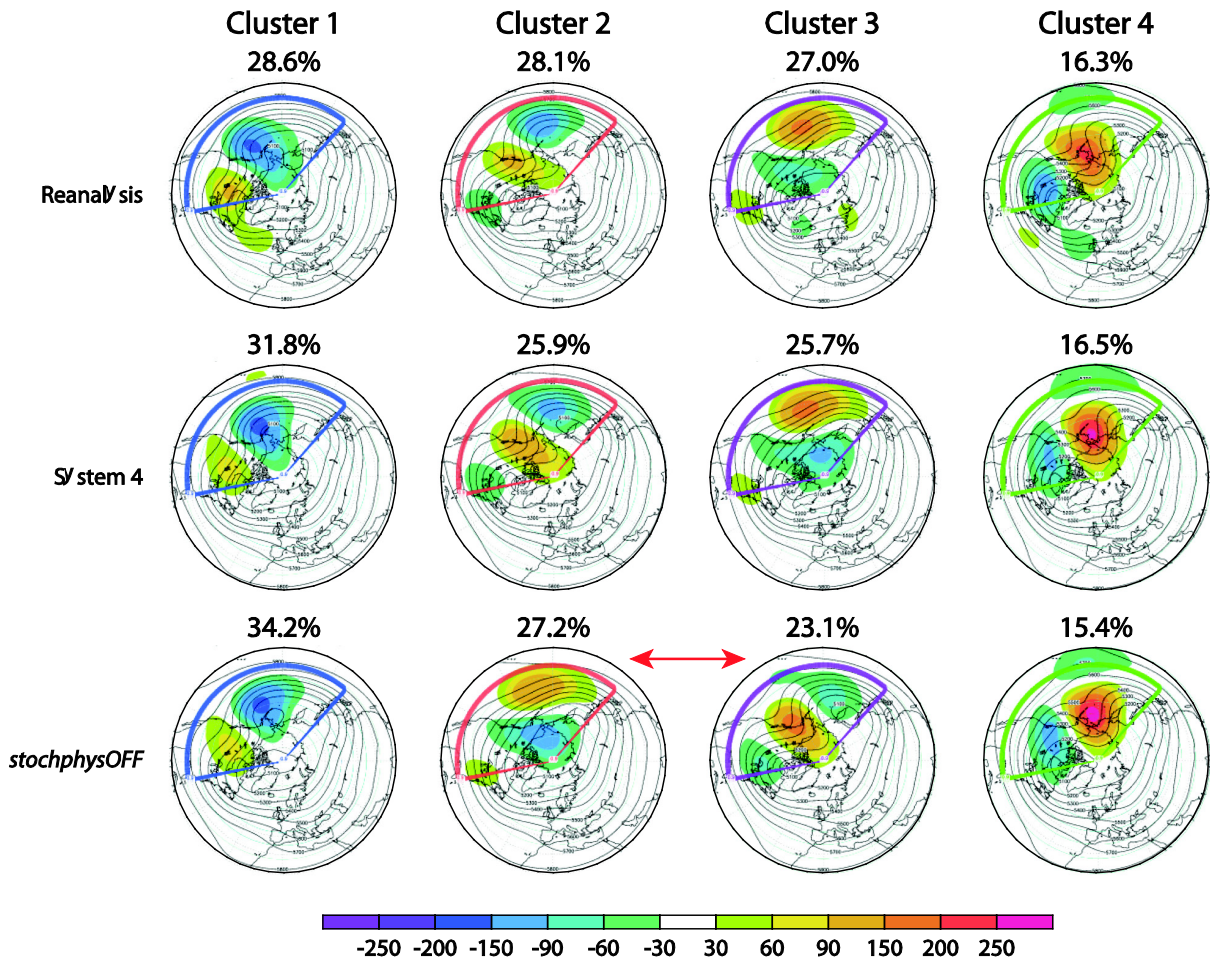


Figure 9: Circulation regimes over the Pacific-North America region in ERA Interim reanalysis data (top row), System 4 (middle row) and in stochphysOFF (bottom row) for anomalies (shades) and full fields (contours) of Z500. The numbers indicate the relative frequency of occurrence of each cluster.

Clusters 2 (28.1%) and 3 (27.0%) of ERA-Interim are the well-known positive and negative PNA patterns, respectively. They closely resemble opposite phases of the one-point correlation maps of Wallace and Gutzler (1981). The year-to-year variability in the frequency of occurrence of cluster 2 is only weakly related to the ENSO index ($r=0.2$). Cluster 3, the reverse PNA pattern, is negatively correlated ($r=-0.5$) with ENSO.

Cluster 4, the least populated cluster occurring on 16.3% of the days in ERA-Interim, is characterized by a blocked flow (Pacific blocking) and a pronounced ridge over Alaska, in agreement with the findings of Robertson and Ghil (1999) and Straus et al. (2007). We find that this cluster is associated with cold ENSO events ($r = -0.4$).

The circulation regimes detected in System 4 and the *stochphysOFF* experiment are remarkably similar to those of ERA-Interim in the common period indicating that the ECMWF seasonal forecasting system either with and without the stochastic parameterizations is able to reproduce the spatial structure of the flow regimes in the Pacific North American sector. However, despite the good agreement between observed and simulated spatial patterns, there are in both sets of integrations non-negligible differences between the observed and the simulated regime frequencies. In particular, the average frequency of occurrence of cluster 1 (Pacific Trough) is overestimated in both model runs: the estimates of 31.8% for S4 and 34.2% for *stochphysOFF* correspond to a relative overestimation of 11% and 20%, respectively. Thus the stochastic parameterisations in S4 help to reduce the strong overestimation of cluster 1.

In contrast with the strong overestimation of the Pacific Trough regime by the model, both System 4 (25.9%) and the *stochphysOFF* experiment (23.1%) underestimate the occurrence of the positive PNA regime in cluster 2. The degree of underestimation is by 8% of the ERA-Interim frequency of 28.1% in S4 and by a substantial 18% relative to ERA-Interim for *stochphysOFF*.

The negative PNA regime frequency of cluster 3 in the reanalysis is underestimated by S4 (25.7% absolute frequency of occurrence) and slightly overestimated by *stochphysOFF* (27.2%). The underestimation of the positive PNA regime along with the overestimation of the negative PNA regime for the *stochphysOFF* simulations result in a change of the order of the four circulation regimes when sorted according to their frequencies of occurrence for *stochphysOFF* (see Fig. 9).

As in ERA-Interim, cluster 4 represents the Alaskan Ridge pattern in all sets of integrations. However, the experiment without representation of model error *stochphysOFF* (15.4%) underestimates the number of days of such a blocked flow regime when compared to ERA-Interim by relative 6%. System 4 (16.5%) marginally overestimates the occurrence of the Alaskan Ridge cluster by 1%.

The atmospheric flow regimes over the North Pacific area are sensitive to the state of the tropical Pacific Ocean. Our results show that when the stochastic physical parameterizations in the atmosphere are switched off, the two most populated regimes (Pacific Trough and negative PNA) are also the two regimes with the strongest correlation to the ENSO forcing ($r = 0.7$ and -0.5 , respectively). The overpopulation of these two ENSO-related regimes in *stochphysOFF* indicates that the ECMWF coupled system is too sensitive to the boundary forcing in the Equatorial Pacific. Interpreting these results with our conceptual understanding of the impact of stochastic perturbations in a multiple potential well environment as discussed in the Introduction implies that the atmospheric state vector without these perturbations tends to prefer the quasi-stationary circulation regimes associated with the strongest ENSO forcing. As a consequence of this, the frequency of occurrence of the most ENSO-sensitive regimes is overestimated, while the frequency of the regimes less responsive to the forcing is underestimated.

Adding stochastic perturbations to the system, as in System 4, can trigger regime transitions of the state vector from the absolute minimum of the multiple potential well to further local minimum quasi-stationary states that were otherwise populated less frequently (Molteni and Tibaldi, 1990). This is indeed what happens in System 4. The impact of the stochastic parameterizations on the North Pacific circulation regimes is such that they tend to reduce the frequency of occurrence of those two clusters in *stochphysOFF* that have the strongest relationship to ENSO forced variability, the hugely overpopulated Pacific Trough and the slight overestimated negative PNA cluster. At the same time the stochastic parameterisations in S4 increase the frequency of occurrence of the otherwise strongly under-represented positive PNA regime.

It is interesting to note that while the excessive sensitivity of the ECMWF coupled system to the equatorial Pacific SSTs does affect the circulation regime frequencies of occurrence, it does not affect the regime structure per se. The four circulation patterns are very well reproduced in both the *stochphysOFF* and S4 simulations. This might be further evidence to the suggested paradigm that the time-mean response of a system to some imposed forcing manifests itself through a change in frequency of their naturally occurring quasi-stationary regimes (Palmer, 1993; Palmer, 1999 Corti et al. 1999).

A similar analysis over the Euro-Atlantic area was performed but no evidence for differences between S4 and *stochphysOFF* in terms of circulation regime structure or frequency of occurrence could be found. It has to be noted that the Euro-Atlantic area is a very noisy region in the model (signal-to-noise ratio of approx. 0.2) and thus it is intrinsically more difficult to detect any impact of stochastic perturbations.

7 Summary and Conclusions

The impact of two stochastic parameterisation schemes in the atmosphere of the ECMWF coupled seasonal forecast System 4 has been analysed. The schemes which are also used in ECMWF's medium-range ensemble forecasts perturb the total tendencies of all diabatic (parameterised) processes (SPPT scheme) and the backscatter of kinetic energy from small to large scales (SPBS scheme). The impact has been quantified by comparing a 30-year retrospective forecast series with lead-times of 2-4 months with and without these two schemes activated. It was found that the system without stochastic perturbations generates large areas of excessively strong tropical convection, especially over the Indonesian warm pool area and the Western tropical Pacific. The stochastic schemes, and in particular SPPT, weaken the convective activity in these areas leading to reduced biases of outgoing longwave radiation, cloud cover, precipitation and near-surface wind. It should be noted, however, that the stochastic schemes do not eliminate these biases entirely. The stochastic backscatter scheme has an overall neutral impact.

A longstanding problem in modelling tropical convection is the Madden-Julian intraseasonal Oscillation. The ECMWF seasonal forecast system generally underestimates the frequency and amplitude of daily MJO events. It has been demonstrated that the stochastic parameterisation schemes help to improve the MJO statistics consistently across start dates throughout the year. However, the magnitude of frequency improvements of approx. 10% is rather small compared to the overall underestimation of approx. 30%. The largest contribution to the improvements originates from the SPPT scheme. The perturbed physical tendencies also have a positive impact on the distribution of the

amplitudes of MJO events by increasing the number of stronger MJO events and reducing the number of weaker events.

Along with systematic improvements in the tropical climate, it was found that ENSO forecast quality, in particular over the Western tropical Pacific, has increased in System 4 due to the stochastic physics scheme. After forecast month 1 the schemes lead to a systematic and significant reduction of the ensemble mean RMSE and a substantial increase in the ensemble spread of SST forecasts in the Niño4 region as well as to increased anomaly correlations. Again, the SPPT scheme has the largest contribution to these improvements while the SPBS scheme shows little impact on seasonal timescales.

Finally, a cluster analysis of the mid-latitude quasi-stationary circulation regimes over the North Pacific and North American region was performed. The impact of the stochastic parameterisations on the regimes is such that they tend to reduce the frequency of occurrence of those two clusters in *stochphysOFF* that are strongest linked to ENSO forced variability (Pacific Trough and the negative PNA cluster). At the same time the stochastic parameterisations in S4 increase the frequency of occurrence of the otherwise strongly under-represented positive PNA regime. This shift in the frequency of occurrence of circulation regimes due to stochastic perturbations is in agreement with the notion of noise-activated regime transitions.

What are the implications of this study? The stochastic parameterisation schemes used in this model were primarily developed for application in NWP. Indeed, they have been successfully used in ECMWF's operational medium-range (10-15 days) ensemble forecasts for some years. More recently the SPPT scheme has also become part of the Ensemble of Data Assimilation (EDA) system at ECMWF to provide ensembles of initial conditions (Bonavita et al., 2012). The successful operation of these schemes on such a range of time scales from a few hours to several months can be seen as an exemplification of the seamless prediction concept where climate models should be tested in weather prediction mode where more verification data are available. It suggests that the results presented here may also be relevant on longer multi-decadal timescales and that stochastic parameterisations should now be developed for multi-decadal climate predictions using earth-system models.

A question that remains open is why the stochastic backscatter parameterisation has so little effect on the seasonal forecast simulation. Finding the reasons behind this will be a focus of future investigations. One possible explanation could be that the model error component due to the upscale energy transfer is relatively small and that the total model error is dominated by contributions from those physical sub-grid scale parameterisation schemes that are perturbed in the SPPT scheme, e.g. cloud microphysics and convection. A further uncertain effect is the impact of the temporal perturbation time scales of 6 hours, 3 days and 30 days used in SPPT but not in SPBS. Here the longest scale projects well onto the seasonal time scale of the simulations discussed in this paper. While initial results from a sensitivity study with varying perturbation amplitudes for the three time scales showed no clear indication of a systematic effect, this too is an area of planned future research.

For the future it is planned to investigate in more detail how and why the stochastic parameterisation scheme influences tropical convection. First indications of daily grid-point precipitation time series point towards a potential forced suppression of convective rainfall and thus an increase in dry days (reduction of drizzle days) when the stochastic perturbations are applied.

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