Influence of the Madden Julian Oscillation on Precipitation and Surface Air Temperature in South America

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16   **Abstract**
17
18   The regional influence of the Madden-Julian Oscillation (MJO) on South America is described.

19   Maps of probability of weekly-averaged rainfall exceeding the upper tercile were computed for all seasons

20   and related statistically with the phase of the MJO as characterized by the Wheeler-Hendon Real-Time

21   Multivariate MJO (RMM) index and with the OLR MJO Index (OMI). The accompanying surface air

22   temperature and circulation anomalies were also calculated.

23   The influence of the MJO on regional scales along with their marked seasonal variations was

24   documented. During December-February when the South American monsoon system is active, chances of

25   enhanced rainfall are observed in southeastern South America (SESA) region mainly during RMM phases 3

26   and 4, accompanied by cold anomalies in the extratropics, while enhanced rainfall in the South Atlantic

27   Convergence Zone (SACZ) region is observed in phases 8 and 1. The SESA (SACZ) signal is characterized

28   by upper-level convergence (divergence) over tropical South America and a cyclonic (anticyclonic) anomaly

29   near the southern tip of the continent. Impacts during March-May are similar, but attenuated in the

30   extratropics. Conversely, in June-November, reduced rainfall and cold anomalies are observed near the coast

31   of the SACZ region during phases 4 and 5, favored by upper-level convergence over tropical South America

32   and an anticyclonic anomaly over southern South America. In September-November, enhanced rainfall and

33   upper-level divergence are observed in the SACZ region during phases 7 and 8. These signals are generated

34   primarily through the propagation of Rossby wave energy generated in the region of anomalous heating

35   associated with the MJO.

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37   **Keywords:** Madden-Julian Oscillation, South America, precipitation, surface air temperature, impacts
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1. Introduction

During the last decade it has been increasingly recognized that climate information, if it could be provided weeks in advance, would be extremely important for decision making within many socio-economic sectors. Such information relies on the monitoring and prediction of the intraseasonal (IS) variability and in particular of the Madden-Julian Oscillation (MJO). MJO impacts have been assessed globally (e.g., Donald et al. 2006) and regionally for different parts of the world, such as for the United States (Zhou et al. 2012; Jones et al. 2011), Chile (Barret et al. 2012), the Caribbean (Martin and Schumacher 2011), Australia (Wheeler et al. 2009), Southeast China (Zhang et al. 2009), India (Pai et al. 2009), Mexico and Central America (Barlow et al. 2006) and East Africa (Pohl and Camberlin 2006), and in many other regions (see Lau and Waliser 2012).

Precipitation in South America exhibits considerable variability on IS timescales in all seasons (e.g., Liebmann et al. 1999 for austral summer and Alvarez et al. 2013 for austral winter). During summer, Nogues-Paegle and Mo (1997) detected a dipole in the IS variability of convection, a pattern that shows centers of action of opposite signs between the South American convergence zone (SACZ) and southeastern South America (SESA). The MJO influence in South America has been identified in both austral summer precipitation (e.g., Liebmann et al. 2004, Jones et al. 2004, De Souza and Ambrizzi 2006) and in the occurrence of extreme wet and dry events (e.g., Muza et al. 2009). A large modulation of precipitation by the MJO in the area of the SACZ has been found (e.g., Paegle et al. 2000; Carvalho et al. 2004). Furthermore, large IS variability has also been recorded in surface air temperature anomalies in southern South America (e.g., Cerne and Vera 2011), which seems to be at least partially influenced by MJO activity (Naumann and Vargas 2010).

Nevertheless, detailed knowledge of the MJO influence on South America climate is still quite incomplete. A more detailed description of the influence of the MJO on rainfall, temperature and circulation as well as its seasonal variations would provide a fundamental basis for MJO monitoring in the region. This work is inspired by the study of Wheeler et al. (2009), who quantified the MJO influence on precipitation in Australia. This has allowed operational monitoring of that influence by the Australian Bureau of Meteorology (http://www.bom.gov.au/climate/mjo/).

The aim of this work is to provide a quantitative analysis of the variability of both precipitation and temperature explained by the MJO in South America, and a discussion of the large-scale circulation

71 anomalies that account for that influence. The study covers the entire seasonal cycle, as both regional climate

72 and MJO activity have a strong seasonality. The paper is organized as follows: Section 2 describes the data

73 and methodology used; Section 3 describes the seasonal evolution of regional climate anomalies in South

74 America associated with MJO activity as well as the associated large-scale circulation anomalies; and

75 conclusions are presented in Section 4.

76

2. Data and Methodology

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78
79 **Data**
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81   Daily values of 250-hPa geopotential heights, 0.21-sigma level velocity potential, and surface air

82 temperature were taken from the National Center for Environmental Prediction – National Center for

83 Atmospheric Research (NCEP-NCAR) reanalysis dataset (Kalnay et al. 1996), from December 1979 to

84 November 2012. These datasets are on a 2.5ºx 2.5º grid. Daily precipitation on a 1ºx1º grid is from the dataset

85 developed by Liebmann and Allured (2005), within the period December 1979 to November 2011.

86   Wheeler and Hendon (2004) constructed the Real-time Multivariate (RMM) index to monitor MJO

87 evolution. They used the two leading empirical orthogonal functions (EOFs) of the combined fields of

88 normalized 850-hPa zonal wind, 200-hPa zonal wind and outgoing longwave radiation (OLR) data averaged

89 from 15S-15N. The RMM index is defined from the two principal component time series, with RMM1

90 associated with EOF1 and RMM2 with EOF2. The index is used to describe the temporal evolution of the

91 amplitude and phase of the MJO and is divided into 8 phases, according to the region in which convection is

92 enhanced. The same EOF pair is used for the entire year, and despite strong seasonality in the latitude of

93 convection, during all seasons in phases 8 and 1 convection is maximum in the western hemisphere and

94 Africa, phases 2 and 3 correspond to a maximum over the Indian Ocean, phases 4 and 5 peak over the

95 Maritime Continent, and phases 6 and 7 over the western Pacific (Wheeler and Hendon 2004). It has been

96 shown that statistical prediction of the RMM index has useful skill out to two weeks by using RMM1 and

97 RMM2 as predictors at an initial time (Maharaj and Wheeler 2005).

98   The analysis presented here was repeated with an OLR only based MJO index (OMI) derived by Kiladis et

99 al. (2014). This index is based on the first two EOFs of "MJO-filtered" OLR, calculated daily using a sliding

100 121 day window to take into account the seasonal migration of the MJO OLR activity. Since RMM is

101   dominated by the circulation component of the MJO (Straub 2013), there can be substantial differences

102   between the amplitude and phase of the OMI and RMM for individual MJO events, although differences are

103   less pronounced for statistical results using either index (Kiladis et al. 2014). Results for this study were quite

104   similar using either index, so we focus on the results for RMM for consistency with Wheeler et al. (2009). A

105   brief discussion and some examples of the RMM-OMI comparison can be found in the Appendix.

106

107   **Methodology**

108

109   All calculations were done separately for the 3-month seasons December-February (DJF), March-May

110   (MAM), June-August (JJA) and September-November (SON). Daily anomalies of temperature, geopotential

111   height and velocity potential were calculated at every grid point by subtracting the long-term average for that

112   day so as to remove the seasonal cycle.

113   Following Zhou et al. (2011), composites of temperature, geopotential height and velocity potential

114   anomalies were generated for each MJO phase through regression modeling. The advantage of the regression-

115   based approach is that it fits the regression model to observations from all phases (without reducing the

116   dataset length). The linear model presented by Zhou et al. (2011) was used in this study, to quantify the linear

117   response (E) of a given atmospheric variable to the MJO at a certain location. At every grid point a linear

118   regression is then computed using RMM1 and RMM2 (hereafter x_1 and x_2) as predictors, obtaining two

119   regression constants, β_1 and β_2; that is

$$E = \beta_1 x_1 + \beta_2 x_2$$

120   which can be written as,

$$E = \gamma_1 A \, \cos(\theta - \gamma_2)$$

121   where $\gamma_1 = \sqrt{\beta_1^2 + \beta_2^2}$ scales the instantaneous amplitude of the MJO ($A = \sqrt{x_1^2 + x_2^2}$) and $\gamma_2 =$

122    $\tan^{-1}(\beta_2/\beta_1)$ shifts its phase $\theta = \tan^{-1}(x_2/x_1)$.

123   It is possible to estimate for every grid point and for a given phase the expected response in order to

124   generate composites using a fixed amplitude, which was set in this study to its mean value, while varying

125   x_1 and x_2 to define the phase according to the phase-space defined by x_1 and x_2. For example, θ in MJO

126   phase 5 was set to $\pi/8$, in MJO phase 6 to $3\pi/8$ and so on, adding $\pi/4$ for the next phase in a counter-

5

127 clockwise direction. Since all phases are used to fit the regression, a sinusoidally varying model is produced,

128 so, for example, MJO phases 5 and 1 are the exact opposites, as their phases are shifted by π.

129 Two maps can be constructed to describe the composites: a map of γ_1, that shows the amplitude of the

130 response E to a complete cycle of the MJO, and a map of γ_2, that shows the phase at which E is maximum.

131 These maps are known as coamplitude and cophase maps. If the instantaneous amplitude of the MJO is

132 smaller than 1, then it is considered a neutral MJO day. Statistical significance of the composites was tested as

133 in Zhou et al. (2011), who used Monte Carlo techniques to create an approximated sampling distribution of

134 the coefficient of determination, assuming that the dependent variable is not related to the dependent variables

135 (x_1 and x_2).

136 Composites for rainfall were computed following Wheeler et al. (2009), although they explored additional

137 rainfall metrics than the present study. Wheeler et al. (2009) computed daily anomalies and the probability of

138 7-day running mean rainfall exceeding different thresholds: the upper tercile, the highest decile and 1 mm

139 day^{-1}. Wheeler et al. (2009) concluded that the probability of exceeding the weekly tercile was the most

140 appropriate metric, as they are less influenced by outliers than daily anomalies, and occur more frequently

141 than highest decile events, therefore achieving greater statistical confidence in the results. Furthermore, as the

142 upper-tercile threshold fluctuates with location and season, it is more appropriate than a constant metric.

143 Hence, the upper tercile was the metric chosen for this study.

144 The tercile exceedences were computed from 7-day running mean precipitation. For each phase the

145 number of days in which weekly rainfall was above the upper tercile (67th percentile) was counted and divided

146 by the total number of days in each phase to obtain the probability of exceeding the threshold. Therefore, the

147 probability composites for each phase show the chance that precipitation has exceeded the upper tercile at a

148 given location during that phase. The composites are scaled by the local mean probability of exceeding the

149 threshold, which is nominally 33%. Statistical significance was tested following the nonparametric re-

150 sampling approach proposed by Wheeler et al. (2009), which consists of generating 400 synthetic realizations

151 of the probability composites, obtained by successively shifting the time sequence of the observed MJO

152 phases relative to the rainfall time series, to create the null distribution with which to compare the composite.

153

154 # 3. Results

155

156   **a. Large-scale dynamics**

157

158   The influence of the MJO on circulation anomalies in the vicinity of South America can be exerted mainly

159   by two different ways: i) changes in the tropical circulation associated to the eastward passage of MJO

160   diabatic heating anomalies along the equator; and ii) changes in the extratropical circulation anomalies

161   through Rossby wave trains extending between tropical western Pacific-Indian Ocean sector and South

162   America (Berbery and Nogues-Paegle 1993; Mo and Higgins 1998; Kiladis and Mo 1998; Kidson 1999;

163   Revell et al. 2001). During austral summer, changes in the divergent tropical circulation can enhance or

164   inhibit convection associated with the South American Monsoon System (SAMS), mainly within the SACZ,

165   which in turn impacts the vertical motion in the subtropics. At the same time, regional circulation anomalies

166   mainly over southern South America can be influenced by the large-scale extratropical circulation anomalies

167   in turn induced by the convection enhanced or suppressed by the MJO over tropical western Pacific-Indian

168   tropical oceans. While these two mechanisms have been highlighted in previous works focused on summer

169   (e.g., Cavalho et al. 2004, Liebmann et al. 2004), neither their combined influence over South America nor

170   their seasonality have been explored in detail.

171   The following sub-sections focus on the circulation anomalies associated to MJO that can help to explain

172   the MJO signals of both rainfall and temperature anomalies identified in South America. Composites of large-

173   scale anomalies of geopotential height at 250 hPa and velocity potential at 0.21 sigma-level are analyzed as

174   the key features associated with the extratropical and tropical circulation changes, respectively. They are

175   presented in Figures 1-4 for each season and for MJO phases 1 to 4, which, with the opposite sign, are to be

176   interpreted as MJO phases 5 to 8. Note that the eastward MJO propagation, depicted by the upper-level

177   velocity potential anomalies along the tropics (Figs. 1-4), represents the mean evolution of the oscillation.

178   Individual MJO events may not have such coherent behavior.

179

180   **i. December-February**

181   Anomalous upper-level tropical convergence (represented by positive velocity potential anomalies)

182   progresses eastwards from western tropical Pacific during phase 1 and arrives in tropical South America by

183   phases 4 and 5 (Fig. 1), inhibiting upward motion in that region. At the same time, between phases 2 and 5, a

184 Rossby wave train develops between Australia and the Bellinghausen - Amudsen Seas and is refracted

185 equatorward, resulting in an extratropical cyclonic anomaly over subtropical South America. Its development

186 promotes anomalous upward motion over SESA and subsidence in the SACZ region.

187   On the other hand, from phases 6 to 1, anomalous upper-level tropical divergence (indicated by negative

188 velocity potential anomalies) progresses from the western tropical Pacific and reaches tropical South America

189 by phase 8, (Fig. 1) where it favors anomalous upward motion through phase 1 and consequently inhibits

190 upward motion in the corresponding subtropics due to compensatory subsidence. In addition, through phases

191 6 to 1, a Rossby wave train extends between Indian-western Pacific tropical oceans and South America,

192 which contributes to the development of an anticyclonic anomaly in the southern tip of the continent that also

193 favors subsidence in the subtropics and extratropics of South America.

194

195   **ii. March-May**

196   The tropical divergent circulation anomalies in MAM (Fig. 2) are similar to those observed in summer

197 (Fig. 1), inhibiting upward motion over tropical South America mainly between phases 4 and 5 and favoring it

198 mainly between phases 8 and 1 (Fig. 2). During this season, however, the extratropical Rossby wave train,

199 which emerges from the anomalous equatorial convection in the equatorial Indian Ocean (Fig. 2, phases 3-5

200 and 7-2), propagates poleward farther to the west than in summer. This results in less influence of the

201 rotational circulation anomalies over the continent. As a consequence, the associated cyclonic circulation

202 anomaly is over the southeastern Pacific (Fig. 2, phases 2-4), whereas during summer it was centered over the

203 tip of the continent (Fig. 1, phases 1-4). This feature therefore contributes less to inducing anomalous upward

204 motion in SESA. The opposite happens with the Rossby wave train observed between phases 6 and 1, which

205 is related to an anticyclonic circulation anomaly located over the southeastern Pacific, farther to the west than

206 in summer.

207

208   **iii. June-August**

209   During winter, significant changes are observed in the behavior of the extratropical Rossby wave train as

210 compared to that observed in summer and fall. The Rossby wavetrain emerging from the Indian Ocean

211 observed in winter is associated with a more zonally oriented circulation anomaly pattern with a lower

212 planetary wave number that extends more towards the Antarctic coast, closer to the Antarctic Peninsula (Fig.

213 3). Furthermore, a zonally oriented Rossby wave train is discernible mainly between phases 3 and 4 (and with

214 opposite sign between phases 7 and 8) in the subtropical latitudes of the South Pacific, likely favored by the

215 presence of the winter mean subtropical jet. Such combination of wave trains evolving at both subtropical and

216 subpolar latitudes of the South Pacific has also been identified in previous works of austral winter IS

217 variability (e.g., Alvarez et al. 2013). Between phases 2 and 4 (6 and 8), an anticyclonic (cyclonic) anomaly

218 in subtropical South America and cyclonic (anticyclonic) one further south are evident.

219   Regarding the divergent circulation, upper-level divergence is observed over the continent during MJO

220 phases 8 and 1, favoring ascent in the region, while the opposite is found when upper-level convergence

221 anomalies associated with MJO cross the continent mainly between phases 4 and 5 (Fig. 3). In particular, the

222 features observed between phases 2 and 3 agree broadly with that identified by Alvarez et al. (2013) in

223 association with the wet phase of the activity of the leading pattern of rainfall variability on IS timescales,

224 which is characterized by a spatial monopole extended over tropical South America.

225

226   **iv. September-November**

227   During this trimester the rainy season onset occurs on average in tropical South America and both SAMS

228 and SACZ related convection develops (e.g. Vera et al. 2006). Moreover, tropical divergent circulation

229 anomalies associated with MJO activity (Fig. 4) evolve quite similarly to those observed in DJF (Fig. 1).

230 During phases 7 to 1 (4 and 5) upper-level divergence (convergence) is evident over tropical South America,

231 promoting chances of upward (downward) motion over the SAMS-SACZ region (Fig. 4). On the other hand,

232 the mean extratropical circulation in the South Pacific during this season shares some similarities to that

233 observed in winter (Fig. 3). In particular, the Rossby wave train associated to MJO activity is very well

234 defined and coherent along the high-latitude South Pacific, except that it exhibits an equatorward bend at

235 around 110W compared to the pattern in winter (Fig. 3). Consequently, this refraction and the equatorward

236 propagation are mainly along the southwestern Atlantic Ocean, influencing the circulation anomalies in the

237 continent to a lower degree.

238

239   **v. Coamplitude and cophase**

240   The characteristics of the large-scale circulation anomalies described above are summarized in Figure 5,

241   which shows for each season the maps of coamplitude (defined in section 2) for 250-hPa geopotential height

242   anomalies associated with MJO activity. In DJF, the signal extends from Australia southeastward to

243   Bellinghausen - Amundsen seas and refracts equatorward over South America, with the largest amplitude to

244   the north of Ross Sea. In MAM, the signal is much weaker in general and the pattern seems to be refracted at

245   higher latitudes and farther west than in DJF, so the influence over South America is less evident. In JJA, the

246   signal has increased, it is very coherent, and it seems to be associated with a lower planetary wave number

247   than in the previous season. During this season, the signal is refracted near the Antarctica coast and at a

248   longitude closer to the Antarctica Peninsula. A zonally oriented Rossby wave train of moderate amplitude

249   along the subtropical latitudes of the South Pacific is also evident. In SON the Rossby wave train arching

250   between Australia and the South Atlantic has the largest amplitude among all seasons and it is also very

251   coherent. It refracts equatorward at the same longitude than in winter but at lower latitude, while the signal

252   continues to be very large and coherent well into the South Atlantic Ocean. On the other hand, no signal

253   associated with subtropical wave trains is discernible in this season.

254   Figure 6 shows the cophase (defined in section 2) of the 250-hPa negative-geopotential height anomalies

255   associated with MJO activity. Each color defines the phase at which the cyclonic anomaly of geopotential

256   height is most intense at a certain location. In the subtropics from the Indian Ocean to South America, the

257   phase increases smoothly at all seasons, indicating the eastward-propagating MJO signal in the circulation.

258   Within the extratropics, there is evidence of the signal propagating along an arch between mainly Indian

259   Ocean-Australia sector and South America-South Atlantic sector but with large seasonal variation. In DJF,

260   there is a dominant cyclonic signal at the SACZ oceanic portion location on phases 7-8-1, while further south

261   it is during phases 3-4. In MAM, the most evident signal over South America is within the tropical regions

262   during phases 7-8, while there is no signal at the southern tip of the continent. On the other hand, in JJA the

263   cyclonic signal goes from central South America during phase 7 to both equatorward and poleward in phases

264   8-1 and even in phase 2 in Patagonia. In SON, while both the subtropical and northern portion of South

265   America exhibit significant signal between phases 1 and 2, in the SACZ region this is present in phases 7 and

266   8.

267   Overall, the results of this subsection substantiate the fact that in the mean, MJO heating initiates Rossby

268   wave energy propagation into the South Pacific sector, some of which refracts equatorward over the South

269   American sector, with the amount varying by season. At the same time, the tropical portion of the MJO

270   dynamical signal also induces circulation anomalies over tropical South America that would either favor or

271   disfavor convective activity. We now examine the impacts of these circulations on the surface variability over

272   South America.

273
274   **b. Daily temperature composites**
275

276   Daily temperature anomalies were composited according to a mean-amplitude MJO, for each MJO phase,

277   and by season. During DJF (Fig. 7), warm anomalies are present over the extratropical part of the continent

278   from phase 6 to 1, when anomalous downward (upward) motion is favored over the SESA (SACZ) region

279   (Fig. 1). This is in agreement with the mechanism described by previous works (e.g., Cerne et al 2007):

280   compensatory subsidence over subtropical South America, clear skies and diabatic warming is promoted

281   during enhanced convection over the SACZ region. On the other hand, cold anomalies are more intense over

282   extratropical South America from phases 2 to 5. We note that the vertical structure of the extratropical

283   anomalies isolated in this study are nearly equivalent barotropic, with only a slight southwestward tilt with

284   height (not shown), as was found in previous studies (e.g. Liebmann et al. 2004). Thus the cold anomalies

285   over extratropical South America in these phases can be related to cold advection and the anomalous upward

286   motion promoted in turn by the cyclonic anomaly observed over this region (Fig. 1). Temperature anomalies

287   are large over northern Patagonia, central-western Argentina and central Chile. Northeastern Brazil also

288   shows cold (warm) anomalies in phases 1 to 3 (5 to 7).

289   In MAM (Fig. 8), cold (warm) anomalies are stronger mainly over northern Chile, western Bolivia,

290   eastern Paraguay and southern Brazil from phases 8 to 2 (4 to 6), when anomalous upward (downward)

291   motion is favored due to the cyclonic (anticyclonic) anomaly observed in the region. Meanwhile, warm

292   (cold) anomalies are observed within northwest South America. Throughout JJA (Fig. 9) significant cold

293   (warm) anomalies are observed in phase 8 (4) over northern Chile and extending to the south and west in

294   phases 1 to 3 (5 to 6), which can be associated with the cyclonic (anticyclonic) anomaly located in southern

295   South America (Fig. 3).

296   In SON (Fig. 10), warm anomalies extend from central Chile and central-western Argentina towards

297   northwestern Argentina and Paraguay from phases 6 to 8, explained both by warm advection from the north

298   and also partially by compensatory subsidence conditions promoted by the upper-level divergence located

299   over tropical South America (Fig. 4). The latter is similar to the mechanism described during summer. The

300   southwestern Atlantic Ocean also shows significant warm anomalies during these phases, and in phase 8 cold

301   anomalies start to develop over the continental SACZ region, which are evident until phase 2. On the other

302   hand, the subtropical regions of the continent exhibit cold anomalies from phases 2 to 4, as does the

303   southwestern Atlantic Ocean, which is the result of cold advection between the large anticyclone over the

304   Amundsen Sea in combination with the strong South Atlantic cyclone in Fig. 4. From phases 4 to 6 warm

305   anomalies are observed over the SACZ region, a signal at least in part due to the tropical subsidence induced

306   by upper level convergence.

307

308   **c. Weekly rainfall probability**
309
310   In this section we discuss changes in South American precipitation variations associated with the MJO. As

311   discussed above, these are quantified in terms of the probability of precipitation exceeding the upper tercile.

312   The probabilities are scaled such that a greater (less) than 1.0 ratio of probabilities would mean an increased

313   (reduced) chance of above-threshold precipitation during a certain phase of the MJO. As an example, a ratio

314   of 1.5 (0.5) would mean that the chance of exceeding the threshold was increased (reduced) by 50%. As the

315   nominal probability of exceeding the upper tercile is 33%, a ratio of 1.5 (0.5) during a certain phase means

316   that there is a 49.5% (16.5%) of probability of exceeding the threshold during that phase. Maps of the mean

317   seasonal rainfall, the value of the event threshold and the composite for the neutral MJO cases are also shown

318   for reference. Changes in precipitation are related with those identified in the circulation anomalies at large

319   and regional scales (Figs. 1-4). Such analysis provides some indications of the mechanisms explaining the

320   MJO impact on the precipitation. A more detailed study of the dynamic and thermodynamic processes

321   involved is beyond the scope of the present work.

322   During DJF (Fig. 11), there is an increased probability of above-threshold precipitation in eastern Brazil

323   during phase 1, which disappears in phase 2 except along the northern coast. During phases 3 and 4 there are

324   ratios in excess of 1.6 over SESA, as well as lower than 1.0 ratios in the continental portion of the SACZ, a

325 pattern of summer variability that resembles the dipole first described by Nogues-Paegle and Mo (1997). This

326 can be related to anomalous upward motion over SESA promoted by the cyclonic anomaly observed over

327 extratropical South America (Fig. 1). Furthermore, during phase 4 there is an increased chance of exceeding

328 the threshold in central eastern Argentina. Centered on phase 5, but also distinguishable in phases 4 and 6,

329 there is a dramatic decrease in probabilities over most of eastern Brazil, including the climatological SACZ

330 region, with the ratios less than 0.4 in some regions. The reduced probabilities are associated with the

331 anomalous upper-level tropical convergence that produces subsidence, consistent with positive velocity

332 potential anomalies in Fig. 1. In MJO phase 8, central and eastern Brazil shows regions of ratios in excess of

333 1.2, in association with upper-level divergence over that region (Fig. 1).

334   During neutral MJO conditions (lower-right panel of Fig. 11), the probability of exceeding the threshold in

335 the position of the climatological SACZ (in SESA) is slightly above (below) 1.0 ratio, and there is no other

336 large region with a marked influence of MJO. Furthermore, the SACZ and SESA have been previously

337 identified as having large IS variability also on timescales closer to 20 days (e.g., Gonzalez and Vera 2013),

338 associated with alternating centers of enhanced and suppressed precipitation between those two regions (e.g.,

339 Paegle et al. 2000).

340   In MAM (Fig. 12), during phase 2 and to a lesser extent in phases 1 and 3, much of eastern Brazil exhibits

341 elevated probabilities, though the large scale circulation might be able to explain this only during phase 1,

342 given that upper-level divergence is observed over tropical South America as well as a cyclonic anomaly over

343 SESA (Fig. 2). An area of eastern Brazil with ratios below 1 appears in phase 4, and continues to expand

344 through phase 6, when low ratios are prevalent over most of eastern Brazil. At the same time ratios above 1

345 are observed in SESA, although the associated circulation anomaly pattern is not clear. This area switches to

346 negative by phase 8. During other phases and neutral conditions, only scattered areas of abnormal

347 probabilities are evident.

348   JJA is the dry season throughout tropical South America and there are fewer areas of coherent ratios than

349 in the other seasons. During phases 8 and 1, however, greater chances of enhanced rainfall are observed in

350 northern South America (Fig. 13) in association with the passage across the continent of the upper-level

351 divergence anomalies associated with MJO (Fig. 3). The opposite is found when the upper-level convergence

352 anomalies associated with MJO cross the continent mainly between phases 4 and 5. The far northwest of the

353 continent seems to be particularly responsive to these circulation changes, as there is an increased probability

354 of enhanced rainfall in phases 8, 1 and 2, a probability which turns to lower than nominal during phases 4 and

355 5. MJO phase 8 also shows excess ratios in southeastern Brazil (Fig. 13). The regional circulation

356 configuration may explain this, as during phase 8 a cyclonic anomaly is observed in eastern subtropical South

357 America, which would force upward motion over the region (Fig.3).

358   SON (Fig. 14) shares characteristics with both summer and winter. During phases 4 and 5 ratios are

359 smaller than 1.0 in eastern Brazil, but they are weaker than those observed in DJF. The prominent dipole of

360 the summer, present to a lesser extent in MAM, is distinctly missing in SON. On the other hand, during phase

361 7 enhanced ratios are observed in the region of Brazil centered at 15S. Similar to JJA, a cyclonic anomaly

362 centered at around 20S enhances upward motion, which would promote enhanced rainfall over this region

363 (Fig. 4). On the contrary, the opposite flow configuration between phases 3 and 5 would reduce the chances of

364 enhanced rainfall.

365   Further south, the cyclonic anomaly that evolves from west of the Antarctic Peninsula in phase 7, to

366 subtropical South America on phase 1 (Fig. 4) appears to develop favorable conditions for enhanced

367 precipitation over SESA during that phase. Accordingly, the anticyclonic anomaly located over southern

368 South America during phases 6 and 7 seems to reduce chances of enhanced rainfall over SESA (Fig. 14).

369 During neutral MJO conditions the pattern of ratios is mostly scattered.

370

371 4. Conclusions

372   The impact of the MJO on precipitation and surface air temperature over South America was analyzed,

373 providing a reference about the timing and intensity of MJO signal over this continent that can be used for

374 monitoring and prediction activities in the region. The precipitation changes associated with MJO activity

375 were quantified following Wheeler et al. (2009), in probabilistic terms of the probability of exceeding the

376 upper tercile of the weekly-averaged rainfall distribution. In addition, the anomalies of surface air temperature

377 in South America and large-scale upper-level circulation in the Southern Hemisphere were described using

378 the linear regression model proposed by Zhou et al. (2011). The signals were obtained with respect to the

379 Wheeler and Hendon (2004) RMM index, and were found to be robust for the most part when using the OLR-

380 only derived index of Kiladis et al. (2014) as shown in the Appendix.

381   MJO influence on regional climate in South America was detected in all seasons, but with large seasonal

382   variations. In DJF, when the SAMS is active, increased chances of precipitation exceeding the upper tercile

383   are observed in the SESA (SACZ) regions mainly between phases 3 and 4 (8 and 1). Such a pattern is favored

384   by upper-level convergence (divergence) over tropical South America and a cyclonic (anticyclonic) anomaly

385   around its southern tip, both being circulation responses to MJO activity. During MAM, the impacts are

386   somewhat similar to those observed in DJF except that the extratropical Rossby wave train influences

387   extratropical South America to a lower degree. On the other hand, in JJA and SON, during the dry season in

388   the tropics, reduced chances of rainfall exceeding the upper tercile are observed in SACZ mainly between

389   phases 4 and 5, favored by upper-level convergence over tropical South America and an anticyclonic anomaly

390   located further south, both being circulation responses to MJO activity.

391   Results suggest that the SAMS activity induces a large modulation on the MJO influence on climate

392   variability in South America. It is also evident that in all seasons circulation anomalies over South America

393   that in turn induce both precipitation and surface air temperature anomalies are a combination between the

394   divergent circulation response to MJO with largest amplitude at the tropics and the rotational circulation

395   response to MJO, with largest amplitude at the extratropics. However, the controlling mechanisms of the

396   circulation response, such as timing and signal location over both South America and the South Pacific

397   Ocean, require further investigation. Therefore, an improved understanding of the tropical-extratropical

398   processes associated with the MJO signal propagation over the South Pacific from the Indian Ocean-Australia

399   sector towards South America-South Atlantic sector will be the purpose of a future study.

400

Appendix

401

402

403   The phase of the OMI was made directly comparable to RMM Index following Kiladis et al. (2014), and

404   the calculations in this work were then repeated using that index. As the RMM Index is constructed using

405   OLR and circulation, it was expected for the RMM composites to show more signal overall, particularly in the

406   geopotential height anomalies composites. As an example, Figure 15 and 16 shows the large-scale anomalies

407   of geopotential height at 250 hPa and velocity potential at 0.21 sigma-level and for MJO phases 1 to 4, which,

408   with the opposite sign, are to be interpreted as MJO phases 5 to 8, for DJF and SON respectively.

409   The OMI-based (Fig. 15) and the RMM index-based (Fig. 1) composites for the DJF season are

410   remarkably similar. The extent of the statistically significant signals and the amplitude of the anomalies are

411   generally reduced, although the locations of the centers agree well. The OMI-based composites for MAM and

412   JJA (not shown) also resulted comparable to the RMM index-based, though some centers over the southern

413   Indian Ocean presented larger amplitude when using the OMI during MAM. During JJA, significance spans

414   slightly larger regions using RMM index, and is particularly strong to the southwest of South America on

415   phases 1 and 2 (and 5 and 6, Fig. 3), which was not the case when using OMI.

416   Table 2 of Kiladis et al. (2014) shows that the OMI leads the RMM Index by 4 days in SON, being the

417   greatest lag of the four seasons. It was therefore expected that we would find the greatest differences in the

418   composites during SON. Figure 16 shows that phases 2, 3 and 4 of the OMI-based composites may be

419   associated to phases 1, 2 and 3 of the RMM Index-based composites respectively (Fig. 4), consistent with the

420   lag between the indexes. The OMI-based composites (Fig. 16) did not show a significant signal to the

421   southwest of South America, and significance and amplitude of the centers were reduced compared to RMM

422   index-based composites (Fig. 4).

423   Figures 17 and 18 show the rainfall probability composites for DJF and SON respectively, analogous to

424   Figures 11 and 14 but using the OMI as opposed to the RMM index. Again, during DJF both composites

425   results are quite alike (Figs. 11 and 17), although the OMI-based probability composites seem to have

426   significant signal over more regions of South America, with a few exceptions, as eastern Brazil in MJO phase

427   8 and during neutral MJO cases, when OMI-based composites do not show a coherent signal (Fig. 17). During

428   MAM, the OMI-based composites (not shown) are overall similar to RMM index-based ones, however, the

429   most remarkable discrepancies are that the former showed a stronger signal with ratios lower than 1 over

430   SESA (eastern Argentina) on MJO phase 1 (3) and greater than 1 ratios over SESA and west of the South

431   Brazilian Bight on MJO phase 8. During JJA, OMI-based composites are seen to have an overall larger signal

432   (not shown), though these signals are, as in RMM-based composites, less coherent than in the other seasons.

433   As previously seen with the circulation composites, during SON, OMI-based rainfall probability

434   composites (Fig. 18) lead RMM index-based ones (Fig. 14) by one MJO-phase, that is, OMI-based composite

435   on MJO phase 1 resembles the RMM index-based composite during MJO phase 8, and so on. The most

436 remarkable differences when comparing both composites were observed over eastern Argentina and SESA,

437 though the general pattern resulted similar.

438   The OMI-based temperature composites (not shown) presented overall less regions with statistically

439 significant signal. The regional pattern observed in DJF was quite similar to the RMM index-based

440 composites (Fig. 7), the latter presenting higher values over northern Patagonia. During MAM, RMM index-

441 based composites showed significance over SESA and slightly higher anomalies over the continent compared

442 to the OMI-based composites, while during JJA the extratropical significant signal using OMI was

443 considerably reduced. Finally, during SON, the lag observed in the comparison with the other variables was

444 also present in temperature composites. In particular, the signal over northwestern Argentina and in the South

445 Atlantic Ocean was noticeably reduced when the OMI was used. The fact that OMI signals are comparable to

446 those using RMM is reassuring, although it is perhaps not surprising that in some cases there is less

447 significance to the OMI results, since a significant portion of the RMM signal is likely related to circulation

448 anomalies over the South America sector (Straub 2013; Kiladis et al. 2014).

449

450 ## Acknowledgments

453

454 ## References

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456   the cold season. Clim Dyn. doi:10.1007/s00382-013-1872-z

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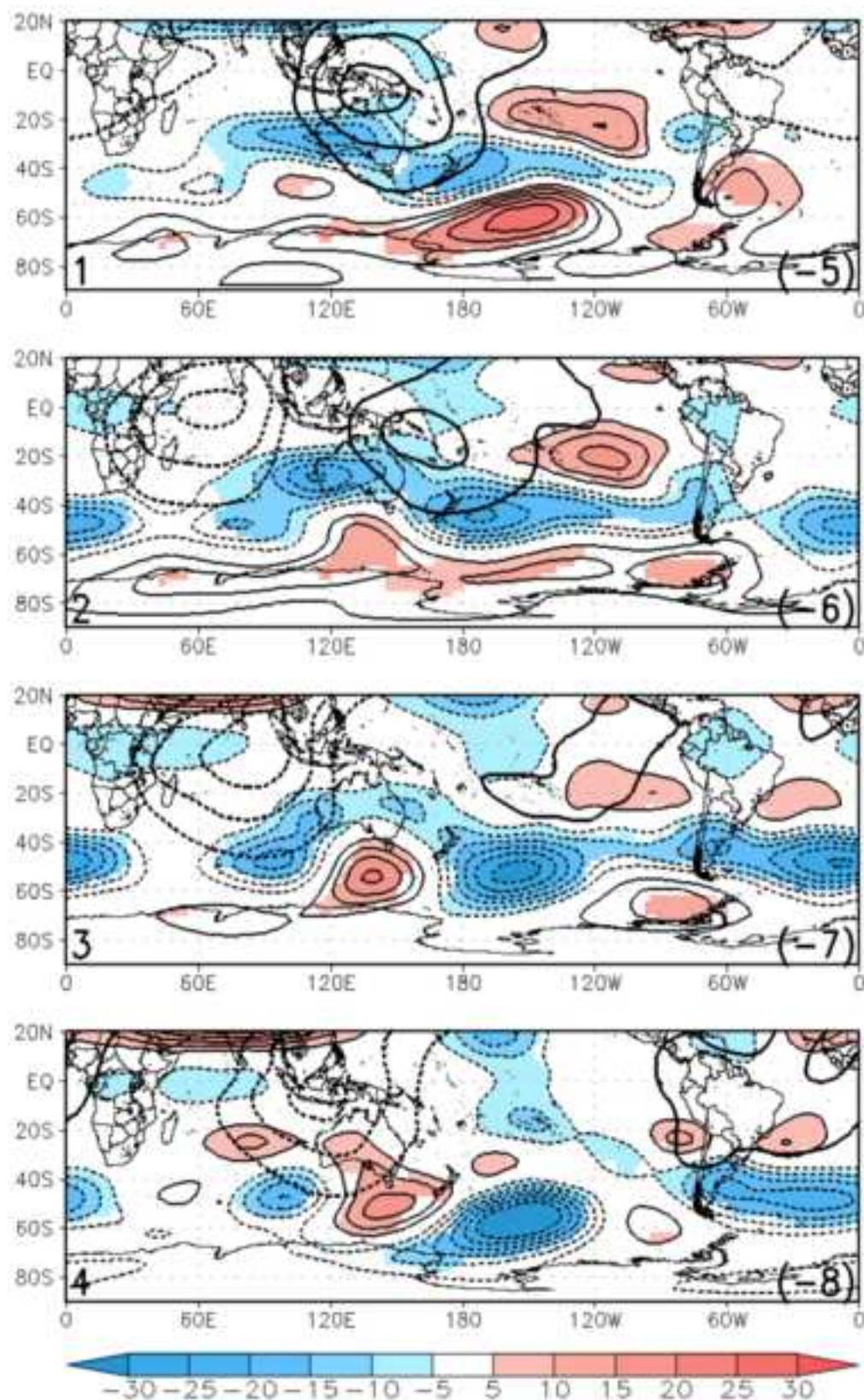
536

537 **Figure Captions**

538 **Fig. 1** Composites of DJF 250 hPa geopotential height anomalies (shaded and contours) and 0.21 sigma-
539 level velocity potential (thick contours) according to RMM index-defined MJO phases 1 to 4 (expressed
540 on the bottom left of each panel) obtained with the regression model. The composites for MJO phases 5
541 to 8 are identical but with the sign reversed (expressed on the bottom right of each panel, see
542 Methodology). Only 95% significant values are shaded for the geopotential height anomalies. Contour
543 interval is 5 gpm and 0 contour is omitted. Velocity potential contour interval is 1×10^7 m^2 s^{-1} and the first
544 contour is 2×10^7 m^2 s^{-1}; negative contours are dashed

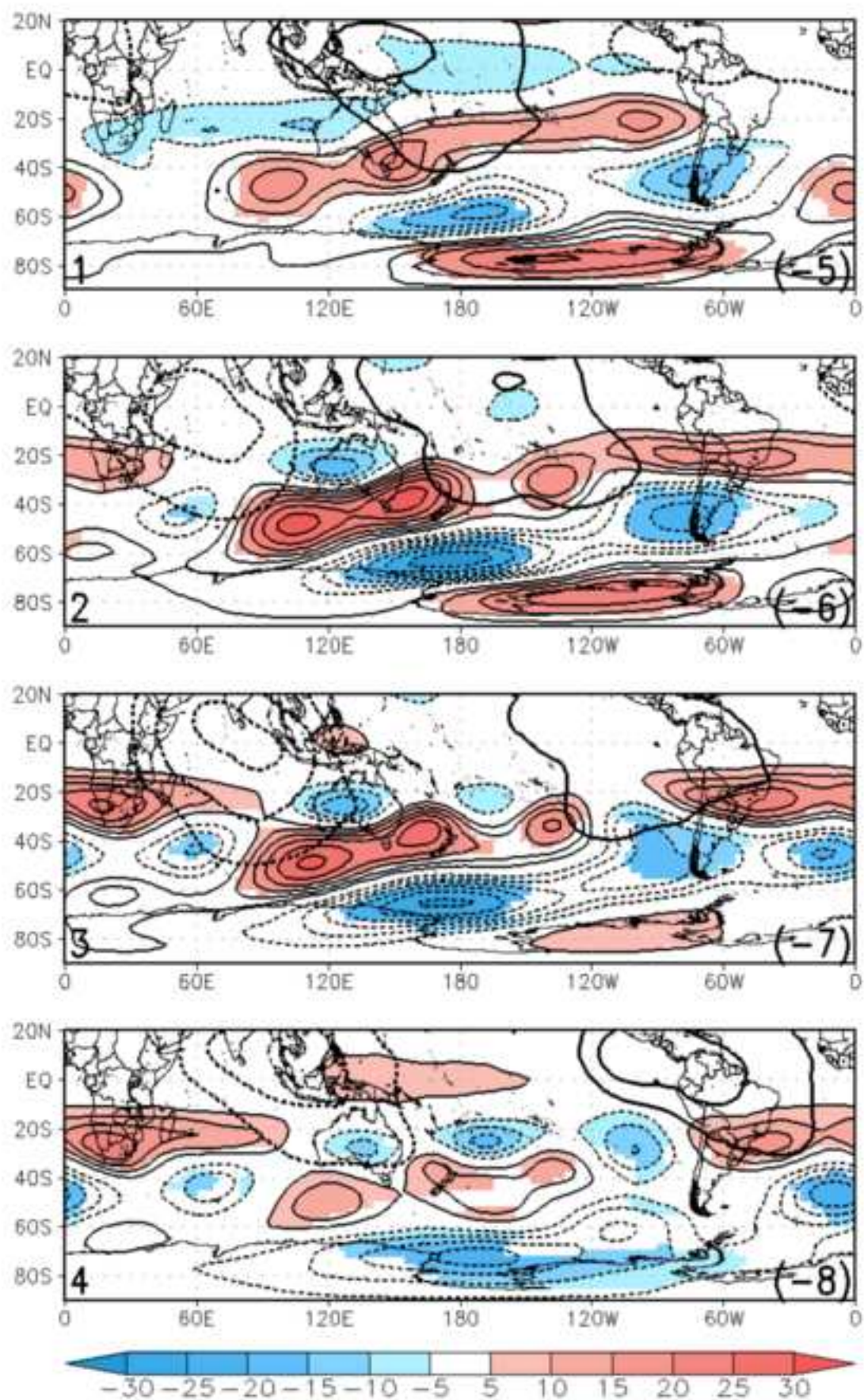545 **Fig. 2** As in Fig 1 but for MAM

546 **Fig. 3** As in Fig 1 but for JJA

547 **Fig. 4** As in Fig 1 but for SON

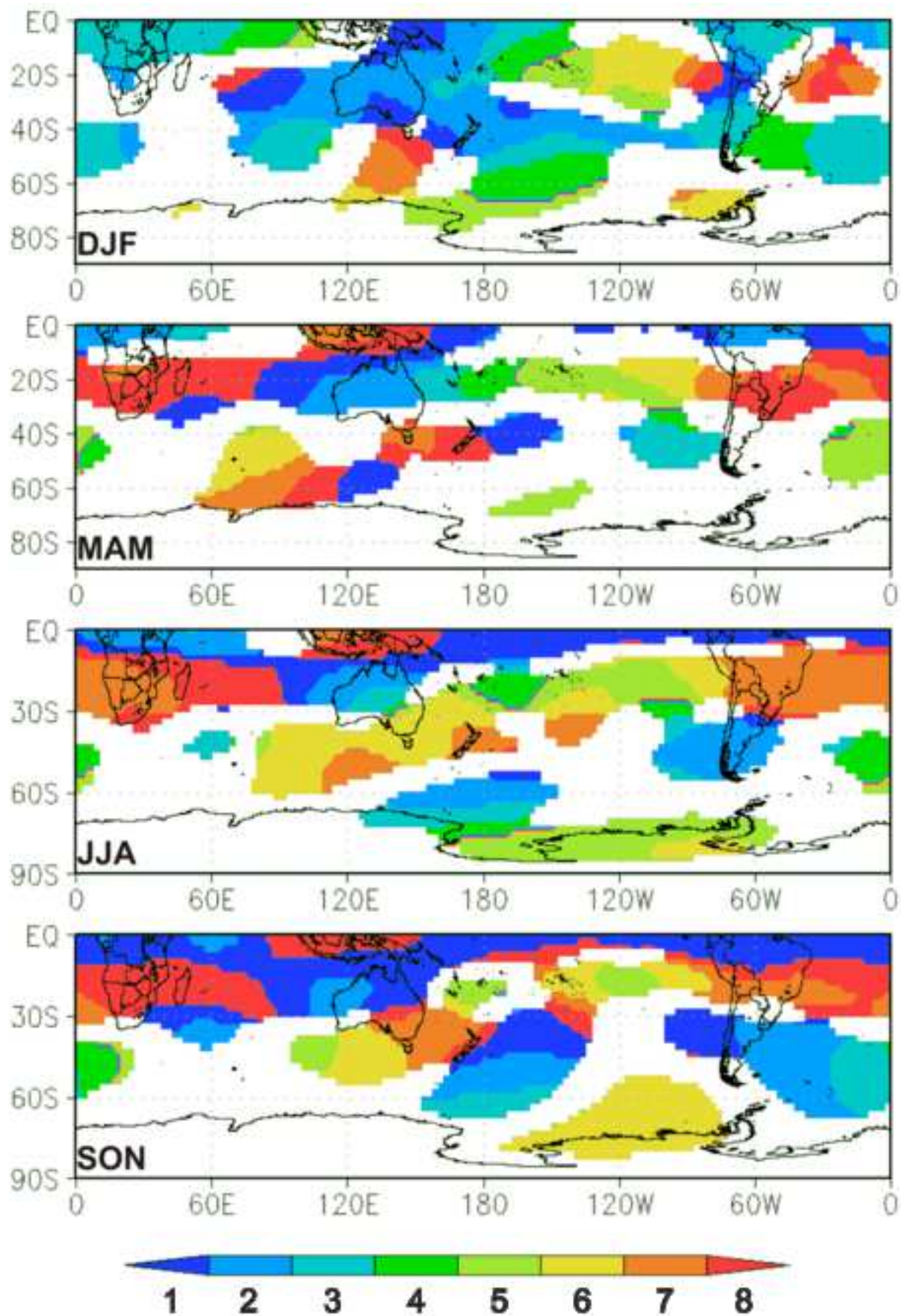548 **Fig. 5** Coamplitude maps of 250 hPa geopotential height anomaly for each season

549 **Fig. 6** Cophase maps of negative 250 hPa geopotential height anomaly for each season. Each color
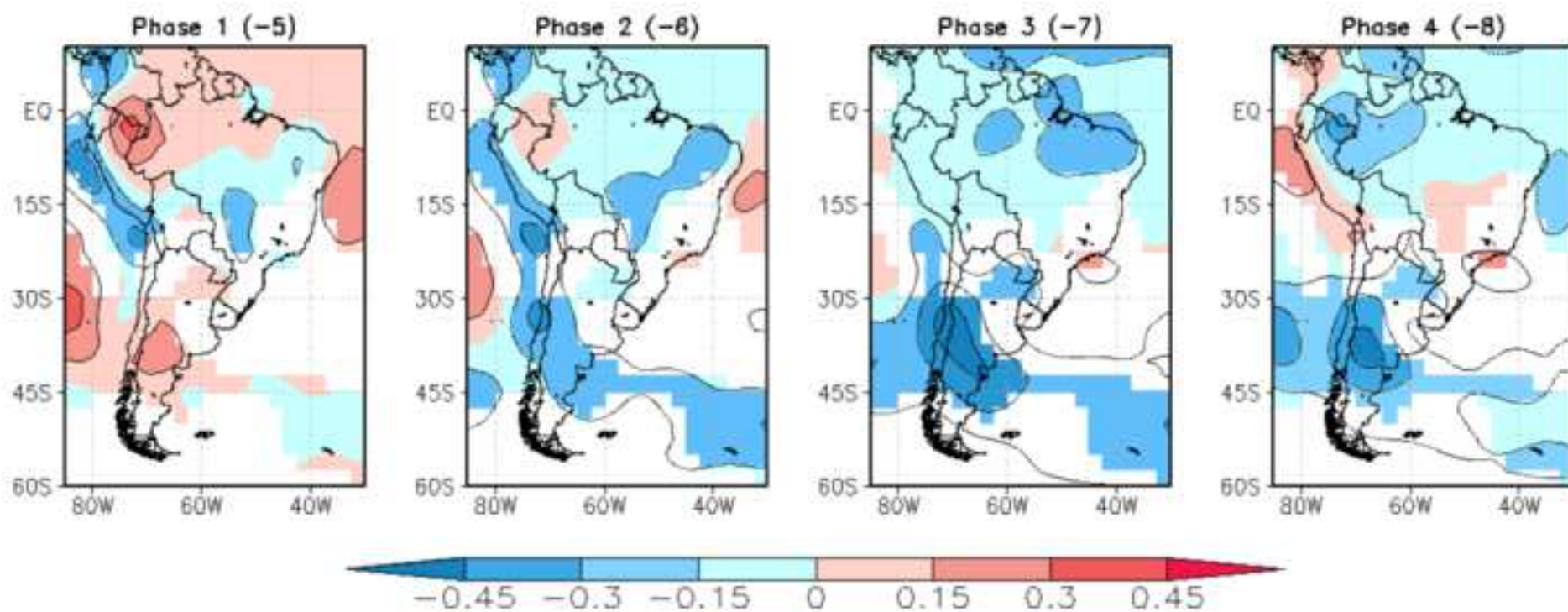550 defines one of the 8 RMM phases of the MJO

551 **Fig. 7** Composites of DJF surface air temperature anomalies according to RMM index-defined MJO
552 phase 1 to 4 obtained with the regression model. The composites for MJO phases 5 to 8 are identical but
553 with the sign reversed, and those are indicated between parentheses (see Methodology). Only 95%
554 significant values are shown. Contour interval is 0.15 degrees Celsius and 0 contour is omitted

555 **Fig. 8** As in Fig 7 but for MAM

556 **Fig. 9** As in Fig 7 but for JJA

557 **Fig. 10** As in Fig 7 but for SON

558 **Fig. 11** DJF season (top and middle rows) composites of weekly rainfall probabilities for RMM index-
559 defined MJO phases 1 to 8. The probabilities refer to the chance of weekly averaged rainfall exceeding
560 the upper tercile, expressed as a ratio with the mean probability (nominally 33%) for every grid point.
561 Only 10% significant values are shown and those gridpoints with missing values were masked out in
562 grey. (bottom right) MJO composite of weekly rainfall probabilities for neutral MJO cases. (bottom left)
563 Climatological DJF mean weekly rainfall in South America. (bottom middle) Weekly rainfall threshold

564 **Fig. 12** As in Fig 11 but for MAM

565 **Fig. 13** As in Fig 11 but for JJA

566 **Fig. 14** As in Fig 11 but for SON

567 **Fig. 15** As in Fig 1 but using the OMI to generate the composite

568 **Fig. 16** As in Fig 4 but using the OMI to generate the composite

569 **Fig. 17** DJF season composites of weekly rainfall probabilities for OMI-defined MJO phases 1 to 8 and
570 neutral MJO cases. The probabilities refer to the chance of weekly averaged rainfall exceeding the upper
571 tercile, expressed as a ratio with the mean probability (nominally 33%) for every grid point. Only 10%
572 significant values are shown and those gridpoints with missing values were masked out in grey

573 **Fig. 18** As in Fig 17 but for SON

574

575

576

Fig. 1 Composites of DJF 250 hPa geopotential height anomalies (shaded and contours) and 0.21 sigma-level velocity potential (thick contours) according to RMM index-defined MJO phases 1 to 4 (expressed on the bottom left of each panel) obtained with the regression model. The composites for MJO phases 5 to 8 are identical but with the sign reversed (expressed on the bottom right of each panel, see Methodology). Only 95% significant values are shaded for the geopotential height anomalies. Contour interval is 5 gpm and 0 contour is omitted. Velocity potential contour interval is 1×10^7 m^2 s^{-1} and the first contour is 2×10^7 m^2 s^{-1}; negative contours are dashed
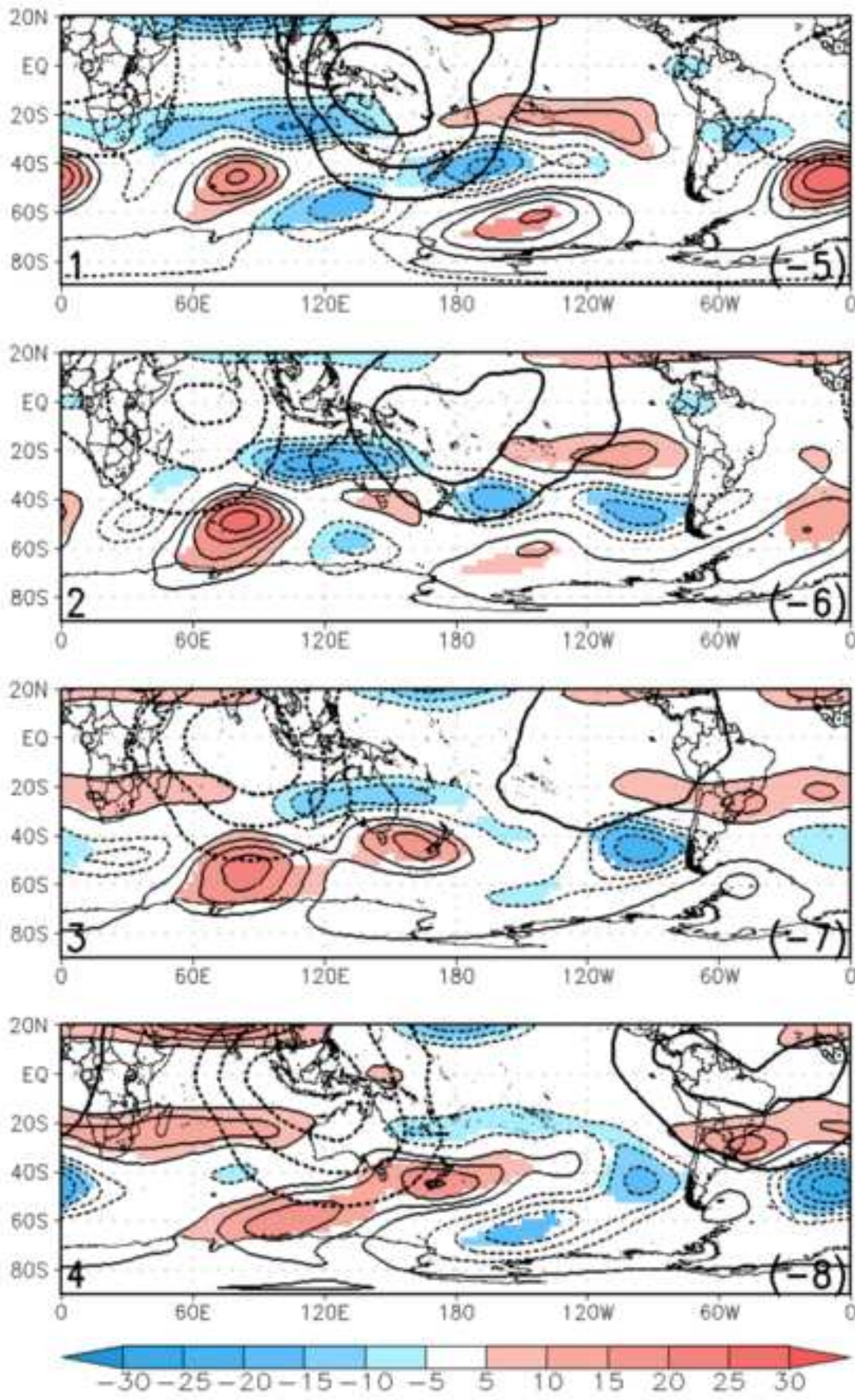
Fig. 2 As in Fig 1 but for MAM

Fig. 3 As in Fig 1 but for JJA
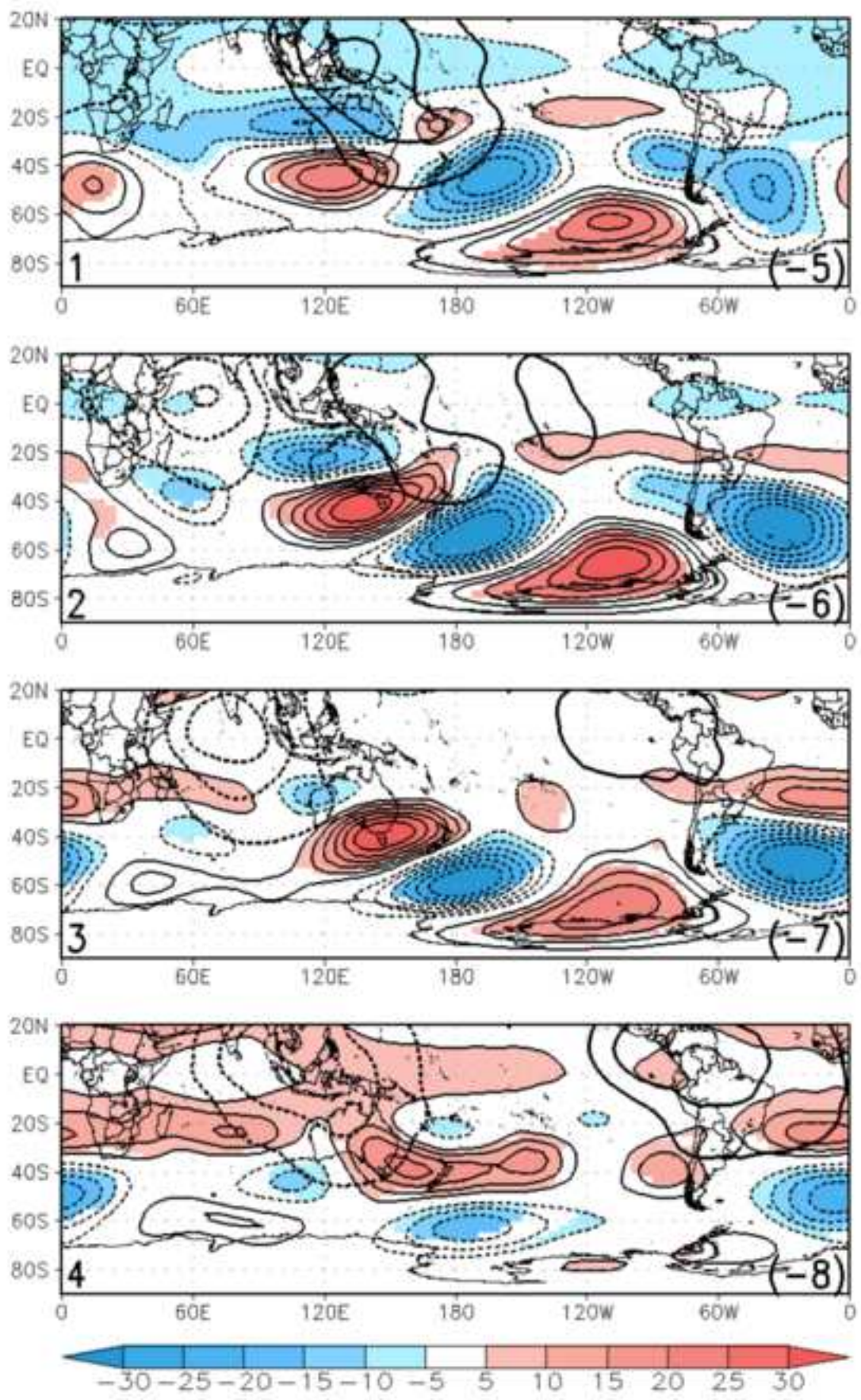
Fig. 4 As in Fig 1 but for SON
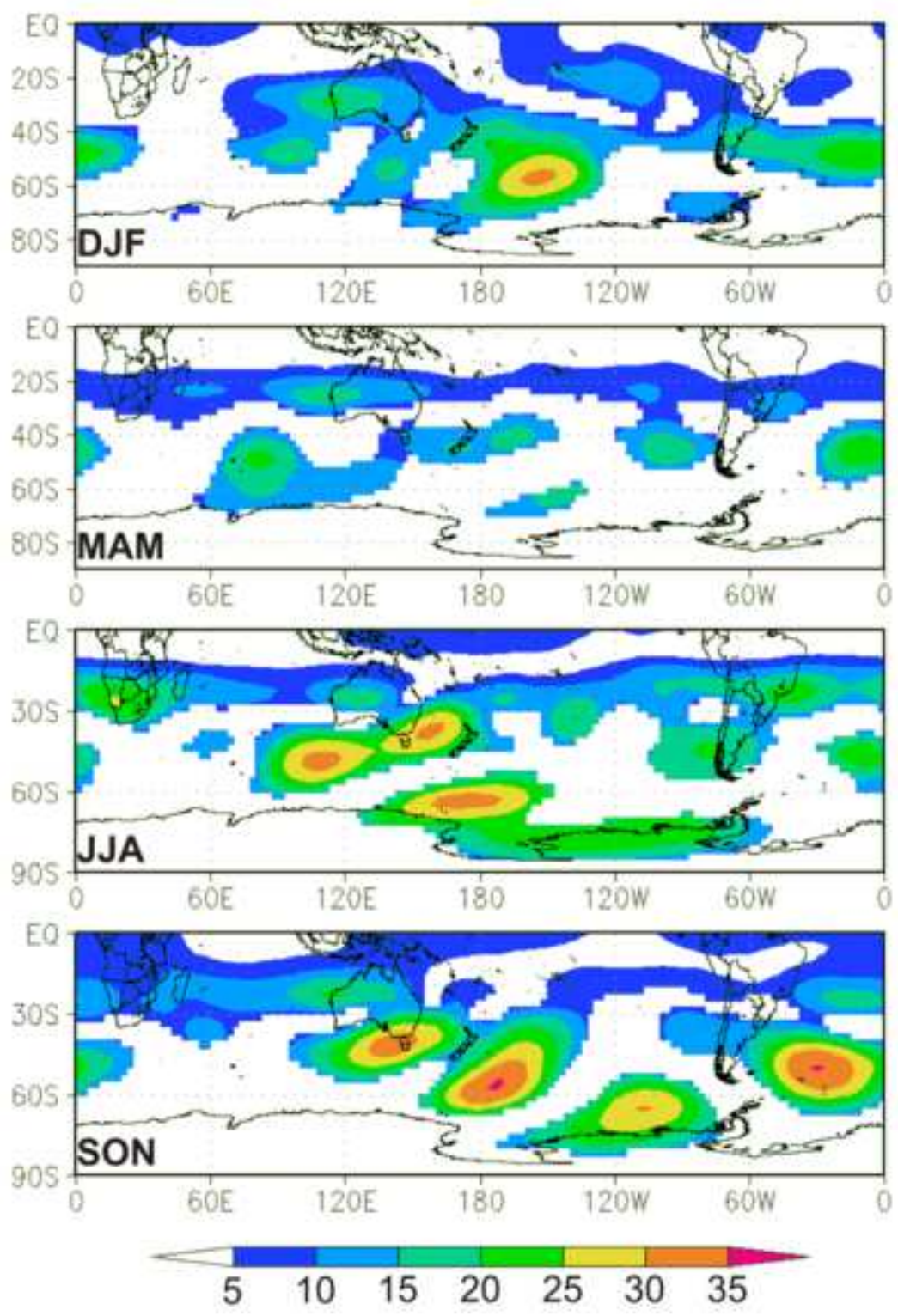
Fig. 5 Coamplitude maps of 250 hPa geopotential height anomaly for each season

Fig. 6 Cophase maps of negative 250 hPa geopotential height anomaly for each season. Each color defines one of the 8 RMM phases of the MJO

Fig. 7 Composites of DJF surface air temperature anomalies according to RMM index-defined MJO phase 1 to 4 obtained with the regression model. The composites for MJO phases 5 to 8 are identical but with the sign reversed, and those are indicated between parentheses (see Methodology). Only 95% significant values are shown. Contour interval is 0.15 degrees Celsius and 0 contour is omitted

Fig. 8 As in Fig 7 but for MAM
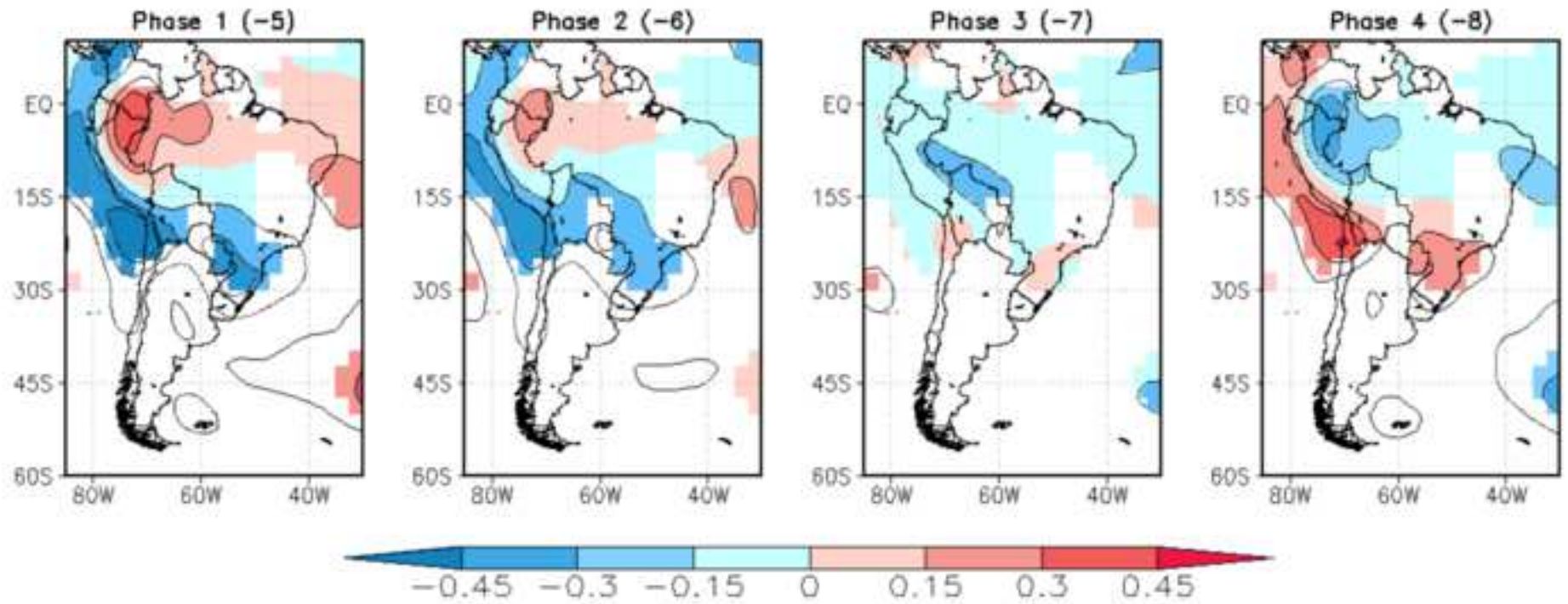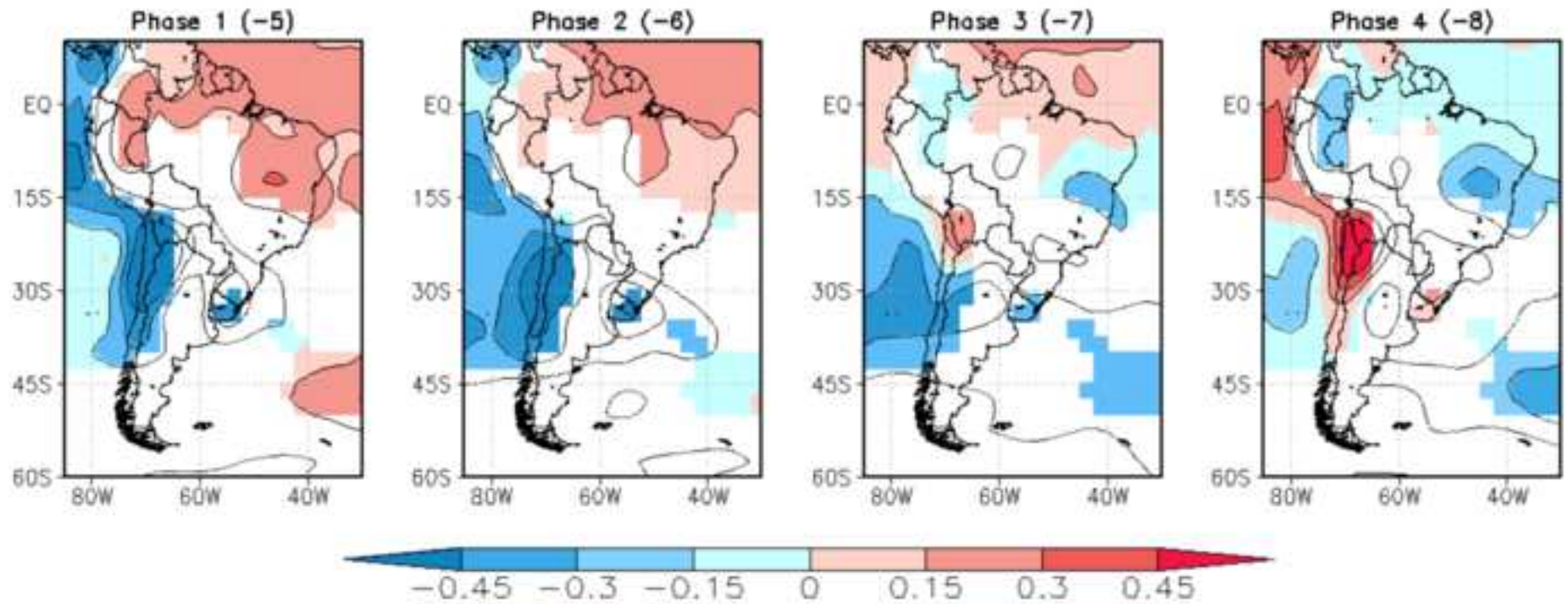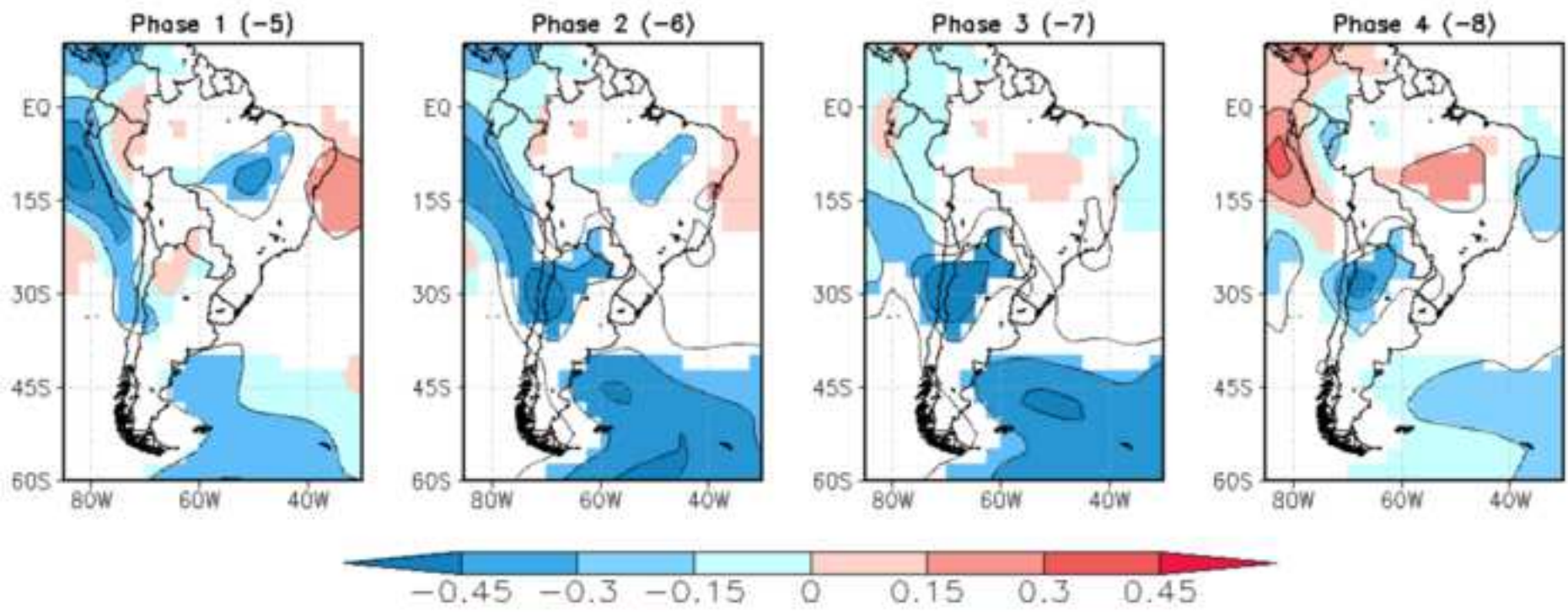
Fig. 9 As in Fig 7 but for JJA

Fig. 10 As in Fig 7 but for SON
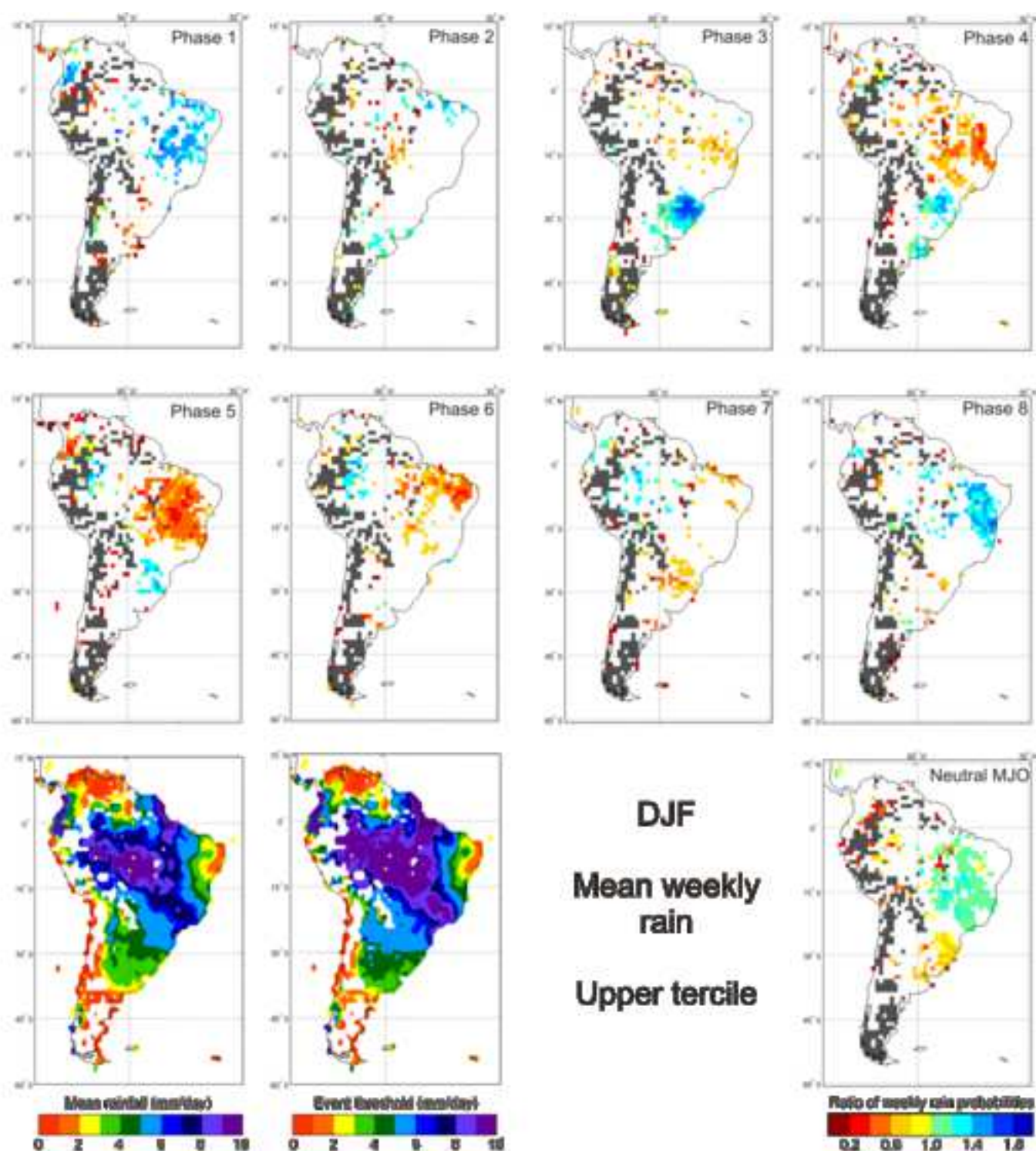
Fig. 11 DJF season (top and middle rows) composites of weekly rainfall probabilities for RMM index-defined MJO phases 1 to 8. The probabilities refer to the chance of weekly averaged rainfall exceeding the upper tercile, expressed as a ratio with the mean probability (nominally 33%) for every grid point. Only 10% significant values are shown and those gridpoints with missing values were masked out in grey. (bottom right) MJO composite of weekly rainfall probabilities for neutral MJO cases. (bottom left) Climatological DJF mean weekly rainfall in South America. (bottom middle) Weekly rainfall threshold

Fig. 12 As in Fig 11 but for MAM
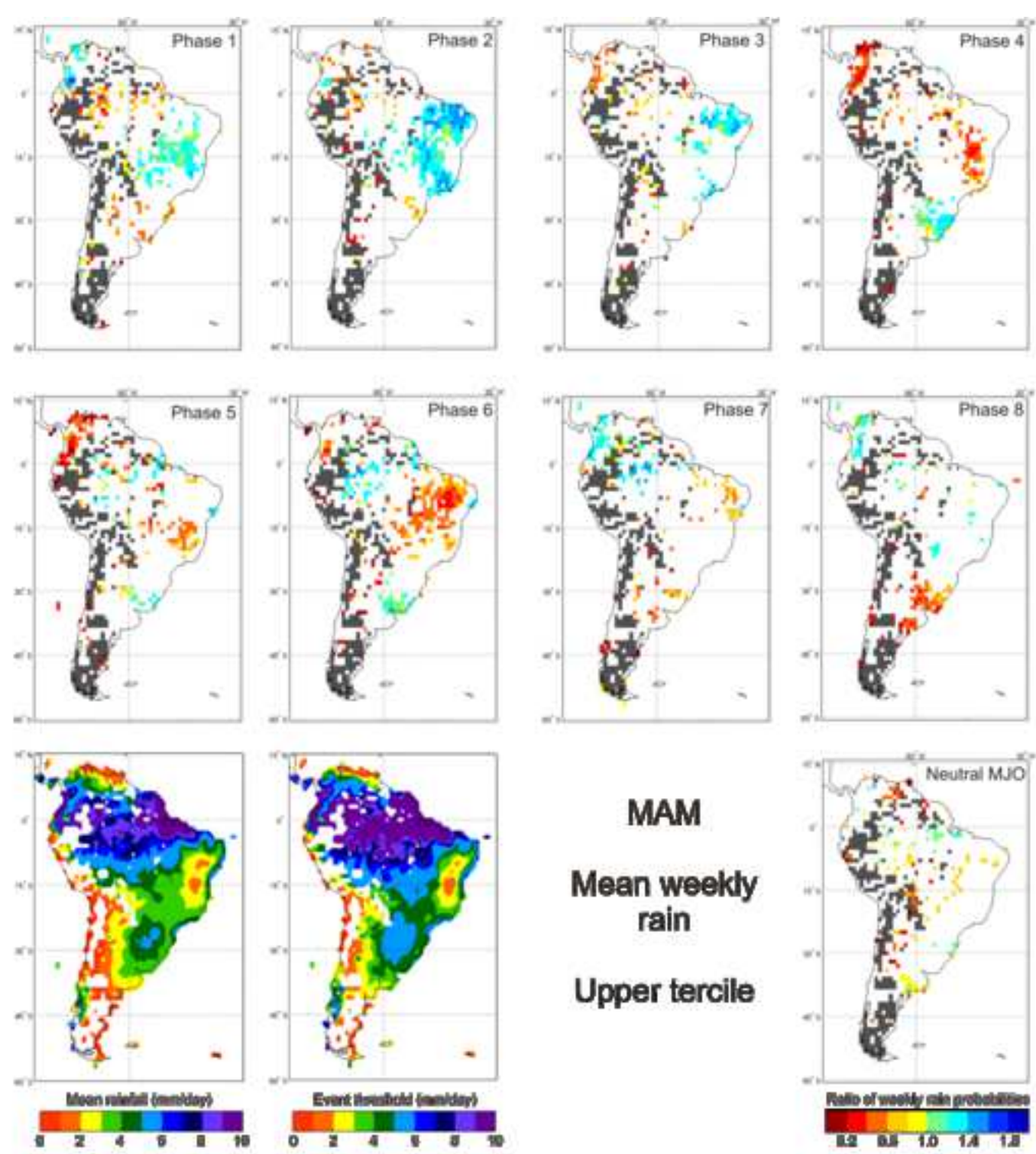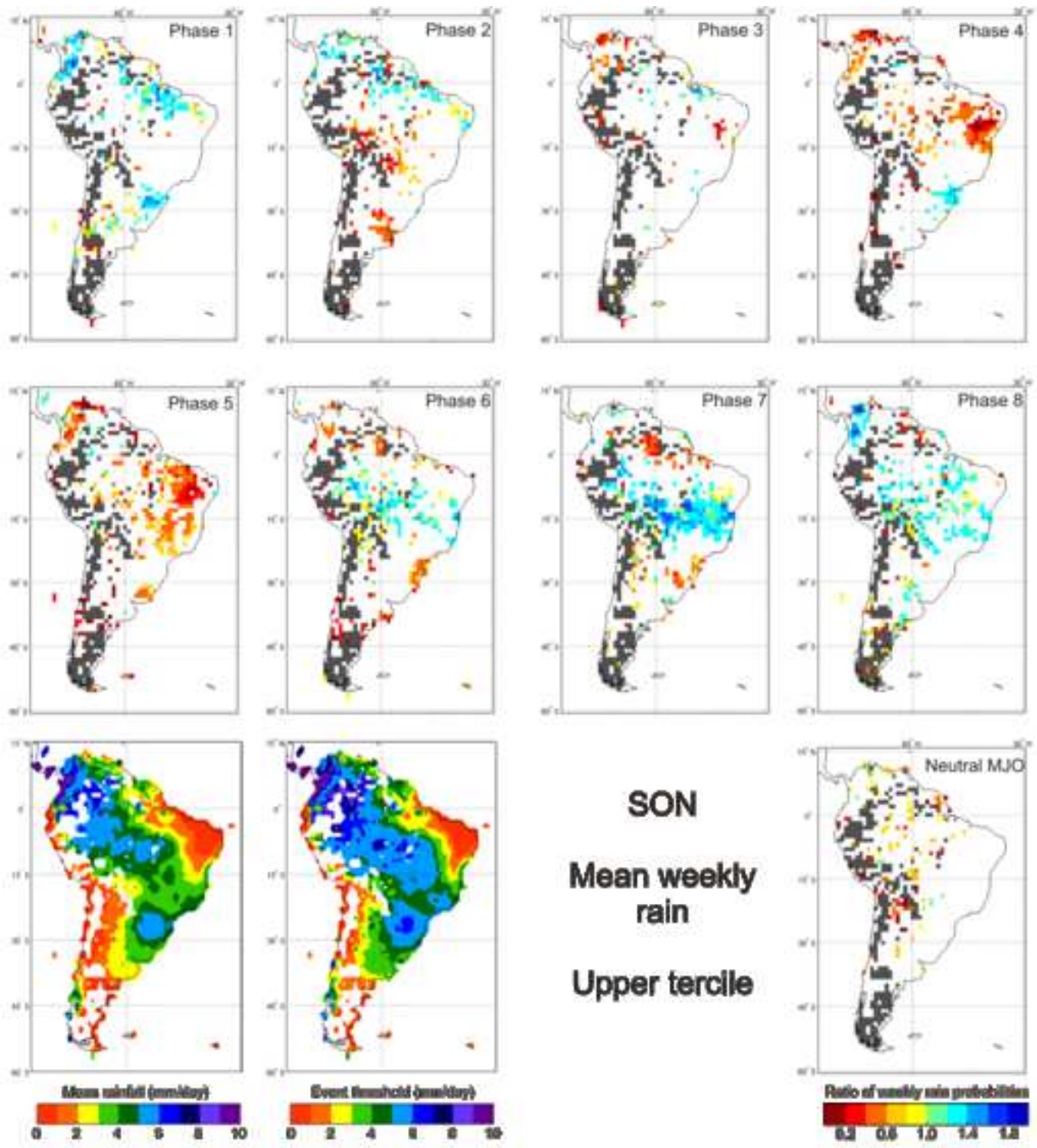
Fig. 13 As in Fig 11 but for JJA

Fig. 14 As in Fig 11 but for SON
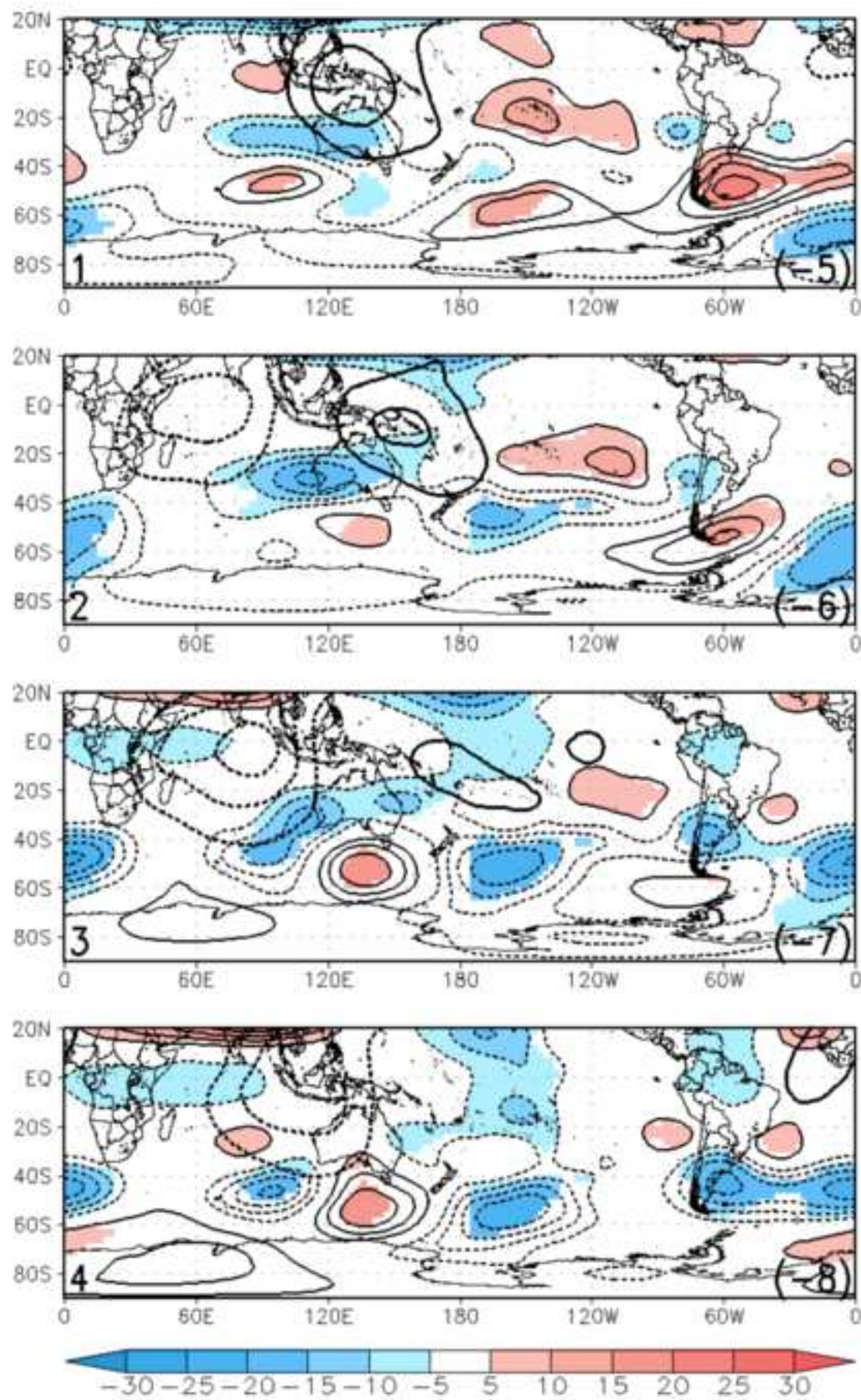
Fig. 15 As in Fig 1 but using the OMI to generate the composite

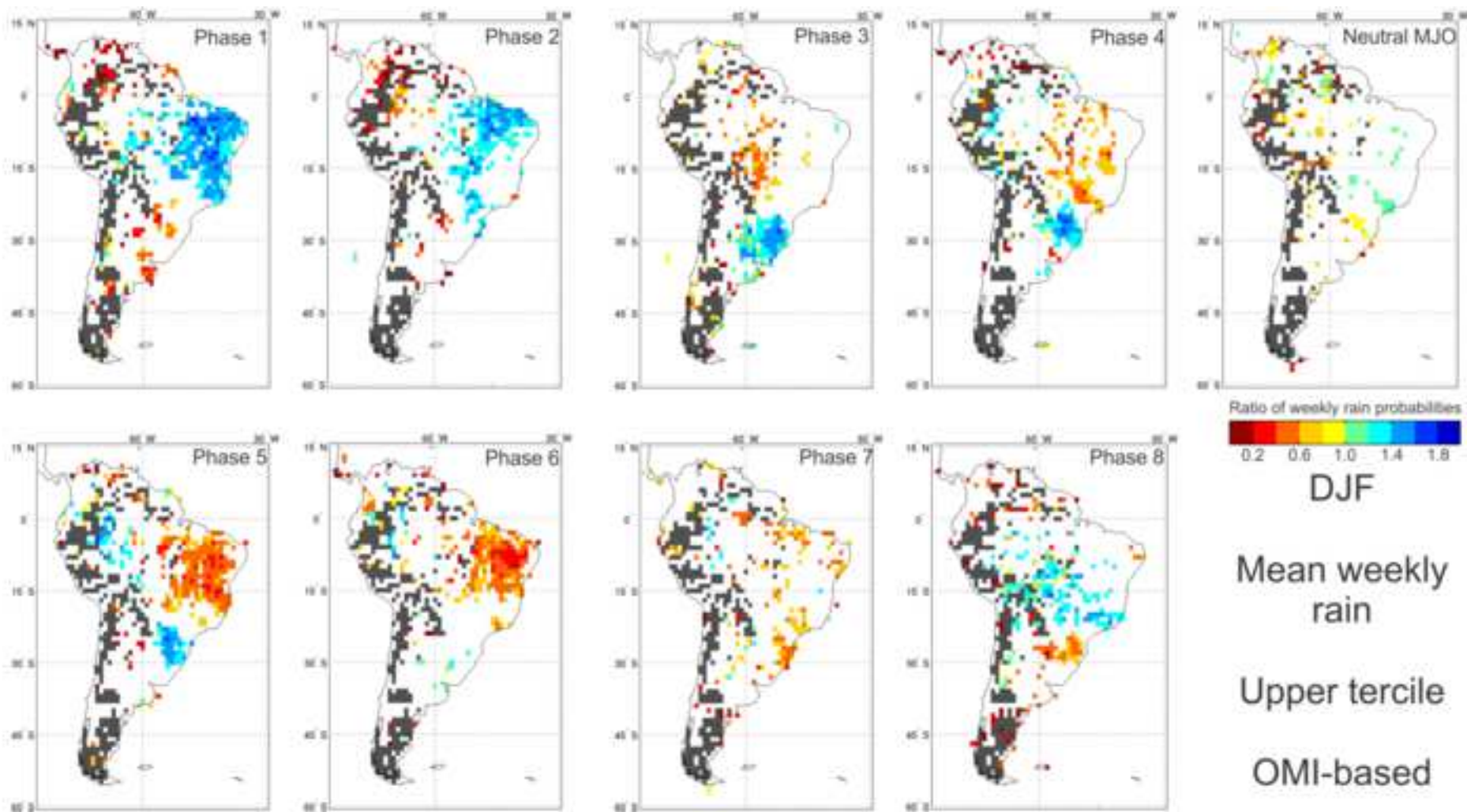Fig. 16 As in Fig 4 but using the OMI to generate the composite

Fig. 17 DJF season composites of weekly rainfall probabilities for OMI-defined MJO phases 1 to 8 and neutral MJO cases. The probabilities refer to the chance of weekly averaged rainfall exceeding the upper tercile, expressed as a ratio with the mean probability (nominally 33%) for every grid point. Only 10% significant values are shown and those gridpoints with missing values were masked out in grey
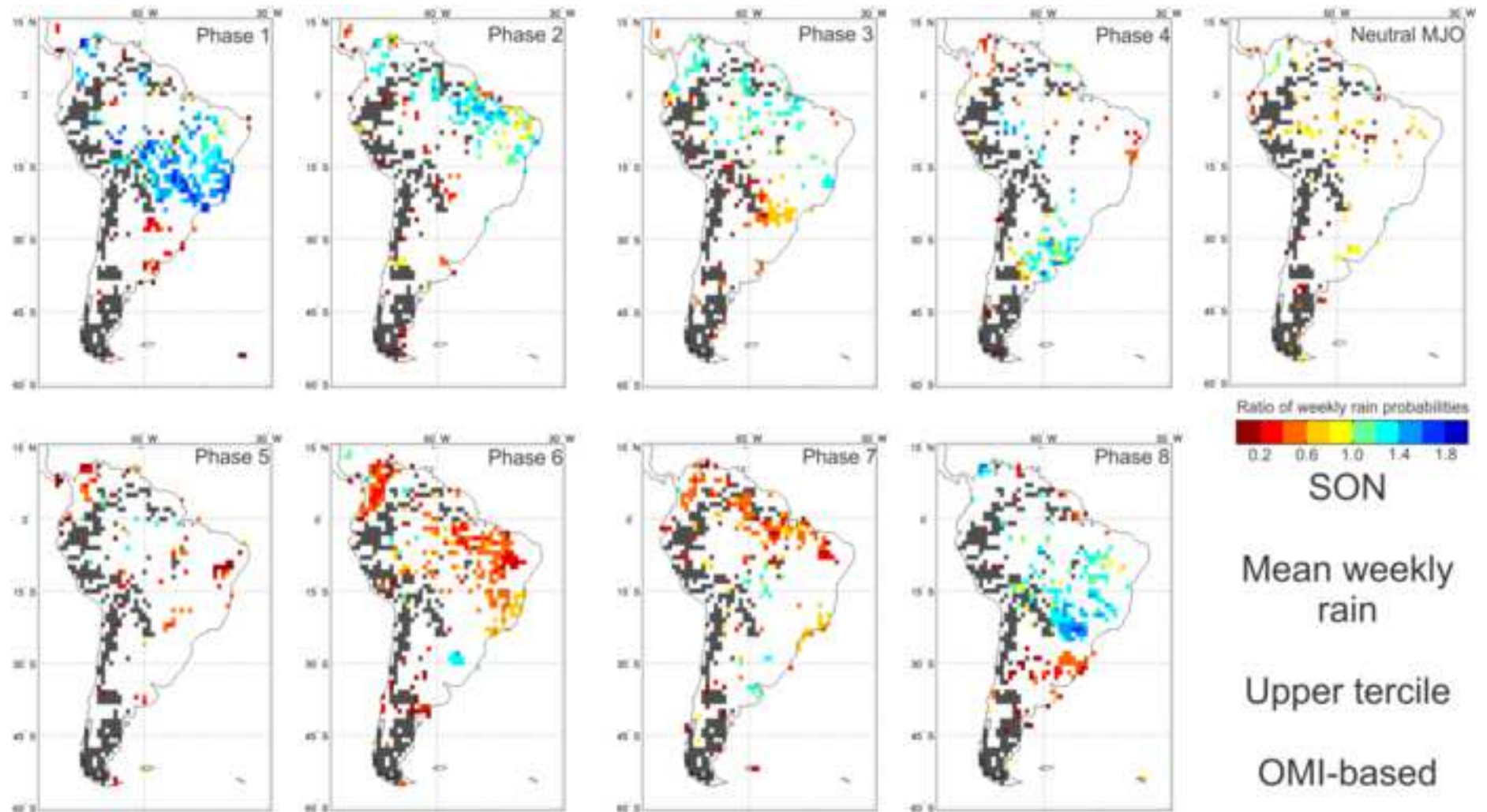
Fig. 18 As in Fig 17 but for SON