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1 **Coupled versus uncoupled hindcast simulations of the**
2 **Madden-Julian Oscillation in the Year of Tropical**
3 **Convection**

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4 This study investigates the impact of a full interactive ocean on daily ini-
5 tialised 15 day hindcasts of the Madden Julian Oscillation (MJO), measured
6 against a Met Office Unified Model (MetUM) atmosphere control simulation
7 (AGCM) during a 3 month period of the Year of Tropical Convection (YOTC).
8 Results indicate that the coupled configuration (CGCM) extends MJO pre-
9 dictability over that of the AGCM, by up to 3-5 days. Propagation is im-
10 proved in the CGCM, which we partly attribute to a more realistic phase
11 relationship between sea surface temperature (SST) and convection. In ad-
12 dition, the CGCM demonstrates skill in representing downwelling oceanic
13 Kelvin and Rossby waves which warm SSTs along their trajectory, with the
14 potential to feed back on the atmosphere. These results imply that an ocean
15 model capable of simulating internal ocean waves may be required to cap-
16 ture the full effect of air-sea coupling for the MJO.

1. Introduction

17 The MJO [*Madden and Julian, 1971*] is the leading mode of intraseasonal variability
18 in the tropics. It exerts considerable influence on tropical weather and climate variabil-
19 ity, such as the Indian and Asian monsoons [*Goswami, 2005; Hsu, 2005; Wheeler and*
20 *McBride, 2005*] and tropical cyclone activity [*Vitart, 2009*], and can modulate extrat-
21 ropical weather patterns through forcing of atmospheric Rossby waves by the divergent
22 outflow from tropical convection which propagate towards the mid latitudes [*Ferranti*
23 *et al., 1990; Cassou, 2008*].

24 It has been demonstrated the forecast skill of MJO improves in atmospheric simulations
25 if forced with high temporal frequency SST variability and such simulations also display
26 better rainfall variability [*Klingaman et al., 2008; Matthews, 2004*]. The importance of 2-
27 way interaction between atmosphere and ocean components in models [*Woolnough et al.,*
28 *2007; Fu et al., 2013*] has also been suggested. Another potentially important aspect in
29 successfully simulating the MJO in models is maintaining a correct phase relationship in
30 the atmospheric response to SST anomalies [*Kim et al., 2010; Fu et al., 2007*].

31 Evidence is increasing that suggests ocean models may be necessary to capture dynam-
32 ical ocean feedbacks important for initialising and maintaining the MJO. *Webber et al.*
33 [2010, 2012] highlight the important role of ocean dynamics particularly in the Indian
34 Ocean, where a tropical ocean internal wave response to the MJO leads to SST anoma-
35 lies with the potential to feed back on the atmosphere and trigger further MJO events.
36 Anomalous easterlies in the equatorial Indian Ocean can act to force a westward propa-
37 gating downwelling (upwelling) Rossby wave and SST increases (decreases) in phase with

38 the passage of the wave [Seiki et al., 2013; Shinoda et al., 2013]. Drushka et al. [2012]
39 demonstrate that mixed layer depth variations on MJO time scales modulate the heat
40 budget by 40% in the warm pool region. These studies imply that to accurately model
41 the MJO, ocean dynamics may need to be simulated adequately enough to resolve inter-
42 nal waves as well as SST anomalies forced by waves. Developing a better picture for how
43 MJO forcing impacts the ocean, and how this may feed back onto the MJO, is necessary
44 for improving MJO prediction and modelling.

45 This study extends previous work by carrying out daily initialised MJO simulations with
46 a global coupled MetUM configuration and by using a more complex ocean model than
47 has been previously applied to MJO and air-sea interactions investigations on medium
48 range timescales. The experimental setup, outlined in section 2 permits us to examine the
49 influence of the sub-surface ocean on MJO simulations. As MetUM uncoupled operational
50 forecast models already have a good general representation of the MJO on these timescales
51 [Gottschalck et al., 2010], we consider the model a suitable tool for analysing the impact
52 of 2-way air-sea coupling on mechanisms instrumental in the lifecycle and predictability
53 of the MJO.

2. Data and Methods

54 We compare MetUM models for a set of daily initialized 15 day hindcasts with obser-
55 vation and analysis data, for the period falling within the Year of Tropical Convection
56 (YOTC). Two strong MJO episodes denoted as YOTCE (15 October - 6 Dec 2009) and
57 YOTCF (16 Dec 2009 - 29 Jan 2010) with reference to Figure 3 of Waliser and Coauthors
58 [2012] form the central focus for our analysis.

59 The models used are a MetUM CGCM and a corresponding AGCM with prescribed
60 ocean boundary conditions using persisted SST anomalies. Anomalies in the MetUM
61 analysis are calculated relative to Hadley Centre Sea Ice and Sea Surface Temperature
62 data set (HadISST) climatology [*Rayner et al.*, 2003]. The anomaly is added to the
63 evolving climatological cycle of SST on a daily basis to obtain the AGCM SST forcing.
64 We persist SST anomalies instead of persisting initial SSTs as the seasonal cycle affects
65 the amplitude of SSTs within a few days, indicated by sensitivity tests carried out at the
66 Met Office.

67 The atmospheric model physics is based on the GlobalAtmos3.0 version [*Walters and*
68 *Coauthors*, 2011], at a resolution of 60km in the horizontal with 85 vertical levels. The
69 ocean component is based on Nucleus for European Modelling of the Ocean (NEMO) con-
70 figured with version 3.2 physics on a 0.25° horizontal grid, with 75 vertical levels and 1m
71 vertical resolution in the top 10m, coupled to the The Los Alamos sea ice model (CICE).
72 The atmosphere is initialised from MetUM analyses, the ocean component is initialised
73 from NEMOVAR (NEMO VARIational data assimilation system) analyses [*Mogensen*
74 *et al.*, 2009] and the models communicate on a 3 hourly coupling frequency. Any dif-
75 ference in hindcast skill in the CGCM compared to AGCM measures the impact of 2-way
76 air-sea interaction between the model components in dynamically predicting SSTs.

77 In order to measure MetUM performance and ability to represent processes key to the
78 MJO, a number of metrics are calculated. This study focuses on dates which contain
79 an MJO in the initial conditions; it does not include hindcasts from prior to the start
80 of the MJO events. RMM1 and RMM2 are formed following the Wheeler and Hendon

81 (*Wheeler and Hendon* [2004]; hereinafter WH) method, removing the annual mean and
82 the first 3 harmonics of the annual cycle. Anomalies of Outgoing Longwave Radiation
83 (OLR), and winds at 850hPa (u850) and 200hPa (u200) are combined and projected onto
84 WH empirical orthogonal functions to yield real time multivariate time series RMM1
85 and RMM2. Anomaly correlations are calculated against MetUM operational analysis
86 following the method of *Gottschalck et al.* [2010], as a measure of MJO predictability in
87 both model configurations. Significance of the correlation coefficients are tested using the
88 Pearson critical value table. The sample sizes for YOTCE and YOTCF are 50 and 44,
89 respectively.

90 We are interested in relationships which exist between the atmosphere and ocean and
91 the method of time lagged correlations is used to examine the forcing of the atmosphere
92 by the ocean and vice versa. The model data was regridded to a $2.5^\circ \times 2.5^\circ$ grid, to
93 match NOAA OLR observations. A band pass filter is commonly used to isolate the MJO
94 related signal between 30-80 days in longer simulations, but it is not possible to apply this
95 technique to 15 day hindcasts as the band pass length exceeds hindcast length. Instead,
96 to minimise high frequency variability prior to calculating lagged relationships, a 5 day
97 running mean is applied to the data. Either side of each 15 day hindcast is padded with
98 MetUM analyses data, a viable technique at the beginning of the hindcast when model
99 fields are close to initial conditions, but we acknowledge that the end of the hindcast
100 will likely erroneously improve due to influence of the analysis. Therefore, we disregard
101 hindcast data past day 13 that has been treated in this manner. This smoothing has only
102 been applied to data used in figure 2.

103 The lagged phase relationship between SST and convection is calculated, using OLR as
104 a proxy for convection. A single 15 day initialised hindcast does not provide a sufficiently
105 long timeseries to adequately assess lagged relationships. To circumvent this issue, we
106 collect all of the day 5 lead times from each 15 day hindcast over the YOTCE and
107 (separately) YOTCF period. We extract the Indian Ocean region from the full global
108 dataset and average over latitudes between 10°N and 10°S, for each point of longitude
109 between 60°E-100°E between the SST and OLR datasets. We subsequently perform lagged
110 correlations between the datasets for lags of up to 15 days. At each longitude, the latitude-
111 averaged OLR is lag correlated with the latitude-averaged SST, for leads and lags up to 15
112 days. NOAA OLR [*Liebmann and Smith, 1996*] observations and operational sea surface
113 temperature and sea ice analyses (OSTIA) [*Donlon et al., 2012*] are used to verify the
114 data. Previous work [*Klingaman et al., 2011*] suggests that correlations between these
115 fields peak at a 10 day lag (see supplementary plot). In order to examine propagation
116 of each YOTC event, we additionally calculate lagged correlations of OLR at a base
117 point(70°E) with latitude-averaged OLR at all points of longitude in the Indian Ocean.

118 *Chelton et al.* [2003] demonstrated that Rossby waves generally have a sea surface
119 height (SSH) maxima centred 4 degrees of latitude away from the equator, with positive
120 (negative) SSH anomalies associated with a downwelling (upwelling) Rossby wave. To
121 assess the modelled representation of tropical ocean waves associated with the MJO, we
122 examine anomalies of both SSH and depth of the 20C isotherm (Dep20) and verify against
123 daily Forecast Ocean Assimilation Model (FOAM) analyses [*Storkey et al., 2010*] for these
124 quantities. We validated the daily SSH FOAM analysis against Archiving Validation and

125 Interpretation of Satellite Oceanographic Data (AVISO) observations and these largely
126 agree (not shown). To search for propagating Rossby waves, we form a latitudinal average
127 between 2°N - 8°N and 2°S - 8°S in the Indian Ocean and plot time longitude diagrams for
128 the period spanning Sept 2009 to Jan 2010 for analyses and CGCM hindcasts at day 1
129 and day 14. To study equatorial Kelvin wave propagation, a latitudinal average is formed
130 over the equatorial wave guide between 2°N - 2°S in the Indian Ocean.

3. Results

131 During YOTCE, the CGCM demonstrates enhanced performance for RMM1 over that
132 of the AGCM from day 4 for combined fields, extending predictability by 3 days based
133 on a threshold of 0.6 (Fig. 1, left). The configurations display similar skill out to day 11
134 for RMM2, after which the CGCM is slightly more skilful. The persistence hindcast is
135 shown to rapidly diverge from the dynamical hindcasts at day 1, indicating a rapid loss
136 of predictability. Over YOTCF, the AGCM has greater RMM1 predictability from day 5
137 out to day 10, after which the score rapidly deteriorates. CGCM anomalies remain above
138 a correlation of 0.6 in these later lead times (Fig. 1, right) and extends predictability by
139 5 days in the case of RMM1 for combined fields based on a threshold of 0.6. However,
140 both configurations are similar in the case of RMM2.

141 CGCM correlation scores for OLR are demonstrably better than the AGCM for both
142 RMM1 and RMM2. Over the YOTCE period, the CGCM shows greater performance from
143 day 8 (RMM1) and from day 4 (RMM2) and similarly for the YOTCF event, from day
144 6 (RMM1) and day 8 (RMM2). Performance is comparable for upper level winds as the
145 two configurations remain close throughout lead times. Nonetheless, the CGCM displays

146 a slight improvement over YOTCE, particularly for RMM2 and for RMM1 between days
147 12-15. In the case of U850, the CGCM shows generally greater predictability in the latter
148 5 days for YOTCF but similar performance over YOTCE. In general, the CGCM has
149 greater predictability particularly for OLR and U850 and is capable of maintaining higher
150 correlation scores over the entire hindcast length. The results for both simulations are
151 found to be mostly significantly different from zero (denoted as triangles in Fig.1) but the
152 differences between the two simulations are not found to be significant. We acknowledge
153 that the study is somewhat limited by focusing on deterministic hindcasts of two MJO
154 events and would expect some variation in evolution and characteristics between MJO
155 events.

156 We next examine possible mechanisms leading to the improved predictability seen in
157 the CGCM hindcasts. Propagation of the convective centre of action of the MJO through
158 the Indian Ocean over YOTCE is illustrated in Fig. 2 (a-c). The eastward propagation
159 of the MJO is apparent in the observations throughout the period (Fig 2.a). As the main
160 centre of convection follows a trajectory across the Indian Ocean and clear skies (positive
161 OLR) turn cloudy (negative OLR), the correlations switch sign from negative to positive.
162 The AGCM simulated MJO is stationary by day 5 (Fig 2.c). Lead-lag correlations as
163 shown in Fig.2b for day 5, but constructed using respectively later days in the hindcast,
164 indicate that the CGCM is still able to propagate the MJO out to day 9 hindcasts, though
165 slower than observed (not shown). This result indicates that dynamically evolving SSTs
166 play a role in improving propagation of the MJO and is corroborated by other studies [*Fu*
167 *et al.*, 2007; *Waliser et al.*, 1999].

168 The lack of propagation of the MJO in the AGCM after a few days could be related to a
169 loss of coherent evolution between atmospheric convection and underlying SST anomalies
170 related to the MJO [*Waliser et al.*, 1999; *Klingaman et al.*, 2011]. In figure 2(d-f), the
171 SST-convection relationship is investigated through calculation of the lagged correlation
172 between OLR and SST anomalies. Figure 2 (e & f) depict the lagged correlation coeffi-
173 cients in the Indian Ocean for all day 5 hindcasts for the CGCM and AGCM for YOTCE.
174 Similar results are obtained for YOTCF and in the Western Pacific (not shown). Observed
175 warm SSTs are shown to lead enhanced convection by 5-10 days and conversely, active
176 convection leads cool SSTs by 5-10 days (Fig 2.d). The CGCM reproduces the observed
177 phase relationship, though it is slightly weaker and maintains the relationship out to day
178 13 lead time (not shown). However, in the AGCM experiment, convection adjusts to a
179 location where SST anomalies peak, which results in co-located OLR and SST anomalies
180 by day 5. In reality, warm SST anomalies not only influence the convection but are con-
181 currently influenced by the atmospheric state. The AGCM is unable to reproduce this key
182 air-sea interaction and the MJO simulation suffers. A phase relationship analysis of op-
183 erational global MetUM and climate model configurations is presented in supplementary
184 material which corroborates results presented here.

185 *Fu et al.* [2013] found that an AGCM forced by daily observed SSTs can sustain the SST-
186 convection relationship and that the match between the atmospheric MJO conditions and
187 underlying SST is the important factor. However, this is not practical from an operational
188 forecasting standpoint when the future evolution of the SST is unknown. Thus the only

189 way that this mechanism can be represented to the advantage of operational forecasting,
190 is through an interactive ocean.

191 It is clear from Figure 2 that that SST modulates and is modulated by the MJO. We
192 next consider the CGCM representation of tropical ocean waves, which play a role in
193 modulating the SST in the tropical warm pool [*Mccreary*, 1983; *Shinoda*, 2005]. Down-
194 welling waves deepen the thermocline and raise the SST by reducing entrainment of cold
195 sub-surface waters, while upwelling waves lead to enhanced entrainments and cooling.
196 *Suryachandra et al.* [2012] demonstrate through a budget analysis that advection plays
197 a key role in warming SSTs in the region, suggesting that it is important that tropical
198 waves are well simulated in a GCM.

199 Enhanced convection and strong surface winds likely associated with the MJO YOTCE
200 activity in mid October excites an oceanic Kelvin wave which propagates eastward along
201 the equator (Fig. 3a) reaching the Maritime Continent in late November, visible as a
202 positive anomaly moving eastward in the FOAM analysis Dep20 field. The perturbation
203 in the ocean height (equatorial SSH, not shown) and at the thermocline (Dep20) is well
204 reproduced in CGCM day 1 and day 14 hindcasts, with a propagation speed and amplitude
205 similar to the FOAM analysis (Fig 3.b,c). The modelled OLR is similar to observed
206 OLR anomalies at day 1 (Fig 3.b, contours) in magnitude and propagation but appears
207 stationary by day 14 (Fig 3.c).

208 Several westward propagating, downwelling Rossby waves are noticeable over the period
209 between Oct 2009 and Jan 2010 (R1-R3). R1 propagates west from 65°E between Sept
210 and early November (Fig 3.d), R2 moves from 90°E to 60°E between Sept and January.

211 The third observed wave (R3) is triggered in late November coinciding with YOTCE MJO
212 propagation into the Maritime Continent and moves west from early December towards
213 80°E by mid January. A potential mechanism for the trigger of R3 could be through
214 reflection and splitting of the earlier Kelvin wave back into the Indian Ocean along the
215 Rossby wave guide at 4°N/S [*Chelton et al.*, 2003].

216 Though SST is sensitive to many processes and the daily SST anomaly field will contain
217 high frequency variability caused by surface fluxes and the diurnal cycle; there are clearly
218 some westward propagating SST anomalies which follow the trajectory of the westward
219 propagating Rossby waves (Fig 3.g). The R1 wave seen in the SSH propagates westward
220 at the same speed and direction as a warm SST anomaly seen in the OSTIA dataset (Fig
221 3.g). It is possible that this wave could have had warmed SSTs prior to YOTCE, creating
222 conditions more amenable to large-scale convection. Competing processes clearly play a
223 role and the prominent SST cooling caused by the passage of the YOTCE and YOTCF
224 events is visible in the anomalously cool conditions in mid November and again in late
225 December. Warming induced by the passage of R2 is likely overshadowed by entrainment
226 of deeper, cooler waters brought about by strong winds and large scale convection asso-
227 ciated with the MJO event moving through the Indian Ocean. However, it does appear
228 that there is westward propagation of positive SST anomalies superimposed on top of this
229 pattern (Fig 3.g). This is particularly obvious as a break in the eastward propagation of
230 cool SST anomalies between 15-25 November, where the anomalies briefly turn slightly
231 positive for about 10 days. Again in the case of R3, there is an indication of westward
232 motion of warm SSTs. The CGCM captures all 3 Rossby waves and the SST anomaly

233 fields largely resemble the OSTIA analysis. The influence of data assimilation is likely to
234 be large on the initial days of the hindcast (Fig. 3h), however SSH and SST anomalies for
235 day 14 hindcasts still retain resemblance to the analyses (Fig. 3.f,i). Warm SSTs advected
236 by the tropical waves could potentially act as a positive feedback onto further convective
237 events. *Webber et al.* [2012] showed that MJO events can coincide with the arrival of a
238 downwelling oceanic equatorial Rossby wave in the western Indian Ocean, implying that
239 such waves could act as a trigger.

4. Conclusions

240 Our findings indicate that an interactive ocean produces improved MJO hindcasts over
241 those of an AGCM forced with persisted SST anomalies. It is clear that there is potential
242 for SST anomalies to be a key component of the MJO. Skill measures are improved in
243 the CGCM likely because of the dynamical prediction of SSTs. We have not considered
244 the complex impact of drift in the mean state of the CGCM on MJO hindcasts here, as
245 SSTs in the Indian Ocean display minimal drift by day 14 over YOTCE/F (not shown).
246 *Klingaman and Woolnough* [2014] address the separation of climate mean state influence
247 on MJO simulation from improvements due to coupled processes in the Met Office Hadley
248 Centre model and we will address contributions from SST drifts on NWP timescales in
249 future work. We have demonstrated that the propagation of the MJO suffers in the
250 AGCM simulation, which could result from the failure to represent the phase relationship
251 that exists between convection and SST. The CGCM shows skill in representation of both
252 oceanic equatorial Kelvin waves and of westward propagating Rossby waves out to 15
253 days. It has also been shown that while SST is sensitive to many different processes,

254 anomalously warm waters occur along the trajectory of downwelling tropical waves and
255 this process could be important to the lifecycle of the MJO. The case for using an ocean
256 model capable of simulating waves seems strong, given that tropical waves appear both
257 to influence and be influenced by the MJO.

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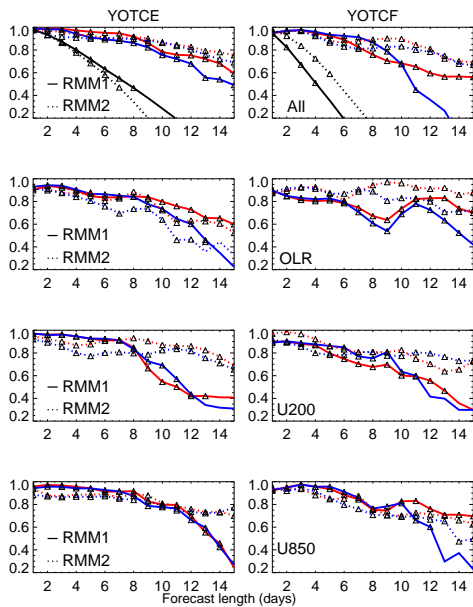


Figure 1. Hindcast anomaly correlation scores during YOTCE(left) and YOTCF(right) for combined fields (top), OLR (2nd from top), U200 (3rd from top) and U850(bottom) as measured against MetUM analyses, for MJO amplitudes exceeding 1. All phases are included in each plot. The CGCM is in red and AGCM in blue. A persistence hindcast (black) is shown for combined fields. Significance at 99% level is denoted by a triangle.

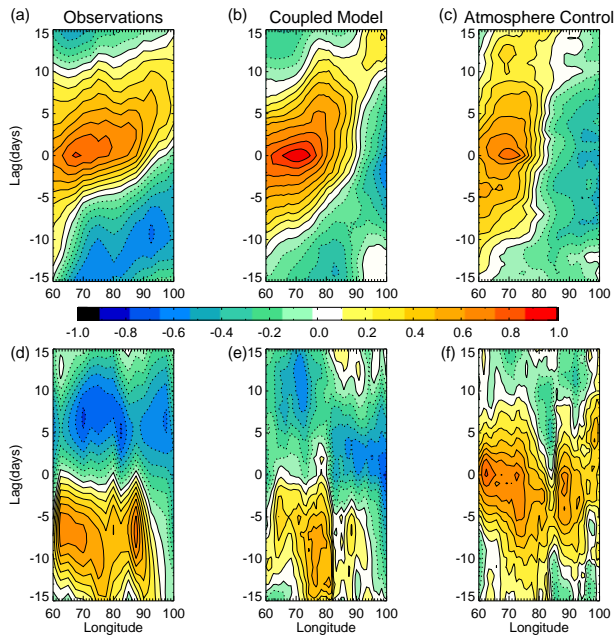


Figure 2. Lead-lag correlations for OLR at a base point of 70°E with OLR at all points of longitude in the Indian Ocean over YOTCE period [15 Oct-6 Dec 2009] for: (a) observations (b) CGCM and (c) AGCM, for all day 5 hindcasts. Lead-lag correlations over YOTCE period [15 Oct-6 Dec 2009] for SST correlated with OLR in the Indian Ocean for (d) observations, (e) CGCM hindcast and (f) AGCM hindcast(surface temperature at sea points), for all day 5 hindcasts.

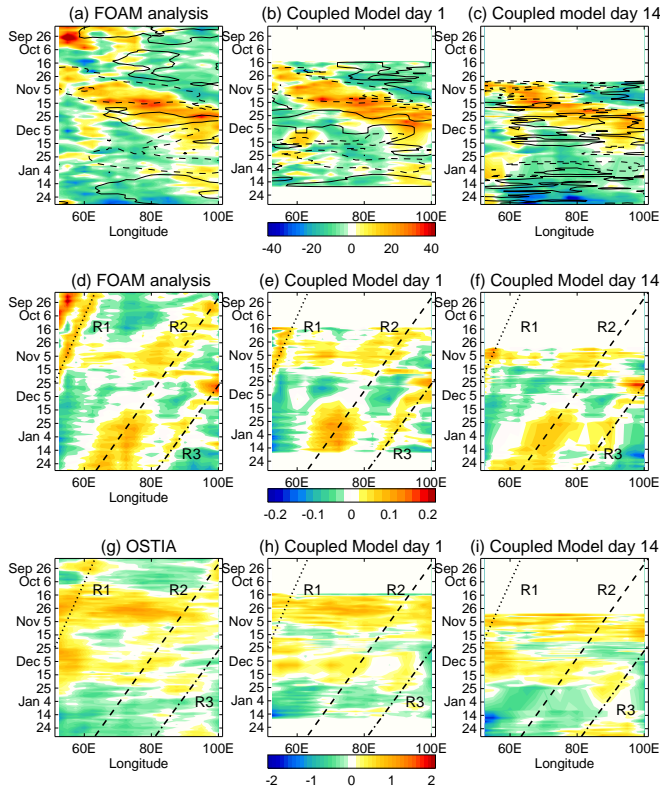


Figure 3. Time-longitude plots for (Top) Dep20 anomaly(m) and OLR anomaly (+/-10 Wm⁻²) for (a) FOAM analysis(shading) and NOAA OLR (contours) (b) day 1 CGCM hindcasts and (c) day 14 CGCM hindcasts averaged between 2°N-2°S; (Middle) SSH anomaly (m) for (d)FOAM analysis (e) day 1 CGCM hindcasts and (f) day 14 CGCM hindcasts averaged between 2°N-8°N and 2°S-8°S.; (Bottom) SST anomaly field for (g) OSTIA (h) day 1 CGCM hindcasts and (i) day 14 CGCM hindcasts averaged between 2°N-8°N and 2°S-8°S. Diagonal lines (R1,R2,R3) in (d)-(i) represent downwelling Rossby waves propagating from East to West across the Indian Ocean.