

Bulletin of the American Meteorological Society

The Intra-Americas Seas: A Region of Challenges and Opportunities to Understand North American Climate Variability and Predictability --Manuscript Draft--

Manuscript Number:	BAMS-D-14-00223
Full Title:	The Intra-Americas Seas: A Region of Challenges and Opportunities to Understand North American Climate Variability and Predictability
Article Type:	Article
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Manuscript Classifications:	1.096: North America; 2.040: Atmosphere-ocean interaction; 2.044: Atmospheric circulation; 5.028: Climate records; 8.020: Climate models; 9.020: Climate variability
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	<p>representation of the atmospheric low-level jets in the region are also apparent in many climate models. Lack of observations in both the atmosphere and ocean in the IAS, which is one of the most poorly observed regions of the world, limits our ability to improve models. There are however emerging opportunities that could be leveraged to ameliorate some of these issues.</p>
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August 1, 2015

Dear Dr. McPhaden,

Please find attached our revised manuscript (BAMS-D-14-00223) including the supplementary material along with the point-by-point response to the review comments from the three reviewers. We appreciate your kind gesture to provide us an avenue to respond to the review comments. We acknowledge the thoughtful comments and suggestions that the reviewers provided. By addressing them, we feel we have clarified several issues in the manuscript and made it more readable to the BAMS audience.

I look forward to your response at your earliest convenience.

Sincerely,

A handwritten signature in blue ink that reads "vasubandhu".

Vasubandhu Misra,
Associate Professor,
Florida State University

1 **The Intra-Americas Sea: A Region of Challenges and Opportunities to Understand**
2 **North American Climate Variability and Predictability**

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Abstract:

The Intra-Americas Seas (IAS), which includes the Gulf of Mexico and the Caribbean Sea is part of the largest warm water pool in the Western Hemisphere and is a primary moisture source for precipitation in the Americas. This IAS region is known to affect the North American climate variability across spatio-temporal scales as well as extreme weather events such as Atlantic tropical cyclones and southeast US tornadoes. The IAS also displays an active land-ocean-atmosphere interaction, with some of the largest river discharges producing extensive barrier layers which significantly affect the overlying atmospheric behavior. Most climate models display significant cold SST and dry rainfall bias over the IAS with a corresponding underestimation of their variability. In addition, significant biases in IAS surface and deep ocean currents, and poor representation of the atmospheric low-level jets in the region are also apparent in many climate models. Lack of observations in both the atmosphere and ocean in the IAS, which is one of the most poorly observed regions of the world, limits our ability to improve models. There are however emerging opportunities that could be leveraged to ameliorate some of these issues.

53 **1 Introduction**

54 The Intra-Americas Seas (IAS) comprising of the Gulf of Mexico (GoM) and the
55 Caribbean Sea with its proximate location to North America and a seasonally appearing
56 very warm SST ($>28.5^{\circ}\text{C}$) in the boreal summer and fall seasons is recognized to be
57 significant source of moisture that fuels the hydroclimatic variations of North America
58 (Wang and Enfield 2001, 2003; Ruiz-Barradas and Nigam 2005; Mestas-Nunez et al.
59 2007). This body of warm water in the IAS with some parts of western tropical North
60 Atlantic is a major part (over 80%) of the larger Western Hemisphere Warm Pool
61 (WHWP; Wang and Enfield 2001; Fig. 1a), the second largest body of very warm water
62 on Earth. A much smaller part of the WHWP resides in the northeast tropical Pacific west
63 of Central America (also known as the Eastern Pacific Warm pool [EPWP]). The western
64 tropical North Atlantic with the IAS is also collectively referred as the Atlantic Warm
65 Pool (AWP). The WHWP is the second largest body of very warm water ($\geq 28.5^{\circ}\text{C}$) on
66 Earth and hosts the second largest diabatic heating center of the tropics during the boreal
67 summer and fall seasons (Wang and Enfield 2001). The warm pool ($\geq 28.5^{\circ}\text{C}$) appears
68 initially in late boreal spring as EPWP followed by a warming of the AWP in boreal
69 summer and fall seasons.

70 The IAS while geographically limited to the GoM and the Caribbean Sea is
71 however dictated in its variations and teleconnections to the North American
72 hydroclimate by symbiotic relation with overlying large-scale atmospheric circulation
73 including the North Atlantic Subtropical High (NASH), the myriad atmospheric low level
74 jets (LLJs; e.g. Caribbean, North American, Choco, Tehuantepec, Papagayo LLJs),
75 complex cloud-radiation, and air-sea interactions. Additionally, ocean processes

76 impacting the IAS region include the upper branch of the Atlantic Meridional
77 Overturning Circulation (AMOC) that includes the Loop Current and the associated
78 eddies in the GoM, prevalent subtropical cells, and the Caribbean current system with its
79 ubiquitous mesoscale and sub-mesoscale eddies. Embedded within these defining
80 features of the IAS are extreme events that are influenced by it like Atlantic tropical
81 cyclones (TCs), tornadoes in the CONUS, large and intense meso-scale convective
82 systems of the monsoons extending from central America to southwestern US (Maloney
83 and Hartmann 2000a, b; Wang and Lee 2007; Wang et al. 2007, 2008a; Klotzbach 2014;
84 Crosbie and Serra 2014; Serra et al. 2014).

85 The purpose of this paper is to highlight IAS variability that includes its surface
86 and sub-surface oceanic and overlying atmospheric variability and its remote
87 teleconnections to the climate of North America. This is followed by a discussion of the
88 limitations of our current climate models and observational networks to effectively
89 predict and monitor the observed IAS climate and its teleconnections over North
90 America, respectively. We also present outstanding issues and emerging opportunities to
91 improve climate predictability and monitoring of IAS variability spanning from intra-
92 seasonal timescales to secular changes.

93

94 **2 The IAS Variability**

95 **a) AWP Teleconnections**

96 **i) Sea Surface Temperature**

97 The AWP defined by the 28.5°C surface isotherm (Fig. 1a) has a distinct seasonal
98 cycle (Wang and Enfield 2001, 2003; Enfield and Lee 2005; Lee et al. 2007). It reaches a
99 maximum in the area enclosed by 28.5°C in early September (Misra et al. 2014). The
100 choice of the 28.5°C isotherm to define the AWP stems from its close correspondence
101 with the variations in the IAS mixed layer depth (Wang and Enfield 2003), its notable
102 impact on organized convection (Graham and Barnett 1987), and the display of the
103 strongest interannual variations of the area enclosed by this isotherm in the IAS (Misra et
104 al. 2013; Figs. 1b-d). The surface heat budget studies of the AWP indicate that the
105 surface radiative fluxes dominate in the GoM while in the Caribbean Sea upwelling and
106 advective cooling also play significant role in regulating the SST (Lee et al. 2007; Misra
107 et al. 2013).

108

109 **ii) Atmospheric circulation**

110 The seasonal peak of the AWP-induced heating forces a Gill-type atmospheric
111 response (to off equator forcing) as well as extratropical stationary waves (Fig. 2) that
112 produces rainfall variability over the CONUS (Fig. 3a), while modulating the subtropical
113 highs in the North Atlantic (Fig. 3b) and in the southeastern Pacific (not shown; cf Fig. 8
114 in Wang et al. 2010). AWP variations and their teleconnections to North American
115 hydroclimate are also observed to be largely independent of the El Niño and the Southern
116 Oscillation (ENSO) variations in the equatorial Pacific (Wang et al. 2006, 2008; Zhang
117 and Wang 2012; Misra et al. 2013).

118 During the boreal summer season, the easterly trade winds advect moisture from the

119 tropical North Atlantic (TNA) into the Caribbean Sea where the flow accelerates as the
120 Caribbean low-level jet (CLLJ). To the first order the CLLJ is geostrophic (Wang 2007;
121 Cook and Vizy 2010) and thus is controlled by the strong meridional pressure gradient
122 established by the NASH and heating over northern South America (Fig. 1a; Amador and
123 Magana 1999; Poveda and Mesa 1999; Wang 2007). Furthermore, Wang et al. (2008)
124 and Rauscher et al. (2011) show that the magnitude of the SST anomaly in the Caribbean
125 also influences the strength of the CLLJ. The CLLJ bifurcates as it transits the Caribbean
126 Sea: one branch turning northward and forming the Great Plains LLJ (GPLLJ) while the
127 other branch continues westward across Central America into the eastern North Pacific.
128 Modeling and observational studies indicate that a large (small) AWP is associated with
129 weakening (strengthening) of the summertime NASH and strengthening (weakening) of
130 the summertime continental low over the NAM region (Fig. 3b; Wang et al. 2008a). The
131 observational studies also confirm that in response to the pressure changes, a large
132 (small) AWP weakens (strengthens) the southerly GPLLJ (e.g. Wang 2007), which
133 results in reduced (enhanced) northward moisture transport from the GoM to the region
134 east of the Rocky Mountains and thus decreases (increases) the moisture available for
135 summer rainfall over the central United States (Wang et al. 2006; 2008; Ruiz-Barradas
136 and Nigam 2006; Mestas-Nuñez et al. 2007).

137

138 **iii) Precipitation**

139 A strong (weak) easterly CLLJ associated with small (large) AWP area results in
140 southerly (northerly) wind anomalies to the United States, which would transport more

141 (less) moisture and consequently cause more (less) rain in the Great Plains region (Wang
142 and Enfield 2003; Ruiz-Barradas and Nigam 2005; Wang 2007). Concomitantly, a strong
143 CLLJ is associated with above normal rainfall over the Caribbean coast of Central
144 America, including Nicaragua and Costa Rica, particularly during the boreal summer
145 (May–September), through large-scale low-level convergence at the jet exit (Waylen et
146 al. 1996; Magaña et al., 1999; Amador et al. 2000; Magaña and Caetano, 2005; Cook and
147 Vizy 2010; Herrera et al. 2014). Such enhanced summertime convective activity on the
148 upslope side of the terrain acts to deprive moisture to the Pacific coast of Central
149 America and results in rainfall deficits there (Amador 1998; Cook and Vizy 2010; Martin
150 and Schumacher 2011b).

151 The rainfall over the AWP alternates with the Amazon basin in South America as
152 the seasonal heating source for the regional Hadley and Walker type circulations in the
153 Western Hemisphere (Wang et al. 2006; 2010; Poveda et al. 2006). During the boreal
154 summer/fall season, a strong regional Hadley-type circulation is established, with
155 ascending motion over the AWP and subsidence over the southeastern tropical Pacific. A
156 large (small) AWP during the boreal summer/fall results in a strengthening (weakening)
157 of this regional Hadley-type circulation with enhanced descent (ascent) over the
158 southeastern tropical Pacific (Wang et al. 2006, 2010, 2014; Lee et al. 2013b).

159

160 **b) Secular change¹ in the IAS**

¹ Secular change refers to the change in the variable in question with the sign of the change remaining the same throughout a long time period.

161 Among the challenges in interpreting observations of climate variability in the
162 IAS region are the detection and attribution of low–frequency variability and long–term
163 trends in SST. In particular, the IAS region is home to substantial internal multidecadal
164 variability (Ting *et al.* 2011) that can mask forced long–term trends using instrumental
165 records alone (Wang and Dong 2010) and often require historical hindcast model
166 experiments to interpret (Ting *et al.* 2009). Moreover, future hydroclimate projections by
167 state–of–the–art GCMs suggest that EPWP and most of the IAS region including the
168 Caribbean islands, Central America, Mexico, and the southern United States should
169 anticipate a robust and severe reduction in precipitation (Neelin *et al.* 2006; Meehl *et al.*
170 2007; Taylor *et al.* 2012; Maloney *et al.* 2014), which is thought to be critically
171 dependent on the magnitude and spatial patterns of ocean warming (Schubert *et al.* 2009;
172 Xie *et al.* 2010; Rauscher *et al.* 2011; Lee *et al.* 2011).

173 Future projections by the Coupled Model Intercomparison Project phase 5
174 (CMIP5) models predict that under the Representative Concentration Pathway (RCP8.5),
175 GoM SST will warm in a spatially uniform fashion in the multi–model ensemble mean at
176 a rate of 3–4°C century⁻¹ by the end of the 21st century, and 2–3°C century⁻¹ in the
177 Caribbean Sea (IPCC AR5, WG1, Ch. 12, Fig. 12.11 [Collins *et al.* 2013]). The projected
178 trends in these marginal seas approximately mirror those for the open Atlantic Ocean
179 regions immediately to their east.

180 A comparison of four gridded instrumental datasets (see supplementary material
181 [SM] S.1) agree on a broad warming across the western tropical Atlantic Ocean and the
182 Caribbean Sea of ~0.4°C century⁻¹ with the greatest warming found along the northern
183 coast of South America in the southern Caribbean Sea (Fig. SF1). In a similar vein, the

184 regional ocean model projections of Liu et al. (2015) suggest that there is a downward
185 relaxation of isotherms along the coasts of Colombia and Venezuela to geostrophically
186 balance the weakening of the Caribbean Current, which further enhances the warming of
187 the upper ocean. In stark contrast, the observed SST trends within the GoM are spatially
188 heterogeneous and vary substantially from one product to another (Fig. SF1). Of
189 particular relevance to recent and ongoing observational efforts is that SST changes in the
190 GoM are highly divergent among the four data sets, varying by $\sim 0.5^{\circ}\text{C}$ relative to their
191 1951-1980 base periods. Published proxy reconstructions of water temperature
192 corroborate the trends in the super ensemble of observations² (Fig. 4). The strongest
193 proxy reconstruction trends are in the central Caribbean Sea (Fig. 4), where the super
194 ensemble shows agreement with a positive trend. The weakest trends are in the GoM, but
195 they are calculated from sediment cores with few points covering the 20th century
196 (Richey et al, 2004; Richey et al., 2008). The record from the Cariaco Basin (off the north
197 central coast of Venezuela; Black et al., 2008) is based on high time resolution through
198 the 20th century, and it is the only proxy reconstruction in the basin that approaches the
199 sign and magnitude of the trends in the super ensemble. The magnitude of these trends is
200 based on species-specific calibrations that, in the case of the Caribbean Sea and GoM,
201 seem to over-estimate long-term temperature change. It is important to note that records
202 from Jamaica (Hase-Schramm et al., 2003), Pedro Bank (central Caribbean, Haase-
203 Schramm et al., 2003), and the Bahamas (Rosenheim et al., 2005) are from shallow
204 subsurface records (28–67m). The general pattern of change in the instrumental SST

² See SM S.1 on further details of super ensemble of observations

205 products (smaller and/or less robust warming trends in the GoM than in the Caribbean
206 Sea) is exactly opposite to the future trends projected by CMIP5 models.

207 However, it is important to point out that future projections by CMIP5 models
208 may need to be downscaled or modeled at high resolution to better understand the
209 regional response of the IAS, as the models seem to have significant ocean circulation
210 bias in the IAS (Liu et al. 2102, 2015). Liu et al. (2015) downscaled the CMIP5 model
211 simulations under historical and two future emission scenarios using an eddy-resolving
212 regional ocean model. They reported that the simulated volume transport by the western
213 boundary current system in the IAS, including the Caribbean, Yucatan and Loop
214 Currents, was reduced by 20-25% during the 21st century, consistent with a similar rate
215 of reduction in the AMOC. Their modeling analysis also showed that the projected
216 reduction of the IAS western boundary current system was linked to reduced upwelling
217 and enhanced warming along the western boundary. Over most of the GoM the
218 downscaled model yields less warming than the low resolution IPCC models because of
219 the latter's inability to correctly resolve the volume transport through the Yucatan
220 Channel and the Florida Straits.

221

222 **c) The monsoons and the IAS**

223 The IAS by its proximate location to the monsoons of the Americas serves as a
224 bridge to unify the South American Monsoon (SAM) and North American Monsoon
225 (NAM) systems. Observations have shown a negative correlation between boreal winter
226 rainfall anomalies over the IAS region and those over the NAM and Southern Amazonia

227 on interannual (Wang and Fu 2002) and multi-decadal time scales (Arias et al. 2015). On
228 interannual time scales these relationships are linked by the reversal of the cross-
229 equatorial flow over the Americas associated with ENSO (Arias et al. 2015). Misra and
230 DiNapoli (2013) also find that the anomalous meridional migration of the ITCZ in the
231 western Atlantic Ocean dictated by the intensity of the seasonal rainfall activity in the
232 equatorial Amazon during boreal winter is negatively correlated with the upper ocean
233 heat content (not shown) and surface temperature variability of the IAS in the subsequent
234 seasons (Fig. 5). This teleconnection is established by the modulation of the atmospheric
235 heat fluxes regulated by the overlying regional Hadley circulation, which gives rise to a
236 robust negative correlation between austral summer rainfall over the equatorial Amazon
237 and SST variability in the IAS during the subsequent boreal summer season.

238 On decadal time scales the negative correlation of rainfall between the NAM and
239 the SAM is also related to the intensification of rainfall over the IAS region, causing an
240 early retreat of the NAM and a late onset of the rainy season over southern Amazonia.
241 These variations following Arias et al. (2012, 2015) seem to be a combined result of the
242 westward shift of the NASH (a response to increased land-ocean contrast [Li et al. 201;
243 Cook and Vizy 2010]) and the warm phase of the Atlantic Multidecadal Oscillation
244 (AMO). The westward shift of the NASH enhances moisture transport from the IAS to
245 the U.S. Great Plains, which in turn, weakens moisture transport to the NAM region
246 (Arias et al 2012) and enhances the southerly cross-equatorial flow over South America
247 and moisture export from southern Amazonia (Arias et al 2015). The warm phase of the
248 AMO leads to warmer SST anomalies and stronger ITCZ over the TNA and northern
249 South America, resulting in an equatorial contraction of the tropical meridional

250 circulation over the American-Atlantic sector, stronger subsidence and moisture
251 divergence over the NAM and southern Amazonia.

252 Previous studies on the sources of NAM moisture indicate that moisture at upper
253 levels (above 700 hPa) originates to the east of the Sierra Madres Occidental and over the
254 GoM, while low-level moisture of oceanic sources originates predominantly from the
255 tropical Pacific Ocean and the Gulf of California (Schmitz and Mullen 1996; Adams and
256 Comrie 1997). In addition to these oceanic sources, studies using a two-dimensional
257 dynamic recycling model find that NAM terrestrial evapotranspiration accounts for
258 approximately 40% of the total moisture sources to the NAM (Dominguez et al. 2006; Hu
259 and Dominguez, 2015), similar to estimates of terrestrial sources for the May-July period
260 based on moisture tracers in a GCM (Bosilovich 2003).

261 While the seasonal migration of the monsoon ridge is fundamental to the onset
262 and demise of the NAM, monsoon precipitation is highly dependent upon intra-seasonal
263 variability (ISV), especially in the southwestern United States at the northern edge of the
264 monsoon. ISV in the IAS (see Serra et al. 2014 for a review) plays a particularly
265 important role in supporting NAM rainfall events through gulf surges, or surges of
266 moisture up the Gulf of California (e.g., Stensrud et al. 1997), and through IAS TC
267 activity that recurves directly over the NAM region (Collins and Mason 2012; Ritchie et
268 al. 2011; Corbosiero et al. 2009; Wood and Ritchie 2013). The link between tropical
269 disturbances, gulf surges, the MJO, and NAM rainfall events has not been fully explored;
270 however studies suggest that positive rainfall anomalies extend into the NAM region
271 during the transition to the MJO westerly phase, when TC and easterly wave activity is

272 also enhanced and shifted along the Mexican west coast (Lorenz and Hartmann 2006;
273 Crosbie and Serra 2014; see SM [S.2])

274 The Mid-Summer Drought (MSD; Fig. 6) phenomenon characterized by a
275 minimum rainfall that separates two peaks in rainfall across the Caribbean and Central
276 America during boreal summer season has been associated with the westward expansion
277 and intensification of the NASH and associated CLLJ variability resulting in moisture
278 flux divergence (Hastenrath 1976, 1978; Granger 1985; Magana et al. 1999; Giannini et
279 al. 2000; Mapes et al. 2005; Wang 2007; Wang and Lee 2007; Misra et al. 2014). As the
280 NASH expands westward during the summer months precipitation is suppressed via
281 large-scale subsidence and increased stability (Knaff, 1997; Mapes et al. 2005; Wang and
282 Lee 2007; Kelly and Mapes 2011). In addition, the enhancement of the easterly trade
283 winds in the southern Caribbean leads to greater evaporative cooling and lower SST
284 which further suppresses summer convection (Muñoz et al. 2008, Xie 2006, Martin and
285 Schumacher 2011b).

286

287 **d) The ocean circulation in the IAS**

288 The IAS is comprised of a very complex ocean circulation system from the
289 smallest spatial scales (e.g. ubiquitous presence of mesoscale and sub-mesoscale eddies;
290 see SM [S.3]) to hosting the upper branch of the AMOC (e.g. Caribbean current system,
291 GoM loop current and the southern branch of the Gulf stream system). These ocean
292 current systems that bring relatively warm and saline water from the equatorial Atlantic
293 to the GoM are fundamental to the regulation of the SST in the IAS (Jayne and Maotzke
294 2002; Chang and Oey 2010; Liu et al. 2012; Misra et al. 2015). Owing primarily to

295 shortcomings in long-term observational network of the IAS, substantial uncertainty
296 exists regarding the magnitude of inter-annual flow variability within the channels
297 (Yucatan, Old Bahama [OBC] and Northwest Providence [NWP] channels) that connect
298 to the Florida Straits at 27° N (Rousset & Beal 2014; see SM [S.4]).

299 The southern Caribbean upwelling system significantly contributes to the mean
300 SST distribution and its seasonal and interannual variability in the Caribbean Sea. The
301 upwelling follows a semi-annual cycle resulting in surface manifestation of relatively
302 cold SST, which peaks in December–March and July (Fig. 7) in response to semi-annual
303 intensification of the along-shore CLLJ (Wang 2007; Wang and Lee 2007) and its
304 associated changes in wind stress curl (Inoue et al. 2002; Andrade and Barton 2005;
305 Cook and Vizy 2010). Jouanno and Sheinbaum (2013) also find that vertical turbulent
306 mixing is important in regulating the surface cooling at the coast. The intense vertical
307 mixing at the coast arises from vertical shear between the shallow and strong Caribbean
308 Current and the subsurface Caribbean coastal undercurrent. This southern Caribbean
309 upwelling region limits the southward extent of the AWP during its onset and peak phase
310 (Lee et al. 2007) and modulates the meridional gradient of SST over the Venezuela and
311 Colombia basins, with possible feedback to the trade winds (Chang and Oey, 2013). See
312 SM (S.5) for further discussion on the rectification effect on the atmosphere from the
313 cold SST's of this upwelling region.

314 It is also observed that a net freshwater gain (loss) in the TNA region coincides
315 with the large (small) AWP regimes on interannual and multi-decadal timescales (Wang
316 and Zhang 2013; Zhang and Wang 2012). They show that on these time scales, in
317 association with large (small) AWP, warmer (colder) SSTs induce anomalous low-level

318 convergence (divergence), which favors anomalous ascent (descent) that generates more
319 (less) precipitation. Zhang et al. (2014) further confirm that this AWP induced freshwater
320 flux plays a negative feedback role that acts to restore the AMOC from its anomalous
321 state through basin-scale gyre circulation adjustments.

322

323 **e) The IAS extreme events**

324 A number of studies have shown that IAS variability modulates Atlantic TC activity
325 (Fig. 8; e.g. Molinari et al. 1997; Maloney and Hartmann 2000a,b; Higgins and Shi 2001;
326 Wang and Lee 2007, 2009; Wang et al. 2007, 2008a, 2011; Aiyyer and Molinari 2008;
327 Jiang et al. 2012; Klotzbach 2014; Crosbie and Serra 2014). Calculated over a 34-year
328 period (1979-2012), 90 named Atlantic TCs occurred in small AWP years versus 163 for
329 large AWP years (Fig. 8). Wang and Lee (2007) argued that the observed relationship
330 between AWP SST and Atlantic TC activity is a result of the AWP SST-forced changes
331 of the vertical wind shear and moist static stability in the Atlantic TC Main Development
332 Region (MDR).

333 Dynamically, the AWP-forced atmospheric circulation pattern is baroclinic within
334 the tropical latitudes, with a large AWP producing a cyclone in the lower troposphere and
335 an anticyclone in the upper troposphere, both situated on the northern flank of the AWP
336 (Wang et al. 2008a; Fig. 2). This anomalous circulation structure reduces the lower
337 tropospheric easterly flow and the upper tropospheric westerly flow in the MDR, thus
338 reducing the vertical wind shear in a way that favors atmospheric convection (or TC
339 development; Wang et al. 2007; 2008a). Similarly, the modulation of large-scale

340 environmental factors including tropospheric humidity, vorticity, vertical shear, and SST
341 by the MJO and other modes of ISV can also manifest in AWP-Atlantic TC and extreme
342 rainfall teleconnections (Maloney and Hartmann 2000a; Camargo et al. 2009; Martin and
343 Schumacher 2011a; Jiang et al. 2012). Furthermore, precursor disturbances for TCs in the
344 form of easterly waves are also modulated on intraseasonal timescales in the IAS region
345 (e.g. Maloney and Hartmann 2001; Crosbie and Serra 2014; Rydbeck et al. 2014).
346 Thermodynamically, the AWP increases convective available potential energy (CAPE)
347 that provides the fuel for moist convection and thus facilitates the formation and
348 development of TCs (Wang et al. 2008). AWP-forced extra-tropical stationary Rossby
349 waves influence the barotropic atmospheric flow over North America and the Atlantic in
350 boreal summer (Lee et al., 2009), which then affects the steering flow of North Atlantic
351 TCs (Wang et al., 2011; see SM [S.6]).

352 Boreal spring (April and May) is the primary season for tornadoes in the US. The
353 convergence of dry upper level air from higher latitudes and low-level warm moist air
354 from the GoM results in a conditionally unstable environment to the east of the Rockies
355 with a raised CAPE that makes it conducive for tornadogenesis. Lee et al. (2013a) show
356 that the April-May tornado outbreaks in the US are significantly correlated with moisture
357 transport from the GoM (Fig. 9) and lower tropospheric vertical wind shear in the central
358 and eastern US. Muñoz and Enfield (2011) find that the tornadic activity in lower
359 Mississippi, Tennessee, and Ohio is particularly related to the interannual and decadal
360 variability of the LLJs (Caribbean and North American) that dictate the moisture flux to
361 the region (e.g., Maya express [Dirmeyer and Kinter 2009]).

362

363 **f) The barrier layers of the IAS**

364 The thick and persistent barrier layers or fresh water lens that form in the
365 northwest tropical Atlantic Ocean is a result of the large volume of fresh water influx
366 from some of the major continental rivers in northern South America (e.g., Orinoco and
367 Amazon; Pailler et al., 1999). The barrier layers of the IAS are one of the most prominent
368 structures in the world tropical and subtropical oceans (Mignot et al. 2007), which reflect
369 the prevalence of the robust land-atmosphere-ocean coupling in the region. The mighty
370 Amazon and Orinoco River systems together form the biggest river system in the world
371 in terms of discharge (0.2 Sv). The Guyana current carries a significant portion of this
372 water into the Caribbean Sea during boreal summer and fall (Hu et al., 1997), providing
373 the largest term in the surface salinity balance of the region (Foltz and McPhaden, 2008;
374 see SM S.7). Satellite and *in situ* observations confirm the occurrence of large interannual
375 anomalies in the spatial extent of the riverine barrier layer over the western TNA and
376 eastern Caribbean (Johns et al. 2014; Fig. SF8).

377 Because of the barrier layer role in trapping heat within the upper ocean layer and
378 reducing surface cooling, the barrier layer in the northwestern tropical Atlantic has the
379 potential to affect Atlantic TC activity (Ffield 2007; Vizy and Cook 2010, Balaguru et al.
380 2012). When TCs pass over barrier layers, the reduced efficacy of vertical mixing in
381 these highly stratified layers leads to reduced SST cooling, which then impacts TC
382 evolution by maintaining strong air–sea fluxes. In the northwestern tropical Atlantic,
383 Balaguru et al (2012) reported that the mean rate of increase of intensity of Atlantic TCs
384 increases from 0.48 ms^{-1} over a 36-hour period in non-barrier layer regions to 0.98 ms^{-1}
385 over the same time period in barrier layer regions.

386

387 **3 The limitations of numerical models simulating and predicting IAS climate**

388 The surface temperature of the IAS and its variability are grossly underestimated
389 by a majority of the CMIP models that participated in the IPCC AR4 and AR5 especially
390 in the boreal summer and fall seasons (Fig. 10; Misra et al. 2009; Kozar and Misra 2012;
391 Liu et al. 2012, 2013; Ryu and Hayhoe 2013). A majority of the CMIP5 models
392 underestimate the area of the AWP in their 20th century simulation (Fig. 10). Surface heat
393 budgets computed over the IAS reveal that the radiative fluxes of downwelling shortwave
394 and longwave radiation dominate the maintenance of the AWP (Misra et al. 2013).
395 However, the important and subtle role for air-sea turbulent fluxes in the variability of the
396 AWP and its interplay with the variability of the overlying low-level easterlies, which is
397 related to the strength and position of the NASH, cannot be overemphasized (Misra et al.
398 2009). Liu et al. (2012) and Misra et al. (2013) find that a majority of current global
399 circulation models (GCMs) and reanalysis products of the ocean and the atmosphere
400 produce a qualitatively consistent surface heat budget in the IAS. However, when
401 compared to reanalysis, GCMs have a tendency to underestimate latent heat flux and
402 downwelling shortwave flux, and overestimate sensible heat flux. Liu et al. (2012) also
403 indicate that the upper ocean heat budget in the GoM is a complex balance of contrasting
404 warming influence of upper ocean heat transports (e.g. Loop Current) and cooling
405 influence of the net surface heat flux. With significant GCM biases prevalent in surface
406 fluxes and ocean circulation over the region (Liu et al. 2015), it is not surprising to note
407 such large SST errors over the IAS in GCMs (Fig. 11). In addition, Xu et al. (2014) found
408 that the persistent warm bias over southeastern tropical Atlantic across generations of

409 climate models (Fig. 11; e.g. Richter and Xie, 2008; Richter et al. 2014) can remotely
410 force a significant cold SST bias and dry precipitation bias in the IAS region (cf. their
411 Fig. 18; Xu et al. 2014).

412 The IAS region is also characterized by significant deficiencies in the simulation
413 of convection and related processes. For example, ISV in the east Pacific and Caribbean
414 is poorly simulated in amplitude and spatial structure in climate models (Jiang et al.
415 2013), with poor performing models also tending to have common mean state biases in
416 winds and other fields. Model ISV in the IAS region can be improved by suppressing
417 convection through enhanced moisture sensitivity or other means, although often the
418 quality of the mean state degrades when such modifications are not done with care (e.g.
419 Kim et al. 2011; Maloney et al. 2014a), suggesting that such changes can improve ISV
420 for the wrong reasons (e.g. Maloney et al. 2014a; Hannah and Maloney 2014). Martin
421 and Schumacher (2012) and Ryu and Hayhoe (2013) showed that the cold SST bias in the
422 IAS further exacerbates the dry rainfall bias over the Caribbean and central America
423 across CMIP3 coupled historical simulations. In recent CMIP5 historical simulations,
424 large precipitation and SST biases across the Caribbean are still evident in both coupled
425 (historical) and uncoupled (AMIP) simulations (see SM [S.8]; Sheffield et al. 2013).
426 Furthermore, the timing of NAM precipitation also exhibits substantial biases, with
427 models generally producing too little precipitation in the NAM region in early and mid
428 boreal summer, and excessive precipitation late in the monsoon period (Liang et al. 2008;
429 Sheffield et al. 2014a), associated with difficulty in ending the monsoon (Geil et al.
430 2013).

431 The recent effort to make seasonal predictions from multiple models like the
432 North American Multi-Model Ensemble project (NMME; Kirtman et al. 2014) routinely
433 available allows us to assess skill of predicting SSTs over the AWP, and land-surface
434 (e.g. precipitation, surface temperature) anomalies over the surrounding areas. Misra and
435 Li (2014) find that the seasonal predictability of the AWP in the NMME models is
436 promising compared to earlier generation GCMs (Misra et al. 2009), but also displays
437 notable limitations. For example, NMME mean forecasts indicate that skill in predicting
438 seasonal mean SSTs in the AWP is much less than the skill in predicting SST variability
439 in the equatorial eastern Pacific associated with ENSO (Niño3.4 region; Fig. 12).
440 Anomaly correlations averaged over the AWP region are in the range of 0.5 – 0.6, much
441 less compared to those over the eastern equatorial Pacific (Niño3.4 region). Prediction of
442 terrestrial climate anomalies around the IAS relies on skillful prediction of IAS SSTs, and
443 hence seasonal prediction over land areas cannot be improved until skill in predicting
444 SST is improved. An assessment of the corresponding JJA seasonal mean precipitation
445 anomalies confirms this (Fig. 13) in which prediction skill (anomaly correlation of the
446 ensemble mean) generally does not exceed 0.3. See SM (S.10) for comparison of this
447 skill with the boreal winter season.

448

449 **4 The observing network in the IAS**

450 A gradually and significantly degrading observational network for the atmosphere
451 and ocean in the IAS region also exacerbates the modeling challenges described in the
452 previous section. For example, the radiosonde network in the region is quite sparse (Fig.

453 SF10; SM [S.9]) and is currently unable to sample the core of the CLLJ. In addition, for a
454 region that displays a highly heterogeneous distribution of rainfall, the rain gauge
455 network is highly inadequate (Fig. SF11). The complex spatial structure of rainfall in the
456 IAS (with topographic, island, and LLJ effects) raises a challenge for observing and
457 monitoring the climate of the region. For example, Figs. 6a and b show rainfall
458 measurements from the satellite based Tropical Rainfall Measuring Mission (TRMM)
459 and merged satellite and in-situ Global Precipitation Climatology Project (GPCP) data,
460 respectively, and differences between the products are evident in both the location and
461 magnitude of rainfall features across the region, which is largely a reflection of the
462 differences in spatio-temporal resolution of the two datasets. Using TRMM precipitation
463 radar data, Sobel et al. (2011) show that rainfall enhancement relative to the surrounding
464 oceanic region is more significant over larger (greater than 315 km²) islands than smaller
465 islands in the Caribbean and that smaller islands have a negligible or even negative
466 change in rainfall intensity and frequency relative to surrounding oceans. However, while
467 high-resolution satellite data such as TRMM and the newly launched Global Precipitation
468 Measurement (GPM) satellites can provide useful information, the 0.25° TRMM
469 resolution (~28km) provides fewer than 3 measurements for most of the smaller islands
470 in the Lesser Antilles. For example, the island of Dominica (approximately 25km wide
471 and 50 km long) has large zonal variations in rainfall intensity and frequency as measured
472 during the DOMEX (Dominica Experiment) field campaign that are not captured by
473 current satellite measurements of rainfall (Smith et al. 2012, Minder et al. 2013).

474 In-situ ocean observational networks in the IAS have also diminished
475 considerably over time. ARGO floats, which have the operating depth of about 2000m

476 cannot pass the Lesser Antilles to reach the Caribbean Sea. As a result, the IAS is
477 currently one of the most mostly poorly observed oceans at depth (Fig. SF12). This poor
478 observational network leaves some basic issues unresolved including characteristics of
479 the seasonal cycle of the oceanic variables in the IAS and its relation to the Loop Current
480 and eddy shedding dynamics, and the different pathways of the flow that can impact the
481 salt, temperature and fresh water transport by the AMOC through the western boundary.
482 As mentioned earlier, there is significant disparity in the diagnosis of the observed long-
483 term variations of SST in the IAS.

484 One promising area for alleviating the lack of ocean profile data in the IAS is the
485 deployment of ocean gliders that can sample temperature, salinity and other variables at
486 depths up to 1000 meters. At present there are an average of 10 gliders operating in the
487 GoM at any given time but fewer than half of them transmit publicly available data
488 through the global telecommunication system (GTS). Only two gliders operate in the
489 Caribbean north and south of Puerto Rico, the basis of a pilot project designed to assess
490 the potential of gliders for predicting the intensification of hurricanes. However the
491 project sunsets in 2015 and no other glider sampling is projected for the Caribbean.
492 Glider sampling has its limitations and can't entirely satisfy the need for subsurface
493 ocean data. But because research vessels are expensive and ARGO floats can't be
494 navigated away from grounding depths in a confined marginal sea, more glider-based
495 research is clearly needed, especially in the Caribbean.

496

497 **5 Discussion and Conclusions**

498 **i) Outstanding issues**

499 A growing body of literature on IAS climate has revealed that IAS is a primordial
500 soup of a spectrum of important scales of variations that has to be viewed not in isolation
501 but as part of the complex surrounding land, local and remote oceans and atmosphere.
502 The continued underperformance of the global models over the IAS through several
503 generations of model development is of grave concern. The IAS provides an ideal test
504 bed in the proximate location of North America:

- 505 • To examine the role of scale interactions in the manifestation of its important
506 scales of variations; the synergy of the IAS mean state and variations with the
507 atmospheric LLJ's and the mesoscale eddies in the ocean has to be more clearly
508 understood.
- 509 • To understand the mechanisms of a seasonally persistent warm pool and the
510 stratification of the upper ocean vis-à-vis continental monsoon dynamics and
511 convection in the barrier layer formation; similarly the role of ocean dynamics,
512 air-sea fluxes, and cloud radiative feedbacks has to be more carefully studied in
513 the context of the AWP.
- 514 • The delineate source of variability from natural and anthropogenic influence in a
515 region like the IAS is very important as it displays robust manifestation of the
516 AMO and hosts the upper limb of the AMOC.
- 517 • The role of dust and Saharan Air Layer (SAL) in the IAS climate variations and
518 their influence on the genesis of TC in the western Atlantic have to be further
519 quantified.
- 520 • The uncertainty in the diagnosis of long-term changes in the surface temperature
521 of the IAS needs to be reconciled while equally importantly quantification of

522 changes to upper ocean stratification is necessary to understand the observed
523 long-term changes in upper ocean tropical cyclone activity

- 524 • Climate projections for the IAS have to be understood more holistically than in
525 isolation especially when it is being recognized that land hydrology has an
526 important role to play both via river discharges into the IAS as well as through
527 atmospheric response to latent heat release.
- 528 • In the absence of far less than ideal observing systems, reconstruction of the
529 history of IAS climate especially to decipher important variations of features like
530 LLJ's, mid-summer drought, tropical cyclones, mesoscale convective systems is
531 dependent on developing robust reanalysis at significantly high resolution that
532 take in to account the land hydrology-ocean-atmosphere interactions.

533

534 **ii) Emerging opportunities**

535 Coordinating with ongoing projects, partnering with local organizations in the
536 region, and leveraging technological advances could significantly ameliorate the
537 observational gaps in the IAS and its adjacent nations. For example, in response to the
538 need to monitor both short and long term natural hazards throughout the Caribbean and
539 Mexico, the National Science Foundation (NSF) has funded two GPS-based atmospheric
540 sounding initiatives: The Continuously Operating Caribbean Observation Network
541 (COCONet) (Braun et al. 2012) and the Trans-boundary, Land and Atmosphere Long-
542 term Observational and Collaborative Network (TLALOCNet) in Mexico. Mexican
543 partners, including the National Autonomous University of Mexico (UNAM) will also
544 add to this network (see SM S.11). Data products from these networks include estimates

545 of column integrated tropospheric water vapor; surface meteorological variables
546 including wind speed and direction, air temperature, humidity and precipitation; time
547 series of daily positions and component velocities for each station (used to quantify
548 tectonic changes in the region); and high-rate low-latency data from a subset of stations.
549 Similarly, new techniques like Global Positioning System (GPS) Radio Occultation (RO)
550 measurements can provide relatively accurate atmospheric sounding data with high
551 vertical resolution especially above the atmospheric boundary layer (Anthes et al. 2008)
552 that could supplement the sparse upper air network in the region.

553 Several important measuring and modeling projects for the GoM are currently in
554 progress or are about to be financed either by the oil industry and/or government agencies
555 from different countries (e.g. the Gulf of Mexico Research Institute). A coordinated
556 approach to achieve some basic common goals among these projects could help sustain a
557 multinational long-term observing and monitoring program at least for the GoM. In
558 addition, new technologies including underwater gliders appear to be particularly ideal
559 for setting up a relatively low cost long-term observing program for the IAS in which
560 cross-sections across the Caribbean Current or in the GoM could be regularly sampled.
561 Choosing some of these sections to coincide with satellite-altimetry tracks would provide
562 invaluable information for calibration of altimetry against observed stratification and heat
563 content. Glider observations seem especially well suited for studies of hurricane
564 intensification, which could be supplemented with greater coverage by surface drifters
565 and IRIDIUM-controlled ARGO floats. A pilot underwater glider project for the
566 Caribbean Sea has already started since 2014
567 (<http://www.aoml.noaa.gov/phod/goos/gliders>). Coordinated intensive field observations

568 can also be planned to provide high temporal and spatial resolution atmospheric and
569 oceanic observations in limited regions to better understand local and regional physical
570 process and to provide high quality datasets for improving models. High resolution
571 modeling studies may also provide a bridge to improving global model physical
572 parameterizations, if coordinated with such field programs. The fundamental challenge
573 for future IAS research is to create sustainable funding to maintain these observational
574 systems (e.g., gliders and GPS networks). There are also ongoing efforts to rescue
575 historical meteorological data in the Caribbean through the Caribbean Agro-
576 Meteorological initiative (<http://www.cimh.edu.bb/cami/>). Likewise there are capacity
577 building measures by Caribbean Institute for Meteorology and Hydrology and other such
578 regional institutions which raise our hopes to promote better observational platforms in
579 the region.

580 Another of the current grand challenges in seasonal-to-interannual prediction is
581 rainfall during the warm season over North America, which is a difficult problem because
582 much of the rainfall is associated with relatively small-scale structures (e.g.,
583 thunderstorms and mesoscale convective complexes) that are not adequately resolved by
584 the current generation of seasonal-to-interannual prediction systems. As a consequence,
585 large systematic errors occur in the predicted rainfall anomalies that seriously limit
586 forecast quality. Fundamental predictability issues also exist, namely that remote forcing
587 from remote climate variability (e.g. ENSO) is relatively weak and the rainfall signal-to-
588 noise ratio over North America is comparatively small. Nevertheless, our current
589 understanding indicates that current prediction systems are underperforming, even with
590 the limited predictability (see SM [S.10]).

591 The IAS climate processes outlined in this paper provide opportunities to improve
592 local and remote North American hydroclimate prediction across temporal scales. An
593 opportunity also exists to provide a more holistic picture of Western Hemisphere climate
594 and its prediction by bridging tropical South American climate variability with that of the
595 IAS. Moving forward, the modeling and observational challenges of IAS have to be
596 overcome for improved climate monitoring and prediction of North America.

597

598 **Acknowledgements**

599 We acknowledge the help of graduate student Michael Kozar of FSU in preparing Fig. 8.
600 We also thank Kevin O'Brien of NOAA for generating Fig. SF12. We thank the three
601 anonymous reviewers who greatly helped in improving this manuscript from its earlier
602 version with their thoughtful suggestions. We also acknowledge the support of NSF,
603 NASA, NOAA, CISCE. Chunzai Wang, Sang-Ki Lee and David Enfield acknowledge
604 the support of the base funding to NOAA/AOML. We also acknowledge data resourced
605 from the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at
606 <http://www.esrl.noaa.gov/psd/>, UCAR from their website <http://dss.ucar.edu>

607

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- 1064

1065 **Figure Captions**

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1120 moisture transport for the (c) 10 most active and (d) 10 least active U.S. tornado years in
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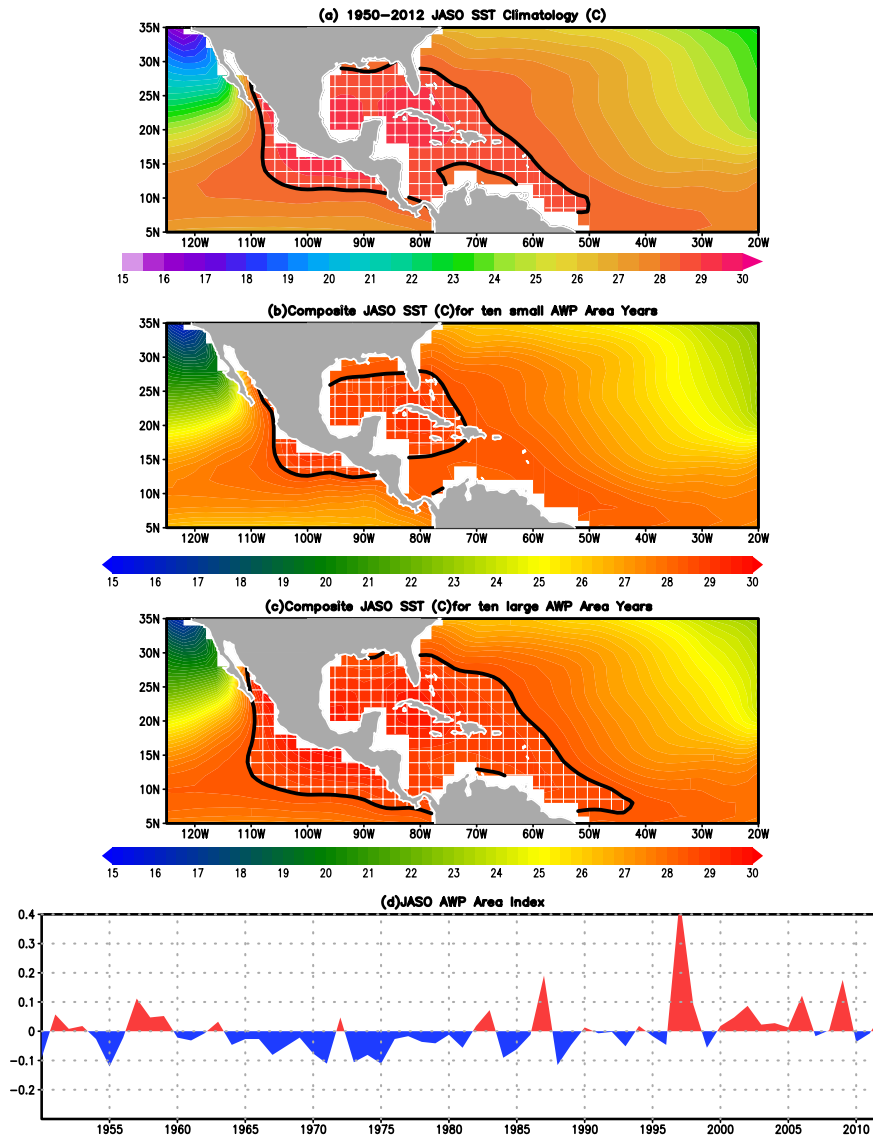
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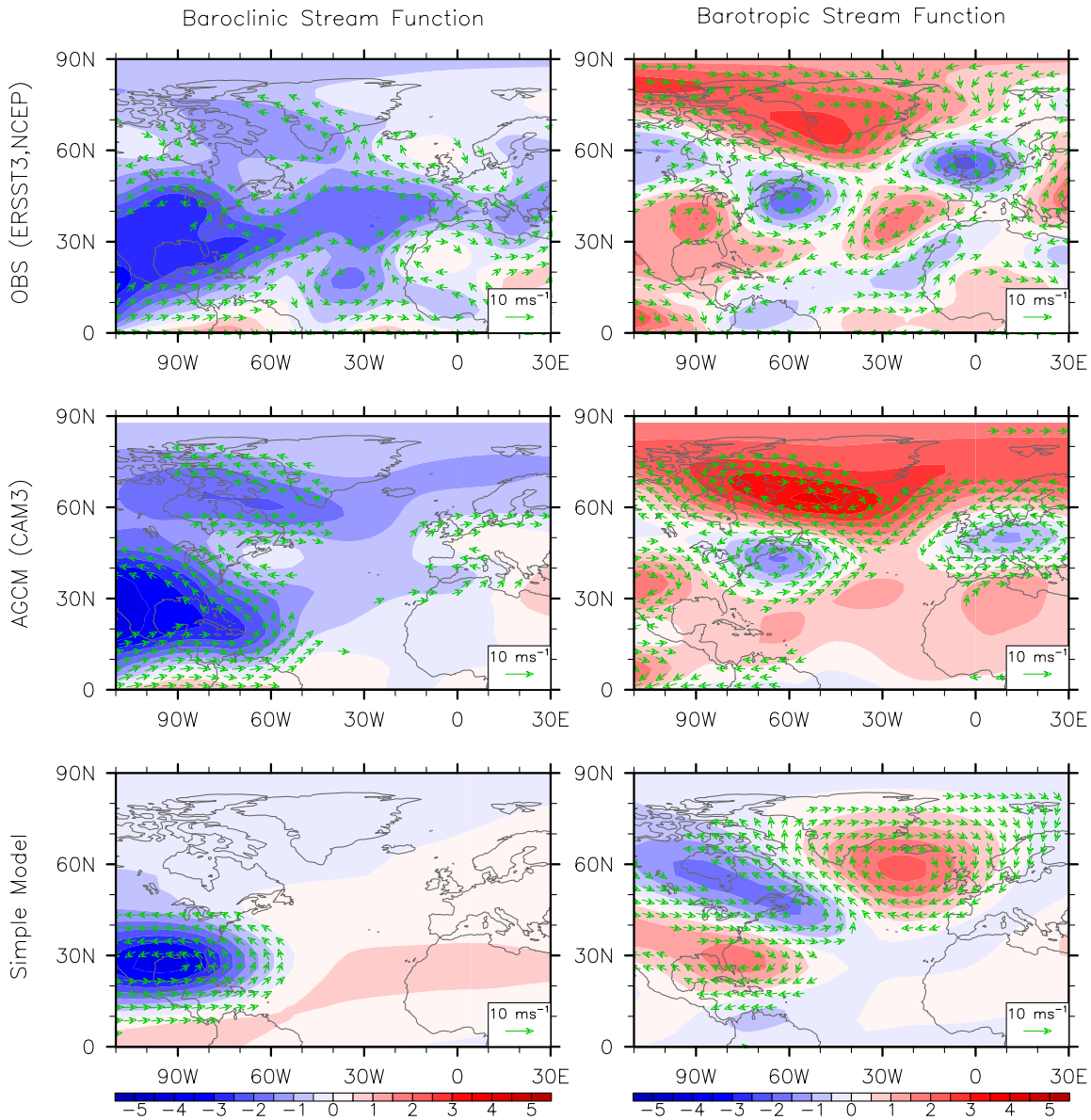
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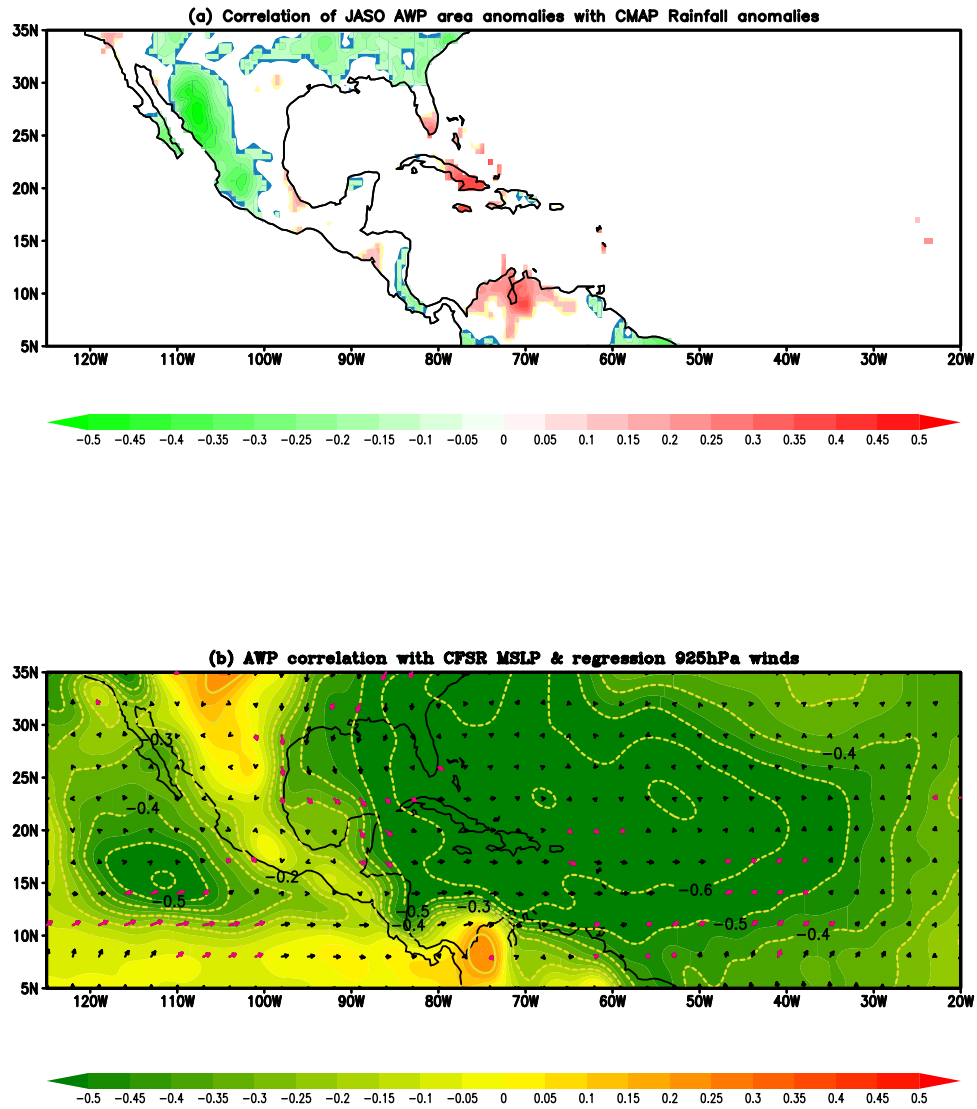
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Summertime Atmospheric Teleconnections Linked to Large–Small AWP



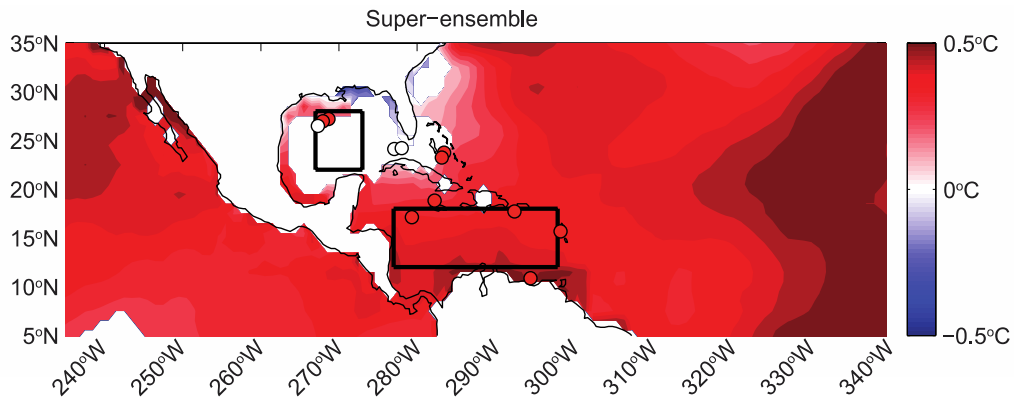
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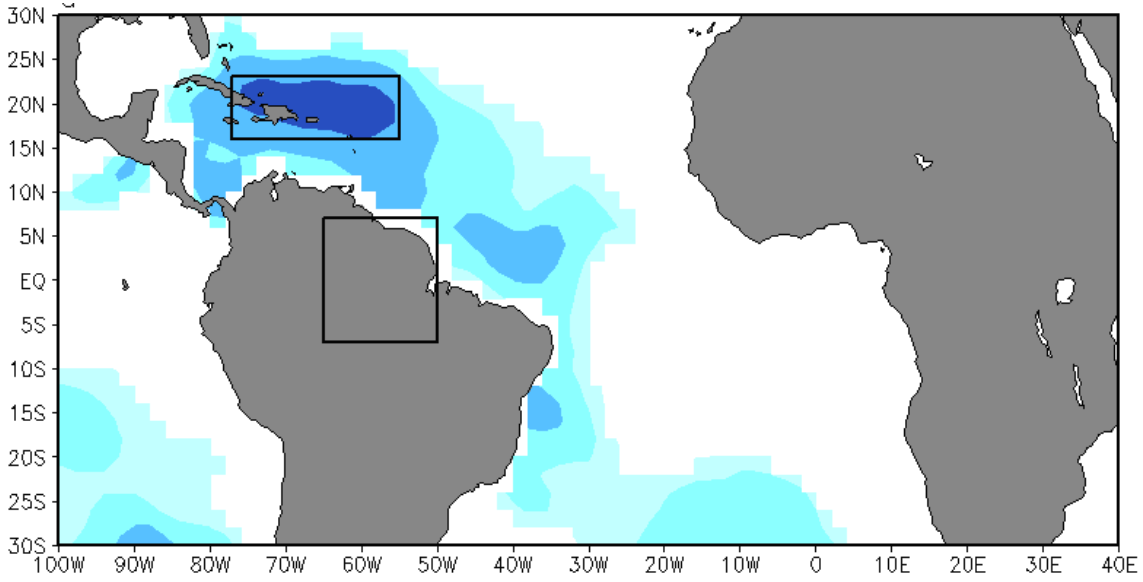
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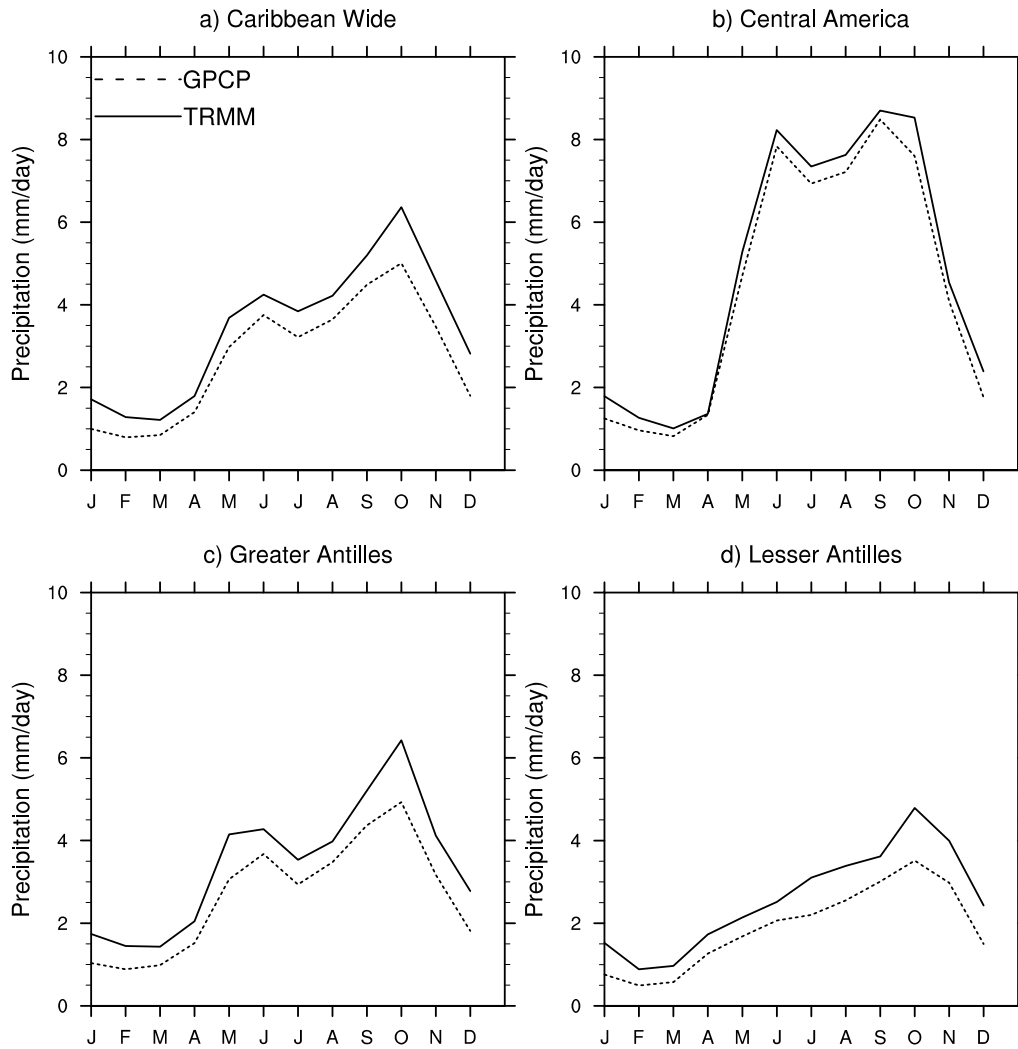
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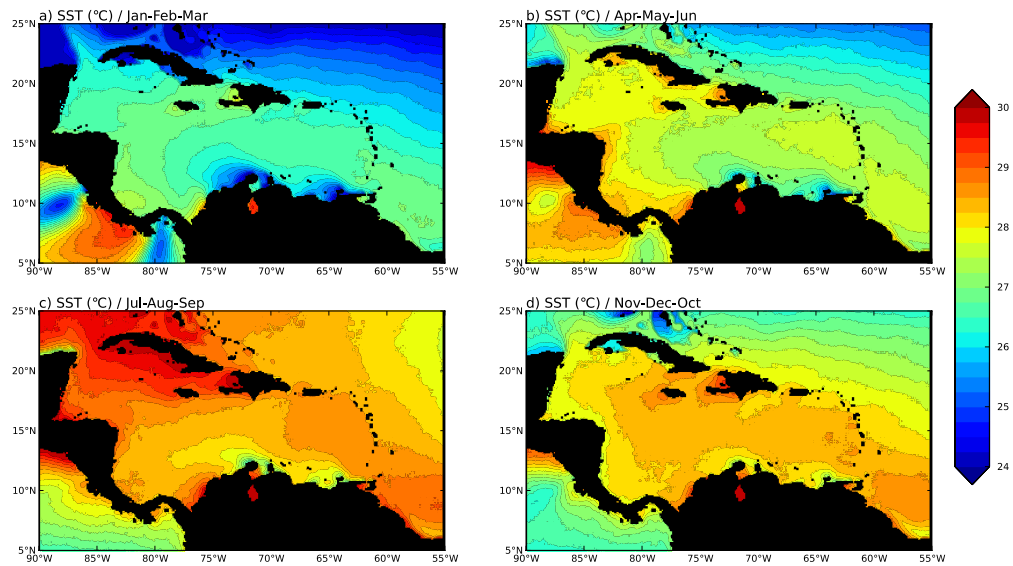


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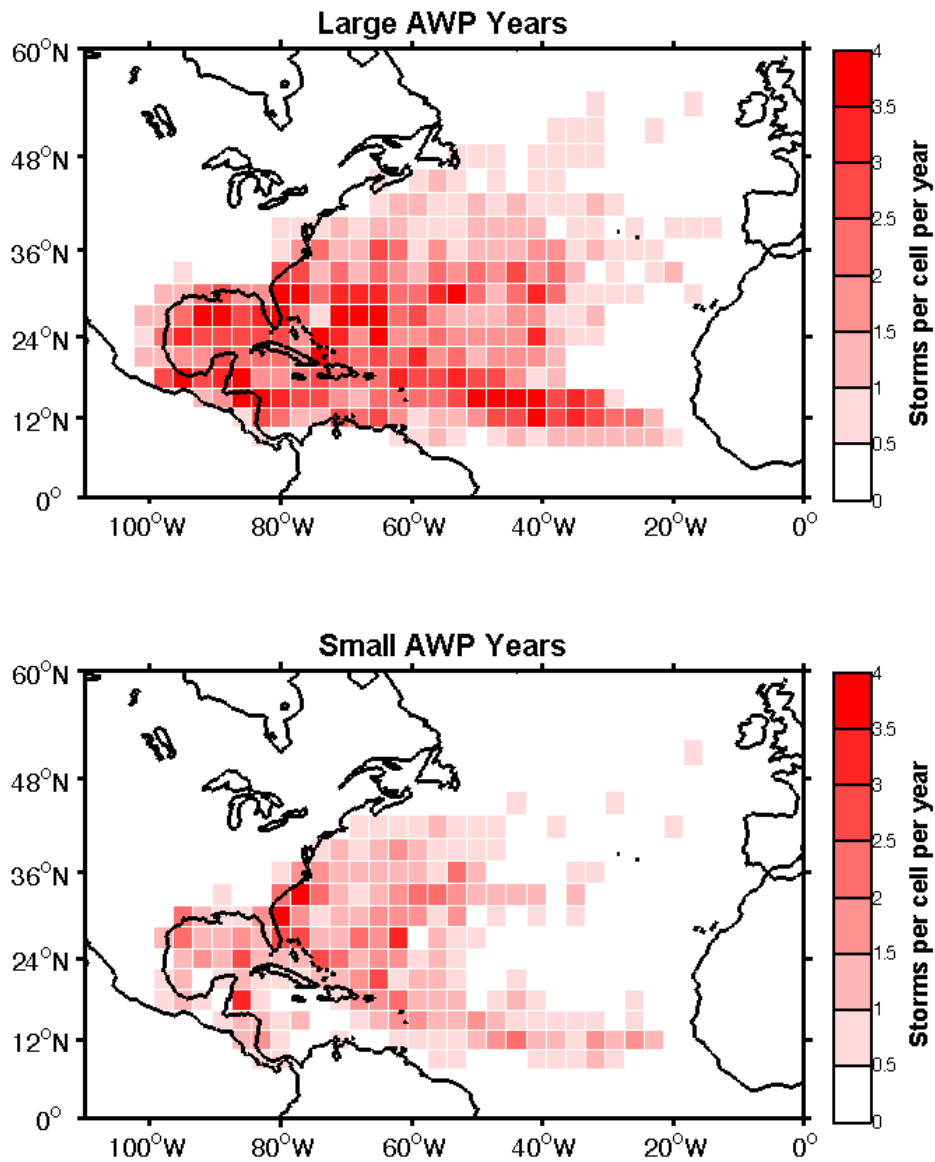
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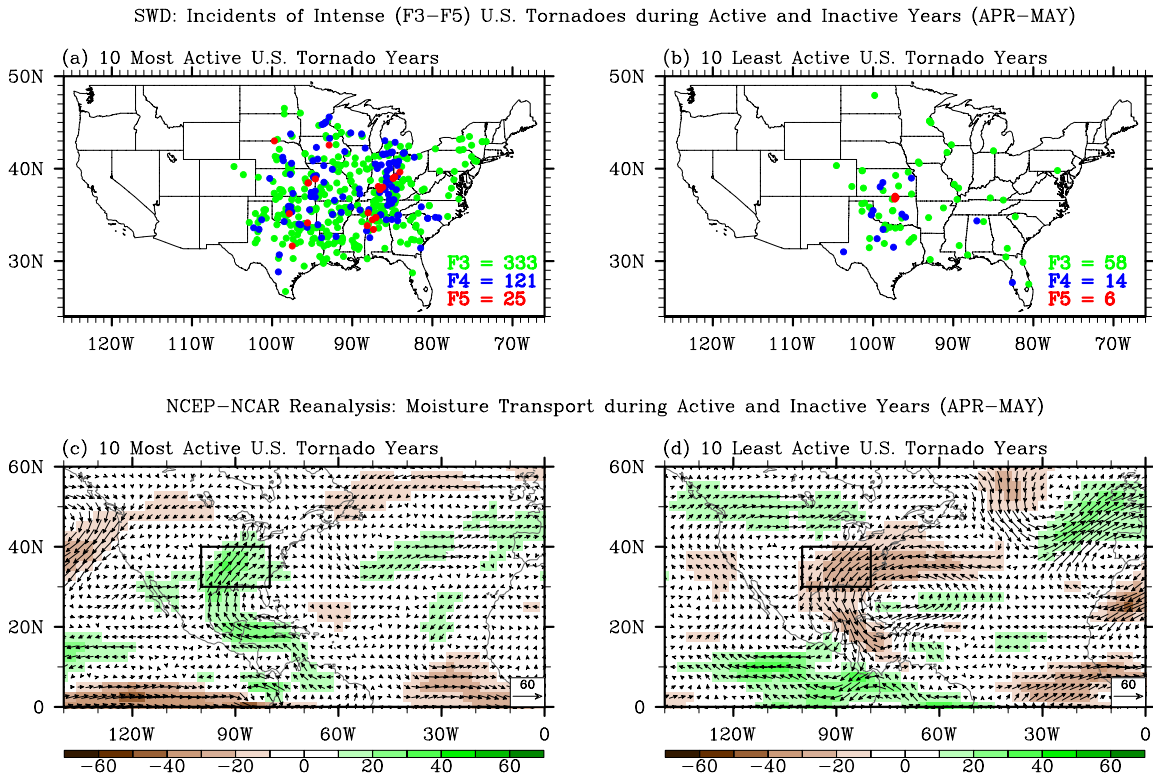


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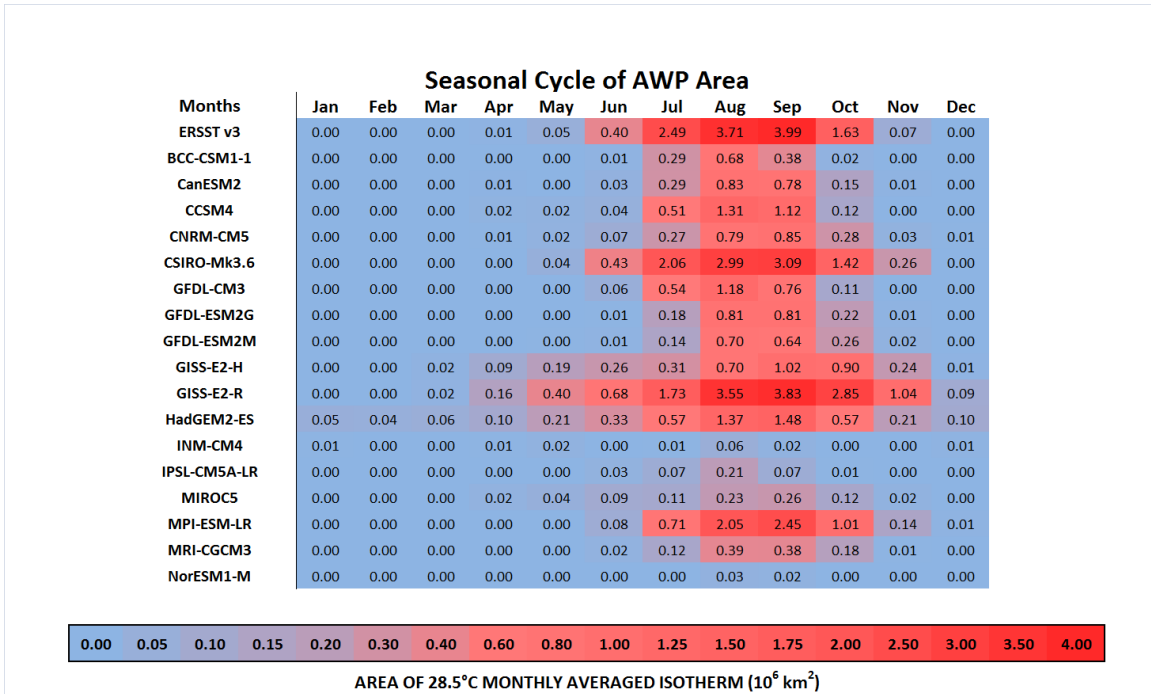
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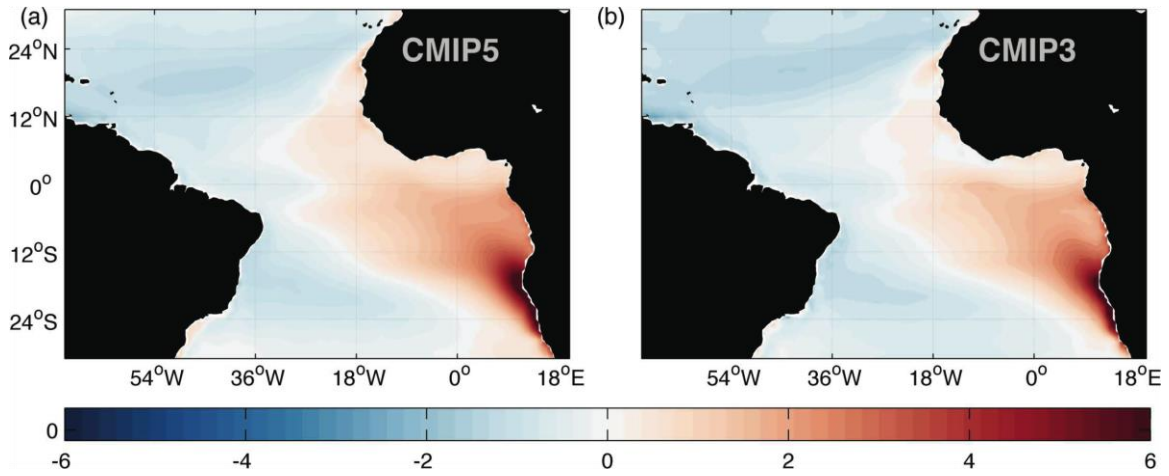
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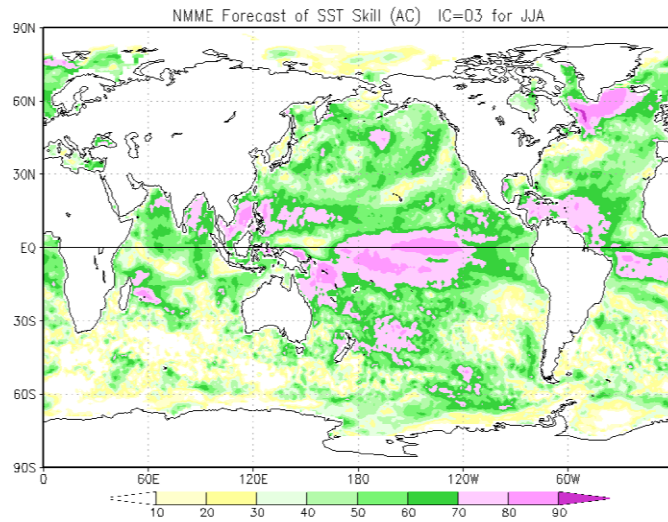
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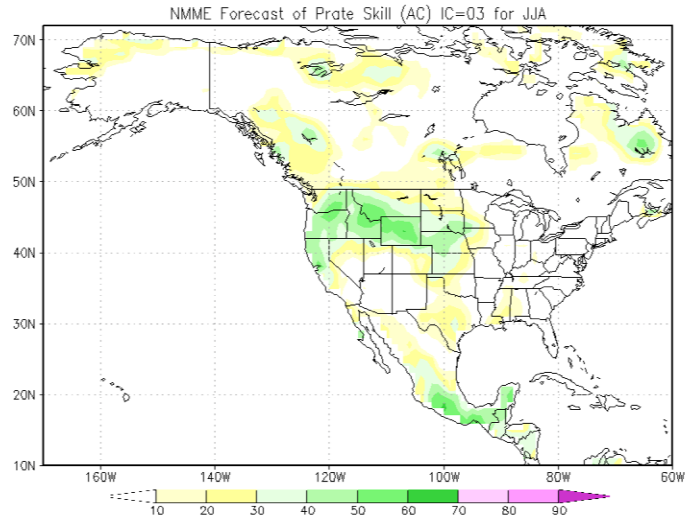
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Supplemental Material

[Click here to download Supplemental Material: bams-supplementary-R.docx](#)

Response to review comments

We appreciate the detailed review comments provided by the three reviewers. We have revised the manuscript accordingly and have provided here our point-by-point response (regular font) to their thoughtful comments (*italicized*).

Reviewer #1

General Comments

This manuscript is the result of a collaborative effort to present a view of advances in our understanding of climate dynamics in the so-called Intra Americas Seas region, with particular interest in the role of the IAS in forcing climate variability over North America. For this purpose, a large number of scientists put together a sort of review on what they consider are the most important challenges to improve our ability to predict and project climate on various time scales over the IAS region (or maybe, over North America, the title is not clear on this respect).

The authors have drafted this manuscript to highlight the fact that the Intra-Americas Sea (IAS) is an under-tapped source of climate predictability for North America across time scales. The manuscript is about the IAS with a motivation that it influences North American climate. The manuscript points to sufficient evidence in modeling and with available observations to suggest that the IAS is an influential source of the North American Climate variability that can be capitalized on. However as the paper indicates, we are far from realizing this given the poor predictability and the simulation fidelity for the North American region shown by our current climate models. These model limitations as the paper now clearly states possibly stem from our lack of understanding of the IAS processes that regulate its upper ocean heat content, sea surface temperature, the potential external forcing (e.g. ENSO, continental monsoons) that could pre-condition the teleconnections emanating from the IAS, and or the role of IAS intrinsic variability. The IAS is also a unique region that displays an active land-atmosphere-interaction through very extensive barrier layer formations from major river discharges, which affect the atmospheric behavior. In other words land interaction is not a passive component but an active player of the IAS climate system. In addition, we are beset with a situation of rapidly degrading observations in the region with a far less than optimal climate monitoring network.

Yes, the primary focus of the paper is on the Atlantic warm pool (AWP) that has a strong seasonal component and offers a strong case for an alternative source of climate predictability in seasons when influence of ENSO is weak over North America. And the geographical focus is on the IAS and its teleconnections. We clearly note that the IAS is a subset area of the AWP. Given that the AWP is a seasonal phenomenon but varies from the intra-seasonal to secular time scales and the IAS does not cease to interact and contribute to the regional climate in the rest of the year, we have to weave tactfully between the IAS and AWP through the paper, which we have attempted in the revised manuscript. Furthermore, there are other interesting scales like the intra-seasonal variations, the decadal variations, and the influence on the winter Gulf cyclones, mesoscale ocean eddies and currents, atmospheric low level jets which additionally make

the IAS a very pertinent region to observe throughout the year. This article is an honest attempt to bring the attention of the BAMS readership on the opportunities and challenges that the IAS offers to mitigate the vulnerability of a growing population to the vagaries of climate affected by the IAS.

We have slightly modified the title of the paper to provide more clarity and we have made substantial changes to the text throughout the manuscript in response to the review comments.

The effort is far from becoming an adequate review article on the role of the IAS on the North American climate. Even more, it seems a failure in terms of identifying the dynamic and physical elements that are necessary to define research priorities, as was the case of IASCLIP. By the way, the original scientific plan of IASCLIP was a much better review work on the IAS climate. It is clear that in order to write a good review it is not enough to bring together a large group of people, but to have a deep understanding of the scientific problem, a non-biased view of what the relevant literature is in order to cite it, and the guidance of someone capable of self-criticism. I would like the authors to do a critical review of their work and think of ways to prepare something more adequate to be published in BAMS. In its present form, the manuscript is simply a collection of incoherent statements, ideas, hypothesis, speculations and lots of their own or preferred scientific references.

We acknowledge and appreciate the candid and frank review of our article by the reviewer. We have followed the suggestion of reviewer 3 to reorganize the paper. We have made the pressing scientific issues clearer with a separate subsection on outstanding issues. We also appreciate the recognition of the original scientific plan of IASCLIP, which many of the current authors of this paper were involved with. The key science issues raised in the original science plan of IASCLIP (http://www.eol.ucar.edu/system/files/iasclip_prospectus_latest.pdf; pages 25-30) are also raised in the revised manuscript. Indeed, we have added more issues to the list that has stemmed from the burgeoning relevant literature over the years (e.g. role of the IAS on tornado activity, uncertainty in diagnosing trends in the IAS, role of upper ocean stratification in the IAS on future projections of TC activity, role of oceanic mesoscale processes in maintaining the warm pool, etc).

The authors describe some processes on various temporal and spatial scales without making reference to scale interactions as part of an important physical element of climate variability. Even more, authors refer indistinctly to various warm pools in the region (western hemisphere warm pool, IAS, eastern Pacific, Atlantic) depending on their points of view. This shows in the contrasting domains used for the maps they present in the manuscript. The supplementary material does not really help to complement the information provided in the main text. The quality of plots is low, and there should have been an effort to decide on what the domain or characteristics of the figures should've been. The jumps from one subject to another make the text difficult to follow.

We concur with the reviewer that we did not mention the role of scale interactions, which

we recognize is an integral component of the climate system in the region. As a review article that uses material from a variety of sources and authors, this disparity of reviewing a broad range of spatio-temporal scales becomes evident for the region. But it also highlights the influence of the IAS spanning a broad range of time and space scales-all the more a reason to bring this article out. We have now indicated the potential role of scale interactions in the IAS as an outstanding issue.

We have clarified the definition of various references to warm pool in the introduction. We have also tried to conform some of the figures (Figs. 1, 3, 4, Fig. SF1) to similar domains. However, given the regional and hemispheric influence of the warm pool, it is necessary to sometimes be flexible with the domain. Some of the works reviewed are specific to the domain shown. For example, the mesoscale oceanic features in the IAS, which cannot be arbitrarily formalized to a specific domain.

The supplementary material has been revised to compliment the main text. However, in the absence of specific comments, we have used our best collective judgment to arrive at the revisions for the supplementary material. Overall we have made our best attempt to improve the quality of the plots. We have followed the suggestion from reviewer 3 to reorganize the sections and sub-sections of the revised manuscript.

In summary, this is not even close to a scientific paper of the level one may expect to find in the Bulletin of the AMS. It should definitely be rejected. It is a rather confusing text for non-specialists.

We have sincerely considered the comments and suggestions made by the reviewer to make our best attempt in revising the manuscript.

Minor comments:

L36, should be "...the IAS are part of the Western Hemisphere warm pool".

Corrected

L39-40any region of the world undergoes "significant (climate) variability from interannual"

Agreed. The phrase is removed.

L44rephrase. Only momentum sources can modify the trade winds

Agreed. Corrected as: The onset of North and South American monsoons are coincident with changes to the trade winds with potential impacts on IAS surface fluxes and sea surface temperature (SST) variability.

L50one of the most poorly observed regions of the worldThis is questionable
The supplementary material (S. 9) and Fig. SF12, which shows the current ocean

observations (as of 2014) justifies this statement. Furthermore, we have added more text in Section 4 (last paragraph) on the current state of Glider observations in consultation with NOAA NDBC. We have however removed the sentence comparing IAS with the Polar Oceans. We can state conclusively that IAS is indeed one of the most poorly observed regions of the world.

L52.... Provides recommendations to advance understanding of IAS climate variabilityis also questionable given the way the information is presented.

We now provide a sub-section on outstanding scientific issues in addition to the sub-section on the emerging opportunities that give a basis for this statement.

L65 what is meant by "appears first in late boreal spring..? What is the criteria to define its first appearance? Does it fade and then "reappears"?

The WHWP is a seasonal phenomenon. The onset and demise of the WHWP, AWP and that of EPWP can be objectively defined (Misra et al. 2014, 2015). The onset is defined as the day when the area of the warm pool exceeds its climatological annual mean value of warm pool. Likewise the demise is defined as the day after the onset when the area of the warm pool recedes below the climatological annual mean value. By these definitions one can arrive at specific dates of onset and demise of the AWP.

L69 what do you mean by terrestrial variability?within the IAS??

It was meant to be terrestrial hydrologic variability in continental North America. The sentence has however been removed.

L73 What is the IAS system? The Caribbean sea and the GoM? Do you also include the eastern Pacific warm pool in it?

The IAS as stated is Caribbean Sea and the GoM. It does not include eastern Pacific.

L77 The Influence of NASH over the Papagayo or the Choco LLJ is more a hypothesis than a fact.

There is evidence that the CLLJ, and their branches across Tehuantepec, Papagallo and Panama have to do with an amplification of the large scale circulation of the NASH. See for example Fig 1 in Elinor R. M. and C. Schumacher (2011). Also, the CLLJ boreal summer maximum is related to the strengthening and westward extension of the NASH (Wang and Lee 2007; Wang 2007; Munoz et al. 2008; Cook and Vizy 2010). We have edited the manuscript to provide more clarity.

We agree that as for the Choco jet, the influence of the NASH is more a hypothesis than a fact. We have added this as part of the outstanding issue in the revised manuscript.

L79Ocean processes impacting the region.....What region ?

We meant the IAS. It is stated now.

L84 Aren't the GoM and the Caribbean Sea part of the Atlantic?

Yes they are. We have edited the phrase in the revised manuscript.

L85 Do you mean the monsoon severe thunderstorms, those in the southwest US?

Yes, but also includes severe thunderstorms in Mexico and rest of Central America. We have revised the sentence for clarity.

L90 What is the IAS variability?

The IAS variability is the in-situ surface and sub-surface ocean variability, which in turn is related to overlying and remote atmospheric variability and terrestrial climate that is connected through river discharges into the IAS. This manifests in the form of AWP variability in the boreal summer and fall seasons and the associated air-sea interaction, atmospheric variations of LLJ's, moisture flux, leading to wide range of spatio-temporal variability.

L92 ...to effectively predict the observed IAS climate? The title of the manuscript makes reference toChallenges and Opportunities to Understand North American Climate Variability and Predictability

As stated earlier, the IAS is crucial to North American climate variability. However we have changed the sentence to add "... to effectively predict the observed IAS climate and its teleconnections over North America..."

L100 maximum of what? Do you really mean September 3????

The seasonal peak is reached when the area enclosed by 28.5C isotherm reaches a maximum. We have revised the sentence for clarity. Yes climatologically, the seasonal peak of the area of the AWP reaches on September 3 as defined objectively in Misra et al. 2014. However we now state that it is in early September. Also see our response to L65 comment.

L110 What type of Gill-type response? The one when the forcing is off the equator? The Gill-type response requires a steady convective forcing. This is not the case over the Caribbean Sea (or the GoM) where tropical convection is associated with transient systems.

Yes, it is the one when the forcing is off the equator. In Gill's (1980) physics, the atmospheric response to a heating source is baroclinic; that is, a positive heating induces a cyclonic circulation in the lower troposphere and an anticyclonic circulation in the upper troposphere. What we mean here is that the mechanism of AWP's heating is

similar to Gill's (1980) physics. Wang et al. (2008) used the NCAR CAM3 model to perform two sets of ensemble model simulations that corresponded to heating in: large AWP (LAWP) and small AWP (SAWP). The atmospheric circulation responses to LAWP – SAWP are shown in Fig. 1 (below). Consistent with Gill's (1980) dynamics, the atmospheric response to the AWP's heating is baroclinic. The lower troposphere shows a cyclonic circulation in the AWP and eastern North Pacific (Fig. 1b; below), whereas the upper troposphere has an anticyclonic circulation pattern (Fig. 1a; below). Furthermore, a vast majority of the observed soundings in the Caribbean have moist tropical air mass characteristics that have a very low lifting condensation level (~944hPa; Dunnion 2011). In addition, the study also suggests that the CAPE in the soundings over the Caribbean region indicate a moderately unstable environment. In other words, there is a near steady cloud distribution in the Caribbean, which provides a steady heat source.

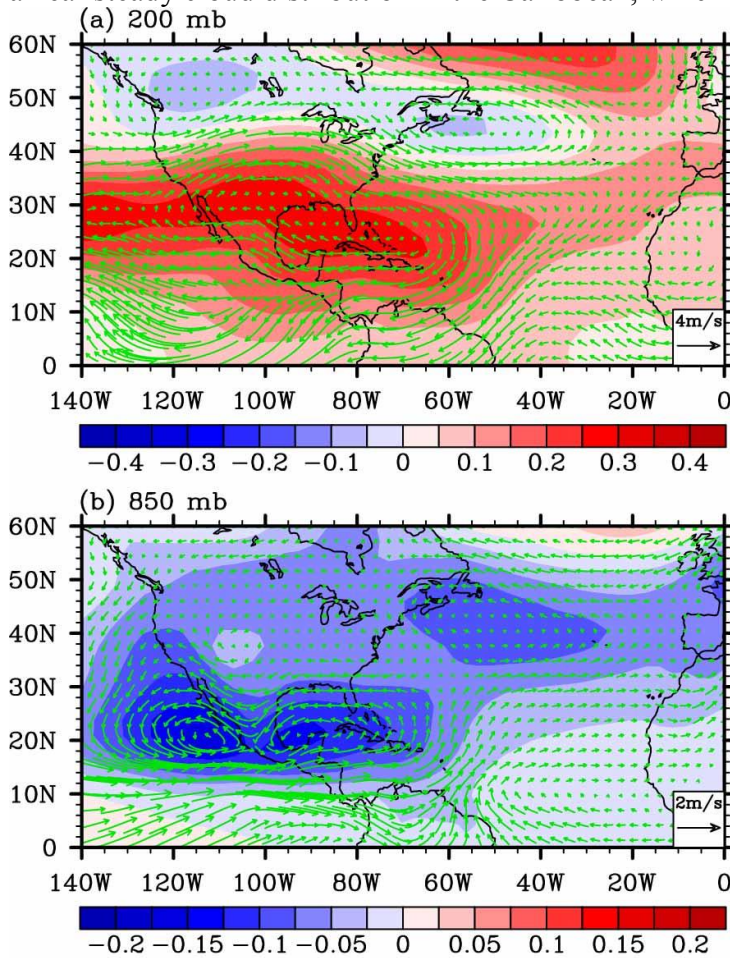


Figure 1: Atmospheric response to the LAWP and SAWP model ensemble runs (LAWP – SAWP). Shown are (a) geopotential height (10^2 m) and wind (m s^{-1}) at 200 mb, and (b) geopotential height and wind at 850 mb (Wang et al. 2008).

Dunnion, J. P., 2011: Rewriting the climatology of the Tropical North Atlantic and Caribbean Sea Atmosphere. *J. Climate*, 24, 893-908.

L107 Why is the EPWP included in a discussion that focuses in the IAS warm pool?

The reference to EPWP has been removed.

L113-115 The AWP is not independent of the ENSO signal, given the CLLJ (strength) is modulated by El Niño and La Niña on interannual time scales, and this in turn affect upwelling off the coast of northern South America.

AWP area variation is largely independent of ENSO (Wang et al. 2006; Zhang and Wang 2012; Misra et al. 2013). Zhang and Wang (2012) used the data from 1950-2010 to show that of the 17 large AWP, 10 large AWP in the summer and fall are preceded by an El Niño event in the Pacific during the preceding winter, whereas 7 large AWP are not preceded by an El Niño event in the preceding winter. Although ENSO sometimes coincides with AWP variability, an El Niño in the preceding winter does not necessarily follow a large AWP in the summer.

It is the area variation of the AWP, which has the large-scale teleconnections that affect the hydroclimate of the continental North America. However the CLLJ is undoubtedly affected by ENSO, which in turn affects the SST along the coast of northern South America, which is at a much smaller scale than the size of the AWP. Furthermore, the CLLJ has much higher interannual frequency than the ENSO's broad 2-7 periodicity (Wang 2007) indicating that ENSO is not the only remote forcing affecting CLLJ's interannual variability. In fact Wang (2007) showed that the CLLJ, which has a bimodal peak in its annual cycle, has a stronger correlation with Niño3 SST index in boreal winter than in the boreal summer season when CLLJ has a higher peak. Therefore in the context of the boreal summer season CLLJ variability we say it is "largely" independent of ENSO.

L118 Why do you consider the Caribbean Sea a separate region from the Atlantic?

The Caribbean Sea is a marginal Sea of the Atlantic. It is semantically not a separate region from the rest of the Atlantic. But the oceanic processes of the mesoscale eddies generated by the relatively strong currents along the coasts of South America, the water mass exchange through the passages of the Caribbean islands provides a distinctness to this marginal Sea. We have edited the sentence to suggest that "... winds advect moisture from the eastern tropical north Atlantic Ocean...".

L119 Have you looked at the momentum balance in the CLLJ region? Have you consider a geostrophic balance in which the mass field adjusts to the wind field? This is a more local effect, since the NASH does not enhance everywhere but over the Caribbean Sea only.

As noted by Wang (2007) and Cook and Vizy (2010), the CLLJ is geostrophic to first order, thus it is controlled by gradients in pressure (geopotential). As the NASH expands and strengthens, the meridional pressure gradient across the Caribbean Sea is increased and the CLLJ strengthens (Wang 2007; Muñoz et al. 2008; Whyte et al. 2008; Cook and Vizy 2010). The opposite occurs when the CLLJ contracts. Wang (2007) and Muñoz et al. (2008) show that the semiannual cycle of the CLLJ is in phase with the semiannual cycle

of the meridional SLP gradient across the Caribbean Sea. Meridional gradients in SST across the region also show a semiannual cycle that is in phase with that of the CLLJ. This suggests a feedback between the atmosphere and the ocean that acts to reinforce the CLLJ through the effect of opposite values of wind stress curl and hence upwelling on either side of the jets zonal axis (Wang 2007). Using an idealized modeling study, Wang et al. (2008) also showed that the magnitude of the SST anomaly in the Caribbean Sea influences the strength of the CLLJ through interactions with the NASH. This result is also echoed by the results of Rauscher et al. (2011). When Caribbean SST is anomalously warm (cold), the CLLJ is anomalously weak (strong). A brief discussion on this has been added.

L125 Correlations do not mean a dynamical analysis (momentum balance) or understanding of the process.

Indeed correlations are not by itself a complete understanding of the process. But in this case it is the manifestation of the underlying dynamical mechanisms. As shown with the Gill response to the AWP forced atmospheric diabatic heating, the regional meridional overturning circulation is modulated, that affects the strength of the NASH.

L139 The maximum in convective activity in the Caribbean coast of Costa Rica and Nicaragua occurs over flat terrain (no orographic forcing)

Point well taken. The maximum in convective activity in the Caribbean coast of Costa Rica and Nicaragua occurs at the jet exit region of the CLLJ and fluctuations of the CLLJ as pointed in Herrera et al. (2014).

L149 Why is the southeastern tropical pacific examined in the context of the IAS or the North American region? This is confusing!

It is to demonstrate that the IAS through the AWP has a large-scale influence on the western hemisphere climate that extends south of the equator as well. In other words, this is evidence of the large-scale improvements that can be anticipated by improving our ability to simulate and predict AWP variations.

L161 Do you mean that the EPWP is part of the IAS? (not clear)

No, EPWP is not part of the IAS. We have modified the sentence to improve clarity.

L163 Have you looked at recent decadal trends in precipitation over the IAS and Central American region to evaluate the quality of state-of-the-art GCMs?

We have plotted in Fig. 2 (below) the precipitation trends for the four seasons from the multi-model mean of 28 CMIP5 models for the 1950-2004 period and compared it with the corresponding CRU observations. The figure indicates that the multimodel ensemble mean has significant differences from the observed trend. Qualitatively, the sign of the trends are reasonable despite its muted magnitude in the model simulations. However,

some individual ensemble members from some models produce similar trend patterns as observations (not shown). However, one has to be extremely cautious in interpreting the fidelity of model simulations over one time period for another, especially when the external radiative forcing is substantially changing (Reifen and Toumi 2009; Pierce et al. 2009; Santer et al. 2009).

Pierce, D. W., T. P. Barnett, B. D. Santer, and P. J. Gleckler, 2009: Selecting global climate models for regional climate change studies. *Proc. Natl. Acad. Sci. U. S. A.*, 106, doi:10.1073/pnas.0901736106, 8441-8446.

Reifen, C. and R. Toumi, 2009: Climate Projections: Past Performance no guarantee of future skill? *Geophys. Res. Lett.*, 36, L13704, doi:10.1029/2009GL038082.

Santer B., and coauthors, 2009: Incorporating model quality information in climate change detection and attribution studies. *Proc. Natl. Acad. Sci., U. S. A.*, 106, doi:10.1073/pnas.0901736106, 14, 778-14, 783.

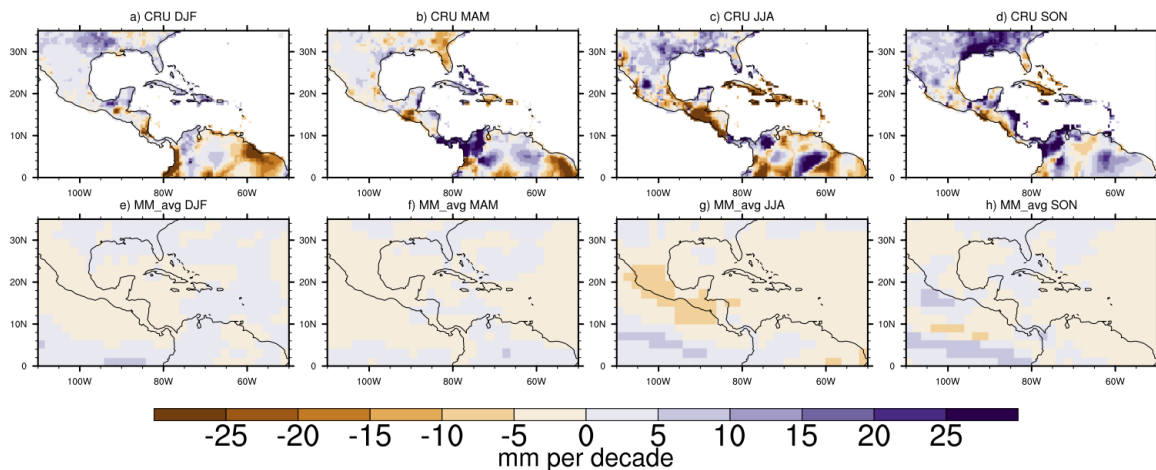


Figure 2: Top row: Observed precipitation trends by season. Bottom row: Multimodel mean precipitation trends from 28 CMIP5 models. The trends have been computed for 1950-2004 period.

L168 Are CMIP5 predictions of future climate or simple scenarios or sensitivity experiments?

These are CMIP5 centennial projections under RCP8.5.

L198 Do the authors really think that downscaling GCM output (with all the systematic bias and errors) will help to better understand the regional response of climate change?

The referred papers seem to suggest that downscaling to higher resolution improves the volume transport. So the evidence does seem to suggest that downscaling GCM output in the event that GCM resolutions don't increase to resolutions of 10km or less in the near future for routine projections of the CMIP type may be one of the alternatives for the region. More than advocating downscaling, the study seems to indicate the role of

increased resolution on resolving the ocean currents and consequently affecting the upper ocean heat content in the region. We have however avoided using the word downscaling in the referred sentence.

Reviewer #2

General comments:

This paper by Misra et al. reviews the variability and changes of Intra-Americas Seas (IAS), summarizes the role of IAS in the climate of North (and northern South) America, and discusses the limitations of current model simulations and observations. Some parts of the paper (including monsoons in section 4, tropical cyclones and tornadoes in section 6) are pretty good, whereas some parts (including ocean circulation in section 5, barrier layer in section 7, and observing network in section 9) need significant improvement. Meanwhile, the authors need to explicitly identify the critical and unresolved scientific issues/questions for each topic and provide insightful comments/suggestions (not only those well known, such as Lines 529-535). In addition, some irrelevant discussions should be removed. Overall, the paper needs a major revision before it can be considered for publication.

We have substantially revised the sections on ocean circulation, barrier layer and observing network based on the specific suggestions provided by the reviewers. We have also added a new section on outstanding issues that explicitly identifies the critical and unresolved scientific questions. We have followed the reviewer's suggestion to edit discussions on some of the sub-topics.

Other major points:

Lines 56-66: I think it is unnecessary to describe the Western Hemisphere Warm Pool (WHWP) in detail at the beginning of the introduction. It would be better to start with a discussion of the importance of IAS and a brief description of the connection between IAS and WHWP.

We have modified the paragraph to begin with the IAS and introduce the WHWP subsequently.

Lines 110-113 and Fig. 3: I cannot see the effect of the AWP-induced diabatic heating on the subtropical high in the southeastern Pacific. Please clarify.

We have not shown the subtropical high in the southeastern Pacific. But Wang et al. (2008) clearly show its influence over the southeastern Pacific. We have revised the sentence and directed the readers to Fig. 8 in Wang et al. (2010) for clarity.

Section 2: The section title is about "IAS", but the entire section actually discusses the AWP. This is sort of confusing, as the two concepts are not the same. The same issue can also be found in other sections.

Good point. A majority of the AWP is however in the IAS. We have renamed the section title to AWP teleconnections.

Lines 127-132: "a large AWP weakens the southerly GPLLJ", but I see a strengthened southerly (the red wind vectors over 100-90W, 20-40N) in Fig. 3b. Please clarify.

Thank you for pointing this apparent mistake—we apologize. We resolved a bug in our drawing script and have now revised the figure. It now shows that large AWP weakens the GPLLJ.

Lines 229-230: Please explain the physical mechanisms.

The westward shift of the NASH enhances moisture transport from the IAS to the U.S. Great Plains, which in turn, weakens moisture transport to the NAM region (Arias et al 2012) and enhances southerly cross-equatorial flow over South America and moisture export from southern Amazonia (Arias et al 2015). The warm phase of the AMO leads to warmer SST anomalies and stronger ITCZ over the tropical North Atlantic and northern South America, leading to an equatorial contraction of the tropical meridional circulation over the American-Atlantic sector, stronger subsidence and moisture divergence over the NAM and southern Amazonia. This is explained in the revised text.

Lines 292-296: What causes the coincidence between a net freshwater gain in the TNA region and the large AWP regime? Also, does "coincides" correspond to "induced"?

The point here is that the AWP variability affects the freshwater flux and ocean salinity. The moisture budget analysis demonstrates that a large (small) AWP is associated with a local freshwater gain (loss) to the ocean, less (more) moisture transport across Central America and a local low (high) ocean salinity. In association with a large (small) AWP, warmer (colder) than normal SSTs induce anomalous low-level convergence (divergence), which favors anomalous ascent (descent) and thus generates more (less) precipitation. On the other hand, a large (small) AWP weakens (strengthens) the trade wind and its associated westward moisture transport to the eastern North Pacific across Central America, which also favors more (less) moisture residing in the Atlantic and hence more (less) precipitation. We have included a brief discussion of this.

Lines 307-309: This discussion is irrelevant. Please remove it.

Removed.

Lines 344-350: I am not convinced that the intensification of the 1993 Superstorm can be attributed to the presence of warm eddies. In Fig. 10, the storm kept intensifying along its entire pathway, independent of the presence of warm or cold ocean eddies. Atmospheric conditions may be dominant.

This section has been removed from the revised manuscript.

Lines 395-402: I understand that the authors intend to explain that the cold SST bias and dry bias in the IAS may be related to the warm SST bias in the southern tropical Atlantic. But the authors do not need to use one paragraph to describe the bias over the equatorial Atlantic. Please shorten it.

We have shortened this discussion.

Lines 403-429: I have trouble following the logic of these two paragraphs (deficiency in simulated convection -> ISV -> SST bias -> precipitation and SST bias -> precipitation bias -> deficiency in convection parameterization -> ISV). Please rewrite these two paragraphs.

We have revised the paragraphs to suggest that deficiency in convection parameterization fundamentally leads to bias in SST, precipitation and ISV.

Lines 473-474: The statement that "the IAS is currently as poorly observed as the polar oceans" sounds to be exaggerated. How about ship-based observations and glider measurements in the IAS?

We have revised the sentence to suggest that the IAS, especially the Caribbean Sea is one of the most poorly observed regions of the global oceans. We have obtained specific information from NOAA NDBC on the current distribution of ocean observing systems and added a paragraph to Section 4 regarding the current state and future potential of glider deployments. Fig. SF8 shows the data available in real time on GTS, which is freely available.

Section S7 Ocean barrier layer: the two cases shown in Fig. SF8 are irrelevant to the IAS.

We have removed the figure as suggested. However, we have replaced it with another figure that shows the extensive influence of fresh water plumes in the IAS from river discharge.

Minor points:

Lines 107-109: Using "however" here appears to emphasize the importance of the Eastern Pacific Warm Pool (EPWP). Would it be better to combine this sentence with the previous one to something like "The variability of the WHWP is dominated by the AWP variability owing to its relative size and seasonal persistence compared to the EPWP component, although the EPWP plays an important role in ..."?

Suggestion is followed.

Line 320: change "however" to "furthermore"?

The referred sentence is removed.

Line: 370: What is the "intensification factor"? Please explain it briefly in the text.

The rate of increase of intensity is the intensification factor. We have explained this in the revised text.

Lines 432-433: What are "terrestrial anomalies"? Please state them explicitly in the text.

We meant land surface anomalies (e.g. precipitation, surface temperature). This is now stated in the revised text.

Lines 455-459: The difference between the TRMM and GPCP data is not big given their different spatial (and temporal) resolutions.

The authors agree that the differences in rainfall observations are not “big” (and this description is not used in the text) considering the different resolutions of the data (1° vs 0.25°). However, differences are as large as 15-30 % in some months and locations (e.g. the Great and Lesser Antilles in October) and this has been quantified in the text. On average over the whole Caribbean, TRMM data is 20-31% higher than GPCP 1DD data and while the temporal variability matches well (see below), the spatial variability contains differences, even when averaged over the whole period (see figure below). We believe that it is important to be aware and try to address such observational discrepancies (e.g. increased in-situ network over land and ocean) in a region such as the IAS due to the range of spatial scales of precipitation in the region. This is also illustrated in the annual mean rainfall map from GPCP and TRMM, shown below. These issues have been addressed in the text. It is also worth noting that the high resolution TRMM (and GPM) data that begins to resolve some of the smaller islands only began in 1997, and is only just reaching the threshold for adequate climate observations (unlike GPCP which is available since 1979 but at even lower resolution than the daily data shown here).

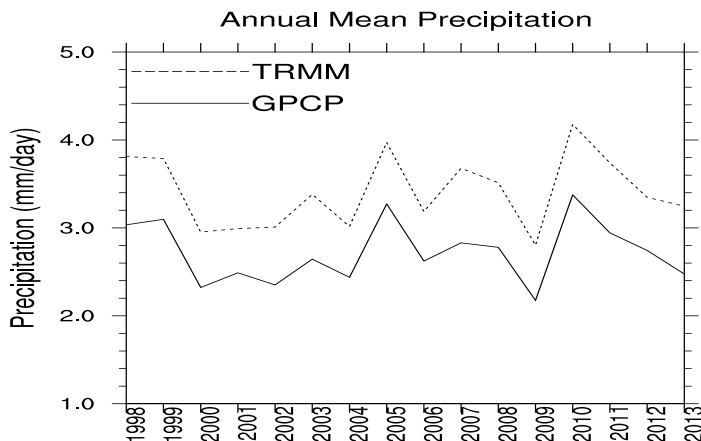


Figure: Time series of annual mean, Caribbean-wide precipitation from 1998-2013 from TRMM and GPCP data.

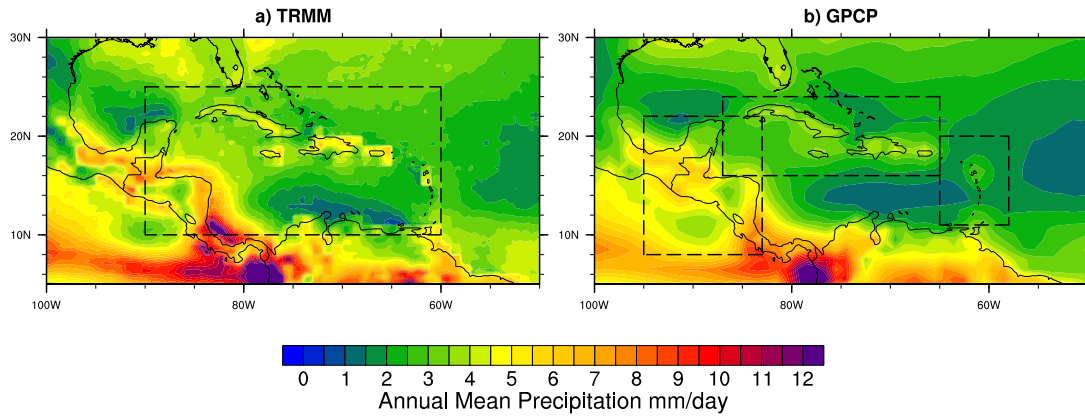


Figure: Annual mean precipitation from 1998-2013 from TRMM (a) and GPCP (b) data.

Line 460: I do not understand the word "enhancement" here? Relative to what?

The rainfall enhancement over the island is relative to the rainfall over the surrounding ocean. This has been clarified.

Lines 488-490: Combine them to "including modulation of low level moisture transport, and changes in convection and their induced remote teleconnections"?

Changed.

Reviewer #3

I was very excited to review this manuscript when I saw the title. We need more research that focuses on the IAS. So first and foremost, congratulations on submitting on a topic that is begging for activity.

Thank you for the encouraging note.

GENERAL COMMENTS:

In general, as a reviewer I am trying to make the connection with the title, text, and background subject material. The title identifies the IAS as the subject. Confusion occurs when trying to digest the real definition of the IAS. Some literature suggests that the IAS is a region that is composed of many variables. However, upon reading the manuscript, the IAS seems more defined as a water-body defined by SST and its variability. Personally, I believe the IAS represents the sum of water and land masses in the region and not just the Caribbean Sea and Gulf of Mexico. Thus, perhaps your title could be strengthened to focus on SST since that seems to be the over-riding variable that defines the IAS region. There is no mention of other circulation trends throughout the IAS like upper level zonal wind, low level flow, etc

In addition, I sense that this manuscript could be greatly improved by the addition of a more detailed section break-down. The organization is clearly noted beginning on line 89: 1) IAS variability, 2) model limitations, and 3) recommendations. Why not uses these three topics as major sections followed by detailed sub-sections? The current organization of the manuscript makes it difficult for the reader to transition between sections.

The IAS variability is the in-situ surface and sub-surface ocean variability, which in turn is related to overlying atmospheric variability and terrestrial climate through river discharges. This manifests in the form of the AWP in the boreal summer and fall seasons and the associated atmospheric variations of LLJ's, moisture flux, air-sea interaction leading to wide range of spatio-temporal variability.

The IAS indeed touches the realm of all three spheres of the physical climate system viz., land, ocean, and atmosphere. However as this revised manuscript is presented, we are focusing on understanding the Atlantic warm pool residing in the IAS and its influence on the regional climate of North America including the Caribbean. Oceanic, atmospheric and land processes undoubtedly play an important role in regulating the AWP. The role of land-atmosphere interactions is probably vital to understand the remote influences of the warm pool over terrestrial North America. The river discharge from some of the major rivers (e.g. Amazon, Orinoco) into the IAS does indeed play a vital role in defining the upper ocean stratification. We have followed your suggestion to reorganize the manuscript.

DETAILED COMMENTS:

Line 68: How does the IAS play a significant role?

We meant AWP variability (not IAS alone) plays a significant role (e.g., Wang et al. 2006; Wang et al. 2008). The variations of the AWP between anomalously small and large sizes of the area enclosed by 28.5C isotherm is shown to produce a Gill type atmospheric response to off equatorial forcing (see our response to Reviewer 1, L110 comment) that affects the subtropical high and the trade winds. We elaborate on these points in the subsequent sections.

Line 70: Geographic description should be refined. "Locally within the IAS" is the same thing as CONUS, CA, and northern SA; each sub-region is technically part of the IAS.

Point well taken. We have revised the sentence accordingly.

Line 73: Define a topic sentence for this paragraph.

We did not quite understand this comment.

Line 73: substitute the word "features" with "and oceanographic circulation variability"

We list only atmospheric features in that sentence. A sentence later we list oceanographic features.

Line 79: reference the statement beginning on line 78

The paragraph has been reorganized based on Reviewer 2's suggestion.

Line 89: Consider beginning a new paragraph before, "The".

Done.

Line 97: This section is dominated by descriptions of SST consider renaming or adding subsections to include SST and precip.

We have now added separate subsections for SST, atmospheric circulation, and precipitation.

Line 110: consider rewriting in the following: "The seasonal peak of the AWP heating forces and Gill-type....". Also, one of your co-authors, Kirtman, will argue that diabatic and heating are synonyms. There is only heating and adiabatic heating (I learned this as his pet-peeve as a student in one of his classes.).

Corrected.

Line 111: Could figure 2 include TRMM rainfall so that rainfall is plotted throughout the majority of the IAS including open water rather than plotting with an ocean mask?

Unfortunately TRMM data is available since only Jan 1998, which provides for only

about 17 years of data. Moreover Fig. 3a highlights the remote teleconnection of AWP with continental rainfall over North America..

Line 117: substitute "carry" with advect.

Changed.

Line 118: "flow intensifies forming the CLLJ..."....This is a pet-peeve of mine. By definition, a jet is in response to a thermal wind imbalance therefore, a discussion of horizontal temp / density gradients must be discussed when defining the CLLJ as a real jet. And, at its peak in July, the CLLJ rarely exceeds 13m/s, which is a very weak jet streak to define a jet. I would suggest modifying the phrase "flow intensifies forming...." The SAL and cold tongue are not mentioned in this sub-section. Purposely omitted?

This has been addressed in conjunction with comments from reviewer 1 (L119 comment) concerning the momentum balance of the CLLJ. As discussed in Cook and Vizy (2010), the CLLJ is geostrophic to first order and is related to both westward extension of NASH and the heating over northern South America (hence the thermal wind imbalance that the reviewer refers to). A brief discussion of the momentum balance and reference to Cook and Vizy (2010) has been added. The text has been rewritten to address the reviewers concerns. The role of dust on CLLJ is not known. However we now list it as one of the outstanding issues.

Line 121 rewrite as: The CLLJ bifurcates as it transits the Caribbean Sea: one branch.....

Changed.

Line 133: Identify a topic sentence

We did not quite understand this comment. We interpreted it as providing a section heading in this context and have done so.

Line 133: How is the CLLJ "associated" with reduced precip? Timing? Dynamically? How?

With moisture flux modulation and consequent change in moisture flux convergence (Wang 2007; Munoz et al. 2008; Cook and Vizy 2010; Ellinor and Schumacher 2012). It is now clarified.

Line 154: I feel that the term "secular" should be defined in this manuscript. It is not a commonly used term within the physical sciences.

We have provided a footnote to define secular change.

Line 176: are you able to provide any suggestions as to why the greatest warming is

found along the northern coast?

This warrants further investigation as stated in S.1. However there is a modeling result from Liu et al. (2015), showing that the Caribbean Current weakens along the coast of Colombia and Venezuela, resulting in greater oceanic heating to the south (their Figs. 4-5). Liu et al. (2015) indicate that there is a downward relaxation of isotherms along the coast to geostrophically balance the weakening of the Caribbean Current.

Line 213: substitute negative correlation for "anti-correlation" since correlations are both + and -. An anti-correlation might imply no correlation.

Changed.

Line 220: substitute the word correlated with "associated". In general, associated is extremely broad and does not provide any real description.

Done.

Line 226: anti-correlation appears again.

Changed to negative correlation.

Line 244: could you reference the term "Maya Express" for surges of moisture? Or does the Maya Express only refer to the atmospheric rivers of the Caribbean? Either way, Maya Express could bolster the descriptive aspect of this manuscript (see line 338).

These surges are further west of the Maya Express suggested in Dirmeyer and Kinter (2009). However we have used this reference in reference to line 338 in the old version of the manuscript.

Line 262: replace "winds in the CLLJ" with "winds in the southern Caribbean"

Changed.

Line 263: add the word "summer" between suppresses and convection.

Changed.

Line 346: outline on figure 10 where exactly is the Eddy Vasquez feature

This figure is removed following comments from reviewer 2.

Line 375: I believe the verb should be "are".

Changed.

Line 412: Should "produce too little" be substituted with "underestimate"?

Changed.

Line 546: Only the last sentence of the manuscript mentions any sort of societal importance. I would suggest to expand on this connection in the intro or omit the final sentence.

The sentence is removed.

FINAL THOUGHTS:

There are currently great strides being taken by those who live and work in the Caribbean region. This manuscript should highlight the work being done by these organizations as not to undermine their work and contributions to the IAS research. As North American researchers, we need to be sensitive to the efforts from our fellow colleagues in the IAS. Examples of such efforts include:

1) Data rescue initiatives in Cuba, the DR, and Jamaica just to name a few. Their contributions will support the observational network and historical data archive.

We fully agree with you. Effective IAS research must necessarily involve a partnership between as many of the countries in the region as possible in order to bring all resources and knowledge to bear on a problem critical to all concerned. We now mention the data rescue efforts of the Caribbean countries.

2) Increasing amount of station observations on the island of Jamaica by the Jamaican met. Service and in other islands.

We have made a reference to this in the revised manuscript.

3) Perhaps mention the ongoing work by the CIMH to serve the Caribbean community. In general, it would be nice to have some input from specific programs in the region. These are examples of progress that help to reduce the data limitations. Plus, broadly interested BAMS readers will appreciate the detail.

COCONet is a great example of the kind of international cooperation needed. COCONet has established 46 GPS and meteorological ground stations throughout the Caribbean from the Bahamas through Central and northern South America and all strategically located islands. These stations take surface met observations, they remotely determine the vertically integrated water vapor above each GPS station and through radio occultation of GPS transmissions can provide vertical profiles of temperature and humidity over subregions. We also mention CIMH in the revised manuscript.

Figure 1

[Click here to download Non-Rendered Figure: Fig_1_mishra_R.eps](#)

Figure 2

[Click here to download Non-Rendered Figure: Fig_2_SangKi.eps](#)

Figure 3

[Click here to download Non-Rendered Figure: Fig_3_mishra_R.eps](#)

Figure 4

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Figure 5

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Figure 6

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Figure 7

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Figure 8

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Figure 9

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Figure 10

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Figure 11

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Figure 12

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Figure 13

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