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1	Open ocean nocturnal insect migration in the Brazilian South Atlantic with
2	comments on flight endurance
3	
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19 Abstract

20

21 We report a nocturnal insect swarm observed aboard the oceanographic ship Cruzeiro do Sul of 22 the Brazilian Navy, while conducting a survey of the Montague guyot (seamount), 389 km distant 23 from the nearest land in the South Atlantic. The insects came from open sea towards the ship in 24 all directions, attracted by powerful lighting of the deck. Except for one specimen, their 25 provenance from another island or another ship were discarded. Most insects collided with the 26 hull and fell into the ocean, but we managed to capture and determine seventeen (13 Hemiptera 27 of a single species, three Lepidoptera and one Odonata). Considerations about the geographic 28 origin and flight endurance of these insects are supported by the reconstruction of wind speed and 29 direction provided by the crew of the ship and Hysplit modelling of air current trajectories. 30 31 **Keywords** 32 33 Aeshnidae, Dispersal, Migration, Nocturnal flight, Pentatomidae 34 35 Introduction 36 37 Insects, with more than one million species, represent two thirds of the total metazoan diversity 38 (Zhang 2011, 2013). Undoubtedly the ability to fly is among the causal explanations of their 39 evolutionary success (Grimaldi 2010). Indeed, winged insects alone correspond to 69% of all 40 animal species and excluding vertebrates such as birds and bats are the only extant Arthropods 41 using flapping wings for locomotion. One of their extraordinary capabilities is long-distance 42 flight or migration, which is well-documented for several groups including dragonflies, locusts, 43 and butterflies (e.g. Holzapfel & Harrell, 1968; May 2013, Chapman et al. 2015). Definitions of 44 migration are numerous in the literature, but there is a reasonable agreement with Dingle's (2006: 214) concept of migratory behavior as "persistent and straightened-out movement effected by the 45 46 animal's own locomotory exertions or by its active embarkation upon a vehicle". By vehicle the 47 author means wind. 48 Night flight of insects has been less studied because it is more difficult to observe, but

49 observations of it began as early as the 1930s by use of airborne traps (Glick, 1939). Progress in

that direction, pioneered by Fowler & Lagrone (1968) was eventually made by deployment of entomological Radar, with which Riley (1975) found insects flying against the wind, while several recent studies have found such insects capable of active downwind flight (*e.g.* Reynolds *et al.* 2010a, 2010b, 2016 and references therein). There is mounting evidence for the geomagnetic orientation capabilities of various insects, which corroborates their flight capabilities in the dark and strengthens the hypothesis for active migration (*e.g.* Vácha, 1997; 2015; 2017).

57 The assemblage of Odonata, Hemiptera and Lepidoptera attracted to light and captured by 58 us on a ship in open South Atlantic Ocean appeared so distant from the mainland, at a point 59 where no islands are nearby. There were also no other ships in the vicinity, which could have 60 been transporting the insects. This fact leads us to pose the same question as Reynolds *et al.* 61 (2010a, 2010b): "How do insects maintain wind-related orientation at altitudes of several 62 hundreds of metres in the dark?" Immediately questions arose as to how they arrived at such a 63 distant point of open ocean. Could they have come as stowaways from Trindade island, the 64 closest oceanic land mass in South Atlantic? What were the insects doing so far from land? Were 65 they migrating *sensu* Dingle (2006) or were they accidentally dispersed to open ocean, victims of 66 weather extremes? What was the minimal duration of their sustained flights? 67 In this paper we undertook, face to this nocturnal insect swarm, a study of the known 68 natural distributions of the identified species, reconstruction of wind conditions preceding

capture, their hypothetic flight paths and their probable source locations, and to estimate theduration of their sustained flights.

71

72 Material and Methods

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Background. Of the Brazilian islands in the South Atlantic, only Trindade (Barth, 1958; Becker,
1998) and Fernando de Noronha (Alvarenga, 1962) have been surveyed by entomologists in the
1950s and 1960s. Insects registered on Trindade are mostly continental species with only 11
species of Lepidoptera, 8 of true bugs and 2 species of dragonflies. Of the latter, apparently only *Pantala flavescens* (Fabricius, 1798) a characteristically migrant species and well-known as
successful in colonization (*e.g.* Santos, 1981; Mesquita & Matteo, 1991) survives at present.

Insects endemic to Trindade are *Liagonum beckeri* Jeannel, 1961 (Coleoptera: Carabidae) and *Limonethe beckeri* Costa Lima & Guitton, 1961 (Hymenoptera: Ichneumonidae).

82

Study area and sampling. On May 28th, 2014, the ship Cruzeiro do Sul of the Brazilian Navy, 83 84 on its way from the Archipelago of Trindade & Martin Vaz to the port of Rio de Janeiro. 85 southeastern Brazil, stopped above the Montague seamount (20°21'57.60"S, 36°38'46.80"W), a 86 guyot which is part of the Vitória-Trindade oceanic mountain chain (Fig. 1). From this point of open ocean, the distance to the nearest land in the continental Brazil is 389 km. The ship lowered 87 88 a measuring apparatus into the water and the white walls of the hull and deck were illuminated by 89 ca. 10,000 Watts of spotlights composed by incandescent (minority) white halogen bulbs (most) 90 and several white fluorescent lights. The maneuver was executed starting 22:25h and 23:00h 91 UTC. Shortly after the lights were turned on, insects were observed flying straight toward the 92 ship from all directions, evidently attracted by the lighting. Most of them collided against the hull 93 and fell into the ocean, but with help from crew and other researchers, two of us (NGS and 94 RJVA) were able to capture most of those which landed on deck.

95 The specimens were preserved pinned or in envelopes and deposited in the Department of 96 Entomology of the Museu Nacional (MNRJ), Universidade Federal do Rio de Janeiro, Rio de 97 Janeiro, Brazil. On 2 September of 2018 occurred one of the biggest tragedies for the research on 98 natural history when the MNRJ burned on fire and almost all its heritage of 20 million of items 99 was lost (see Zamudio *et al.* 2018), including the material reported here (Figs 2A–C). These specimens were determined by coauthors LAAS (Hemiptera), AS (Lepidoptera) and APP 100 101 (Odonata). All material was collected in accordance with the Brazilian biodiversity policies, 102 under Instituto Chico Mendes de Conservação da Biodiversidade - ICMBIO/SISBIO licenses 103 numbers 25034-6 and 41194-4.

104

Analysis. The crew provided us with measurements of wind direction and intensity for a period of 21h prior to the capture event. This was essential to estimate the trajectory which a hovering insect could have performed during that time. The capture occurred on the night immediately preceding the new moon, hence the night was very dark, and our ship was the only light source in a vast region of open ocean. The air temperature measured on deck was 25.4 °C.

110 We first reconstructed changes in wind speed and direction using the ship' log data and 111 calculated the trajectory an idle floating object would have had spanning 21h prior to capture. We 112 calculated the distance to the closest coastal point in Brazil to our acquired GPS (WGS84) 113 coordinates from the capture site. 114 Subsequently we reconstructed 24 Hysplit trajectories backward preceding capture by 34h 115 and 48h and forward 180h toward the African coast (Stein et al. 2015; Rolph et al. 2017), not 116 leading into account heading deviations by active flight of the insects. Hysplit settings used: 117 Backward trajectory direction; runtimes:; altitudinal range 10–3000 m asl. 118 119 Results 120 121 Flight endurance. According to the trajectory reconstructions, the minimum flight time from the 122 continent was 34h, when a single backward trajectory had its starting point on the coast between 123 the Brazilian states of Espírito Santo and Bahia, 380 km from the point of capture (Fig. 3). With a 124 48h flight duration, three additional potential points of origin on the coast were reconstructed 125 (Fig. 4). If the migration of the insects were to continue toward Africa from the point of capture, 126 assisted by prevailing winds, another 180h of flight time would be needed, and the insects would 127 need to gradually ascend to high altitudes accompanying the air currents (Fig. 5). 128 129 **Insects at the open ocean.** There are no Trindade endemics species among the insects we 130 captured. Hemiptera were the most numerous, with 13 individuals of only one species, several of 131 which emitted a strong odor resembling green apples, an odor still present in 2017, after three 132 years of preservation. Three different species of Lepidoptera were distinct moths. A single very 133 large dragonfly completes the list. 134 135 **Odonata: Anisoptera: Aeshnidae** 136 137 1. Anax amazili (Burmeister, 1839) 138 (Fig. 2A) 139 140 Material examined. One female (MNRJ ODO-0012).

141 **Remarks.** Species of *Anax* are known as migratory, spending many weeks in migration routes 142 undertaking distinct behaviors such as foraging (cf., May 2013). Anax amazili is a New World species widespread along the entire American continent occurring from the USA (Needham et 143 144 al., 2000), through central America and the Caribbean Islands (Calvert, 1905) to southern 145 Argentina (von Ellenrieder & Muzón 2008). It also occurs as a resident species in the Pacific 146 archipelago of Galápagos about of 1,000 km from the coast (Calvert, 1905, Peck, 1992). The site 147 of capture was about 380 km from Brazilian cost and almost 800 km west of the closest 148 archipelago, Trindade & Martin Vaz, from which only two different Odonata were recorded to 149 date (MNRJ): Pantala flavescens and Rhionaeschna sp. (see Santos, 1981). the pantropical 150 Libellulidae glider Pantala flavescens in the best-known migrant dragonfly species (Samways & 151 Osborn 1998), for which the early expectations of this species forming a global panmictic 152 population were recently supported (Troast *et al.* 2016). However, if there is a regular migration 153 route among these land masses is an open question. 154 155 Hemiptera: Heteroptera: Pentatomidae 156 157 2. Alcaeorrhynchus grandis (Dallas, 1851) 158 (Figs 2B–C) 159 160 Material examined. 12 specimens, 4 males, 8 females, including one *in copula*. Many more 161 were seen drowning alongside the deck. 162 **Remarks.** Recorded from Brazil, Colombia, Mexico, and the southern United States (Ribeiro *et* 163 al., 2010); Argentina, Bolivia, Cuba, Ecuador, Paraguay and the Galapagos (Dellapé et al. 2003). 164 In Brazil there are collections from Bahia: (*sine loco*); Goiás: (Capada dos Veadeiros); Minas 165 Gerais: (Belo Horizonte – sucking a caterpillar); Mato Grosso: (sine loco); Espírito Santo (20 ° 166 40'S 40 ° 30'W); Rio de Janeiro: Angra dos Reis; Petrópolis; Rio de Janeiro (Copacabana; Quinta 167 da Boa Vista); Serra dos Órgãos; Paraná: (sine loco); Santa Catarina: (sine loco); São Paulo: (sine

- 168 *loco*) (MNRJ collection); Pará (Ribeiro *et al.* 2010); Rio Grande do Sul (Dellapé *et al.* 2003;
- 169 Magistrali *et al.* 2014).
- 170 This stink bug was considered an introduced or invasive species in the oceanic
- archipelago of Galápagos, Ecuador where it was first recorded in 1937 and was argued to have

172	arrived by passive transport through plants on Floreana Island (Peck et al., 1998), distant just
173	over one thousand kilometers from continental South America. Our observation of this species in
174	open ocean provides support to a distinct hypothesis whereby active migration is a suitable
175	explanation for the occurrence of this insect in the Galapagos. To support this, however, these
176	events should be dated by means of populational and migratory studies and modelling of air
177	currents.
178	
179	Lepidoptera: Erebidae
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181	3. Eudocima procus (Cramer, 1777)
182	
183	Material examined. one male/female
184	Remarks. Originally described from Surinam (Zaspel & Branham, 2008), this species has a
185	widespread distribution in Neotropics (Zilli & Hogenes 2002); in Brazil, it occurs at least in the
186	states of Santa Catarina and Rio Grande do Sul (material previously deposited in MNRJ).
187	
188	4. <i>Mocis repanda</i> (Fabricius, 1794)
189	
190	Material examined. one specimen.
191	Remarks. Widespread in South America: Argentina, Bolivia, Brazil, El Salvador, Colombia,
192	Guyana, Mexico, Nicaragua, Surinam, Venezuela, West Indies (Muthaiyan, 2009). Also found in
193	Central America and the Caribbean, including Cuba, the Dominican Republic, Guadeloupe,
194	Martinique, Guatemala, Jamaica, Puerto Rico and Saint Thomas; Strays can be found in the
195	United States, up to southern Texas as well as subtropical Africa south of the Sahara, including
196	the islands of the Indian Ocean.
197	
198	5. Undetermined species (damaged specimen)
199	
200	Material examined. one specimen.
201	
202	Discussion

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One of the most interesting questions about insects flying over open ocean on a moonless night at
such a large distance from land is whether they (and which ones) were flying in a chosen
direction or changed directions responding to changing environmental factors, *e.g.*, geomagnetic
cues (Vácha 1997; 2015); the time-compensated sun-compass (Reppert, Gegear & Merlin, 2011;
Guerra *et al.*, 2014) or the wind cues described by Reynolds *et al.* (2010a; 2010b; 2016). How, if
at all, did our sampled insects orient themselves before they were attracted to and flew actively
towards the ship's lights at night?

The fact that hundreds of insects actively pursued the ship in the dark of a moonless night suggests that light is a stronger cue to them than the wind characteristics proposed by Reynolds *et al.* (2010a, 2010b).

214 Geijskes (1968) considered the dragonfly Anax amazili as having predominantly 215 crepuscular behavior and sometimes being attracted by light at night. However, this species 216 presents a more complex behavior than previous expected. In Rio Grande do Sul State at latitude 217 of 30° south, it has been collected in light traps, and observed foraging and ovipositing in with 218 small open swamp areas at noon (APP, unpublished). Our data shows that while migrating, this 219 species is also capable of night flight. However, if this species was truly migrating, where was it 220 heading? After all, the known distribution includes neither Africa nor the islands in the South 221 Atlantic.

222 Glick (1939) did not register any Odonata flying at night. To 14 individuals of the related 223 Anax junius (Drury, 1773), Wikelski et al. (2006) attached miniaturized radio transmitters and 224 followed them during migration for up to 12 days, using receiver–equipped airplanes and ground 225 teams. They found an average net advance of 11.9 + 2.8 km/day, exclusively during the day 226 time. Hence our record of *Anax amazili* migrating during the night might well be the first ever. 227 Of the species captured by us, the moths *Mocis repanda*, and *Eudocima procus* were also 228 collected in Santa Catarina and Rio Grande do Sul (SpeciesLink, 2017). Mocis repanda was 229 registered as the most abundant moth on island in 1957 (Barth, 1958), and probably persisted 230 there in the 1960s (Becker, 1998). Mocis repanda is a widespread species considered a pest of various grasses including corn. 231

The remaining identified insect species occur in Brazil, some also extending to countries north and south, but none to Africa. Combining the ranges of distribution with reconstructions of

wind speed and direction during the days preceding capture, it is hence reasonable to suppose all
captured insects began their flight in Brazil, somewhere on the coast between Espírito Santo and
Bahia.

Hence there is a remote chance this species could have come aboard the ship from that island (either flying or stowed in cargo), hitched a ride aboard, flown out to sea prior to capture, and then returned toward the suddenly illuminated ship from open ocean. Even based on the observed event that favoring the hypothesis of active flight hundreds of kilometers from closer land mass at least for these moths, we not discarded that already were on the ship and started to flight after ships' lights turned on.

243 Insects flying at night often align their flight paths with the wind (Riley, 1975; Reynolds 244 et al. 2010a; 2010b; 2016). Whether the insect's bodies are heading upwind or downwind during 245 such aligned night flights probably depends on the wind speed and has been subject to some 246 debate. Several studies indicate the insects increment their self-propelled velocities by actively 247 travelling downwind (Reynolds et al. 2010a; 2010b; 2016) even though Riley (1975) observed 248 the contrary. In the Northern Hemisphere, Hu et al. (2016) found that the insects tend to fly 249 slightly to the right in relation to the wind axis and aligned themselves with the flow direction 250 with greater accuracy with increasing flight altitude.

Monarch butterflies can fly in still air at average speeds of 37.5 km/h and probably up to 50 km/h, and they usually fly close to the ground, but have been registered at altitudes of ca. 3,500 m asl.; and have been known to fly more than 600km over water non-stop in 16 hours (Poirier, 1995). Even though Monarchs are considered day butterflies, a part of that 16h flight would obviously happen in the dark. On the other hand, the three Lepidoptera we captured were noctuid moths. Open ocean night flight seems to be a novelty for the captured dragonfly and the stink-bug species.

If Monarch butterflies could cover the expanse of ca. 400 km from the continent to the capture site in just under 11 hours of sustained flight, it is quite possible that other insects could reach the site in comparable speeds, and that migration across the entire Atlantic between South America and Africa could be achieved in 3.6 days in still weather. If winds are factored into the equation. the migration could potentially be much slower or much faster.

263	Even though some insects have been observed to rest on the surface of a calm ocean and
264	resume flight (Walker, 1931 and references therein), the ocean conditions during our capture
265	were 3 on the Beaufort scale – hardly considered calm.
266	
267	Acknowledgments
268	
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273	
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Figures and captions 383

384



385 Figure 1. Part of South Atlantic Ocean depicting the location of Southern Brazil, Montague seamount (site of 386 anchorage of the hidrooceanographic ship Cruzeiro do Sul of the Brazilian Navy, 20°21'57.60"S, 36°38'46.80"W) and Trindade Island. Abbreviations for the Brazilian States: ES: Espírito Santo; RJ: Rio de Janeiro. Map data: Google, image Landsat/Copernicus, SIO, NOAA, U.S. Navy, NGA, GEBCO.

387 388 389



- 390 Figure 2. Habitus of insects collected at South Atlantic, Montague seamount aboard the hidrooceanographic ship
- 391 Cruzeiro do Sul of the Brazilian Navy 20°21'57.60"S, 36°38'46.80"W) during a nocturnal swarm flight. A. female
- 392 of Anax amazili (Burmeister, 1839) in lateral view, B-C. male (B) and female (C) of Alcaeorrhynchus grandis
- 393 (Dallas, 1851) in dorsal view. Scale bar = 10 mm. Photos credit: Ângelo P. Pinto.



- 394 395 vector originated on the coast of the states of Espírito Santo and Bahia.
- 396



Figure 4. Backward reconstruction 48h Hysplit model of windvectors originated on the coast of Espírito Santo and Bahia.



Figure 5. Forward reconstruction 180h Hysplitarriving in Namibia on the African coast.