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1 **TROPICANA (TROPICAL Cyclones in ANthropocene: physics, simulations,**
2 **and Attribution)**

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ABSTRACT

20 The TROPICANA program, held in June 2024, represented a pioneering interdisciplinary effort
21 to address the intricate challenges surrounding tropical cyclones, medicanes, and their connection
22 with climate change. These cyclones, known for their devastating impacts, pose substantial threats
23 to both life and property. The event adopted a multifaceted approach encompassing physics,
24 modeling, statistical methodologies, and climate attribution studies to enhance our understanding
25 of tropical cyclones and medicanes. Spanning four weeks, the program included lectures, poster
26 sessions, hands-on training sessions, discussions, and a public panel with a strong press presence.
27 TROPICANA aimed to foster collaboration, knowledge sharing, and project development. TROP-
28 ICANA sought to strengthen the community and make a significant and lasting contribution to the
29 science of tropical cyclones and medicanes.

30 **1. Introduction**

31 Tropical cyclones (TCs) are among the most destructive natural disasters, causing significant
32 fatalities and economic damage due to multiple hazards such as extreme winds, precipitation,
33 storm surge, flooding, ocean waves, and tornadoes (Emanuel 2003; Rappaport 2014). These
34 combined hazards increase the risk of loss of life and property damage, and are a forecasting
35 challenge (Grinsted et al. 2019; Nielsen et al. 2015). The most substantial economic losses are often
36 caused by intense landfalling tropical cyclones, such as Hurricanes Katrina (2005), Harvey (2017),
37 Maria (2017), and Typhoon Haiyan (2013). Post-tropical cyclones, especially those undergoing
38 extratropical transition, can also impact mid-latitudes, affecting regions like Northeast US, Canada
39 and Europe (Baker et al. 2021; Hart and Evans 2001).

40 In the Mediterranean, storms with tropical cyclone characteristics (presence of a central eye,
41 spiral cloud bands, symmetric deep warm core), known as medicanes, occur one or two times
42 a year Flaounas et al. (2022). These hybrid storms form over the Mediterranean Sea and may
43 undergo a tropical transition, possessing traits of both tropical cyclones and mid-latitude frontal
44 systems either at different stages of their lifetime or simultaneously. While medicanes rarely reach
45 hurricane strength, they pose significant wind and rain hazards, threatening life and property in the
46 Mediterranean region (Romero and Emanuel 2013; Cavicchia et al. 2014; Miglietta and Rotunno
47 2019).

48 Scientists have studied the effects of climate change on the characteristics of tropical cyclones
49 and medicanes, in particular how often they will occur (i.e., frequency), how strong they will be
50 (i.e., intensity), and their associated risks (Knutson et al. 2010, 2019, 2020; Camargo et al. 2023),
51 in the future. The IPCC Sixth Assessment Report (Masson-Delmotte et al. 2021) states that in a
52 warmer climate, there will be a: “Likely decrease or no change in frequency of tropical cyclones,

53 likely increase in mean maximum wind speed, but possibly not in all basins, likely increase in
54 heavy rainfall associated with tropical cyclones”. While the large uncertainty in the changes in
55 TC frequency makes it hard to project their risk, the consensus is that when a TC (or a medicane)
56 makes landfall, the stronger winds and heavier rainfall, combined with sea level rise due to climate
57 change, will lead to more severe impacts.

58 The Institut Pascal allowed us to address the uncertainties in these issues in a unique setup. Each
59 participant came to our “temporary lab” and the schedule left significant free time to foster new
60 collaborations and stimulate discussions on specific topics chosen by the participants. Scheduled
61 activities included seminars, poster sessions, discussions, round-tables, a public lecture, and train-
62 ing sessions, focusing on the physical understanding, diagnostic tools and numerical simulations,
63 methods for creating synthetic cyclones (i.e., cyclones that could have happened in certain climate
64 conditions), and attribution of TCs and medicanes to climate change.

65 **2. Week 1: Defining Medicane in the landscape of Mediterranean Cyclones**

66 During the first week of TROPICANA at the Institut Pascal, we delved into several critical
67 questions regarding the physics and modeling of medicanes. To mark the launch of the program on
68 Monday, June 3 2024, a public lecture was given by Kerry Emanuel, which illustrated the common
69 features of hybrid cyclones happening in the subtropics and extratropical regions (Emanuel 2018).
70 The talk proposed that, while different names are used for these cyclones depending on the region of
71 development (medicanes, polar lows, Kona storms, subtropical cyclones), the physics is essentially
72 the same, and hence that, from a physical point of view, they should be treated as the same category.
73 The lecture was followed by a panel discussion and a press briefing, which allowed a dozen of
74 French and international journalists to ask questions to a panel of experts on medicanes, TCs, and
75 climate change.

76 During the remainder of the week, we explored different perspectives on how to precisely
77 define a “medicane”, trying to reconcile the proposed definition with existing ones (Moscatello
78 et al. 2008; Fita and Flaounas 2018) and distinguishing its unique characteristics from other
79 subtropical and extratropical storm types. Process-based and structural definitions were considered
80 in the discussion, and the group agreed upon a satellite-based structural definition for medicanes
81 (D’Adderio et al. 2024), accessible to non-scientific observers. We also examined the factors
82 governing their frequency and interannual variability. Discussions included the formation of
83 medicanes, including in situ formation, as well as from disturbances generated by extratropical
84 storms, and the observed differences in their development mechanisms. We discussed how to adapt
85 TC tracking methodologies for medicanes and the necessary modifications required to track these
86 hybrid storms effectively, and the optimal approach to produce reference datasets for Mediterranean
87 cyclones (Flaounas et al. 2023). Additionally, we focused our attention on how to study these
88 phenomena in various simulation frameworks, such as global and regional parameterized models,
89 coupled ocean-wave-atmosphere, convection-permitting models, synthetic medicanes, and the
90 potential benefits of combining these approaches.

91 Regarding the modeling of medicanes, one important issue to consider is spatial resolution, which
92 is crucial to simulate tracks and impacts accurately in the Mediterranean basin, as it is smaller and
93 has a more complex geography than other ocean basins (Flaounas et al. 2022). Addressing these
94 model deficiencies involves several pathways, each one with its own set of challenges: switch-
95 ing to regional climate model configurations, developing non-hydrostatic or convection-resolving
96 models (Coppola et al. 2020), and improving sub-grid scale parametrizations of convection and
97 boundary layer processes. These discussions were fruitful for advancing our understanding and how
98 to improve the modeling of medicanes in the future, laying a strong foundation for the subsequent
99 weeks of the program. During the first week, we also highlighted how international projects such

100 as eXtreme events : Artificial Intelligence for Detection and Attribution (XAIDA) and Climate
101 Intelligence (CLINT) [Horizon Europe], A transdisciplinary network to bridge climate science
102 and impacts on society (FutureMed) and the European network for Mediterranean cyclones in
103 weather and climate (MedCyclones) [European Cooperation in Science and Technology (COST)
104 Actions] can advance the understanding of Mediterranean cyclones and provide opportunities for
105 near real-time analyses and communication.

106 **3. Week 2: Climate Change Impacts and Attribution of Medicanes**

107 During the second week of TROPICANA at the Institut Pascal, we concentrated on enhancing our
108 understanding of the future climatology and attribution of medicanes within the context of climate
109 change (González-Alemán et al. 2019). We discussed how the physical properties and formation
110 mechanisms of medicanes might evolve in the future, with the goal of refining our projections and
111 models. In a future climate where medicanes could be more intense or more frequent, accurately
112 representing the interactions between the atmosphere, ocean, and waves becomes increasingly im-
113 portant. Recent evidence, such as the impact of cold wakes on medicane development (Karagiorgos
114 et al. 2024), supports this view.

115 In this week we also discussed whether attribution studies, increasingly common for specific
116 tropical cyclones (Reed et al. 2020) or cyclone seasons (Reed et al. 2022) could be applied
117 to medicanes as well as Mediterranean cyclones in general . In particular, these attribution
118 studies would involve methodological adaptations to account for the specific environmental and
119 geographical features of the Mediterranean basin. The debate highlighted that ideally attribution
120 would require large ensemble of convection permitting simulations with and without the influence
121 of climate change (see e.g., Koseki et al. (2021)). The capabilities of the rapid attribution framework
122 of ClimaMeter (Faranda et al. 2022, 2024) were presented and, as a training activity, we produced

123 a rapid attribution ClimaMeter report for the case of Medicane Ianos. The conclusions of the
124 report stated that Mediterranean depressions like Ianos have similar atmospheric pressure and up
125 to 15% higher precipitation in the present than in the past decades. We interpreted Medicane
126 Ianos as a largely unique event in which natural climate variability played a significant role. Many
127 presentations during the week also addressed classification and impacts of medicanes.

128 **4. Week 3: Tropical Cyclone Genesis and Simulations**

129 On the second half of TROPICANA at the Institut Pascal, our discussions shifts toward TCs
130 and impacts of climate change on these phenomena. The third week started with a keynote talk
131 given by Zhuo Wang, who discussed processes, from mesoscale to planetary scales, that are related
132 to tropical cyclogenesis, and how these processes are seen in observations and numerical model
133 simulations (e.g., Bister and Emanuel (1997); Dunkerton et al. (2009); Ritchie and Holland (1997);
134 Sobel et al. (2021a); Vecchi et al. (2019); Wang et al. (2010); Wang (2012, 2014); Wang et al.
135 (2020))

136 We explored the factors that influence TC frequency and genesis globally and across basins,
137 including the role of TC seeds in determining TC frequency (Vecchi et al. 2019; Sobel et al.
138 2021b; Rios-Berrios et al. 2024). We also investigated the mechanisms influencing regional and
139 interannual variations in TC activity (Wu et al. 2020; Feng et al. 2022).

140 While the term “TC seed” is frequently used in the scientific community in recent years, it lacks
141 a rigorous definition. Participants shared their different views of the concept and collaborated in
142 developing a physics-based definition. The task of defining what exactly a TC seed is and what
143 parameters need to be considered in a seed tracker is complicated by the different tropical cyclogenesis
144 pathways in different basins. Furthermore, although most, if not all, TCs in the real world originate

145 from pre-existing disturbances, it is not clear whether TCs actually need a seed to form based on
146 idealized model simulations (Patricola et al. 2018; Ramsay et al. 2020).

147 We have known for a long time which large-scale environmental variables are important for a
148 TC genesis conducive environment, as well as the modulation of TC activity (Gray 1968, 1979).
149 However, the interactions across multiple climate modes of variability and among different basins
150 are not well understood yet. For example, there is emerging evidence for the existence of opposite
151 trends of TC activity in the North Atlantic and the western North Pacific basins (Liu and Chan
152 2022; Huang et al. 2023; Patricola et al. 2022), which remains to be explained. Potential trends
153 associated with changes in the large-scale environment remain also challenging to identify. As
154 an illustration, we discussed the upcoming Northern Hemisphere TC season and how it might be
155 influenced by the combined effects of the cold phase of the El Niño-Southern Oscillation (i.e., La
156 Niña) and the specific pattern of the anomalously warm Atlantic sea surface temperatures.

157 Furthermore, we discussed attribution studies for tropical cyclones (Patricola and Wehner 2018;
158 Wehner et al. 2019). Such studies typically focus on changes in the characteristics of tropical
159 cyclones, such as their intensity, associated rainfall, or storm surge (e.g., Reed et al. 2020, 2022).
160 However, as the hazards associated with tropical cyclones occur concurrently, there is a need to
161 develop a more comprehensive attribution framework that takes into account the compound effect
162 of tropical cyclone attributes and impacts.

163 **5. Week 4: Tropical Cyclones Climate Change, Risk, Attribution and Machine Learning**

164 During the final week of TROPICANA at Institut Pascal, our focus turned to the tools we have to
165 understand TCs and predict their future changes and impacts, including dynamical and statistical
166 models, as well hybrid statistical-dynamical models.

167 While there is an agreement that anthropogenic climate change is increasing the intensity and
168 rainfall rates of TCs, there is still no consensus about changes in TC frequency (Knutson et al.
169 2020; Sobel et al. 2021b; Camargo et al. 2023), mainly due to the lack of a complete theory for
170 the climate control on TC frequency. Furthermore, projections of other TC characteristics can
171 be difficult, partly due to the limitations of state-of-the-art climate models (Knutson et al. 2020;
172 Judt et al. 2021). While model resolution has been a limitation for a long time, TROPICANA
173 showcased the emergence of many new high-resolution approaches. Standard climate models can
174 now be run at 25-km grid spacing or finer, as was done for the HighResMIP multi-model effort
175 (Roberts et al. 2020; Bourdin et al. 2024), which showed a large improvement in the properties of the
176 simulated TC statistics (e.g., frequency, intensity, geographical distribution) as the model resolution
177 becomes finer, although substantial regional biases still remain in some basins. At much finer
178 resolutions, cloud-resolving/convection-permitting models can resolve the mesoscale processes
179 within the cyclones, but can only be run for short periods of time (Judt et al. 2021). By resolving
180 these fine scales, TC intensification rates are close to observations, and rapid intensification is
181 captured. Such models also capture the observed relationship between high intensification rate
182 and small inner-core size, and outer wind field size and structure (Baker et al. 2024; Schenkel
183 et al. 2023). The use of regional climate models (e.g., Tran et al. (2022)), including stretched
184 grid configurations such as those presented in McGregor and Dix (2008); DeCiampa and Zarzycki
185 (2023); Ocasio and Dougherty (2024), were presented as a way to bridge the gap between low-
186 resolution climate models and convection-permitting simulations capable of resolving important
187 processes in TCs. More idealized simulations were also shown to be an important avenue for an
188 increasing understanding of the TC-climate relationship (Hsieh et al. 2020; Rios-Berrios et al.
189 2023).

190 The keynote talk given by Ning Lin on TC hazards and risk, discussed downscaling techniques
191 which bring additional insight that would complement the limitations of global climate models
192 for TC risk assessment. While dynamical downscaling faces constraints due to computational
193 costs and limited geographical extent (e.g., single basin), statistical-dynamical downscaling and
194 their resulting synthetic tracks (e.g., Emanuel 2006; Lee et al. 2018; Jing and Lin 2020) offer the
195 advantages of providing a very large sample size of TCs for estimating TC impacts in a changing
196 climate. It is however noted that such assessment requires careful consideration of the underlying
197 assumptions.

198 Furthermore, downscaled TC datasets are limited by the biases of the large-scale environmental
199 fields inherited from the global climate models, which highlights the need for effective and efficient
200 bias correction techniques. When using bias correction, the global climate model fields need to
201 maintain physical consistency across variables like wind, precipitation, and sea-level pressure,
202 thereby preserving an accurate assessment of the impact of climate change on TCs. Furthermore,
203 the presence of systematic biases across global climate models, such as the historical trends in
204 the tropical Pacific sea surface temperature (Seager et al. 2019, 2022), could potential lead to an
205 underestimation of the existing uncertainty of TC projections (Sobel et al. 2023).

206 Throughout the week, the applications of machine learning (ML) for improving TC simulations,
207 understanding, and attributions were a key theme (Tam et al. 2024; Lockwood et al. 2024). We
208 explored how ML frameworks can refine model projections, correct biases, and contribute to more
209 reliable assessments of climate change impacts on TC characteristics. Furthermore, we discussed
210 the potential for ML to complement or replace traditional dynamical modeling in TC research.
211 Important topics include the critical role of TC data quality, as ML models are limited by their
212 input data. Synthetic data generation was proposed as one way to address gaps in observational
213 records (Yang et al. 2022). There are questions about how ML can capture the effects of climate

214 change, predict extreme events, and maintain physical realism in its projections (Molina et al.
215 2023; Beucler et al. 2024). Currently, the potential of ML to bridge the gap between weather and
216 climate research communities is being explored, along with the need for robust evaluation metrics
217 and stakeholder involvement (Eyring et al. 2024). Concerns are also raised about the limitations of
218 current ML methods and the importance of leveraging causal methods to enhance model robustness
219 (S. Ganesh et al. 2023).

220 Our conclusion was that there is no optimal tool to study TCs, but rather we need to work on
221 improving all these approaches to address different questions from different perspectives using
222 different tools, and, ultimately, provide enough evidence that will help us understand TCs, and how
223 they might change in the future.

224 Finally, we have conducted a comprehensive assessment of the hazards posed by tropical cyclones
225 by discussing historical storm data, presenting models to address their impacts, and examining
226 methods to define the impact of these storms on coastal communities and ecosystems (Luu et al.
227 2021; Xi et al. 2023). This included discussing ways to assess wind speed, storm surge, and rainfall
228 patterns to better understand their potential damage and to improve preparedness and adaptation
229 strategies.

230 **6. Perspectives**

231 White papers, tutorials, and recommendations aimed at defining medicanes and tropical cyclone
232 seeds, along with a comprehensive review paper on their impacts, will pave the way for a follow up
233 event, TROPICANA 2, in 2027. TROPICANA 2 will aim at consolidating the work on medicanes
234 and tropical cyclones, but also will expand towards others types of cyclones, including sub-tropical,
235 mid-latitude and polar cyclones. We want to continue to strengthen our ability to predict, respond,
236 and make projections of all types of storms, by looking at all cyclones comprehensively.

237 Prior to 2027, TROPICANA will continue to drive initiatives through meetings at American
238 Geoscience Union and European Geoscience Union, as well as an email list and an active Slack
239 channel, fostering ongoing collaboration and knowledge exchange among experts. These platforms
240 will serve as crucial forums for discussing emerging research, methodologies, and findings in
241 tropical cyclone and medicane studies.

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