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Davide Faranda, Stella Bourdin, Suzana J. Camargo, Chia-Ying Lee,  
Sébastien Fromang

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

3 Davide Faranda\*

4 *Laboratoire des Sciences du Climat et de l'Environnement, UMR 8212 CEA-CNRS-UVSQ,*

5 *Université Paris-Saclay & IPSL, CEA Saclay, 91191, Gif-sur-Yvette, France;*

6 *London Mathematical Laboratory, 8 Margravine Gardens, London, W6 8RH, UK;*

7 *Laboratoire de Météorologie Dynamique/IPSL, École Normale Supérieure, PSL Research*

8 *University, Sorbonne Université, École Polytechnique, IP Paris, CNRS, Paris, France*

9 Stella Bourdin

10 *Atmospheric, Oceanic and Planetary Physics, Department of Physics, University of Oxford,*

11 *Oxford, United Kingdom*

12 Suzana J. Camargo & Chia-Ying Lee

13 *Lamont-Doherty Earth Observatory, Columbia University, Palisades, USA*

14 Sébastien Fromang

15 *Laboratoire des Sciences du Climat et de l'Environnement, UMR 8212 CEA-CNRS-UVSQ,*

16 *Université Paris-Saclay & IPSL, CEA Saclay, 91191, Gif-sur-Yvette, France*

17 The TROPICANA Collaboration\*

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\*Tommaso Alberti, Alexander J. Baker, Lisa Bernini, Tom Beucler, Stella Bourdin, Sophia E. Brumer, Adrien Burq, Suzana J. Camargo, Andrina Caratsch, Carmen Alvarez Castro, Leone Cavicchia, Greta Cazzaniga, Marco Chericoni, Erika Coppola, Vesna Cupic, Stavros Dafis, Apolline

<sup>19</sup> \**Corresponding author*: correspondence to [davide.faranda@cea.fr](mailto:davide.faranda@cea.fr)

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Dekens, Jean Philippe Duvel, Kerry Emanuel, Mohammed Nabil El Korso, Davide Faranda, Xiangbo Feng, Emmanouil Flaounas, Chauvin Fabrice, Mireia Ginesta, Giacomo Giuliani, Juan Jesus Gonzalez Aleman, Milton Gomez, Jesús Gutiérrez-Fernández, Roméo Hatchi, Falko Judt, Samira Khodayar Pardo, Chia Ying Lee, Marie Dominique Leroux, Dianyi Li, Hui Li, Jonathan Lin, Ning Lin, Chen Lu, Joshua Macholl, Mario Marcello Miglietta, Maria J. Molina, Henrique Moreno Dumont Goulart, Kelly Núñez Ocasio, Itxaso Odériz, Florian Pantillon, Salvatore Pascale, Claudia Pasquero, Alice Portal, Flavio Pons, Hamish Ramsay, Marco Reale, Rosimar Rios Berrios, Elizabeth Ritchie, Malcolm Roberts, Romualdo Romero March, Leo Saffin, Benjamin Schenkel, Paolo Scussolini, Alyssa Stansfield, Daniel Stern, Frederick Iat-Hin Tam, Pradeebane Vaittinada Ayar, Pier Luigi Vidale, Françoise Vimeux, Zhuo Wang, Michael Wehner, Emily Wisinski, Victor Xing, Qidong Yang, Pascal Yiou, Jingyi Zhuo, Colin Zarzycki.

## 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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