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# Understanding Tropical Cyclones in the Anthropocene: Physics, Simulations, and Attribution

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**KEYWORDS:**

Mediterranean Sea;  
Dynamics;  
Extreme events;  
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**The Tropical Cyclones in Anthropocene: Physics, Simulations, and Attribution (TROPICANA) Meeting**

**What:** The meeting aimed to enhance our understanding of tropical cyclones in the Anthropocene. This pioneering interdisciplinary effort focused on addressing the complex challenges related to tropical cyclones, medicanes, and their links to climate change.

**When:** 1–28 June 2024

**Where:** Saclay, France

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## 1. Introduction

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

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

Scientists have studied the effects of climate change on the characteristics of tropical cyclones and medicanes, in particular how often they will occur (i.e., frequency), how strong they will be (i.e., intensity), and their associated risks (Knutson et al. 2010; Knutson et al. 2019, 2020; Camargo et al. 2023), in the future. The IPCC Sixth Assessment Report (IPCC 2021) states that in a warmer climate, there will be a “Likely decrease or no change in frequency of tropical cyclones, likely increase in mean maximum wind speed, but possibly not in all basins, likely increase in heavy rainfall associated with tropical cyclones.” While the large uncertainty in the changes in TC frequency makes it hard to project their risk, the consensus is that when a TC (or a medican) makes landfall, the stronger winds and heavier rainfall, combined with sea level rise due to climate change, will lead to more severe impacts.

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

## 2. Week 1: Defining medican in the landscape of Mediterranean cyclones

During the first week of TROPICANA at the Institut Pascal, we delved into several critical questions regarding the physics and modeling of medicanes. To mark the launch of the program

on Monday, 3 June 2024, a public lecture was given by Kerry Emanuel, which illustrated the common features of hybrid cyclones happening in the subtropics and extratropical regions (Emanuel 2018). The talk proposed that, while different names are used for these cyclones depending on the region of development (medicanes, polar lows, Kona storms, and subtropical cyclones), the physics is essentially the same, and hence that, from a physical point of view, they should be treated as the same category. The lecture was followed by a panel discussion and a press briefing, which allowed a dozen of French and international journalists to ask questions to a panel of experts on medicanes, TCs, and climate change.

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

Regarding the modeling of medicanes, one important issue to consider is spatial resolution, which is crucial to simulate tracks and impacts accurately in the Mediterranean basin, as it is smaller and has a more complex geography than other ocean basins (Flaounas et al. 2022). Addressing these model deficiencies involves several pathways, each one with its own set of challenges: switching to regional climate model configurations, developing nonhydrostatic or convection-resolving models (Coppola et al. 2020), and improving subgrid scale parameterizations of convection and boundary layer processes. These discussions were fruitful for advancing our understanding and how to improve the modeling of medicanes in the future, laying a strong foundation for the subsequent weeks of the program. During the first week, we also highlighted how international projects such as two Horizon Europe projects—Artificial Intelligence for Detection and Attribution (XAIDA) and Climate Intelligence (CLINT)—and two European Cooperation in Science and Technology projects—FutureMed (A transdisciplinary network to bridge climate science and impacts on society) and MedCyclones (the European network for Mediterranean cyclones in weather and climate)—can advance the understanding of Mediterranean cyclones and provide opportunities for near-real-time analyses and communication.

### **3. Week 2: Climate change impacts and attribution of medicanes**

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

In this week, we also discussed whether attribution studies, increasingly common for specific tropical cyclones (Reed et al. 2020) or cyclone seasons (Reed et al. 2022), could be applied to medicanes as well as Mediterranean cyclones in general. In particular, these attribution studies would involve methodological adaptations to account for the specific environmental and geographical features of the Mediterranean basin. The debate highlighted that ideally attribution would require large ensemble of convection permitting simulations with and without the influence of climate change (see, e.g., Koseki et al. 2021). The capabilities of the rapid attribution framework of ClimaMeter (Faranda et al. 2022, 2024) were presented and, as a training activity, we produced a rapid attribution (<https://www.climameter.org/20200917-18-medicane-ianos>) report for the case of Medicane Ianos. The conclusions of the report stated that Mediterranean depressions like Ianos have similar atmospheric pressure and up to 15% higher precipitation in the present than in the past decades. We interpreted Medicane Ianos as a largely unique event in which natural climate variability played a significant role. Many presentations during the week also addressed classification and impacts of medicanes.

#### **4. Week 3: Tropical cyclone genesis and simulations**

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

We explored the factors that influence TC frequency and genesis globally and across basins, including the role of TC seeds in determining TC frequency (Vecchi et al. 2019; Sobel et al. 2021; Rajasree et al. 2023; Núñez Ocasio et al. 2024; Rios-Berrios et al. 2024). We also investigated the mechanisms influencing regional and interannual variations in TC activity (Wu et al. 2020; Feng et al. 2022).

While the term “TC seed” is frequently used in the scientific community in recent years, it lacks a rigorous definition. Participants shared their different views of the concept and collaborated in developing a physics-based definition. The task of defining what exactly a TC seed is and what parameters need to be considered in a seed tracker is complicated by the different tropical cyclogenesis pathways in different basins. Furthermore, although most, if not all, TCs in the real world originate from pre-existing disturbances, it is not clear whether TCs actually need a seed to form based on idealized model simulations (Patricola et al. 2018; Ramsay et al. 2020).

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

Furthermore, we discussed attribution studies for tropical cyclones (Patricola and Wehner 2018; Wehner et al. 2019). Such studies typically focus on changes in the characteristics of

tropical cyclones, such as their intensity, associated rainfall, or storm surge (e.g., Reed et al. 2020, 2022). However, as the hazards associated with tropical cyclones occur concurrently, there is a need to develop a more comprehensive attribution framework that takes into account the compound effect of tropical cyclone attributes and impacts.

#### **5. Week 4: Tropical cyclones climate change, risk, attribution, and machine learning**

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

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

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

Furthermore, downscaled TC datasets are limited by the biases of the large-scale environmental fields inherited from the global climate models, which highlights the need for effective and efficient bias correction techniques. When using bias correction, the global climate model fields need to maintain physical consistency across variables like wind, precipitation, and sea level pressure, thereby preserving an accurate assessment of the impact of climate change on TCs. Furthermore, the presence of systematic biases across global climate models, such as the historical trends in the tropical Pacific sea surface



temperature (Seager et al. 2019, 2022), could potentially lead to an underestimation of the existing uncertainty of TC projections (Sobel et al. 2023).

Throughout the week, the applications of machine learning (ML) for improving TC simulations, understanding, and attributions were a key theme (Tam et al. 2024; Lockwood et al. 2024). We explored how ML frameworks can refine model projections, correct biases, and contribute to more reliable assessments of climate change impacts on TC characteristics. Furthermore, we discussed the potential for ML to complement or replace traditional dynamical modeling in TC research. Important topics include the critical role of TC data quality, as ML models are limited by their input data. Synthetic data generation was proposed as one way to address gaps in observational records (Yang et al. 2022). There are questions about how ML can capture the effects of climate change, predict extreme events, and maintain physical realism in its projections (Molina et al. 2023; Beucler et al. 2024). Currently, the potential of ML to bridge the gap between weather and climate research communities is being explored, along with the need for robust evaluation metrics and stakeholder involvement (Eyring et al. 2024). Concerns are also raised about the limitations of current ML methods and the importance of leveraging causal methods to enhance model robustness (Ganesh et al. 2023).

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

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

## 6. Perspectives

White papers, tutorials, and recommendations aimed at defining medicanes and tropical cyclone seeds, along with a comprehensive review paper on their impacts, will pave the way for a follow-up event, TROPICANA 2, in 2027. TROPICANA 2 not only will aim at consolidating the work on medicanes and tropical cyclones but also will expand toward other types of cyclones, including subtropical, midlatitude, and polar cyclones. We want to continue to strengthen our ability to predict, respond, and make projections of all types of storms, by looking at all cyclones comprehensively.

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

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