Tracking evolving views of the 2024 Atlantic hurricane season with an expert prediction market

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Introduction

Prediction markets use the mechanics of betting to aggregate the views of many participants into probability forecasts. Their application to climate-related topics has been advocated by economists and climate scientists (e.g. Hsu, 2011; Vandenbergh *et al*., 2013), and pilot markets on horizons of up to a year indicate that they can produce well-calibrated probabilistic predictions (Roulston and Kaivanto, 2024). A recent prediction market, the CRUCIAL Atlantic Hurricane Market 2024 (CAHM24), which forecasted the total number of hurricanes that would occur during the 2024 Atlantic hurricane season (1 June to 30 November 2024) provides an interesting case study to illustrate their use.

The 2024 hurricane season

Before the 2024 hurricane season began, several groups had issued forecasts predicting that it would be exceptionally active. The previous season was a 'tug of war' between the two main drivers: the hurricane favourable warm Atlantic Ocean and hurricane suppressing El Niño conditions (Klotzbach *et al*., 2024). However, in early 2024, the ENSO phase was projected to flip to La Niña conditions and align with a warm Atlantic (https://www.noaa.gov/news-release/noaa-predicts-above-normal-2024-atlantic-hurricane-season). This led many statistical and dynamical forecasters to make record predictions and there was a rare consensus among the 25 forecasters contributing to the prediction platform at https://seasonalhurricanepredictions.bsc.es/ that the season would be very active.

In early April, five forecasting groups (Colorado State University, Tropical Storm Risk, Météo-France, University of Arizona and University of Missouri) predicted 11 hurricanes would occur – in contrast to a mean of 7.7 observed hurricanes per season since 2004 and 6.1 since 1924 (calculated from HURDAT2 database, Landsea *et al*., 2015).

The season opened with Tropical Storm *Alberto*, and before the end of June, Hurricane *Beryl* formed and became the earliest Category 5 storm ever recorded. However, as September approached, normally the peak period for hurricanes, the rate of hurricane formation did not pick up. After *Ernesto*, in mid-August, there were no more tropical storms until *Francine*, almost a month later. This period of low activity came to a halt with hurricanes *Helene*, *Isaac*, *Kirk*, *Leslie* and *Milton* all forming within a 2-week period in late September. In October, *Oscar* and *Rafael* brought the season total to 11; exactly what many forecasters had predicted in April. The season's storms are summarised in Figure 1.

While the season total was in line with the pre-season predictions, the final predictions from forecast groups were issued in early August, before the atypical period of inactivity began. We do not know how this period may have caused forecasters to revise their predictions. Although none of the groups issuing predictions took part in CAHM24, other academics and professional forecasters did. The behaviour of the market

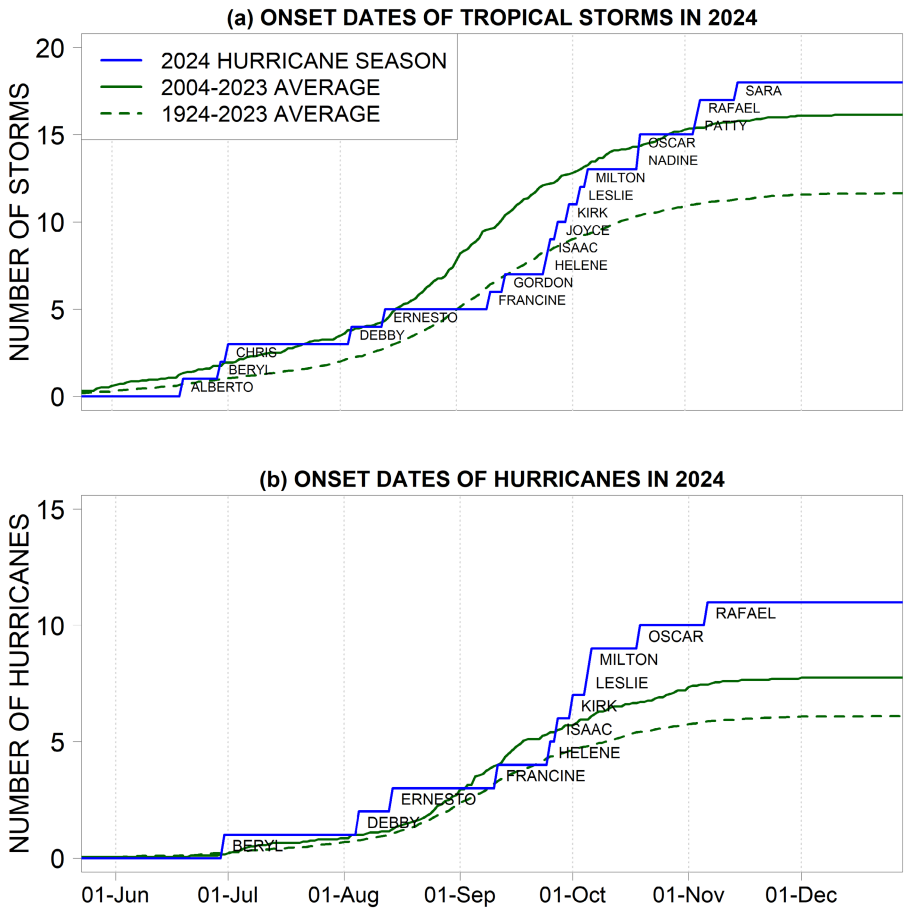

Figure 1. The 2024 Atlantic hurricane season exceeded the average of 6.1 hurricanes per season over the past century as well as the 20-year average of 7.7 hurricanes. (Source: data from the HURDAT2 database, Landsea et al., *2015.)*

prices provides insight into how their thinking and assumptions may have been affected by the mid-season lull.

CAHM24 prediction market

The CAHM24 prediction market opened on 10 December 2023 and closed on 30 November 2024. Each participant in the market was given 500 credits on CRUCIAL's Agora platform. With these credits they could buy outcomes for the total number of hurricanes that would occur during the 2024 season. There were 21 outcomes: zero hurricanes, one hurricane, and so on, up to '20 or more hurricanes'. At the end of the hurricane season, the outcome corresponding to the actual number of 11 hurricanes became worth 1.00 credit while all the other outcomes became worthless. Participants were then paid £1 for every credit they had accumulated above their original 500 credit allocation.

During the trading period, outcomes were priced between 0.00 and 1.00 credit. These prices were set by an automated market maker (AMM) that priced each outcome based on its relative popularity. The AMM used a pricing algorithm that rewards participants according to the logarithmic scoring rule, a common score for evaluating probabilistic forecasts (Hanson, 2007). Since the outcomes were defined so that one *had* to occur, but *only* one could occur, the AMM ensured that the prices for all outcomes always added up to 1.00.

Buying an outcome on Agora is equivalent to fixed-odds betting: for example, buying an outcome for 0.25 that will pay out 1.00 if it is correct is the same as placing a

Box 1. Trading in the CAHM24 prediction market

When the market opened, the price of '11 hurricanes' was 0.02 credits. If a participant believed the chance of 11 hurricanes was substantially higher than 2%, they might have bought 100 contracts covering this outcome, which would have cost them 2.00 credits. By the end of September, the price of 11 hurricanes had risen to 0.20 credits, due to this outcome's popularity. The participant could have sold their 100 contracts then for a net profit of 18.00 credits. If instead they held these contracts to the end of the season – when 11 was confirmed as the correct outcome – they would have received 1.00 credit for each contract, giving them a net profit of 98.00 credits.

Participants were not restricted to a single outcome but could buy a portfolio of outcomes, based on how underpriced they believed them to be.

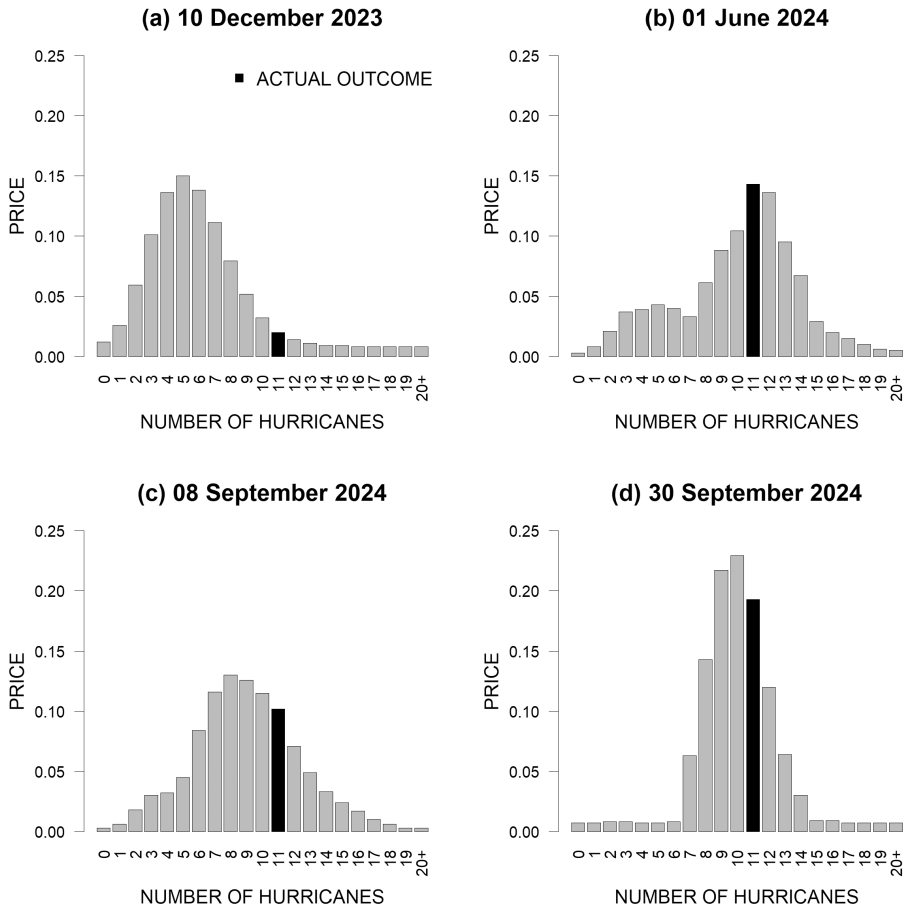

Figure 2. Snapshots of the distribution of prices on 4 days during the market: (a) are the initial prices, based on the climatology of hurricanes over the past century; (b) is the first day of the season; (c) is at the end of the mid-season quiet period and (d) is at the end of September after five hurricanes occurred in close succession. The actual number of hurricanes that occurred in 2024 was 11.

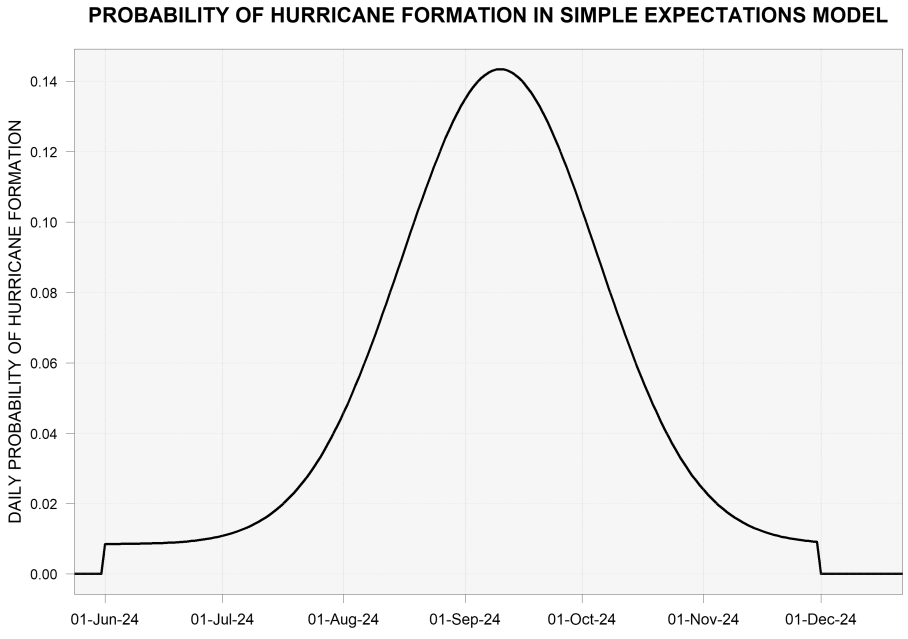

Figure 3. The daily probability of hurricane formation in the simple expectations model. It is a stylised version of the climatology of Atlantic hurricanes (https://www.nhc.noaa.gov/climo/). The probabilities outside of the official hurricane season are set to zero because they did not count under the rules of the market. The probabilities add up to 10 to reflect the pre-season estimate for the number of hurricanes that would occur during the season.

Box 2. A simple model for the expected number of hurricanes

If PROB_t is the probability of a hurricane forming on day t then the expected number of hurricanes for the full season on day T is given by

$$\text{Expected hurricanes} = \text{Observed hurricanes} + \sum_{t \geq T} \mathrm{PROB}_t$$

which is just the number of hurricanes that have already occurred plus the sum of the probabilities for the remaining days in the season.

The standard deviation for the number of hurricanes can also be estimated using the normal approximation of a binomial distribution.

$$\text{Standard deviation} = \sqrt{\sum_{t \geq T} \left(\mathrm{PROB}_t \cdot \left(1 - \mathrm{PROB}_t\right)\right)^2}$$

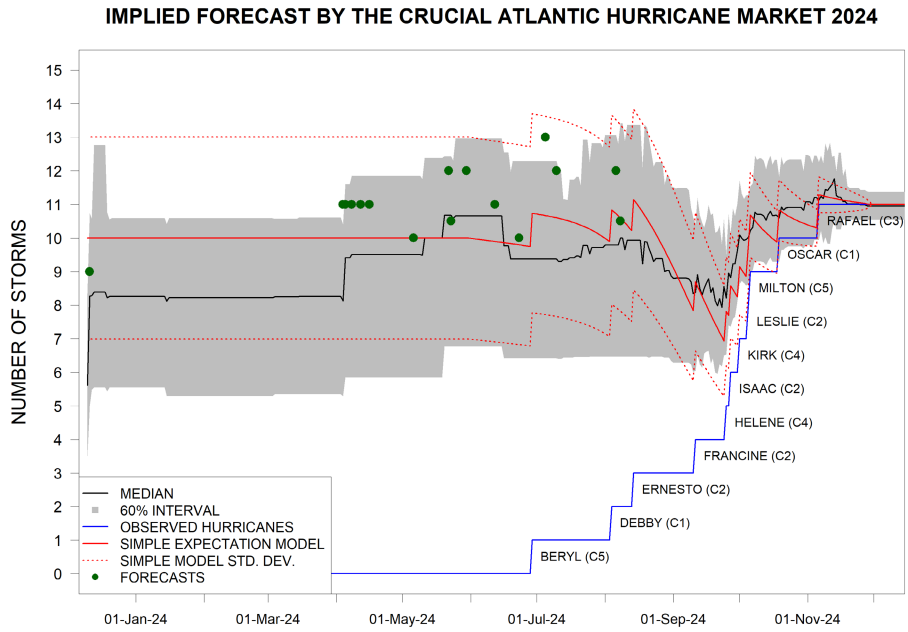

Figure 4. The evolution of the probability distribution for the number of hurricanes during the 2024 season implied by the prices in the CAHM24 prediction market (the distributions shown in Figure 2). The black line is the median of the distribution while the grey envelope shows the interval between the 20th and 80th percentiles. The observed number of hurricanes is shown in blue. The red lines represent the expected number of hurricanes implied by a model that assumes the probability of hurricane formation for each day follows the distribution shown in Figure 3. The dark green dots are forecasts that were issued by academic groups and other forecasting centres.

bet at odds of 3:1 against. Agora, however, allows participants to sell outcomes they have previously bought (Box 1). This enables the market prices to reflect the changing views of the participants. If we assume that the prevailing prices of outcomes reflect their expected values, then these prices can be interpreted as probabilities that the outcomes will occur, according to the collective wisdom of the market participants.

Of 19 candidate participants selected for their expertise, 15 completed the informed-consent form approved by Lancaster University's Research Ethics Committee. 60% of the participants were based in academia, while the remaining 40% were in the private sector or non-profit organisations. Of the 15 participants endowed with on-platform credits, 10 subsequently engaged in trading on the platform during the hurricane season.

Evolution of CAHM24 prices

The prices in the market were initialised based on the climatology of Atlantic hurricanes over the last century, during which the average number of hurricanes per season has been around six (Landsea *et al.*, 2015). The initial price distribution is shown in Figure 2(a). The market opened in December 2023, and by the start of the 2024 season, on 1 June, the prices had evolved to reflect the consensus that it would be a very active season (Figure 2b), with 11 being the most likely number of hurricanes. By the end of the mid-season quiet period, on 8 September, the peak of the distribution implied by CAHM24 prices had slipped from 11 to 8 hurricanes (Figure 2c). Three weeks later, after three more hurricanes had occurred, the mode of the distribution had increased again to 10 hurricanes (Figure 2d).

A simple model of expectations

To gain insight into the behaviour of the market we can use a simple model in which the assumed probabilities of a hurricane forming on each day are specified, as shown in Figure 3. The peak probability occurs on 10 September. The probabilities outside of the official season are zero because, according to CAHM24 rules, out-of-season storms did not count. The daily probabilities add up to 10, reflecting the pre-season median estimate of the market that about 10 hurricanes would occur.

Under this model, on a particular day, the expected total number of hurricanes for the season is given by the number of hurricanes observed so far plus the sum of the probabilities for the days remaining in the season. If no hurricane occurs today, then tomorrow's estimate of the season total will decrease by today's probability (Box 2).

The model is analogous to a die that is thrown 60 times. Before the first throw, the expected number of sixes will be 10. Once the throws have started, the expected number of sixes will be the number already thrown plus one sixth of the number of remaining throws.

Figure 4 shows the evolution of the probability distribution implied by the prices from the opening of the market in December 2023 to the end of the 2024 season. It shows that immediately after the market opened, the median estimate rose from 6 to 8 hurricanes before rising again to 10 in early April, when several groups issued forecasts expecting 11 hurricanes. The median increased to 11 just before the start of the season. It remained close to 10 until the onset of the quiet period, when it began to decline, reaching a minimum of eight hurricanes. This was followed by the formation of five hurricanes (*Helene* to *Milton*) in quick succession, which moved the median estimate back above 10, where it stayed until the season ended with a total of 11 hurricanes.

The expected number of hurricanes, and the standard deviation, implied by the simple expectations model are also shown in Figure 4. The fall in the expected number during the quiet period implied by the model, followed by its recovery after this period had ended, match what was observed in the prices. This suggests that the fall could have been driven by partici-

pants responding to the lack of hurricanes, but that they were not revising their estimated probabilities that hurricanes would form on subsequent days.

Conclusions

Price behaviour in the CAHM24 prediction market suggests that during the period of low activity in the Atlantic basin from mid-August to mid-September 2024, the participants in the market rationally updated their expectations for the total number of hurricanes based on the low number of observed hurricanes. However, the price movements provide no evidence that participants reappraised their estimated probabilities that more hurricanes would occur during the remainder of the season.

While CAHM24 illustrated the ability of prediction markets to incorporate new information in real time, as it became available to participants, in any verification study it would only be a single data point, so we cannot use it to draw conclusions about forecast accuracy – see Roulston and Kaivanto (2024) for a verification study of previous climate-related prediction markets. For seasonal forecasts, it can take years to accumulate enough out-of-sample data to draw statistically meaningful conclusions about accuracy and reliability. CRUCIAL intends to continue running prediction markets for climate risks to study their effectiveness. We have recruited teams with relevant expertise from academic institutions and the private sector to collaborate and participate in these markets.

Prediction markets can combine and summarise the judgements of forecasters with diverse expertise and different approaches. If CRUCIAL can establish their effectiveness, prediction markets could become a new type of institution for synthesising climate research and an alternative mechanism for allocating funding for climate forecasting. For this to happen, climate forecasters and organisations that fund climate forecasting would need to become comfortable with this market-based approach to generating climate predictions.

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Author Contributions

Mark Roulston: Conceptualization; methodology; writing – original draft; writing – review and editing; investigation; formal analysis. **Kim Kaivanto:** Conceptualization; methodology; investigation; writing – review and editing; project administration; formal analysis. **Ralf Toumi:** Conceptualization; writing – review and editing.

Conflict of interest statement

The authors declare no conflicts of interest.

Data availability statement

Code and data are available at https://doi.org/10.7910/DVN/SUDJSQ.

Supporting Information

CRUCIAL Atlantic Hurricane Market 2024 (CAHM24) was approved by Lancaster University's Faculty of Arts and Social Sciences and Lancaster University Management School's joint Research Ethics Committee under the Lancaster Experimental Economics Laboratory (LExEL) track (reference number FASSLUMS-2023-4156-LeXeL-2).

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