Weather forecast for the 35th America’s Cup (2017) winners based on a limited area model

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Abstract
The America’s Cup (AC) is the oldest trophy in international sport and sailing regatta. The 35th AC occurred during spring 2017 in Bermuda. A new generation of sailing boats was in use, while the technical advances required back-stage to enable a victory were equally impressive. The availability of accurate wind fields with a grid spacing of < 1 km from numerical meteorological forecasts was one of those key advances, used for both strategic and tactical planning. The study describes the limited area model, explicitly resolving the convection, used to generate weather forecasts for Emirates Team New Zealand (ETNZ) challenger, the challenger and winning team. In particular, it illustrates an ability to forecast accurately the wind variability in space and time, which helped achieve victory.

KEYWORDS
explicit convection modelling, sailing, very-high resolution numerical forecast

1 | BACKGROUND
The America’s Cup (AC) sailing trophy is held in a trust as a perpetual challenge trophy to promote friendly competition among nations. In 2017, in the Bermuda Islands, Emirates Team New Zealand (ETNZ) beat Oracle Team USA (OTUSA). This 35th AC saw the arrival of an advanced AC45 Catamaran Class sailing boat, combining the use of hydrofoils as well as a solid vertical wing sail, enabling a cruising speed of up to 40 kn and the boat to “fly” 100% of the time. While the weather forecast is not the only factor required to achieve victory, it is a necessary condition. Hence, ETNZ worked with a dedicated weather forecast team. Their weather forecasts became crucial a few hours before the afternoon races for tactical reasons, as well as on the eve of a race since technical choices and adjustments had to be performed one day before the race.

The AC45 had several sets of hydrofoils designed for low, medium and strong wind ranges. The choice of the set had to be performed the day before the race because of the time required to set the hydrofoils. Additionally, teams must declare their foil settings to the umpires by early morning each day. The accuracy of the day + 1 early weather forecast was thus crucial at this stage.

The boats were designed to “fly” over the water, and as soon as a hull is in the water, the boat speed collapses. The design of the water foils was a crucial issue and the teams did not have the same foil types. However, once the water foils were loaded, their onshore as well as dynamic offshore settings were real issues for boat stability. A failure in the foil choice or regulation may drive
to a dramatic loss of control. Such a failure led to the semi-final race capsize which caused significant damage.

The AC official competition started by May 26, 2017, for ETNZ and ended on June 25. ETNZ started the final AC matches one point behind, since OTUSA had taken a bonus point through a pre-regatta process during the Louis Vuitton Cup organized ahead of the AC to select an official challenger to OTUSA from the four challengers: Sir Ben Ainslie Racing (UK), Artemis Racing (Sweden), Soft Bank Team (Japan) and ETNZ (NZ). ETNZ were 4-0 up after five races and only then did OTUSA manage to win a race. At 4-1 up, speculation was rife that ETNZ would again falter and allow OTUSA back into the regatta, but they went on to win the next three races sweeping to victory over OTUSA by 7-1.

The Bermuda Islands competition site was in the Atlantic Ocean (Figure 1a). The Bermuda main island exhibits 103 km of hilly coastline with a highest point at 79 masl.

The Great Sound is an ocean inlet (a sound) located in main Bermuda island (Figure 1). It forms a natural harbour and is surrounded by land, except for the northeast (Dundonald channel), where the water area connects to the Atlantic through a reef, located towards the western side of Bermuda.

The Great Sound and Dundonald channel were chosen as locations for the races. The race area orientations were adjusted as a function of afternoon mean wind direction (the race main axis must be windward).

Bermuda is under a marine climate influence, which moderates temperatures with cool, moist winters and warm, moist summers. The islands are situated on the western end of the Bermuda–Azores High, which during the winter is located to the distant southeast, and during the summer to the northeast. During the winter, most of the cold fronts that move south and east off the US East Coast cross Bermuda, and although modified by the Gulf Stream and Western Sargasso, are often quite intense, with strong winds. In summer, fronts are slowed or stopped, with only a few crossing the island and migrating northwards. Summers typically experience relatively light circulation varying from east to southwest.
The competition period (May–June) is outside the official hurricane season and is considered a transition period when a change from a winter to a summer pattern occurs.

The Bermuda Weather Services (BWS) manages several meteorological stations (BWS, 2017) located close to the competition site (Figure 1): Pearl Island (32.29° N, 64.84° W), Saint Georges Airport (32.36° N, 64.70° W) and Crescent Reef (32.41° N, 64.82° W). The first two are located over the main islands, while the latter is located north, surrounded by water on the reef. The nearest station was Pearl Island since it is at the immediate vicinity of the sailing race area.

For AC preparation and climatological study purposes, the Saint Georges Airport station data set was preferred since it has the longest historical record. Table 1 presents the mean temperature and wind velocity over 30 years for May–June as well as the monthly means for 2017.

The AC competition period (May 24–June 26, 2017) experienced a synoptic set-up such that the centre of the Bermuda–Azores High varied its location over 2,000 km from the northeast to the southeast of the island, with a ridge that was periodically weakened by frontal boundaries extending over the local area towards Florida. Frontal boundaries with significant pressure drops and strong winds occurred from May 26 to 27 and from June 6 to 9. The daily mean air temperatures were above the daily normal. The absolute lowest (highest) air temperatures were recorded as 22.9°C (29.7°C) on the June 11 (26). In the meantime, the daily mean sea surface temperatures (SST) were amongst the warmest on record since 1950.

The daily 10 min mean surface wind speeds observed at the airfield ranged from calm to 27 kn. June 11 marked a shift from the daily mean wind speed of between 6 and 20 kn (with a maximum to minimum variation of > 10 kn) to a daily mean between 5 and 11 kn (and a variation < 10 kn). The absolute maximum speed was recorded on June 7 as 27 kn, peaking at 39 kn. The dominant wind directions were southwest to west. The greatest variation within a day, including a northwest to northeast wind, were observed on May 31 and June 4, 11 and 16. An east to southeast wind was observed from June 17 to 20.

Thunderstorms were recorded on June 3 and on June 10–13 when a funnel cloud was also officially observed.

### 1.1 Weather forecast challenge

Compared with other international sailing competitions (Olympic Games and world championships), the AC organization does not provide official weather services; it makes available the observations collected by the BWS.

Most teams had their weather experts and access to additional weather data: satellite (GOES and/or METEOSAT), BWS Airport radar images (it was out of order during the final of the AC) and synoptic analysis from the European Centre for Medium-Range Weather Forecasts and/or National Centers for Environmental Prediction. Some teams, such as ETNZ, deployed a dedicated weather forecasting system based on a limited area model specially parameterized, being suitable for the location.

Regarding the forecast, the interaction between the synoptic wind and local sea breeze circulation superimposed onto remarkable terrain a hook-like shape (Figure 1) that presented a very challenging modelling issue which was reviewed by Crosman and Horel (2010). Previous studies also associated the sea breeze circulation to the gradient wind (Crooks and Brooks, 1987) and the sea–land temperature contrast (Zhong and Takle, 1992; Connor, 1997; Mestayer et al., 2017). Common characteristics of the sea breeze based upon the synoptic setting, or large-scale flow, were also noted by Arritt (1989, 1993), Houghton (1992), and Atkins and Wakimoto (1997).

The Great Sound is also a nearly closed water body only open on its northeast side. It is bounded all around by the Atlantic Ocean, while several hills with greatly

| TABLE 1 | Thirty years of climatology for Bermuda international airport station |
|---------------------------------|------------------|------------------|------------------|
| **T (°C)** | **Wind (kn)** | **2017** | **Wind (kn)** |
| **30 years, 1981–2010** | | **Mean = 22.4** | **Westsouthwest mean = 11.2, SD = 4.4** |
| **May** | Southwest mean = 10.3, SD = 4.1 | | **Maximum = 24.6, minimum = 19.6** |
| | Maximum = 29.8, minimum = 12.2 | Maximum = 34.0, minimum = 0 |
| **June** | Southsouthwest mean = 9.6, SD = 3.8 | Mean = 25.6 | Southwest mean = 10.3, SD = 3.2 |
| | Maximum = 32.2, minimum = 15.3 | Maximum = 27.1, minimum = 22.9 | Maximum = 25.0, minimum = 0 |

Note: The compass point direction is the mean direction from all observations at the airport. Data are the mean/standard deviation (SD) of the mean; absolute monthly maximum/minimum. Speeds are in knots (kn).
varying altitudes surround the Great Sound. The absence of other natural barriers therefore suggests a major land/topographical control of the local and inner circulation over the Great Sound in May and June, as the synoptic flux weakens. Indeed, although the convection is not a persistent feature over Bermuda, it usually appears by late May when synoptic flux magnitude decreases (BWS, 2017). The image of a cumulus cloud above the Bermuda Islands’ immaculate blue seascape displayed on the AC2017 official website (Figure 1d) (not available anymore) is an illustration of the local convection that may change surface winds in speed and direction. In addition to variable synoptic conditions, local processes may modify or even drive the local weather conditions (especially for wind). Dynamic flows on surface discontinuities (such as islands) or SST fronts and eddies often exhibit a wind flow disturbance (Small et al., 2008; Messager et al., 2012). In addition, the land/sea contrast (elevation, albedo, bare soil, urban, vegetation variability) locally affects the wind flow and tends to enhance/inhibit local convection by modifying upward fluxes (Kirshbaum and Smith, 2009; Kirshbaum, 2011).

As a result, surface wind variability of the Great Sound under weak wind conditions is notoriously complex.

2 | THE HIGH-RESOLUTION, LIMITED AREA NUMERICAL WEATHER PREDICTION SYSTEM

Several forecasts were requested each day for (1) the current day’s races (tactical use) and (2) the day after (day + 1 strategic use). The latter was devoted to the settings of hydrofoils, which was a lengthy operation. Table 2 illustrates the daily flowchart of the high-resolution weather forecasts. A first forecast covering the day of the race from 1200 UTC (0900 LT) to 2100 UTC (1800 LT) was performed from the 00Z analyses. A second forecast was performed 6 hr later to update the first one and extended to day + 1 from 1200 UTC (0900 LT) to 2100 UTC (1800 LT). The two forecasts used were by the tactician, skipper and helmsman to prepare for the afternoon races (tactical use), while the latter was dedicated for strategic purposes (foil settings and navigation strategy) and intended for onshore engineers, technicians, tactician, skipper and helmsman to prepare for the day + 1 afternoon races.

Regarding Bermuda’s climatology and local effects to obtain an accurate high-resolution forecasting system adapted to the specificities of the racing area, a focus was necessary on the orography, surface albedo, vegetation, convection processes and synoptic conditions (Wang and Kirshbaum, 2015). The numerical prediction system was designed for the Bermuda site and, furthermore, customized for May–June. It is made of a numerical model with all components required to run in real time.

The model adapted was the Weather Research and Forecasting (WRF) model, 3.8.1 version. This limited area model (also called a regional model) allows realistic high-resolution simulations over regional areas by nesting subdomains to increase the horizontal grid spacing step by step. Domains nesting allows the model to reach high horizontal grid spacing, starting from a synoptic scale with standard meteorological analyses (grid spacing ranging from 0.5 to 0.25°) towards the mesoscale (a few tens of km) or the sub-mesoscale (a few hundred metres) and large eddy simulation (LES) scale. In this kind of nesting approach, the information of the outer domain is communicated to the inner domains and so on up to the desired grid spacing (Skamarock et al., 2008).

In order to reach the sub-meso to the LES scales, the WRF model was deployed from the synoptic scale down to an inner domain with 220 m of horizontal grid spacing by using five embedded domains, following the nesting methods (Heath et al., 2017) (Table 3).

The topography used was retrieved from the Global Multi-Resolution Terrain Elevation Data (GMTED) from the United States Geological Survey (USGS) at 7.5 arc-seconds horizontal grid spacing. The soil types and soil covers were computed from the Moderate Resolution Imaging Spectro (MODIS) radiometer (onboard the Terra and Aqua satellite platforms) database at 15 arc-seconds.

<table>
<thead>
<tr>
<th>Synoptic analyses</th>
<th>Reception time</th>
<th>Run start UTC/LT</th>
<th>Run time length (min)</th>
<th>Forecast length (hr)</th>
<th>Forecast time coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tactical use</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0000 UTC</td>
<td>0400 UTC</td>
<td>0415/0115</td>
<td>60</td>
<td>21</td>
<td>1200 UTC (0900 LT)–2100 UTC (1800 LT)/same day</td>
</tr>
<tr>
<td>Strategy use</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0600 UTC</td>
<td>1000 UTC</td>
<td>1015/0715</td>
<td>80</td>
<td>39</td>
<td>1200 UTC (0900 LT)–2100 UTC (1800 LT)/day + 1</td>
</tr>
</tbody>
</table>
horizontal resolution. Note that elevation, soil type and land use were corrected manually to match the in situ reality of coverage better.

For May–June, convection over Bermuda modulates the synoptic flux, and high-frequency time sampling was necessary to describe the rapidly varying phenomena such as convection. Thus, the innermost domain (Domain 5) was at 220 m grid spacing with a corresponding model time step of 0.72 s to reproduce realistic processes. The model time step was also constrained by the vertical grid spacing in the lower boundary layer. A 52 level distribution was selected to provide the best trade-off between accuracy and computational cost.

It was also necessary to describe the atmosphere and its interactions with the marine and terrestrial surfaces processes. Since Bermuda has a very small shallow land surface surrounded by the wide ocean, the main local influence comes primarily from orography, albedo and terrestrial skin effects, while deeper soil interactions can be neglected. Similarly, only temperature was considered as relevant for sea surface–atmosphere interactions. The WRF model was thus coupled with a surface model based on a single thermal diffusion scheme (Dudhia, 1996). The simplicity and robustness of this surface scheme was also preferred for this real-time application.

The choice of the boundary layer scheme followed the assumption that near-surface processes are driven by the vertical temperature profile. Consequently, the Yonsei University scheme (Hong et al., 2006), with a revised Jimenez surface layer scheme, was selected (Jimenez et al., 2012). The vertical diffusion in the boundary layer was then controlled by the buoyancy/shear ratio (the latter tends to mix), which was necessary for the site since the topography is expected to introduce the main flow disturbance, modulated by the island surface diurnal heating (Anber et al., 2015).

The short wave radiative scheme was based on the solar downward radiation source using atmospheric dispersion as well as the water vapour absorption scheme and cloud, including their albedo (Dudhia, 1989). For the long wave radiative scheme, a spectral method was preferred, using cloud interaction and ozone and CO₂ interactions (Mlawer et al., 1997).

The model targeted an explicit simulation of the convection, which constrains the choice of proper parameterization for cloud microphysics. Indeed, some very detailed and sophisticated microphysics schemes exist with various hydrometeor as well as different degrees of interaction with the other model schemes. However, at high resolution, the use of such schemes leads to an explosion of computational time and an overestimation of cloud cover with a too strong ice phase and the production of high-level clouds (Arbizu-Barrena et al., 2015). As a result, these clouds may completely alter the convection processes. Thus, a simpler microphysics scheme was preferred (Lin et al., 1983).

Note that the convection was not parameterized in the higher (inner) resolution domains, while a robust and standard parametrization scheme (Kain-Fritsch

<table>
<thead>
<tr>
<th>TABLE 3</th>
<th>Domains, resolutions and scales used with the model over Bermuda</th>
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<tbody>
<tr>
<td>Domain 1</td>
<td>Domain 2</td>
</tr>
<tr>
<td>Horizontal dimensions (km²)</td>
<td>1,675 × 1,675</td>
</tr>
<tr>
<td>Horizontal resolution (m)</td>
<td>17,820</td>
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<tr>
<td>Modelling scale</td>
<td>Meso</td>
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</table>

Note: LES: large eddy simulation.

<table>
<thead>
<tr>
<th>TABLE 4</th>
<th>Domain 5 Pearl Island and Crescent Reef statistics analysis for tactical use (forecast from 0000 UTC analyses)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pearl Island</td>
<td>Wind speed (kn)</td>
</tr>
<tr>
<td>OSTD</td>
<td>4.40</td>
</tr>
<tr>
<td>FSTD</td>
<td>4.03</td>
</tr>
<tr>
<td>BIAS</td>
<td>−2.08</td>
</tr>
<tr>
<td>MAE</td>
<td>2.92</td>
</tr>
<tr>
<td>RMSE</td>
<td>3.48</td>
</tr>
<tr>
<td>PR_CORR</td>
<td>0.84</td>
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</tbody>
</table>

Note: BIAS: bias (f – o); FSTD: forecast standard deviation; MAE: mean absolute error; OSTD: observation standard deviation; PR_CORR: Pearson correlation co-efficient; RMSE: root mean square error (√MSE).
scheme; Kain, 2004) was used for the outer domain at a 17,820 m grid spacing. Thus, the convection was parameterized and initiated in the larger domain associated with meso-scale processes, while inner domains convection was supposed to be explicitly initiated (Done et al., 2004).

### 3 | FORECASTS VERSUS OBSERVATIONS: FOR TACTICAL USE

The tactical use of the model forecast must be understood as the use of morning forecasts (0000 UTC) for the

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**FIGURE 2** Domain 5 wind daily forecast from 00Z analysis versus observations at Pearl Island station between May 27 and June 26, 2017: (a) time series of wind speed forecast versus observation; (b) wind roses for observation and forecast; and (c) histogram of forecast versus observation for both wind magnitude and direction.
afternoon sailing race. Table 4 presents standard statistics for high-resolution Domain 5 only.

Among all in-situ stations available for the assessment of the model forecasts, the Pearl Island and Crescent Reef ones were the closest to the race location. The assessment was performed for these two stations, but the Pearl Island station is highlighted due to its proximity to the race area. Raw observation data were gathered from different devices, each having its own sampling rate. Besides, time series from the model are recorded at station locations at the model integration frequency. In order to obtain a homogeneous data set, both observational and model data are resampled over 1 hr intervals. Within each interval, the minimum, maximum and average were recorded. Regarding wind speed, the statistics presented are based on the averages. On the other hand, wind direction statistics use the minimum 1 hr interval in order to avoid spurious means when the distribution of directions across the interval includes the north cardinal direction.

The numerical weather forecast system assessment is presented from May 27 to June 26, 2017, when the AC races took place. The time series of the observed and forecasted wind speeds as well as the scatterplots of model versus observations are presented in Figure 2. The analysis in Table 4 and Figure 2 shows that the model realistically forecasted the time variability of wind speed, while a systematic bias is highlighted for model outputs: underestimation of 2.28 and 1.44 kn at Pearl Island and Crescent Reef, respectively. The histogram of the observed wind speed at Pearl Island illustrates the fact that the observed wind magnitude was mainly between 7 and 16 kn, while the corresponding forecast wind was mainly between 5 and 11 kn. Some exceptions occurred when winds were overestimated, particularly on June 12. Since the model forecast wind underestimation was nearly systematic, it was easy for ETNZ weather forecast staff to anticipate and correct the wind magnitude bias from the model. The wind analysis is completed by the wind rose plots in Figure 2b, which strengthened the previous analyses. Note that the model performs slightly better over Crescent Reef for wind speed, while the wind direction is better forecasted at Pearl Island.

For Pearl Island, the cross-analysis of wind roses and wind direction scatterplot shows that the forecast error is the highest mainly for simulated wind from 0 to 50°, while the corresponding observations are from all directions. However, this class of wind direction occurred very rarely (see the observed wind direction histogram in Figure 2c).

The time correlation between the observation and numerical forecast is also significantly high for both wind speed and wind direction at Pearl Island and Crescent Reef. For the latter, less sensitive to coastal and orographic effects, the assessment shows better results for wind speed compared with Pearl Island station, as can be noted in Table 4.

Note that the particular overestimation forecasted but not observed the June 12 at Pearl Island is actually recorded at Crescent Reef, but it was still overestimated in the model.

For all other days, the model forecast at Crescent Reef suffers from the same systematic slight wind speed underestimation, even if the latter is lower compared with Pearl Island (bias of −1.36 kn). Also, the correlation for wind direction is high for both Pearl Island and Crescent Reef (0.74).

Finally, the correlation between the short-term wind magnitude forecast and the observation is high, while a systematic slight underestimation may be observed. However, the systematic nature of this bias was corrected by the forecaster. The wind direction was mainly very well forecast for southerly to southwesterly winds, which was the dominant direction during the AC 2017 competition period. The comparison of the observed and forecasted time series of wind magnitude also illustrates the very good ability of the model to forecast wind changes (a systematic bias of −2 kn is quite low combined with the very reasonable forecast of the direction).

### 4 FORECASTS VERSUS OBSERVATIONS: FOR STRATEGIC USE

Regarding the computing cost, the very high-resolution Domain 5 was used only for the forecast of the current day (tactical use), while the slightly lower resolution (660 m) Domain 4 model outputs were used for the day + 1 forecast (strategic use).

The interest for the day + 1 forecast was focused on the choice of the relevant hydrofoils designed for the correct wind magnitude. As a result, Table 5 presents FOR STRATEGIC USE

For abbreviations, see Table 4.
the statistics relative to wind magnitude forecast only, for day + 1 for Pearl Island and Crescent Reef stations. The bias remains close to that for the daily short-term forecast with still a systematic underestimation. Again, since the bias was systematic, the weather forecaster was able to manage it and deliver an accurate bulletin to the team. The time correlation between observed wind magnitudes remained significantly high (0.81 and 0.79 for Pearl Island and Crescent Reef stations, respectively). As discussed for tactical use, the day + 1 strategic weather forecast was thus mainly good with a systematic underestimation of 2.63 kn for wind speed. The wind roses in

![Wind Speed (knots) / Pearl Island](a)

![Wind Speed (knots) / The Crescent](c)

**FIGURE 3** Domain 4 wind day + 1 forecast from 06Z analysis versus observations at Pearl Island (a, b) and Crescent Reef station (c, d) between May 27 and June 26, 2017: (a, c) time series of wind speed forecast versus observation; and (b, d) wind roses for observation and forecast.
Figure 3 illustrate the correct direction forecasted in terms of occurrence.

Such as for tactical use, the day + 1 forecast perfectly reached its objectives and provided crucial services to ETNZ.

5  |  A PARTICULAR DAY: JUNE 24

This day saw Races #5 and #6 and is detailed here since it is the only day when both ETNZ and OTUSA won 1 point each. ETNZ won Race #5 and led OTUSA 4-0, but during Race (#6), started roughly at 1800 UTC (1500 LT), OTUSA showed good speed, some smooth tacks, made a huge gain under a wind shift and took its first and only point during the AC final. This was the only point conceded by ETNZ in the AC 2017 finals.

After race analysis, one can say that Race #6 was mostly lost by ETNZ owing to a tactical error, while the meteorological forecast was accurate enough to avoid it. Indeed, ETNZ, from being ahead, tacked, staying in the unstable flow rather than switching on the other side in order to take the benefit of a stronger and more stable wind area, as observed along all the AC.

On this afternoon, the racetrack was mostly clear of low cloud: there was a cloud line running parallel and close to the main southwest–northeast axis of the island. There was quite a deal of midlevel clouds Alto cumulus Alto stratus), the day was warm and humid, and the

<table>
<thead>
<tr>
<th>TABLE 6  June 24 Domain 5 Pearl Island statistics analysis for tactical use</th>
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<tbody>
<tr>
<td><strong>Pearl Island</strong></td>
</tr>
<tr>
<td>Wind speed (kn)</td>
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<tr>
<td>OSTD</td>
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<tr>
<td>FSTD</td>
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<td>BIAS</td>
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<td>MAE</td>
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<td>RMSE</td>
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</table>

For abbreviations, see Table 4.

FIGURE 4  Domain 4 wind day + 1 forecast from 06Z analysis versus observations at Pearl Island station on June 24, 2017 (the June 23 forecast for June 24, 2017—Weather Research and Forecasting (WRF) 06Z +24 hr): (a) time series of wind speed forecast versus observation; and (b) wind roses for observation and forecast
breeze looked to be sheared at the surface (i.e. softer at the water surface than immediately aloft). There were also no white caps on the water. The Pearl Island wind sensor recorded a daily average wind direction of westsouthwest that varied between 205 and 296°, and a daily average wind speed of 9.7 kn that varied between 4.7 and 14.8 kn, with a peak gust of 17.9 kn. Examination of the 1 min average data, between 1500 and 2100 UTC (1200–1800 LT), indicates an hour-by-hour backing of winds from approximately 240 to 220° with a minute-by-minute range of 25–30°. Two notable departures from this trend, backing about 25° for 15–30 min, occurred just after 1600 and 1830 UTC (1300–1530 LT). The mean speed through this period increased from approximately 8 to 10 kn, reaching its daily maximum (12–15 kn) around 1630–1700 UTC.
In the meantime, the global forecast system (GFS) data exhibited a mainly synoptic westsouthwesterly wind (data not shown), while average wind from the ETNZ boat for Race #6 was 222°/9.8 kn.

The choice and settings for the hydrofoils were performed on the previous day (June 23), for which Figure 4 presents the outputs of the averaged, minimum and maximum observed and forecasted wind. Note that the June 23 forecast was impressively accurate in terms of magnitude, direction and magnitude of afternoon variability. As observed, the model forecasted a relatively constant period (and overestimated by nearly 1–2 kn between 1200 and 1300 UTC) followed by a peak > 11 kn in observation and within the minimum/maximum spread of the model forecast, at 1600 UTC (1500 LT) followed by a decrease until 1800 UTC (1500 LT) to stay relatively stable afterwards (approximately 10 kn) and underestimated as usual by the model. Therefore, hydrofoils for low-level wind were chosen by ETNZ.

6 illustrates the statistics for the June 24 morning forecast and let appears the same analysis than the one performed for the whole AC period with the systematic bias, even if the bias was improved for both wind magnitude (1.27 kn) and direction.

The wind charts were not the only meteorological field used for boat settings and sailing tactics. Indeed, the absolute vorticity was particularly watched as the model illustrated its ability to simulate and forecast it correctly. The vorticity charts were used to monitor and locate potential convective cloud streets. The surface wind convergence was seen on the 10 m height wind charts, and the vorticity helped assess if the model developed convection to some depth. Indeed, if low-level convection occurs, circulation under cumulus or even cumulonimbus may change the local wind by increasing/decreasing the magnitude locally, especially under the clouds. The main cloud street along the axis of the island is known locally as the “Morgan Cloud” and can be orientated southwest–northeast or northeast–southwest, depending on the prevailing gradient flow. The Morgan cloud development can be from localized cumulus or cumulonimbus development or from the surface convergence across the island.

Figure 5 presents strategic wind and vortices charts produced on June 23 for day + 1 for Domain 4 at 660 m horizontal grid spacing (left column, a–c), while the same charts from the morning June 24 forecast for tactical use (right column, d, e) at 220 m horizontal grid spacing. The model perfectly forecasted the wind convergence on the two sides of the race area (Figure 5e), as well as the difference between the left and right sides of the race area with more turbulence over the right side. In a southwesterly flow such as it was on June 24, the main cloud street (Figure 5f) was usually aligned with the axis of the island with low-level convergence arising from the wind in the Sound to that on the south side of the island closest to the Sound. A secondary cloud street was streaming off the narrow section of land to the northwest of the Sound. Both these cloud streets originated near and over the Sound close to where the top turning mark (the upwind mark in Figure 5e) was positioned, and the exact location of that turning mark was critical for assessing the variability of the surface wind in that area. It is exactly at this mark that ETNZ badly managed tactical water positioning and then failed to outdistance OTUSA and, worse still, lost the lead.

6 | CONCLUSION

It has been mentioned several times that there is a systematic wind bias. It must be noted that the shallow water of the reef was a challenge that had not been fully addressed by lack of time in the preparation phase. The in-situ sea surface temperature (SST) in the shallow Great Sound was thus much more sensitive to solar diurnal radiation compared with the SST reproduced in the GFS analysis valid for the open Atlantic Ocean. For instance, the SST used in the model for June 24 was 25.7°C, while it was recorded as 27.9°C in-situ at the National Oceanic and Atmospheric Administration–USA station at 1600 UTC (1300 LT) (Figure 1) and 28.4°C at 2000 UTC (1700 LT). This large SST difference may have an influence on the systematic forecast bias (O’Neill et al., 2010). Nevertheless, the numerical weather forecasting system reached its objectives considering the difficulties in performing a reliable forecast at a very small scale and high frequency for a small island isolated within the Atlantic Ocean with a low rise, still significant orography, as well as spatial vegetation and urban cover variability.

The aim of this numerical high-resolution weather forecast was to provide a relevant, reliable and accurate tool for tactical and strategic use to the Emirates Team New Zealand (ETNZ) head meteorologist, tactician, skipper and helmsman. The forecast data were first used by the senior forecaster to deliver several daily bulletins to ETNZ’s crew some during the morning for tactical use during the races and some for the day + 1 hydrofoil setting. According to the ETNZ head weather forecaster, the numerical weather forecasts described here were the most accurate compared with all other bulletin sources available. As an illustration of the reliability and accuracy
of the Extreme Weather Expertises (EXWEXs) bulletin, the timing of the ETNZ team daily meetings was adjusted to match the reception times of the numerical weather forecasts. The hydrofoil choices were made on the day − 1 forecast proved to be very successful.

The model’s ability to forecast correctly the hourly variability in terms of wind direction and speed (with systematic bias) showed that it was a very helpful tool since it was reliable and accurate as required for competition. Moreover, the daily short-time weather forecast (a morning forecast for the afternoon) and day + 1 weather forecast never misled the team. This conclusion differs from the previous wind forecasts obtained during the Rio de Janeiro 2016 Summer Olympic Games (Giannaros et al., 2017) where a similar system failed to provide reliable wind guidance on specific days, or from Arrillaga et al.’s (2016) work over Spain.

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