原著論文

Association between order during first upwind leg and finishing place of race in sailing event of Tokyo 2020 Olympic Games

東京 2020 オリンピック大会セーリング競技における第 1 帆走区間の順位とレース着順との関連

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Abstract : It remains unclear whether and how the sailing order during the first upwind leg is related to the finishing place of the race in high-level sailing competitions such as the Olympic Games. The purpose of the present study was to clarify the associations in all ten classes in the sailing event of the Tokyo 2020 Olympic Games. All data were collected from publicly available online GPS sources. The sailing orders during the first upwind leg were calculated for every 10％ phase from the start to the arrival at the first windward mark. Then, for each phase in each class, the percentage of the number of races in which the correlation coefficient between the sailing order at each phase during the first upwind leg and the finishing place was greater than 0.7 was calculated. The percentage of the number of races with a high correlation tended to increase from 10％ to 100％ phase of the first upwind leg. In several races, the sailing order just after the start（i.e., at 10％ phase）correlated with the finishing place of the race. These findings suggest that a superior sailing position during the first upwind leg plays a crucial role in finishing well in the race.

Key words : Olympic sailing classes, strategies/tactics, race phase, high-level competition, podium athletes
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Ⅰ. Introduction

Sailing is conducted in a variety of changing environments (e.g., wind, current, wave) on the water, with the wind as the main driving force. International sailing regattas, which are held according to the rule of the Olympic classes, consist of two to three races per day for nearly a week. In such international sailing regattas, sailors (i.e., competitors) compete in multiple races of the qualification round, with the top 10 in the qualification round advancing to the final race. A sailing course normally consists of two or three upwind-downwind laps, with the wind at almost right angles to the legs, and the sailors start simultaneously from the start line on the water. Sailing race performance is multifactorial, including strategical/tactical[16–18), 26)], technical[8), 13), 15), 19), 26)], psychological[21)], and physical factors[3), 4), 9), 12), 22)]. Thus, the sailors should consider all these factors to enhance their sailing race performance. However, the available evidence is limited on factors influencing sailing race performance in high-level competitions such as Olympic Games.

Recently, a global navigation satellite system, especially a global positioning system (GPS), has been miniaturized and simplified and accordingly used to evaluate sailing performance indices, such as boat velocity, boat angle, sailing distance, and velocity made good (VMG: the best combination of the sailing velocity and angle, making the boat advance as far as possible to wind direction, Figure 1)[1), 5–7), 11), 14), 17–20)]. Furthermore, the GPS data allows sailors to objectively evaluate their strategies and tactics in the races[14), 23)]. Such multiple factors comprehensively influence the sailing position (i.e., order, place) and finishing place in the races of the Olympic classes. Therefore, clarifying the association between the sailing order of each leg during races and the finishing place can be useful for sailors and coaches.

A previous study reported that the finishing place in regattas was highly correlated ($r = 0.874$) to the passing/rounding order of the first windward mark for dinghy yacht and windsurfing races in non-elite sailors[10)]. For the Olympic windsurfing classes of RS: X men and women, the top three ranked boats in each race passed the first windward mark earlier (1st : 2.2 ± 2.1 ; 2.2 ± 1.9, 2nd : 3.7 ± 2.6 ; 3.4 ± 2.2, 3rd : 5.0 ± 3.3 ; 4.0 ± 2.8 of the passing/rounding order for men and

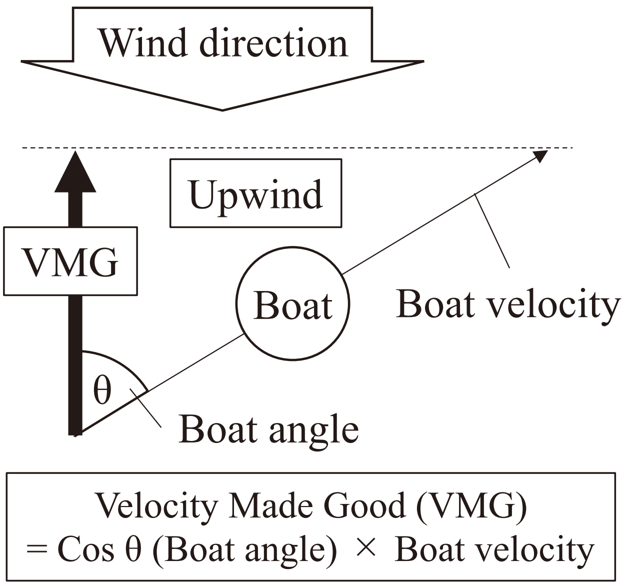

Figure 1. Velocity Made Good (VMG) concept and calculation method

women classes, respectively) in international regattas during the 2017–2018 season[1]. Additionally, it has been reported that superior-ranked boats showed higher boat velocity and VMG at the starting phase in a race at various competition levels: the RS: X in international regattas[11], Olympic 470 class and a windsurfing class in a national competition and simulated races in training[17), 18]. These findings suggest that the starting phase has a crucial impact on the finishing place. Based on these, it is reasonable to presume that sailing a race in a superior position during the first upwind leg (i.e., the route from the start line to the first windward mark) plays an important role in achieving a superior finishing place of the race. Nevertheless, it remains unclear whether and how the sailing order during the first upwind leg could relate to the finishing place of the race in high-level regattas such as the Olympic Games. The purpose of the present study was to clarify the associations of the sailing order during the first upwind leg with the finishing place of the race in all ten classes in the sailing event of the Tokyo 2020 Olympic Games.

Ⅱ. Materials and methods

1. Data collection

All data was collected from publicly available online GPS sources (SAP-Sailing® application)[23] as used in previous studies[1), 5–7), 11]. Table 1 describes the number of participating boats, total races, wind direction, and wind speed in the sailing event of the Tokyo 2020 Olympic Games for each class. For the wind direction, two types were classified: wind from shore-side to sea-side (i.e., off-shore) and wind from sea-side to shore-side (i.e., on-shore) in the race area of the regatta. For the wind speed, four types were categorized : ＜8 knots, 8–12 knots, 12–15 knots, and ＞15 knots. The detailed wind data is attached as Appendix 1. The sailing event was held from 25th July to 4th August 2021.

Table 1. Numbers of participating boats, total races, categorized each wind direction and wind speed of the races in each class of the sailing event of the Tokyo 2020 Olympic Games.

Class	Total boat	Total race	Wind speed and wind direction							
			< 8 knots		8-12 knots		12-15 knots		> 15 knots	
			Off-shore	On-shore	Off-shore	On-shore	Off-shore	On-shore	Off-shore	On-shore
470 men	19	10	0	3	0	3	0	3	0	1
470 women	21	10	0	3	0	5	0	1	0	1
Finn	19	10	0	2	2	3	0	2	0	1
Laser	35	10	0	2	2	2	2	1	1	0
Laser Radial	44	10	0	2	2	1	2	2	1	0
49er	19	12	0	5	0	4	0	2	0	1
49er FX	21	12	0	6	0	0	2	3	1	0
Nacra17	20	12	0	1	0	7	0	3	0	1
RS:X men	25	12	1	0	3	1	0	5	1	1
RS:X women	27	12	0	1	0	2	2	5	1	1
Total	250	110	1	25	9	28	8	27	5	7

Note, Off-shore: wind direction of north component (0–90 and 270–359 degrees) ; On-shore: wind direction of south component (91–269 degrees).
Wind direction and wind speed are classified according to the data at the start of each race.

2. Data analysis

First, the time required from the start (0 %) to the arrival at the first windward mark (100%) for the first-placed boat by race was calculated for each race. Then, the sailing orders up to 90% phase of the first upwind leg were obtained for every 10 % phase according to the time. The sailing order at 100% phase was defined as the passing/rounding order at the first windward mark. In accordance with the manufacturer's instructions, the "Ladder rungs" concept (Figure 2), which is specific to the sailing event, was considered when calculating the sailing order at each phase. The following data were excluded from the analysis (n = 950): (i) all data of each phase of the race in which boats were penalized for infringement of rule, (ii) data of each phase of the race with missing data due to technical errors on the application. Additionally, one final race (called the "medal race") which a boat chose the sailing route to win against a particular opposition without considering the advantages of course and wind direction, was excluded from the analysis.

3. Statistical analysis

All data are presented as means and standard deviations (SD). Spearman's rank-correlation coefficient (r) was calculated between the sailing order at each phase during the first upwind leg and the finishing place for each race in all classes. The statistical analyses were conducted using RStudio statistical computing software version 2022.12.0 + 353 (RStudio, Boston, USA). The significance level for all comparisons was set at $\alpha = 0.05$. In accordance with the previous studies[2), 24)], the value of $r \geq 0.7$ was defined as a high correlation. For each phase in each class, the percentage of the number of races in which the correlation coefficient between the sailing order at

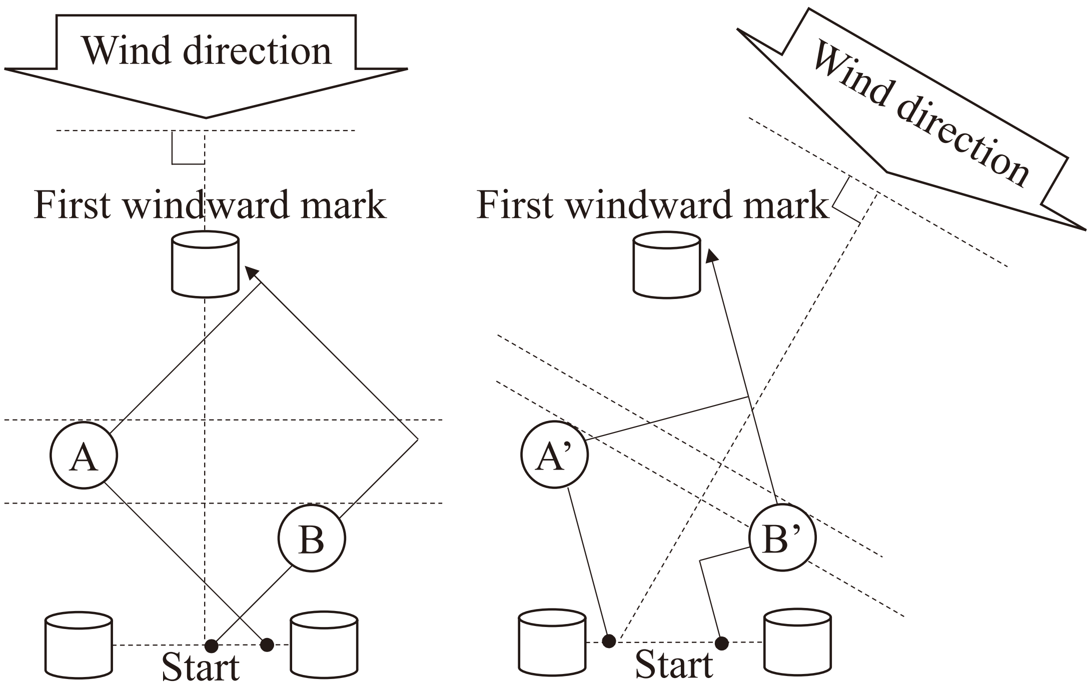

Figure 2. Schematic illustration of the "ladder rungs" concept.
The sailing order of boats during the first upwind leg was determined based on a straight line at right angles to the wind direction. When the wind direction is the same as that from the first windward mark to start-line (left panel), the sailing order is better for boat A than for boat B. Note that, when the position of the boats are spatially the same with left panel but the wind direction is different, the sailing order can be better for boat B'than for boat A' (right penel).

each phase during the first upwind leg and the finishing place was greater than 0.7 was calculated. Additionally, for each class, the sailing positions of all podium boats (i.e., top three boats in the regatta: Olympic medalists) were calculated during 10–100% phases of the first upwind leg and at the finish of the race.

Ⅲ. Results

Table 2 shows the time required from the start to the arrival at the first windward mark for the first-placed boat by class. A large variation was observed between classes.

Table 3 shows the percentage of the number of races in which the correlation coefficient between the sailing order at each phase during the first upwind leg and the finishing place was greater than 0.7 by class. The high correlations were all statistically significant ($p < 0.05$).

Table 4 shows the sailing positions at each phase during the first upwind leg and at the finishing place of the podium boats by class. The position of the podium boats ranged from 8.6 ± 1.7 at 10% phase to 6.8 ± 2.2 at 100% phase and 5.0 ± 1.7 at the finish.

Table 2. Time required from the starting to the arrival at the first windward mark for the first-placed boats.

Class	Time (min:sec)		
470 men (*n*=10)	13:03	±	2:57
470 women (*n*=10)	12:18	±	3:08
Finn (*n*=10)	14:57	±	3:34
Laser (*n*=10)	14:50	±	2:03
Laser Radial (*n*=10)	15:04	±	2:32
49er (*n*=12)	9:57	±	1:34
49er FX (*n*=12)	9:15	±	1:51
Nacra17 (*n*=12)	8:53	±	2:49
RS:X men (*n*=12)	7:13	±	1:24
RS:X women (*n*=12)	7:43	±	0:45
Mean	11:19		
SD	3:05		

Data are shown as mean ± SD.

Ⅳ. Discussion

The purpose of the present study was to clarify the associations of the sailing order during the first upwind leg with the finishing place of the race in all ten classes in the sailing event of the Tokyo 2020 Olympic Games. The present study showed that the percentage of the number of races in which the correlation coefficient between the sailing order at each phase during the first upwind leg and the finishing place was greater than 0.7 tended to increase from 10% to 100% phase of the first upwind leg, and that there were several races with a high correlation from just after the start (i.e., at 10 % phase) for seven classes of all ten classes (470 women, Laser, Laser Radial, 49er, 49er FX, Nacra17 and RS: X women). Furthermore, the sailing positions of the podium boats were within approximately 9th from just after the start (at 10% phase), and their sailing positions gradually improved toward the end of the race. These findings suggest that the superior sailing position during the first upwind leg plays a crucial role in finishing well in the race.

1. The association between sailing order during the first upwind leg and the finishing place

The present study showed that, in most races (approximately 80% of all races), the sailing order at 100% phase of the first upwind leg (i.e., at the first windward mark) highly correlated with the finishing place (Table 3). This finding is in line with a previous study reporting that the finishing place was highly correlated ($r = 0.874$) to the sailing order at the first windward mark for dinghy yacht and windsurfing in Japanese amateur sailors[10]. To the best of our knowledge, the present study is the first to report that the sailing orders of phases before the first windward mark exhibited a high correlation with the finishing place. Notably, in some classes, the sailing order even at 10 % phase of the first upwind leg (i.e., just after the start) was associated with the finishing place. Moreover, the percentage of the number of races in which the

Table 3. Percentage of phases with respect to number of races with a high correlation between the sailing order of each phase during the first upwind leg and the finishing place by class.

Class	% of the phase of first upwind leg									
	10% (%)	20% (%)	30% (%)	40% (%)	50% (%)	60% (%)	70% (%)	80% (%)	90% (%)	100% (%)
470 men (*n*=10)	0	10	10	20	30	30	40	70	80	90
470 women (*n*=10)	10	10	10	40	30	50	70	70	60	80
Finn (*n*=10)	0	10	10	10	20	20	30	60	40	70
Laser (*n*=10)	10	20	10	0	10	20	40	50	30	60
Laser Radial (*n*=10)	10	20	40	50	40	40	60	60	90	100
49er (*n*=12)	8	8	8	17	8	25	17	33	50	75
49er FX (*n*=12)	17	17	25	25	33	33	33	50	50	58
Nacra17 (*n*=12)	8	8	17	17	8	17	17	25	50	67
RS:X men (*n*=12)	0	8	8	33	42	58	75	75	75	92
RS:X women (*n*=12)	8	33	58	50	50	75	83	100	100	100
Mean	7	15	20	26	27	37	47	59	63	79
SD	5	8	16	16	14	18	23	20	22	15

correlation coefficient between the sailing order at each phase during the first upwind leg and the finishing place was greater than 0.7 increased from 10% toward 100% phase of the first upwind leg in all classes (i.e., from 7 ± 5 % at 10 % phase to 79 ± 15 % at 100 % phase, Table 3). Based on these findings, it is suggested that even in a high-level regatta such as Olympic Games, being in a superior sailing position during the first upwind leg is crucial in achieving a better finishing place in the race.

There were some races with a high correlation between the finishing place and the sailing order at even 10% phase (i.e., nearly one min after the start of the race) during the first upwind leg. Previous studies reported that superior-ranked boats showed higher VMG and boat velocity 15 s after the start of a race for the Olympic 470 class and a windsurfing class in a national competition and simulated races in training[17), 18)]. At the start of sailing races, boats compete with each other on the water for positioning and timing so that they can start as fast as possible from a more suitable at the predetermined time. Considering the possibility that the sailing order at 10% phase during the first upwind leg is determined by the sailing performance at the start, an enhanced sailing performance at the start could lead to an improvement in the sailing orders of the first upwind leg, and accordingly the finishing place in the race.

2. The sailing position of each phase in both the first upwind leg and the finish for the podium boats

In the sailing event of the Tokyo 2020 Olympic

Table 4. The sailing position at each phase during the first upwind leg and at the finishing places of the podium boats by class

Class	% of the phase of first upwind leg										Finish (rank)
	10% (rank)	20% (rank)	30% (rank)	40% (rank)	50% (rank)	60% (rank)	70% (rank)	80% (rank)	90% (rank)	100% (rank)	
470 men (*n*=10)	7.0 ± 5.1	5.8 ± 4.6	6.6 ± 4.6	6.4 ± 4.0	5.9 ± 4.1	5.6 ± 3.7	5.4 ± 3.5	4.8 ± 3.2	4.9 ± 3.5	5.1 ± 4.1	4.0 ± 3.1
470 women (*n*=10)	8.1 ± 5.3	7.7 ± 5.7	7.8 ± 5.8	8.5 ± 5.6	8.0 ± 5.7	7.5 ± 5.0	7.1 ± 5.3	7.0 ± 5.2	7.1 ± 5.1	6.2 ± 4.9	4.3 ± 3.5
Finn (*n*=10)	7.9 ± 4.6	8.7 ± 5.0	9.2 ± 5.1	7.3 ± 5.0	7.8 ± 5.2	7.2 ± 5.6	7.3 ± 5.6	6.0 ± 5.0	6.1 ± 4.6	5.9 ± 4.3	3.9 ± 2.4
Laser (*n*=10)	9.3 ± 7.3	9.4 ± 6.9	11.4 ± 9.2	10.1 ± 8.5	11.4 ± 9.7	10.5 ± 8.8	10.5 ± 9.1	10.6 ± 7.9	11.0 ± 8.7	11.2 ± 8.5	7.2 ± 5.1
Laser Radial (*n*=10)	12.5 ± 11.6	10.4 ± 10.0	10.9 ± 10.6	10.8 ± 9.5	12.6 ± 8.8	11.9 ± 9.3	11.9 ± 9.0	12.5 ± 8.6	11.1 ± 8.5	9.6 ± 7.3	7.9 ± 6.7
49er (*n*=12)	8.8 ± 5.6	8.8 ± 5.0	8.7 ± 5.4	7.6 ± 5.3	8.8 ± 5.2	8.2 ± 5.5	7.7 ± 5.5	7.4 ± 5.6	6.9 ± 5.4	6.6 ± 4.8	5.3 ± 3.8
49er FX (*n*=12)	9.7 ± 5.3	9.6 ± 5.4	8.5 ± 5.3	8.7 ± 5.0	8.8 ± 5.0	8.9 ± 4.4	9.3 ± 4.5	9.1 ± 5.1	9.2 ± 5.2	8.1 ± 4.8	6.5 ± 3.8
Nacra17 (*n*=12)	8.9 ± 6.4	8.3 ± 5.6	7.5 ± 5.6	7.5 ± 5.4	6.2 ± 4.5	6.3 ± 4.7	6.0 ± 4.6	5.4 ± 3.9	5.4 ± 3.8	5.7 ± 4.2	3.2 ± 2.1
RS:X men (*n*=12)	6.7 ± 6.2	6.8 ± 5.8	6.0 ± 4.8	5.1 ± 3.8	4.8 ± 3.6	5.2 ± 4.4	5.3 ± 4.8	5.7 ± 5.4	5.5 ± 5.4	5.4 ± 4.6	4.6 ± 3.9
RS:X women (*n*=12)	6.9 ± 5.2	5.6 ± 3.9	4.4 ± 3.9	4.7 ± 3.7	4.8 ± 3.6	5.2 ± 3.9	5.1 ± 3.3	4.5 ± 3.0	4.3 ± 2.7	3.9 ± 3.0	3.0 ± 2.1
Mean	8.6	8.1	8.1	7.7	7.9	7.7	7.6	7.3	7.2	6.8	5.0
SD	1.7	1.6	2.1	2.0	2.6	2.3	2.3	2.6	2.5	2.2	1.7

Data are shown as mean ± SD.

Games, the sailing positions of the podium boats were 8.6 ± 1.7 at 10% phase, 6.8 ± 2.2 at 100% phase of the first upwind leg, and 5.0 ± 1.7 at the finish (Table 4). The present study is the first to show the sailing positions during the first upwind leg of podium boats in a race. The finding indicates that the boats which achieved the podium had possessed within approximately 9th from 10% phase (nearly one min after the start) in a race. Additionally, the sailing positions of the podium boats improved toward the finish (i.e., approximately 7th at the first windward mark to approximately 5th at the finish). In particular, the podium boats for RS: X men and women showed superior sailing ranks at the first windward mark (5.4 ± 4.6 and 3.9 ± 3.0 for men and women, respectively). This finding is in line with a previous study reporting that for the Olympic windsurfing classes of RS: X men and women, the top three boats in each race (i.e., sailors finishing in the top three in each race) passed earlier the first windward mark in international regattas[1]. Considering the present and previous findings, it is likely that the podium boats are already in superior sailing positions at the early phase (nearly one min after the start) of the first upwind leg, and that they can further improve the sailing positions from the first upwind leg to the finish of the race. Further research is warranted to clarify why they can improve their sailing positions in such a way, from a variety of viewpoints, including skills, strategies/tactics, and mindset.

Considering the findings on the sailing positions of the podium boats and the association between the sailing orders during the first upwind leg and the finishing place in the race, it can be concluded that it is quite important for competitive sailors to go ahead and sail aggressively to take the lead during the first upwind leg, especially from just after the start. Such a strategy in competitive sailing seems to be different from other sports, such as marathon races, cycling, and motorsports, in which athletes do not want to take the lead considering various factors, such as minimizing air resistance.

3. Limitation

There is a limitation to the present study. The associations between the sailing order during the first upwind leg and the finishing place of the race were not examined by conditions, such as wind speed (e.g., light, medium, heavy), wind direction (e.g., on-shore, off-shore), types of class (e.g., single-hand vs. double-hand, classical boat vs. hi-speed boat), because of small numbers of races for each class. Further research is needed to examine this point.

Ⅴ. Conclusion

This is the first study to clarify the association of the sailing order during the first upwind leg with the finishing place of the race in all ten classes in the sailing event in a high-level regatta. We demonstrated that, in a relatively large number of races in the sailing event of the Tokyo 2020 Olympic Games, the sailing order during the first upwind leg correlated with the finishing place of the race. Additionally, the sailing positions of the podium boats were within approximately 9th from just after the start (at 10% phase) and improved with the phase toward the finish of the race. These findings suggest that a superior sailing position during the first upwind leg plays a crucial role in finishing well in the race.

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Appendix 1. Wind direction and wind speed for each race in all races of the Tokyo 2020 Olympic Games.

Class	Wind parameter	Race 1	Race 2	Race 3	Race 4	Race 5	Race 6	Race 7	Race 8	Race 9	Race 10	Race 11	Race 12
470 men	Wind direction (degrees)	177	177	180	187	175	165	163	156	177	180	-	-
	Wind speed (knots)	16	13	14	13	7	7	10	11	8	8	-	-
470 women	Wind direction (degrees)	172	167	181	181	178	171	163	158	176	180	-	-
	Wind speed (knots)	16	11	11	13	7	7	9	12	9	7	-	-
Finn	Wind direction (degrees)	359	240	181	178	182	180	230	200	160	164	-	-
	Wind speed (knots)	10	11	15	15	14	12	8	8	11	10	-	-
Laser	Wind direction (degrees)	184	79	74	349	357	234	184	184	174	186	-	-
	Wind speed (knots)	9	16	14	13	12	11	11	15	7	7	-	-
Laser Radial	Wind direction (degrees)	78	183	82	70	353	359	183	184	171	167	-	-
	Wind speed (knots)	9	10	13	12	16	14	14	15	7	8	-	-
49er	Wind direction (degrees)	242	181	178	183	180	185	171	173	174	239	208	188
	Wind speed (knots)	11	15	14	15	10	11	7	8	6	6	7	10
49er FX	Wind direction (degrees)	1	359	5	169	167	174	180	179	183	234	239	206
	Wind speed (knots)	16	15	14	15	14	13	7	6	6	7	6	8
Nacra17	Wind direction (degrees)	163	166	171	181	184	184	240	189	195	163	156	154
	Wind speed (knots)	16	12	14	11	12	15	7	9	10	9	11	11
RS:X men	Wind direction (degrees)	85	88	182	79	59	70	178	183	185	176	183	186
	Wind speed (knots)	9	7	10	15	9	11	15	14	16	12	14	13
RS:X women	Wind direction (degrees)	184	200	198	75	76	81	177	186	174	189	179	182
	Wind speed (knots)	11	10	7	15	16	12	14	15	15	12	14	15

Data shown at the start of each race.