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Review Article

Weather Support for the 2008 Olympic and Paralympic Sailing Events

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The Beijing 2008 Olympic and Paralympic Sailing Competitions (referred to as OPSC hereafter) were held at Qingdao during August 9–23 and September 7–13 2008, respectively. The Qingdao Meteorological Bureau was the official provider of weather support for the OPSC. Three-dimensional real-time information with high spatial-temporal resolution was obtained by the comprehensive observation system during the OPSC, which included weather radars, wind profile radars, buoys, automated weather stations, and other conventional observations. The refined forecasting system based on MM5, WRF, and statistical modules provided point-specific hourly wind forecasts for the five venues, and the severe weather monitoring and forecasting system was used in short-term forecasts and nowcasts for rainstorms, gales, and hailstones. Moreover, latest forecasting products, warnings, and weather information were communicated conveniently and timely through a synthetic, speedy, and digitalized network system to different customers. Daily weather information briefings, notice boards, websites, and community short messages were the main approaches for regatta organizers, athletes, and coaches to receive weather service products at 8:00 PM of each day and whenever new updates were available. During the period of OPSC, almost one hundred people were involved in the weather service with innovative service concept, and the weather support was found to be successful and helpful to the OPSC.

1. Introduction

The Beijing 2008 Olympic and Paralympic Sailing Competitions (termed as OPSC hereafter) were held at Qingdao, Shandong province, during August 9–23 and September 7–13 2008, respectively. Approximately 400 athletes coming from 62 countries and regions competed in 11 sports of Olympic sailing games, and 80 athletes from 25 countries and regions participated in 3 sailing games in the Paralympic sailing competition. The weather support group of Qingdao Meteorological Bureau (QMB) provided weather information for the games. Specialized operational weather service supplied from the national weather support system was the key element for the games, since they are sensitive to local weather situations [1–6]. The Olympic forecasting experience provided an exciting insight into capabilities for future National Weather Services forecast operations. But the atypical weather around the venue as frequent thunderstorm and persistent light winds proved challenging to forecasters, athletes, and Olympic management officials alike [7]. It is a great challenge for weather forecasting to provide detailed wind prediction for sailing competitions. Operational wind forecasting system is more used to support power system at present discussed by Zhu and Genton [8]. A distinguished aspect of OPSC support system is the high-resolution wind forecasting system, which gives a good demonstration for the weather support to large outdoor activities.

The planning for the weather support system began in 2001, shortly after the International Olympic Committee elected Beijing as the site of the 2008 Olympics and

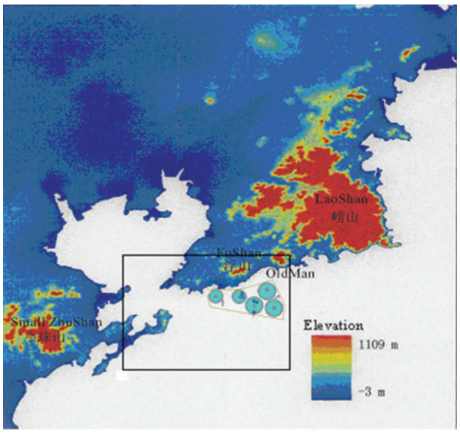


Figure 1: Topography around Qingdao OPSC venues. The region of rectangle is the position of observational system.

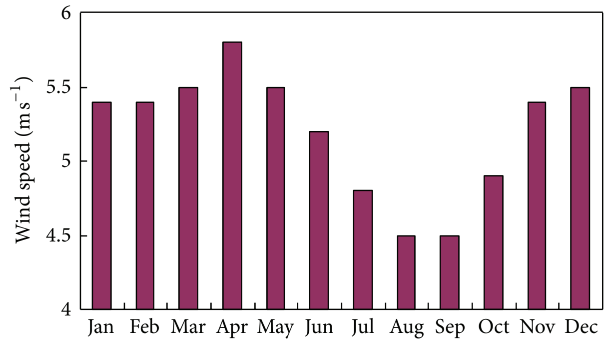


Figure 2: Monthly wind speed of Qingdao based on data of 1971–2007.

Paralympics and Qingdao as the site of the 2008 Olympic and Paralympic Sailing Competitions. The weather support system including monitoring, forecasting, and networking systems was then constructed, evaluated, and improved through weather support for the 2006, 2007 international regattas and the 2008 international regatta for the handicapped.

It is well known that the changes of wind speed and wind direction are of crucial importance for sailing events. First of all, the setting for sailing routes is dependent upon the current wind direction. If the wind direction wasto shift to larger than 50 degrees in a round, the game would have to be canceled. In addition, the required wind speed range is 3–20 m s^{-1}. In the situations of wind speed less than 3 m s^{-1}, the competition cannot go on because the wind is too weak and, therefore, not suitable for driving the sails. During the 2004 summer Olympic games, there were three days of "no wind" appeared at Athens Metropolitan area. On the other hand, when the wind speed exceeds 20 m s^{-1}, it is too dangerous for the athletes to sail. Additionally, a visibility of greater than 1500 m and no possible thunderstorm weather threats are also essential safety conditions for the sailing events. The weather support required for QMB was hourly wind speed and wind direction forecasts aimed at five Olympic venues distributed at the scope of 50 km^2 (Figure 1) as well as any severe weather warnings issued one hour prior to the competition. At the same time, QMB must meet the diverse requirements such as providing flooding and thunderstorm warnings and providing weather support for cleaning the sailing venues due to the breaking out of *Enteromorpha prolifera*. QMB faced an unprecedented challenge in the weather support for 2008 OPSC.

2. Qingdao Climate Analyses

Qingdao, as a coastal city facing the Yellow Sea, lies on the southern tip of Shandong Peninsula. The climate of Qingdao has both monsoon and marine climate characteristics. It is worth noting that the period of OPSC (August 9–September 13) falls within the flood season of Qingdao. Typhoon, heavy rainfall, thunderstorms with gusts, heavy fog, and other high impact weathers occur from time to time. For example, on August 10, 2007, during the period of the 2007 International Sailing Regatta, more than 282.7 mm of precipitation fell on the city of Qingdao from 21:00 Local Standard Time (LST) 10 to 06:00 LST 11 August, with wind gusts of 24.1 m s^{-1}. The loss was estimated to be greater than 2.8 billion Chinese Yuan in the process.

The Olympic sailing field consisted of five venues: A, B, C, D, and E and was set up at an area of 50 km^2 from Fushan Bay to the south of Old Man Bay (Figure 1). Several mountains including Taipingshan (with elevation of 348 m), Fushan (368 m), Wushan (298 m), and Laoshan (1133 m) are all located to the north of the sailing fields. The complicated offshore terrain disrupts the accuracy of wind forecasts, especially for the weak wind conditions. Analyses based on observations at the Qingdao station from 1971 to 2007 indicate that the mean wind speeds in the months of August and September are the smallest, only 4.5 m s^{-1} (Figure 2). The prevailing wind direction in August is southeasterly while northerly and southerly wind in September. Moreover, the sea-land breeze is the main local atmospheric feature along the coast of Qingdao. Usually, the sea breeze appears during the period of 10:00 and 13:00 LST and lasts 6 to 9 hours. For the land breeze, it appears around 3:00 to 5:00 LST and lasts 2 to 4 hours or so. During the daytime in August and September, wind speed rises to over 3.5 m s^{-1} after 9:00 LST, and the maximum wind speed occurs during 13:00–15:00 LST with an hourly average wind speed of 4.3 m s^{-1}. In September, the maximum wind speed occurs between 14:00 LST and 15:00 LST with a maximum hourly speed of 4.4 m s^{-1}. After that time, wind speed decreases gradually and reaches 3.5 m s^{-1} at 21:00 LST (Figure 3). The 2008 Olympic sailing events were begun after 13:00 LST as planned, though there were several competitions delayed or forwarded because of the situations of weak wind speed.

The complicated topography around Olympic sailing fields plays an important role in the strength and direction of wind changes. The sea-land breeze circulation is the most important local wind system in Qingdao. The observations during 1971–2007 indicate that the sea breeze prevails the

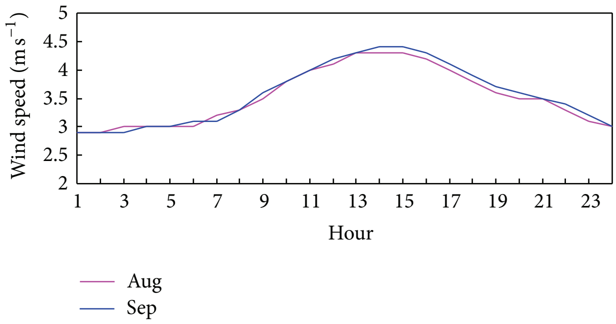


Figure 3: Time series of wind speed in August and September for Qingdao based on data of 1971–2007.

offshore of Qingdao during the daytime with the frequency of occurrence at 35% in August and 25% in September. Figure 3 gives the wind rose of buoy B at 08:00 LST and 16:00 LST in August of 2005–2008. It is shown that the prevailing wind direction is easterly to northwesterly in the morning at the venues, while in the afternoon southerly to southeasterly wind with apparent sea breeze characteristics prevails. The predominant wind speed was 3–6 m s^{-1}. Analyses also show that the strength of sea breeze is related to environmental circulation. While the large-scale geostrophic wind is in the direction of the easterlies, the strength of the sea breeze is stronger (larger than 6 m s^{-1}) just offshore Qingdao; while the large-scale geostrophic wind is northerly, the wind speed of sea breeze is larger than 3 m s^{-1}.

3. Weather Support System for OPSC

Research and assessment have been underway at QMB to improve the understanding and accuracy of prediction of the atmospheric circulation around the sailing venues since 2001. QMB has contributed to the effort in aspects of improvements to the temporal-spatial comprehensive monitoring system, the introduction of high-resolution real-time wind forecast system, and the development of modernized network system for the OPSC weather support. Setting up special projects such as developing high-resolution multimodel real-time mesoscale modeling system and Model Output Statistics (MOS) methods based on these model outputs provided strong technological support for the wind forecasts, especially for the weak wind forecasts under the condition of complex terrain.

3.1. Monitoring System. Under the base of the original monitoring system of QMB, a number of monitoring devices have been installed and have been successively operational in Qingdao since 2001. For example, 107 four-parameter Automatic Weather Stations (AWSs) were installed from 2003 to 2008 (Figure 4 is the schematic of the observational system) which monitored weather processes effectively, for the sailing competition. It consists of Doppler radars, wind profile radars, laser wind-detection radars, and portable weather stations. In addition, five buoys A, B, C, D, and E, are located around the sailing venues. Buoys A, B, and D were set up by the State Oceanic Administration, China, and QMB shared the observed information during the period of competition. Buoys C and E were installed by China Meteorological Administration. Buoy C, with the diameter of 3 m, has been supporting the sailing games since July 30, 2007, and buoy E, with the diameter of 10 m, was put into operation on July 12, 2008. Variables of wind speed, wind direction, temperature, and humidity with an interval of 10 minutes, variables of sea surface waves with an interval of 30 minutes, and current with an interval of 10 minutes were collected from the buoy stations. At the same time, observations from eight AWSs, which are either located offshore or on an island, strengthen the weather support around the sailing venues. All of the high-resolution and multisource observed information was provided to both the committee of OPSC and the athletes through the weather service center in forms of figures and tables. The observed information was also ingested into QMB real-time mesoscale model by data assimilation techniques.

3.2. High-Resolution Wind Forecast System. The multimodel high-resolution sea surface wind forecast system has been constructing to meet high requirements of the sea surface wind prediction for the sailing games since 2001. It has been continuously modified and improved through the application in the 2006, 2007 International Sailing Regattas and the 2008 International Sailing Regatta for the handicapped. Five dynamical models and two statistical modules were included in the forecast system. Table 1 shows the information of five numerical models, including the QMB operational numerical model based on the Pennsylvania State University, National Center for Atmospheric Research fifth generation Mesoscale Model (MM5) [9–11], MM5RUC, and three Weather Research and Forecasting (WRF) systems [12, 13]: WRF (500 m), WRF (3 km), and WRF (5 km) with different horizontal and vertical resolutions and different initial fields. MM5 has been running since 2004 at QMB, and the initial time is at 20:00 LST everyday with a forecast duration of 84 h. Based on this operational modeling system, the model referred to as MM5RUC has been developed by assimilating observations from AWSs, buoys, wind profile radar, Doppler radar, and gradient wind tower around Qingdao, in order to get more accurate initial condition for the model. By the way, the observations were also ingested into the WRF (3 km) modeling system which was provided by Beijing Meteorological Bureau. The WRF (3 km) was updated every 3 hours for a forecasting duration of 24 hours. The WRF model with a horizontal resolution of 500 m uses a high-resolution Qingdao land use data, which was derived from Landsat remote sensing data of 2005, reflecting the influence of detailed land-use characteristics on the sea surface wind around the offshore. The WRF (500 m) finescale simulations are used to investigate impacts of urban processes and urbanization on a localized, summer, heavy rainfall in Beijing presented by Miao et al. [14]. Evaluation using radar and gauge data shows that this configuration of WRF with three-dimensional variational data assimilation of local weather and GPS precipitable water data can simulate storm generally well. The modeling system WRF (5 km) was provided to

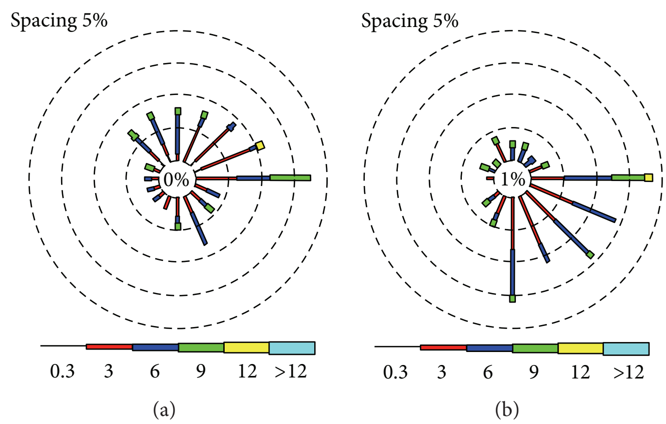


Figure 4: Wind rose of buoy B at 08:00 LST (a) and 16:00 LST (b) based on hourly wind in August of 2005–2008 (Color scale: mean wind speed; ray direction: wind direction; ray length: frequency of wind direction; value in the circular: frequency of calm wind).

QMB by the National Meteorological Center of China, while postprocessing was carried out at QMB. MM5-based model output statistical modules, MOS (MM5) and DAMOS, provided hourly forecasts of wind speed and wind direction at the five venues. During the 2002 Olympic and Paralympic Winter Games, a similar method of MOS was used to provide hourly forecasts for the sites [15]. During the 2008 Olympic and Paralympic sailing games, MOS (MM5) was developed at QMB by considering daily wind observations and 10-year wind diurnal fluctuation. DAMOS was supported by a team from the Department of Marine, Earth, and Atmospheric Sciences and Department of Statistics of North Carolina State University, which considers pre-30-day observations and QMB real-time MM5 output. The two modules were run operationally at QMB once a day during the Olympic game. All products were shown in the form of graphs and tables and then sent to the weather support office before 8:00 AM everyday during the period of the competition. On the basis of these forecast products, QMB weather forecasters then issued the wind prediction around the sailing venues after considering field observations and the local weather situation. Figures 5 and 6 is an example of hourly forecasts for 10 m wind speed and wind direction on August 18, 2008, for Buoy B, in which the ensemble forecast was carried out by considering the prediction from five dynamic models and two statistic modules through a kind of statistical method. The dynamic models (MM5, MM5RUC, and WRF 500 m) showed that there was the west-northwest wind with the force of 7–10 m s^{-1} at the field of OPSC in the morning of August 18 and turned to the southwest wind with the force of 3-4 m s^{-1} in the afternoon (Figures 7 and 8). The competition group of OPSC adopted suggestions from QMB and shifted the games to be held at 11:00 AM. The competition ratio at that day was 81% based on strong support from high-resolution wind forecasting system. This was also a transformation process between land breeze and sea breeze and the wind forecasting systen reproduced the characteristics very well. Moreover, the statistical analyses for the four buoy stations A, B, C, and D during August 9–21, 2008, are shown in Table 2. It is shown that the forecasters' forecasts have the highest accuracy, with the mean RMSE for the four buoy stations being 1.4 m s^{-1} for wind speed and 42 degree for wind direction, respectively.

Table 1: Overview of dynamical models.

Model	Grid	Initial conditions
MM5	4-nested grids (45/15/5/1.67 km)	AVN analyses
MM5RUC	2-nested grids (5/1.67 km)	5 km MM5 forecast
WRF (500 m)	500 m	1.67 km MM5RUC forecast
WRF (3 km)	3-nested grids (27/9/3 km)	AVN analyses
WRF (5 km)	2-nested grids (15/5 km)	T213 forecast

Table 2: Statistical analyses for four buoy stations during the period of August 9–21, 2008.

	Wind speed MAE (ms^{-1})	Wind direction MAE (°)	Wind speed RMSE (ms^{-1})	Wind direction RMSE (°)
Correction from forecasters	1.1	34	1.4	42
Ensembled forecasts	1.2	36	1.4	45
MOS (MM5)	1.3	37	1.6	45
WRF (500 m)	1.5	41	1.8	52
MM5RUC	1.6	38	1.9	49
DAMOS (MM5)	1.7	46	1.9	54
WRF (5 km)	1.9	49	2.2	57
WRF (3 km)	2.0	50	2.4	63

MAE: mean absolute error; RMSE: root mean square error.

3.3. Severe Weather Monitoring and Forecasting System. The QMB severe weather monitoring and forecasting system used throughout the period of OPSC consists of two components. The first component refers to the Severe Weather Integrated

Table 3: Itinerary of Olympic and Paralympic Games.

Date	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	8	9	10	11	12	13
Expected schedule	4	7	15	12	15	15	23	29	21	20	8	8	2			6	9		9	9	7
Actual completion	4	7	15	12	11	0	11	14	11	18	4	8	2	flexible date	Closing ceremony	6	9	flexible date	3	7	6
Competition ratio	100% Rate of fulfillment			rate of fulfillment reached 93%												100%			93.9%		

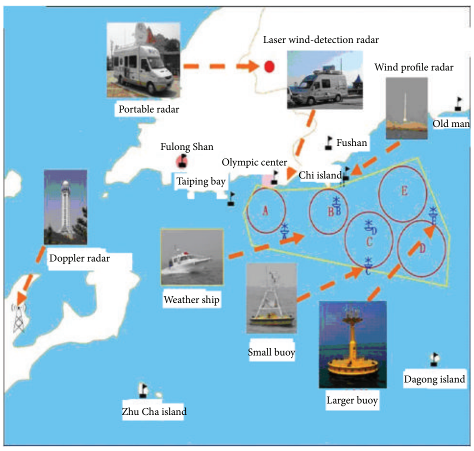


Figure 5: Schematic of the observational system for the sailing competition.

Forecasting Tools (SWIFT), which was originally developed by the Guangdong provincial Meteorological Bureau and was modified and improved by considering operational MM5 forecasts, AWS observations, and GPS/MET data in QMB. Thunderstorms, heavy rainfall, and gale can be detected and forecasted from this system. The second component focuses on lightning monitoring and forecasting by considering the following data: lightning location, surface electric field, and radar around the Qingdao region. The region and probability of lightning can be predicted by this system one hour in advance. Moreover, the sailing field was set as a special monitoring region, and the probability, location, and density of lighting for this region were updated every 15 minutes.

3.4. Weather Information Display and Distribution System. In the display and distribution platform, the latest data monitored by different sensors, historical data, numerical model results, thunderstorm prewarning products, and time series of statistical analyses are all displayed and updated every 10 minutes. The integrated display system is comprised of a multiple screen graphics workstation by using techniques of Oracle database, network communication, and net station designing. China Meteorological Administration, Beijing Meteorological Bureau, Shandong Province Meteorological Bureau, the weather service office at the sailing field, and other departments can access the information through high speed internet, mobile, and satellite. This effective network system guaranteed the successful transmission of multisource data quickly, especially for short-time nowcasts and updated forecasts.

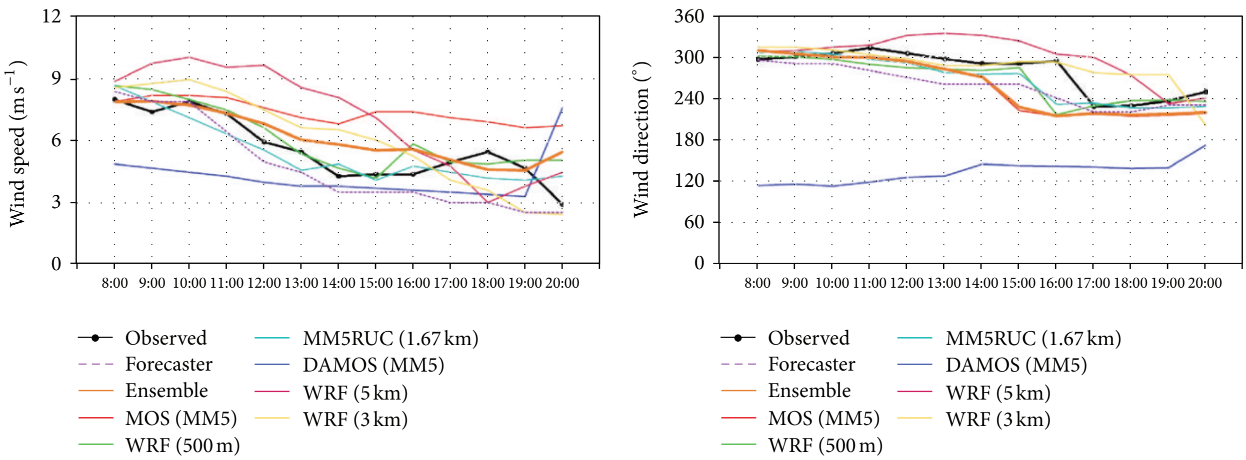
4. Weather Service for OPSC

The weather service group, including almost 100 people, provided OPSC weather support from June 25 to September 13, 2008. The weather service was involved with supporting the cleaning of the *Enteromorpha Prolifera* around the sailing field, the sailing competition, the daily city running, and the opening and closing ceremonies of OPSC. Nine meteorologists who have extensive forecasting experience were responsible for providing detailed wind forecasts and severe weather information for the five venues directly. The refined weather service products were provided to regatta organizers, athletes, and coaches through daily weather information briefings, notice boards, internet, and community short messages. The TV platforms installed in buses, mobile phone text messages, and electronic information displays distributed at arterial streets all played a significant role in improving the coverage of weather information.

Based on fully understanding the demands of different branches, the weather service group used a different service strategy for the games. The government officials were concerned as to whether the sailing games would run smoothly or not. Therefore, the weather service conclusion provided to them would be that, for example, "the current weather situation is unsuitable for the competition under the condition of weak and unsteady winds." In contrast, the competition officials paid attention to the accomplishment ratio. Therefore, the service also provided forecasting and probability of what may happen. For the athletes, the weather service group simply provided them with forecast products since they are concerned about the accuracy of forecasting in order to form their strategy of competition. The International Olympic Committee adjusted the schedules of 11 days according to the weather forecasting in the 18 competition days, and the accomplishment ratio of 2008 Olympic Sailing events is 93% under the condition of two flexible days unused (Table 3). The number in the table is the number of competitions.

5. Conclusions

The Beijing 2008 Olympic and Paralympic Sailing Competitions (OPSC) drew to a close and accurate weather forecast and active weather service assured that the sailing games went on smoothly and successfully. The mean absolute forecast error at four buoy stations for the wind speed was 1.1 m s^{-1} and 34 degrees for the wind direction. The extensive experience for offshore wind forecasting gained from the OPSC will help to improve the understanding of sea-land



(a) (b)

FIGURE 6: Hourly forecasts of 10 m wind speed (a) and wind direction (b) on August 18, 2008 for buoy B.

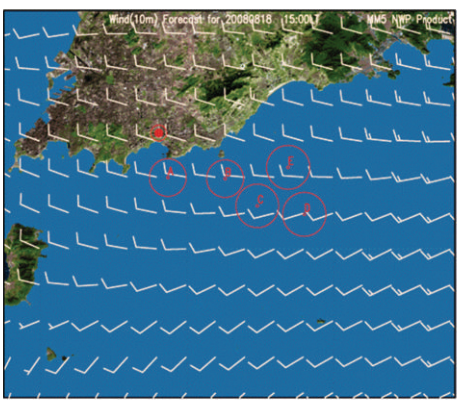


FIGURE 7: Distribution of wind vector at the height of 10 m at 15:00 LST of 18 August, 2008.

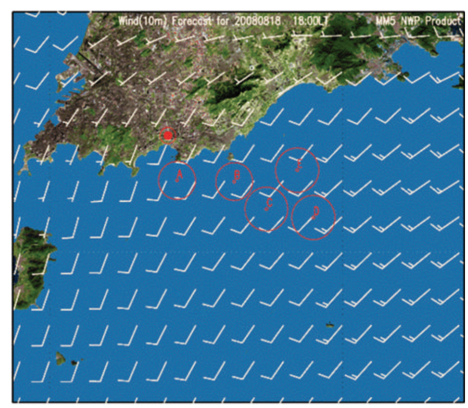


FIGURE 8: Distribution of wind vector at the height of 10 m at 18:00 LST of 18 August, 2008.

breeze circulation in complex terrain, on the aspects of both operational and research models. And the idea of synthetic observation network and service will play a significant role in the weather service of public activities.

Aiming at specific user groups and the public, QMB carried out a customer satisfaction survey on the 2007 international sailing regatta and 2008 Olympic and Paralympic sailing games according to Customer Satisfaction Index of Weather Service (CSIWS). The survey showed that the averaged satisfaction index rose 15% in two years and the satisfaction index reached up to 96.3% in 2008.

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