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Managing the effects of the weather on the Equestrian Events of the 2008 Beijing Olympic Games

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ABSTRACT

This paper describes a 3 year project to investigate and manage the effects of the local weather conditions on horses competing in the 2008 Olympic Games. The first part of the investigation involved estimating the expected heat load on horses during competition and suggesting measures to ensure their safety based on data collected from dedicated weather monitoring at both Olympic venues during August 2006, 2007 and 2008. The aim of the second part was to establish a reliable system of point forecasting to monitor and predict inclement weather that might affect the competitions. This involved setting up automatic monitoring systems and exploiting numerical weather prediction models. The monitoring and predicting capabilities were tested by running two 'virtual' or simulated cross country competitions in 2006 and 2007. They were further trialled with live horses during the Test Event in August 2007, when a rapid cooling system for horses using shade tents, misting fans and iced water was refined.

The results of both parts yielded valuable information which was used to establish a protocol to ensure that horses would not become heat stressed or subjected to dangerous weather conditions. Despite some very high temperatures and humidity, a number of storms and two serious tropical cyclones, there were no disruptions to the competition schedule and no serious injuries or heat stress to the horses throughout the 2008 Equestrian Events.

Introduction

The Equestrian Events of Eventing, Dressage and Jumping have been part of the Olympic Games (OG) since 1912 in Stockholm. For the 2008 Games it was not possible to stage the equestrian competitions at the main Olympic venue in Beijing, China, and they were held in Hong Kong, China from 8–21 August. The competitions took place at two locations. The main venue was converted from the Hong Kong Sports Institute adjacent to the Hong Kong Jockey Club's Sha Tin Racecourse where stabling, training and the dressage and jumping competitions took place. The cross country phase of Eventing was held at a second venue, Beas River, in the North-west New Territories, about 35 km north-west of Sha Tin.

Hong Kong's climate is subtropical, and in August it is hot and humid with air temperatures that can reach 35 °C and a relative humidity of 80–90%. These conditions are difficult and exhausting for horses, especially in the Eventing competition (Kohn and Hinchcliff, 1995; Jeffcott and Kohn, 1999; Kohn et al., 1999a). The situation is further complicated at that time of year by the sporadic occurrence of typhoons and rapidly developing thunderstorms, which pose great challenges to weather forecasting and can potentially disrupt the competition schedule.

It has been established after many years of research and investigation that horses can compete safely in high ambient temperatures (<40 °C), but when this is combined with high relative humidity (>60%) there can be profound effects on performance with the risk of exhaustion and heat stroke (Jeffcott and Kohn, 1999; Kohn et al., 1999a). The introduction in 1995 of the wet bulb globe temperature (WBGT) index has proved to be a much more valuable indicator of the heat load experienced by the horse than simply measuring ambient temperature and relative humidity (Schroter and Marlin, 1995; Schroter et al., 1996). Extensive studies on cooling horses under these conditions have also been undertaken (Bradbury and Allen, 1994; Kohn and Hinchcliff, 1995; Williamson et al., 1995; Marlin et al., 1998; Kohn et al., 1999b).

Despite the success of managing the 1996 Olympics in Atlanta (Jeffcott and Kohn, 1999), the issues we faced in Hong Kong were significantly more serious because of the persistent high humidity throughout the day and the threat of serious storms at this time of year. At the Atlanta OG the relative humidity tended to drop as the temperature increased during the morning. A preliminary study of Hong Kong weather in August 2005 (D.J. Marlin, personal

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communication) confirmed these difficult conditions. The best time for the horses to compete appeared to be in the evening, and this could be achieved using floodlights for Jumping and Dressage. Obviously this was not feasible for the cross country in Eventing. In the light of these difficulties and the necessity to ensure the safety of the horses at all times a study was conducted in the 3 years before the Games with five main objectives:

(1) to estimate the potential heat load on the horses and riders using the WBGT index and other parameters to assist in the planning of competitions, especially the cross country;
(2) to establish the optimum timing for the competitions particularly the cross country;
(3) to develop a protocol for forecasting 'bad weather' that may affect both the competition schedule and the horses' safety;
(4) to develop and test the decision-making process in the event of bad weather, and
(5) to implement, test and refine facilities at both venues to cool horses rapidly after training and competition and prevent the onset of heat stress or exhaustion.

Materials and methods

Weather monitoring facilities and forecasting

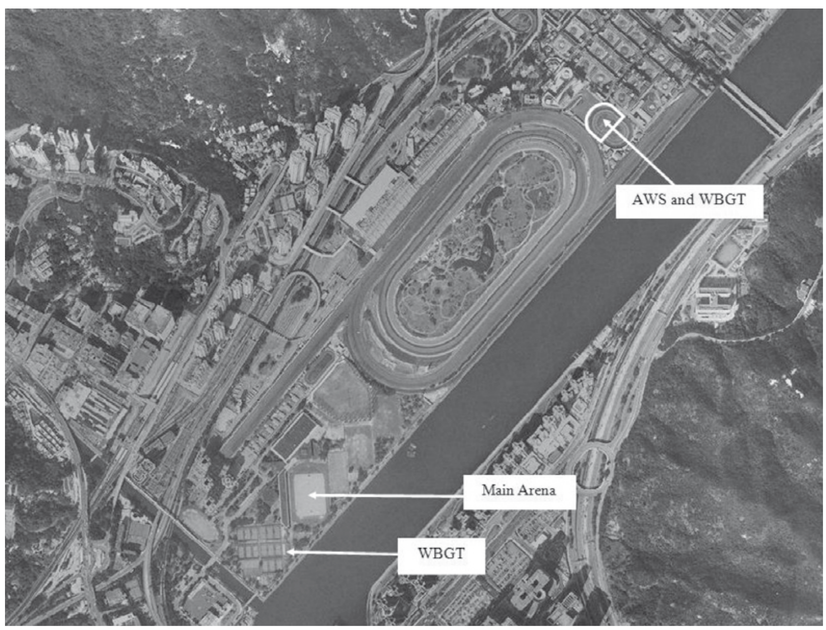
In early 2006, the Hong Kong Observatory (HKO) erected automatic weather stations at the two venues. The location of the instruments and specific elements measured are shown in Figs. 1 and 2. Data of ambient temperature (°C), relative humidity (%), WBGT (°C), wind speed and direction, and rainfall were continuously collected at 1 min intervals starting mid-2006. Running hourly averages for the previous 24 h (updated every 5 min) were produced from these data in both graphic and tabular form. The data from 1–31 August for the 3 years, 2006–2008, were used in the study.

As WBGT is one of the key elements in monitoring the risk of heat stress in horses, it was important that such information could be accessed in real-time (Schroter and Marlin, 1995). The index used here was defined by the equation:

$$\mathrm{WBGT} = 0.7t_{\mathrm{nw}} + 0.2t_g + 0.1t_a$$

where t_{nw} is the natural wet-bulb temperature, t_g the globe temperature, and t_a is the dry bulb temperature.

Since a system for monitoring heat load with the capability for real-time data transmission and data quality assurance was not available, the HKO developed its own system in late 2005 for use in the summer of 2006. The system not only fulfilled the ISO 7243 standards for heat load measurement, but also incorporated an additional solar radiation measurement unit and real-time data quality monitor-

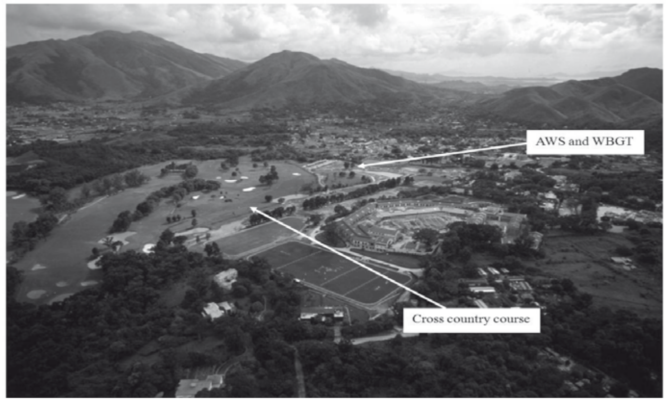


Weather station	Elements measured	Instrument elevations (metres above ground level)
Automatic Weather Station (AWS)	• Wind speed and direction dry • Bulb temperature • Wet bulb temperature • Relative humidity (derived) • Rainfall • Pressure	• Anemometer: 10.0 m • Barometer: 8.1 m • Thermometer: 1.40 m
WBGT measurement system (WBGT)	• Dry bulb temperature • Natural wet bulb temperature* • Globe Temperature (black globe) • WBGT** • Solar radiation	all sensors: 1.5 m

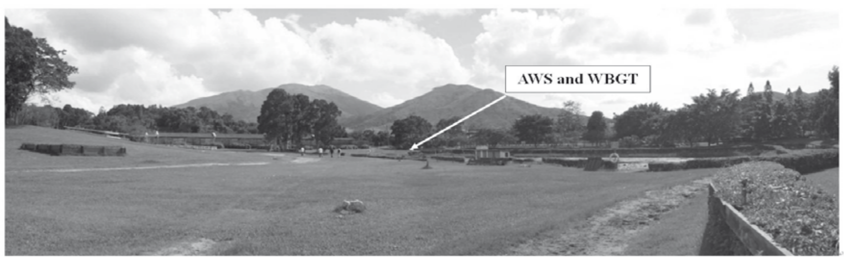
Natural Wet Bulb Temperature sensor exposed to direct sunlight
** Wet Bulb Globe Temperature (WBGT) is derived based on the formula
$\mathrm{WBGT} = 0.7\ t_{\mathrm{nw}} + 0.2\ t_g + 0.1\ t_a$
where t_{nw} = natural wet-bulb temperature, t_g = globe temperature, t_a = dry bulb temperature

Fig. 1. Location of automatic weather stations at the main venue, Sha Tin, and the accompanying instrumentation.

Aerial view of the Cross Country Course



Panoramic view of the Cross Country Course



Weather station	Elements measured	Instrument elevations (metres above ground level)
Automatic Weather Station (AWS)	● Wind speed and direction ● Dry bulb temperature ● Relative humidity ● Rainfall	● Anemometer: 2.5 m ● Thermometer: 1.25 m
WBGT Measurement System (WBGT)	● Dry bulb temperature ● Natural wet bulb temperature* ● Globe Temperature (black globe) ● WBGT** ● Solar radiation	all sensors: 1.50 m

Natural Wet Bulb Temperature sensor exposed to direct sunlight
** Wet Bulb Globe Temperature (WBGT) is derived based on the formula
$WBGT = 0.7\, t_{nw} + 0.2\, t_g + 0.1\, t_a$
where t_{nw} = natural wet-bulb temperature, t_g = globe temperature, t_a = dry bulb temperature

Fig. 2. Location of automatic weather stations at the cross country venue, Beas River, and the accompanying instrumentation.

ing technology to enhance data quality. The system employed wireless communication technology to provide the information at any place covered by the mobile telephone network. As the system has several innovative inventions, it was successfully patented in Hong Kong in 2009.

HKO also provided site specific 3-day forecasts for both venues at 3-h intervals which included air temperature (°C), relative humidity (%), WBGT (°C), wind direction and speed, rainfall in the preceding 3 h, and a brief description of the expected weather (e.g. sunny intervals, cloudy, squally thunderstorms, etc.). A 7-day weather forecast for the whole of Hong Kong was also provided which included a brief description of the weather and wind direction/force, and details of the range of air temperature and relative humidity.

To provide venue-specific forecasts, the HKO made use of three different numerical weather prediction models, namely, a high spatial resolution Operational Regional Spectral Model (ORSM) operated by HKO, a model operated by the Japan Meteorological Agency (JMA) and another model of the European Centre for Medium Range Forecast (ECMWF). These models provided forecasts of the weather parameters at various grid points within Hong Kong, and the forecasts at the grid point nearest to the Olympic venues were chosen. An ensemble forecast of the three models was obtained by a simple equal-weight method. Since the direct output of the models often exhibits a bias from the actual weather, a post-processing of these model outputs was carried out to remove the bias. The bias-corrected model output was then used to generate an automatic forecast for the two venues as a first guess for the forecasters. The forecasters could then exercise their professional judgment to modify the automatic forecast to produce an official forecast for the reference of the Foreign Veterinary Delegate (LJ).

Hong Kong Observatory website

In 2006, the HKO established a dedicated website for continuous dissemination of the weather data to the Foreign Veterinary Delegate. The URL was given to all Team Veterinarians and official veterinarians for their own use at the Test Event in 2007 and throughout the Games in 2008. This was referred to as the Special Website for Equestrian Events (SWEET). To provide weather forecasts and information to the spectators, officials and the Olympic family during the Games in 2008, SWEET was made publicly available. Due to the large demand for SWEET a dedicated server (Government Weather Information Server, GOWISE) was deployed for the Foreign Veterinary Delegate and other Olympic officials to ensure that they had continuous access to all the weather information. The website provided a map of the two venues in relation to the rest of the Hong Kong region with forecasts and weather information for both sites (Fig. 3). In addition it provided general Hong Kong weather information with a 7-day forecast and information on severe weather and tropical

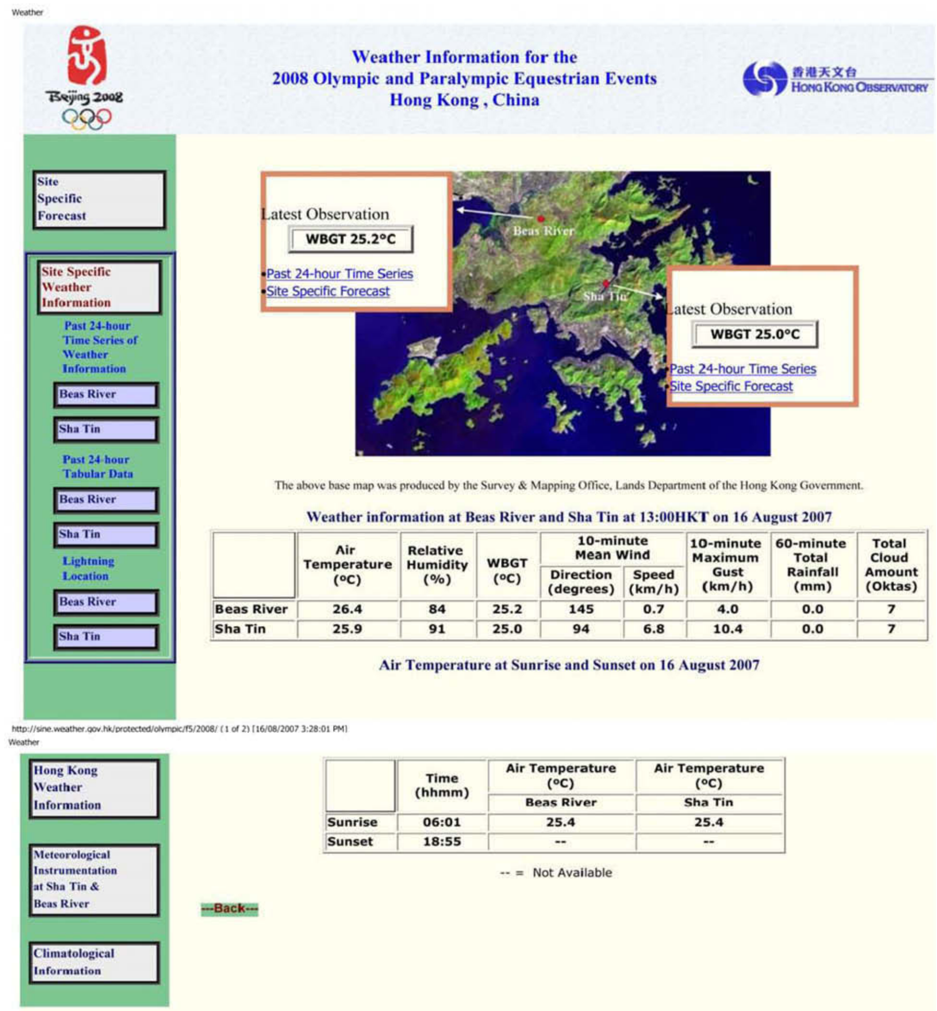


Fig. 3. View of home page of the Hong Kong Observatory website providing weather forecasts and weather information for the two equestrian venues in Hong Kong.

cyclones. Another valuable feature was the radar imagery which provided images of the rain areas over Hong Kong and animated sequences which were updated every 12 min with an automatic alarm to warn the Foreign Veterinary Delegate of lightning strikes within 5 km of the venue.

Project protocol for the 3 years

Year 1 (2006)

Weather data were collected round the clock at both venues for the month of August. The data from 0700 h to 1900 h were used to estimate the heat load on the horses, assist in the planning and design of the cross country course, and evaluate the optimum time for it.

A simulated cross country competition with 75 'virtual' horses was organised on 3 August 2006 to test the 'early warning' system of forecasting and as a means of reporting to the Foreign Veterinary Delegate. In addition a field experiment was conducted to measure the effects of the early morning sun by calculating a 'Shadow Index' on the cross country course. Sunrise at the cross country venue was around 0600 h, when the low sun cast a considerable shadow (Fig. 4). Extended shadows together with the glare of the sun low in the sky were potentially hazardous for horses jumping. In order to provide an objective assessment of this problem, the 'Shadow Index' was calculated as follows:

$$\text{Shadow Index} = \frac{\text{length of object's shadow (m)}}{\text{height of object (m)}}$$

The index was used to decide the optimum time to start the cross country competition. It was estimated by viewing the jumps affected by the sun that once the Shadow Index was <1.5 it was considered safe to start the event.

Year 2 (2007)

In February 2007, a second simulated cross country with 75 'virtual' horses was organised using simulated 'bad weather' data (based on a particular day in August 2006). This was used to test a difficult weather situation in which the previous day's forecast was unable to predict the explosive development of a thunderstorm that eventually led to the issuing of an Amber Rainstorm Warning (i.e. a rainstorm with rainfall intensity of 30 mm/h or higher). This scenario necessitated halting the competition for over an hour, shortening the interval between horses and restarting the competition once the heavy rain had subsided.

The official Test Event for the Olympic Games was held in August 2007 and provided an excellent opportunity to test the work of the previous 2 years with live horses at both venues. During the 11 days of weather monitoring the full range of Hong Kong summer conditions was experienced, namely, very hot and humid, thunderstorms, considerable rainfall, and a tropical cyclone warning (No. 8 Gale or Storm Warning).

The role of the Foreign Veterinary Delegate as the coordinator of weather information and communication with officials was also tested. A dedicated office was provided at each venue to receive weather data from HKO by computer with Internet access, printer, phone and fax. The delegate had excellent access to technical officials, the judges (Ground Jury) and the veterinary team. It was possible to collect weather data as it happened, and follow the changes to provide up to the minute advice on any adverse conditions that might affect the competition.

Year 3 (2008)

The weather forecasting system developed in 2006/07 was available from 24 July (2 days before the first Olympic horses arrived in Hong Kong) to 14 September 2008 (the end of the Paralympic competition). It provided weather information to officials, competitors, teams and the public. In 2008 additional weather information and warnings were also made available (e.g. gust alarm, lightning location and high resolution 64 km radar imagery with animation at 6-min intervals).

Fig. 4. Calculating the 'Shadow Index' at the cross country venue, Beas River, at around 06:45 and 08:00 h in August 2007.

A total of 212 horses competed across three disciplines; 73 in Eventing, 49 in Dressage and 90 in Jumping. All of the horses arrived by air from overseas and were given a recovery and acclimatisation period for 8–17 days before competition. They were accommodated in purpose built air-conditioned stables at the main venue at a temperature of 23–24 °C. Only the Eventing horses left the venue during the Olympic sojourn. They were taken in a convoy of air conditioned vehicles to the cross country venue the afternoon before the competition and returned to the main venue the following afternoon.

Facilities for rapid cooling of horses

A range of facilities was devised for rapid cooling of horses after training exercise and immediately before and after competition. These were largely based on previous experience with some novel components added to optimise their efficacy. Prototype units were designed for the Test Event and modified for the Olympic Games on the basis of experience. Mobile facilities were also constructed for emergency use, in any location to which horses had access including the field of play.

Primary cooling stations ('misting tents') were located adjacent to the main stables, training areas and competition arena in the main venue and in the final warm-up and finish box at the cross country venue. These were built to provide shade from the sun, a strong flow of air containing chilled water droplets and an ample supply of chilled water with facilities to apply it to the horse. This was achieved through construction of a temporary roof structure on a concrete slab (core venue) or well-drained grass (cross country venue). The concrete slabs were covered with a rubber surface and laid to drain effectively. The dimensions of each station were based on anticipated usage and space available (Table 1). Experience from the Test Event showed that a floor area of 7 × 5 m was only sufficient to allow safe cooling of two horses simultaneously, whereas an area of 10 × 10 m was safe for 4–6 horses.

Fans were positioned along two sides of each unit, facing each other. Conventional evaporative misting fans were used in the Test Event (Imasu, EFS-65 M[1]). These rely on a compressor to force water through fine (~5 m diameter) nozzles at high pressure, thereby introducing a constant supply of minute water droplets into the air stream. The droplets absorb energy from the surrounding air while vaporising, thereby cooling the air. Subjective assessment of these fans at the Test Event was disappointing. Frequent blocking of the fine nozzles made them unreliable. The reduced visibility created by clouds of mist compromised safety. Quantitative assessment of the cooling effects was not performed although competitors judged it to be poor.

Different fans were used at the Olympic Games. Larger, more powerful units using a spinning disc on the fan axis to throw larger water droplets into the air stream (centrifugal atomization), avoided the need for fine nozzles and the associated high-pressure water system (Propeller misting fan, FAMS-F3, Ecolo). Each station included a 5000 or 10,000 L reservoir of chilled water. A designated team maintained the temperature of the water and added cubed ice as necessary to keep the temperature at approximately 8 °C. Low pressure pumps provided a constant flow of chilled water to the cooling fans and on demand to 800 L insulated troughs placed strategically around the station. Chilled water was also pumped to 4–6 hoses, each fitted with a spray head, in each station. Buckets, sponges, scrapers and additional 800 L insulated troughs containing cubed ice were also provided at each station. A plan projection of one of the three identical cooling stations provided in the finish box is shown in Figs. 5a and 5b.

A shade tent with four 800 L insulated tanks containing chilled water and four with ice was positioned at the entrance/exit to a cross country training course at the main venue and pairs of 800 L insulated tanks, one with chilled water and one with ice, were positioned close to each training arena. A shade area was constructed adjacent to the final warm-up arena in the core venue. This included three fans, which could be turned on and off by the competitors, and paired 800 L insulated tanks with ice and chilled water.

Mobile cooling units were developed to provide emergency cooling for any horse that was incapacitated away from fixed facilities. These consisted of a 400 L tank with integral petrol engine-driven pump (Squatpak 400L with a Honda 5.5 hp Engine and APS41 Pump[2]) mounted on the back of an agricultural 4-wheel-drive utility vehicle (John Deer ProGator 2030A[3]; Fig. 6). Two such units were available on standby at all times at the main venue and four units were positioned strategically around the cross country course during the competition. The tanks were filled with water chilled to approximately 8 °C by the addition of cubed ice. These units could deliver water through a spray head on the end of a retractable hose at a rate of approximately 38 L/min.

Emphasis was placed on providing cooling for horses competing in the cross country competition, particularly in the design of the finish box. Three 10 × 15 m cooling stations were located around the margins of the finish box, which occupied approximately 0.3 ha (Fig. 7). The entrance to the first of these was approximately 75 m from the finish line so that horses could be walked into the cooling facility as soon as they were pulled up. Once the official veterinarians were satisfied that the horses were out of immediate danger from heat stress they were walked to one of the other two tents where active cooling could be continued in a more relaxed manner for as long as required. Each cooling station was supplied with its own dedicated 10,000 L water tank. Ice used to cool this water was stored in five 6 m (20 ft) reefer containers, in close proximity to the tents. A dedicated team of staff added approximately 3 tonnes of ice to each 10,000 L water tank 4 h before the start and as required throughout the competition.

Results

Weather conditions during 2006–2008

The weather conditions were quite different during August 2006, 2007 and 2008, but only minor differences were recorded between the two venues. The evidence for variable weather patterns for the different years is illustrated in Figs. 8 and 9 by plotting the weather warnings issued by the HKO and the rainfall recorded. A summary in tabular form for both venues including other meteorological elements recorded is shown in Table 2.

August 2006

The weather was generally fine with less than normal rainfall in the month. Apart from heavy showers on 19 and 20 August, rainy weather was caused by the approach of Typhoon Prapiroon (1–4 August), Severe Tropical Storm Bopha (9–10 August) and a Tropical Depression (24–25 August).

[1] See www.imasu.com.

[2] See www.silvanagcess.com.

[3] See www.deere.com.

Table 1
Location and dimensions of cooling stations at both venues (Sha Tin and Beas River) provided for the 2008 Olympic Games.

Location	Cooling station
Main venue	
• Adjacent to stables entrance	Misting tent: 10 × 10 m covered area; 16 misting fans; 5000 L chilled water supply; four hose units, three 800 L insulated chilled water tanks; three 800 L insulated tanks ice
• Close to competition arena	Misting tent: 5 × 14 m; 5000 L chilled water supply; four hose units, three 800 L insulated chilled water tanks; three 800 L insulated tanks ice
• Final warm-up	Shade area; ~5 × 5 m covered area; three fans; one 800 L insulated chilled water tank, one 800 L insulated tank ice
• Adjacent to training arenas in Penfold Park	Misting tent: 5 × 7 m covered area; 12 misting fans; 5000 L chilled water supply; four hose units, four 800 L insulated chilled water tanks; four 800 L insulated tanks ice
• Adjacent to cross country practice course in Penfold Park	Shade area; 5 × 7 m covered area; four 800 L insulated chilled water tank, four 800 L insulated tank ice
Cross-country venue	
• Final warm-up	One misting tent: 10 × 15 m covered area; eight misting fans; 5000 L chilled water supply; one hose unit, two 800 L insulated chilled water tanks; two 800 L insulted tanks ice
• Finish box	Three misting tents: 10 × 15 m covered area; 20 misting fans; 10,000 L chilled water supply; six hose units, six 800 L insulated chilled water tanks; four 800 L insulated tanks ice

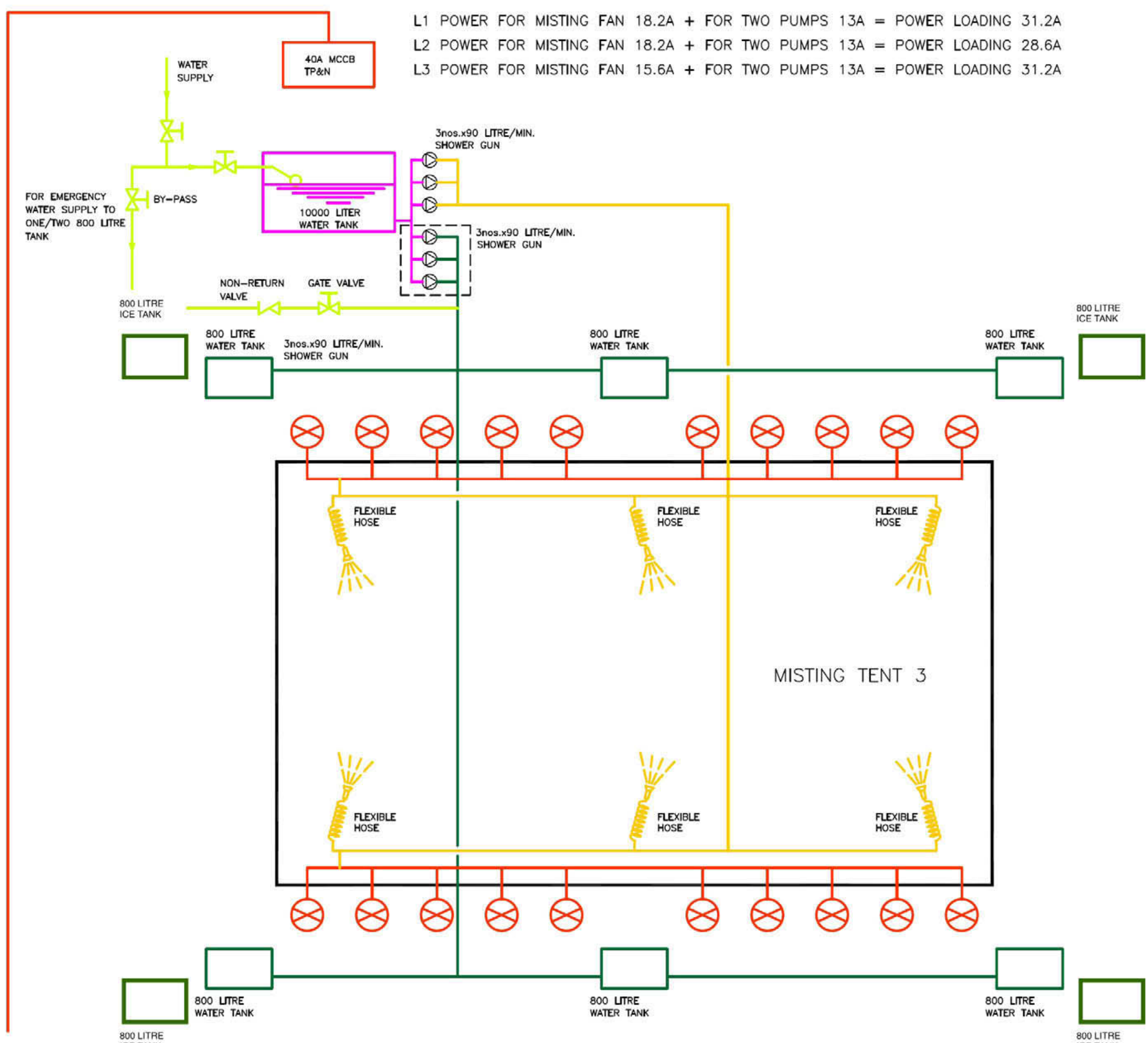


Fig. 5a. Design of one of the three cooling stations located in the Finish box of the cross country course. Two independent series of pumps were used to deliver water cooled to <8 °C with ice from a 10,000 L tank to six 800 L, insulated water troughs (green) or six hand held spray units (brown). Banks of misting fans were mounted down each long side of the tent.

Fig. 5b. Photograph of the cooling station described in Fig. 5a.

August 2007

The month was wetter than normal. Apart from the fine weather in the early part and towards the end of the month, it was cloudy and rainy for the rest of the month due to the influence of Severe Tropical Storm Pabuk (8–11 August) and the active southwest monsoon.

August 2008

The month had 14% more sunshine than normal. It was also relatively dry with only 70% of the normal amount of rainfall. The Olympic events were sandwiched between two tropical cyclones. On 6 August, 2 days before the event started, Severe Tropical Storm, Kammuri brought gale force winds, a No. 8 Gale and Storm Warning Signal and heavy rain to Hong Kong (daily rainfall exceeding 100 mm on 6 and 8 August). Then, Typhoon Nuri passed right through Hong Kong and caused an even higher No. 9 warning signal on 22 August, a day after the conclusion of the event. Thunderstorms in the month were not as active. There was only one occasion during the event when lightning was recorded within 5 km of the main venue.

Fig. 6. A mobile cooling unit. A 400 L tank with integral petrol engine-driven pump was mounted on the back of an agricultural 4-wheel-drive utility vehicle.

Estimation of heat load on the horses and riders using WBGT index and other parameters

This was accomplished from recordings of temperature, relative humidity, rainfall, wind speed and the WBGT index. The overall

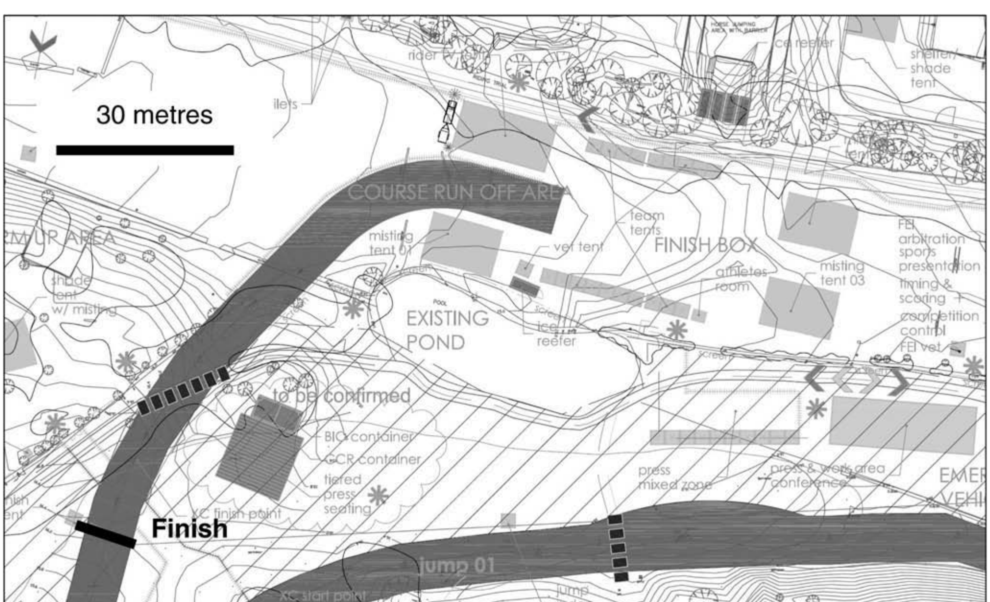


Fig. 7. Plan of the finish of the cross country course. The entrance to the first cooling station (misting tent) was approximately 75 m from the finish line. The two other cooling stations were 50 m away, the other side of an open grass area on which horses could be walked.

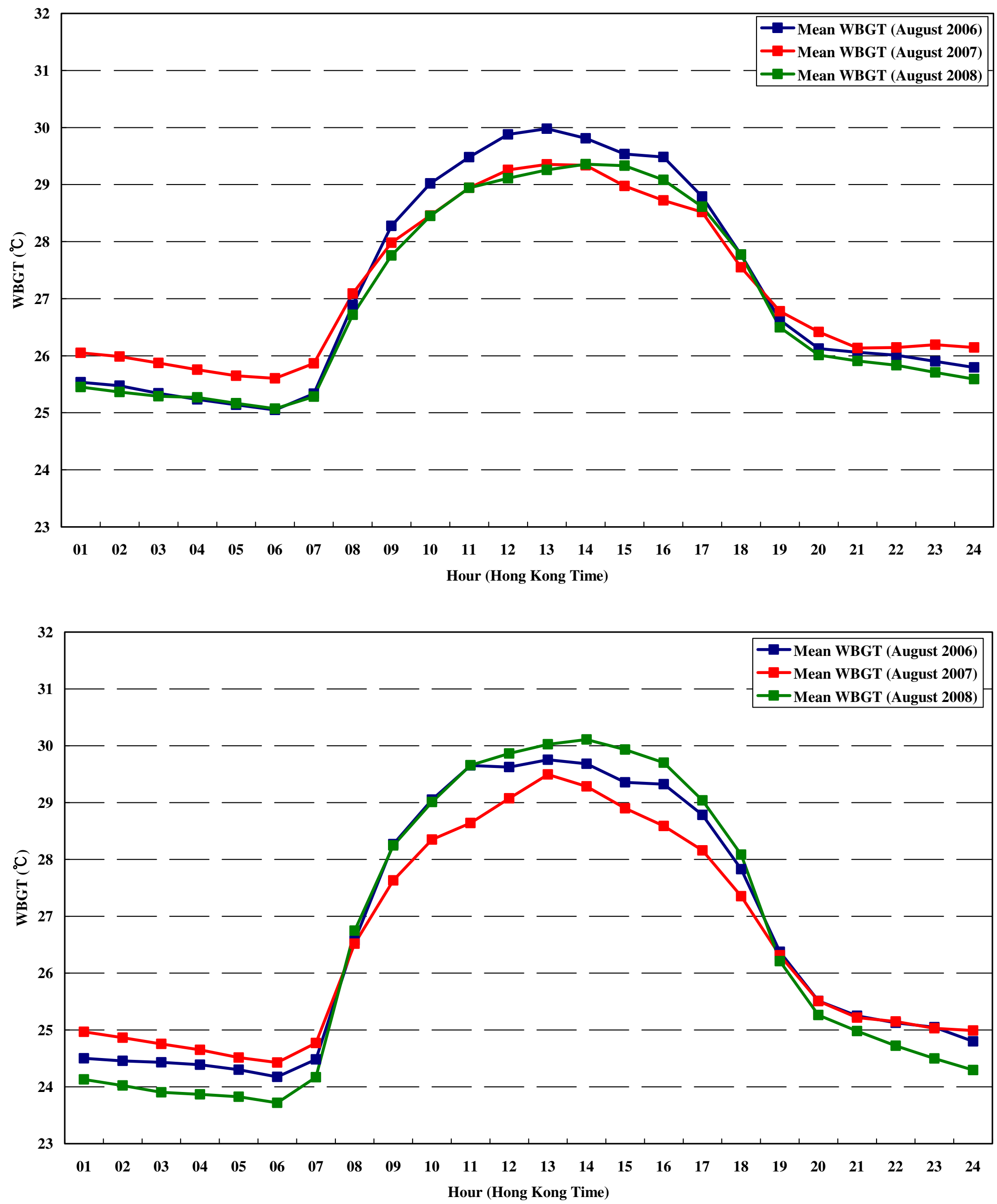


Fig. 8. Summary of hourly mean WBGT (°C) measured in August 2006, 2007 and 2008 at the two venues, Sha Tin (upper graph) and Beas River (lower graph).

picture for daily WBGT recorded at both venues over the 3 years is illustrated in Fig. 8 with the mean hourly values staying within the range of 24–30 °C in August. Dramatic changes were noted in the mean hourly values from around 25 °C at night to a peak of around 30 °C in the late morning/early afternoon. This gave an excellent appreciation of the extent and variation of the environmental conditions, so that the cross country course could be planned.

The initial weather monitoring and WBGT index during 2006 was used to advise the Cross Country Designer and Technical Delegate for Eventing about the length and design of the course. The mean levels of WBGT at Beas River (Fig. 8) were <30 °C at their peak at 1300 h. The officials were advised that provided minimum distances and jumping efforts for an Olympic competition were planned and adequate cooling facilities provided, then the competition design could be approved. A number of loops were included on the course so that distance and jumps could be reduced should there be an unexpected increase of WBGT from 33 °C. Above these levels the possibility of postponement would need to be seriously considered.

The minimum distance for an Olympic course of 4.6 km for the length of the course was recommended with 29 jumps and 34 jumping efforts for the horses.

Establishing the optimum timing of competitions

The weather data collected from 1–31 August 2006 at both venues confirmed the preliminary findings of 2005 that the best time of day for the horses to compete would be in the evening from 1900 to 2300 h. The WBGT was low and showed little variation over the likely duration of each competition (Fig. 10). The early morning was also good from sunrise at 0630–0900 h, but the low position of the sun and extensive shadow production was a serious complication for the cross country competition. As early a start as possible would take advantage of the lower WBGT, although significant variation throughout the duration of the competition (~4 h) was expected, and hence some variation in the conditions experienced by individual competitors was unavoidable.

The first simulation event provided an opportunity to test the Shadow Index and identify a safe time to start the competition. There were eight jumps on the cross country that were seriously affected by the low altitude of the sun (Nos. 1, 2, 8, 11–17). However, by 0800 h the sun's altitude was 26.2° and the Shadow Index was down to 1.44 (Table 3). This was considered safe for the horses and was not expected to affect their vision at these eight fences (i.e. Shadow Index of <1.5).

Developing a protocol for forecasting 'bad weather'

During the Olympic Equestrian Events in Hong Kong (8–24 August, 2008), the performance of the model ensemble and the official forecast provided by the forecasters using the model ensemble for guidance is summarised in Table 4. It can be seen that in producing the official forecasts, the forecasters added value to the guidance of the model ensemble by exercising their professional judgment in producing highly accurate forecasts for the two important parameters, namely air temperature and WBGT. The root mean square error (RMSE) of the official forecasts for both parameters were only 1.5 °C, which compared favourably with 1.8–2.0 °C achieved by the model ensemble forecasts. Verification charts for the various parameters stratified by time of the day are given in Fig. 11.

Developing and testing the decision-making process

(1) Simulated events in 2006 and 2007

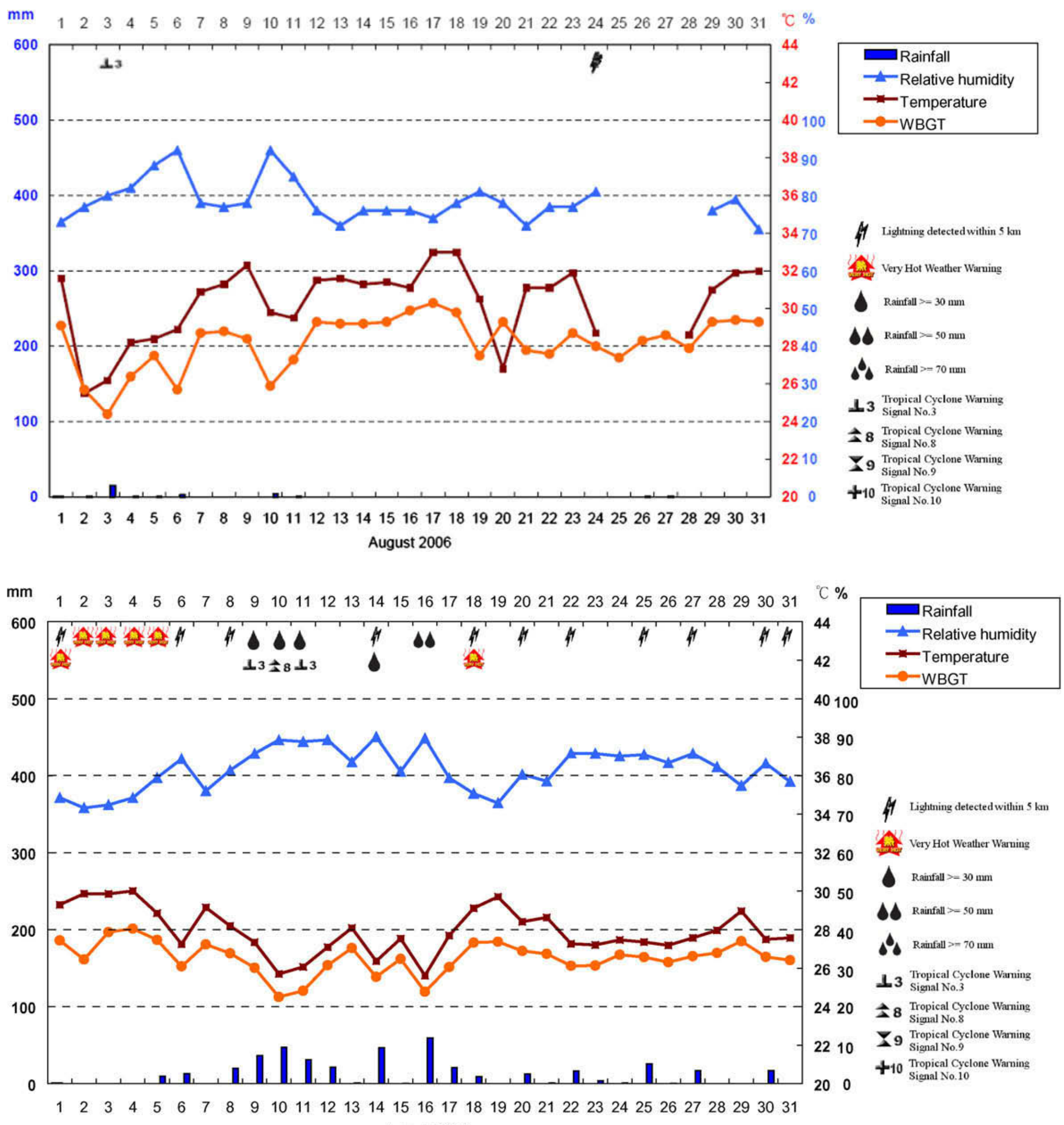


Fig. 9. Composite plot of weather warnings issued by the Hong Kong Observatory in 2006, 2007 and 2008 with total rainfall recorded at the cross country venue, Beas River, over the same period.

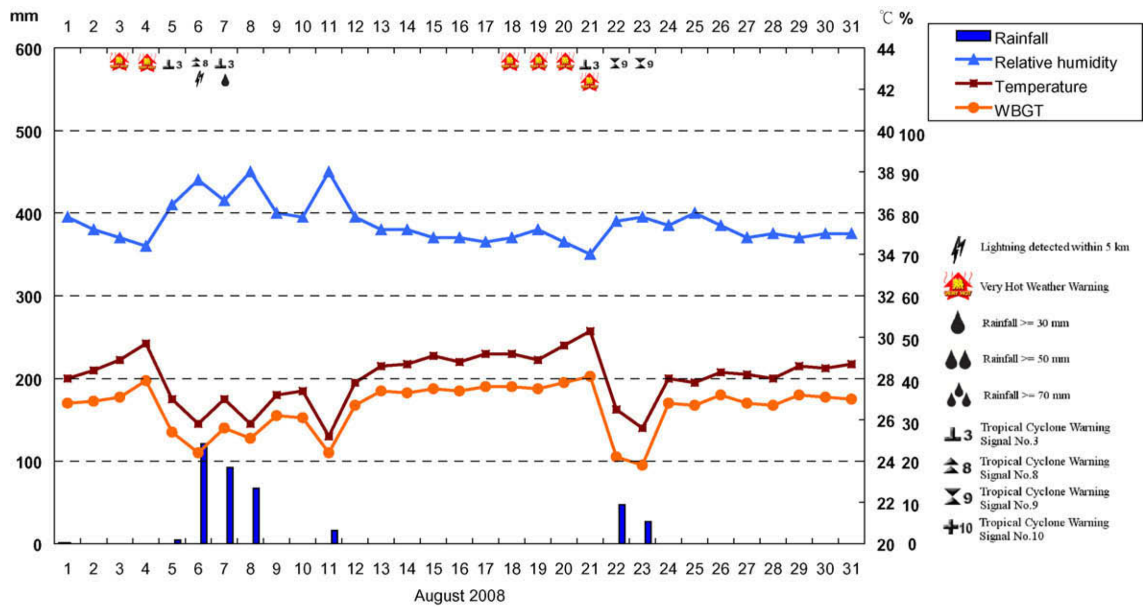


Fig. 9 (*continued*)

Table 2
Summary of weather parameters at both venues (Sha Tin and Beas River) for August 2006, 2007 and 2008.

Meteorological elements	Sha Tin			Beas River		
	August 2006	August 2007	August 2008	August 2006	August 2007	August 2008
Mean maximum temperature (°C)	32.0	31.2	31.6	32.8	32.5	32.8
Mean relative humidity (%)	79	82	77	80	81	80
Total rainfall (mm)	374	531	347.5	412	328	412.0
Mean maximum WBGT (°C)	32.3	31.6	31.0	32.0	31.2	31.9
Total bright sunshine hours	213.2	124.7	215.5	213.2	88.3	213.2
Mean wind speed (km/h)	8.9	9.3	10.3	3.5	3.2	3.8
Number of days with tropical cyclone warning signal No. 3 or above	3	3	6	3	3	6
Number of hours with lightning detected within 5 km	16	19	14	21	25	22

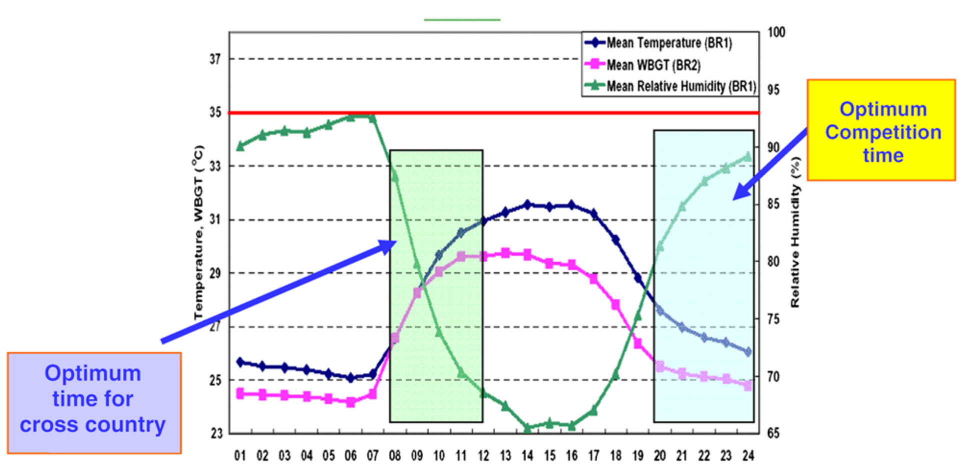


Fig. 10. Weather data recorded during August 2006 showing the high relative humidity (>65%) throughout the day and the optimum times for competition.

The first simulation held at 0800 h on 17 August 2006 was useful to confirm that in hot/humid conditions the horses would be able to safely compete as the WBGT was <30 °C (Schroter et al., 1996). Horses started on course at 2.5 min intervals and with no weather problems the competition was completed by ~1115 h. The forecasting system was extremely accurate and proved satisfactory to the Foreign Veterinary Delegate.

The second simulated competition was run at 0800 h on Tuesday 6 February 2007 after receiving forecasts for satisfactory weather from 0600 h that morning. It was agreed that the weather

Table 3
Results of Shadow Index calculated at the first simulated competition at Beas River on 17 August 2006.

Time (h)	Object height (m)	Shadow (m)	Shadow Index
0645	1.88	12.40	6.6
0730	1.88	5.0	2.65
0800	1.88	2.7	1.44
1000	1.88	1.6	0.85
1200	1.88	0.55	0.29
1500	1.88	1.65	0.87
1700	1.88	3.65	1.84

conditions were unusually favourable and cool for cross country competition, and so a 3 min starting interval was agreed. This would give a finish time for the competition of 1145 h (i.e. 3 h 45 min). It had been raining moderately throughout the night (26 mm recorded since midnight), but this was not anticipated to affect the going for the cross country. The course was expected to cope with a drainage capacity of 50 mm/h to a maximum of 100 mm/day.

The competition commenced as planned and five horses started on the course. At 0815 h an imminent thunderstorm warning was issued by HKO. At this point the rainfall was not heavy (2 mm/h), but because of the impending storm the start interval was reduced to one horse at 2 min followed by the next at 3 min (i.e. overall 2.5 min intervals). At 0845 h HKO issued an Amber Rainstorm warning (i.e. rainfall reaching 30 mm/h) as the storm was moving in much faster than originally forecast. The rainfall had increased on the course to 20 mm/h, although wind speed was only 5 m/s (i.e. 18 km/h) and the visibility was still acceptable. It was agreed to continue the competition for the time being.

At 0900 h the rainfall dramatically increased to 50 mm/h and the storm was in full force (Fig. 12). At 0905 h it was agreed that the competition had to be stopped, having had 23 horses on course. The horses were returned to the stables and a Chefs d'Equipe meeting called to inform the competitors of the weather situation. In view of the encouraging forecast, it was agreed to stop the competition for one hour and restart again at 1005 h if the weather permitted.

At 0930 h the plan was reviewed after receiving a further update from the HKO Duty Forecaster. At this time the weather situation was already improving with the rainfall reduced to 25 mm/h. As it seemed safe to restart the competition the competitors were informed and the horses prepared and warmed up again for the continuation of the cross country. It was agreed that the starting interval should now be 3 min, as it was still cool and there might have been some temporary deterioration of the course (i.e. slippery). This would mean a finish time of 1240 h for the remaining 52 horses. At 1000 h HKO cancelled the Amber Rainstorm warning. The competition was restarted at 1005 h and was able to continue without further weather problems (Fig. 13). However, the rain continued with light to moderate showers and the total rainfall from the start of competition was 66.5 mm.

(2) Olympic Test Event August 2007

This was the final opportunity to trial the weather system before the Games in August 2008. The objective was to rehearse all aspects of the competition and facilities at both venues, and to test the rapid cooling after the cross country. There was a total of 37 horses entered in two competitions, namely, a CCI** with 17 international horses from eight nations, and a national competition (CCI*) with 20 local Hong Kong horses. Both competitions went off well, although the First Horse Inspection for the local horses had to be cancelled because of a No. 8 tropical cyclone warning on Friday afternoon 10 August. This inspection was replaced the next day by a member of the Veterinary Commission examining the horses in the warm-up area before the Dressage.

The First Horse Inspection for the CCI** was postponed from Friday afternoon to early Saturday morning 11 August because of the tropical cyclone warning. The cross country was held on 11 August, and the weather was cool (WBGT ~26 °C and temperature ~26 °C) with persistent, heavy rain. The local horses competed at 450 m/min from 0830 to 0930 h over a 2 km course with 17 fences and 22 jumping efforts. They went well despite the rain and very high humidity (between 80% and 90%) which was very testing. There were no falls or injuries to the 20 horses. From 1000 to 1100 h the 17 CCI** horses also went well over the 4 km course with 24 fences and 34 jumping efforts at 550 m/min. They suffered no injuries, but two horses finished in a very tired state. The horses completed the course with rectal temperatures recorded between 39 and 41 °C. These were successfully reduced to ~38 °C within 30 min by the cooling procedures in the finish box.

The highlights of the weather for the Test Event can be summarised both before and during the competition. In the days prior to competition (3–9 August 2007), the air temperature at the cross country venue was quite high with peaks of around 33 °C, and the relative humidity fell from around 90% in the early morning to around 65% by mid-afternoon (1600 h). The WBGT index did not go much above 30 °C, which meant fairly favourable conditions for the horses with no need for any reductions to the competition format. A number of hot weather warnings were issued, the presence of lightning within 5 km of the venue, and some rainfall were recorded during this period. All these features were accurately predicted in the daily forecasts from the HKO website.

A major weather incident occurred with the approach of a Severe Tropical Storm, Pabuk. This caused some degree of disruption to the competition. It formed on 5 August some way out in the Western Pacific, and entered the South China Sea on 8 August when a standby signal No. 1 was issued. This was upgraded to a Strong Wind Signal No. 3 on 9 August, and was accompanied by occasional strong gusts and heavy rain in both venues. Pabuk passed by Hong Kong during the night of 9 August, and was later downgraded to a tropical depression. However, on 10 August it turned round on itself and moved back towards Hong Kong again and strengthened to a tropical storm (Fig. 14). As a result, a No. 8 Gale and Storm Warning Signal was issued on the afternoon of 10 August which meant there the First Horse Inspection at the

Table 4
Root mean square error (RMSE), and mean error (in parentheses), of official forecasts and model ensemble forecasts during 8–24 August 2008. The model ensemble forecasts included output from the European Centre for Medium Range Forecast (ECMWF) model, the Japan Meteorological Agency (JMA) model and the Operational Regional Spectral Model (ORSM).

	Temperature (°C)	WBGT (°C)	Relative humidity (%)	Wind speed (km/h)	Rainfall (mm/3 h)
Beas River					
Official forecast	1.5 (−0.3)	1.5 (−0.1)	9.8 (4.2)	4.0 (1.7)	3.7 (1.6)
Model ensemble	2.0 (−0.1)	1.9 (−0.2)	10.5 (1.5)	3.8 (0.8)	3.7 (1.4)
Sha Tin					
Official forecast	1.5 (−0.2)	1.5 (−0.1)	9.8 (3.3)	6.0 (1.6)	3.7 (1.6)
Model ensemble	1.8 (0.0)	1.8 (0.2)	9.5 (1.5)	6.3 (−1.8)	3.9 (1.4)

main venue had to be cancelled. Fortunately the storm moved westward away from Hong Kong after traversing the western flank of the territory and all warnings were cancelled by 6.00 h on 11 August. During the period from 8 to 11 August, a total of 197.5 mm of rainfall was recorded at Sha Tin while Beas River recorded 134.5 mm of rainfall.

During the competition itself (10–13 August 2007), the weather pattern for the days of competition was quite different from the previous week. It was generally much cooler with neither the WBGT nor ambient temperature reaching 29 °C. However, the relative humidity remained very high and only decreased to 80% in the early afternoon (Fig. 15). The forecast for the day of the cross country was for some thunderstorms early on followed by rain and showers for the rest of the day. From a series of radar pictures (Fig. 16) the intense echo of heavy rain at 0530 h 12 August could be seen in the northern part of Hong Kong. By 0630 h the southern flank of heavy rain involved the venue for a short period. The storm then tracked eastward with rain affecting the venue. By 0948 h the picture showed the last bit of heavy rain. After that the venue was clear all afternoon.

On arrival for the cross country at 0500 h there was no rain and the conditions were good. By 0600 h the rain started falling as daybreak progressed, and increased in intensity. The radar sequence provided a sufficiently accurate assessment of the evolution of the weather conditions to advise the competition officials that the rain would be intermittent, heavy at times, but would cease around 1000 h. There were no other untoward effects of the weather, other than the excessive humidity which would have certainly

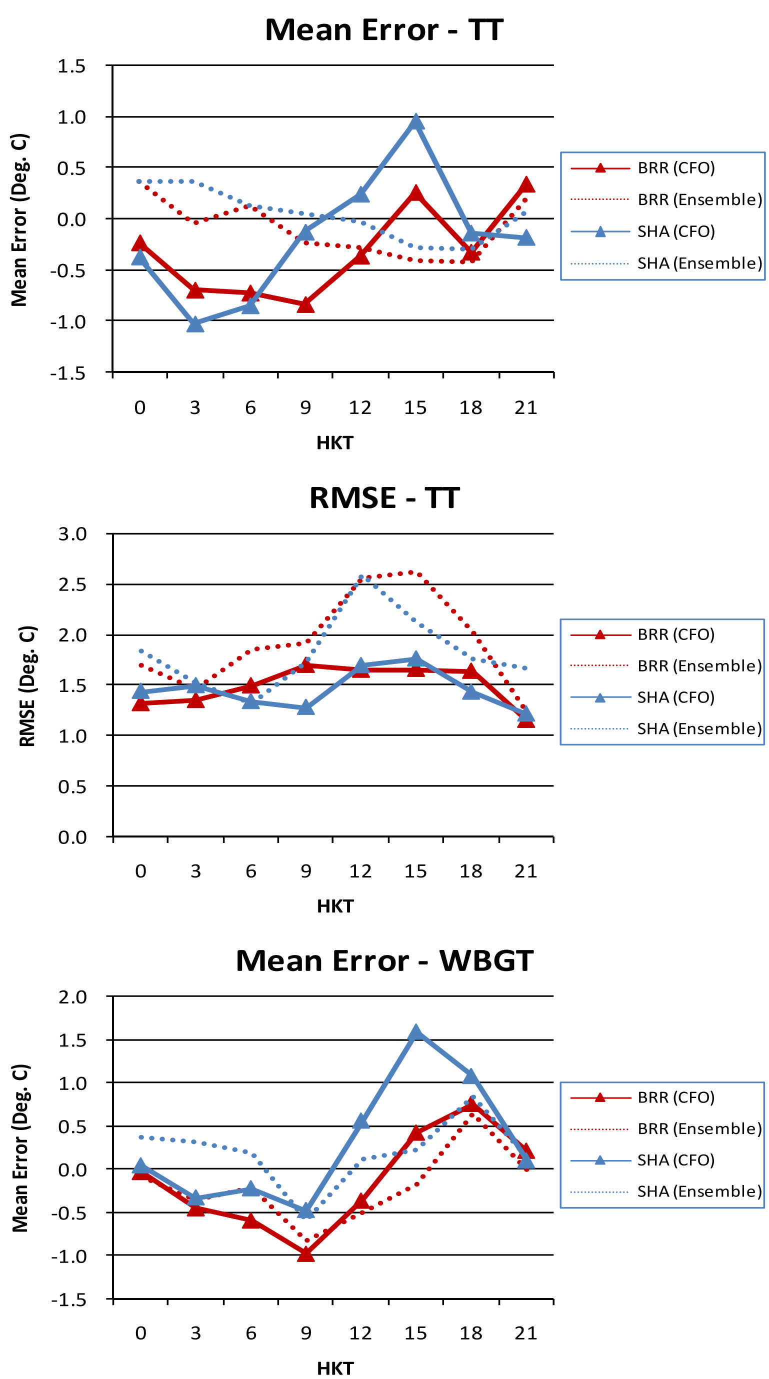


Fig. 11. Verification charts of major weather parameters (temperature, WBGT, rainfall) during 8–24 August, 2008 [BRR(CFO) and SHA(CFO) denote subjective forecasts by forecasters for Beas River and Sha Tin respectively. BRR(Ensemble) and SHA(Ensemble) are objective model ensemble forecasts.]

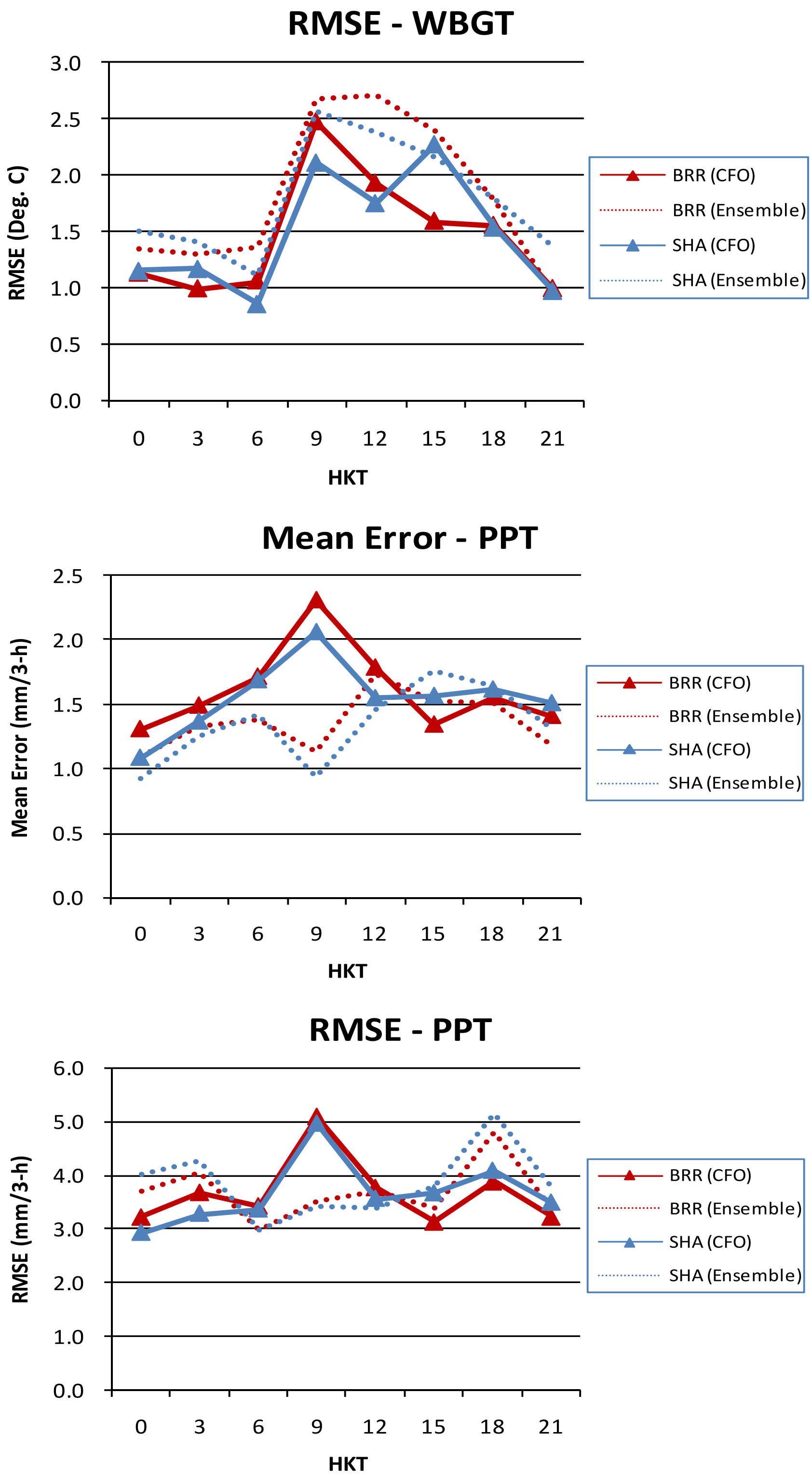


Fig. 11 (*continued*)

affected the horses and made them more tired than expected for the relatively low temperatures. In terms of the heat load on the horses, they were finishing the cross country with rectal temperatures of 39.5–41.0 °C.

(3) Olympic Games August 2008

In the days prior to competition (25 July to 8 August), the horses started arriving at the main venue from 24 July, and over the last few days of July to 4 August the weather was hot/humid and typical for this time of the year. The presence of Severe Tropical Storm, Kammuri, necessitated the issuance of a No. 8 Gale or Storm Warning Signal on 8 August, and there were heavy rain periods from 5 to 8 August (Fig. 8). This caused some disruption to the scheduling of training in Sha Tin and an hour's delay in the start of the cross country rehearsal at Beas River on 8 August. During this period the temperature and WBGT were relatively low (24–27 °C), but the humidity was very high (>80%).

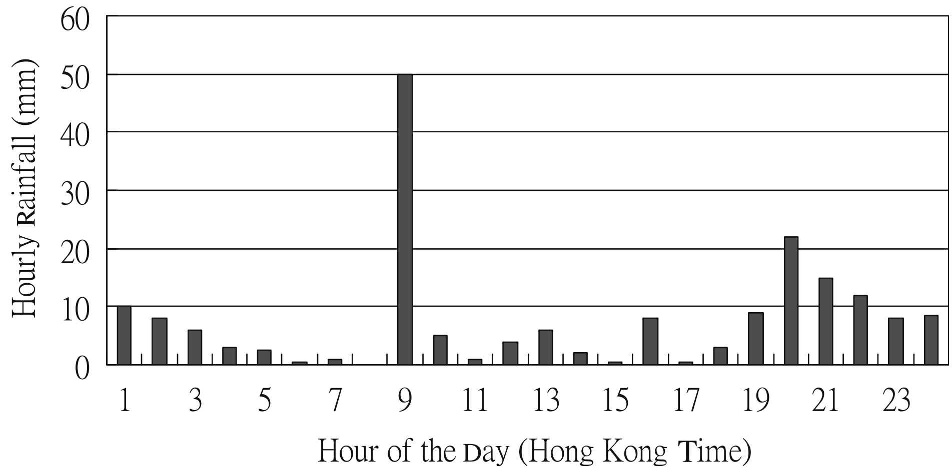


Fig. 12. Hourly rainfall at the cross country venue, Beas River, during the second simulated competition on 6 February 2007.

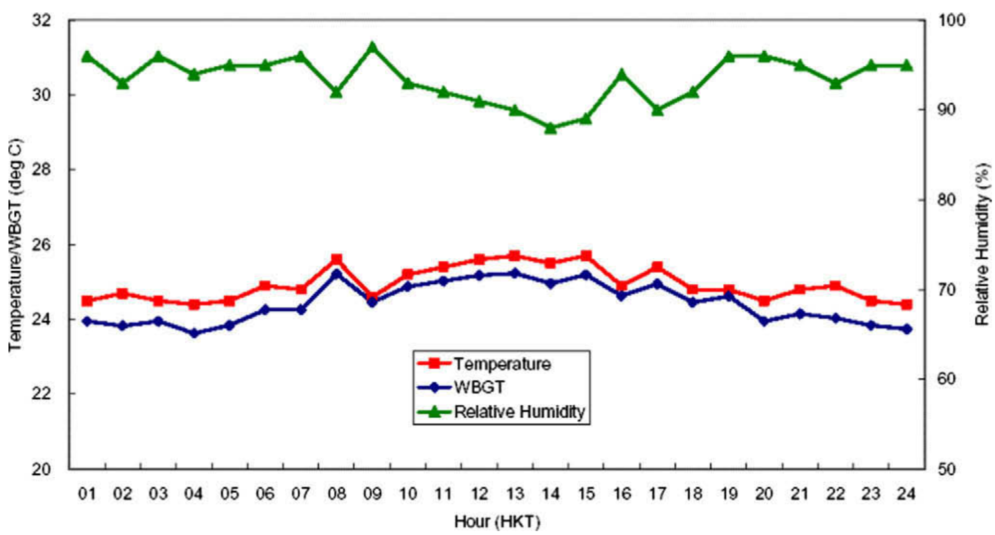


Fig. 13. Weather data collected throughout the day of the simulated cross country competition showing the high relative humidity and relatively low temperature and WBGT.

During the competition (9–21 August), the first Olympic competition was Eventing and the cool/humid conditions continued for the first 2 days of competition (Dressage). The horses were convoyed to Beas River on the afternoon of 10 August to prepare for the cross country the next morning. On Cross country Day (11 August) the schedule for the 69 horses was to complete the cross country course from 0800 to 1145 h. The forecast and pattern of weather leading up to the event was fairly stable, but a warning was issued to the Foreign Veterinary Delegate at 0500 h for rain and possible thunderstorms during the morning. Bouts of quite heavy rain occurred between 0640 and 0700 h, after which the radar picture cleared. Rain ceased at 0750 h, and apart from some light drizzle remained clear until the last horses completed the course. The conditions for the horses were remarkably stable throughout the morning (WBGT 24–26 °C; temperature 25–26 °C and humidity ~90%). The horses competed well and safely with only three falls. Of the 69 horses that started 57 (83%) completed the course with 45 going clear. There were a small number ($n = 5$) of horses that finished looking tired, and 16 were extremely hot with rectal temperatures >41 °C).

The weather for Dressage and Jumping (12–22 August) remained stable throughout most of this period, but was consistently hot/humid during the afternoons with WBGT reaching the 30 °C or more. All of the competitions took place in the early morning or under lights in the evenings. However, a Stand-by No. 1 Signal was issued during the evening of 20 August because of the approach of Typhoon Nuri. On 21 August, the last day of the Jumping competition, Nuri was still heading straight for Hong Kong. At 1700 h that day, Nuri was about 350 km to the southeast of Hong Kong and was moving west-north-westward at 14 km/h. The assessment of the Senior HKO Forecaster at that time was that the No. 3 Strong Wind Signal would very likely be issued that night, and that a No. 8 Gale and Storm Warning Signal (that would bring a compulsory halt to all competition) would be required in the morning of 22 August. Thunderstorms were also forecast from 1700 to 1800 h before the competition was due to start at 1915 h. As it was extremely likely that severe weather resulting from the typhoon would occur in the following 1–2 days, it was decided to take advantage of the window of relatively calm weather on the evening of 21 August to go ahead with the Jumping competition and monitor the weather conditions very carefully. In the event the competition was not disturbed despite the No. 3 Signal at 2040 h, and it was concluded at around midnight. Within 8 h a No. 8 Warning was issued by the HKO,

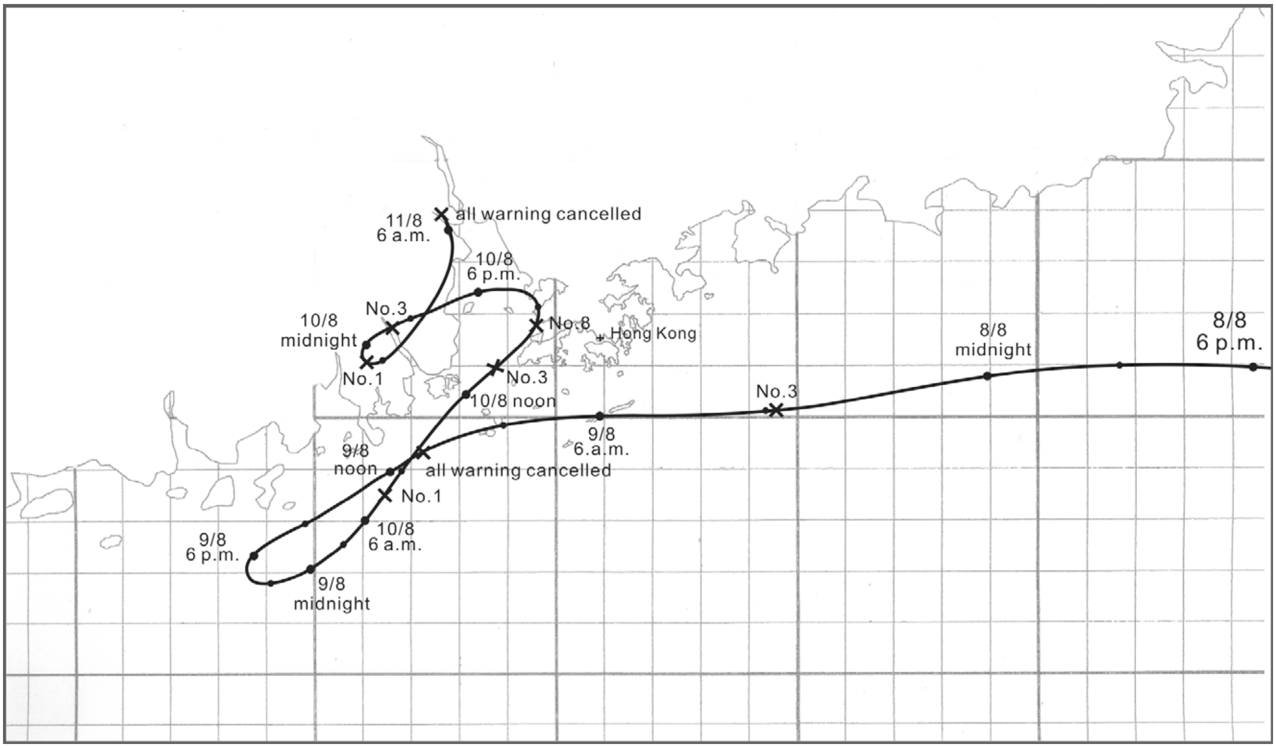


Fig. 14. Path of the severe tropical storm (Pabuk) from 8–11 August 2007 and its close proximity to Hong Kong.

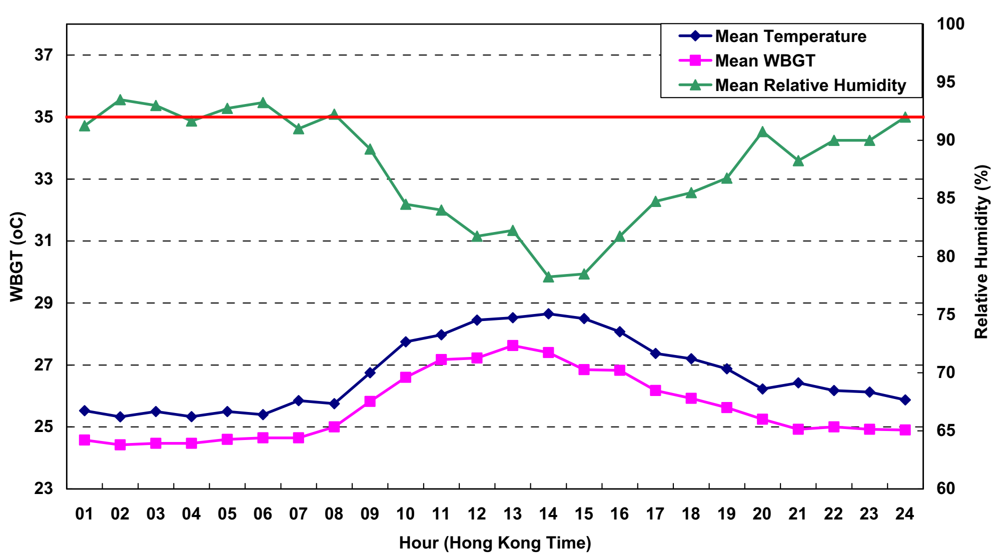


Fig. 15. Graph illustrating the mean hourly temperature (°C), relative humidity (%) and WBGT (°C) at the cross country venue, Beas River, from 10–13 August 2007.

and a few hours later Hong Kong experienced the first direct hit of a typhoon since 1999.

Developing, testing and using rapid cooling facilities to prevent heat stress and exhaustion

The horse cooling facilities functioned effectively throughout the Olympic sojourn. All of the horses that completed the cross country competition responded favourably to aggressive cooling within 10 min of finishing (Fig. 17a–c). The condition of the horses at the finish varied greatly, which was reflected in the range of clinical parameters measured immediately the horses were pulled up (rectal temperature: 39.5–42.5 °C; heart rate: 80–200/min; respiratory rate 50–140/min). The chilled water hoses were highly effective at cooling horses, especially when two or three units were applied to the same horse simultaneously. One horse finished with a rectal temperature of 42.5 °C and appeared disorientated and distressed. It responded rapidly to intensive cooling, appearing to regain a normal mental state within 4 min and a rectal temperature of 41.3 °C in 10 min and 39.2 °C within 30 min. Only one horse required immediate veterinary attention for severe lameness caused by a complete, non-displaced fracture of the first phalanx in the right forelimb.

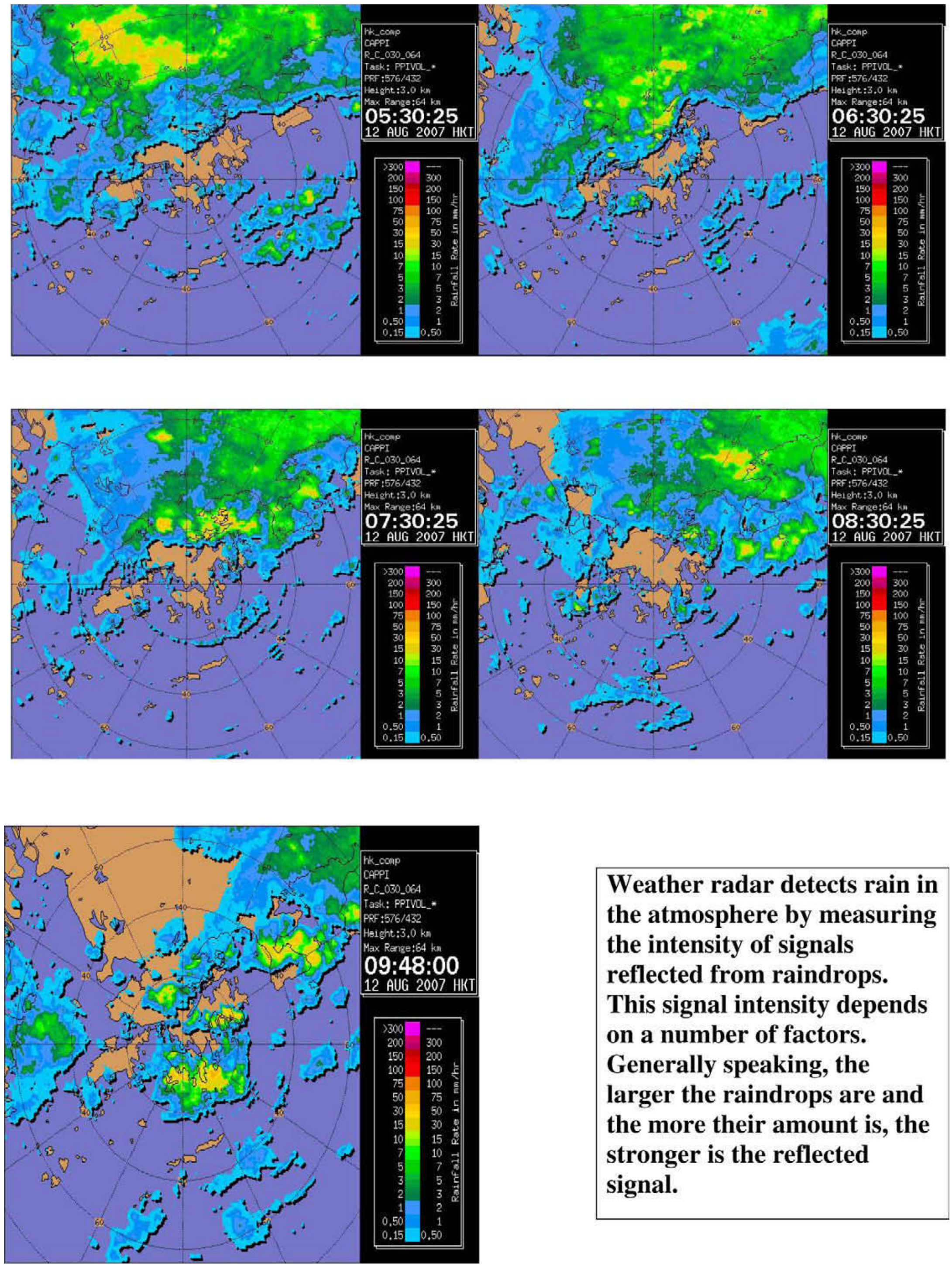


Fig. 16. Illustration of the sequence of weather radar images that can be obtained from the Hong Kong Observatory website, different colours represent different rainfall rate.

The 'misting tents' provided a pleasant environment and were used extensively by competitors cooling their horses after exercise and as a way of relaxing them at the end of the day. The chilled water hoses were effective for rapid cooling of horses with considerably less waste than occurs with buckets. There were no significant technical issues with any of the equipment and the supply of ice was consistent throughout the duration of the games. Pre-stocking reefer containers at the cross country venue 3 days before the competition avoided supply issues on the day of competition, which are inevitably complicated at such an event by security concerns.

Discussion

The equestrian events of the 2008 Olympic Games were highly successful despite the unpredictable and frequently severe nature of the climate and local weather conditions in Hong Kong during the summer season. Meticulous data collection in the years prior to the event combined with local meteorological expertise gave the organisers the opportunity to anticipate and react swiftly to weather conditions at the competition venues, reducing adverse effects on the equine athletes.

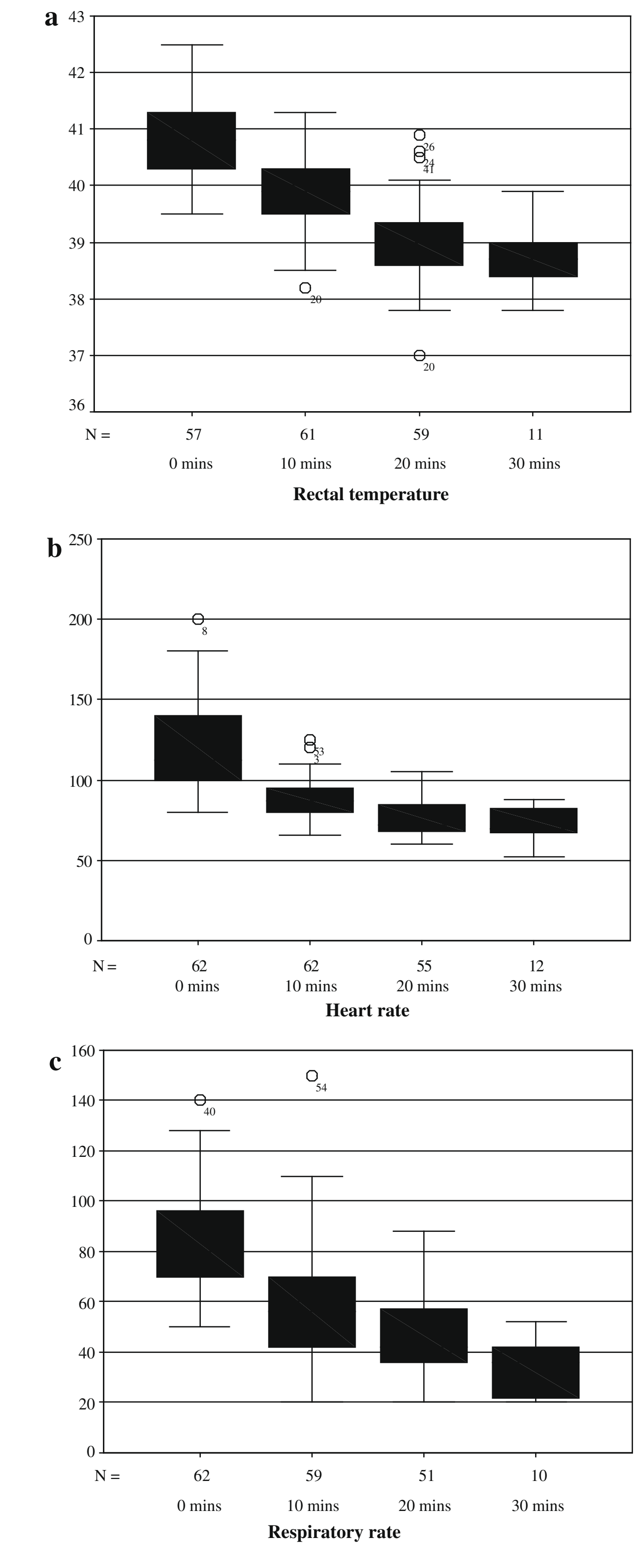


Fig. 17. Box and whisker plots illustrating temperature (a), heart rate (b) and respiratory rate (c) data for horses immediately after completing the cross country competition and 10, 20 and 30 min later, after aggressive cooling.

Design of facilities and procedures

The cumulative knowledge base of weather conditions in Hong Kong gathered during the 3 years prior to the Olympic Games was highly significant in the design of facilities and procedures for the equestrian events. The Olympic facilities at the core venue were designed to withstand extreme weather conditions such as typhoons, and to minimise the heating effect of the climate on the horses. Facilities included air conditioned housing and treatment stables, an air-conditioned training arena and shaded sand rolling yards. Horse cooling stations were in frequent use and effective during pre-competition exercise. During the competition itself fans and cold water were used by some teams in the area next to the entrance to the arena. The cooling station adjacent to the exit from the competition arena in Sha Tin was continuously used and appeared subjectively to be effective, and no cases of heat stress were experienced throughout the duration of the Games.

The cross country course was shorter than usual and designed so that loops in the course could be eliminated if the heat and humidity exceeded specific pre-determined levels. Despite the relatively cool conditions on the day of the cross country competition and the modification of the course, many horses were hyperthermic at the finish, some severely. The cooling fans and chilled water in the finish box were rapidly effective in reducing these horses' rectal temperatures. One horse finished with a temperature of 42.5 °C and appeared disorientated. After 4 min of intensive cooling even this animal regained full coordination and the rectal temperature had reduced to 39.2 °C after 30 min. The following day this horse underwent a veterinary inspection and was judged fit to compete in the Jumping. The mobile cooling units were available to cool any horses that had to be stopped on the course for any reason. In fact, the 12 horses that were withdrawn during the cross country phase were able to walk off the course and were cooled in the finish box, rather than on the course itself.

Analysis of data from preceding years demonstrated a clear diurnal pattern to the weather in which the WBGT rose steadily from approximately 0700 h, peaking at around 1400 h before falling rapidly to approach the overnight low at around 1900 h. This information was a significant factor in the Organising Committee's decision to stage competition in the evening where possible for events under floodlights. It was also a key consideration when formulating schedules that avoided training sessions between 1100 and 1500 h. To accommodate the tight schedule associated with Eventing, one session of the dressage was held in the morning. A 0600 h start took advantage of the end of the overnight cool period.

An early start to the cross country competition had to be balanced against the low position of the sun in the sky. A novel 'Shadow Index' was developed to quantify this effect which demonstrated that by 0800 h this hazard would not affect the horses' or riders' jumping ability.

Contingency planning and rehearsal

The locally variable and rapidly changing weather in Hong Kong in August make it difficult or impossible to predict accurately the conditions at specific locations more than a few hours in advance. As the weather at this time of year can be extreme, it is unacceptable to rely on forecasting and have a fixed plan for each day of competition. Plans may have to be changed frequently, at short notice, during a competition. Once the organising team had a good understanding of the types of weather that could affect the various competitions, contingency plans could be drawn up. Scenarios were then rehearsed to evaluate the effectiveness of the planning and communication in various situations. This process was particularly important for the cross country competition, because the horses had to be transported out of the protected (typhoon safe) Sha Tin stables. Additionally, during the cross country competition itself, horses would potentially have been exposed to poor visibility, unstable footing, lightning and flooding.

The virtual events in July 2006 and February 2007 were a critical part of this contingency planning process that allowed the protocols themselves to be tested by the time of the Olympic Test Event in August 2007. Indeed, the start of the 2* cross country competition at the 2007 Test Event had to be delayed due to security issues that prevented the timely delivery of ice required for the cooling stations. This highlighted the need to design facilities that could be made operational before security lock downs at competition venues, e.g. in 2008, reefers were installed in advance at both venues and loaded with ice several days prior to the start of the competitions.

Ongoing monitoring and decision making

Having drawn up multiple plans for each event according to different weather scenarios, it was imperative to have rapid access to minute by minute meteorological data during the whole competition phase. The organising team acknowledged the significant technical support from the Hong Kong Observatory, who provided the systems and personnel for the Olympic equestrian events. The veterinary services manager ensured that a robust network of communications systems were in place for the games, including Internet, fax and protected mobile phone systems.

Conclusions

It is clear that the equestrian events for the 2008 Olympic Games were successful, not only for the high quality of the performances of the competitors and their horses, but the detailed planning and organisation that was necessary to cover all contingencies including the unpredictability of the weather. This paper has been written to assist in future planning of similar equestrian events and to record the level of meteorological expertise involved as well as the need to collaborate with a team of veterinarians who have relevant experience.

Conflict of interest statement

None of the authors of this paper has a financial or personal relationship with other people or organisations that could inappropriately influence or bias the content of this paper.

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