Wind funnelling underneath the Ħaġar Qim protective shelter

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It is often said that wind and associated processes induced by it have caused damage to the megalithic temples at Ħaġar Qim over the years. The aim of this paper is to explore whether wind funnelling is taking place beneath the protective shelter that now covers the Ħaġar Qim temple complex. A project was set up to test the extent to which the wind speeds beneath the new protective shelter differ from those outside it. Wind speeds were measured inside and outside the shelter in 25 different places and in four directions over a period of four months. The results were mapped using a Geographic Information System facility. It was concluded that wind speed does not increase beneath the protective shelter except at certain points within the temple structure itself.

Shelters have long been considered a means to protect historical sites. Already in the 1950s a decision was taken to shelter three archaeological sites in Sicily (Stanley-Price and Jokilehto 2002). Plans to shelter the prehistoric Tarxien temple complex in Malta from natural elements already existed in 1935 when a grant from the Carnegie Corporation was awarded for the purpose of erecting a shelter over the monument (Stroud 2005). However, studies that consider the effect of such protective shelters on wind processes have been lacking (Aslan 1997; Delmonaco *et al.* 2009; Cassar *et al.* 2011). For instance, aeolian processes are not considered for any of the shelters examined by Aslan (1997) which occur in Mediterranean climates in places like Rome, Syria, Jordan, and the Aegean islands. Of particular interest for its geographical location is the shelter erected over the remains at Piazza Armerina in Sicily in 1957. Even in this case, however, the aeolian processes have not been studied (Stubbs *et al.* 2011). Work on the Ħaġar Qim temple complex by Cassar *et al.* (2011) and the Environmental Monitoring Report commissioned by Heritage Malta (Heritage Malta 2006) acknowledge that the protective shelter over Ħaġar Qim could in fact affect wind processes. In this work we will explore these processes in greater depth and suggest possible management options.

Protecting the Ħaġar Qim temples

Ħaġar Qim is one of the oldest temple sites in Malta. Built about five millennia ago it was only excavated in 1839 (Evans 1971, 80-88). Since then, it has been exposed to the elements and has experienced damage from both physical and anthropogenic agents. It was only at the end of last century that decisions were taken to improve the management of the site. This included the erection of a fence for security purposes, parking facilities, and initial stone conservation measures (LBA & HM 2004). Today, the site is one of the most visited prehistoric monuments, being a prominent destination for tourists and educational visits.

In 1999, an expert group meeting was held by the then Museums Department to discuss the long-term conservation of the Ħaġar Qim temple complex. It was reported that the site deserved specialised conservation measures since it was prone to water-logging, subsequent material leaching, and exposure to salt weathering (LBA & HM 2004; Heritage Malta 2008). In view of this, and in the light of the urgency of the situation, it was decided that the option of shelters to protect the temples from the different weather phenomena was the most feasible of those proposed (Cassar *et al.* 2012) (Fig. 1). Every effort would be made to minimize the aesthetic impact of the shelter through the right choice of material. The

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Figure 1. Ħagar Qim and its protective shelter (photograph by Simon Farrugia).

shelter was to be a reversible intervention until better conservation options were found and, in addition, an information campaign would be launched to bring the project to the attention of the general public.

In their environmental monitoring final report, Lino Bianco and Associates who worked in collaboration with Heritage Malta (LB & HM 2004) also mention the different effects the shelter could have on wind processes. Of major concern was the need for the temples to be protected from increased wind velocity through the shelter in order to prevent problems of exfoliation, wetting and drying cycles, stone flaking, and back weathering (cf. Cassar 2002). Furthermore, the significance of certain astronomical alignments of the temple prevented any supporting structures for the shelters from being placed in front of the temple entrances (spaces 1 and 4 in Fig. 2).

Wind funnelling

Wind is the flow of gases from areas of high pressure to areas of low pressure but its movement is also affected by the earth's rotation, temperature differences, topography, nature and texture of terrain surface, other climatic conditions, and the shape of the built-up zones in urban areas. These built-up zones provide clues to variations in wind velocities and directions due to changes in the morphology of the buildings causing "wind funnelling", characterised by movement of air which is restricted by narrow passageways. This can be explained by the Continuity or Conversion of Mass principle which 'requires that a steadily flowing mass of fluid passing into a given volume must be the same as the mass coming out' (Hidy 1967, 49). Being a compressible fluid, air is easily affected by obstacles in its way from high pressure to low pressure points. Thus, if air travelling to a low pressure point encounters an obstacle in its course, it will alter its characteristics so that the same amount of "air" matter will travel in the same time frame. In this paper, we will call this effect "wind funnelling" as it resembles wind passing through a funnel – from its wide conical basin through its narrow outlet.

Wind funnelling could be happening within the Ħaġar Qim protective shelter if the same shelter is causing a compression of streamlines and forcing an increased wind speed through the gap between the bottom rim of the shelter and the ground – which ranges between 2.3 and 10.4 m in height above ground level (Canobbio 2007). Such compression is quite possible given the large extent of open unobstructed ground over which the wind can blow before reaching the temple and keeping in mind that before reaching the shelter, the wind has the whole troposphere to pass through. Here the shelter may be said to be causing confluence of streamlines 'causing an accumulation in fluid mass' (Hidy 1967, 49) in the volume of space beneath the shelter. It was thus decided that a research project be set up to test whether wind funnelling was occurring at Ħaġar Qim.

Materials and methods

In the absence of past wind-speed data covering the whole site, it was decided to measure directly and compare wind speed outside and inside the protective shelter. A pilot study was conducted in order to assess the feasibility or otherwise of the research project. This entailed setting up five stations for wind speed measurements along the north-south axis – one inside the temple, two at the shelter boundary, and two 30 m outside the shelter (Fig. 2). This distance reflects the theoretical end of the boundary layer, which is the distance from an obstacle where the effect of that obstacle on the trajectory and velocity of the wind stops being observed (Bagnold 1941). A propeller anemometer was used to measure wind speed because of higher resolution readings (0.1 m/s), low starting speed (0.1 m/s), and with less over-speeding errors than cup anemometers (error margin of ± 5%) when compared to the same technical specifications of

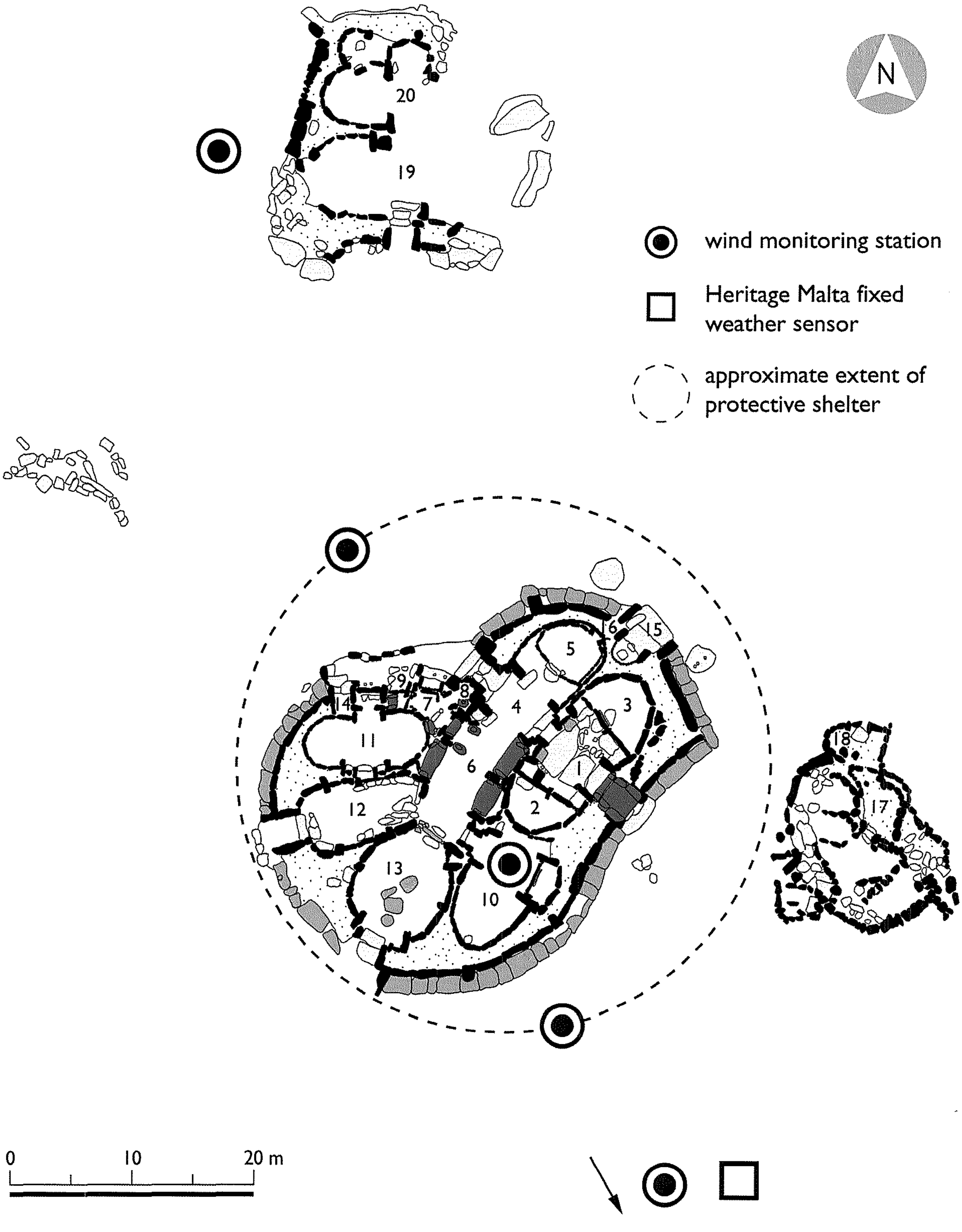

Figure 2. Location of wind speed pilot study and apse numbering (drawn by Maxine Anastasi on data supplied by the authors).

other types of anemometers (Pedersen *et al.* 1999).

The main problem with the propeller anemometer is that it is unidirectional and considers only one horizontal component and wind direction. It was thus important to ensure that both wind speed and direction remained roughly the same while measuring all the stations in a single day. Thus, when it was observed that the average wind direction or velocity being measured at each station changed by more than 5%, a new set of three measurements was taken to replace the previous one. In order to measure wind speed, the anemometer was held as far as possible from the observer and the modal wind speed value over a period of one minute was noted together with the lowest and highest wind speed at that station during that minute (Table 1).

This pilot study was then expanded in order to have a more complete coverage of the temple complex by using 25 wind monitoring stations. The outer six temple apses, the main entrance, and the exit together with the central space (numbered 6 in Fig. 2) had one station each, whilst another eight stations were located just outside each apse and main access ways at the boundary of the protective shelter. The other eight stations were located about 30 m away from the shelter. The purpose of this distribution was to provide a multilateral radial transect study of wind in the area while giving indications about the direction of any possible wind funnelling effect. Readings were taken in four cardinal wind directions

	North-East						West						South–South-West						East–South-East					
	low-limit T	average T	high-limit T	low-limit B	average B	high-limit B	low-limit T	average T	high-limit T	low-limit B	average B	high-limit B	low-limit T	average T	high-limit T	low-limit B	average B	high-limit B	low-limit T	average T	high-limit T	low-limit B	average B	high-limit B
recorded wind speed (m/s) in each of the 25 sampling stations	4	6	10	1	3	4	0	2	3	0	2	4	4	6	11	2	4	7	0	0	1	0	0	0
	0	1	3	0	0	2	1	2	5	1	2	5	2	5	10	2	3	6	0	1	1	0	0	1
	0	1	1	0	0	1	0	0	1	0	0	1	3	5	6	2	4	6	0	1	1	0	0	1
	0	2	3	0	1	2	0	0	1	0	0	1	0	2	7	0	0	1	0	0	1	0	0	1
	1	2	4	1	2	3	0	1	2	0	0	2	0	1	3	0	1	3	0	0	0	0	0	0
	0	1	3	0	2	3	0	0	1	0	1	2	0	5	6	3	4	6	0	0	1	0	0	1
	0	1	3	0	0	1	0	0	1	0	2	5	0	2	3	0	1	2	0	1	3	0	1	4
	0	2	3	0	1	4	0	0	0	0	0	0	0	1	4	0	0	1	0	0	0	0	0	1
	0	1	2	0	0	1	4	6	10	1	2	3	0	1	3	1	2	3	2	3	7	0	1	3
	4	7	11	3	6	10	3	5	6	0	0	1	0	1	1	0	1	2	3	4	6	1	2	4
	5	9	13	3	5	9	1	3	4	1	1	3	0	0	1	0	0	1	3	5	7	1	2	3
	2	5	6	1	2	4	4	5	6	0	2	4	0	1	2	0	0	1	0	3	4	0	1	1
	4	7	11	3	6	10	2	5	8	0	2	3	0	0	1	0	0	1	0	1	2	0	0	2
	4	6	8	0	2	5	3	8	11	2	4	6	2	4	4	0	1	3	1	2	3	1	1	3
	4	6	8	0	1	3	3	7	10	3	6	7	0	3	5	0	2	4	1	2	5	0	1	3
	3	5	6	1	2	3	2	5	9	0	0	2	0	1	3	0	0	3	4	5	6	1	2	5
	3	5	7	2	4	6	1	4	8	0	1	1	1	3	5	1	2	3	4	5	7	2	3	5
	4	6	9	1	1	3	0	1	5	0	0	1	9	10	12	5	7	9	2	4	7	1	2	3
	3	7	12	2	4	8	1	4	5	0	1	2	4	7	9	1	3	6	2	4	5	1	1	3
	2	5	9	0	2	3	3	8	10	2	4	6	4	6	9	2	3	5	2	5	7	1	2	3
	5	7	10	3	5	6	3	5	7	2	4	8	3	5	7	2	4	6	2	3	6	0	0	1
	5	8	11	2	4	6	4	5	6	1	2	3	4	8	10	2	4	8	1	2	5	0	0	2
	1	3	8	0	1	2	2	4	5	1	2	3	4	7	9	1	3	5	2	3	5	0	2	2
	2	5	10	1	3	5	3	5	8	0	1	2	3	6	9	2	4	6	1	3	6	0	0	1
	1	5	9	0	3	5	0	0	2	0	0	1	6	7	10	3	4	6	2	4	5	1	2	4
mean wind speed (m/s)	2.3	4.5	7.2	7.2	2.4	4.4	1.6	3.4	5.4	0.6	1.6	3.0	2.0	3.9	6.0	1.2	2.3	4.2	1.3	2.4	4.0	0.4	0.9	2.3

Key

low-limit T: lowest value of wind speed measured at 2 m above ground level
average T: model wind speed measured at 2 m above ground level
high-limit T: highest value of wind speed measured at 2 m above ground level
low-limit B: lowest value of wind speed measured at 0.1 m above ground level
average B: model wind speed measured at 0.1 m above ground level
high-limit B: highest value of wind speed measured at 0.1 m above ground level

North-East wind readings were taken on 16 January 2010 starting at 13:30 local time.

West wind readings were taken on 24 February 2010 starting at 16:15 local time.

South–South-West wind readings were taken on 30 November 2009 starting at 11:30 local time.

East–South-East wind readings were taken on 3 March 2010 starting at 17:30 local time.

Table 1. Wind speed data and calculations.

on the windiest days of the months between November 2009 and March 2010, as per weather forecast predictions (Table 1). Despite the sources of error of having both the actual wind speed and directions differing from those predicted, relatively high wind speeds were measured from the west, south-south-west, north-east, and east-south-east directions. Wind speeds were measured at heights of 2 m and 0.1 m above ground level respectively in order to have indications of turbulence arising from friction with the ground surface and other obstacles (Bagnold 1941).

GIS Mapping

For a better visualisation and understanding of the wind patterns in the Ħaġar Qim temple area, the wind speed values at each station at heights of 2 m and 0.1 m respectively in each of the four wind directions were inputted into a Geographic Information System, ArcGIS 9.3. Using an Inverse Distance Weighting interpolation (IDW) technique and assuming that the temples lie on a ubiquitous isotropic plane, the software calculated wind speeds based on the assumption that the further away you go from a point, the less the influence of that point on its neighbours and vice-versa (Mitchell 1999). Although this meant that the software itself ignored that there was the protective shelter and the temple itself, this technique was considered as appropriate since wind speeds at two nearby points on similar topography would have similar wind speeds. Moreover, by assuming that there were no obstacles in the trajectory of the wind, any influences of the actual obstacle would presumably be visible on the map by sharp changes in wind speeds (Mitchell 1999).

A power parameter of 4 was assigned in the IDW since it was considered to obtain a balance between the influence of distant points and those of nearby points. With a raster resolution of 0.3 m and a variable radius of 9 m, the algorithm used wind speed data from recorded points within a nine-metre radius of the point to be estimated and calculated a wind speed which could be generalised for a square of side 0.3 m. Wind speed was then categorised into 10 colour-coded classes, with a colour assigned to each class range for distinction purposes (Fig. 3). Although this immediately revealed the existing wind pattern it could easily lead the user to think that there were very sharp boundaries between areas of similar wind speed, which is definitely not the case.

Discussion and observation

The main factor that is apparent from the four maps of wind speed conditions in the Ħaġar Qim area is the general drastic drop in wind speed inside the temple from all the directions that the wind may be blowing (Fig. 3). This immediately seems to prove that no wind funnelling is occurring under the protective shelter or rather, that the wind is actually losing velocity as it passes through the shelter and regains it as it exits from below it. On the other hand, minor increases in wind speed can only be noticed when the airstream passes between two substantially large megaliths and seem to be independent of their location with respect to the shelter itself.

It is only the air at the same height of the shelter (2.3 m at its edges) that is actually passing from one side of the shelter to the other. Due to the dome shape of the protective shelter, the further the airmass entering the shelter travels inside it, the larger is the space which the airmass can occupy since the shelter becomes progressively higher, and has an increased volume. Thus as explained by Bernoulli's principle, the airmass will continue to lose velocity until it reaches the highest point inside the shelter at its centre. At this stage pressure differences will force it to pass through a lower height until it reaches the opposite end of the shelter (Fig. 4). In fact, slight increases in wind speed were observed on the leeward side of the shelter in different wind directions. During north-easterly winds, an increased wind speed was observed to the west of the temple at a distance of about 30 m outside apse 12 and during the observed south–south-west wind, another increase in wind speed was noticed to the north-east of apse 3 (Fig. 2). While this confirms our theoretical explanation, this minor increase is not considered to be significant because the wind speed never reaches the strength it had when it first entered the shelter.

A minor but significant exception to the above generalization would be the case of east-south-east wind at the main Ħaġar Qim entrance facing south-east. Wind funnelling could be observed and felt there since wind speeds just inside the temple complex are slightly higher than those just outside by one to two metres per second as seen in figure 3. While in the map of the east-south-east wind (Fig. 3) the wind

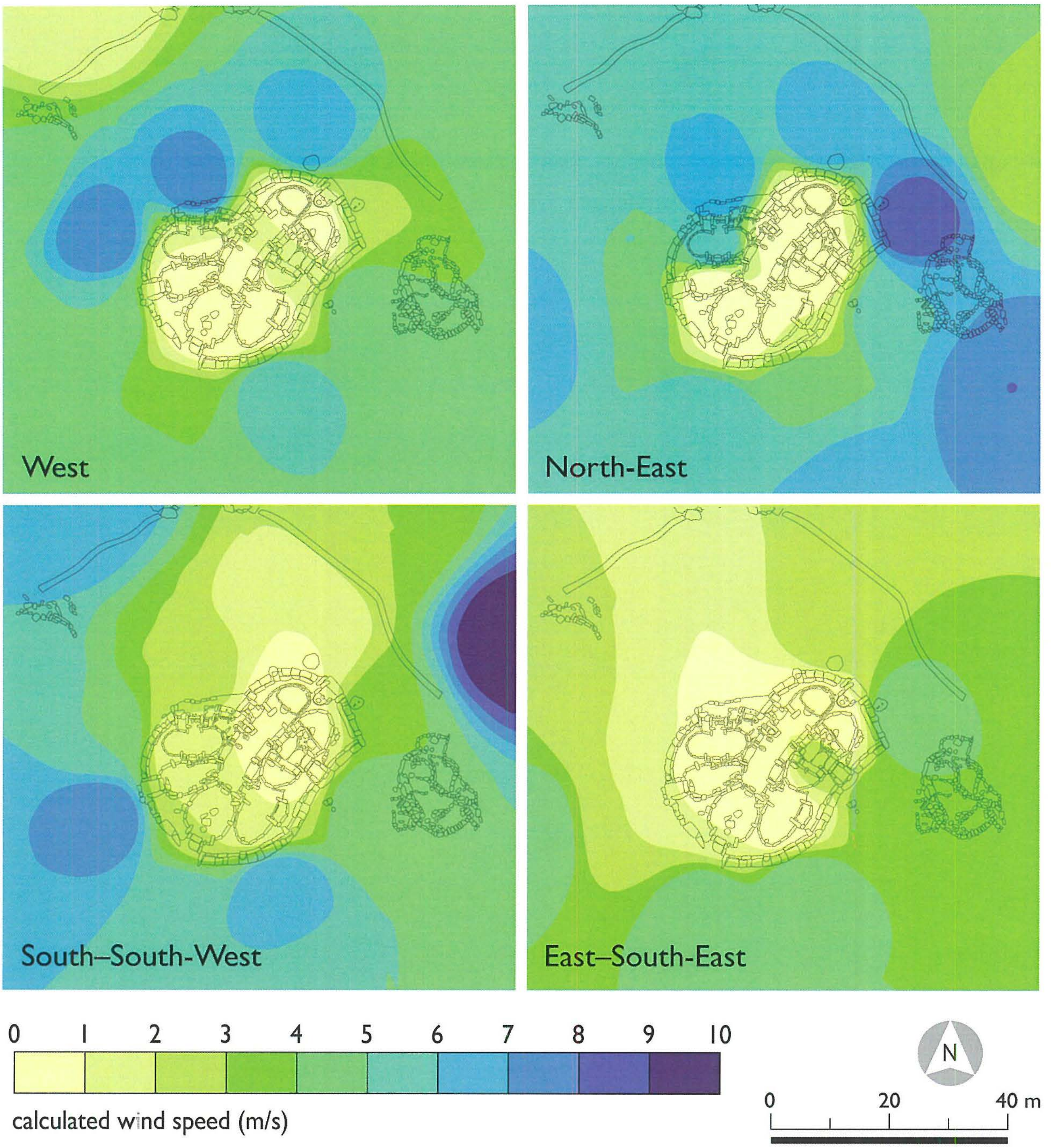

Figure 3. Four Inverse Distance Weighted interpolation maps of wind speeds at 2 metre height under four different directions at the Ħaġar Qim area.

pattern outside the main entrance continues inside the temple complex, the opposite occurs at the same location in the case of wind speeds from the other three directions. In winds coming from the south-south-west, west and north-east, the wind pattern inside the temple continues with a decrease in speed down to less than one metre per second when measured just outside the main entrance.

It is interesting to note that this process is not replicated on the other side of the main corridor, as happens in the case of westerly winds. This may be because the main entrance of the Ħaġar Qim temple complex is the only place where a lintel is still in place over two upright megaliths. Wind funnelling could thus be taking place here as the air stream which passes through the 2.3 m gap at the shelter edges is constrained to pass through a narrower and lower passage into the shelter because of higher pressure outside the main temple entrance. Although there was also an increase in wind speed noted in this same part of this entrance when wind coming from a westerly direction was measured, this was felt throughout the whole passageway and not only in the first part just beneath the lintel as was the case with an east-south-east wind.

Most of the above observations were replicated for wind speeds at a height of 0.1 m even though wind speeds here were much lower (Table 1). Statistical correlation between both datasets resulted in a Pearson coefficient of 0.815 at $p<0.01$ significance level. This agreed with Bagnold's (1941) observations of how wind speed varies with height since over a height of 10 cm friction caused by terrain texture would be at a minimum and the logarithmic relationship between these two variables will approach a straight line. At this point we may predict that physical weathering and erosion processes resulting from wind will be at a minimum inside the temple and we will therefore focus on the possible direct effects of this reduction in wind speed. Although during the first months from the completion of the shelter no significant deposition was observed in any part of the temple (*pers. comm.* J. Cassar 2010) we can however identify areas where this could occur in the future. Empirical evidence suggests that the outer temple walls may be the first structures which could experience deposition. This is mainly because they are an excellent wind barrier in conditions where wind speeds are already decreasing. The lower parts of most of these walls are also covered by vegetation which could encourage the trapping of wind-blown particles. Since the megalithic walls are not smooth, with some of them even showing signs of severe erosion processes (Vannucci *et al.* 1994), wind reflection would be difficult and thus any previously deposited sand would not be easily blown away (Mainguet 1997, 170-92). The inner apses to the west and east of the main corridor could also be prone to deposition, especially on windy days when wind could carry particles in saltation and suspension inside these apses – particularly space 11 (Fig. 2) which stands on ground about 1 m higher than the rest of the temple complex.

Another possible aspect which has been identified and could occur with lower wind speed is the growth of fungi and vegetation which could cause biological weathering and erosion (Heritage Malta 2008). Following empirical observation it was evident that this was also improbable mainly because the shelter protected the area from precipitation and sunlight which are essential for the growth of these organisms. It was also mentioned to us that the gardeners at Ħaġar Qim were finding less vegetation to clean manually in the months following the erection of the shelter, indicating the effect this is having on the growth of flora (*pers. comm.* Grima 2010).

Concluding remarks

After conducting the wind monitoring fieldwork and analyzing the collected data, two main conclusions were drawn for the Ħaġar Qim complex with regard to wind funnelling:

1. The wind is actually losing velocity as it passes through the shelter and regains it as it exits the shelter (Fig. 4);

2. While the protective shelter itself is not causing a significant increase in wind speed, there is an evident increase in wind speed between specific megaliths. This is especially true with south-easterly

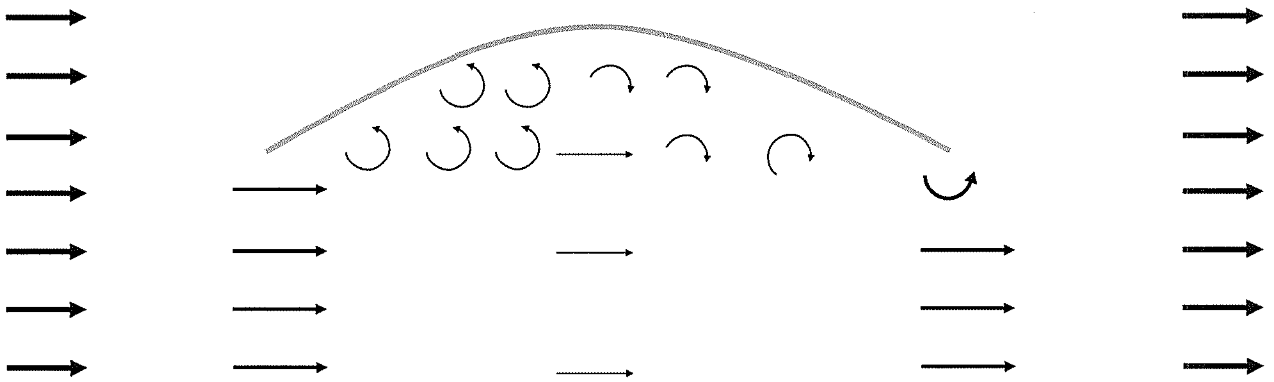

Figure 4. Simplified schematic diagram of wind patterns below the protective shelter as suggested by the authors from the observed results. Increasing arrow thickness indicates higher wind velocities.

winds blowing through the main south-east facing entrance made up of a lintel resting on two megaliths.

These conclusions would be insignificant if they did not lead to management action. Such action should not be focused on any single observation but on a series of detailed observations. The aim should be that of managing several aspects of the environment at Ħaġar Qim so that no one measure would counteract the other. The ideal would be an integrated management approach targeted at keeping wind speeds beneath the Ħaġar Qim protective shelter at a minimum without inhibiting air circulation. Such measures should be easily reversible considering the temporary lifespan of the protective shelter.

More studies are needed to further develop the above observations. As they stand, they can neither be generalized for every weather situation throughout the whole year nor extended to similar megalithic structures, such as those at Mnajdra. More readings should be taken to permit a better sampling of wind speeds. Fixed anemometers such as the one re-installed in May 2011 inside the Ħaġar Qim temple complex would enable a 24-hour continuous wind speed monitoring, thereby permitting wind speed modelling for different microclimatic conditions. Measuring wind speeds at more locations beneath the protective shelter could further explain the processes which are slowing down wind speed. Such data could give additional insight on turbulence inside the temple complex and the shelter and identify areas which would be more susceptible to wind erosion.

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