(Revised) Final Report: Swimmer's Itch Incidence at Crystal Lake (CSA) over 2013-2016
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Summary:

The primary goal of this work was to determine if commonly collected environmental data (e.g., water temperature, wind speed, and wind direction) could be used to predict temporal patterns of swimmer's itch (SI) incidence at the Congressional Summer Assembly beach (CSA) at Crystal Lake. Lifeguards at this beach collected daily data throughout the summer for four years (2013-2016), including the number of reported SI cases and total swimmers, water temperature, and wind speed and direction. Based on results from a binomial mixed-effects regression model, we found wind direction and wind speed were the best predictors of day-to-day variation in the probability of an individual swimmer contracting swimmer's itch at CSA beach. Swimmers that entered the water on days when wind blew directly towards shore, i.e., perpendicular to the shoreline, had the greatest risk of contracting swimmer's itch. However, there was a negative effect of wind speed after accounting for direction. These results suggest that swimmer's itch risk is greatest on days when a gentle, steady breeze blows from directly offshore. We also found that swimmer's itch risk was greater in the morning.

We found no significant effects of current or past temperatures on the probability of a swimmer contracting swimmer's itch, contrary to previous findings by our lab based on cercaria abundance in the water. However, these results only represent a single site and should not necessarily be used to inform other sites. One possible explanation for this discrepancy might be that swimmer's itch risk at CSA beach is primarily driven by cercariae drifting in from deeper offshore waters, rather than cercariae produced by local snails present in the shallow waters where the temperature data were collected.

Introduction:

Swimmer's itch, or cercarial dermatitis, is a painful itchy rash caused by avian schistosomes, a type of snail-borne parasite closely related to tropical species that cause human schistosomiasis (Brant & Loker 2009). Avian schistosomes (mainly *Trichobilharzia* spp.) normally have waterfowl definitive hosts. However, the infective cercaria stage produced by the intermediate host snail (*Stagnicola* spp.) sometimes mistakes human skin as bird skin and attempts penetration, resulting in the rash (ref Verbrugge et al., 2004). In recent years, SI incidence appears to be rising throughout Northern Michigan, where SI has an economic impact on recreational water use (Muzzall et al., 2003).

The goal of this work is to determine what environmental factors are associated with high risk of contracting SI during recreational water use at the Congressional Summer Assembly (CSA) beach on Crystal Lake. Traditional methods for determining SI risk are labor-intensive and require specialized expertise to identify parasites (Kolarova et al., 2010). In 2016, we found lake size and other indirect temperature measures correlate with cercariae and *Stagnicola* snail abundance at a large spatial scale (Muzzall et al., 2003, Raffel 2017). However, many public beaches have staff (e.g., lifeguards and park managers) during the summer months that can collect even more common environmental data including current temperature and wind speed/direction in conjunction with swimmer and SI counts. This study focused on data collected by lifeguards at CSA beach during the summer season over a 4-year period (2013-2016).

Cercariae distribution and dynamics within a body of water has been widely studied (Upatham 1974, Muzzall et al., 2003, Horak et al., 2015, Raffel 2017). Trematode cercariae have various chemical and physical responses to find a suitable host including temperature, skin chemistry, and light (Haas 1987, Brachs & Haas 2008, Haeberlein & Haas 2008). Factors such as wave action or water currents caused by an independent source (i.e., wind) might move cercariae into beaches from off-site locations (Upatham 1974). *Stagnicola* snails are often found in deep off-shore locations and avian schistosome cercariae typically migrate toward the water surface, so surface water currents from off-shore might be important for increasing swimmer's itch risk in some locations. Anecdotally, beachgoers at CSA have reported higher SI incidence when winds originate in the northeast, which is the off-shore direction.

Methods:

Data Collection

Lifeguards at CSA collected daily data for 7 weeks from late June to early August each year during the 2013-2016 period. Lifeguards counted the number of self-reported SI cases (by swimmers), the number of swimmers in the morning and afternoon sessions, the water temperature (measured in Fahrenheit and converted to Celsius for analysis), wind speed (miles/hour), and wind direction to the nearest 8-way direction (N, E, S, W, NE, SE, SW, NW). All other variables were generated based on these measurements. To allow analysis of temporal autocorrelations and lagged effects of past temperatures, we calculated the average of previous 1-, 3-, 5-, and 7-day temperatures and SI cases (AvgPrevTemp1, 3, 5, 7 and PrevTotal1, 3, 5, 7), and we restricted the dataset to days when these data were available (i.e., removing the first 6 days of each year). We also removed two datapoints from the analysis, where one day was missing temperature data, and another was missing wind speed data. There were days where the number of SI cases was greater than the total number of swimmers; in these cases, we adjusted the total number of swimmers to be equal to the number of SI cases (i.e., proportion of Si that day = 1).

Statistical Methods – Environmental factors and time of day

We used generalized linear mixed effects models within the R program to determine the best predictors of the number of SI cases per day. We used a binomial distribution in these models to test for effects of environmental factors on the probability of a given swimmer contracting swimmer's itch. We included a random effect of "Day" in each model to account for daily variation and avoid pseudoreplication. We initially had trouble achieving model convergence due to the large number of predictor variables; however, models converged readily with fewer predictors included. We therefore took a "forward selection" approach to selecting a final model, which allowed us to avoid overly complex models and ensure model convergence (described below). To test for a time of day (TimeOfDay) effect, we ran a separate model in which the morning and afternoon counts were coded separately in the dataset; in this model, the random effect of "Day" mostly serves to account for day-to-day variation.

It is important to note that this modeling approach assumes that the number of swimmers counted in a particular day are the only swimmers available to get SI and report it. This assumption is likely unrealistic because SI symptoms can take greater than a day to appear; thus it is possible for SI reports to come from people who contracted SI the day before and/or at a different beach within the last 24 hours. However, the assumptions of this model may be more valid than that of a negative binomial (count) model we also considered, which has an underlying assumption of an infinite number of swimmers available to contract SI (though swimmer availability could be accounted for by adding it as a covariate).

We used a forward selection approach to model construction to explore contributions of various environmental factors to SI risk. Backward selection (i.e., starting with a full model) was harder to implement due to the failure of many more complex models to converge. In forward selection, we start with simple models that only include one predictor variable at a time, select the predictor that explains the most variation, and systematically add predictors to the model until no additional variables significantly improve the model. We used a p-value threshold of 0.05 for variable inclusion in the final model.

For analysis of wind direction effects in the full binomial model, we paired adjacent wind directions (e.g., N+NE, E+SE, etc.) to help simplify the model; this generated two possible wind-direction variables which we considered as possible predictors in model selection (N+NE; WindDirGroup1 vs. NW+N; WindDirGroup2). We found that WindDirGroup1 was the better predictor of the two wind-direction variables, and the two variables explained much of the same variation leading to exclusion of WindDirGroup2 from the model. Other predictors considered in model selection included: current daily water temperature (WaterTempC), wind speed (WindVel), a wind speed and direction interaction (WindDirGroup1×WindVel), and the average of previous 1-, 3-, 5-, and 7-day temperatures and SI cases (AvgPrevTemp1, 3, 5, 7 and PrevTotal1, 3, 5, 7). To analyze time of day effects, we also used forward selection to select significant predictors.

Post-hoc Comparisons – Wind direction

To further investigate the wind direction effect, we conducted post-hoc comparisons using a simple binomial mixed effects model (as above) in which the dependent variable was the number of SI cases for subsets of the data including all data for each combination of wind direction (e.g., N & NE, NE & E, etc.) to investigate the effect of either direction. Wind direction effect p-values were then corrected to control the false discovery rate for multiple comparisons (FDR = 0.05). We also used simple binomial mixed effects models to further investigate the effect of wind speed (WindVel) on the number SI cases at each wind direction individually (N, NW, W, etc.).

Results and Discussion:

Multiple comparisons analysis showed a significant increase in the average proportion of SI cases on days with winds originating from the northerly directions compared to others, especially from the northeast ($P_{adj} < 0.05$; Fig. 1). No other adjacent wind directions were significant different from each other ($P_{adj} > 0.05$). This supports anecdotal evidence seen at CSA that more SI cases occur when winds are blowing from offshore, perpendicular to the beach. This may be due to most of the cercariae attacked swimmers at CSA beach originating from *Stagnicola* snails living in offshore beds, which are transported to the local site via surface currents driven by onshore winds (Upatham 1974).

The best model for predicting daily SI risk included the wind direction and wind speed variables, both of which were highly significant in the model (Table 1; $P < 0.0001$). Despite previous evidence of past and current temperature effects in lab and field conditions (Paull et al., 2015, Messner 2017), we did not find support for these patterns in the CSA lifeguard dataset. Based on local anecdotes, we expected winds from the northeast to correlate with higher SI cases. The results supported this prediction. However, wind speed had an unexpectedly negative effect on SI risk, in that higher wind speeds resulted in a lower proportion of individual swimmers that would report SI on a given day ($P < 0.0001$; Table 1). This effect was largely driven by winds coming from the North rather than the Northeast (see below). There are a few possible explanations for this result. Northerly winds at CSA are largely along shore (Fig. 1), which might generate currents parallel to the beach rather than directly toward the beach. Higher wind speeds also likely increased wave action and turbulence, which might plausibly decrease the ability of cercariae to locate and find a suitable host by continuously changing their orientations to various stimuli (Upatham 1974, Jousson & Bartoli 2000, Fingerut et al., 2003).

The absence of significant effects of current or past temperatures on SI risk in the CSA dataset might be due in part to cercariae drifting in from an off-site source. The highly significant effect of wind direction on SI risk at CSA beach suggests that a large proportion of the cercariae causing SI at this site are drifting in to shore from deeper water via on-shore water currents. If this is true, then local temperatures at CSA beach might have little effect on cercaria production by the most relevant infected snails, which likely reside in offshore beds. *Stagnicola* spp. snails are often found in deeper, colder waters far from shore and are known to migrate in and out of the shallows (Clarke 1981, Correa et al., 2010). It is possible that lake-wide temperature changes, or changes in snail body temperatures due to their migratory movements, might be more relevant to daily cercaria production near the CSA site than the shallow-water temperature data available for this study.

We further investigated the wind speed results by constructing individual binomial mixed effects modes limited to days when the wind came from particular directions. Wind speed had a significant negative effect on the proportion of SI cases when the wind came from the north ($P = 0.00599$; Table 2) and was not significant in all other directions ($P > 0.05$). We noticed that high speed winds (greater than 10 mph) nearly always came from the north, and it is possible that this tendency drove the overall negative effect of wind speed in the primary model (Fig. 2, 3). Since most of the days with higher speed winds had predominantly northerly winds, it seemed possible that speed was confounded with direction, such that northerly winds result in less SI than northeast winds, but northerly winds were also stronger. Furthermore, the negative effect of wind speed from northerly winds was largely driven by two very windy days with few SI cases. This might have led to an appearance of a wind-speed effect, due to the highest-speed winds happening to occur on days with fewer cases.

We separately tested whether SI risk differed between the morning and afternoon sessions of data collection (Fig. 4). The time of day has a significant negative effect on the number of SI cases reported ($P < 0.0001$; Table 1), with afternoon swimmers being less likely to report SI. This might be attributed to light-induced diurnal patterns of cercaria production by host snails (Horak et al., 2015). Some SI-causing cercariae also have a strong attraction to light (Wright 1974) and exposure to light after prolonged darkness (i.e., night) might induce morning production of cercariae by snails that contain nearly full energy stores for more capable host-seeking ability.

Conclusions:

Overall, wind direction was a key predictor of SI risk at CSA beach. On days when winds originated from the northeast, the proportional risk of swimmers contracting SI was significantly increased, likely due to wind-induced surface currents transporting cercariae from offshore *Stagnicola* snail beds. Relatively slow surface currents have been shown to bring cercariae many times further than a cercaria's natural capabilities (Upatham 1974). We also found that while wind speed was a significant predictor in the overall model, the effect was negative, possibly because high-speed winds create more turbulent water that decrease the ability of the cercaria to find and penetrate hosts. This pattern was driven largely by a negative effect of high-speed winds from the North, which was a direction far less associated with high SI risk than northeasterly winds. .

Time of day was also a key predictor of SI risk at CSA beach. Morning swimmers were more at risk for SI than afternoon swimmers. Many factors contribute to SI-causing cercariae shedding from host snails, including increased light (Wright 1974, Horak et al., 2015). Sunrise in the early morning might trigger cercaria shedding from snails, and cercariae may be more effective at attacking hosts at the beginning of their 24- to 48-hour lifespan when they still have full energy reserves.

As with any correlational study, the patterns we detected in this study would need to be further studied to determine if the predictor variables are truly causal. It is also important to note that this analysis was limited to CSA beach, and further study on additional sites would be needed to determine if any of these conclusions are generalizable to other beaches on Crystal Lake or other lakes.

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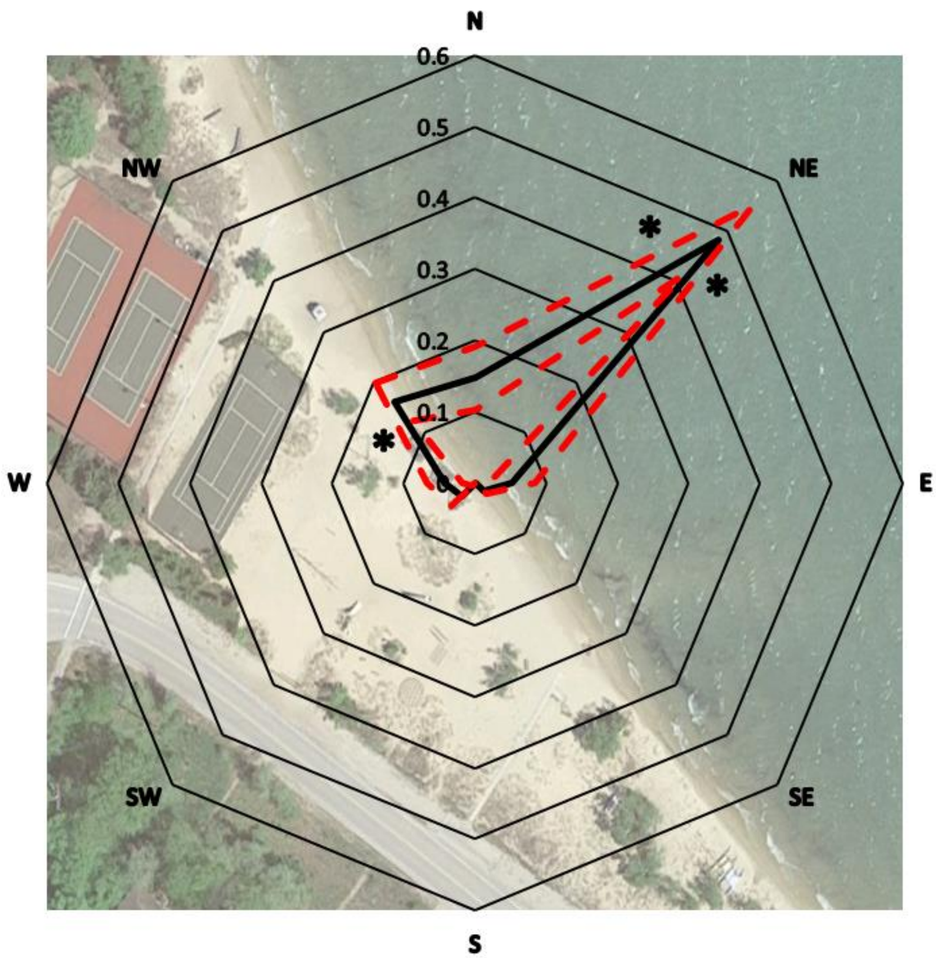

Figure 1: Proportion of positive SI cases associated with wind direction at CSA beach. Solid black line represents the average proportion of SI cases per day (arcsine-square root transformed). Dashed red lines indicate ± 1 Standard Error. Significant differences between adjacent directions are indicated by * ($P_{adj} < 0.05$ after adjusting to control the False Discovery Rate; paired comparisons using the binomial mixed-effects model). CSA beach image © 2017 Google map data, altered by J. Sckrabulis.

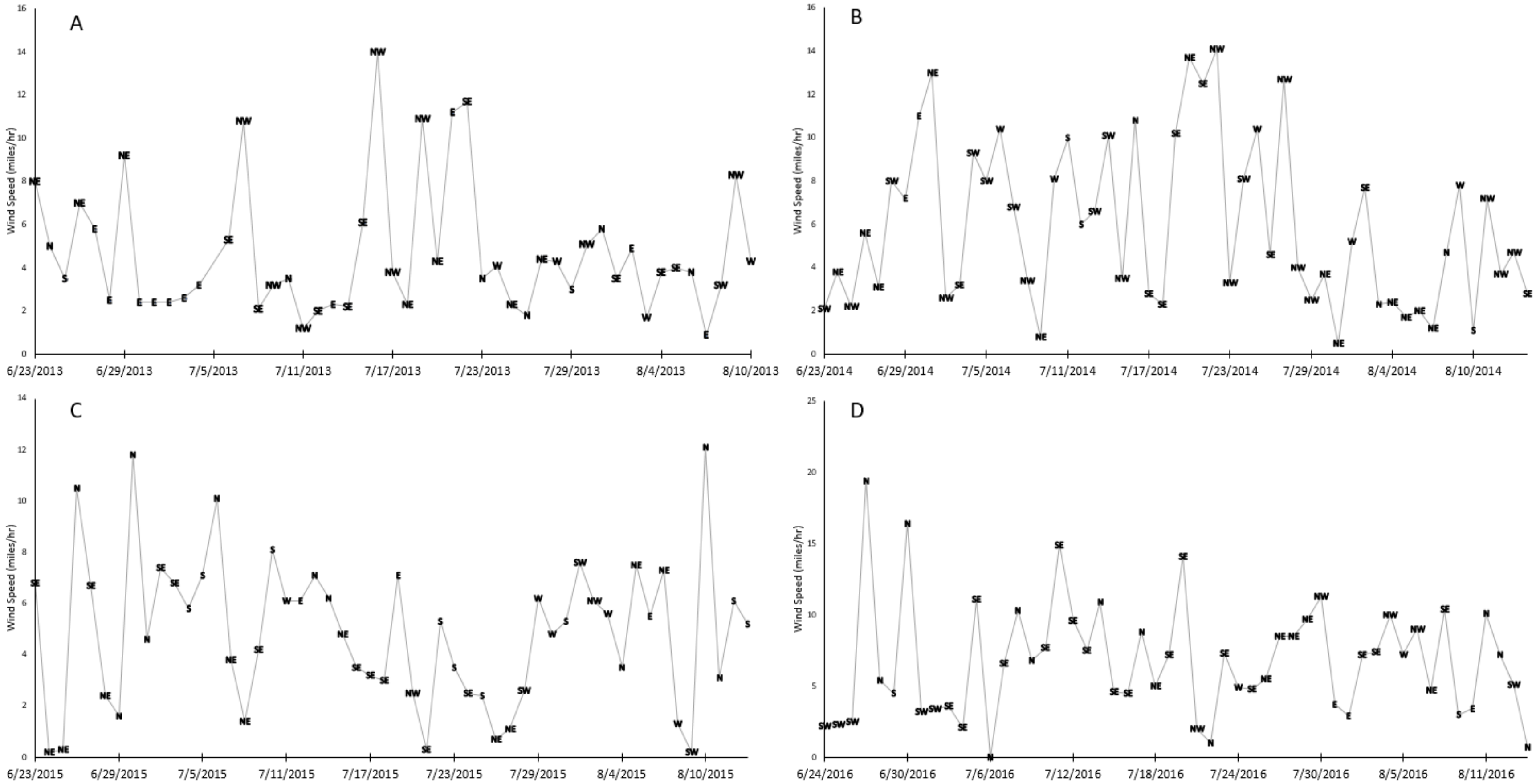

Figure 2: Daily wind speed and direction variation at CSA beach in 2013-2016. Wind direction is indicated by data labels from A) 2013, B) 2014, C) 2015, and D) 2016.

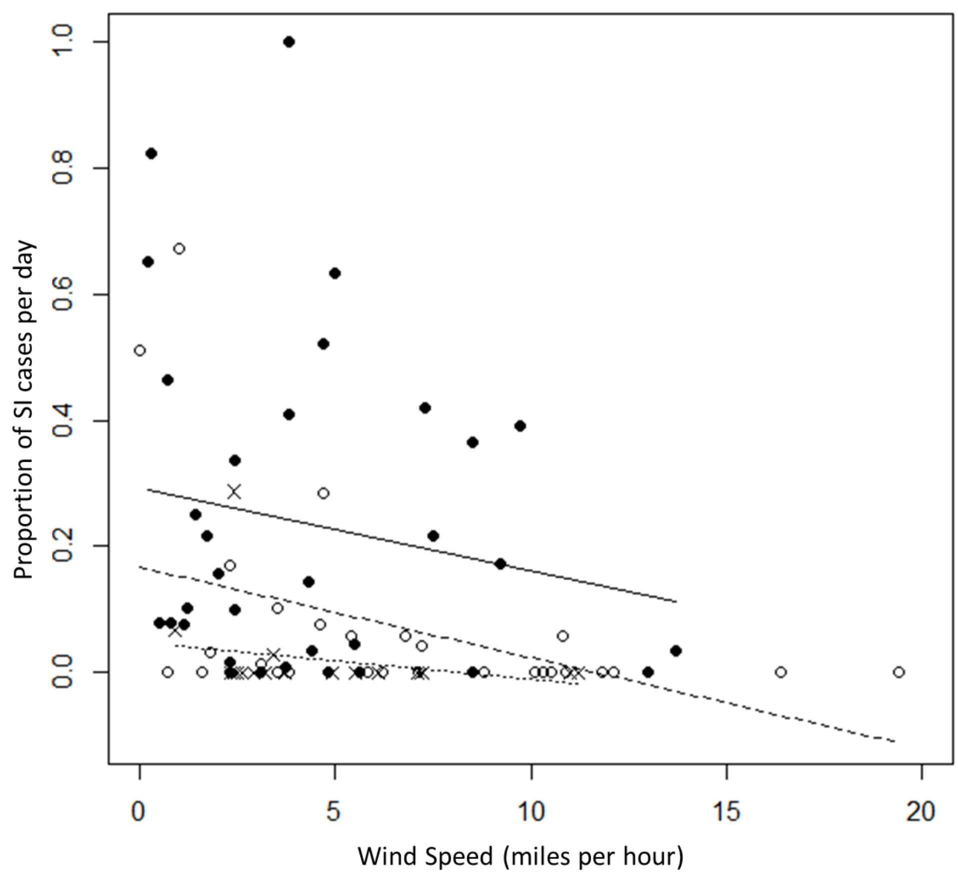

Figure 3: Proportion of SI cases as a function of wind speed, for wind coming from one of three directions: North (open circles; dashed line), Northeast (solid circles; solid line), or East (crosses; dotted line). Lines have been restricted to show model predictions only within obtained data limits.

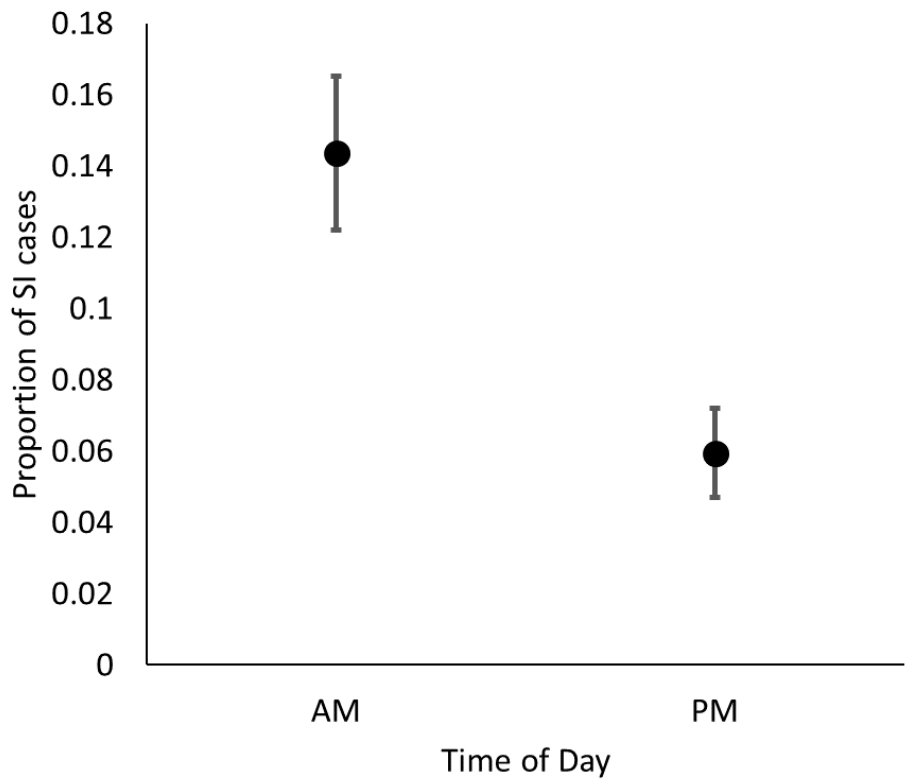

Figure 4: Average proportion of SI cases per day in the morning and afternoon sessions at CSA beach. Error bars represent one SEM.

Table 1: ANOVA statistics of the best fit models for environmental effects and time of day on SI cases

Environmental

Predictors	Coefficient ± SE	χ^2	Df	P value
WindDirGroup1	**NA****	**55.996**	**3**	**< 0.0001***
WindVel	**-0.28 ± 0.08**	**11.510**	**1**	**0.0007***

Time of Day

Predictors	Coefficient ± SE	χ^2	Df	P value
TimeOfDay	**-1.671 ± 0.11**	**226.67**	**1**	**<0.0001***

*Predictor is significant (P < 0.05)

**Categorical predictors are comprised of multiple "dummy variables" and therefore do not have a single meaningful coefficient

Table 2: Binomial generalized linear mixed effects model summary statistics of wind speed effects for each wind direction. The only significant effect of wind speed ($P < 0.05$) is highlighted in bold text.

Direction	Coefficient	Standard Error	P value
E	-2.078	1.771	0.241
N	**-0.412**	**0.1499**	**0.00599**
NE	-0.1413	0.1128	0.2103
NW	-0.2122	0.1812	0.24146
S*	NA*	NA*	NA*
SE	-0.2505	0.2366	0.289713
SW	0.4978	0.7265	0.4932
W	0.2607	0.6618	0.6937

*Model failed to run due to an absence of any swimmer's itch cases on days with southerly winds