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Drought as a climatic driver of an outbreak of diarrhea in Tuvalu, South Pacific

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ABBREVIATIONS

AR	Attack Rate
CI	Confidence Interval
EHC	Effective Harvesting Capacity
ENSO	El Niño Southern Oscillation
L	Liters
lpd	Liters Per Person Per Day
mm	Millimeters
MOH	Tuvalu Ministry of Health
OR	Odds Ratio
PMH	Princess Margaret Hospital
PSSS	Pacific Syndromic Surveillance System
PWD	Tuvalu Public Works Department
SD	Standard Deviation
SOPAC	Secretariat of the Pacific Community’s Applied Geoscience & Technology Division
TMS	Tuvalu Meteorological Service
UN OCHA	United Nations Office for the Coordination of Humanitarian Affairs
WHO	World Health Organization

ABSTRACT

Introduction

Increased rainfall and temperature are well-recognized climatic factors associated with increased rates of diarrhea, yet there is limited information on the role of droughts as the cause of diarrheal outbreaks. In 2011, Funafuti, an island in the Pacific country of Tuvalu, experienced a concurrent severe drought and outbreak of diarrhea. We performed an investigation to identify factors that contributed to epidemic transmission and evaluate the role of interventions in controlling the outbreak.

Methods

We identified cases by performing a review of medical registers in Funafuti (pop. 6,216 inhabitants) during the outbreak period from 29 August 2011 – 16 October 2011. Rainfall data were collected to evaluate the temporal and climatic associations between drought and diarrhea. We performed a case-control study to examine risk factors for diarrhea, interviewed public health officials to identify control measures that were implemented, and assessed the temporal relationship between these interventions and weekly case numbers.

Results

We identified 244 cases of diarrhea during the outbreak period. The overall attack rate was 3.9%, with highest rates (17.5%) occurring in infants with age 0 - 2 years. Peak case numbers occurred during the nadir of recorded rainfall in Tuvalu. Multivariate analyses found that households whose home water tank levels dropped below 20% capacity and that reported decreased hand washing frequency had significantly higher risk (OR 2.31 95% CI [1.16-4.60] and OR 3.00 [1.48-6.08], respectively) of having a member acquire diarrhea. Although drought conditions persisted, weekly case numbers decreased from peak numbers after implementation of a hygiene

promotion and soap distribution campaign.

Conclusion

A severe drought in Tuvalu precipitated a large outbreak of diarrhea due to decreased water availability and personal hygiene. Infants were the age group that was especially vulnerable to drought-associated diarrhea. Interventions that promoted personal hygiene, along with water distribution, appear to have ameliorated the health impact of the drought. These findings highlight the need for contingency planning to address the health impacts of droughts, as they become more frequent and severe occurrences in the Pacific due to climate change.

INTRODUCTION

Climate is a well-recognized cause of elevated rates of diarrhea [1]–[5]. Increased rainfall, either seasonal or in disaster situations, is the climatic factor that has been most widely observed to cause increased risk of diarrhea and epidemics [5]. During periods of heavy rainfall, surface waters are more readily contaminated with human feces than during dryer periods [6]. In addition, heavy rainfall following periods of low rainfall can mobilize contaminants into drinking water sources [7], [8].

However, a less explored phenomenon is the relationship between low rainfall and the risk of diarrheal disease. The association of seasonal periods of low rainfall and higher incidence rates of diarrhea has been observed in a limited number of settings, including the Pacific [1], [9]–[11]. The use of lower quality water for drinking, increased concentration of pathogens in low quantities of stored water, or decreased intensity of hygiene practices have been proposed as mechanisms for increased risk of diarrhea during seasonal periods of low rainfall [12], [13].

There are even fewer reports in the literature that have documented severe decreased rainfall events or droughts as the cause of diarrheal epidemics. Droughts have been reported to be a potential factor in outbreaks of *E. coli* O157 and cholera in Africa [14]–[18]. Only two studies though, have specifically evaluated the role of water access in drought-associated outbreak settings: one in Wales from 1978 and a second in Haiti in 1980 [17], [18]. In the Welsh outbreak, the weekly incidence rate of diarrhea among school children was significantly higher in water-restricted regions than in non-restricted regions. In the Haitian outbreak, higher rates of diarrhea were found among families that had lesser access to water. As a caveat, the Welsh study was only able to monitor this association over two weeks before water access returned to all regions. Furthermore, in the Haitian investigation, the association between water access and drought-related diarrhea was not statistically significant. There is thus a lack of empirical evidence that supports the role of access to safe water, in addition to poorer personal hygiene, in contributing to epidemic transmission of diarrheal disease during droughts.

Tropical Pacific island nations are particularly susceptible to drought, in part due to the El Niño Southern Oscillation (ENSO) cycle, a natural climate event that is characterized by the cyclical warming (El Niño) and cooling (La Niña) of the Pacific Ocean [19]. Such variability has varied effects on global climate patterns and often leads to climate emergencies such as floods, cyclones, and drought [20]. Anthropogenic climate change has and will likely continue to increase the severity of ENSO events [21]. In 2011, a La Niña climate event triggered a severe drought emergency in the South Pacific island nation of Tuvalu. Following three years of decreased rainfall inconsistent with prior patterns, Tuvalu's fresh water reserves reached a nadir from May to November of 2011. In September 2011, the Pacific Syndromic Surveillance System (PSSS) detected a large outbreak of diarrheal illness on the main island of Funafuti [22]. We investigated this epidemic to characterize the key factors that caused a diarrhea epidemic in the context of a drought emergency.

METHODS

Study Site

Tuvalu is a tropical island nation located in the South Pacific Ocean (Fig. 1). It is composed of nine low-lying coral islands and atolls, eight of which are inhabited, with a total population of 10,782 (2012 census) [23]. Funafuti, an atoll with 6216 residents in 2012, is the largest and the most populated of the islands. The largest islet of Funafuti is Fongafale, which contains nearly 97% of the population of Funafuti. Fongafale is geographically divided into seven communities (from South to North): Tekavatoetoe, Vaiaku, Alapi, Senala, Fakaifou, Teone, and Lofeagai (Fig. 1). The average annual temperature of Funafuti is 28°C with minimal variation throughout the year.

Surveillance and Case Finding

The outbreak of diarrheal disease was identified using the World Health Organization Pacific Syndromic Surveillance System (PSSS) [22]. Since mid-November 2010, the PSSS, which serves as an early warning alert system, reports raw weekly case data from Pacific nations of diarrhea, influenza-like-illness, acute fever and rash, and prolonged fever without disaggregation by demographic or other variables. A case of diarrhea was defined as the presence of three loose stools in 24-hours during the outbreak period of 29 August 2011 to 16 October 2011. The outbreak period was defined as when the observed weekly number of diarrhea cases was higher than two standard deviations above the mean number of weekly cases in the PSSS from November 2010 to August 2011. In addition to collecting weekly case counts from PSSS, we identified cases of diarrhea by reviewing outpatient and inpatient records of Princess Margaret Hospital (PMH), which is the sole health care facility in Funafuti. We reviewed outpatient registers that were available for the period from 25 July 2011 – 29 February 2012 and inpatient records that were available from 1 January 2010 – 31 December 2013. We extracted patient age, gender, diagnosis, symptoms, and survival.

Rainfall and Water Usage

We obtained daily 24-hour rainfall records for 2000 - 2013 as well as daily temperature records from 2008-2013 from the Tuvalu Meteorological Service (TMS). The Secretariat of the Pacific Community's Applied Geoscience and Technology Division (SOPAC) 2010 Tuvalu Rainwater Harvesting Survey provided information on the total and residential-specific effective water harvesting capacity (EHC), which refers to the amount of water that can be collected into containers from every millimeter (mm) of rainfall, and the total and residential-specific water storage capacities of Funafuti.

Interventions

We collected information on interventions implemented during the outbreak from unpublished response coordination documents from the United Nations Office for the Coordination of Humanitarian Affairs (UN OCHA) and World Health Organization (WHO). We also obtained information on local control measures that were implemented by performing unstructured interviews with ten governmental officials from the Tuvalu National Disaster Committee, Tuvalu Public Works Department (PWD), Tuvalu Red Cross, Tuvalu Lands Department, UN OCHA, SOPAC, Tuvalu Ministry of Health (MOH), PMH, and the Tuvalu Media Department.

Household Survey

Between 29 May 2014 and 15 July 2014 we conducted a case-control household survey, specifically designed to account for the time lag between the event and the survey by evaluating constant household environmental factors and water-related exposures during the drought. Cases were identified from the outpatient or inpatient hospital records during the outbreak period from 29 August 2011 to 16 October 2011 and were included for selection into the study if they had a known current location in Funafuti. In order to assess current location, a list of the cases in the outbreak was distributed to seven members of the MOH staff. Among traceable cases, we used a random number generator to select a total of 93 cases. Cases were excluded from the study if they resided in the same household as a previously selected case.

Control subjects were systematically sampled by screening every fifth house beginning with a randomly chosen house from the first five northernmost houses of Fongafale. In order to control for the age distribution of the cases, control subjects were frequency matched to the cases by four age groups: less than 1 year, 1 - <5 years, 5 - <15 years, and greater than 15 years. Inclusion criteria for controls included residence on Fongafale in 2011 and the presence of an adult in the household at the time of interview. Households were excluded if subjects reported that a member of the household had diarrhea during the outbreak period or if an adult was not present for an interview after two home visits.

Interviews consisted of questions on household demographic and environmental characteristics such as income and education, location of residence in 2011, and water collection and usage for the drought period as a whole. A specific exposure of interest was the water quantity available to households during the drought and outbreak periods. Since household tanks are divided into fifths by horizontal indentations, we used an ordinal scale of 20% increments to assess water tank reserves.

Analysis

Weekly diarrhea case counts were recorded from the PSSS and converted into monthly records where appropriate in the analysis. We used four age categories from the 2012 census to calculate age-specific attack rates and hospitalization rates: 0-2 years, 3-5 years, 6-15 years, and 16+ years [23]. Data for the outbreak period were analyzed in SAS 9.3 (Cary, NC). All charts were created in Microsoft Excel (Redmond, WA). To estimate the rainfall required to fill storage tanks and sustain a water usage of 50 liters per person per day (lpd) on Funafuti in 2011, we used the following equations. The WHO classifies 50 lpd of water access to be "intermediate access", above which basic sanitation and hygiene practices would be guaranteed [24]. All equations that include storage capacity or EHC were calculated for both total and residential-specific figures.

$$Estimated\ Rainfall\ Needed\ to\ Fill\ Storage\ Tanks = \frac{Storage\ Capacity}{EHC}$$

$$Estimated\ Usage\ Per\ x\ Days = 50\ lpd \times Population \times x\ Days$$

$$Estimated\ Rainfall\ Needed\ to\ Sustain\ 50\ lpd = \frac{Esimated\ Usage\ Per\ x\ Days}{EHC}$$

$$Estimated\ Number\ of\ Days\ Full\ Storage\ Tanks\ Will\ Last = \frac{Storage\ Capacity}{Population \times 50\ lpd}$$

$$\begin{array}{c} Estimated\ Remaining \\ Water\ Reserves \end{array} \begin{array}{l} = Previous\ Reserve\ Amount + (Rainfall \times EHC) - \\ (Estimated\ Usage\ Per\ \boldsymbol{x}\ Days) + Desal\ Production \end{array}$$

We also conducted a correlation analysis between average daily and weekly temperature and diarrhea. Climate analyses were conducted in Microsoft Excel (Redmond, WA). There was no formal analysis performed on the qualitative interviews but the information collected was used to inform the description of the outbreak and interventions that were carried out.

We performed multivariate logistic regression analyses to evaluate the risk association between household characteristics and the presence of a diarrhea case during the outbreak in the case-control investigation. Variables were evaluated for collinearity and collinear variables were removed from the model. Model fit was evaluated by comparing AIC scores. Stratified analyses were attempted for each community but the numbers in some categories were too low to obtain reliable results. A p-value less than 0.05 or a 95% confidence interval that did not include 1 was considered significant. Statistical analyses were performed in SAS 9.3 (Cary, NC). Geo-localization of case and control households, based on 2011 residence, was conducted and spatial-temporal cluster analysis was performed in QGIS, ArcGIS (Redlands, CA), and SatScan (Boston, MA).

Ethical Considerations

Written informed consent was obtained from all study subjects or their legal guardian in the case of children less than 18 years of age. Ethical approval for this study was obtained from the Yale University Human Research Protection Program. As no Institutional Review Board exists in Tuvalu, the Ministry of Health approved the study.

RESULTS

Outbreak Description

The PSSS detected an increase in cases (28) on the week beginning 29 August 2011, which was significantly increased from mean weakly cases (3) from the period of 14 November 2010 to 28 August 2011. The PSSS identified 204 cases of diarrhea during the outbreak period of 29 August 2011 to 16 October 2011. Review of outpatient and inpatient charts identified an additional 40 cases during the same period; thus the total number of cases associated with the outbreak was 244 cases of diarrhea. The outbreak peaked between 11 - 25 September 2011 (53 cases per week). Although the overall attack rate (AR) was 3.9% for the population of Funafuti, the attack rate observed in those aged 0 - 2 years (AR 17.5%) was 11.7 fold higher than that for those over 65 years of age (AR 1.5%) (Table 1).

Cases had a median age of 6 years (range, 0 – 82 years) and 50.8% of the cases were male. Of the 244 patients, 42 (17.2%) also reported vomiting, 8 (3.3%) had a respiratory tract infection, and 7 (2.9%) reported abdominal pain or fever. Twenty-seven cases were hospitalized with a mean hospital stay of 2.5 days (SD ± 2.5). Children aged 0-2 years represented 61.5% of inpatient cases, whereas the same age group represented 32.1% of the outpatient cases. There were no diarrhea-related deaths during the outbreak.

Rainfall and Water Usage

Average rainfall in Tuvalu follows a seasonal pattern with the third week of January on average seeing the highest rainfall (109.5 mm) and the last week of May seeing the lowest (26.8 mm) (Fig. 2). In 2011, after a large downpour in January, the drought persisted from the first week of

February to the beginning of the outbreak on 29 August 2011; all weeks (29) except the last weeks of June and August had an average rainfall of 38.25 mm below the mean (Fig. 2). Furthermore, 20 weeks during the same period had rainfall below 28mm, the figure we calculated would be required per week to sustain a usage of 50 lpd. Monthly rainfall reached a nadir in both July and September when monthly rainfall dropped to 42.5 mm and 38 mm respectively. Notably, monthly rainfall in September 2011 was the lowest monthly rainfall ever observed in Tuvalu's 81 years of climate records. Although temperature fluctuations have previously been correlated with rates of diarrheal illness, there was no significant association in this outbreak [25]–[27].

Funafuti's total and residential specific EHC were 77,547 L/mm and 48,596 L/mm respectively. The total and residential specific storage capacities were 27,247,000 L and 16,962,933 L respectively. We estimated that 351 mm and 349 mm of rainfall would be needed to completely fill the respective total and residential-specific rainfall water storage tanks of Funafuti in 2011. At 50 lpd, full water storage tanks in Funafuti should last 88 days and residential tanks should last 54 days, assuming equal distribution of water. We calculated that total water reserves likely remained above 90% capacity until 2 April 2011 after which the total reserves decreased by an average of 72,716 L/day until the outbreak began on 29 August 2011. When the outbreak period began, total water reserves were estimated to be at 60% total capacity. We furthermore estimated that residential-specific tanks were empty nearly six weeks prior to the onset of the outbreak, from 16 July 2011 to 13 October 2011.

Interventions

Interventions in response to the drought occurred in three phases (Fig. 2). In the first phase, the government implemented a water distribution campaign from July 2011 to September 2011, which initially distributed 90 L per family per day at three distribution centers (Fig. 1) using water produced by a single 45,000 L/day desalinization plant on the island. As more families requested water, distributions decreased to 30 L per family per day by September. In the second phase, the Ministry of Health initiated a household hygiene promotion campaign in September 2011, which provided educational materials on hygiene and sanitation practices, such as the use of boiled water and hand washing, and distributed soap to every household on the island. Furthermore, the Ministry of Health disseminated similar educational information during weekly radio announcements. In the third phase, a relief effort was implemented after an international drought emergency was declared on 28 September 2011. By this date, 90% of cases (219/244) had already occurred and we estimated that total water reserves were at 41% capacity. International agencies delivered a large supply of water (450,000 L) and two desalinization plants that in turn, produced amounts of water such that distributions were again increased to 90 L per family per day at seven distribution points (Fig. 1) throughout October. In addition, relief agencies provided support to the Ministry of Health's efforts to promote hygiene education and distribute hand sanitizers and soap. The third phase continued until 8 November 2011 when sustained rainfall occurred (Fig. 2).

Weekly cases counts dropped sharply (20 cases) in the week following the peak weeks (53 cases) of 11-25 September 2011, after the household hygiene promotion campaign (2nd phase) was implemented and just prior to the initiation of the international relief effort (3rd phase) and subsequent increase in water distribution. Weekly case counts continued to decrease such that by 16 October 2011, the number of weekly cases was below expected numbers, based on pre-epidemic surveillance data.

Household Survey

Among the 93 selected index cases of diarrhea, we enrolled 75 (80.6%) and their households for the case-control investigation. Among selected index cases who were not enrolled, 17 had moved to another island and one had died. Among the 168 selected index control subjects, 141 (83.9%) and their households were enrolled into the study; index control subjects who were not enrolled included 21 who were excluded due to lack of a subject in an eligible age category and six who could not be located at their residence after two interview attempts. There were no significant differences between index cases and age group frequency-matched control subjects with respect to their median age or age category (Table 2). We did not identify significant differences between index cases and control subjects with respect to gender or occupation. Additionally, we did not identify significant differences between case and control households with respect to their household income and other indicators of socio-economic status, total household water storage capacity, boiling practices, or distance to water distribution point.

A significantly higher proportion of case households reported that their tank levels were <20% full (53% vs 43%, $p<0.01$) and that they had decreased the frequency of hand washing (49% vs 21%, $p<0.01$) compared with control households during the drought (Table 2). Using a backwards elimination strategy, the final multivariate regression model included having a low tank, community of residence, household income, ownership of livestock, total household tank volume capacity, and decreased frequency of hand washing during the drought. Multivariate analyses found that households that reported tank levels <20% full during the drought had more than two times higher risk (OR 2.3, [95% CI 1.2 - 4.6]) of having a member acquire diarrhea (Table 3). Reported decrease in the frequency of hand washing was an independent risk factor (OR 3.0 [95% CI 1.5 - 6.1]) for a household having a case of diarrhea during the drought. Although there were differences between the distribution of case and control households among the communities on the island in univariate analyses (Table 2), residence in a community was not found to be an independent predictor of household risk of having a diarrhea case.

DISCUSSION

Our investigation found that a severe drought on Funafuti, Tuvalu in 2011 led to an outbreak of diarrheal illness in September 2011 due to low home water tank availability, which likely decreased the frequency of hand washing. Infants were particularly at risk of acquiring drought-associated diarrhea. By estimating the quantity of rainfall that is required to maintain standard guidelines for minimum water access and appropriate hygiene and sanitation, we found that decreases in weekly rainfall below that required to sustain 50 lpd preceded the epidemic by 20 weeks. Finally, we found that decreases in weekly case counts of diarrhea preceded the large international relief effort, indicating that local interventions that promoted personal hygiene and subsequent behavioral changes in the population attenuated the impact of the diarrhea epidemic. Although the evaluation of rainfall, water access, and diarrhea risk is limited to this single outbreak, this approach may be generalizable to evaluating the risk of drought-associated epidemics of diarrhea in other island nations in the Pacific that are affected by similar severe climatic events and water shortages.

Previous literature suggests that low rainfall can increase diarrhea transmission through three main pathways: the population increasingly accesses poorer quality and less sanitary sources of water, the concentration of pathogens is higher in depleted storage tanks, and people decrease the frequency of hygiene practices such as regular hand washing [1], [12], [15]. Our findings indicate that decreased intensity of basic hygiene, rather than the use of contaminated sources or the lack of access to water distribution, was associated with higher risk for diarrhea during the drought. Funafuti does not have fresh groundwater meaning that the only alternative source of water during the drought was government water distributions. The Tuvalu Public Works

Department reported that water for distribution was tested for pathogens daily and that no contamination was discovered. Furthermore, the case-control investigation did not identify significant risk associations with distance of the household to a water distribution point. We also believe it unlikely that contaminated home water tanks were the primary driver of disease. Although there was a small increase in rainfall in the week prior to the onset of epidemic diarrhea (Fig. 2), which could explain disease through the phenomenon of rainfall following dry periods washing accumulated contaminants such as bird feces into water tanks, we saw a similar increase in rainfall at the end of October, following the driest month of September, without a subsequently observed increase in diarrhea [28]. Furthermore, in our survey, nearly all households reported boiling drinking water prior to consumption, even during the drought, which likely would have obviated such a risk if it had occurred (Table 2).

Our findings thus indicate that decreased hygiene practices, such as hand washing, influenced the epidemic transmission of diarrhea. July and September 2011 both saw rainfall levels far below what is required to sustain the provision of 50 lpd for Funafuti [24]. Furthermore, the significant associations seen in the household survey provide evidence to support this transmission mechanism; low tank level and decreased frequency of hand washing during the drought were both significant independent predictors of disease status. It is unclear though whether this decrease in hygiene practices was due to a real or a perceived lack of water.

The provision of quantity, not necessarily quality, of water was key to the response to this outbreak, as has been identified for mitigating diarrheal illness in previous studies unrelated to drought conditions [29]. When rainfall was at its second lowest in July 2011, the PWD was initiating its water distribution campaign. During this time, reserves were higher and demand was lower, enabling the PWD to provide 90 L of water per family per day. This extra supply of water earlier in the drought likely kept the risk of disease lower. However, when the same low rainfall trend occurred in the outbreak month of September 2011, the PWD reserves were near their lowest when demand was highest, causing a decrease in water distribution to just 30 L per family per day. The observed decrease in weekly case counts prior to the international relief interventions indicates that local control measures, such as hygiene and sanitation promotion and water distribution, albeit limited, ameliorated the overall impact of the epidemic. Furthermore, behavioral modifications in the population's hygiene and sanitation practices may also have had a large contributory effect in preventing diarrhea transmission. The arrival of international aid efforts after the peak of the outbreak indicates that those interventions played a lesser role in stopping the outbreak of diarrhea. However these later interventions likely contributed to maintaining sharp decreases in diarrhea rates until the return of rainfall in November 2011.

The results of this study are though, subject to several limitations. First given the time lag between the event and the data collection, some questions are liable to recall bias. In addition, as our questions pertained to hygiene practices, a social-desirability bias could be present. Nevertheless, we attempted to ask questions by evaluating objective measures of household characteristics and environment. Secondly, our frequency matching of age groups was for the entire island, not within villages. There are differences in the distribution of age category between the northernmost and southernmost communities, which may impact the associations between communities and diarrhea disease risk that we observed (Table 2). Finally, Tuvalu lacks the ability to culture pathogens, making identification of a specific etiology impossible.

Nevertheless, we believe that our analysis is still relevant to controlling future diarrhea outbreaks.

As one of the first studies to address drought and acute outbreaks of diarrhea, this study’s conclusions have implications for extreme drought events in the Pacific and abroad. Tokelau (pop. 1411), a New Zealand island territory 1000 km east from Tuvalu, declared a drought emergency on 3 October 2011 and faced a similar outbreak of diarrhea (50 cases) peaking in September 2011 [22], [30]. This outbreak was also detected using the PSSS. The coincident temporality of the droughts in Tuvalu and Tokelau and the subsequent independent outbreaks in locations with no direct travel between them provides additional evidence for a link between drought and diarrhea outbreaks in the Pacific and further illustrates the potential disease outcomes of weather emergencies. With the escalation of global climate change, understanding these health consequences of climate events is paramount. Evidence is building to support a link between climate change and increased volatility in ENSO [31]. Furthermore, the cyclical nature of ENSO indicates that irrespective of the effects of climate change, such events are likely to occur again. Droughts are predicted to become more severe in Tuvalu and the central Pacific [32], [33]. Other parts of the world are also predicted to face more severe and more frequent droughts [33], [34]. Without proper contingency planning, we might expect diarrhea outbreaks to become more recurring and more dangerous in similarly water-insecure areas.

Investments in resilient water supply infrastructure, particularly in the Pacific islands, need to be prioritized for the prevention of diarrhea. Although Tuvalu has since added three new desalination plants, all three were broken down as of August 2014. Reliance on foreign aid for funding parts and maintenance poses a major challenge to providing a sufficient amount of water, particularly during drought emergencies. Such water distribution and hygiene promotion practices could be the key measures for the mitigation of diarrheal epidemics during similar emergencies in our changing future.

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REFERENCES

[1] D. Bhavnani, J. E. Goldstick, W. Cevallos, G. Trueba, and J. N. S. Eisenberg, "Impact of rainfall on diarrheal disease risk associated with unimproved water and sanitation.," *Am. J. Trop. Med. Hyg.*, vol. 90, no. 4, pp. 705–11, Apr. 2014.

[2] Y. Zhang, P. Bi, and J. E. Hiller, "Climate variations and Salmonella infection in Australian subtropical and tropical regions.," *Sci. Total Environ.*, vol. 408, no. 3, pp. 524–30, Jan. 2010.

[3] R. Reyburn, D. R. Kim, M. Emch, A. Khatib, L. von Seidlein, and M. Ali, "Climate variability and the outbreaks of cholera in Zanzibar, East Africa: a time series analysis.," *Am. J. Trop. Med. Hyg.*, vol. 84, no. 6, pp. 862–9, Jun. 2011.

[4] L. McIver, A. Woodward, S. Davies, T. Tibwe, and S. Iddings, "Assessment of the health impacts of climate change in Kiribati.," *Int. J. Environ. Res. Public Health*, vol. 11, no. 5, pp. 5224–40, May 2014.

[5] K. F. Cann, D. R. Thomas, R. L. Salmon, A. P. Wyn-Jones, and D. Kay, "Extreme water-related weather events and waterborne disease.," *Epidemiol. Infect.*, vol. 141, no. 4, pp. 671–86, Apr. 2013.

[6] K. Levy, A. E. Hubbard, K. L. Nelson, and J. N. S. Eisenberg, "Drivers of water quality variability in northern coastal Ecuador.," *Environ. Sci. Technol.*, vol. 43, no. 6, pp. 1788–97, Mar. 2009.

[7] E. J. Carlton, J. N. S. Eisenberg, J. Goldstick, W. Cevallos, J. Trostle, and K. Levy, "Heavy rainfall events and diarrhea incidence: the role of social and environmental factors.," *Am. J. Epidemiol.*, vol. 179, no. 3, pp. 344–52, Feb. 2014.

[8] J. T. Watson, M. Gayer, and M. A. Connolly, "Epidemics after natural disasters.," *Emerg. Infect. Dis.*, vol. 13, no. 1, pp. 1–5, Jan. 2007.

[9] M. Hashizume, B. Armstrong, S. Hajat, Y. Wagatsuma, A. S. G. Faruque, T. Hayashi, and D. A. Sack, "Association between climate variability and hospital visits for non-cholera diarrhoea in Bangladesh: effects and vulnerable groups.," *Int. J. Epidemiol.*, vol. 36, no. 5, pp. 1030–7, Oct. 2007.

[10] M. Vargas, J. Gascon, C. Casalds, D. Schellenberg, H. Urassa, E. Kahigwa, J. Ruiz, and J. Vila, "Etiology of Diarrhea in Children Less Than Five Years of Age in Ifakara, Tanzania," *Am J Trop Med Hyg*, vol. 70, no. 5, pp. 536–539, May 2004.

[11] R. B. Singh, S. Hales, N. de Wet, R. Raj, M. Hearnden, and P. Weinstein, "The influence of climate variation and change on diarrheal disease in the Pacific Islands.," *Environ. Health Perspect.*, vol. 109, no. 2, pp. 155–9, Feb. 2001.

[12] E. Moors, T. Singh, C. Siderius, S. Balakrishnan, and A. Mishra, “Climate change and waterborne diarrhoea in northern India: impacts and adaptation strategies.,” *Sci. Total Environ.*, vol. 468–469 Su, pp. S139–51, Dec. 2013.

[13] C. Stanke, M. Kerac, C. Prudhomme, J. Medlock, and V. Murray, “Health effects of drought: a systematic review of the evidence.,” *PLoS Curr.*, vol. 5, Jan. 2013.

[14] P. Effler, M. Isaäcson, L. Arntzen, R. Heenan, P. Canter, T. Barrett, L. Lee, C. Mambo, W. Levine, A. Zaidi, and P. M. Griffin, “Factors Contributing to the Emergence of Escherichia coli O157 in Africa,” *Emerg. Infect. Dis.*, vol. 7, no. 5, pp. 812–819, Oct. 2001.

[15] R. V Tauxe, S. D. Holmberg, A. Dodin, J. V Wells, and P. A. Blake, “Epidemic cholera in Mali: high mortality and multiple routes of transmission in a famine area.,” *Epidemiol. Infect.*, vol. 100, no. 2, pp. 279–89, Apr. 1988.

[16] M. Bradley, R. Shakespeare, A. Ruwende, M. E. Woolhouse, E. Mason, and A. Munatsi, “Epidemiological features of epidemic cholera (El Tor) in Zimbabwe.,” *Trans. R. Soc. Trop. Med. Hyg.*, vol. 90, no. 4, pp. 378–82, Jan. .

[17] M. L. Burr, A. R. Davis, and A. G. Zbijowski, “Diarrhoea and the drought.,” *Public Health*, vol. 92, no. 2, pp. 86–7, Mar. 1978.

[18] S. B. Thacker, S. I. Music, R. A. Pollard, G. Berggren, C. Boulos, T. Nagy, M. Brutus, M. Pamphile, R. O. Ferdinand, and V. R. Joseph, “Acute water shortage and health problems in Haiti.,” *Lancet*, vol. 1, no. 8166, pp. 471–3, Mar. 1980.

[19] C. F. Ropelewski and M. S. Halpert, “Global and Regional Scale Precipitation Patterns Associated with the El Niño/Southern Oscillation,” *Mon. Weather Rev.*, vol. 115, no. 8, pp. 1606–1626, Aug. 1987.

[20] M. Dilley and B. N. Heyman, “ENSO and Disaster: Droughts, Floods and El Niño/Southern Oscillation Warm Events,” *Disasters*, vol. 19, no. 3, pp. 181–193, Sep. 1995.

[21] J. L. Gergis and A. M. Fowler, “A history of ENSO events since A.D. 1525: implications for future climate change,” *Clim. Change*, vol. 92, no. 3–4, pp. 343–387, Oct. 2008.

[22] J. L. Kool, B. Paterson, B. I. Pavlin, D. Durrheim, J. Musto, and A. Kolbe, “Pacific-wide simplified syndromic surveillance for early warning of outbreaks.,” *Glob. Public Health*, vol. 7, no. 7, pp. 670–81, Jan. 2012.

[23] “Tuvalu Statistics.” [Online]. Available: http://www.spc.int/prism/tuvalu/. [Accessed: 03-Apr-2015].

[24] G. Howard and J. Bartram, “Domestic Water Quantity , Service Level and Health,” 2003.

[25] W. Checkley, L. D. Epstein, R. H. Gilman, D. Figueroa, R. I. Cama, J. A. Patz, and R. E. Black, “Effects of EI Niño and ambient temperature on hospital admissions for diarrhoeal diseases in Peruvian children,” *Lancet*, vol. 355, no. 9202, pp. 442–450, Feb. 2000.

[26] P. R. Hunter, “Climate change and waterborne and vector-borne disease,” *J. Appl. Microbiol.*, vol. 94, no. s1, pp. 37–46, May 2003.

[27] R. M. D’Souza, G. Hall, and N. G. Becker, “Climatic factors associated with hospitalizations for rotavirus diarrhoea in children under 5 years of age,” *Epidemiol. Infect.*, vol. 136, no. 01, pp. 56–64, Mar. 2007.

[28] W. Ahmed, L. Hodgers, J. P. S. Sidhu, and S. Toze, “Fecal Indicators and Zoonotic Pathogens in Household Drinking Water Taps Fed from Rainwater Tanks in Southeast Queensland, Australia,” *Appl. Environ. Microbiol.*, vol. 78, no. 1, pp. 219–226, Oct. 2011.

[29] S. A. Esrey, R. G. Feachem, and J. M. Hughes, “Interventions for the control of diarrhoeal diseases among young children: improving water supplies and excreta disposal facilities.,” *Bull. World Health Organ.*, vol. 63, no. 4, pp. 757–72, Jan. 1985.

[30] “Final count for 2011 Tokelau Census of Population and Dwellings.” [Online]. Available: http://stats.govt.nz/browse_for_stats/people_and_communities/pacific_peoples/2011-tokelau-census-landing-page/final-count-2011-tokelau-census.aspx. [Accessed: 30-Apr-2015].

[31] K. M. Cobb, N. Westphal, H. R. Sayani, J. T. Watson, E. Di Lorenzo, H. Cheng, R. L. Edwards, and C. D. Charles, “Highly variable El Niño-Southern Oscillation throughout the Holocene.,” *Science*, vol. 339, no. 6115, pp. 67–70, Jan. 2013.

[32] “Climate Variability, Extremes and Change in the Western Tropical Pacific 2014 Report | Pacific Climate Change Science.” [Online]. Available: http://www.pacificclimatechangescience.org/publications/reports/climate-variability-extremes-and-change-in-the-western-tropical-pacific-2014/. [Accessed: 05-Apr-2015].

[33] A. Dai, “Drought under global warming: a review,” *Wiley Interdiscip. Rev. Clim. Chang.*, vol. 2, no. 1, pp. 45–65, Jan. 2011.

[34] G. S. Mimura, N., L.A. Nurse, R.F. McLean, J. Agard, P. Briguglio, R. Lefale, R. Payet, “16: Small islands,” in *Climate Change 2007: Impacts, Adaptation and Vulnerability Contribution of Working Group II in the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. [Parry, M., O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson (*, 2007, pp. 687–716.

Table 1: Age-Specific Attack Rates and Hospitalization Rates during the Drought-Associated Outbreak

Age Group (years)	Population	No. Cases (% of total)	Attack Rate[a]	Hospitalized[b]	Hospitalization Rate[a]
Total	6216	244 (100%)	3.93	27	0.43
0-2	480	84 (35.29%)	17.50	16	3.33
3-5	459	33 (13.87%)	7.19	2	0.44
6-15	1104	64 (26.89%)	5.80	1	0.09
16+	4173	57 (23.36%)	1.37	7	0.17

[a] Rates expressed per 100 people

[b] Mean hospital stay was 2.5 days.

Table 2: Characteristics of Index Case and Control Subjects and their Households[a]

Characteristics	**Cases** N=75	**Controls** N=141	P[b]
	No. (%) or Mean ± SD		
Index subjects			
Mean age (years)	15.6 ± 19.8	14.8 ± 18.1	NS
Age group[c]			NS
0-2 years	27 (36.0)	36 (25.5)	
3-5 years	6 (8.0)	27 (19.2)	
6-15 years	21 (28.0)	39 (27.7)	
16+ years	21 (28.0)	39 (27.7)	
Male	37 (49.3)	65 (46.1)	NS
Occupation			NS
None	31 (41.3)	53 (37.6)	
Student	28 (37.3)	63 (44.7)	
Government	11 (14.7)	10 (7.09)	
Private Sector	4 (5.3)	11 (7.8)	
Clergy	1 (1.3)	4 (2.8)	
Households			
Community			*
Tekavatoetoe	12 (16.0)	11 (7.8)	
Vaiaku	12 (16.0)	18 (12.8)	
Senala	14 (18.7)	20 (14.2)	
Alapi	10 (13.3)	31 (22.0)	
Fakaifou	22 (29.3)	31 (22.0)	
Teone	1 (1.3)	10 (7.1)	
Lofeagai	4 (5.3)	20 (14.2)	
Household members	8.3 ± 4.2	7.6 ± 4.0	NS
Household income[d]	432.2 ± 388.9	491.4 ± 397.5	NS
Highest education level[e]			NS
Primary	4 (5.4)	17 (12.1)	
Secondary	22 (29.7)	41 (29.3)	
Tertiary	48 (64.9)	82 (58.6)	
Distance to water distribution point[f]	457.62 ± 627.96	710.78 ± 1036.85	NS
Tank storage capacity (L)	29722.7 ± 32700.9	26650.4 ± 21765.5	NS
Always boiled drinking water	74 (98.7)	133 (94.3)	NS
Tank levels less than 20% full	40 (53.3)	49 (34.8)	**
Reported decreased frequency of hand washing	36 (48.7)	29 (20.6)	**
Livestock Ownership	60 (80.0)	125 (88.7)	NS

[a] Numbers may not sum to total due to missing data, and percentages may not sum to 100% due to rounding.

[b] NS= P > 0.05;*=P ≤ 0.05; **=P ≤ 0.01; ****=P ≤ 0.0001

[c] Controls were matched to cases by age category.

[d] Household income in Australian Dollars per fortnight for the household in 2011.
[e] This represents the highest level of education attained by anyone living in the household in 2011.
[f] Mean distance in meters to a water distribution point prior to 3 October 2011. Case figure is based on a subset analysis of those who became ill prior to 3 October 2011. P-value is based on a Wilcoxon Rank-Sum Test.

Table 3: Multivariate analysis of risk factors for diarrhea during the drought

Risk Factor	OR[a]	95% CI[b]	P[c]
Tank levels <20% full	2.31	1.16-4.60	*
Livestock ownership	0.43	0.16-1.12	NS
Reported decreased frequency of hand washing	3.00	1.48-6.08	**

[a] OR = odds ratio
[b] CI = confidence interval
[c] NS= $P > 0.05$;*=$P \leq 0.05$; **=$P \leq 0.01$

Figure 1: Map of Fongafale, showing Emergency Water Distribution Points during the Drought

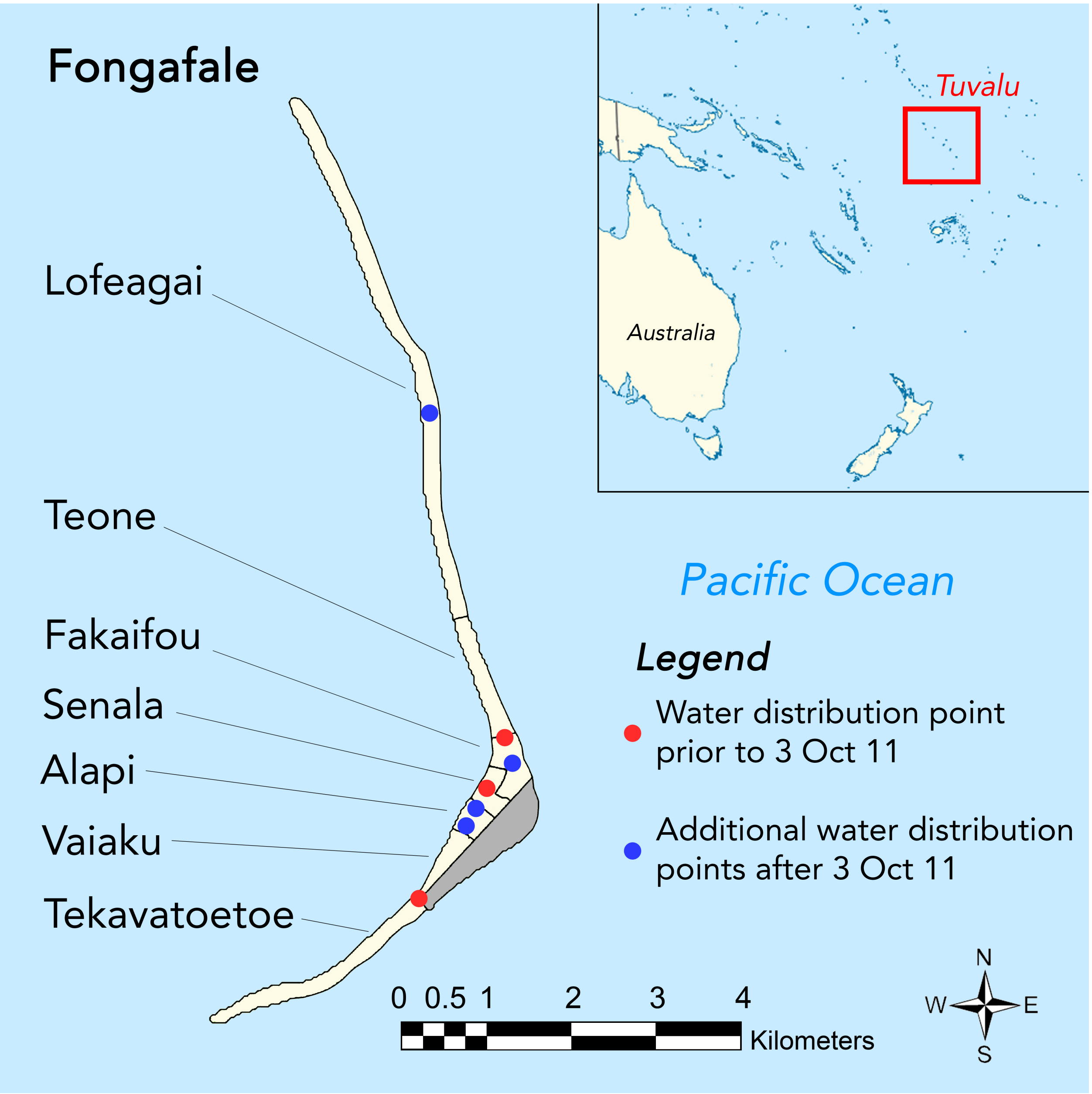

Figure 2: Weekly Rainfall, Diarrhea Case Counts, and Emergency Interventions during the Drought-Associated Outbreak of Diarrhea on Fongafale, 2011