The Influence of Climate Variation and Change on Diarrheal Disease in the Pacific Islands

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Freshwater resources are a high-priority issue in the Pacific region. Water shortage is a serious problem in many small island states, and many depend heavily on rainwater as the source of their water. Lack of safe water supplies is an important factor in diarrheal illness. There have been no previous studies looking specifically at the relationship between climate variability and diarrhea in the Pacific region. We carried out two related studies to explore the potential relationship between climate variability and the incidence of diarrhea in the Pacific Islands. In the first study, we examined the average annual rates of diarrhea in adults, as well as temperature and water availability from 1986 to 1994 for 18 Pacific Island countries. There was a positive association between annual average temperature and the rate of diarrhea reports, and a negative association between water availability and diarrhea rates. In the second study, we examined diarrhea notifications in Fiji in relation to estimates of temperature and rainfall, using Poisson regression analysis of monthly data for 1978–1998. There were positive associations between diarrhea reports and temperature and between diarrhea reports and extremes of rainfall. These results are consistent with previous research and suggest that global climate change is likely to exacerbate diarrheal illness in many Pacific Island countries. *Key words:* climate change, diarrheal disease, epidemiology, Pacific islands, rainfall, temperature, water resources. *Environ Health Perspect* 109:155–159 (2001). [Online 24 January 2001]
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Freshwater is a renewable but finite resource. The scale of its development and use therefore must not exceed certain limits if the ecologic balance is to be maintained (*1*). These limits are generally determined by the rates of recovery—that is, both the regenerative rate of the hydrologic cycle as well as the assimilative capacities of receiving water bodies (*2*). The main principles for the sustainable development of the water resources are that the rate of extraction from both ground and surface water resources should not exceed the rate at which the resource is renewed and extraction must not seriously compromise the health and biodiversity of the ecosystem (*2–4*). For example, the extraction of surface water upstream should not affect water quality and biodiversity of river ecosystems downstream.

According to the Intergovernmental Panel for Climate Change (IPCC), in almost all countries in Asia and the Pacific, there have been growing environmental problems due to unsustainable use and development of water resources (*3*). Water pollution has become a major environmental problem, and excessive use of groundwater is adversely affecting the availability of safe drinking water in some countries. The IPCC stresses the vulnerability of small islands to increasing amplitudes and frequency of high tides, greater wave damage, and intrusion of salt water into the islands' underground freshwater lens (*3*). On high islands, changes in rainfall patterns either from interannual variations due to El Niño Southern Oscillation (ENSO) or a changed climate regime have caused severe shortages of water (*3–5*).

Sea level rise is a significant climate-related change anticipated to affect small islands, especially in low-lying island states and atolls such as Tokelau, Kiribati, Tuvalu, and the Marshall Islands (*5*).

Because of these problems, management of drinking water resources is a high priority in the region (*4*). In many island countries, the differential between wet and dry season rainfall is in the order of 80:20%. Consequently, small islands often have serious water shortages in the dry season. The total volume of rainfall on small atolls is low, and most of it is lost through evapotranspiration and runoff. Although many high islands have high rainfall, they are mostly volcanic and seldom have the geomorphology necessary for good water retention. Flash flooding is frequently a problem, and water discharges rapidly into the sea without having been used beneficially. On atoll islands, which are mostly low lying, there are very limited possibilities for large-scale surface storage.

Collectively, the Pacific Island countries (PICs) use a wide range of technologies to provide water, and in many PICs there are frequent periods of insufficient water to meet population needs (*1,3,4*). Marshall Islanders use rainwater collected from the international airport runway, as well as groundwater and desalinated seawater. Rivers, springs, and drilled wells are used for the water supply to Honiara in the Solomon Islands (*5*). South Tarawa, in Kiribati, obtains much of its freshwater from the Bonriki groundwater lens, whereas Funafuti in Tuvalu relies almost entirely on roof catchment and storage of rainwater. Nauru has previously imported water but is now largely dependent on desalination. Many of the small island countries do not have the capacity, funds, or resources necessary for the explorations, assessment, planning, and development that are required to solve water supply problems. In a number of islands, demand for water already exceeds its availability, and decisions have to be made regarding the allocation of water among various sectors (*4*).

Volcanic rocks of the high islands form "perched" (elevated) aquifers, which are small and have limited yields. Acquifers are of three main types: *a*) freshwater lenses (and aquifers that occur in low-lying, sandy coastal plains which are similar to lenses); *b*) perched aquifers, which occur within the volcanic islands at different levels (these are small and have limited yields); and *c*) basal (deep level) groundwater under the volcanic center of a high island, which is difficult to detect and very costly to exploit.

In the few cases where suitably porous rocks do occur, deep drilling is needed to reach groundwater (*4*). Close to the shoreline where groundwater can be found at shallow depths, there is a considerable risk of intrusion of seawater. On coral atoll islands, groundwater may be present in thin, lens-shaped bodies, which are easily degraded or salinated by excessive abstraction of freshwater, saltwater intrusion, overtopping of waves, and during droughts (*2,4,5*). Additionally, being so close to the ground surface, such water is easily contaminated by human and industrial wastes. With little surface storage and limited groundwater reserves, small islands are more vulnerable to the effects of droughts and rainfall variability than larger countries (*6*). Because of the factors listed above, there are many difficulties in small

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islands associated with providing a secure supply of water to meet domestic, commercial, agricultural, and industrial requirements (*7,8*).

El Niño and Communicable Diseases

The El Niño phenomenon has raised awareness of the potential effects of climate variability on health and disease transmission (*9, 10*). El Niño has been linked to outbreaks of malaria (*11,12*), cholera (*13*), dengue fever (*14,15*), and other emerging infectious diseases (*16*).

Several recent papers discuss the effects of El Niño on diarrheal diseases. Salazar-Lindo et al. (*17*) reported a marked increase in the number of cases of diarrhea and dehydration in infants and young children in Lima, Peru, during an El Niño event, and Checkley et al. (*18*) described the effects of El Niño and ambient temperature on children admitted to the hospital with diarrheal diseases. A 2-fold increase in hospital admissions was evident during the winter of 1997–1998, suggesting that El Niño had an effect on hospital admissions for diarrhea which was far greater than that explained by seasonal temperature changes. Finally, in Fiji, the 1997–1998 El Niño event resulted in a complete failure of the wet season, and many areas experienced the driest 10 months on record (*19*). This drought was associated with an increase in reported cases of infantile diarrhea, and during the first 3 months of 1998 the case numbers of infantile diarrhea were markedly increased above the mean monthly totals for the preceding 5-year period (*20*).

The above authors suggested a clear relationship between climate variability and rates of diarrhea, but based their interpretation on single regional climatic events. To study this relationship on broader geographic and temporal scales, we examined average annual reports of diarrhea in adults for 18 PICs in relation to estimated temperature and potential water availability, as well as gross national product (GNP). We also performed a time–series analysis of infant diarrhea reports in Fiji in relation to temperature and rainfall.

Methods

Cross-sectional study. Reports of diarrhea in children and adults were obtained from the South Pacific Epidemiological and Health Information Service (*21*). Diarrhea cases per month were recorded, but no information about the causative agent was available. Population statistics were obtained from the Secretariat of the Pacific Community (*22*). Land area and precipitation rates were obtained from the International Research Institute for climate prediction (IRI). Information on the geology, geography, and GNP of the Pacific Islands was obtained from various regional and global sources (*3, 23–25*). Scatter plots were made of the average annual diarrhea rates, GNP, temperature, and water availability for 1986–1994. Pearson correlation coefficients were calculated. Finally, multivariate linear regression analyses were attempted.

The null hypotheses were that there are no statistically significant associations between the rate of diarrhea reported and average temperature, potential water availability, or GNP among 18 Pacific islands.

Time–series study in Fiji. Monthly reports of diarrhea in infants for the years 1978–1998 were obtained from the Secretariat of the Pacific Community and Fiji Ministry of Health. Data for 1990 and 1991 were entirely missing, and these years could therefore not be analyzed. In the remaining data, about 5% missing values were estimated by imputation based on seasonal patterns. We used Poisson regression to analyze data for the years 1978–1989. Long-term trends were modeled using a dummy variable. Seasonal patterns were modeled using sinusoidal wave functions:

$$\alpha \sin(2\pi tk/12) + \beta \cos(2\pi tk/12), \qquad [1]$$

where α and β are determined as regression coefficients, t is the month, and k represents the number of months between major seasonal peaks (*26*).

Temperature and rainfall data were obtained from the IRI. The INGRID World Wide Web interface (*27*) was used to access the gridded National Center for Atmospheric Research/National Centers for Environmental Prediction (NCAR/NCEP) reanalysis data set (*28*).

A smoothed scatter plot of the number of diarrhea reports against rainfall suggested that diarrhea reports increased with both high and low extremes of rainfall (Figure 1). Rainfall was therefore recoded using two dummy variables to indicate departure above and below the median value of 5×10^{-5} kg/m^2/min. The effect of 1-month lag variables for temperature and rainfall were tested.

Finally, the regression model based on 1978–1989 data, together with climate data for 1993–1998, were used to generate predictions of diarrhea reports from 1993 to 1998.

Results

Cross-sectional study. Figure 2 shows the relationship between the annual average temperatures and the reporting rates for diarrhea in the Pacific islands from 1986 to 1994. There was a positive association between the annual average temperature and the rate of diarrhea.

New Caledonia, with an average annual temperature of approximately 25°C, reported 15 cases per 1,000 population per year, while Tokelau, with an average annual temperature of 29°C, reported approximately 215 cases per 1,000 population per year. The low islands generally showed a higher diarrhea rate, the exceptions being Nauru and Niue.

Figure 3 shows the relationship between potential annual water availability and reported rates of diarrhea. There was an inverse relationship between water availability and the number of reported diarrhea cases; that is, higher water availability was associated with lower reported rates of diarrhea. The Solomon Islands and Niue, with the highest water availability, showed much lower diarrhea rates than the atolls. Other islands, such as Guam, Nauru, Fiji and Samoa, reported even lower rates.

Figure 4 shows the relationship between the GNP and the reported rate of diarrhea. There was an inverse association between GNP and the reported number of diarrhea cases: Nauru and New Caledonia have a higher GNP in comparison to Kiribati, Vanuatu, and Samoa and had a lower rate of diarrhea.

Multiple regression analyses were uninformative, perhaps due to a lack of statistical power.

Time–series study. Poisson regression modeling indicated that in Fiji, extremes of rainfall were independently associated with increased reports of diarrhea in infants, controlling for the effect of season. The model that fitted the data best included seasonal terms (k = 1,2), variables representing rainfall above and below 5×10^{-5} kg/m^2/min, and a temperature variable (lagged by 1 month). Diarrhea reports increased by 2% [95% confidence interval (CI), 1.5–2.3%] per unit increase in rainfall above 5×10^{-5} kg/m^2/min and by 8% (7.6–9.2%) per unit decrease in rainfall below 5×10^{-5} kg/m^2/min. When rainfall variables were lagged by 1 month, the effect of low rainfall was unchanged, but increased rainfall was associated with a small decrease in diarrhea.

The effect of temperature was statistically significant only when the temperature variable was lagged by 1 month. There was approximately a 3% (CI, 1.2–5.0%) increase in diarrhea per degree increase in temperature in the previous month, controlling for season.

The model was found to be a good predictor of diarrhea reports for 1993–1998 (Pearson correlation coefficient for model predictions vs. actual diarrhea reports = 0.49, $p < 0.001$).

Discussion

Using average data for 1986–1994, we found that low-lying atolls such as Tokelau, Tuvalu, and Kiribati tend to have the highest average temperatures and among the lowest potential water availability and the highest rates of diarrhea. However, Nauru is an exception to this pattern, with a high temperature but low rate of diarrhea. This could be because Nauru is a phosphate-rich country, with a high GNP, and can therefore afford desalination plants and other sanitary infrastucture. In general, islands with higher GNPs such as French Polynesia, American Samoa, New Caledonia, and Nauru tend to have low rates of diarrhea. Several islands such as New Caledonia, Palau, Vanuatu, Niue, and the Solomons, with higher potential water availability, have a relatively low rate of diarrhea.

Good information on water resources in the Pacific Islands is limited. Therefore, we calculated a crude estimate of potential water availability by multiplying the land area by the average annual precipitation rate. The metric is undoubtedly a good estimate of the theoretical maximum water availability from rainfall. However, the actual availability of usable water will be influenced by multiple factors including *a*) climate variability in the short term (such as cyclones), at the interannual scale (ENSO), and in the long term (through global climate change); *b*) natural and human-managed hydrology; and *c*) the geographic relationships between rainfall, supply infrastructure, and population distribution.

Ideally, the estimate of water availability could be refined by including information on some or all of the above factors in the analysis. The major difficulty is lack of spatially referenced geophysical or population data for the islands.

The results of Poisson regression analyses of monthly data for Fiji from 1978 to 1989 were consistent with the above descriptive findings. There was a significant positive association between monthly temperature and diarrhea reports in the following month. Low rainfall was associated with statistically significant increases in diarrhea in the same month and the following month. High rainfall was associated with statistically significant increases in diarrhea in the same month but decreased diarrhea in the following month.

The data are undoubtedly "noisy" (indicated by the scattering of points in Figure 1), probably due to a combination of chance and the contribution of multiple nonclimate factors to the monthly incidence of diarrheal disease. Nevertheless, a clear climate signal is seen in monthly diarrhea reports. This is biologically plausible because higher temperatures favor the growth of food spoilage organisms, whereas low rainfall can be expected to interrupt water supply and contribute to poor hygiene. A likely initial effect of high rainfall is to flush fecal contaminants from pastures and dwellings into water supplies, but continued rain could lead to a subsequent improvement in water quality.

In most islands, urban water is fully treated with monthly routine monitoring,

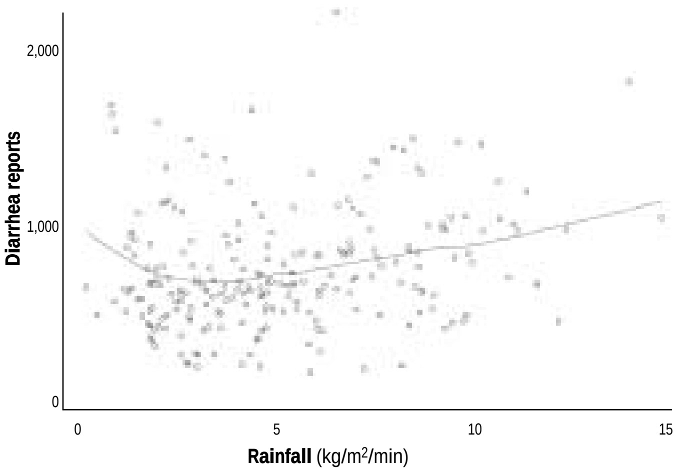

Figure 1. Dose–response relationship between rainfall (kg/m^2/min) and diarrhea reports. Diarrhea reports were adjusted for season as described in the text. The Lowess smooth is a locally weighted average. The Lowess smoother bandwidth = 0.8.

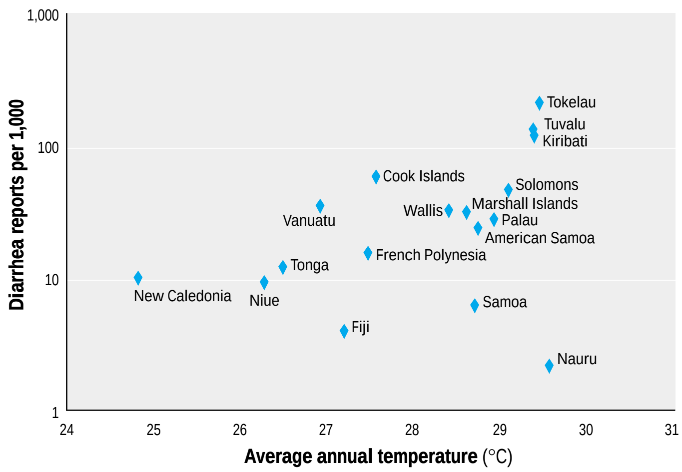

Figure 2. Annual average temperature and average reporting rates for diarrheal disease, Pacific Islands (1986–1994). $r^2 = 0.49$; $p < 0.05$.

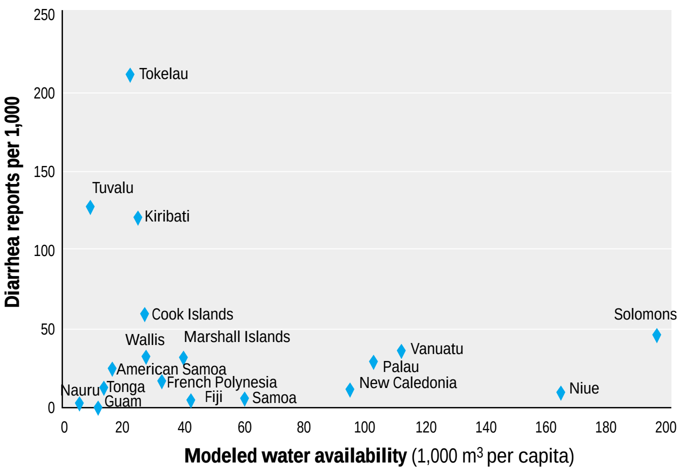

Figure 3. Annual potential water availability and average reporting rates for diarrheal disease, Pacific Islands (1986–1994). $r^2 = -0.24$; $p < 0.35$.

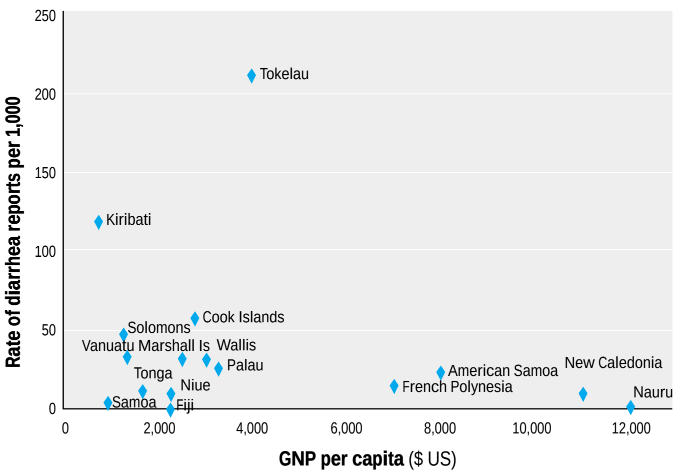

Figure 4. GNP per capita and the average reporting rates for diarrheal disease, Pacific Islands (1986–1994). $r^2 = 0.22$; $p < 0.42$.

but in the rural areas, there is no provision for sewage treatment, and most often there are no reticulated water supplies (*29*). Rural water sources, in particular, are likely to be contaminated during both droughts through stagnation and floods through runoff. Similarly, sewage treatment facilities (largely in urban centers) are often overloaded by flooding. Disruption of electric power also affects water pumping and reticulation systems in urban areas. For example, in many rural areas of Fiji, communities are dependent on unprotected water sources such as river catchments, shallow, open wells, and streams. Water from such sources is often not treated and is prone to contamination from upstream sources (*20*). Rural localities are generally located upstream on hilly terrain, and shortage of water is not only more frequent, but signs of shortage appear earlier. In the lowlands and coastal zone where urban centers are situated, contamination of water sources from floods poses a major problem.

Most of the potential mechanisms considered above are applicable regardless of the specific pathogens involved. All cases of diarrhea are eligible to be reported to the Secretariat of the Pacific Community by national authorities, within age categories of infant (< 1 year), child (1–4 years), and adult (all other ages). One of the main limitations of our study is that the diarrhea reports were aggregated, and the causes of the diarrhea were not available. However, this is unlikely to have generated spurious associations. To the extent that there are different mechanisms linking climate and disease for different pathogens, the effect estimates in our regression model are likely to be biased toward null. Although the degree of underreporting is likely to have varied between islands and during the study period, this seems unlikely to be related to variations in average climate and therefore unlikely to have resulted in spurious associations with temperature or water availability. It is likely that richer countries would have more complete reporting than poorer ones, which would lead to the opposite association between diarrhea and GNP to that reported. Therefore, although there is likely to be substantial underreporting of gastrointestinal disease, this is unlikely to have led to spurious associations, and the true effect of climate on diarrhea may be greater than those reported here. Fiji is almost unique in that it has large rural populations relying on unprotected water catchments, yet has good communicable disease surveillance systems for a nonindustrialized country.

Generalizability of results. From first principles, it is likely that factors such as sanitation and water treatment and supply infrastructure will strongly modify the effect of climate on diarrheal disease. Water supply and sanitation infrastructure is likely to vary according to GNP and other factors; therefore it is unlikely that the precise dose–response relationships reported for Fiji would be found in other islands.

Infants are likely to be the most vulnerable to effects of climate on diarrheal illness, as they may be highly exposed (via close contact with the environment or bottle feeding) and highly sensitive (because of their relatively poorly developed immunity). For the same reasons, adults are likely to be least vulnerable, and children of intermediate vulnerability.

For these reasons, the dose–response relationships reported here are unlikely to be widely generalizable. In the future, it will be important to attempt to validate these findings in data on diarrheal illness in children and adults, as well as infants, in other countries.

Implications for climate change. Although there is uncertainty concerning the magnitude of change in future average temperatures in the Pacific, there is reasonable certainty that climate change will be associated with increases in average temperatures. There is less certainty regarding the effect of climate change on rainfall. In the Pacific region, climate models do not agree on either the direction or magnitude of rainfall change, with some models showing an increase and others showing a decrease for some of the PICs. It is possible that there will be an increase in rainfall variability with more extremes. Furthermore, in terms of rainfall, there is some evidence that climate change will be associated with a more El Niño-like mean state and also that daily extremes in rainfall may increase (*30*).

In the light of the findings reported here, climate change is likely to worsen the problem of diarrheal disease in many PICs. Because PICs already experience a high degree of climate variability, many climate change adaptation measures will be the same as existing measures. Such measures have value regardless of the magnitude and direction of long-term climate change. Given the uncertainties of how climate may change in the Pacific region, there is widespread agreement that a no-regrets approach to adaptation is appropriate (*31–34*).

We recommend three areas for adaptation responses to minimize the health impacts we have discussed: improved access, quality and reliability of water supplies; improved sanitation and sewage disposal facilities, and increased provision of, and access to, primary health care. Because diarrheal diseases are already a current, important public health issue in PICs and because diarrheal disease is associated with present-day extremes of climate variability, it follows that public health and environmental management initiatives to reduce the incidence of diarrheal disease today are the most important long-term climate change adaptation measures.

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