## Title

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**Authors**

Dimitrova, Anna
Gershunov, Alexander
Levy, Morgan C
et al.

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# Uncovering social and environmental factors that increase the burden of climate-sensitive diarrheal infections on children

Anna Dimitrova[a,1], Alexander Gershunov[a], Morgan C. Levy[a,b], and Tarik Benmarhnia[a]

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**Climate-sensitive infectious diseases are an issue of growing concern due to global warming and the related increase in the incidence of extreme weather and climate events. Diarrhea, which is strongly associated with climatic factors, remains among the leading causes of child death globally, disproportionately affecting populations in low- and middle-income countries (LMICs). We use survey data for 51 LMICs between 2000 and 2019 in combination with gridded climate data to estimate the association between precipitation shocks and reported symptoms of diarrheal illness in young children. We account for differences in exposure risk by climate type and explore the modifying role of various social factors. We find that droughts are positively associated with diarrhea in the tropical savanna regions, particularly during the dry season and dry-to-wet and wet-to-dry transition seasons. In the humid subtropical regions, we find that heavy precipitation events are associated with increased risk of diarrhea during the dry season and the transition from dry-to-wet season. Our analysis of effect modifiers highlights certain social vulnerabilities that exacerbate these associations in the two climate zones and present opportunities for public health intervention. For example, we show that stool disposal practices, child feeding practices, and immunizing against the rotavirus modify the association between drought and diarrhea in the tropical savanna regions. In the humid subtropical regions, household's source of water and water disinfection practices modify the association between heavy precipitation and diarrhea. The evidence of effect modification varies depending on the type and duration of the precipitation shock.**

precipitation | hygiene | childhood diarrhea | immunization | child feeding practices

Preventable diarrheal diseases remain among the leading causes of child death globally. In 2016, diarrheal diseases claimed nearly 450,000 lives of children younger than 5 y, most of which occurred in sub-Saharan Africa and South Asia (1). When it comes to the containment of infectious diseases, low- and middle-income countries (LMICs) face mounting challenges posed by global warming. Climate conditions are becoming increasingly more suitable for the transmission of various water- and vector-borne illnesses (2). At the same time, the increased incidence of extreme weather events attributed to climate change (3) is shown to enhance disease transmission channels, such as concentration of pathogens in the environment during droughts (4) and contact with contaminated water following floods (5–7). Still, the literature is inconclusive concerning the magnitude and the direction of the association between extreme weather events and diarrheal disease (8, 9). Moreover, little is known about the modifying role of contextual factors, such as social and environmental factors, which can have important implications for developing public health interventions (10, 11).

In this study, we explore the link between precipitation shocks (drought and heavy precipitation events) and diarrheal disease in young children using data for 51 LMICs in combination with high-resolution precipitation data. We stratify observations by climate zone and use symptoms of diarrhea as a proxy for the presence of diarrheal illnesses in children under 3 y of age. We additionally investigate the role of contextual factors that may attenuate or exacerbate these climate–health associations. In particular, we focus on the following social determinants of vulnerability to infectious diseases: water source, type of sanitation facility, hygiene practices, feeding practices, and vaccination against the rotavirus. These factors present some of the root causes of vulnerability to diarrheal diseases in LMICs (12, 13).

For example, outbreaks of diarrheal diseases are common in places where access to safe drinking water and clean sanitation is a problem (14–16). Even among households with access to clean water and sanitation, poor hygiene practices, such as unsafe stool disposal and handwashing habits, can increase exposure to pathogens (15–18). Unhygienic conditions create an environment that is conducive to the outbreak of communicable diseases, and these vulnerabilities may become amplified during periods of anomalous dryness or heavy precipitation (8, 9, 11). Drought, for example, can lead to the accumulation of

## Significance

We use geolocated survey data from 51 low- to middle-income countries to show that precipitation shocks are related to symptoms of diarrheal disease in children under 3 y of age. We show that the direction of the association is determined by background climate features—in the topical savanna regions, anomalous dryness is associated with increased risk of diarrhea, while in the humid subtropical regions the same health risk is associated with heavy precipitation events. We additionally explore how various social factors exacerbate or attenuate these health risks in the two climate zones. We present evidence that different health interventions may be effective, depending on local climate conditions and the type and duration of the precipitation shock.

Author affiliations: [a]Scripps Institution of Oceanography, University of California, San Diego, CA 92037; and [b]School of Global Policy and Strategy, University of California, San Diego, CA 92037

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The authors declare no competing interest.

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[1]To whom correspondence may be addressed. Email: adimitrova@ucsd.edu.

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pathogens in limited water supplies, which may be used as sources of drinking water by households who lack safer options. Heavy rainfall and flooding can transport pathogens into surface water supplies or contaminate groundwater, among other channels (9). The timing of the extreme precipitation event may also be important. Studies suggest that heavy precipitation during a dry period may lead to the flushing of pathogens into water sources in one concentrated dose, whereas during wet periods, pathogens may get regularly flushed into water sources in small doses, creating a so-called dilution effect (8). However, we still have a poor mechanistic understanding of these climate–disease relationships and the role of water, sanitation, and hygiene (WaSH) in modulating them.

Indirectly, exposure to drought has been linked to worse child nutrition outcomes (19), which is known to increase susceptibility to diarrheal disease (1, 18). In fact, undernutrition is a leading risk factors for diarrheal disease in infants and young children (1, 18) and increases the risk of diarrheal death (20). Micronutrient deficiencies, which are common with malnutrition, are known to suppress immune system function and are associated with increased incidence of persistent diarrhea in children (13, 21, 22). Increased contact with pathogens linked to exposure to extreme climate conditions may impact immunocompromised children more severely. However, little is known about the cumulative impact of these health risks.

Apart from improving child nutrition and WaSH, potential interventions may target increasing appropriate vaccinations in LMICs. The rotavirus is one of the few vaccine-preventable diarrheal pathogens, and it is the main cause of severe diarrhea in young children (1). Moreover, there is evidence that rotavirus transmission is influenced by environmental factors, with cool and dry seasons coinciding with a spike in the transmission of rotavirus in the tropics (23, 24). However, there is still insufficient knowledge about the efficacy of the rotavirus vaccine for the prevention of climate-related diarrheal diseases, particularly in high child-mortality countries where the overall effectiveness of rotavirus vaccines is shown to be reduced (25, 26).

The containment of infectious diseases in LMICs is likely to become more challenging due to the impacts of climate change (3). Global warming is altering the global water cycle, driving a phenomenon known as “dry-becomes-drier, wet-becomes-wetter” (27–29). Beyond warming, which increases evaporation and enhances drought by drying soils, the total annual or seasonal precipitation, for any region of the world, relies on both frequency and intensity of individual storms. While precipitation intensity is expected to increase in most regions due to the increasing capacity of warmer air to hold moisture (29), the expected changes in the frequency of precipitation show more variation across the globe (30). Frequency and intensity of precipitation are, for some regions, particularly the subtropics, projected to evolve in conflict with each other whereby rainfall frequency decreases while the intensity of the most intense storms increases (30).

In all regions where the frequency of precipitation is expected to decrease, the hydroclimate becomes more variable, developing larger swings between dry and wet years (30). This increased volatility in water supply is due to shrinking annual or seasonal samples of storms resulting in larger sampling variance between years or seasons. Increased volatility manifested in increasingly more frequent and intense droughts and floods is bolstered by an increasing reliance on a handful of the most extreme storms to provide a growing proportion of the total annual or seasonal rainfall (30). Large swaths of Africa, South and North America, Australia, Southern Europe, and Central Asia are at risk of such projected changes to the regional hydroclimates. Regional idiosyncrasies, however, in both historical and projected precipitation regimes, can result from specific meteorological features (e.g., storm systems) at play in dominating each regional hydroclimate (31).

It is unclear how these regionally specific changes in precipitation patterns may affect the incidence of infectious diseases, and particularly waterborne diseases (9, 11, 32). It is imperative to better understand what are the types of precipitation shocks that are most likely to lead to disease outbreaks, and what is the influence of social and environmental factors, such as climate type, living conditions, and human behavior. To shed more light on the above issues, we analyze large-scale survey data from 51 LMICs spanning different climate zones. We construct measures of precipitation anomalies to capture both droughts and heavy precipitation events. Here we focus on observed historical climate conditions. We note, however, that climate types themselves are projected to shift with climate change (33, 34)—a process, which has probably already started (35). We provide additional evidence on the role of contextual factors (water, sanitation and hygiene, feeding practices, and rotavirus vaccination) in modifying these climate–disease relationships.

## Results

**Precipitation Anomalies and Reported Symptoms of Diarrheal Disease.** Our analysis relies on survey data for 611,154 children under 3 y of age collected in 51 countries between 2000 and 2019. We stratify observations by climate type and construct measures of precipitation anomalies which capture the accumulation of water excess or deficit over the 2-, 4- and 8-wk periods prior to the interview date (see *Methods*). Overall, 17.7% of children in the sample had symptoms of diarrhea in the 2 wk preceding the interview. Some differences by climate zone can be observed, with children in the tropical savanna and subtropical highland zones reporting the highest incidence (18.5% and 18.3%, respectively) and children in the humid subtropical zone reporting the lowest incidence (16.6%) (see *SI Appendix*, Tables S3–S5 for detailed descriptive statistics).

In Fig. 1, we present the results of a multivariate logistic regression model where we measure the accumulation of precipitation anomalies over the 4-wk period prior to the interview date. After controlling for potential confounders, we find that negative precipitation anomalies, indicating abnormally dry conditions, are associated with an increased risk of diarrhea in the tropical savanna regions (Fig. 1*A*). In the humid subtropical regions, the opposite pattern is observed, with positive precipitation anomalies, indicating heavy precipitation events, associated with an increased risk of diarrhea (Fig. 1*B*). The results for 2- and 8-wk exposure periods are in line with the findings presented in Fig. 1 (*SI Appendix*, Figs. S5 and S6). For the other climate zones, we do not find consistent and strong evidence of an association between reported symptoms of diarrhea and precipitation anomalies accumulated over the various exposure periods (*SI Appendix*, Fig. S7).

For the rest of the analysis, we replace the cubic splines with categorical measures for precipitation anomalies, ranging from mild to severe (see *Methods*). In the tropical savanna regions, we focus on exposure to dry (negative) anomalies whereas in the humid subtropical regions we focus on exposure to wet (positive) anomalies. At 4-wk exposure, we find that severe dry anomalies are associated with an increased risk of diarrhea in the tropical savanna regions (aOR = 1.08 with 95% CIs: 1.04 to 1.13; Fig. 1*C* and *SI Appendix*, Table S6). Stratifying observations by season of exposure, we find that the association between severe

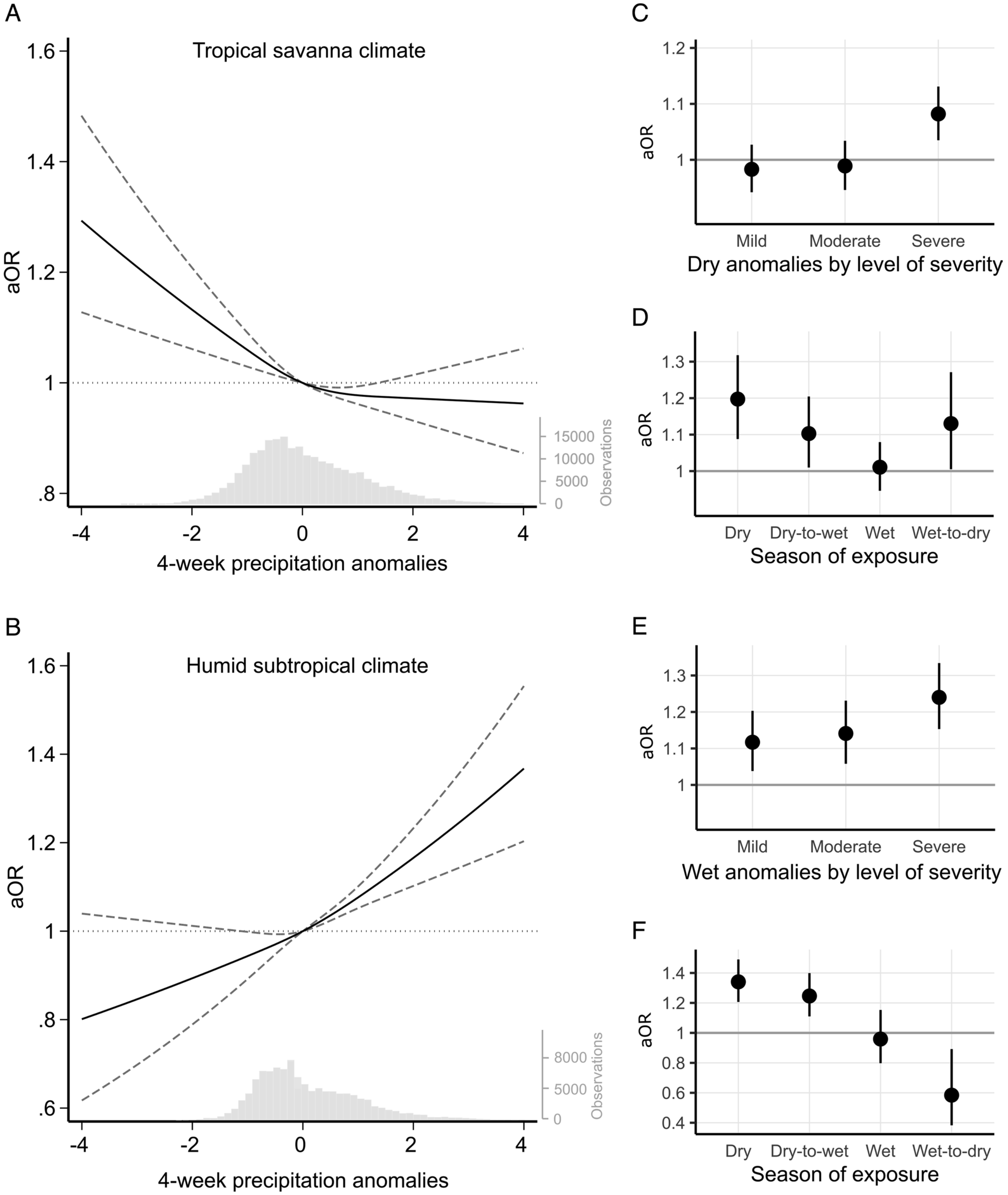

**Fig. 1.** Associations between diarrhea symptoms and 4-wk precipitation anomalies by climate type. Panels *A* and *B* show adjusted odds ratios (aOR) for diarrhea (solid lines) with 95% CIs (dashed lines) based on a restricted cubic regression spline. The histograms show the distribution of observations at various levels of precipitation anomalies. Panels *C* shows the associations between diarrhea and categories of dry precipitation anomalies by level of severity for the tropical savanna zone. Panel *E* shows the associations between diarrhea and categories of wet precipitation anomalies by level of severity for the humid subtropical zone. Panels *D* shows the associations between diarrhea and severe dry anomalies for the tropical savanna zone by season of exposure. Panel *F* shows the associations between diarrhea and severe wet anomalies for the humid subtropical zone by season of exposure. All estimates are adjusted for potential confounders (see *Methods*). Detailed results are available in *SI Appendix*, Tables S6- S9.

dry anomalies and diarrhea is observed during the dry season (aOR = 1.2 with 95% CIs: 1.09 to 1.32), the dry-to-wet (aOR = 1.1 with 95% Cis: 1.01 to 1.2), and wet-to-dry (aOR = 1.13 with 95% CIs: 1.01 to 1.27) transition seasons at 4 wk of exposure (Fig. 1*D* and *SI Appendix*, Table S8). No association is found for the wet season at 4 wk of exposure.

In the humid subtropical regions, we find that wet anomalies are associated with an increased risk of diarrhea (aOR = 1.12 with 95% CIs: 1.04 to 1.2 for mild, aOR = 1.14 with 95% CIs: 1.06 to 1.23 for moderate and aOR = 1.24 with 95% CIs:1.15 to 1.33 for severe wet anomalies at 4 wk of exposure; Fig. 1*E* and *SI Appendix*, Table S7). Positive associations between severe wet anomalies and diarrhea in this climate zone are observed during the dry season (aOR = 1.34 with 95% CIs: 1.21 to 1.49; Fig. 1*F* and *SI Appendix*, Table S9) and the dry-to-wet transition season (aOR = 1.25 with 95% CIs: 1.11 to 1.4) at 4 wk of exposure. Interestingly, we find indication that severe wet anomalies during the wet-to-dry transition season are associated with a reduced risk of diarrhea in this climate zone (aOR = 0.58 with 95% CIs: 0.38 = 0.89 at 4 wk of exposure). The results for 2 and 8 wk of exposure for both climate zones are presented in *SI Appendix*, Tables S6–S9.

**The Role of Social Vulnerabilities.** We additionally explore whether household's access to piped water and improved sanitation facilities, hygiene and child feeding practices, and the child's rotavirus immunization status modify the associations between precipitation anomalies and reported diarrhea symptoms in children. We test for heterogeneity in the effect estimates between groups using a Wald test and conclude that there is evidence of effect modification if pairwise differences are statistically significant at 0.1 level. Our results suggest that different factors may exacerbate or attenuate the climate–health associations, depending on local climate conditions and the duration of the precipitation shock. Detailed results for all models are available in *SI Appendix*, Tables S10–S15.

In the tropical savanna regions, we find evidence that the treatment of water before consumption, stool disposal practices, child feeding practices, and rotavirus immunization status each modify the association between drought and diarrhea symptoms (Fig. 2*A* and *SI Appendix*, Table S10). Specifically, at 8 wk of exposure, we observe a positive and statistically significant association between severe dry anomalies and diarrhea among children whose households do not appropriately treat water before consumption (aOR = 1.07 with 95% CIs: 1.01 to 1.13; Fig. 2*A*), whereas no association is found among children whose households use appropriate water treatment methods (aOR = 0.95 with 95% CIs: 0.86 to 1.05). The heterogeneity test shows that the pairwise difference is statistically significant (*P*-value = 0.04; *SI Appendix*, Table S10). We do not find evidence of effect modification by water treatment method at 2 and 4 wk of exposure to severe dry anomalies in this climate zone (Fig. 2*A* and *SI Appendix*, Table S10).

Additionally, among households who not safely dispose of children's stools in the tropical savanna regions, we see a positive and statistically significant association between diarrhea symptoms and severe dry anomalies at 2 and 4 wk of exposure (aOR = 1.14 with 95% CIs: 1.05 to 1.22 at 2 wk and aOR = 1.16 with 95% CIs: 1.07 to 1.25 at 4 wk of exposure; Fig. 2*A* and *SI Appendix*, Table S10), whereas this association is weaker or null among households who safely dispose of children's stools (aOR = 1 with 95% CIs: 0.95 to 1.07 at 2 wk and aOR = 1.07 with 95% CIs: 1.01 to 1.13 at 4 wk of exposure). The heterogeneity test shows that the difference in the effect estimates between the effect modifier categories is statistically significant for both periods of exposure (*P*-value = 0.01 at 2 wk and *P*-value = 0.07 at 4 wk of exposure; *SI Appendix*, Table S10). A similar pattern is observed at 8 wk of exposure as well, but the heterogeneity test falls short of statistical significance (*SI Appendix*, Table S10). Interestingly, we do not find evidence of effect modification by source of drinking water and type of sanitation facility used by households in this climate zone.

We also find that in the tropical savanna regions exposure to severe dry anomalies accumulated over a 2-wk period is associated with an increased risk of diarrhea among children who do not receive adequate diet (aOR = 1.07 with 95% CIs:1.01 to 1.14; Fig. 2*A* and *SI Appendix*, Table S10) whereas no association is found among children who receive adequate diet (aOR = 0.94 with 95% CIs: 0.82 to 1.09). The heterogeneity test shows that the pairwise difference is weakly statistically significant (*P*-value = 0.1; *SI Appendix*, Table S10). We find a similar pattern at 4 wk of exposure to severe dry anomalies, but the heterogeneity test falls short of statistical significance (Fig. 2*A* and *SI Appendix*, Table S10).

Additionally, severe dry anomalies accumulated over an 8-wk period are positively associated with diarrhea among children who are not immunized against the rotavirus (aOR = 1.27 with 95% CIs: 1.1 to 1.47; Fig. 2*A* and *SI Appendix*, Table S10), whereas no association is found among children who are fully immunized (aOR = 0.96 with 95% CIs: 0.83 to 1.1) in the tropical savanna regions. The pairwise difference is highly statistically significant (*P*-value = 0.004; *SI Appendix*, Table S10).

In the humid subtropical regions, we find evidence that households' water source and hygiene practices modify the association between severe wet anomalies and child diarrhea symptoms (Fig. 2*B* and *SI Appendix*, Table S11). Interestingly, among children whose households have access to piped water we find a positive and statistically significant association between severe wet anomalies and diarrhea at every period of exposure (aOR = 1.19 with 95% CIs: 1.08 to 1.3 at 2 wk of exposure; aOR = 1.31 with 95% CIs: 1.2 to 1.44 at 4 wk of exposure; aOR = 1.29 with 95% CIs: 1.17 to 1.41 at 8 wk of exposure; Fig. 2*B* and *SI Appendix*, Table S11). In contrast, among children whose households do not have access to piped water, this association is weaker or null (Fig. 2*B* and *SI Appendix*, Table S11). The heterogeneity test shows that the pairwise differences are statistically significant at every exposure period (*P*-value=0.1 at 2 wk, *P*-value = 0.002 at 4 wk, *P*-value=0.08 at 8 wk of exposure; *SI Appendix*, Table S10).

The water treatment practices of households also modify the association between severe wet anomalies and child diarrhea symptoms in the humid subtropical regions. Among children whose households adequately treat water prior to consumption, we do not find an association between severe wet anomalies and diarrhea at either period of exposure (Fig. 2*B* and *SI Appendix*, Table S11). In contrast, this association is positive and statistically significant among children whose households do not use adequate water treatment methods (aOR = 1.14 with 95% CIs: 1.05 to 1.23 at 2 wk of exposure; aOR = 1.21 with 95% CIs: 1.12 to 1.3 at 4 wk of exposure; aOR = 1.23 with 95% CIs: 1.14 to 1.34 at 8 wk of exposure; Fig. 2*B* and *SI Appendix*, Table S11). The pairwise differences are statistically significant at every period of exposure (*P*-value = 0.07 at 2 wk, *P*-value=0.02 at 4 wk, *P*-value = 0.05 at 8 wk of exposure; *SI Appendix*, Table S11).

To further understand the role of water source and water treatment practices, we combine the two variables into four groups (access to piped water only, adequate water treatment only, both, and neither, see *Methods*). The results presented in *SI Appendix*, Table S14 reveal that the association between severe wet anomalies and diarrhea is strongest among children whose households have access to piped water but do not treat the water prior to drinking (aOR = 1.18 with 95% CIs: 1.07 to 1.31 at 2 wk of exposure and aOR =1.33 with 95% CIs: 1.20 to 1.46 at 4 wk of exposure). In comparison, no association is found among children whose households have access to piped water and treat the water prior to consumption (aOR = 1.02 with 95% CIs: 0.81 to 1.28 at 2 wk of exposure and aOR = 1.03 with 95% CIs: 0.83 to 1.3 at 4 wk of exposure). The

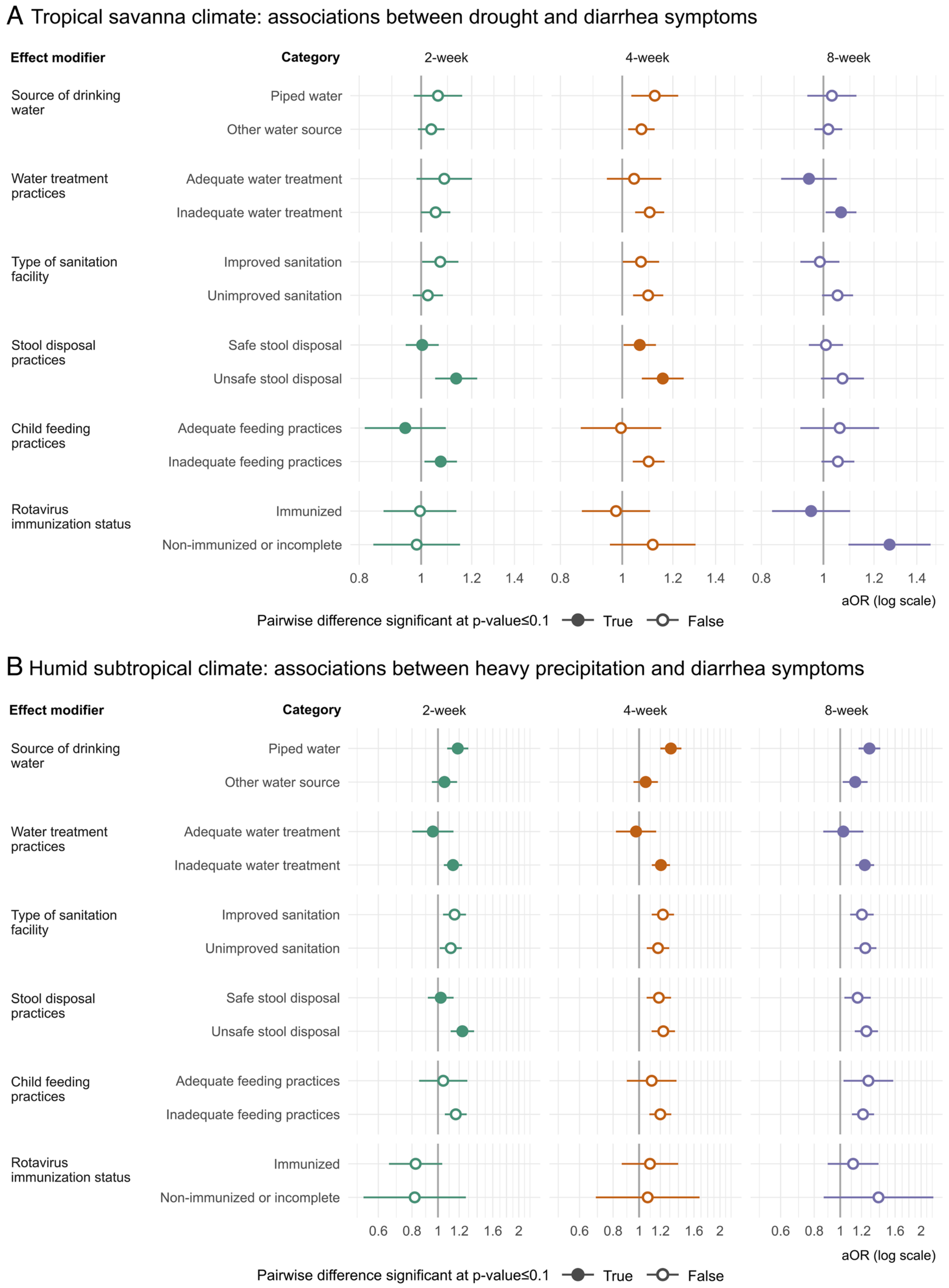

**Fig. 2.** Associations between diarrhea symptoms and precipitation shocks by climate zone, exposure period, and various effect modifiers. Panel *A* shows the associations between diarrhea and severe dry anomalies for the tropical savanna zone. Panel *B* shows the associations between diarrhea and severe wet anomalies for the humid subtropical zone. Feeding practices are assessed for children between 6 and 23 mo of age due to data availability. Rotavirus immunization is assessed for children between 3 and 35 mo of age and for a limited number of countries due to data availability. Detailed results are available in *SI Appendix*, Tables S10 and S11. All estimates are adjusted for potential confounders (see *Methods*). Wald test is used to determine statistically significant pairwise differences in effect estimates between effect modifier categories.

heterogeneity test shows that the above pairwise differences are statistically significant only at 4 wk of exposure to severe wet anomalies ($P$-value = 0.05; *SI Appendix*, Table S15).

Additionally, we find evidence that in the humid subtropical regions, severe wet anomalies accumulated over 2 wk are positively associated with diarrhea symptoms among children whose caregivers do not safely dispose of the child's stool (aOR = 1.23 with 95% CIs: 1.15 to 1.36; Fig. 2*B* and *SI Appendix*, Table S11), whereas this risk is close to null among children whose caregivers dispose of the child's stool in a safe way (aOR = 1.02 with 95% CIs: 0.92 to 1.14). The pairwise difference is strongly statistically significant (*P*-value = 0.01). At longer periods of exposure (4 and 8 wk), we do not observe evidence of effect modification by stool disposal practices.

We do not find evidence that type of sanitation facility, child feeding practices or rotavirus immunization status modify the association between severe wet anomalies and diarrhea symptoms in the humid subtropical climate zone (Fig. 2*B* and *SI Appendix*, Table S11).

## Discussion

We show evidence that symptoms of diarrhea in children under three are strongly associated with precipitation shocks and that the size and direction of the association is determined by climate type. In the perennially arid topical savanna regions, we find an association between anomalous dryness and the risk of diarrhea, and this association is observed during the dry season and the wet-to-dry and dry-to-wet transition seasons. Tropical savannas are characterized by high inter-seasonal and inter-annual variability in rainfall, with pronounced dry seasons and frequent episodes of water deficit that can last for most of the year, including the wet season (36). Reduced access to clean water during droughts is a recurrent problem in this climate region and has been identified as a major risk factor for contracting infectious diseases (37).

In the humid subtropical climate zone, we find an association between heavy precipitation events and diarrhea, particularly during the dry season and dry-to-wet transition season. We also find some indication that heavy precipitation is associated with a reduced risk of diarrhea during the wet-to-dry transition season. A similar pattern has been documented in earlier research, with extreme precipitation increasing the risk of diarrhea following dry periods and reducing it following wet periods (8). The "concentration-dilution hypothesis" has been proposed as a possible explanation for these conflicting results (4, 8, 38). The hypothesis suggests that pathogens concentrate in the environment during dry periods and, with the onset of heavy rainfall, get flushed into surface water in a concentrated dose. During wet periods, however, pathogens may get regularly flushed into water sources in smaller doses, creating a dilution effect.

More importantly, we uncover certain social vulnerabilities that modulate these climate–disease relationships and present an opportunity for public health intervention. We show that the source of drinking water, hygiene practices, child feeding practices, and vaccination against the rotavirus modify the association between precipitation shocks and children's risk of diarrhea. However, the magnitude of the effect modification varies depending on the type and duration of the precipitation shock and background climate characteristics.

In the humid subtropical climate zone, we find strong evidence that household's source of water and water disinfection practices modify the association between heavy precipitation and diarrhea. In particular, we find no association between heavy precipitation and the risk of diarrhea among children whose households disinfect water before consumption. In contrast, this association is positive and strong among households who do not disinfect water prior to consumption, especially if the household has access to piped water in the dwelling. The above results suggest that the degraded quality of water obtained from otherwise improved sources may be important for the transmission of diarrheal pathogens during heavy precipitation events. Indeed, previous research has shown that heavy precipitation and flooding can overwhelm water systems and disrupt water treatment infrastructure, leading to higher rates of water-borne illnesses (9). Our results suggest that interventions should aim at improving education about water treatment methods during heavy precipitation events, particularly among households with access to piped water in the dwelling who may be unaware of the degraded quality of the water.

We do not find evidence that the type of sanitation facility used by households (improved or unimproved) modulates the risk of diarrhea associated with heavy precipitation events in the humid subtropical climate zone. Similar findings have been documented in the literature before (38). While providing access to improved sanitation facilities, meaning sanitation that prevents contact with human waste, has been shown to substantially reduce the incidence of diarrheal infections among children in LMICs (39), sanitation facilities may become disrupted or destroyed during periods of heavy precipitation leading to sewage overflower and increased contact with contaminated food and water. We find some evidence that stool disposal practices modify the association between heavy precipitation accumulated over 2 wk and diarrhea. However, no evidence of effect modification is found at longer exposure periods (4 to 8 wk). Stool disposal practices in the community rather than at the individual level may be more important for the spread of diarrheal infections during long periods of heavy precipitation, when flood water can transport feces into drinking water supplies and the living environment (15).

In the tropical savanna regions, where droughts are associated with increased odds of diarrhea symptoms in children, we find that stool disposal practices modify this association. In particular, we find no or weak association between drought and diarrhea among children whose households practice safe stool disposal, and this result is consistent across different exposure periods. The importance of the fecal-oral route for the transmission of diarrheal infections among children has been well documented in the literature (14–16). What is more, children's stool may be an important source of contamination even among households with access to improved sanitation facilities, since infant and young children's stools are often considered innocuous and not properly disposed of (16). Drought may aggravate the fecal-oral route for the transmission of diarrheal infections due to the accumulation of pathogens in the environment and the deterioration of other hygiene practices, such as handwashing before taking food and after defecation.

We do not observe effect modification by source of drinking water in the tropical savanna. This finding is in line with earlier research, which shows that having access to piped water is a poor indicator for water quality in water-stressed locations (37). We find some evidence that the disinfection of water before consumption modifies the association between drought and diarrhea at 8 wk of exposure but not at shorter exposure windows (2 and 4 wk).

Furthermore, we find evidence that child feeding practices modify the association between drought and diarrhea in the tropical savanna regions. We find no association among children who receive adequate diet, whereas the association is strong among children who are not adequately fed, particularly at 2 and 4 wk of exposure to drought. The importance of good nutrition during the first years of life has been well established in the literature. Among other health risks, childhood undernutrition increases susceptibility to diarrheal diseases and is a major cause of child death (1, 18, 40). The presented findings highlight the need to reach food insecure households and integrate minimum nutrition standards in food aid programs targeting young children (41). Improving knowledge about healthy feeding practices can also be implemented at a low cost in places where such practices are not widely followed (42).

Finally, we present some evidence of effect modification by rotavirus immunization status in the tropical savanna regions. Among children who were not immunized, we see a strong association between 8-wk drought and diarrhea, whereas no association is found among fully immunized children. The rotavirus infection is a serious issue in LMICs, where it is the leading cause of severe diarrhea in children (1, 43). Previous research has shown that rotavirus transmission increases among communities using water from slow-moving or stagnant sources (24), which is likely to be the case in areas affected by prolonged drought. The rotavirus vaccine is strongly recommended by the WHO for inclusion in national immunization programs worldwide (44); however, coverage remains low (45). Moreover, there are large inequalities in coverage within countries that still need to be addressed (46). Given the growing risks to child health posed by climate change, it is becoming increasingly more important to close this vaccination gap.

This study has certain limitations that need to be acknowledged. We do not measure the presence of diarrheal infections in children directly but rely on reporting of symptoms by the mother, which is subject to misreporting bias (i.e., underreporting). It should be noted that such reporting bias may be related to the baseline prevalence of diarrhea (e.g., in regions where diarrhea is common, children's loose stool may be consistently underreported). However, such potential misclassification is likely related to an underestimation of true effect sizes. The same limitation applies to our measures of feeding practices, hygiene practices, and immunization status (in the cases when no immunization card was shown to validate the information provided by the mother). Moreover, we do not have information about the specific pathogens that caused the symptomatic illness in children, which limits our understanding of the routes of transmission. The analysis of effect modification relies on cross-sectional differences in outcomes between groups rather than random assignment. Nonetheless, we use an exogenous variation in the exposure of interest and combine data from multiple countries and survey rounds, implying that the effect modifiers used in this paper are unlikely to be dependent on the acute extreme precipitation anomalies we studied.

In conclusion, our findings point toward certain cost-effective interventions that may reduce the burden of climate-sensitive diarrheal diseases on young children. The vulnerabilities uncovered here are precisely of the type enhanced by the warming climate as arid climate regimes become drier while wet climates become wetter (27–29). More research is needed, however, to better understand the complex causality between climatic conditions, weather extremes, disease susceptibility factors, and child health outcomes. While climate change is disproportionately impacting LMICs and structural changes may require significant efforts, funding, time and will, we provide evidence of cost-effective and easily implementable interventions to mitigate the infectious disease burden associated with precipitation anomalies.

## Materials and Methods

**Health Data.** We obtained data from multiple rounds of DHS surveys collected between 2000 and 2019 (47). DHS surveys have been carried out in more than 90 LMICs and are an important source of information on health, nutrition, and wellbeing of women and children. The survey design is based on a two-step procedure, which ensures that the samples are representative at national and subnational levels (usually administrative unit 1, e.g., province or state) (48).

The core interviews are conducted with women aged 15 to 45 and include questions concerning living conditions, birth history, and health-seeking behavior, among other topics. We restricted our analysis to countries for which global positioning system (GPS) information (latitude and longitude) was collected for each primary sampling unit (PSU). A PSU is defined as a city block in an urban area and a village in a rural area. The GPS information allowed us to link the survey data with high-resolution gridded climate data.

For the purpose of this study, we focus on children under 3 y of age for whom detailed health information was collected, including instances of diarrhea, living conditions, immunization status, feeding practices, and other caregiving behavior. Symptoms of diarrheal illness were reported by the child's mother if these occurred in the two weeks preceding the interview date. The sample was restricted to children who are usual residents at the place of interview and who are living with their mother to reduce the chance of misreporting. This left us with a total sample size of 611,154 children from 108 surveys conducted in 51 countries (see *SI Appendix*, Fig. S1 and Table S1 for an overview of countries and survey rounds included in the analysis).

**Climate Data.** Gridded precipitation data were retrieved from the Climate Hazards Group InfraRed Precipitation with Station (CHIRPS) database (49). The data are based on integrated weather station and satellite information, which provides greater precision for sparsely gauged locations. We used daily precipitation data at 0.25° spatial resolution, which are available from 1981 to near-present day.

PSUs from the DHS surveys (*SI Appendix*, Fig. S2) were matched with the nearest centroid of the gridded precipitation data and a historical record of daily precipitation (in mm) was obtained for every PSU. We determined a 4-wk period prior to the interview day as our exposure window. We also generated 2-wk and 8-wk exposure windows to allow for different time lags between exposure to a precipitation shock and symptomatic illness.

Finally, we calculated the total amount of precipitation that has accumulated over each exposure period and converted it into precipitation anomalies, measured as standard deviations from the long-term precipitation mean for the same location and period. This measure is also known as z-scores and has been widely used in related studies (see for example refs. 50 and 51). The long term is the period from 1981 to 2019. We prefer the measure of precipitation anomalies to precipitation level because it allows us to detect both heavy precipitation events (positive anomalies) and droughts (negative anomalies), and it accounts for seasonal and location-specific differences in precipitation patterns.

We additionally acquired daily maximum and minimum temperature data from the National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center (52), which are available at 0.5° spatial resolution. Daily temperature means were calculated based on the maximum and minimum temperature values, and averaged over the 2-, 4-, and 8-wk exposure periods.

**Climate-Type Classification.** Since local climate differs substantially in the 51 countries included in the analysis, we expect that different types of precipitation shocks may pose different risks to health. To account for this, we use an update Köppen–Geiger (KG) climate classification map available at a 1-km resolution to determine the climate zone in which PSUs fall (33) (*SI Appendix*, Fig S3). The KG climate classification system distinguishes between five main climate types and 30 sub-types based on air temperature and precipitation data, corrected for topographical effects. We group all observations that fall within the same climate zone. Since DHS survey samples are representative at the administrative level rather than the PSU level, we account for the survey design by determining the predominant climate type in the respective administrative unit and assigning it to all PSUs within the same administrative area.

**Season.** We determined the season of exposure based on the annual precipitation pattern that is observed at the specific location. For every PSU, we estimated the historical daily distribution of precipitation (in mm) and smoothed it over the 2-, 4- and 8-wk exposure periods. We then estimated the 25th and 75th percentiles of the distribution of the historical daily precipitation. Days of the year when daily precipitation was above the 75th percentile were classified as wet and days of the year when it was below the 25th percentile were classified as dry. The days in between were classified as dry-to-wet or wet-to-dry transition periods. *SI Appendix*, Fig. S4 shows as an example the distribution of historical daily precipitation for two PSU locations, the first one characterized by a single wet season (unimodal precipitation pattern) and the second one characterized by two precipitation peaks separated by a dry period (i.e., bimodal precipitation pattern).

**Effect Modifiers.** We selected the following variables a priori to investigate possible effect modification in the relationship between precipitation shocks and reported symptoms of diarrheal disease: household's source of drinking water, type of sanitation facility, treatment of water before drinking, child stool disposal practices, feeding practices, and rotavirus immunization status. A short description of each variable is provided below; more detailed information is included in *SI Appendix*, Table S2.

Drinking water sources and sanitation facilities are classified based on WHO/UNICEF guidelines (53). We distinguish between water that is piped into the dwelling and other sources of drinking water. Sanitation facilities are also classified as either "improved" or "unimproved." "Improved" facilities include flush toilet, piped sewer system, septic tanks, and other safe facilities which do not contaminate the living environment. "Unimproved" facilities include pit latrine, bucket toilet, other unsafe facilities, or the general lack of sanitation facilities on the premise.

The water treatment method is classified as "adequate" if it makes the water safe for consumption and "inadequate" otherwise. Adequate treatment methods include boiling, adding bleach, or chlorine and solar disinfection, among other methods (*SI Appendix*, Table S2).

Child stool disposal practices, which are an important but often overlooked aspect of sanitary behavior in poor settings (54), are classified as "safe" or "unsafe." Unsafe disposal can lead to contamination of the living environment (15). In fact, exposure to children's stool is considered riskier than adult feces due to high concentration of pathogens (54). Despite that, children's stool is often improperly disposed of due to the false assumptions that is it innocuous (16). To be considered safe, the stool must be either disposed of in a toilet/latrine or buried.

Although some DHS surveys provide data on additional hygiene practices such as handwashing, water treatment and stool disposal were the only variable concerning hygiene behavior available in most surveys included in the analysis. Moreover, safe stool disposal has been identified as a primary barrier to the transmission of pathogens and may be more important than handwashing which constitutes a secondary barrier (14).

We additionally group the WaSH variables to explore their combined effect. In particular, drinking water source is grouped with water treatment method, whereas type of sanitation facility is grouped with stool disposal practices.

Feeding practices are assessed based on the WHO/UNICEF guidelines for infants and young children (55). Under 6 mo of age, it is recommended that children are exclusively breastfed. Beyond 6 mo of age, the introduction of complementary foods is essential for the healthy development of children (56). We use information about children's dietary diversity and meal frequency collected for children between 6 and 23 mo of age. Detailed description of this variable is available in *SI Appendix*, Table S2. We exclude children under 6 mo of age from the analysis since the information provided in DHS is not sufficient to infer their meal frequency. Additionally, formula feeding may be adequate for this age group if clean water is available; however, we do not have a reliable indicator for the quality of water used to prepare the formula.

Finally, we extract information about children's rotavirus immunization status. In DHS, vaccination status, including number of doses and age at vaccination, is collected from vaccination cards. If such cards are not presented, mother's recall is used instead. Depending on the national immunization programs, children are usually administered two or three doses of the vaccine. We classify children as immunized if they completed the full immunization schedule. Information about rotavirus immunization was only collected in DHS round VII and for a limited number of countries. For this reason, our analysis concerning rotavirus immunization was restricted to 86,413 observations from 19 surveys.

**Estimation Strategy.** We use a mixed effect logistic regression with random effects at the PSU level and robust standard errors clustered at the PSU level to assess the relationship between precipitation anomalies and reported symptoms of diarrhea illness. To allow for a nonlinear association with diarrhea, we apply a restricted cubic spline transformation of the anomalies measure with three equally spaced knots. We tested for different number of knots (three to six), which resulted in similar Akaike criterion. We opted for three knots to avoid over-fitting. We additionally generate categorical measures of precipitation shocks by level of severity based on percentile cut points. The top (bottom) 30th, 20th, and 10th percentiles of the distribution of the precipitation anomalies measures were used to categorize anomalies into mild, moderate, and severe, respectively.

We control for mean daily temperature and its squared term during the exposure period and for various individual, maternal, and household characteristics, which we identified as confounders. The following variables are included in the regression as covariates: child's sex, age of the child in months, low birthweight, age of the mother, highest achieved educational level of the mother, whether the mother is living with a partner or not, number of household members, urban-rural place of residence, source of drinking water, type of sanitation facility, and household wealth index.

The household wealth index was constructed following standard DHS procedures, using detailed information about household assets and building characteristics but excluding water source and type of sanitation facility (57). We used the following indicators to construct the wealth index, which were available for all surveys included in the analysis: main floor material, access to electricity, ownership of radio, TV, fridge, bike, motorbike, and car.

Additionally, fixed effects for country, DHS wave, and season of interview were included in the regression to account for time-invariant and time-trending factors. Another variable indicating whether a vaccination card was shown during the interview was also included in the regression to control for recall bias concerning child's immunization history.

To account for differences in local climate conditions, we stratify observations by climate type using an updated KG climate classification map and determining the predominant climate zone in the administrative area in which households are located (33). Effect modification by water, sanitation, hygiene practices, feeding practices, and rotavirus immunization status is investigated via an interaction term between the precipitation measure and each of the effect modifiers.

We test for heterogeneity between effect estimates using a Wald test and conclude that there is evidence of effect modification if pairwise differences are statistically significant at 0.1 level.

**Data, Materials, and Software Availability.** Some study data available (The survey data used in this study originate from the Demographic and Health Surveys and cannot be shared due to confidentiality agreement with the survey participants.).

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