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# Improving Humanitarian Response to Slow-Onset Disasters Using Famine-Indexed Weather Derivatives

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## Abstract

This paper illustrates how weather derivatives indexed to forecasts of famine can be designed and used by operational agencies and donors to facilitate timely and reliable financing for effective emergency response to climate-based, slow-onset disasters such as drought. We provide a general framework for derivative contracts, especially in the context of index insurance and famine catastrophe bonds, and show how they can be used to complement existing tools and facilities in drought risk financing through a risk-layering strategy. We use the case of arid lands of northern Kenya, where rainfall proves a strong predictor of widespread and severe child wasting, to provide a simple empirical illustration of the potential contract designs.

*Key words:* catastrophe bond, covariate risk, famine relief, food aid, food insecurity, Kenya, pastoralists, weather derivatives

Climate variability and extreme weather events are among the main risks affecting the livelihoods and well-being of poor populations. In sub-Saharan Africa, around 140 million people are exposed to the constant threat of famine induced by natural disasters such as droughts and floods. The capacities of communities, social networks, or families to buffer members' welfare are, however, insufficient to prevent widespread hunger and severe human suffering when covariate shocks hit. Due to limited insurance against covariate weather risks, short duration but highly catastrophic shocks can have serious long-term consequences for children's development, household productivity, asset accumulation, and income growth (Dercon and Krishnan, 2000; Hoddinott and Kinsey, 2001; Dercon and Hoddinott, 2005; Hoddinott, 2006).

Governments, external relief organizations, and players in the international aid community commonly step in as insurance providers of last resort for vulnerable populations, providing emergency response to humanitarian crises in the wake of extreme weather shocks. Their commitment to humanitarian relief exposes operational agencies and donors financially to catastrophic weather risks in developing countries worldwide. As the frequency and intensity of natural disasters and food emergencies have increased in recent decades (Munich Re, 2006), so has the number of people needing humanitarian assistance, requiring more resources from external agencies and donors. With limited available funds to support emergencies, rigorous tools for efficient planning and

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prioritization of interventions and resource allocation become crucial to enhance the humanitarian and economic value of emergency operations.

Recent innovations in weather derivatives<sup>1</sup> and the booming market for transferring covariate weather risks provide considerable promise to mitigate weather-related catastrophic shocks that threaten humanitarian crises. Improved early warning systems and emergency needs assessment practices have used timely monitoring and analysis of situations in vulnerable areas to significantly improve humanitarian response in recent decades (Barrett and Maxwell, 2005).

The goal of this paper is to show how weather derivatives can be designed and used by governments and operational agencies to improve humanitarian response to slow-onset disasters, especially drought. The contracts we propose, "famine-indexed weather derivatives" (FIWDs), comprise two main characteristics. First, the weather variables used to trigger contract payouts need to be indexed to some indicators of forecasted prevalence and severity of food insecurity conditions in the targeted areas, and second, the timing and frequency of the cash payouts need to facilitate potential early interventions.

We motivate this idea by briefly reviewing current innovations in the weather derivatives market and its potential in developing countries. The rationale for FIWDs and the contracts' main characteristics are then described. We provide a general framework for two distinct contract structures—weather index insurance and a famine catastrophe bond—and explain how developing country governments and international organizations might combine these

derivative products with other funding opportunities (e.g., contingent grant or debt from international development banks) to enhance catastrophic risk transfer opportunities and to obtain cost-effective catastrophic risk financing (Hess, Wiseman, and Robertson, 2006; Syroka and Wilcox, 2006; Hess and Syroka, 2005). Finally, we illustrate the possibilities with an application to the arid lands of northern Kenya, an area that suffers recurring, severe droughts often requiring a massive international humanitarian response to avert famine.

## **Weather Derivatives and Their Potential in Developing Countries**

A weather derivative is a type of parametric contingent claim contract whose payoff schedule depends on a measure of meteorological outcomes, such as inches of rainfall, at a certain location during the contract period (Chicago Mercantile Exchange, 2002). The weather derivative contract specifies a specific event or threshold that triggers payments and a payment schedule as either a lump-sum payment or a function of index values beyond that threshold. A variety of derivatives can be issued on well-specified weather variables or a single- or multiple-specific weather event (Dischel, 2002; Turvey, 2001). The most common types of contracts are put and call options, mostly seen in the form of weather-indexed insurance—swaps and collars.

If weather variables are highly correlated with covariate economic loss, derivatives on appropriate weather variables can be used to effectively hedge against such loss. The contracts can be written on various weather risks, and traded like financial assets. The weather derivatives market therefore provides opportunities for covariate weather risks to be transferred and managed either as part of a diversified global weather risk portfolio (weather risks in Kenya, for example, are potentially uncorrelated with those in other geographic areas) or as part of a diversified

<sup>1</sup>We refer to weather derivatives loosely as financial contracts that derive values from weather variables. In this context, weather derivatives may thus refer to weather index insurance offered by reinsurers, weather indices, or weather-related contracts traded in the exchange.

capital market portfolio (Hommel and Ritter, 2005; Froot, 1999). The weather derivatives market has grown dramatically, to the notional value of US\$19.2 billion in 2006/07, from US\$2.5 billion in 2001/02.<sup>2</sup> To date, the market has expanded to cover weather risks outside the United States, Europe, and Japan.

Among the popular products, catastrophe (cat) bonds are weather derivatives that have been issued primarily by reinsurance companies to facilitate transfer of the risk of highly catastrophic events with very low annual loss probabilities (mostly less than 1% per annum) to capital markets. Cat bonds are typically high-yield derivatives with the return conditional on well-defined weather conditions indicating the occurrence of a catastrophic event. From the perspective of the investor, cat bonds yield above-market rates [typically a 3%–5% spread over LIBOR (Banks, 2004; Bantwal and Kunreuther, 2000)] encompassing various compensating premiums,<sup>3</sup> while offering diversification. Consequently, there is an increasing appetite for these products in the market. Hedge funds, institutional money managers, commercial banks, pension funds, and insurance companies are regularly investing in cat bonds. The market to date is concentrated in reinsurance of U.S. hurricane and Japanese earthquake risk, but has been extended beyond natural perils to provide risk coverage against epidemics and manmade disasters.

The total cat bond market size grew to almost US\$5 billion in 2005 (Guy Carpenter and Co., 2006), and it is expected to continue trending upward as the cost of issuing declines with the

development of more standardized bond structures and as the investor base expands and becomes more knowledgeable (Bowers, 2004). Recently, there has been an attempt to design cat bonds to securitize systemic risks in agriculture (Vedenov, Epperson, and Barnett, 2006). Cat bonds—or at least the principles that underpin them—might serve as a means to transfer highly catastrophic but low probability weather risks from developing countries to the global capital market (Hofman and Brukoff, 2006).

The weather risk market also facilitates reinsurance opportunities. For example, Indian weather risks are currently reinsured in the weather derivatives market, allowing local insurance companies to sell weather insurance against drought to small farmers since 2002. The Mexican public reinsurance company Agroasemex has similarly provided weather index insurance to state governments to protect farmers against drought in most of the dryland areas since 2001. Weather insurance contracts are also currently sold in Malawi, Tanzania, and Thailand as part of pilot programs.<sup>4</sup>

The market also facilitates transfer of highly catastrophic weather risks that can trigger emergency needs by governments, donors, or international humanitarian organizations (Hess et al., 2005; Alderman and Haque, 2007). The United Nations World Food Programme (WFP) successfully took out US\$930,000 in drought insurance from an international reinsurer, AXA Re, for Ethiopia's 2006 agricultural season covering 17 million people at risk of livelihood loss (WFP, 2005). In December 2007, the WFP announced it was expanding "the first humanitarian insurance policy" in Ethiopia, hoping to raise US\$230 million in insurance and contingency funds to cover 6.7 million

<sup>2</sup>The survey has been conducted yearly by the Weather Risk Management Association (WRMA) and PriceWaterhouseCoopers. (For further detail see <http://www.wrma.org>.)

<sup>3</sup>Apart from the risk premium on comparably rated corporate bonds, premiums are needed to compensate for ambiguity about the probability of rare catastrophic events, costs of the learning curve for a complex product and market, and loss aversion which results in overvaluation of loss probability (Banks, 2004; Bantwal and Kunreuther, 2000; Nell and Richter, 2004).

<sup>4</sup>Various weather index insurance products are currently being developed in Bangladesh, Honduras, Kazakhstan, Morocco, Nicaragua, Peru, Senegal, Vietnam, and several of the Caribbean islands (Barnett and Mahul, 2007).

people if there is a drought comparable to the one in 2002/03 (IRIN Africa, 2007). In addition, the Mexican government issued a US\$160 million cat bond in 2006 to insure its National Fund for Natural Disasters (FONDEN) against the risk of a major earthquake (Hofman and Brukoff, 2006; Guy Carpenter and Co., 2006).

Similar products currently being explored include a Caribbean Catastrophe Risk Insurance Facility aimed at allowing Caribbean countries to pool and transfer natural disaster risks to the capital market (World Bank, 2006), and multinational insurance pools for the Southern African Development Community (SADC) that can facilitate transferring catastrophic weather risk as part of a regional strategy to obtain reinsurance cost reduction (Hess and Syroka, 2005). The World Bank is also currently establishing a new reinsurance vehicle, the Global Index Insurance Facility (GIIF), as a risk-taking entity to originate, intermediate, and underwrite indexable weather, disaster, and commodity price risks in developing countries (World Bank, 2006).

## **Using Weather Derivatives to Improve Emergency Response to Droughts<sup>5</sup>**

### **Rationale**

While weather shocks are neither necessary nor sufficient to induce widespread humanitarian crises, there is a strong historical correlation (Dilley et al., 2005; Ó Gráda, 2007) that potentially can be exploited. The effectiveness of humanitarian response to weather-induced crises depends not only on the quantity of aid provided but when and how assistance is provided. Timely delivery of food, medicine, and other essential supplies is crucial to effective emergency response.

<sup>5</sup>This section draws extensively on ideas and texts from Chantarat et al. (2007).

Since slow-onset disasters such as droughts exhibit foreseeable patterns, drought-induced humanitarian crises may be somewhat predictable. When seasonal rains fail to arrive, agricultural production generally deteriorates, leading to increasing food shortages and prices, depressed rural livelihoods, and acute food insecurity. Progress has been made by local governments and operational agencies (e.g., United Nations agencies such as the WFP and FAO) in developing credible emergency needs assessments and reasonably accurate early warning systems<sup>6</sup> for identifying where and when to intervene, and at what scale. However, resources are limited in part by a general lack of timely and reliable funding to respond to emergency needs.

At present, the main mechanism for financing emergency operations is through the appeal process, where early warning systems trigger a field emergency needs assessment that leads to an international appeal for appropriate funding. The main problem with this approach is that donor funding is unreliable and often quite delayed, with actual humanitarian delivery taking as long as four to eight months (Morris, 2005; Haile, 2005). Delays are costly. As an emergency progresses, unit costs per beneficiary increase sharply as more expensive, processed commodities become increasingly needed for therapeutic feeding, donors pay premia for faster transport (including airlift), and populations migrate to camps where broader support costs (e.g., shelter, water, medical care) become essential. In the 2004/05 Niger emergency, for example, the cost for WFP's deliveries increased from \$7 to \$23 per beneficiary due to a six-month delayed response.

<sup>6</sup>Programs such as the Global Information and Early Warning System (GIEWS), WFP's Vulnerability Analysis and Mapping (VAM), the Strengthening Emergency Needs Assessment Capacity (SENAC) project, and USAID's Famine Early Warning Systems Network (FEWS-NET) currently collaborate and facilitate early warning and emergency needs assessment capacity.

### Famine-Indexed Weather Derivatives

The most crucial attribute of weather derivatives for any humanitarian response system is the capacity to make immediate cash payouts for timely emergency intervention. The key to designing weather derivatives to improve emergency response to slow-onset disasters such as droughts is a well-established correlation between the specific event weather variable (s) and estimated humanitarian needs, and an appropriate contractual payout structure.

Humanitarian crises often result from successive drought episodes, late arrival of the main rains, or discontinuous rainfall patterns within the season, occurring in spatially widespread locations. Although simple rainfall volume matters, so does the temporal and spatial distribution of rainfall within seasons. Therefore, an appropriate weather derivative contract to properly hedge against widespread suffering should take into account these rainfall variables and events. Such patterns can be clearly observed in the case of arid pastoral areas of northern Kenya, discussed in more detail in our illustration provided later. Mude et al. (2006) show that drought episodes are strongly associated with sharply higher prevalence of severe child wasting.<sup>7</sup>

Formally, weather variables and other weather-related covariates ( $W$ )—rainfall volume, distribution, multiple rainfall events, etc.—may be indexed to some indicator of severe and widespread human suffering from food crises ( $F$ ) by an established empirical forecasting model:

$$(1) \quad F = f(W) + \varepsilon,$$

where  $f(\cdot)$  is a general function and  $\varepsilon$  is a standard mean zero disturbance term.

The value of this pure reduced-form estimation is that the forecasted human impact conditional on observed weather depends solely on observed weather and immutable or exogenous covariates (e.g., location or seasonal dummy variables). It is objective, verifiable, and extremely difficult to manipulate. Therefore,  $f(W)$  can serve as a parametric “famine index” that forecasts the risk of widespread, severe undernutrition associated with observed weather events.

New forecasts may be generated in near-real time based on the arrival of new weather data, so the famine index can evolve over time throughout the contract coverage. Hence, this may better capture not only the impact of shortfalls in rainfall quantity in a specific time or season, but also the timing and distribution of rainfall within a season or across seasons.

Finally, assuming  $f(\cdot)$  is invertible, one can recover an extreme weather trigger  $W^*$  corresponding to an appropriate critical threshold of forecasted degree of human suffering,  $F^*$ , which triggers emergency response intervention such that  $W^* = f^{-1}(F^*)$  (Turvey, 2001).

### Establishing Appropriate Contractual Payout Structures

Since timely financing for effective early intervention is a goal, weather derivative contracts derived through the forecast-based famine index,  $f(W)$ , should trigger indemnity payouts as soon as the famine index meets or exceeds the prespecified thresholds, or allow multiple triggered payouts within the contract term, rather than paying out only at the end of the contract term. Response delays can be costly and even deadly. Thus, if the seasonal rains failed badly and widely, the contract might trigger indemnity payments well before the end of the contract so as to allow more effective and lower cost intervention. In the following section, we

<sup>7</sup> Among the covariates used in Mude et al.'s (2006) forecasting model are various autoregressive lags of prevalence of severe child wasting, herd dynamics, food aid, and forage availability, some of which are not objectively measured. Thus, they may be prone to moral hazard if directly used as triggers for derivative contracts. To further develop these measures as triggers for weather derivative contracts, slight modifications are needed to ensure that the covariates used are transparent and free from tampering.

provide a general framework for such contracts that can be designed and used to improve emergency response to drought.

### Structure and General Framework

Generally, contingent debt or grant facilities offered by the World Bank and other international financial institutions on concessionary terms to developing countries affected by either natural or manmade disasters may be used to support countries' early intervention in response to drought. The catastrophic layer of drought risk, where such facilities are no longer available or suitable to accommodate the emergency need, then can be managed through global financial market mechanisms. For this purpose, weather index insurance or catastrophe bonds may facilitate transfer of extreme drought-induced famine risk to market players willing to accept the risk at some cost. We now consider these two forms of famine-indexed weather derivatives, which can complement other available financing facilities to hedge against various layers of drought-induced famine risk.

#### Weather Index Insurance

Weather index insurance can allow governments and/or international aid agencies to transfer drought-induced famine risk to international insurers or reinsurers, most likely with the donor community funding the insurance premium *ex ante*. A well-designed contract can be beneficial to both beneficiary and donors alike. On the one hand, if the insurance is triggered, the indemnity payout will be released to a government and/or nongovernmental operational agencies to finance effective emergency response. On the other hand, pre-financing humanitarian aid allows donors to hedge against the risk of volatile demand for overseas development assistance (Skees, 2002; Syroka and Wilcox, 2006).

We refer to  $\Pi_T(W, W^*)$  as the total payoff at the terminal period  $T$  of a famine-indexed insurance contract<sup>8</sup> covering a vulnerable period  $[0, T]$  and based on the observed specific weather event ( $W$ ), the famine index function  $f(W)$ , and a prespecified anthropometric trigger  $F^*$ . It is  $F^*$  that determines the index trigger  $W^* = f^{-1}(F^*)$ . Depending on the nature of drought risk and financial exposure of organizations in the affected countries, various index and payout structures can be considered.

Famine-indexed insurance can be in the form of a simple put option, establishing payout at the end of the contract  $T$ . Thus,

$$(2) \quad \Pi_T(W, W^*) = \text{Max}[C(W^* - W_T), 0],$$

where  $C(\cdot)$  is some function that maps the severity of weather shortfalls relative to the extreme weather threshold to the associated funds required for immediate humanitarian assistance. For example,  $C(\cdot)$  might be defined by  $(W^* - W_T)^x$ , where  $x \geq 1$ , which captures the intensity of the famine index relative to the weather event, especially if the extent of potential suffering is nonlinearly related to precipitation shortfalls. The required funds can be estimated from past emergency operations or can be based on the drought contingency planning system a developing country might already have in place.

To ensure timely funding, weather-linked famine insurance can also be designed to make a payout at any first time  $t$  within the vulnerable period coverage,  $[0, T]$ , if the weather index  $W$  reaches the threshold  $W^*$ . The payoff at terminal period  $T$  can be written as:

$$(3) \quad \Pi_T(W, W^*) = e^{r(T-t)} C(W^* - W_t) + \mathbf{1}_{\{W, W^*\} \leq T},$$

where  $r$  is a required rate of return, which, for simplicity, is assumed to be

<sup>8</sup> Alternatively, the insurance payoff also can be structured in terms of a direct famine index  $f(W)$  relative to the anthropometric famine trigger  $F^*$ . Thus, the payoff  $g_j(f(W), F^*) = \text{Max}[C(f(W) - F^*), 0]$ .

deterministic.<sup>9</sup>  $1_A$  is an indicator function of an event  $A$ ;  $t(W, W^*)$  is the first time passage of  $W$  to reach the threshold  $W^*$ ; and  $1_{t(W, W^*) \leq \tau} = 1$  is an indicator function designed to capture a trigger at any period  $t$  within  $[0, T]$  and 0 otherwise.

The insurance coverage  $[0, T]$  can be chosen so that it covers the entire period each year when people are vulnerable to extreme weather, e.g., the whole rainfall season. Finally, the function  $C(\cdot)$  in this digital, down-and-in option may simply represent a lump sum of required funding released to finance baseline early intervention to the forecasted drought event triggered.

Famine-indexed insurance also can be designed to cover multiple drought events (usually multiple years  $(N)$  with one event in a vulnerable period  $[0, T]$  each year) and thus to establish multiple triggered payouts at any year  $n$  within the  $N$ -year coverage. The total payoff realized at the end of the contract at year  $N$  can be represented by:

$$(4) \quad \Pi_N(W, W^*) = \sum_{n=1}^N e^{r(N-n)} \Pi_n(W, W_n^*),$$

where  $\Pi_n(W, W_n^*)$  represents insurance payoff at the terminal date of any year  $n$  within the  $N$ -year coverage.<sup>10</sup> For example,  $\Pi_n(W, W_n^*) = \text{Max}[C(W_n^* - W_n), 0]$  if a yearly contract is a simple put option. Moreover, a cap of  $\bar{\Pi}_n$  can be applied to limit the insurer's maximum loss each year, thereby

potentially increasing market supply. The total payoff at the end of this contract is written as:

$$(5) \quad \Pi_N(W, W^*) = \sum_{n=1}^N e^{r(N-n)} \text{Min}[\Pi_n(W, W_n^*), \bar{\Pi}_n].$$

Furthermore,  $W_n^*$  and  $\bar{\Pi}_n$  are subscripted, indicating the trigger and the cap can change over time. If the trigger and the cap are the same in all periods, then (4) and (5) can be converted to simple annuities.

The actuarially fair premium for the insurance contract is calculated by taking the expectation of the insurance payoff with respect to the underlying distribution or process of weather variable  $W$ , and discounting the term with the appropriate discount rate.<sup>11</sup> Hence, the actuarially fair premium for a famine-indexed insurance covering  $N$  years of drought events (with one event in a vulnerable period  $[0, T]$  each year) can be expressed as:

$$(6) \quad \text{Premium} = e^{-rN} E^\omega[\Pi_N(W, W^*)],$$

where  $E^\omega$  indicates expectation at the beginning of the contract with respect to a state variable  $\omega$  that pertains to some catastrophic weather risk governed by the underlying distribution of weather variable  $W$ . To this fair rate, a loading factor  $m > 1$  is usually added to capture insurers' attitudes toward ambiguity of the underlying weather, their opinions about weather forecast, and their aversion toward catastrophic risks.

### Catastrophe Bonds: Famine Bonds

While weather index insurance contracts can facilitate the transfer of drought risks to international insurers or reinsurers, the extreme layer of the catastrophic weather risks may not feasibly and/or

<sup>9</sup>A stochastic required rate of return may be applied as it captures interest rate risk under a variety of assumptions (Heath, Jarrow, and Morton, 1992) and other related risks due to factors other than a catastrophic event. The adjusted discount rate with stochastic required rate of return can be designated by

$$r(t) = \int_0^t r(s) ds.$$

<sup>10</sup>Since the coverage period of  $[0, T]$  is fixed across years, for simplicity, the yearly contract can be designed such that the terminal coverage period  $T$  is also the terminal period of a year. Hence, the period between the end of year 1 and the start of the contract, year  $T_1 - T_0 = 1$  year, and the period between the end of the contract and the end of any year  $n$ ,  $T_n - T_n = N - n$  years. Therefore, subscript  $T$  is dropped from the yearly terminal payoff  $\Pi_n(W, W_n^*)$  of any year  $n$ .

<sup>11</sup>If a stochastic discount rate is considered, the premium will have to be calculated based on the joint distribution of weather variable  $W$  and the appropriate term structure of interest rate.

cost-effectively be absorbed by a single or a small number of insurers or reinsurers. Extreme drought risks that cannot be absorbed through the reinsurance market using weather index insurance potentially can be securitized and transferred to the capital market in the form of catastrophe (cat) bonds—or simply “famine bonds” in this setting.

Catastrophe bonds are typically engineered as follows. The hedger (e.g., governments, agencies) pays a premium in exchange for a prespecified coverage if an extreme weather event occurs; investors purchase cat bonds for cash. The premium plus cash proceeds are directed to a special-purpose company, generally an investment bank, which then invests in risk-free assets (e.g., treasury bonds) and issues cat bonds to investors. Investors then hold cat bonds whose cash flows (principal and/or coupon) are contingent on the risk occurrence. If the covered event takes place during the coverage period, the special-purpose company compensates the hedger and there is full or partial forgiveness of the repayment of principal and/or interest to investors. Otherwise, the investors receive their principal plus interest, which incorporates the associated risk premium.

Conceptually, governments or international organizations can initiate the issuance of zero-coupon or coupon catastrophe bonds, for which principal and/or interest payments to bondholders are conditional on the occurrence of extreme drought-induced famine identified by the constructed famine index relative to a specified threshold. For government or humanitarian agencies, famine bonds simply offer an insurance function just like weather index insurance for the highly catastrophic layer of drought risk by releasing immediate cash payment for emergency operations once the famine index is triggered. Thus, government and operational agencies finance famine bonds similarly to paying index insurance premiums. They can appeal to the donor community for premium contributions in advance, i.e., in the form of disaster pre-financing (Goes and Skees, 2003).

Generally, the price of a famine cat bond issued at time 0 with face value  $P$ , annual coupon payments  $c$ , and time to maturity of  $N$  years, at which the bondholder agrees to forfeit a fraction of the principal payment  $P$  by the total insurance payoff  $\Pi_n(W, W_n^*)$  at maturity, can be written as:

$$(7) \quad B(0, N) = e^{-rN} E^w \left[ P - \text{Min} \left[ \sum_{n=1}^N e^{r(N-n)} \Pi_n(W, W_n^*), \bar{\Pi} \right] \right] + \frac{c}{r} (1 - e^{-rN}),$$

where  $\bar{\Pi} < P$ . A famine bond therefore can be structured as a coupon bond that is embedded with a short position on a weather-linked option based on a trigger established by the famine index—specifically, famine-indexed insurance. Equation (7) is a multi-year bond issue that deducts from principal the indemnity in each year compounded to year  $N$  at the continuous compounding rate  $r$  and subject to a cap  $\bar{\Pi}$  that cannot exceed principal. Like typical bonds, famine bonds are valued by taking the discounted expectation of the coupon and principal payments under the underlying distribution of the weather index and the required rate of return on investment.<sup>12</sup> Alternatively, if the coupon  $c = 0$ , the bond will be issued as a discount bond, and if  $N = 1$ , a one-year bond.

The main advantage of securitizing and managing famine risk using cat bonds over index insurance is the potential to avoid default or credit risk with respect to catastrophe reinsurance. The threat of widespread catastrophic losses imposes a significant insolvency risk for reinsurance

<sup>12</sup>A stochastic rate

$$r(t) = \int_0^t r(s) ds$$

may be used as the adjusted required return representing interest rate risk under a variety of assumptions (Heath, Jarrow, and Morton, 1992) and other related risks due to factors other than a catastrophic event, which can be incorporated into the bond pricing by setting the discount rate  $r(t)$  equal to the rate of return required by investors in general bonds of comparable risk.

companies, and hence for their capacity to compensate such losses. In contrast, cat bonds permit division and distribution of highly catastrophic risk among many investors in the capital market, and so may allow greater diffusion of the extreme weather risk. Moreover, funds invested in a cat bond are collected *ex ante*, which implies that such credit/default risk is minimized to the default risk connected with the investments made by the special-purpose vehicle. Comparing the premium costs between the two requires further investigation of market capacity and opportunity.

Empirical pricing of the weather index insurance and famine bonds based on the framework provided above can be done in various ways, depending largely on assumptions, model specifications, and the methodology used to derive or calibrate the empirical distribution of the famine index,  $f(W)$ , and the term structure of interest rates. A variety of such models applied to credit instruments are presented in Turvey and Chantararat (2006) and Turvey (2007).

It is arguable that various option valuation models (e.g., Black and Scholes, 1973) widely used in finance are inappropriate in this context. The extreme weather events characterized in the constructed index tend not to follow geometric Brownian motion, thus violating the underlying assumption of the models, as weather patterns tend to be autocorrelated, mean-reverting, and exhibit seasonal trends (Dischel, 1998; Martin, Barnett, and Coble, 2001; Richards, Manfredo, and Sanders, 2004; see Turvey, 2005, for an exception). Moreover, because a weather index does not have a traded underlying asset, and unlike a financial index, there is no spot market or price for weather events, then applying the principle of risk-neutral valuation or a replicating portfolio to the value of weather options is inappropriate (Davis, 2001; Martin, Barnett, and Coble, 2001; Hull, 2002).

Weather derivatives are frequently priced using actuarial methods (Turvey, 2001, 2005). This approach to empirical pricing

of index insurance and cat bonds may involve two general steps: (a) estimating the distribution of the weather index and thus the probabilities of triggering the payout, and (b) incorporating the estimated probability distribution and the required rate of return into the actuarially fair pricing framework provided above.

We illustrate these concepts by pricing the illustrative famine-indexed weather derivatives for northern Kenya using the comparable historical burn rate, which assumes that variability of past weather reflects the expected variability of future weather, and therefore uses the observed historical distribution of the weather variable in calculating actuarially fair prices. We also employ Monte Carlo simulation, which simulates the probability distribution of the weather variable using a sufficiently long time series of available weather data and an assumed structure of randomness as the main inputs. Further explorations are needed to allow for price discovery of these innovative weather derivatives in the market.

### **Incorporating FIWDs to Enhance Effective Drought Risk Financing Strategies**

The famine index could be used to layer drought-induced famine risks such that financial tools and facilities appropriate for each layer can be applied cooperatively. One possible example, considered also by Hess, Wiseman, and Robertson (2006) and Hess and Syroka (2005), combines international development banks' debt/grant facilities, index-based risk-transfer products, and the traditional donor appeals process in drought emergency response financing.

Beyond the nation's self-retention layer (i.e., interventions in response to frequent, local, and low-loss drought events can be managed using national resources), a famine index could be used as a trigger for the release of contingent grants and/or debt with fixed and preestablished terms

to governments or operational agencies for early intervention in emergency response.<sup>13</sup> Combinations of weather index insurance and catastrophe bonds then can be used to transfer the catastrophic layer of drought risks beyond the capacities of the institutional grants/debt facilities.

All in all, a risk manager's decision on an effective risk-layering strategy, as well as optimal risk allocation arrangements among available strategies and instruments within each layer of risk, becomes a problem of minimizing risk financing costs—financially and economically—with respect to resource availability and market prices for FIWDs. But timely and predictable payouts from FIWDs now replace delayed and unreliable humanitarian aid in response to severe drought events when FIWDs are used to complement traditional donor appeal processes.

### **Potential for Famine-Indexed Weather Derivatives in Northern Kenya**

The arid areas of northern Kenya are largely inhabited by marginalized pastoral and agro-pastoral populations that traditionally rely on extensive livestock production for their livelihood, and consequently are particularly vulnerable to covariate shocks in the form of drought and flood. To address the vulnerability of its populations and to improve their ability to manage risks, the Government of Kenya's Arid Lands Resources Management Project (ALRMP) has been funded by the World Bank since 1996, aiming to develop and implement a community-based drought management system. A community-based early warning system based on monthly household and environmental surveys that collect detailed information on livelihoods, livestock

production, prices, and the nutritional status of children is currently used to signal various stages of drought and food insecurity situations, and thus to help government and operational agencies manage droughts.

In the context of FIWD design, these survey-based variables may not all be suitable as a direct index to hedge against famine risk, because they may be manipulable by prospective beneficiaries. However, since drought episodes are strongly associated with sharply higher food insecurity in the pastoral communities (WFP, 2001–2006), the predictive relationship between rainfall variables associated with extreme rainfall events and available food insecurity indicators such as nutritional status of children, levels of exogenous food availability (e.g., existing food aid pipeline commitments), real prices of key staple crops, etc., could be used in a parametric famine index for various derivative contracts.

For illustrative purposes, the relationship between rainfall variability and the directly observed proxy of prevalence and severity of child undernutrition is used to develop a famine index for FIWDs for the study areas.<sup>14</sup> Specifically, we obtained sample readings of the mid-upper arm circumference (MUAC) for children aged 6–59 months in each of 44 communities in three arid districts—Turkana, Samburu, and Marsabit—for which sufficient continuous monthly observations from 2000–2005 were available.<sup>15</sup> These three districts are rated most vulnerable to food

<sup>13</sup> Further, the debt triggered may be attached with the index insurance (Turvey and Chantarat, 2006) whereby the debt repayment is contingent upon the occurrence of disaster (i.e., when  $W' > W$ ).

<sup>14</sup> Other factors, such as domestic and international policies or other economic criteria, may influence pricing variables, and so their capacities to truly reflect the needs of the affected population.

<sup>15</sup> Theoretically, 30 households are randomly selected per community, and they are revisited each month. However, because of incompleteness due to poor data organization and storage of these repeated cross-sectional household data (described in detail in Mude et al., 2006), a subset of suitable data, for which a sufficient number of continuous observations were available, was chosen for the analysis of community-level impact of covariate shocks.

insecurity, and thus their populations are among the majority of Kenyan populations to receive yearly food assistance, making these areas very suitable as an illustrated case for our study.<sup>16</sup>

As a measure of wasting, MUAC reflects short-term fluctuations in nutritional stress and is typically easier and less costly to collect than weight-for-height data, the most commonly used and most documented anthropometric measure of wasting. Furthermore, several studies have found MUAC to be a far better predictor of child mortality than weight-for-height (Alam, Wojtyniac, and Rahaman, 1989; Vella et al., 1994). We calculate the proportion of children in each community with a MUAC z-score of  $-2$  or lower<sup>17</sup> and use this as a proxy for widespread acute food insecurity. This coincides with other measures used among operational agencies and in anthropometric research in various disciplines—for example, Howe and Devereux's (2004) definition of "famine" as a condition where 20% or more of children in a specified area are severely wasted (i.e., with z-score of an anthropometric measure of malnutrition  $\leq -2$ ) and "severe famine" when 40% or more of children in a specified area are severely wasted. This MUAC measure of the prevalence of severe child wasting can be used to quantify the level of drought-induced famine risks and thus to establish appropriate thresholds that trigger weather derivative payout for emergency response.

These data are then matched with the 1961–2006 rainfall series, comprised of

1961–1996 CHARM historical rainfall data estimated from historical satellite imagery (Funk et al., 2003) and 1996–2006 METEOSAT-based daily rainfall estimates.

### Rainfall Variability and Food Insecurity in Northern Kenya

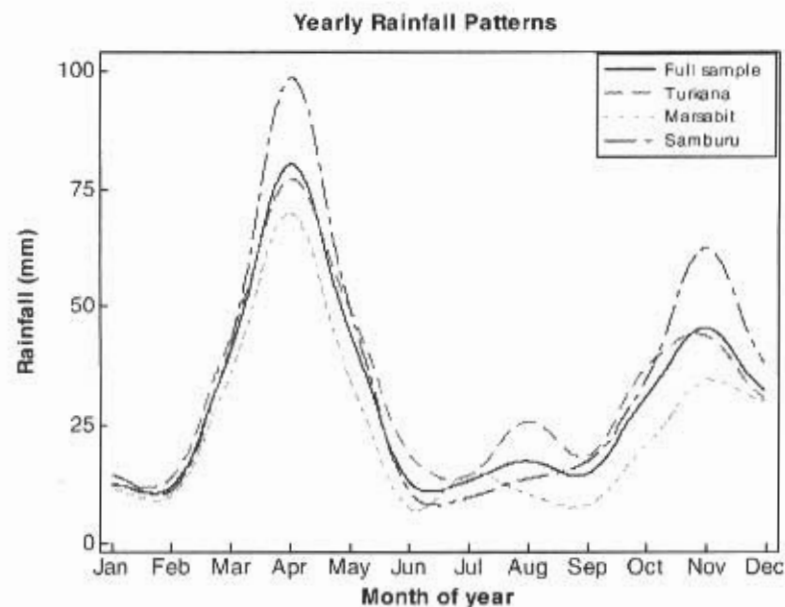
The pastoral areas examined here are generally characterized by bimodal rainfall with short rains falling October–December, followed by a short dry period (January–February), and long rains in March–May followed by a long dry season from June–September. This pattern is shown in Figure 1, which plots kernel density estimation of yearly rainfall patterns in the three northern Kenyan districts we study. Pastoralists rely both on rains for water and pasture for their animals, as well as occasional dryland cropping. Dry seasons are typically hunger periods in these pastoral communities.

In a normal year, water availability suffices to ensure adequate yields of milk, meat, and blood, most of which is consumed within pastoral households, with the remainder sold in order to purchase grains and nonfood necessities. While localized rain failures may occur, migratory herders commonly are able to adapt to spatiotemporal variability in forage and water availability. But when the rains fail across a wide area, especially if short and long rains both fail in succession, catastrophic herd losses often occur and bring with them severe human deprivation.

Chantararat et al. (2007) report that the major recent droughts with dire humanitarian consequences—1997/98, 2000/01, and 2005/06—were all years in which not only was aggregate rainfall low, but it was also spatially widespread and continued across multiple seasons. Moreover, evidence of the effect of variability in seasonal rainfall on the prevalence and severity of malnourished children can be clearly observed in the following dry season, as shown in Figure 2, which plots the dynamics of rainfall and nutritional status characterized by the

<sup>16</sup> These three pastoral districts also share similar socioeconomic characteristics, climate patterns, natural resource endowments, and livelihood portfolios according to the WFP's 2001 Vulnerability Analysis and Mapping (VAM) pilot study on chronic vulnerability to food insecurity, allowing the application of similar concepts and tools to drought response across this vast area.

<sup>17</sup> MUAC data are standardized using the internationally recognized 1978 CDC/WHO growth chart. The threshold  $z \leq -2$  is consistent with the benchmark often employed by emergency relief agencies to define famine (Howe and Devereux, 2004; World Food Programme, 2000).



**Figure 1. Kernel Density Estimation of Yearly Rainfall Pattern in Three Pastoral Districts of Northern Kenya, 1961–2006**

proportion of severely wasted children in a community from 2000–2005 in the three districts of our study. The impact of 2000's failed long rains resulted in a larger proportion of malnourished children in the following long dry season, whereas the localized failure of the 2003 short rains resulted in a temporary peak in proportion of malnourished children in the following short dry season at the start of 2004.

Kenya's current drought response system is illustrated in Figure 3. Seasonal rain forecasts are conducted two months before the start of the seasonal rains with the goal of producing early warning to help herders improve their livelihood decisions as well as to facilitate drought response planning among agencies. Approximately two-month-long seasonal rain assessments then take place after the end of the seasonal rains. These result in estimates of the affected populations and the associated funding needs, information which is then used in the donor funding appeals. It usually takes at least five months from the end of each rainy season until the newly programmed

humanitarian aid is actually delivered. Consequently, aid delivery under the current response system might fail to preserve livelihoods or even the lives of some affected populations.

### **Predictive Relationship Between Rainfall and Humanitarian Needs**

To assess how FIWDs can be designed to hedge against drought-induced famine risks in northern Kenya, we explore the predictive relationship between seasonal rains and the prevalence of severely wasted children in each subsequent dry season. For illustrative purposes, we use the cumulative long rains (mm, from March to May) and short rains (mm, from October to December) to characterize seasonal rains in each community. The area average of each of these two seasonal rains is constructed by weighted averaging across 44 communities using communities' mean proportion of severely wasted children as weights. These weighted long rains and short rains represent overall exposure to drought risk in these northern Kenya communities.

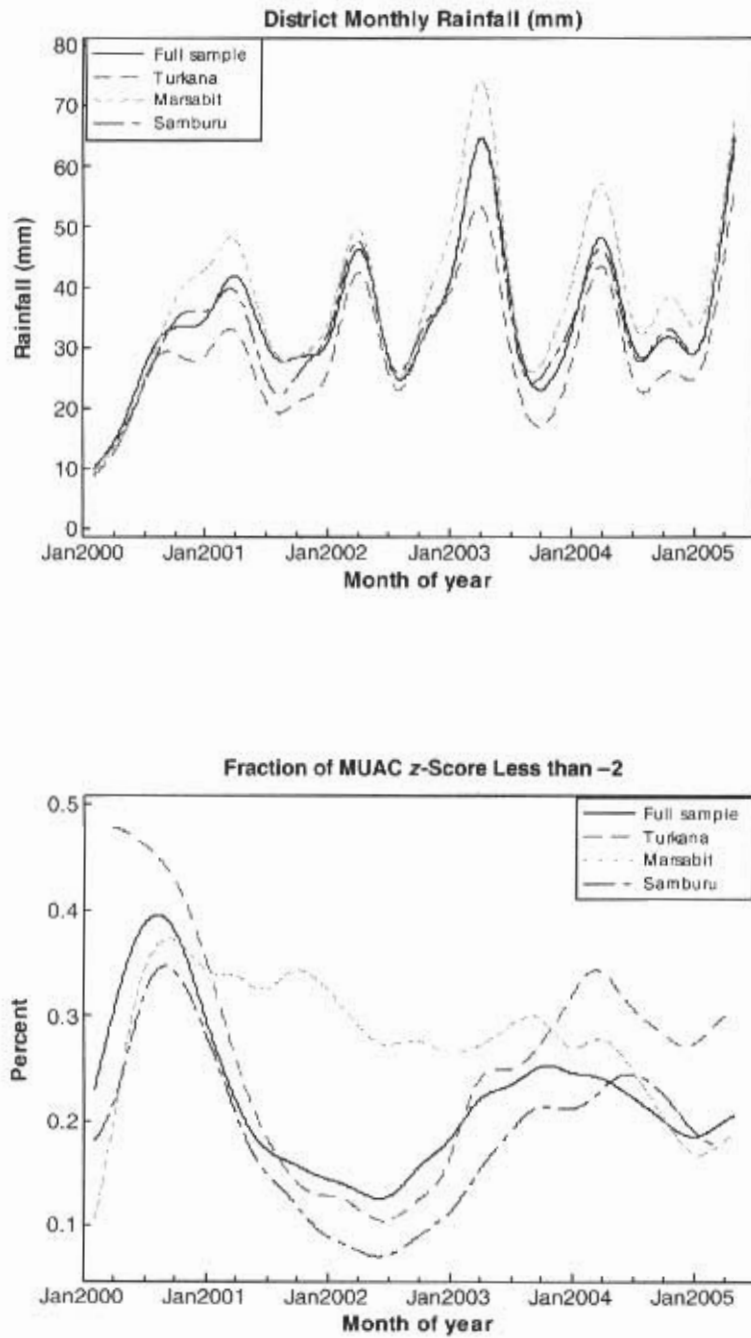


Figure 2. Kernel Density Estimations of Monthly Rainfall and Proportion of Severely Wasted Children, 2000–2005

Season	Long Dry (Hunger Period)	Short Rains	Short Dry (Hunger Period)	Long Rains	Long Dry (Hunger Period)	Short Rains	Short Dry (Hunger Period)
Month	Jun - Sep	Oct - Dec	Jan - Feb	Mar - May	Jun - Jul	Aug - Sep	Oct - Dec
Current System	Short rains forecast		Short rains assessment  Long rains forecast	Appeal	Donor Response  Long rains assessment	Aid delivery  Appeal	Donor Response  Aid delivery
System with FIWDs	Establish FIWD contract to hedge against risk of widespread acute food insecurity during the following short and long dry seasons		★ First payout  triggered at the end of short rains after the realization of cumulative short rains  Funding available for early intervention		★ Second payout  triggered at the end of long rains after the realization of both cumulative long rains and preceding cumulative short rains  Funding available for early intervention		

Figure 3. Kenya's Current Drought Emergency Response System

This area average is the appropriate measure to use to hedge against drought-induced risk since localized droughts can be managed by transferring resources from unaffected areas, and so only catastrophic droughts that affect most of the areas need to be transferred.<sup>18</sup>

Table 1 reports sample district-level and overall (basket weighted)-level statistics of the proportion (%) of severely wasted children averaged over short dry (January-February) and long dry (June-September) periods, cumulative long rains (mm), cumulative short rains (mm), monthly average normalized vegetative index (NDVI, a measure of forage availability for herds), and percentage of communities experiencing failed long rains or short rains, where "failure" reflects cumulative seasonal rainfall more than one standard deviation below the community-specific long-term mean.

<sup>18</sup> Correlation coefficients of seasonal rains across these 44 communities vary from 0.16 to 0.98 for long rains and 0.33 to 0.99 for short rains.

On average, the proportion of severely wasted children is higher in the long dry period than in the short dry period (Table 1). Marsabit experienced the highest proportion of wasted children despite its more favorable rainfall. Turkana is typically the most arid district with the lowest mean cumulative short rain and the lowest monthly NDVI. Years when 100% of communities faced failed long rains are observed in all three districts. A high percentage of communities with failed short rains are also observed. On average, 26% of children are severely wasted during long dry seasons and 21% during short dry periods, with mean cumulative long rain and short rain volumes of 218 mm and 136 mm, respectively.

Taking the observed rainfall volume and temporal and spatial effects of rainfall into account, we use two consecutive preceding seasonal rains in predicting the prevalence of severely wasted children in each of the two dry seasons. Seemingly unrelated regression is applied in fitting these two relationships using six years of 44 community basket-weighted variables available from the 2000-2005 ALRMP data.

**Table 1. Sample Statistics of Weather and Proportion of Severely Wasted Children**

District	Statistics	Short Dry (% MUAC $z < -2$ )	Long Dry (% MUAC $z < -2$ )	Long Rain (mm)	Short Rain (mm)	Percent Failed LR (%)	Percent Failed SR (%)	NDVI
<b>Marsabit</b> 9 communities	Mean	0.20	0.29	233	162	14	15	0.32
	Std. Dev.	0.11	0.04	86	70	30	27	0.15
	Minimum	0.00	0.24	53	8	0	0	0.09
	Maximum	0.31	0.35	454	327	100	100	0.69
<b>Samburu</b> 14 communities	Mean	0.16	0.22	214	144	15	15	0.29
	Std. Dev.	0.07	0.11	84	68	27	27	0.12
	Minimum	0.09	0.07	62	12	0	0	0.05
	Maximum	0.26	0.38	417	313	100	93	0.64
<b>Turkana</b> 21 communities	Mean	0.25	0.26	217	119	16	10	0.22
	Std. Dev.	0.09	0.12	59	66	26	17	0.12
	Minimum	0.14	0.10	78	20	0	0	0.05
	Maximum	0.34	0.46	317	395	100	67	0.62
<b>All (weighted)*</b> 44 communities	Mean	0.21	0.26	218	136	15	13	0.26
	Std. Dev.	0.09	0.10	69	62	25	21	0.14
	Minimum	0.00	0.07	66	15	0	0	0.05
	Maximum	0.34	0.46	371	344	100	82	0.69

Notes: Proportion of severely wasted children (% MUAC  $z < -2$ ) statistics are from 2000-2005, rainfall statistics are from 1961-2006, and normalized vegetative index (NDVI) statistics are from 1990-2005.

\* Forty-four communities are weighted using their mean proportion of children with MUAC  $z < -2$  in dry seasons.

The estimated forecasting model of basket-weighted proportion of severely wasted children in the long dry season is written as:

$$(8) \ln(F_{LD})_t = 3.607 - 0.619 \ln(LR)_t - 0.177 \ln(SR_{-1})_t - 0.224 \ln(AID_{LD})_t + \varepsilon_t$$

(2.34) (0.13) (0.35) (0.07)

$$R^2 = 0.753.$$

Standard errors are reported in parentheses,  $F_{LD}$  is the proportion (%) of severely wasted children averaged over the long dry season (June-September),  $LR$  denotes the cumulative long rains (mm),  $SR_{-1}$  represents the immediate leading cumulative short rains (mm) of the preceding year,  $AID_{LD}$  is the basket-weighted average of communities' mean quantity of food aid (kg) received per household per year calculated from October of the preceding year to September (the end of the long dry period), and  $t$  represents time in years.

Similarly, the forecasting model for proportion of severely wasted children in the short dry period is expressed as:

$$(9) \ln(F_{SD})_t = 5.28 - 0.248 \ln(LR_{-1})_t - 1.113 \ln(SR_{-1})_t - 0.119 \ln(AID_{SD})_t + \varepsilon_t$$

(2.60) (0.247) (0.52) (0.15)

$$R^2 = 0.563.$$

Standard errors are given in parentheses,  $F_{SD}$  is the proportion (%) of severely malnourished children averaged over the short dry season (January-February),  $LR_{-1}$  represents the cumulative long rains (mm) of the preceding year, and  $AID_{SD}$  is the mean quantity of food aid (kg) received per household per year calculated from March of the preceding year to February (the end of the short dry period).

The above model specifications were used in this illustrative case for a variety of reasons. First, the basket-weighted average covariates represent the weighted

aggregate of the overall exposure to drought-induced famine risks in the communities under study. Second, the coefficients are consistent with our priors about the relationship between rainfall and malnutrition. Third, the estimated parameters showed reasonable statistical significance, even though the number of observations was very low. Fourth, the model selected was the best of many models examined. Finally, although our data were obtained from a large number of monthly observations, we were limited in time to annual counts of the proportion of wasted community children to six annual measures. This is a data limitation that will be overcome in time,<sup>19</sup> but for the purely illustrative purposes of this paper and the FIWD concepts and pricing methods it introduces, there is no better measure to directly predict prevalence and degree of food insecurity, and we would rather err on the side of precision.

We should also explain that food aid variables were included in these forecasting models purely to control for (a) non-weather effects (e.g., disease, conflict) that matter to the variability of the proportion of severely wasted community children, and (b) pre-programmed food aid flows (e.g., school feeding and other non-emergency food aid as well as food aid resulting from prior years' appeals).<sup>20</sup> The predictive relationships between the two preceding seasonal rains and the prevalence of severely wasted children conditional on an ex ante expectation of a food aid pipeline now can be used to develop a parametric famine index for FIWDs.

According to (8), a 1% increase in the basket-weighted long rains will decrease the overall proportion of severely wasted children by 0.619%, whereas a 1%

increase in short rains will decrease the malnutrition proportion by 0.177%. Clearly, the influence of the long rains is more indicative of wasting in the long dry season than the prior fall short rains. And as expected, (9) also suggests that the preceding short rains seem to have a more significant impact on malnutrition status in the short dry period compared to the preceding long rains. Nonetheless, with significantly different impacts, two preceding seasonal rains are both critical predictors of short dry seasons' prevalence of severely wasted children. The combination of these two rain events characterizes a joint weather-event trigger for derivative contracts.

### Designing Famine-Indexed Weather Derivatives for Northern Kenya

Using the forecasted proportion of severely wasted children as an indicator of acute food insecurity, the famine index derived from the predictive relationship in (8) for the long dry season is thus  $F_{LD} = 36.845 LR^{-0.619} SR_{-1}^{-0.177} AID_{LD}^{-0.224}$ . Holding the prevalence of child malnutrition constant at  $F_{LD}^*$ , and incorporating the food aid variable based on ex ante expectation of  $\overline{AID}_{LD}$  (40 kg/household food aid in the preexisting pipeline)<sup>21</sup> into the intercept, we use:

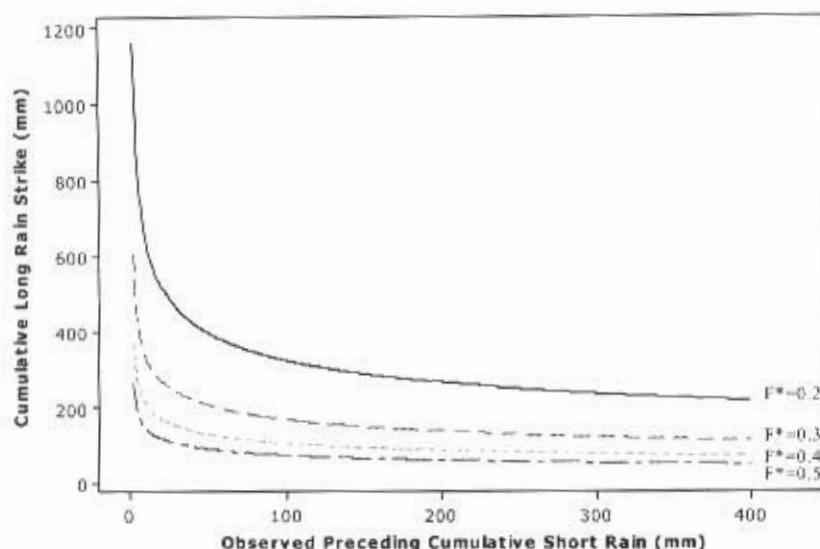
$$(10) \quad LR^*(SR_{-1}(F_{LD}^*)) = \left[ \frac{36.845 \overline{AID}_{LD}^{-0.224} SR_{-1}^{-0.177}}{F_{LD}^*} \right]^{1/0.619}$$

to obtain the conditional trigger of cumulative long rains contingent upon the already observed outcome of the preceding cumulative short rains. Critically important is the inclusion of the famine index, in terms of proportion of wasted children ( $F_{LD}^*$ ), not as an outcome, but as a policy variable. Here (10) represents what we will refer to as an iso-food insecurity index curve, as depicted in Figure 4.

<sup>19</sup>Phase two of the ALRMP project from 2005 onward continues to collect data from these communities.

<sup>20</sup>The weighted average yearly food aid variables used are not statistically determined by the prevalence of severely malnourished children in dry seasons. Thus, reverse causality does not appear to be an issue in these data.

<sup>21</sup>The level of food aid at 40 kg/household/year, used here for illustrative purpose, is approximately a 75% standard deviation below the 2000–2005 mean.



Note: Calculations are based on ex ante expectation of food aid delivery of 40 kilograms per household per year.

**Figure 4. Iso-Food Insecurity Index Relations for Hedging Against Levels of Prevalence of Severely Wasted Children ( $F^*$ )**

This is similar to an isoquant in classical production economics. At a particular level of expected aid delivery, this curve shows the loci of strike or trigger long rain levels,  $LR^*(SR_{-1}(F_{LD}^*))$ , given an observed preceding  $SR_{-1}$  that probabilistically leads to a level of prevalence of severely wasted children  $F_{LD}^*$  in the long dry season. It can therefore serve as an early warning mechanism for slow-onset food crises.

The critical calculus is

$$\frac{\partial LR^*(SR_{-1}(F_{LD}^*))}{\partial F_{LD}^*} < 0,$$

and so as the chosen level of prevalence of severely wasted children to hedge against ( $F_{LD}^*$ ) increases, the long rain trigger decreases. This is depicted in Figure 4 as a downward shift in the iso-food insecurity index curve. In addition,

$$\frac{\partial LR^*(SR_{-1}(F_{LD}^*))}{\partial SR_{-1}} < 0$$

indicates that as the observed preceding short rain increases, the long rain strike required to hedge against a given level of

prevalence of severely wasted children ( $F_{LD}^*$ ) is lower. Thus, the long rain strike  $LR^*(SR_{-1}(F_{LD}^*))$  is determined jointly by the random outcome in the preceding short rains and the chosen level of  $F_{LD}^*$ .

The meaning of  $F_{LD}^*$  is critical. Like a deductible in conventional insurance, the choice of  $F_{LD}^*$  represents the level of food insecurity for which the government or operational agencies can provide assistance using existing resources (food and cash) but above which additional resources will be needed. Hence, if  $F_{LD}^* = 0.3$ , the iso-food insecurity index curve determines the boundary of short and long rain combinations, below which prevalence of wasted children  $F_{LD}^* > 0.3$  could arise probabilistically. In other words, to ensure that cash for emergency food relief is available for early prevention of the predicted prevalence of severe child malnutrition beyond a prespecified level  $F_{LD}^*$  in the long dry season, this model is equivalent to a random strike model, with the indemnity payout at the end of the long rain established by  $\Pi = \text{Max}[C(LR^*(SR_{-1}(F_{LD}^*)) - LR), 0]$ .

Here,  $C(\cdot)$  links the particular prevalence and severity of child wasting resulting from a long rain shortfall to the appropriate dollar amount of humanitarian assistance needs and the long rain strike  $LR^*(SR_{-1}(F_{LD}^*))$  below which the contract triggers a payout. Importantly, its determination is based on the realization of the preceding cumulative short rain.<sup>22,23</sup>

For illustrative purposes, we consider a derivative contract written before the short rain period (in September) to hedge against the potential widespread food insecurity event in the short dry season (during January-February of the following year) as well as the long dry (June-September of the following year) season. The specific instruments we investigate first are index insurance contracts with:

$$(11) \quad \Pi_{SD(t)} = \$1,000,000 + 1_{(SR_t < 65 \text{ mm})},$$

$$(12) \quad \Pi_{LD(T)} = \$1,000,000 \\ + \text{Max}\left\{\left[LR^*(SR_{-1}(F_{LD}^*)) - LR\right]^x, 0\right\},$$

$$(13) \quad \Pi_T = e^{-r(T-t)} + \Pi_{SD(t)} + \Pi_{LD(T)},$$

where (11) is a binary option with an indemnity paid out at the end of the short rain season (in January) if there is a severe shortfall in the cumulative short rain below 65 mm. This indemnity structure takes into account the need for an immediate cash payout to finance early intervention should weak short rains lead to a catastrophic food crisis in the short dry period.<sup>24</sup>

<sup>22</sup> Random strike models are useful when there is a causal intertemporal relationship between one weather event and a subsequent event on a particular outcome. See Turvey, Weersink, and Chiang (2006) for an example of a random strike price in a different context.

<sup>23</sup> A similar procedure could be used to derive an indemnity structure for hedging against prevalence of widespread child wasting in the short dry season based on a random short rain strike conditional on the observed preceding long rain. However, our investigation indicates that prevalence is established relative to the short rains.

<sup>24</sup> The short rain strike of 65 mm is obtained in similar fashion to that of  $LR^*(SR_{-1}(F_{LD}^*))$ . Specifically, the short rain strike conditional on the preceding long rain outcome observed before the start of the contract can be written as follows:

Equation (12) is the main indemnity structure and the primary vehicle for the famine insurance product for hedging widespread food crisis in the critical long dry season. It holds a tick of \$1 million for every millimeter of long rain falling below the strike,  $LR^*(SR_{-1}(F_{LD}^*))$ . The payoff may be raised to the power  $x$ , which increases this payoff fractionally as the long rain shortfall increases. The idea here is that there is a nonlinear relationship between drought and prevalence of child malnutrition, with the risk of famine increasing convexly with respect to decreases in rainfall.

The total indemnity payoff at the end of the contract is thus provided in (13) by adding the value of the short dry indemnity paid immediately after the short rain season adjusted for time value by discount factor  $r$ , and the long dry indemnity paid at the end of the long rain season, which is assumed to be the end of the contract. A cap ( $\bar{\Pi} \geq 0$ ) on the maximum indemnity payout can be applied in order to limit the insurer's losses so that the total payout at the end of the contract ( $T$ ) becomes:

$$(14) \quad \Pi_{capped} = \text{Min}\left[e^{-r(T-t)} + \Pi_{SD(t)} + \Pi_{LD(T)}, \bar{\Pi}\right].$$

Next, we consider the simple one-year, zero-coupon famine bond with principal  $P$ , rate of required return  $r$ , and an indemnity payout structure  $\Pi_{capped}$  described in (14) and capped at  $\delta\%$  of the principal. We then price this based on:

$$(15) \quad B(0, T) = e^{-rT} + [P - \Pi_{capped}],$$

where  $\bar{\Pi} = \delta P$ .

The famine bond is initially sold at a discount. The bondholder's realized annual return if the insurance indemnity is not triggered is therefore the difference

$$SR^*(LR_{-1}(F_{SD}^*)) = \frac{196.429 \bar{AID}_{SD}^{-0.119} LR_{-1}^{-0.248} (1/1.113)}{F_{SD}^*}$$

The strike  $SR^*(LR_{-1}(F_{SD}^*)) = 65$  mm is based on the expectation of  $\bar{AID}_{SD} = 75$  kilograms per household per year,  $F_{SD}^* = 0.3$ , and an average long rain of 210 mm.

between the principal and the purchased bond price. The structure of these famine-indexed weather derivative contracts is shown in Figure 3. The next section analyzes the expected payoffs from contracts with various combinations of these factors.

### Famine-Indexed Weather Derivatives Pricing

We present the pricing results from the insurance product first and the famine bond second. As discussed previously, the two are related in that it is the indemnity structure of the weather insurance product which determines the discount on the famine bond.

Two methods are used for purposes of comparison. In the top panels of Tables 2, 3, and 5, the results are derived using a burn rate approach, which is based on the actual historical outcomes from 46 years of rainfall data. The bottom panels are based on 50,000 Monte Carlo simulations using the best fit distributions for basket-weighted cumulative short rain ( $\text{gamma}(8.0525, 21.279)$ ) and cumulative long rain ( $\text{lognormal}(3.357.6, 68.56)$ ).<sup>25</sup>

The long rain strike used throughout these results is based on a minimal level of food aid delivery of 40 kilograms per household per year, about a 75% standard deviation below its 2000–2005 mean. The insurance indemnity payouts are based simply on the parameter  $\alpha = 1$ , so payouts are linearly related to rain shortfall relative to the trigger level. The tables present the expected indemnity payoff for index insurance contracts in order to reflect the value of the products as determined by the distribution of short and then long precipitation risk. Actuarially fair premiums can be derived easily by discounting these expected payoffs with an appropriate discount rate.

<sup>25</sup> Distributions are written as  $\text{gamma}(\alpha, \beta)$ , where  $\alpha > 0$  determines shape or skewness and  $\beta > 0$  determines scale or width of the distribution, and  $\text{lognormal}(\mu, \sigma)$  with parameters for mean and variance, respectively.

For the insurance contracts for hedging against a given level of child wasting prevalence  $F^*$  defined from 0.2 to 0.5 for each column, the expected long rain strike decreases from 308.6 to 70.2 millimeters (Tables 2 and 3). Specifically, the higher the level of malnutrition prevalence one wants to hedge against, the lower is the likelihood and magnitude of contract payout. The expected payoffs in the long dry season (contingent on conditional long rain strike) therefore decrease substantially as the level of  $F^*$  increases. These values range from about \$97.2 million and \$95.6 million for  $F^* = 0.2$ , to \$3,532 and \$388,426 for the burn and Monte Carlo estimates, respectively, at the higher level of  $F^* = 0.5$  with much rarer trigger probability (Table 2).

According to the 46-year historical data, the contract covering  $F^* = 0.5$  made one payout in the year 2000, the worst drought in the past 40 years in Kenya. In contrast, the fact that the contract covering  $F^* = 0.2$  triggered payouts in 39 out of 46 years is expected, as the average proportion of severely wasted community children in these particular districts of Kenya is already as high as 0.26 in the long dry season. Two payouts were made (in 1997 and 2000) at  $F^* = 0.45$  and  $F^* = 0.4$ , implying a frequency of one in 23 years.

The contingent claim on short rains failure occurs only under severe conditions (specifically in 1970, 1997, and 2005, coinciding with the historical record of devastating droughts due to short rains failure). The payoff of \$65,217 based on historical measures compares to \$102,780 using the Monte Carlo simulation, suggesting the best fit distribution is skewed more negatively than history might have recorded. The total expected payoffs from contingencies on both short and long rains range from \$97.3 million to \$70,929 using the burn approach and \$95.7 million to \$494,634 using the Monte Carlo approach (Table 2).

The range of payoffs is much higher using the Monte Carlo approach. The differences between the burn approach and the Monte

**Table 2. Weather Index Insurance Expected Payoff Statistics, 1961–2006**

Pricing Method	Famine Trigger ( $F^*$ ), where Strike $SR^* = 65$ mm						
	0.2	0.25	0.3	0.35	0.4	0.45	0.5
<b>Historical Burn Rate<sup>a</sup></b>							
Expected Strike $LR^*$ (mm)	308.61	215.21	160.30	124.96	100.72	83.26	70.23
Expected <i>SD</i> Payoff (\$)	65,217	65,217	65,217	65,217	65,217	65,217	65,217
Expected <i>LD</i> Payoff (\$)	97,220,597	29,505,197	10,353,626	4,055,296	1,425,886	600,631	3,532
Expected Total Payoff (\$)	97,287,994	29,572,594	10,421,023	4,122,693	1,493,283	668,028	70,929
Std. Dev. Total Payoff (\$)	81,419,233	49,554,422	27,145,007	13,906,329	6,969,875	3,023,025	272,219
Minimum Payoff (\$)	0	0	0	0	0	0	0
Maximum Payoff (\$)	374,106,609	205,193,020	113,205,263	69,259,487	39,104,762	17,402,449	1,195,889
<i>SD</i> Triggered Years	3	3	3	3	3	3	3
<i>LD</i> Triggered Years	39	23	10	5	2	2	1
<b>Monte Carlo Simulation<sup>b</sup></b>							
Expected Strike $LR^*$ (mm)	308.16	214.90	160.07	124.77	100.58	83.15	70.13
Expected <i>SD</i> Payoff (\$)	102,780	102,780	102,780	102,780	102,780	102,780	102,780
Expected <i>LD</i> Payoff (\$)	95,571,430	28,752,950	8,916,012	3,218,886	1,350,931	690,477	388,426
Expected Total Payoff (\$)	95,677,680	28,859,160	9,022,220	3,325,094	1,457,118	796,706	494,634
Std. Dev. Total Payoff (\$)	76,621,900	45,106,260	24,514,640	14,297,660	8,521,659	5,823,947	4,233,706
Minimum Payoff (\$)	0	0	0	0	0	0	0
Maximum Payoff (\$)	996,512,400	648,651,000	542,513,000	599,369,000	432,394,500	194,205,900	116,622,200

Notes: The expected total payoffs are calculated at the end of the contract, where the expected *SD* payoffs are brought forward using an 8% rate of return. The actuarial fair premium can be calculated by discounting the expected total payoff with the appropriate discount rate.

<sup>a</sup> The historical burn rate is based on actual historical outcomes from 46 years of rainfall data.

<sup>b</sup> The Monte Carlo simulation is based on 50,000 simulations using the best fit distributions.

Carlo approach are due to the sampling frame. The burn approach assumes that all possible outcomes are contained within the history of the sample, while the Monte Carlo approach, driven by a defined distribution, assumes the existence of rarer events on the downside which were not realized during the historical period strata. Especially at  $F^* = 0.5$ , with only one payout triggered historically, the 50,000-iteration Monte Carlo approach would have sampled more possible severe outcomes, as rare as they might be.

The capped insurance results are reported in Table 3. The caps—ceiling of covering insurance payout that limits the insurer's loss—used were approximately 70% of the largest historical payoff. The capped products are remarkably similar, with expected payoffs (and standard deviations) between the burn and Monte Carlo approaches very close. Under the Monte Carlo approach, the effects of the caps reduced total expected payoffs from \$95.7 million to \$94.2 million for  $F^* = 0.2$ , and from \$494,634 to \$93,282 for  $F^* = 0.5$ . More generally, as the cap increases, so too would the range of payouts and hence the cost of the insurance.

The one-year catastrophe bond discounts are provided in Table 4 for various combinations of caps as a percentage of principal and various required rates of return, where the difference from the risk-free rate represents risk premiums investors required. These rates are chosen such that they reasonably represent spreads required by investors in the existing cat bond markets (according to Froot, 1999). The values in Table 4 indicate the retail price of a bond per dollar of principal. The total annual return realized by the bondholder will always be higher than the required rate of return if the triggering widespread acute food insecurity event does not occur. The difference between the two therefore represents an additional premium required associated with the catastrophic famine risk.

For example, a famine bond covering prevalence of severe wasting of  $F^* = 0.3$

with a required rate of return of 8% and cap at 30% is priced at \$0.8787 and will pay \$1 principal one year later should the famine condition not be triggered. Thus the total return realized by the investor if a critical drought event is not triggered<sup>26</sup> is 12.13%, which can be interpreted as an additional 4.13% premium associated with the famine risk contingency and above the risk premium required for other sources of risk (e.g., default risk, interest rate term structure risk, etc.). However, if triggered, principal payment decreases to as little as \$0.3 for a loss of 57.8%.

In general, for a given cap level and required rate of return, the famine bond prices decrease with the level of malnutrition prevalence to be insured against, since the lower  $F^*$  trigger means that the bond has a higher probability of triggering payout and hence is more risky. Similarly, famine bond prices decrease as the cap level increases, because the smaller proportion of repaid principal if the bond triggers translates into the higher risk of loss. And finally, it is straightforward to observe that the bond prices decrease as the required rates of return increase.

### Using Famine-Indexed Weather Derivatives to Improve Drought Emergency Response

The risk-transferring potential of the FIWD contracts proposed here vary greatly with the frequency of the extreme events as well as their degree of catastrophe. For example, as shown in Table 3, capped weather index insurance covering severe wasting prevalence  $F^* = 0.2$  results in a prohibitive premium with expected payoff of \$93.9 million. The contract triggers payout in 39 of 46 years due to the fact that the average proportion of severely wasting condition in northern Kenya is already as high as 0.26 in the long dry season.

<sup>26</sup> Equivalently, the total return of a famine bond can be interpreted as a 7.18% spread over the one-year LIBOR rate of 5.12%. The LIBOR rate is as of September 11, 2007.

**Table 3. Capped Weather Index Insurance Expected Payoff Statistics, 1961–2006**

Pricing Method	Famine Trigger ( $F^*$ ), where Strike $SR^* = 65 \text{ mm} / (\$ \text{ Cap at } 70\% \text{ of historical maximum})$						
	0.2 (\$260,000,000)	0.25 (\$140,000,000)	0.3 (\$80,000,000)	0.35 (\$50,000,000)	0.4 (\$28,000,000)	0.45 (\$10,000,000)	0.5 (\$800,000)
<b>Historical Burn Rate</b>							
Expected Strike $LR^*$ (mm)	308.61	215.21	160.30	124.96	100.72	83.26	70.23
Expected Total Payoff (\$)	93,989,039	27,253,505	9,070,036	3,701,586	1,251,876	479,714	52,174
Std. Dev. Total Payoff (\$)	72,109,066	42,354,305	22,431,866	12,060,865	5,718,127	2,063,170	199,710
Minimum Payoff (\$)	0	0	0	0	0	0	0
Maximum Payoff (\$)	260,000,000	140,000,000	80,000,000	50,000,000	28,000,000	10,000,000	800,000
<b>Monte Carlo Simulation</b>							
Expected Strike $LR^*$ (mm)	308.16	214.90	160.07	124.77	100.58	83.15	70.13
Expected Total Payoff (\$)	94,215,120	27,636,790	8,035,131	2,673,187	972,646	321,917	93,282
Std. Dev. Total Payoff (\$)	71,489,720	40,392,290	19,479,810	9,651,412	4,457,400	1,445,366	256,701
Minimum Payoff (\$)	0	0	0	0	0	0	0
Maximum Payoff (\$)	260,000,000	140,000,000	80,000,000	50,000,000	28,000,000	10,000,000	800,000

**Table 4. Zero-Coupon Famine Bond Prices for Different Bond Specifications (\$)**

Required Return	Cap (% Face)	Famine Trigger ( $F^*$ )						
		0.2	0.25	0.3	0.35	0.4	0.45	0.5
6%	30%	0.7083	0.8262	0.8959	0.9218	0.9325	0.9367	0.9382
	50%	0.5707	0.7752	0.8791	0.9160	0.9306	0.9358	0.9376
	70%	0.4502	0.7395	0.8697	0.9134	0.9296	0.9354	0.9374
8%	30%	0.6956	0.8120	0.8787	0.9040	0.9139	0.9179	0.9196
	50%	0.5611	0.7605	0.8621	0.8983	0.9118	0.9170	0.9191
	70%	0.4429	0.7238	0.8527	0.8952	0.9109	0.9166	0.9188
10%	30%	0.6819	0.7959	0.8613	0.8861	0.8958	0.8998	0.9014
	50%	0.5499	0.7454	0.8451	0.8805	0.8937	0.8988	0.9009
	70%	0.4341	0.7094	0.8358	0.8775	0.8928	0.8985	0.9006
12%	30%	0.6684	0.7802	0.8442	0.8686	0.8780	0.8819	0.8835
	50%	0.5391	0.7307	0.8283	0.8630	0.8760	0.8810	0.8830
	70%	0.4255	0.6954	0.8192	0.8601	0.8751	0.8807	0.8828

Note: Prices are based on 50,000 Monte Carlo simulations using best fit distributions.

But the results in Table 3 further suggest that early intervention at  $F^* = 0.3$  or higher (with the frequency of 10 in 46 years) may feasibly be financed using famine index insurance. The insurance contract that covers up to \$80 million requires a premium with expected payoff of approximately \$8 million. Alternatively, intervention triggered by  $F^* = 0.4$  or more (occurring in 1-2 of 46 years) also may be feasibly financed using famine bonds. At the required rate of return of 8% and with a 50% cap, famine bonds covering  $F^* = 0.4, 0.45,$  or  $0.5$  can be issued at the total rate of return of 8.82%, 8.3%, and 8.09%, respectively.

While these derivative products can be used to finance emergency response to catastrophic drought risk, coordinating them with other sources of humanitarian funding and the country's existing drought contingency resources may further enhance the potential and cost-effectiveness of the early intervention. Integrated risk financing ideas proposed by Hess, Wiseman, and Robertson (2006) and Hess and Syroka (2005) for Ethiopia and Malawi can be similarly illustrated in the context of drought emergency response financing for arid northern Kenya. Suppose early emergency response is crucial if  $F^* = 0.25$ . The financial exposure associated with the emergency intervention costs can be first layered by their frequency and level of catastrophe. The instruments covering various layers of these exposures, characterized by different conditional long rains strike and cap levels, are derived and reported in Table 5.

For illustrative purposes, financial exposure can be disaggregated into four layers and then can be managed sequentially by (a) government reserves or preestablished contingency funds, (b) contingent debt/grants, (c) famine-indexed insurance, and (d) famine bonds—which now becomes feasible for the layer of a 4-in-46-year loss event (or with approximately 8.7% probability of occurrence per year). The first layer covers the most frequent loss exposure (a 23-in-46-year loss event) and up to \$30

million. This layer covers the operational costs on the most recurrent but relatively minor losses, e.g., local droughts occurring almost every two years, which lead to an expected loss as high as \$11.67 million. The second contract covers the loss beyond the first contingency layer, up to another \$30 million. Since this layer of loss still occurs with relatively high probability, it may be too costly for any commercial risk transfer products and thus may be appropriately financed by a contingent debt or grant from development facilities available from many international financial institutions (e.g., World Bank). The expected loss of \$7.1 million will be financed in this layer.

The major catastrophic losses requiring an extensive emergency response then can be financed using index insurance or a famine (cat) bond. However, the probability of occurrence of the next layer of risk still may be too high (an 8-in-46-year loss event) to be appropriate for a cat bond. A weather index insurance contract may first be used to cover this immediate layer of losses up to \$60 million, with a premium representing expected payoff of \$7.3 million. Finally, a famine bond contract can be designed for the last, low-probability/catastrophic-loss layer, up to \$100 million in humanitarian budgetary needs.

The donor appeals process can then resume for any remaining costs not covered by these financing mechanisms (e.g., costs exceeding \$100 million or extra costs not fully captured in the derivative contracts). But with an initial, substantial funding layer in place and available for immediate payout, both the overall costs and the time pressures should be reduced, making the appeals process a viable vehicle for topping up pipelines begun through these other risk management instruments.

It is worth noting that the total drought risk financing costs will vary with the layering strategy as well as with the combinations of instruments used.

**Table 5. Layering Financial Exposure in Providing Emergency Intervention to Drought Events Using Triggering Level of Prevalence of Child Malnutrition of  $F' = 0.25$  and Strike  $SR' = 65$  mm**

Pricing Method	Layering Strike $LR'$ / (\$ Cap for $LR$ Payoff)			
	$LR'$ (\$30,000,000)	$LR'-30$ (\$30,000,000)	$LR'-60$ (\$60,000,000)	$LR'-120$ (\$100,000,000)
<b>Historical Burn Rate</b>				
Expected Strike $LR'$ (mm)	215.21	185.21	155.21	95.21
Expected Total Payoff (\$)	11,671,814	7,146,556	7,301,997	3,519,623
Std. Dev. Total Payoff (\$)	13,576,351	12,150,113	18,276,614	15,399,052
Minimum Payoff (\$)	0	0	0	0
Maximum Payoff (\$)	30,000,000	30,000,000	60,000,000	85,193,020
<b>Monte Carlo Simulation</b>				
Expected Strike $LR'$ (mm)	214.93	184.90	154.90	94.93
Expected Total Payoff (\$)	12,049,830	7,849,441	6,994,606	1,995,035
Std. Dev. Total Payoff (\$)	13,838,810	12,357,140	16,692,620	10,344,390
Minimum Payoff (\$)	0	0	0	0
Maximum Payoff (\$)	30,000,000	30,000,000	60,000,000	100,000,000

The main idea, therefore, is that contracts based on forecasted prevalence and severity of food insecurity can be designed and used as a trigger mechanism to coordinate multiple prospective sources of emergency funding in order to increase cost-effectiveness and timely response to drought-induced humanitarian disasters.

## Discussion and Implications

There is no general approach for the design and pricing of famine-indexed weather derivative contracts. This paper presents the first attempt. The results from our illustrative northern Kenya case are of course specific to the assumptions we made and replicable only over the equivalent distributions of climate and human ecology. Accordingly, it is best to focus on the principles involved and not on the specific numerical estimates. These principles and their numerical illustrations are nonetheless both important and exciting.

Our objective was to develop a weather-based famine insurance product that could be used by governments, operational

agencies, or NGOs to enhance the timeliness and reliability of funding for emergency intervention to catastrophic but slow-onset droughts. We proposed a general structure for famine-indexed weather derivatives, but emphasize two common yet critical characteristics.

- First, weather variables or event trigger(s) need to be indexed to a forecasted degree of prevalence and severity of food crisis so that they can serve as both an early warning to trigger early intervention and to provide the cash necessary for such intervention.
- Second, as delayed humanitarian assistance is costly, even deadly, contractual payouts need to be structured to cover potential emergency response over all possible vulnerable periods in the year.

FIWDs with these two features can be integrated with existing humanitarian funding facilities.

Though using the best measures available given the problem identified, the FIWDs designed for northern Kenya should be

taken as an illustrative case only and, for a variety of reasons, require further investigation if considered for real applications. First, though derivative prices are based on 46 years of high-quality rainfall data, the predictive relationship between weather and food insecurity is derived from only six years of available household data. It is therefore critical to reestimate the relationships with additional data in order to minimize potential basis risk. Second, the suitability of communities' proportion of severely wasted children (measured by MUAC z-score < -2) as a proxy for severe human suffering relies on an accurate and continued data collection process at the community level. The principles and results generated in this study emphasize the importance of and the need for improving data collection and standardization, which can strengthen the potential and feasibility of famine-indexed weather derivatives in the near future.

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