

# Prediction of a Rift Valley fever outbreak

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**El Niño/Southern Oscillation related climate anomalies were analyzed by using a combination of satellite measurements of elevated sea-surface temperatures and subsequent elevated rainfall and satellite-derived normalized difference vegetation index data. A Rift Valley fever (RVF) risk mapping model using these climate data predicted areas where outbreaks of RVF in humans and animals were expected and occurred in the Horn of Africa from December 2006 to May 2007. The predictions were subsequently confirmed by entomological and epidemiological field investigations of virus activity in the areas identified as at risk. Accurate spatial and temporal predictions of disease activity, as it occurred first in southern Somalia and then through much of Kenya before affecting northern Tanzania, provided a 2 to 6 week period of warning for the Horn of Africa that facilitated disease outbreak response and mitigation activities. To our knowledge, this is the first prospective prediction of a RVF outbreak.**

El Niño | Horn of Africa | vegetation index | risk mapping | zoonotic disease

Rift Valley fever is a viral disease of animals and humans that occurs throughout sub-Saharan Africa, Egypt, and the Arabian Peninsula. Outbreaks of the disease are episodic and closely linked to climate variability, especially widespread elevated rainfall that facilitates Rift Valley fever (RVF) virus transmission by vector mosquitoes (1–3). A RVF outbreak in 1997–1998 was the largest documented outbreak in the Horn of Africa and involved 5 countries with a loss of  $\approx 100,000$  domestic animals,  $\approx 90,000$  human infections (4), and had a significant economic impact due to a ban on livestock exports from the region (5).

The 1997–1998 epizootic/epidemic was important in explicitly confirming the links between episodic RVF outbreaks and El Niño/Southern Oscillation (ENSO) phenomena, which are manifested by episodic anomalous warming and cooling of sea-surface temperatures (SSTs) in the eastern equatorial Pacific Ocean (2). Other vector-borne diseases have also been associated with ENSO-related variations in precipitation (6–11). Concurrently, anomalous warm SSTs in the equatorial eastern-central Pacific Ocean region and the western equatorial Indian Ocean result in above-normal and widespread rainfall in the Horn of Africa (2). This excessive rainfall is the principal driving factor for RVF outbreaks there (1, 3).

Each of the 7 documented moderate or large RVF outbreaks that have occurred in the Horn of Africa (Fig. S1) over the last 60 years have been associated with ENSO-associated above-normal and widespread rainfall (Fig. S2) (2, 12). Exceptions to this association can occur, but are localized, such as the 1989 Kenyan outbreak that was related to local heavy rainfall at the focus of the outbreak (13, 14). Earth observation by satellite remote sensing over the last  $\approx 30$  years has enabled systematic mapping of driver indicators of climate variability including SST patterns, cloud cover, rainfall, and ecological indicators (primarily vegetation) on a global scale at high-temporal and moderate spatial

resolutions (2, 15–18). These systematic observations of the oceans, atmosphere, and land have made it possible to evaluate different aspects of climate variability and their relationships to disease outbreaks (16), in addition to providing valuable long-term climate and environmental data (Table S1).

In most semiarid areas, precipitation and green vegetation abundance are major determinants of arthropod and other animal population dynamics. There is a close relationship between green vegetation development and breeding and upsurge patterns of some insect pests and vectors of disease such as mosquitoes and locusts (1, 17–19). The successful development and survival of mosquitoes that maintain, transmit, and amplify the RVF virus is closely linked with rainfall events, with very large populations of mosquitoes emerging from flooded habitats after above-normal and persistent rainfall (20–22). The close coupling between ENSO, rainfall, vegetation growth, and mosquito life cycle dynamics, and improvements in seasonal climate forecasting have provided a basis for using satellite time series measurements to map and predict specific areas at elevated risk for RVF activity.

Retrospective analysis of a satellite-derived time series vegetation measurements of photosynthetic activity, known as the normalized difference vegetation index (NDVI) (23), has shown that such data, in combination with other climate variables, can be used to map areas where RVF occurred (1, 2, 12, 16, 20). In 1999, the Department of Defense Global Emerging Infections, Surveillance and Response System, in collaboration with National Aeronautics and Space Administration (NASA) Goddard Space Flight Center and the United States Department of Agriculture, initiated a program to systematically monitor and map areas at potential risk for RVF outbreaks. The program focuses on sub-Saharan Africa, the Nile Basin in Egypt, and the western Arabian Peninsula, with an emphasis on the RVF endemic region of the Horn of Africa (Fig. S1). The risk monitoring and mapping system is based on the analysis and interpretation of several satellite derived observations of SSTs, cloudiness, rainfall, and vegetation dynamics (12). These data

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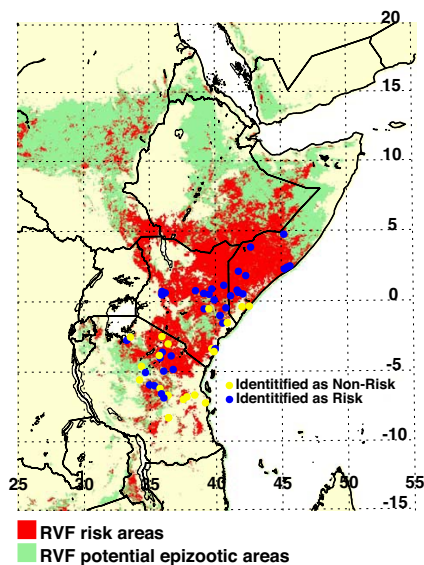
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**Fig. 7.** Overall RVF risk areas shown in red for the period September 2006–May 2007 with human case locations depicted by blue and yellow dots. Blue dots indicate areas of RVF human case locations that were mapped to be within the risk areas (red) and within the potential epizootic area (green). Yellow dots represent human case locations outside the risk areas; 64% of all human cases fell within the areas mapped to be at risk to RVF activity during this period.

specific domestic animal vaccination and mosquito control programs in at-risk areas. Starting in mid-December 2006, most of the reported human RVF cases were from eastern Kenya, especially the Garissa and Ijara districts (Figs. S8 and S9), with limited reports from Somalia, and no reports from southern Ethiopia. This lack of disease surveillance information from Somalia and southern Ethiopia was not surprising, given an ongoing conflict between Ethiopia and Somalia at this time (28).

From December 2006 to May 2007, RVF human cases were reported in Somalia (114 cases reported, 51 deaths), Kenya (684 cases reported, 155 deaths), and Tanzania (290 cases reported, 117 deaths) (28). A postoutbreak mapping of human case locations on the aggregate potential RVF risk map from September 2006 to May 2007 found 64% of the cases were reported in areas mapped to be at risk within the RVF potential epizootic area, whereas 36% were reported in adjacent areas not mapped to be at risk of RVF activity (Fig. 7). However, the spatial distribution of these case locations shows that most of the cases in nonrisk areas were in close proximity (< 50 km) to areas mapped to be at risk. Thus, we are confident that most of the initial RVF infection locales were identified.

We hypothesize that the disease outbreak was more widespread than reported, because of civil and military conflicts in the region (especially in Somalia) and limited health infrastructure in many locales. Our risk mapping predictions performed better in Kenya and Somalia than in Tanzania. This asymmetry in the performance of predictions could be due to several factors, including: (i) misclassification of the potential RVF epizootic area in Tanzania and coastal Kenya, so that areas prone to RVF

activity may not have been included; and (ii) delayed disease control response to the outbreak in Tanzania, with movement of animal and human cases outside of the affected areas. Large areas of Somalia have been subject to civil conflict over the last several years, and there is no government infrastructure in place to collect epidemiological data. Also, a number of areas in northern and eastern Kenya were inaccessible under widespread flood conditions, and there were no reports from southern Ethiopia.

## Conclusion

This report documents a prospective operational prediction of a RVF outbreak in animals and humans. As in previous RVF outbreaks in the Horn of Africa (Fig. S2), the convergence of ENSO conditions in the eastern Pacific and concurrent warming of SSTs in the western equatorial Indian Ocean region was the trigger mechanism behind this outbreak. The late 2006–early 2007 outbreak adds to the historical evidence that interannual climate variability associated with ENSO has a large influence on RVF outbreaks in the Horn of Africa through episodes of abnormally high rainfall there. This analysis demonstrates that satellite monitoring and mapping of key climate conditions and land surface ecological dynamics (Fig. S9) are an important and integral part of public health surveillance and can help reduce the impact of outbreaks of vector-borne diseases such as RVF. This is one of many societal benefits that result from a robust earth observing system that monitors key climate variables in a systematic and sustained fashion.

## Methods

We mapped and analyzed global satellite-derived time series measurements of SSTs, OLR, rainfall, and the NDVI. Indices of SSTs extracted from the eastern-central equatorial Pacific Ocean and the western equatorial Indian Ocean were used as leading indicators to show that interannual variability in SSTs associated with ENSO is an important factor driving the atmospheric response, as manifested by OLR and rainfall anomaly patterns. The land surface response to these variations in rainfall was captured through NDVI, with greener-than-normal conditions indicative of above-normal rainfall and vice versa. All data were converted into anomaly metrics expressed as differences of monthly measurements from their respective long-term mean values. The combination of excess and widespread rainfall and anomalous vegetation growth (Figs. S8 and S9) created ideal conditions for the emergence of RVF virus-carrying mosquito vectors from flooded habitats known as dambos in the Horn of Africa. The RVF risk mapping algorithm captured the persistence in greener-than-normal conditions over a 3-month period to identify areas with conditions for potential RVF activity in the RVF potential epizootic/epidemic areas within the Horn of Africa region. These mapped risk data were provided as early warning information to concerned agencies to guide vector surveillance and control, and to structure other mitigation activities. The risk mapping was implemented dynamically by using a 3 month moving window with early warnings issued routinely every month to keep track of changing climatic and ecological conditions, and consequently the changing nature of areas at risk for RVF activity in the disease endemic region through time.

For detailed data sources, methods, and analysis descriptions, see *SI Materials and Methods*.

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