Climate Change, Extreme Weather Events, and Fungal Disease Emergence and Spread

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Abstract: *Empirical evidence from multiple sources show the Earth has been warming since the late 19th century. More recently, evidence for this warming trend is strongly supported by satellite data since the late 1970s from the cryosphere, atmosphere, oceans, and land that confirms increasing temperature trends and their consequences (e.g., reduced Arctic sea ice, rising sea level, ice sheet mass loss, etc.). At the same time, satellite observations of the Sun show remarkably stable solar cycles since the late 1970s, when direct observations of the Sun's total solar irradiance began. Numerical simulation models, driven in part by assimilated satellite data, suggest that future-warming trends will lead to not only a warmer planet, but also a wetter and drier climate depending upon location in a fashion consistent with large-scale atmospheric processes. Continued global warming poses new opportunities for the emergence and spread of fungal disease, as climate systems change at regional and global scales, and as animal and plant species move into new niches.*

Our contribution to this proceedings is organized thus: First, we review empirical evidence for a warming Earth. Second, we show the Sun is not responsible for the observed warming. Third, we review numerical simulation modeling results that project these trends into the future, describing the projected abiotic environment of our planet in the next 40 to 50 years. Fourth, we illustrate how Rift Valley fever outbreaks have been linked to climate, enabling a better understanding of the dynamics of these diseases, and how this has led to the development of an operational predictive outbreak model for this disease in Africa. Fifth, We project how this experience may be applicable to predicting outbreaks of fungal pathogens in a warming world. Lastly, we describe an example of changing species ranges due to climate change, resulting from recent warming in the Andes and associated glacier melt that has enabled amphibians to colonize higher elevation lakes, only to be followed shortly by the emergence of fungal disease in the new habitats.

1.Introduction: Observational Evidence for Global Warming

Among many non-scientists, there appears to be controversy over climate change and its causes. This is paradoxical because there is little debate over human caused climate change within academic communities, except for some peripheral issues, as noted by Lockwood (2009) and others. Let us look to observational evidence from multiple and different sources to better understand climate change and its implications in this persisting pseudo-controversy (figure 1).

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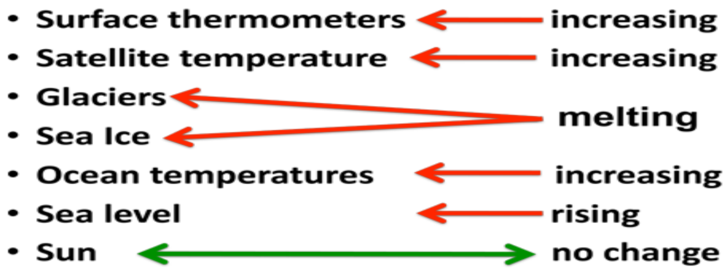

Figure 1. Summary of observations that show the Earth is warming (red arrows) while the Sun has been constant over the same period of time (Tucker NASA/GSFC).

There are a number of methods used to collect consistent and long-term datasets to monitor Earth's properties. Observations of temperatures by thermometers at the surface and by satellite microwave "sounding" of atmospheric temperature profiles are important components of our understanding global temperature. Since 2003, we are able to measure ocean temperatures profiles using the ARGO global array of 3,000 free-drifting robotic probes that measure the temperature and salinity of the upper 2000 m of the ocean. This provides continuous monitoring of ocean temperature, salinity, and currents with all data made publicly available within hours after collection (Wells et al. 2009, Lyman et al. 2010). The ARGO data are fundamental to climate studies because the oceans absorb ~ 90% of the heat from global warming.

We can measure the extent of glaciers and their variation over time, frequently drawing upon historical paintings, photographs, maps, and satellite image archives to determine if they are getting smaller or larger. We also measure the extent of sea ice weekly and monthly using passive microwave radiometers. More recently, we are able to measure ice mass variations for the Greenland and Antarctic ice sheets, using gravity data from the joint US-German Gravity Recovery and Climate Experiment (GRACE) satellite mission (Swenson and Wahr 2002).

We have measured sea level globally since 1993 using radar altimeters onboard satellites. Sea level is an unequivocal proxy for global warming: as the Earth warms, sea level rises; as it cools, sea level falls. Lastly, since 1979 we have been able to measure the Sun's energy output using satellites above the Earth's surface. The convergence of observational evidence from all of these sources makes a compelling case that the Earth is warming and this warming is not due to the Sun.

2. Convergence of Observations Showing Global Warming

A. Surface Thermometers

There are four global surface temperature data sets available from the following locations: NASA/Goddard Institute of Space Studies (Hansen et al. 2010), NOAA's National Climatic Data Center (Smith et al. 2008), the University of East Anglia's Climate Research Unit (Rayner et al. 2006), and the Japanese Meteorological Agency (http://www.jma.go.jp/jma/indexe.html). These four data sets all use the same input data and differ only in interpolation techniques between sparse observations, how the polar regions are treated, and the reference period for which means are calculated. Not surprisingly, they are very similar (figure 2).

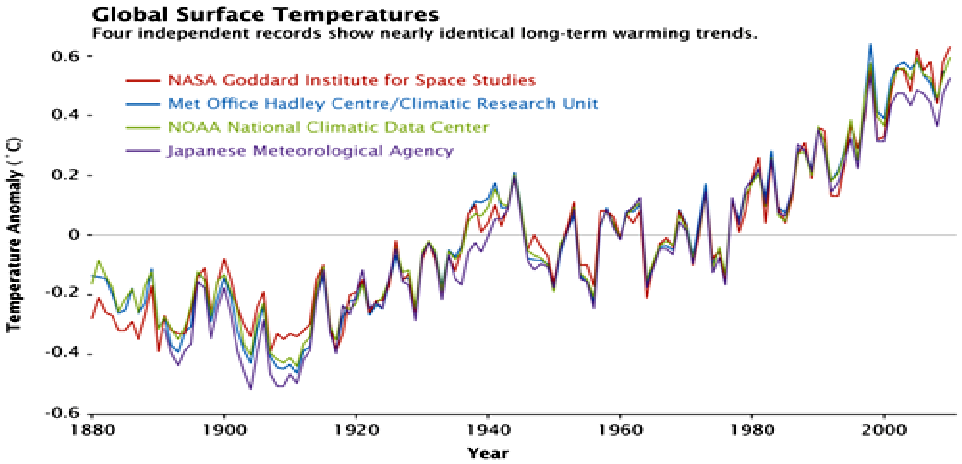

Figure 2. A comparison of the existing four global surface temperature data sets that are used in climate analyses. These data sets are based upon the same input data and differ by interpolation among stations, treatment of missing data, and the length of the record. The data in this figure have been adjusted to a common baseline period (James Hansen NASA/GISS).

B. Atmospheric temperature profiles

Since late 1978, polar-orbiting satellites have provided global air temperature profiles with altitude or “soundings” using passive microwave radiometers operating between 23 and 89 GHz frequencies. These measurements started with the microwave sounding unit instruments and were followed by the advanced microwave sounding unit instruments that began operation in 1988. As is not uncommon in science, early work using atmospheric temperature soundings produced a range of temperature trends. Recent work on atmospheric temperatures has shown no reasonable evidence of disagreement between these measurements and surface observations (Thorne *et al.* 2011).

C. Arctic Sea Ice

Satellite observation of sea ice is accomplished with a very high degree of accuracy. This results from spectral emissivity differences between open water (~0.4-0.5) and sea ice (~0.9-1.0) at a wavelength of 1.5 cm (Kwok 2002). Furthermore, passive microwave radiometers are translucent to clouds, are weather insensitive, and operate from a polar orbit that provides near daily observations of Arctic sea ice. All months (i.e., all Januaries, all Februaries, all Marches, etc.) show declining Arctic sea ice with time from the late 1970s to 2010/2011 (National Snow and Ice Data Center 2011, http://nsidc.org/arcticseaicenews/).

D. Sea Level

Sea Level is of direct interest to climate science because it varies directly with global mean temperature over short time scales. Temperature affects sea level through two mechanisms: (1) sea level rises through the thermal expansion of water as it warms; or it falls through thermal contraction of water as it cools; and (2) warmer global temperatures melt ice stored on land in glaciers and ice sheets and the resulting ice loss raises sea level, while cooler global temperatures result in more water being stored on land in glaciers and ice sheets and sea level falls. Thus sea level variations are an excellent unambiguous indicator of planetary cooling or warming. For example, at the last glacial maximum, occurring before 20,000 years ago, sea level was >100 m lower than it is at the present time (Clark et al. 2009). This huge quantity of water was stored on land in the form of glaciers and ice sheets (Lambeck et al. 2010).

Although tide gauges provide centennial-scale sea level records from close to ten locations around the world, these few locations are insufficient for a global study of sea level. Researchers have also measured vertical accretion rates in salt marshes as a sea level proxy, using radiocarbon, pollen, foraminifera, and other markers (reviewed in Mitchum et al. 2010). Since 1993, however, radar altimeters have measured sea level globally and directly with a high precision (figure 3).

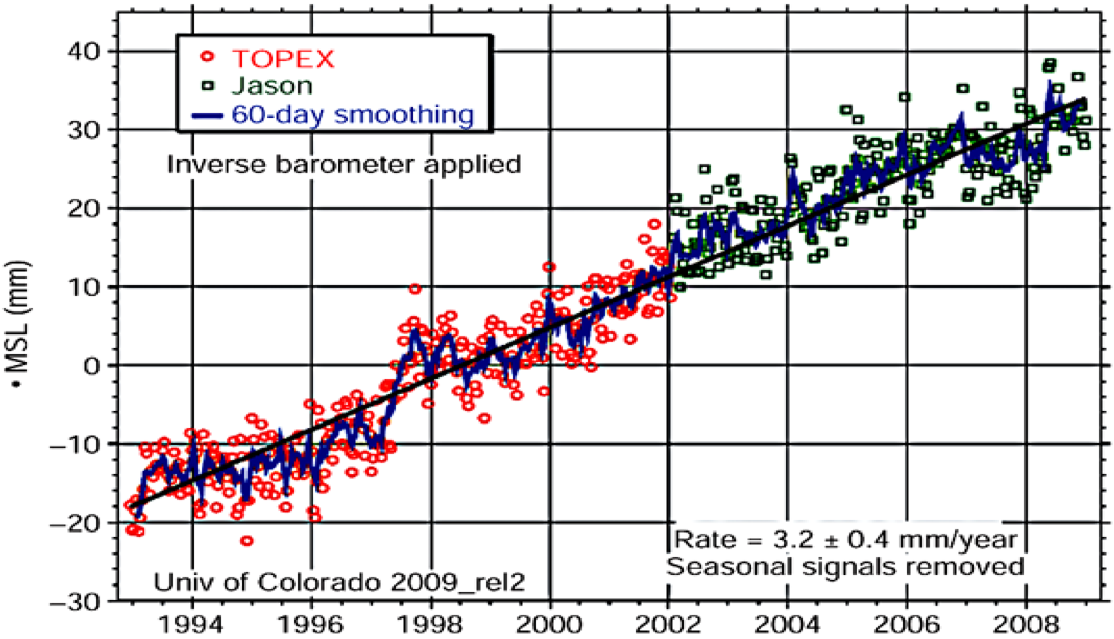

Figure 3. Sea level rise based upon radar altimeters from TOPEX and Jason with seasonal variations removed (Mitchum et al. 2010).

We have briefly reviewed global surface thermometer data, atmospheric temperature profile data from satellites, variations in Arctic sea ice, and sea level data. All of these data unambiguously show the effects of increasing global temperatures.

3. Earth's Climate and the Sun

Since the late 1970s, the study of the Sun with instruments on satellites has progressed with continuous observations being collected. Lockwood and Frohlich (2007 and 2008) have shown that the three mechanisms where the sun can influence the Earth's temperature (total solar irradiance, changes in the spectral distribution of solar irradiance, and the solar wind-magnetic field-cosmic ray-cloud hypothesis) have all been opposite to the observed increases in temperatures (Figure 4). The Sun's output is currently at record low values since the satellite era began in the late 1970s (Lockwood 2010).

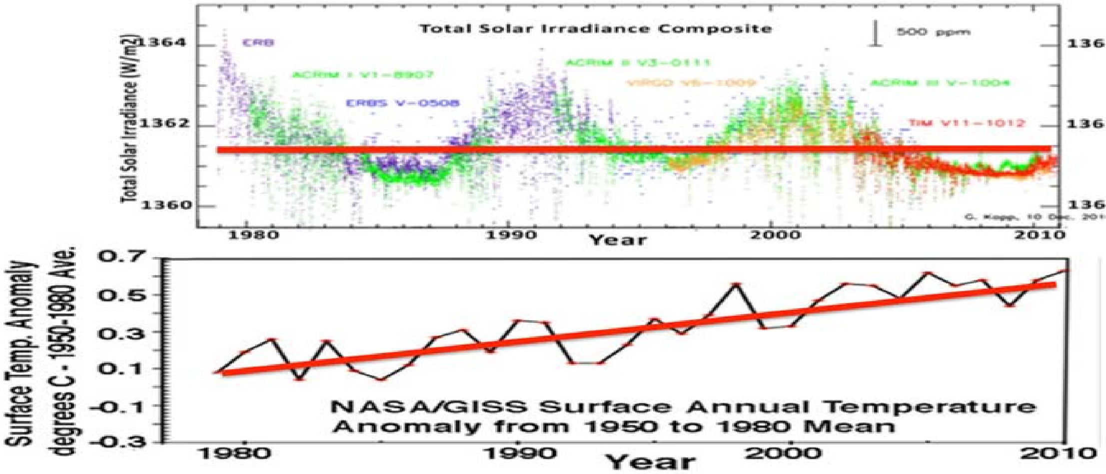

Figure 4. A comparison between the total solar irradiance (top) and the NASA/GISS surface temperature data (bottom), both from 1979 to 2010. Note the stability of the total solar irradiance and the increasing surface temperature data. This shows the sun is not responsible for the 1979 to 2010 increased surface temperatures (Tucker NASA/GSFC).

Thus the Sun is not to blame for the observed global warming since the late 1970s to the present.

4. Projections of Warming Trends Upon Weather and Climate

Numerical simulation models of the Earth's weather and climate are called general circulation models because they simulate the circulation of the atmosphere. They are representations of the ocean, land, sea ice, and atmosphere where the Earth is a series of grid cells driven by energy, moisture, and pressure. Each grid cell interacts with adjacent cells horizontally and vertically to simulate climate (figure 5). Model interactions are governed by systems of differential equations and incorporate climate forcing factors such as land cover change, volcanic aerosols, and increasing greenhouse gas concentrations. Weather and climate models have been shown to be realistic at reproducing the global temperature and precipitation patterns of the 20th century and are widely used in weather and climate research (Delworth et al. 2006).

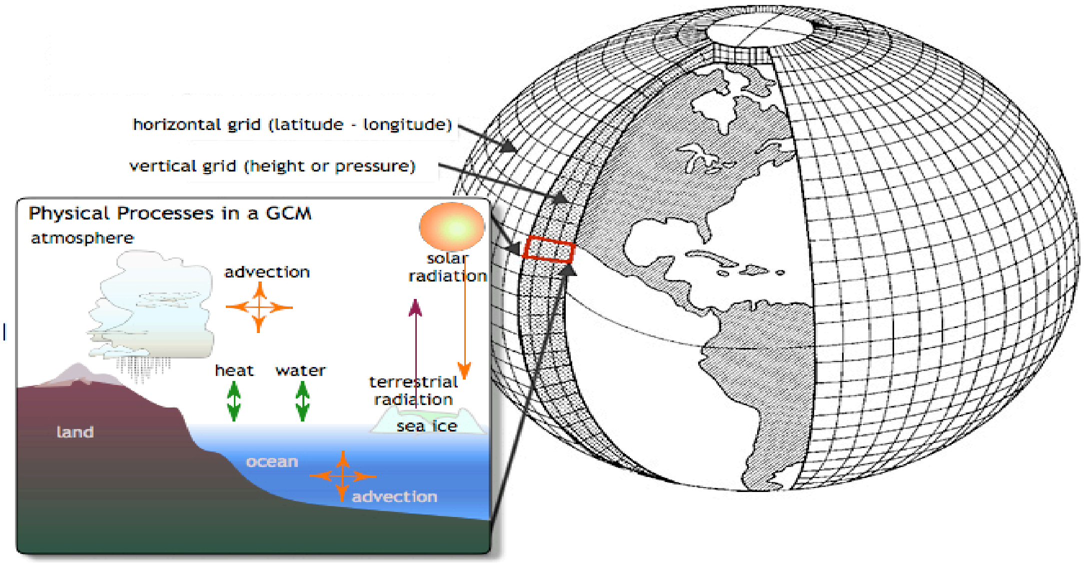

Figure 5. Representation of a general circulation model illustrating the grid cell nature of the model on the right, while on the left, many of the different important components of these models are shown (from Colorado State University http://www.cmmap.org/learn/modeling/whatIs2.html)

Climate model simulations, incorporating increasing greenhouse gas concentrations in the atmosphere, have been used to extrapolate precipitation patterns into the 21st century as surface temperatures increase. Several of these climate model simulation predictions can be described as "*the wet getting wetter and the dry getting drier*" (Held and Soden 2006). The displacement of arid and semi-arid zones northward results from an expansion from the Hadley circulation cell under global warming (Figure 6) (Lu et al. 2007). These changes in climate have direct impacts on vegetation and biodiversity across the globe, including species range shifts, changing phenology, new invasive species, and new disease outbreaks (Parmesan and Yohe, 2003; Walther et al., 2002).

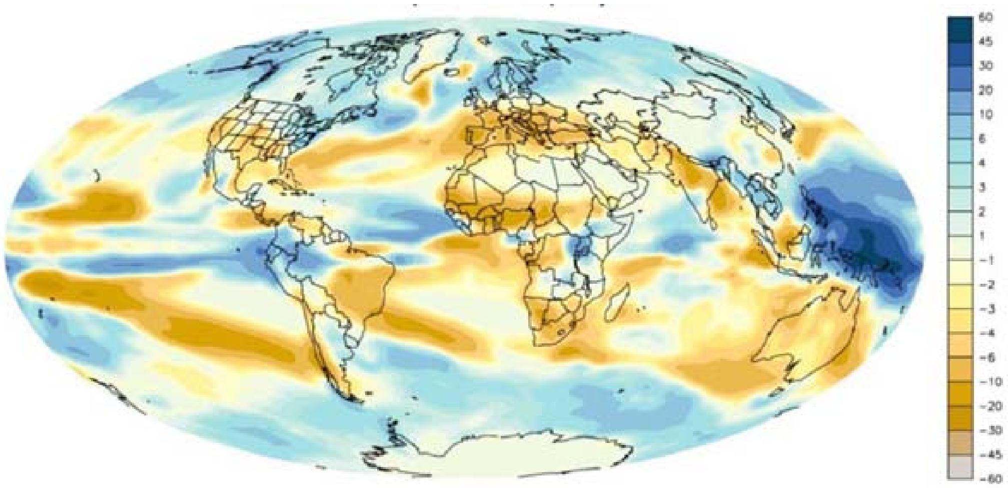

Figure 6. Change in precipitation between the 1971 – 2000 average and the 2091 to 2100 average in inches of liquid water/year (Held et al. 2006).

5. Linkages between Vector and Non-Vector Diseases and Climate

A variety of infectious diseases have been linked to variations in climate (reviewed in Patz *et al.*2005). These include diarrheal diseases (Checkley *et al.*1997), cholera (Colwell 1996, Pascual *et al.*2000), salmonella (Kovats *et al.*2004), viral pneumonia (Ebi *et al.*2001), hantavirus (Glass *et al.*2000), influenza (Viboud *et al.*2004), flea associated plague (Parmenter *et al.*1999), *Culicoides* biting midge associated bluetongue (Baylis *et al.*1999, Purse 2005), African Horse sickness (Baylis *et al.*1999), mosquito-associated Murray Valley encephalitis (Nicholls 1986), Ross River virus (Woodruff *et al.*2002), dengue (Hopp and Foley 2003, Linthicum et al. 2007) chikungunya (Chretien *et al.*2006.), malaria (Bouma *et al.*1996, Bouma and Dye 1997), and Rift Valley fever (Linthicum *et al.*1999). Of these, we use the example of Rift Valley fever outbreaks to show the use of climate data to understand in what regions and at what times these disease outbreaks will occur.

The link between epizootics of Rift Valley fever and rainfall was first documented by Davies *et al.* (1985). Through an analysis of time series rainfall data records from numerous stations in Kenya between 1950 and 1982, it was determined that periods with extended positive surplus rainfall corresponded to periods when Rift Valley fever epizootics occurred. Widespread, frequent, and persistent rainfall was shown to be a prominent feature of all epizootic periods. Heavy rainfall raises the level of the water table in certain areas, flooding grassland depressions that are the habitat of the immature stages of certain ground-pool-breeding mosquitoes of the genus *Aedes*. These findings have been collaborated by findings in Southern Africa (Swanepoel 1976) and West Africa (Bicout and Sabatier 2004). Rift Valley fever virus is thought to be initially transmitted transovarially in these species. Under prolonged flooded conditions, large numbers of *Culex* species mosquitoes emerge and are an amplification vector for Rift Valley fever. Following the development of these conditions, Rift Valley fever first occurs in animals and subsequently in humans.

Linthicum *et al.* (1999) established that outbreaks of Rift Valley fever are closely coupled with above normal rainfall that is associated with the occurrence of the warm phase of ENSO (Cane 1983; Ropelewski and Halpert 1987; Nicholson 1986) and warm events in the equatorial western Indian Ocean (Saji *et al.*1999; Anyamba *et al.*2002; Birkett *et al.*1999). Such warm ocean events precede by two to three months above normal and extended rainfall over East Africa, and are further enhanced when both the sea surface anomalies in the western Indian Ocean and equatorial central-eastern Pacific are synchronized. More than 90% of Rift Valley fever outbreak events since 1950 have occurred during warm ENSO events (Linthicum et al. 1999; Figure 7). The inter-epizootic period is dominated by La Niña events (the cold phase of ENSO), which results in drought in East Africa and wetter than normal conditions in Southern Africa (Nicholson and Entakhabi 1986; Anyamba et al. 2002). Recent evidence shows that Rift Valley fever outbreaks in Southern Africa are coupled with La Niña patterns (Anyamba *et al.*2010).

Interannual variability, in part driven by ENSO events with differential impacts on rainfall anomaly patterns on Eastern and Southern Africa, largely influences the temporal outbreak patterns of Rift Valley fever.

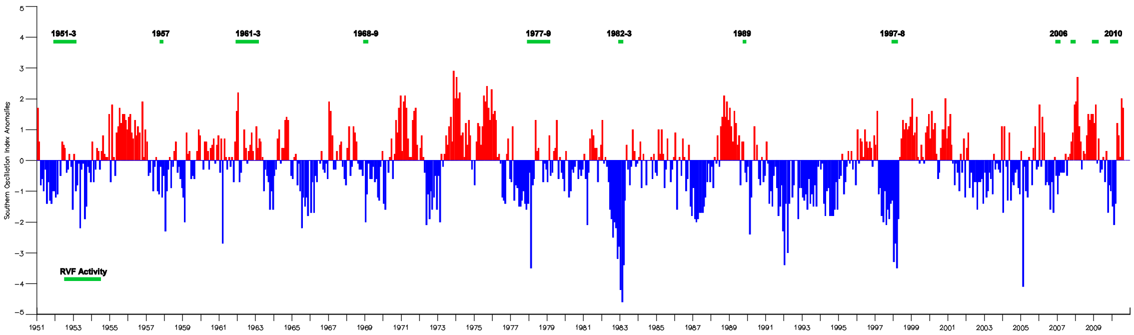

Figure 7. Rift Valley fever major outbreak events plotted against time and the Southern Oscillation Index, a measure of the phase of El Niño / Southern Oscillation events. Most Rift Valley fever outbreaks events have occurred during the warm phase of ENSO (negative Southern Oscillation index shown in blue). (Linthicum *et al.*1999 and updated).

Our work on Rift Valley fever prediction thus uses climate data to inform us when and where regionally we should expect outbreaks. Subsequent detailed daily satellite observations identify specifically where outbreaks will occur with a high degree of geographical specificity (~60%).

6. Prediction of Rift Valley fever Outbreaks

Developed by Anyamba *et al.* (2002), prediction of Rift Valley fever outbreaks includes several components: (1) mapping of potential epizootic/epidemic regions through the combined use of satellite data, climate data, and historical reports; (2) following closely sea surface temperatures anomalies with reference to phase and amplitude in the NINO 3.4 tropical Pacific and equatorial western Indian Ocean areas; (3) monitoring patterns of outgoing long wave radiation anomalies to infer and detect large scale changes and shift in the major atmospheric centers of tropical convection as a result of ENSO; and (4) monitoring patterns of normalized difference vegetation index anomalies over Africa as a proxy for excessive rainfall.

The first successful prediction using this system was made in 2006 (Anyamba et al. 2006 and 2009) and provided a lead time of 3 to 4 months (Figure 8) to respond, although response and mitigation activities only started one month prior to the first reported outbreak. The predictions were subsequently confirmed by entomological and epidemiological field investigations of virus activity in the areas mapped to be at risk in Kenya, Somalia and Tanzania with a geographic accuracy of 60%. Following the outbreak in East Africa, this system provided further predictions of outbreaks in Sudan in late 2007 and January 2008, 2009 and 2010 in Southern Africa. These predictions and outbreak assessments are described in detail in Anyamba et al. (2010).

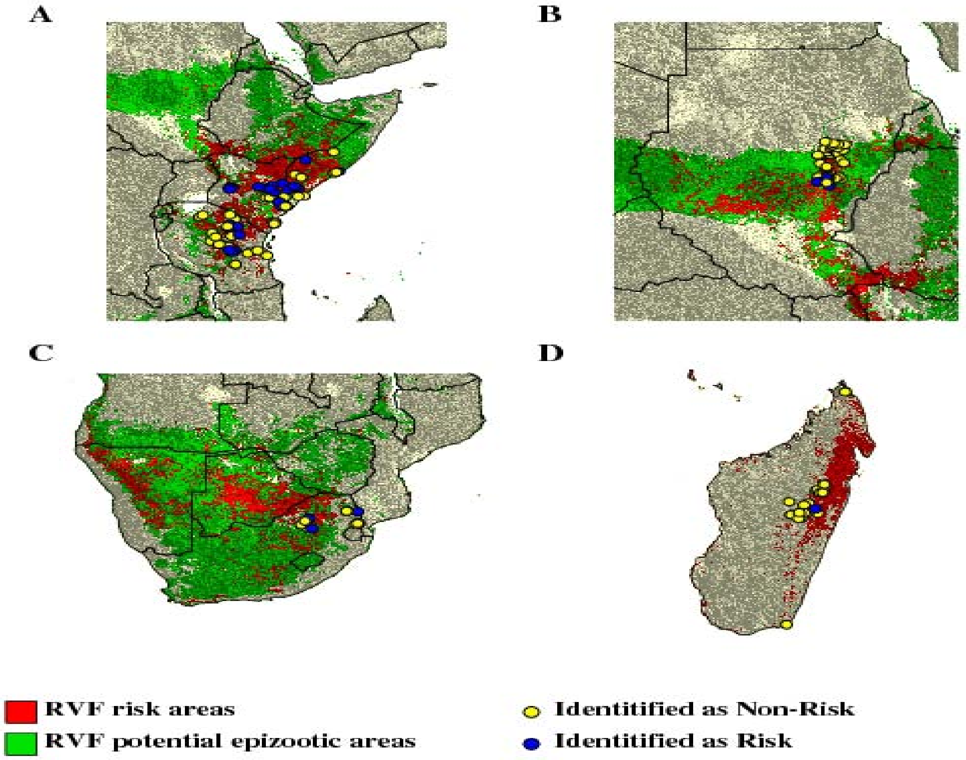

Figure 8. Summary Rift Valley fever risk maps for (A) Eastern Africa – September 2006 – May 2007, (b) Sudan. May 2007 – December 2007 (C) Southern Africa – September 2007 – May 2008 (D) Madagascar: September 2007 – May 2008. Areas shown in green represent Rift Valley fever potential epizootic areas, areas shown in red represent pixels that were mapped by the prediction system to be at risk for Rift Valley fever activity during the respective time periods, blue dots indicate human cases identified to be with the Rift Valley fever risk areas while yellow dots represents human cases in areas not mapped to be at risk (after Anyamba *et al.*, 2010).

7. How Tools and Previous Approaches Could Have Relevance to Anticipating Conditions for Fungal Disease Emergence.

We (Linthicum, Anyamba, and Tucker) have been studying the use of satellite data to predict Rift Valley fever outbreaks since the mid-1980s. Our study of Rift Valley fever occurrence led us to the antecedent role of high sea surface temperatures in the tropical Pacific and Western Indian Oceans that results in higher than average rainfall in East Africa that triggers Rift Valley fever outbreaks. Alerted when the antecedent sea surface temperature conditions are present, we then step up our near-real time satellite data surveillance in East Africa that provides very specific location information for control measures to be put in place.

We propose a similar approach for anticipating conditions for fungal disease emergence: Use satellite data to map the abiotic conditions associated with fungal disease outbreaks; evaluate historical fungal outbreaks with respect to antecedent abiotic conditions; and use this knowledge to predict where and when future fungal outbreaks would occur.

A recent example how our prediction model could be applied elsewhere was the role that the very heavy 2011 summer rains have played in increased transmission of Murray Valley encephalitis virus, Ross River virus, and Kunjin virus in Australia (ProMed 2011b). This same climate anomaly also produced widespread moist soil conditions and increased the likelihood of fungal diseases of cereal crops such as *Puccinia graminis_ f. sp._tritici* producing wheat stem rust (Figure 9), resulting in the release of warnings for the occurrence of fungal diseases in cereal crops in eastern and southern Australia (ProMed 2011a).

Figure 9. Stem rust symptoms on wheat (from http://www.ars.usda.gov/images/docs/9910_10104/stemrust_inset.jpg)

8. Tropical Glacier Recession, Amphibian Migration, and Subsequent Fungal Migration

Our group at NASA/Goddard Space Flight Center has documented New World tropical glacier variation from the mid-1980s to the present, including glaciers in the Cordillera Vilcanota in Peru. This heavily glaciated range, with multiple peaks over 6,000 m, is a key watershed for regional river systems, including the Amazon. Rapid environmental changes are documented in the region including record tropospheric warming of 0.3˚ C per decade between 1974 and 1998 (Vuille *et al.* 2003), rise in freezing level (Diaz and

Graham, 1996), and deglaciation (Bradley *et al.* 2006; Thompson *et al.* 2003). According to our current estimates, between the mid-1980s and mid-2000s, there has been approximately 30% glacial loss in this particular mountain range of southern Peru (Slayback and Tucker, NASA/GSFC in preparation). We have found warmer temperatures were largely responsible for tropical glacier recession in these areas (figure 10). No variations in cloud cover or precipitation have been found, indicating global warming as the primary driver of glacial change.

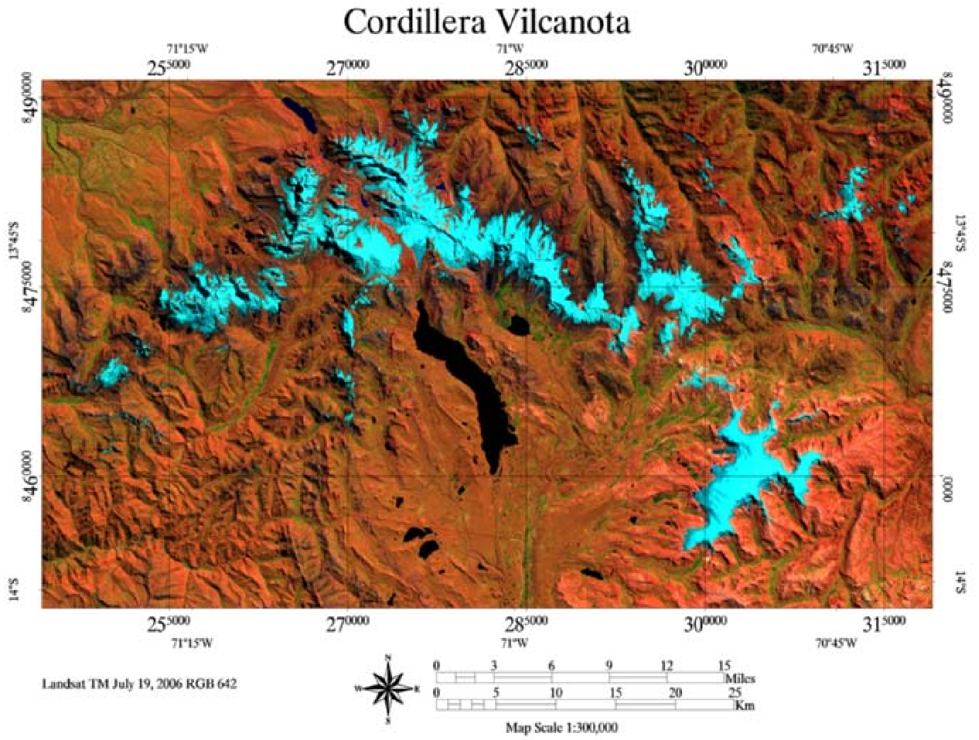

Figure 10. False color Landsat satellite data (RGB 642) showing glaciers as the blue colors, the green colors represent green vegetation, and the red colors representing areas of rock, sand, and soil (Yager NASA/GSFC).

Interdisciplinary research in the Cordillera Vilcanota, around Lake Sibinacocha, has been conducted for several years to investigate the impacts of climate change on local ecosystems (Seimon *et al.* 2010). This work includes research on glaciers, vegetation, colonization of microbes in newly deglaciation soils, fossil plants, agro-pastoralism, species migration, and amphibian studies (Halloy *et al.* 2006, Nemergut *et al.* 2007, Seimon *et al.* 2007, Yager *et al.* 2010). Glacier retreat at higher elevations in the watershed has been rapid, resulting in the creation of new corridors and newly habitable areas for species migration and the upward range extension of numerous species, including plants, animals, amphibians, and also pathogens.

Herpatologists on the team have documented the higher-elevation colonization of three species of anurans *Telmatobius marmoratus*, *Rhinella spinulosa*, and *Pleurodema marmorata* that have expanded their ranges and moved to unprecedented elevations for amphibians (5200-5400 m), into new lakes and ponds created by recent deglaciation (Seimon *et al.* 2007). In the case of *P. marmorata*, climatic warming has resulted in an approximate 200 m vertical increase in its range, corresponding to the amount of glacier retreat since 1880.

These amphibian species are opportunistic in their adaption to the warming climate by migrating to and spawning in ever-higher terrain. However, new climate conditions are also proving advantageous for the spread of epidemic disease, and in particular Chytridiomycosis. This pathogenic chytrid (*Bd)* produces aquatic zoospores on amphibian skin, and under certain conditions becomes a highly lethal infection (Seimon *et al.* 2005). Chytrid fungus has been linked to amphibian population declines and even species extinction across the globe (Daszak *et al.* 1999, Pounds *et al.* 2006).

New challenges are being presented for the long-term survival of amphibian species in this watershed with climate change. Since 2003, a year after *Bd* was first detected in this region, all three species have been decreasing in number and *T.marmoratus* has not been documented in the Sibinacocha watershed since 2005 (Seimon *et al.* 2007, Yager *et al.* 2010). The current research indicates that recent warming, and intense solar heating of glacier ponds during the day, may be contributing to the ability of chytrid to expand and thrive at unprecedented altitudes and terrain (Seimon *et al.* 2007). In addition, as the glaciers continue to melt, ponds that were once inhabited by amphibians are experiencing a reduction in meltwater or are drying up altogether leading to loss of habitat and contributing to subsequent population declines. Amphibians are some of the most sensitive species to environmental changes, and are becoming more susceptible to life threatening disease and possible extinction under current climate patterns.

9. Conclusions

Although the Earth's climate is warming and our Sun is not responsible, weather and climate simulation models project even warmer temperatures by the middle of this century, with some areas also getting wetter while others drier. These changing patterns of temperature and precipitation will alter endemic areas for various plant and animal diseases, including fungal pathogens. We reviewed how knowledge of climatic linkages is being used to predict the outbreak regions of Rift Valley fever in Africa, complemented by detailed satellite observations to identify specific locales where control measures should be undertaken. We advocate a similar approach to identify areas where fungal diseases may emerge: understand the biology of specific fungal pathogens; use satellite data to establish temperature and precipitation climatology in the areas of interest; associate this information with documented fungal outbreaks; and use this knowledge in conjunction with satellite data to predict the impacts of a changing and variable climate on fungal pathogens.

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