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Impact of temperature and precipitation on propagation of intestinal schistosomiasis in an irrigated region in Ethiopia: suitability of satellite datasets

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Summary

OBJECTIVE To assess the suitability of satellite temperature and precipitation datasets for investigating the dependence of *Schistosoma mansoni* disease transmission on meteorological conditions in an irrigated agricultural region in Ethiopia.

METHODS Data used were monthly number of patients infected with *S. mansoni* and seeking treatment at the local hospital, monthly maximum air temperature from a local weather station, monthly average land surface temperature from MODIS satellite data, monthly total precipitation from a local rain gauge and precipitation estimates from four widely used satellite products, namely, TMPA 3B42RT, TMPA 3B42, CMORPH and PERSIANN. The number of patients was used as proxy for vector abundance.

RESULTS Temperature and precipitation play a role in the transmission of *S. mansoni* disease. There is a weak but significant positive correlation between monthly maximum air temperature derived from a meteorological station (or average land surface temperature derived from MODIS satellite product) and the number of patients in the same month. There is a significant negative correlation between monthly precipitation volume (derived from rain gauge or satellite data) and number of patients at lags of 1 and 2 months.

CONCLUSION Satellite temperature and precipitation products provide useful information to understand and infer the relationship between meteorological conditions and *S. mansoni* prevalence.

keywords schistosomiasis, precipitation, temperature, satellite

Introduction

Schistosomiasis, also known as bilharziasis, is one of the most prevalent water-based vector-borne diseases in the world. It infects more than 200 million people worldwide (Wu & Halim 2000), and puts at risk about 779 million people, of whom 106 million live in or near irrigated agricultural areas and in close proximity to large reservoirs (Steinmann *et al.* 2006). The burden of the disease is disproportionately concentrated in Africa: 97% of the infections and 85% of the people at risk are in Africa. In sub-Saharan Africa schistosomiasis contributes to more than 280 000 deaths annually and causes 0.5–0.6% of disability weights and a total of 1.53 million disability adjusted life years (DALYs) (WHO 2002; Gryseels *et al.* 2006). Schistosomiasis cases have recently begun appearing in high-altitude (>2000 m a.s.l.) regions, which were historically free from this disease (Githeko *et al.* 2000). There is an increasing concern that this may be attributable to climate change. It is, therefore, important to understand and characterize the connection between schistosomiasis prevalence and hydrometeorological conditions.

In this study, we endeavoured to assess the suitability of satellite temperature and precipitation datasets for investigating the relationship between *Schistosoma mansoni* disease transmission and meteorological conditions in an irrigated agricultural region in Ethiopia. Gridded maps of satellite temperature and precipitation estimates are a convenient source of data on account of their rapid availability and comprehensive coverage across the world. However, satellite estimates are subject to a variety of error sources, and their suitability for schistosomiasis studies needs to be first confirmed.

Background

Schistosomiasis is caused by blood flukes belonging to the genus *Schistosoma* and three major species account for the pathogens in humans: *S. haematobium, S. mansoni,* and *S. japonicum*. The transmission cycle requires contamination of surface water by excreta, specific fresh-water snails as intermediate hosts, and human water contact (Gryseels *et al.* 2006). The life cycle of schistosome parasites needs definitive and intermediate hosts that are accompanied by freely swimming larval stages (called cercaria). Cercaria penetrates the intact skin of humans who contact contaminated water. Inside the human body, cercaria shed their tails and become schistosomula. Schistosomula migrate through the body until they develop into sexually mature adults and produce eggs (this takes 25–30 days). More than half of the eggs are trapped inside tissues, and these eggs are responsible for the pathology of the disease (Gryseels *et al.* 2006). The eggs released out of the human body with faeces (*S. mansoni, S. japonicum*) or urine (*S. haematobium*) hatch in fresh water into larvae called miracidia and later penetrate the snail host (genus *Biomphalaria* for *S. mansoni*, *Bulinus* for *S. haematobium* and *Oncomelania* for *S. japonicum*). After the miracidia further develop into cercaria, they migrate out of the snail (25–30 days after the snail has been infected) and begin to search for a human host to start the cycle again (Wu & Halim 2000).

Rainfall and temperature are important drivers of malaria and schistosomiasis transmission. Rainfall is largely responsible for creating the conditions that allow sufficient surface water accumulating in ponds and providing abundant snail breeding sites. However, intense rainfall often results in increased runoff volume channelled through irrigation canals. This, in turn, results in high flow velocities and the associated high values of turbulent shear that may kill the cercaria. The exact mechanism and precipitation intensity where a cross-over exists between increasing *vs.* decreasing cercaria infectivity is not clear. The temperature of water bodies governs the development rate of the parasites within snails and the infectivity of cercaria. The optimum temperature for the development of *S. mansoni* is 20–27 °C (Malone 2005). Cercaria remains infective for 5–8 h once they are released under optimum temperature conditions, and this duration becomes shorter under non-optimum temperature conditions.

Table 1 summarizes existing studies of the relationship between *S. mansoni* transmission and meteorological conditions. The meteorological factors associated with the disease incidence and prevalence are temperature (minimum, maximum, average, diurnal difference) and rainfall. Little work exists in irrigated fields, and therefore the effect of meteorological conditions on *S. mansoni* transmission is poorly understood in irrigated fields. Moreover, to the best of our knowledge no prior effort to link satellite

Table 1 Some studies on the dependence of *S. mansoni* on meteorological factors

Study	Region	Major findings
Non-irrigated area		
Malone *et al.* (1997)	Nile-Delta	dT (derived from AVHRR) negatively correlates with *S. mansoni* prevalence
Abdel-Rahman *et al.* (2001)	Egypt	dT negatively correlates with *S. mansoni* prevalence, snail population abundance and snail infection rates
Malone (2005)	Nile-Delta; East Africa	High *S. mansoni* prevalence found in areas with NDVI[!] = 0.27–0.43 and land surface temperature = 17–25 °C; the major transmission period for *S. mansoni* occurs in the months following the rainy season
Malone *et al.* (2001a,b) and Kristensen *et al.* (2001)	Ethiopia	High *S. mansoni* prevalence found in areas with NDVI = 0.25–0.45 and land surface temperature = 20–33 °C
Brooker *et al.* (2001)	Kenya	Distance from the lake negatively correlates with *S. mansoni* prevalence
Stensgaard *et al.* (2005)	Uganda	High *S. mansoni* prevalence found in areas with MODIS NDVI = 0.56–0.77, daytime land surface temperature = 25–35 °C, and nighttime land surface temperature = 12–20 °C
Ekpo *et al.* (2008)	Nigeria	The presence or absence of schistosomiasis can be predicted by land surface temperature; the probability of an area having disease prevalence ≥50% can be predicted by land surface temperature, rainfall and soil type
Bavia *et al.* (1999)	Brazil	Length of dry period negatively correlates with *S. mansoni* prevalence
Bavia *et al.* (2001)	Brazil	*S. mansoni* prevalence negatively correlates with dT but positively correlates with NDVI
Guimarães *et al.* (2008)	Brazil	*S. mansoni* prevalence positively correlates with summer minimum temperature and winter NDVI but negatively correlates with elevation
Irrigated area		
Yapi *et al.* (2005)	Côte d'Ivoire	*S. mansoni* prevalence is higher in irrigated areas than in non-irrigated areas

AVHRR = Advanced Very High Resolution Radiometer; ^MODIS = Moderate-Resolution Imaging Spectroradiometer; dT = Diurnal temperature difference, mid-daytime temperature–mid-nighttime temperature; NDVI, Normalized difference vegetation index.

meteorological datasets to *S. mansoni* transmission has been reported. This provides motivation for the present study.

Data and methods

Study region

The study area, Wonji, is located in central Ethiopia, approximately 110 km southeast of the capital Addis Ababa. Wonji has a semi-arid climate and receives a mean annual rainfall of 820 mm with >70% falling in the summer monsoon season, and mean annual maximum and minimum temperatures of 27.6 °C and 15.2 °C. The region hosts the nation's largest irrigated sugar cane field. The source of irrigation water is the Koka Dam, and the type of irrigation is furrow (Figure 1) with canals having typical water depths in the order of half a meter or less. The irrigation scheme releases uniform amounts of water without major variations inducing sub-critical flow in the canals. The only major variation in the irrigation-induced flow exists during significant rainfall when the release of water from the Koka Dam is stopped and flow in the canals is primarily due to rainfall. The canals provide an ideal habitat for snails. The region is known for its highest rates of schistosomiasis prevalence in Ethiopia. As shown in Table 2, the schistosomiasis prevalence rate among the Wonji's school children has been fluctuating between 50% and 90% over the past two decades.

Data

We obtained monthly data on the number of *S. mansoni* patients, monthly maximum air temperature and monthly total precipitation between September 1998 and August 2009 from the only hospital in Wonji and the Ethiopian Meteorological Office, which maintains a weather station in the area. We recognize that employing number of patients rather than vector density does not capture the mechanistic biological link. However, in order to conduct a preliminary assessment of the ability of satellite meteorological products to capture the relationship between ground-based relevant data and disease transmission we use number of patients as a proxy for vector abundance.

We also obtained land surface temperature and precipitation estimates from standard satellite products. The land surface temperature estimates are taken from the MOD11 product (Wan 1999), derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor on board the polar-orbiting satellites Terra and Aqua which pass over a given region once a day. The MOD11 product represents the instantaneous land surface temperature observations at 10:30 AM local time within an 8-day period at a spatial resolution of 1 km.

Precipitation estimates can be obtained from a variety of satellite precipitation products. The concept behind the high resolution satellite precipitation algorithms is to combine information from the more accurate (but infrequent) microwave with the more frequent (but indirect) infrared to take advantage of the complementary strengths. The combination has been done in a variety of ways leading to different precipitation products. In this study, we employed the widely used satellite rainfall products discussed above: TMPA 3B42RT, TMPA 3B42, CMORPH and PERSIANN. These satellite products are described in Appendix A.

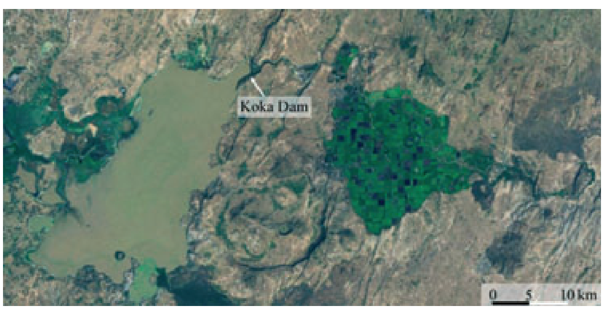

Figure 1 Satellite image of Wonji (ArcGlobe, ESRI®).

Statistical analysis

We used the Spearman rank correlation, available in MATLAB, to measure the association between the number of *S. mansoni* patients and temperature or precipitation. A time lag was defined as the time span between observations on climatic conditions and number of patients.

Table 2 *S. mansoni* prevalence and intensity (eggs per gram faeces) among 5–14 years old school children in Wonji

Sex/age category		Prevalence/ intensity	April 1989	April 2009
Sex	Male	Prevalence	83.12%	60.26%
	Female	Prevalence	80.72%	54.67%
Age (years)	<7	Prevalence	72.40%	52.94%
		Intensity	297.00	129.88
	8–11	Prevalence	87.30%	59.69%
		Intensity	433.00	141.99
	12–14	Prevalence	84.10%	53.76%
		Intensity	376.00	163.10
Total		Prevalence	81.90%	57.48%
		Intensity	377.00	147.83

Results

S. mansoni prevalence

Figure 2 presents the time series of the number of *S. mansoni* patients on a monthly scale. It is worth noting that no month over the recent decade has passed without new *S. mansoni* cases. The number of patients varies every month, from 6 in September 2008 to 108 in November 1999, with an outlier of 201 in March 2007.

Effect of temperature

The monthly maximum air temperature, obtained from a local meteorological station, is shown superimposed on the number of patients in Figure 3a. The monthly maximum air temperature varied in the range of 24–31 °C, with a mean of 27.4 °C. The land surface temperature as observed by MODIS is also shown superimposed on the number of patients in Figure 3b. Note the slightly shorter (by 2 years) length of land surface temperature data. The land surface temperature varied in the range of 24–40 °C, with a mean of 32 °C. There exists an apparent association between temperature and number of patients since most peaks and valleys of the two time series appear synchronized. The results of the Spearman rank correlation between number of patients and maximum air temperature or MOD11 MODIS land surface temperature, for various time lags, are shown in Figure 4. The maximum air temperature has a statistically significant positive correlation with the number of patients at lag 0 (correlation = 0.29, P-value = 0.005). This correlation decreases for lag 1 month and is no longer statistically significant. Furthermore, the monthly average land surface temperature as derived from the MOD11 MODIS satellite product appears to provide a more significant correlation with disease prevalence for lag zero (correlation = 0.40, P-value < 0.005) and it remains statistically significant even for lag 1 month (correlation = 0.30, P-value = 0.005).

Since the optimum temperature for the development of *S. mansoni* is 20–27 °C (Malone 2005), only a small air and land surface temperature window (24–27 °C) corresponds to optimal conditions. However, the heat transfer at the air–water interface in the irrigation canals is not significant enough (smaller temperature differential and shorter temporal window) to warm the whole water column and thus provides the cercaria with only intermittent optimal infective conditions. Conversely, this heat transfer mechanism is by far more significant at the soil–water interface and thus warms the shallow water column better, which most likely results in more continuous optimal infective conditions for cercaria. This explains the stronger correlation for MODIS and its persistence in terms of statistical significance for lags of 1 month. However, we would be remiss to not note that the overall strength of the correlations is weak, indicating that monthly maximum air temperature or monthly average land surface temperature alone is not enough to explain the month-to-month variability in the disease prevalence.

Effect of precipitation

The monthly total precipitation, obtained from a local rain gauge station, is shown superimposed on the number of patients in Figure 5. The time series of precipitation and number of patients are mostly out of phase with each other. The Spearman rank correlation between number of patients and monthly total precipitation derived from rain gauge and several satellite-derived precipitation products, for various time lags, is shown in Figure 6. The strongest correlations were observed at lags of 1 and 2 months. Intense rainfall often results in turbulent, high flow velocities that may kill the cercaria through high shears. It may also be associated with lowering the water temperatures since there exists no time for the heat transfer to warm the flowing waters. The exact mechanism and precipitation intensity where a cross-over exists between increasing *vs.* decreasing cercaria infectivity is not clear. Among the four satellite precipitation products, 3B42RT yielded correlation results similar to those obtained from the rain gauge station. This is consistent

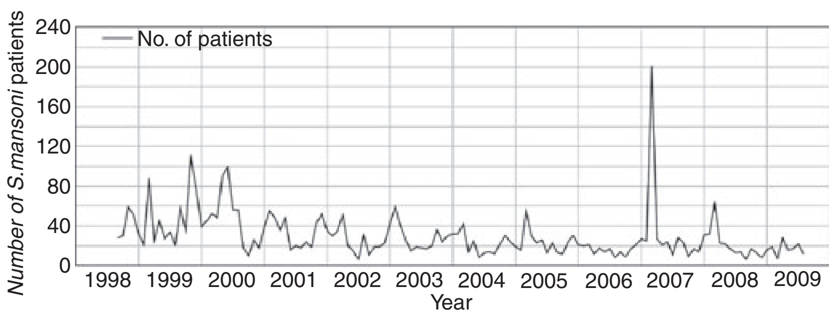

Figure 2 Time series of monthly number of *S. mansoni* patients in Wonji, from 1998 to 2009.

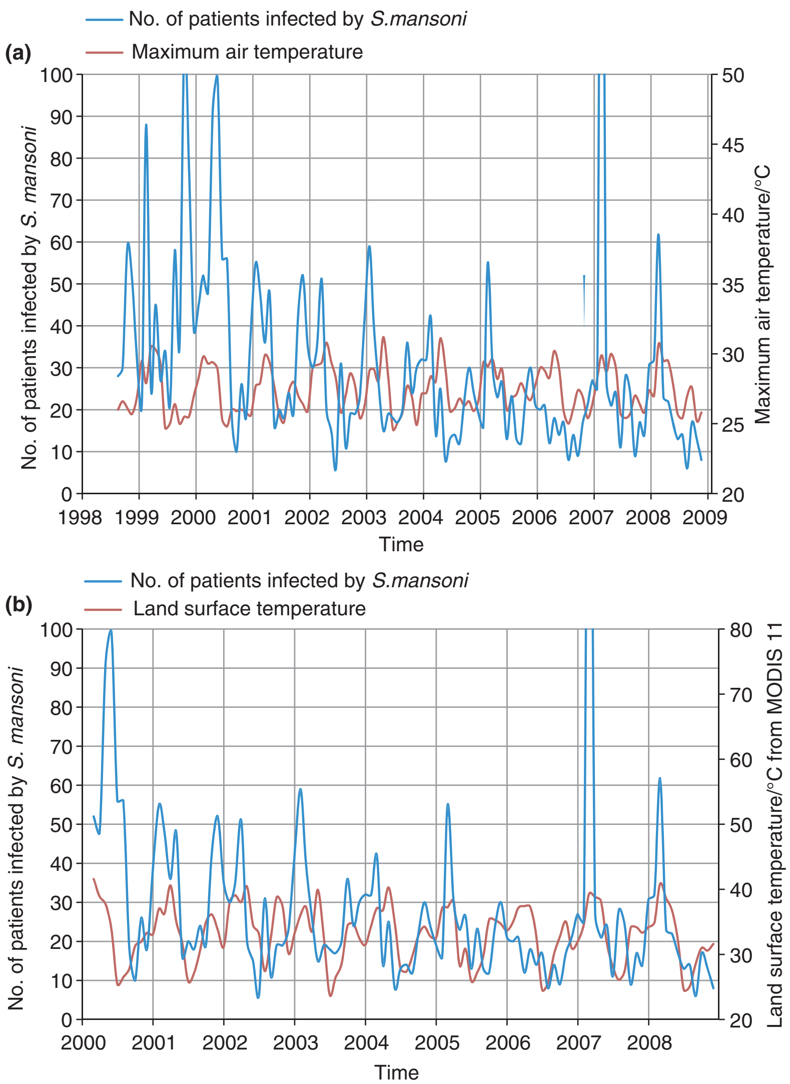

Figure 3 Time series of monthly number of *S. mansoni* patients with: (a) monthly maximum air temperature in Wonji and (b) land surface temperature in Wonji, as observed by MODIS.

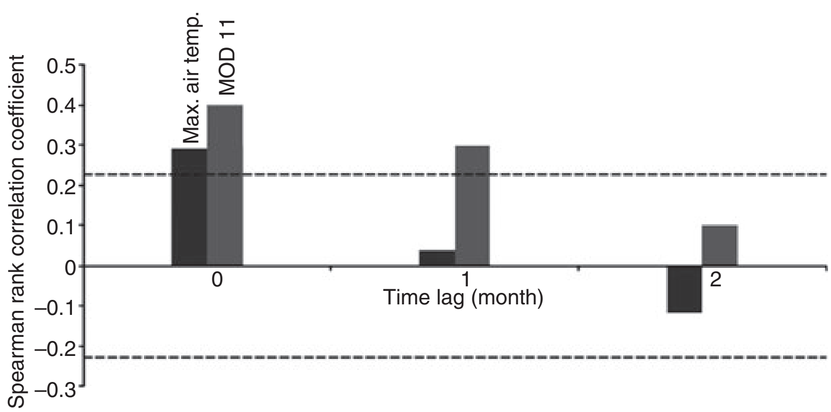

Figure 4 Spearman rank correlation coefficients between number of *S. mansoni* patients and temperature (monthly maximum air temperature from a local meteorological station, and monthly average land surface temperature derived from the MOD11 MODIS satellite product). Dashed line shows significant value of correlation at 5% level of confidence.

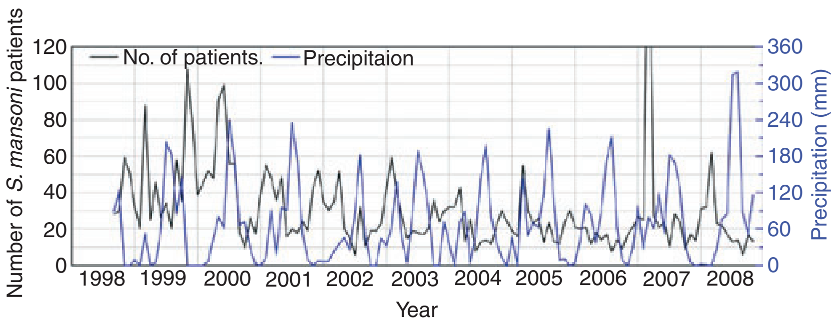

Figure 5 Time series of monthly number of *S. mansoni* patients and monthly precipitation volume derived from a rain gauge station in Wonji.

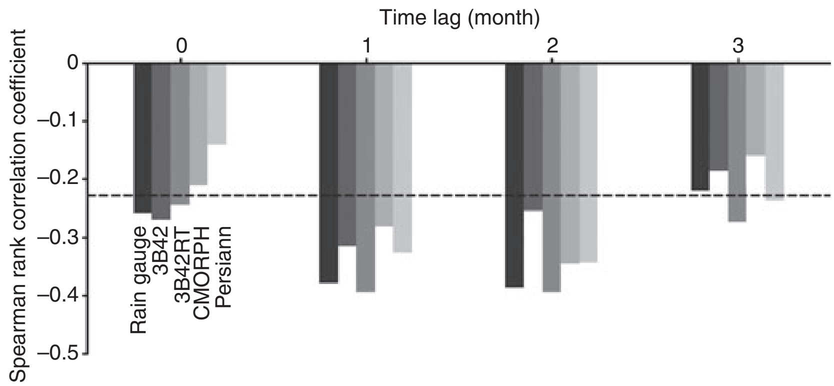

Figure 6 Spearman rank correlation coefficients between number of *S. mansoni* patients and monthly precipitation volume inferred from rain gauge and each of the four satellite precipitation products. Dashed line shows significant value of correlation at 5% level of confidence.

with our previous finding that the 3B42RT products have better accuracy, among the four satellite precipitation products, in estimating monthly total precipitation over Ethiopia (Hirpa *et al.* 2010). Therefore, it appears that satellite products could indeed provide a valuable tool for forecasting *S. mansoni* disease prevalence.

Discussion and conclusions

Understanding the dependence of *S. mansoni* transmission on meteorological factors (temperature and precipitation) is a critical step towards improving predictability of the disease prevalence and assessing the impact of climate change and variability. In this study, we used the monthly number of patients with *S. mansoni* treated at the local hospital as a proxy for vector abundance, monthly maximum air temperature from a local weather station, monthly average land surface temperature from satellite data, monthly total precipitation from a local rain gauge and four widely-used satellite products in order to study the role of temperature and precipitation in the transmission of *S. mansoni* disease in an irrigated agricultural region in Ethiopia.

Temperature and precipitation play significant roles in the transmission of *S. mansoni* disease. A weak but significant positive correlation was found between monthly maximum air temperature derived from a meteorological station (or average land surface temperature derived from MODIS satellite product) and number of patients in the same month. This correlation was stronger for land surface temperature than for air temperature; it also persisted in terms of statistical significance for lags of 1 month. This is explained on the basis of a weak heat transfer mechanism at the air–water interface in the irrigation canals (smaller temperature differential and shorter temporal window) as opposed to a far more significant heat transfer at the soil–water interface, which most likely results in more continuous optimal infective conditions for cercaria. There was a significant negative correlation between monthly precipitation volume (derived from rain gauge or satellite data) and number of patients at lags of 1 and 2 months. Possible explanations for this finding are: (i) intense rainfall and the associated turbulent, high flow velocities may kill the cercaria through high shears; and (ii) intense rainfall may also be associated with lowering the water temperatures thus interrupting the optimal infective conditions for cercaria. The exact mechanism and precipitation intensity where a cross-over exists between increasing *vs*. decreasing cercaria infectivity is not clear.

We iterate the limitations of this study. Using number of patients as opposed to vector density does not capture the mechanistic biological link for disease transmission. Only monthly data were used, as data were not available at finer temporal scales. Important fluctuations at sub-monthly scales could be lost in the monthly average comparisons. Skewed distribution of data (e.g., disease detection early in the month and heavy rainfall at the end of the month), if there were to exist, could also affect the accuracy of the results.

Results indicate that satellite temperature and precipitation products provide useful information to understand and model the relationship between meteorological conditions and *S. mansoni* prevalence. This is an important preliminary finding that supports the suitability of satellite meteorological products to capture the relationship between ground-based relevant data and disease transmission. If our current data collection efforts that focus on snail populations corroborate this finding, this may have important public health implications for development of *S. mansoni* early warning systems. Whereas currently there exists no mechanism to predict increases in vector prevalence, establishing a correlation between vector density and incipient meteorological conditions would allow early intervention that could lead to vector eradication. Satellites provide near real-time meteorological data of consistent quality, which is of immense value in Ethiopia where ground-based data is scarce.

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Appendix A

The TMPA (Tropical Rainfall Measuring Mission Multi-satellite Precipitation Analysis; Huffman *et al.* 2007) method uses microwave (MW) data to calibrate the infrared (IR) derived estimates and creates estimates that contain MW-derived precipitation estimates when and where MW data are available and the calibrated IR estimates where MW data are not available. The CMORPH (Climate Prediction Center's morphing technique; Joyce *et al.* 2004) obtains the precipitation estimates from MW data but uses a tracking approach in which IR data are used only to derive a cloud motion field that is subsequently used to propagate raining pixels. The PERSIANN (Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks; Sorooshian *et al.* 2000) method uses a neural network approach to derive relationships between IR and MW data that are applied to the IR data to generate precipitation estimates. So, CMORPH products rely primarily on MW data for precipitation estimates, PERSIANN relies primarily on IR data, and TMPA relies on MW when MW data are available and on IR data when MW data are not available. CMORPH and PERSIANN products are available only post-real-time. The TMPA products are available in two versions: real-time version (TMPA 3B42RT, or 3B42RT for short) and post-real-time research version (TMPA 3B42, or 3B42 for short). The main difference between the two versions is the use of monthly rain gauge data for bias adjustment in the post-real-time research product. The 3B42 products are released 10–15 days after the end of each month, and the 3B42RT are released about 9 hours after overpass.

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