Relationships of climate and irrigation factors with malaria parasite incidences in two climatically dissimilar regions in India

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Submitted to Journal of Arid Environments

Abstract

We examine how climate and irrigation conditions are associated with malaria infection from 1986-1995 in two climatically dissimilar regions in India. We analyze annually averaged malaria parasite incidence (API) and seasonally averaged climate and irrigation variables in western Rajasthan and Arunachal Pradesh. In arid western Rajasthan, API is significantly positively correlated with summer precipitation and soil moisture, and negatively correlated with summer potential evapotranspiration. Irrigation variables during boreal spring show a significant positive correlation with API in the moisture-limited region. In humid Arunachal Pradesh, API is positively related to summer temperature, but negatively related to summer precipitation and spring irrigation variables, while no statistically significant correlations are observed. During the years of high sea surface temperatures (SSTs) in the tropical western Pacific, increasing precipitation (accompanied by decreasing temperature) in northwestern India appears to promote malaria infection in arid western Rajasthan. However, during the same years, decreasing precipitation and increasing temperature result in increasing malaria incidence in humid Arunachal Pradesh. The statistically significant relationships of climate and irrigation factors with API in western Rajasthan suggest that increasing spring irrigation activity and wetter summer climates related to warmer SST in tropical western Pacific could increase malaria risk in the arid climate region.

Keywords: Malaria; Precipitation; Temperature; Irrigation; Sea surface temperatures; India

1. Introduction

Malaria is one of the world's most serious and complex public health problems. In 2010, an estimated 219 million cases of malaria (with an uncertainty range of 154-289 million) occurred worldwide and 660,000 (with an uncertainty range of 490,000-836,000) people died, most of them young children (WHO, 2012). Malaria is caused by *Plasmodium* sp. parasites, and the mosquito vectors are of the genus *Anopheles*. The spatial distribution of the malaria vectors is influenced by climate in the tropical regions across the globe including sub-Saharan Africa, South and Southeast Asia, and Central and South America. Arid environments can also provide habitat for mosquito vectors of malaria, contributing to a growing list of human health issues linked desertification, drought and land degradation (Patz et al., 2012).

The malaria parasite is temperature-limited and cannot develop in temperatures below 16 °C, assuming adequate humidity (Craig et al., 1999). Recently, a malaria model, including empirically derived nonlinear thermal responses, predicted optimal malaria transmission at 25°C which is 6°C lower than estimates from previous mechanistic models such as Parham and Michael (2010) (Mordecai et al., 2013). In addition, pools of water and humidity are required for mosquito larval habitat and adult survival (Gray and Bradley, 2005). Thus, climate is one of the primary determinants of malaria transmission. Climatic conditions in India are directly and indirectly connected to the variability of sea surface temperatures (SSTs) in the surrounding Indian Ocean and tropical Pacific Ocean, which are correlated with El Niño/Southern Oscillation (ENSO) (Pant and Parthasarathy, 1981; Rasmusson and Carpenter, 1983). Therefore, the malaria parasite in India may also be responsive to large-scale climate forcings related to SSTs.

Previous studies unveiled links between climate and malaria transmission, but there is still uncertainty about the potential impact of climate change on malaria (IPCC, 2007). Efforts of malaria studies to date have mainly focused on global (e.g., Rogers and Randolph, 2000) and regional scales in sub-Saharan Africa (e.g., Thomson et al., 2006; Zhou et al., 2004), but relatively few studies in India have been reported (Bhattacharya et al., 2006; Singh and Sharma, 2002). However, Dhingra et al. (2010) suggested that malaria might be a cause of more than 200,000 deaths per year in India, which is an order of magnitude above the World Health Organization (WHO) estimates (about 15,000). Previous studies have examined the isolated relationships between epidemic malaria in India and temperature (Jhajharia et al., 2013), rainfall

caused by ENSO (Bouma and Kaay, 1996; Bouma and Kaay, 1994) or irrigation practice (Baeza et al., 2011; Joshi et al., 2006; Tyagi et al., 1995; Sharma et al., 1994).

During the last few decades, the expansion and intensification of agricultural practices have altered land surface conditions all over the Indian subcontinent, especially in the Indo-Gangetic Plain in northern India where irrigated areas exceed 90% of the land area (Lee et al., 2009). Due to the high demand for irrigation, one of the world's largest irrigation projects, which is the Indira Gandhi Nahar Pariyojana (IGNP) project, was established in the Thar Desert of northwestern India in 1958 (Tyagi and Chaudhary, 1997). Under the IGNP project, extensive irrigation with water from the three different canal systems of Gang, Bhakra-Sir Hind Feeder, and Indira Gandhi has altered the desert environment (Tyagi, 2004), especially since the mid-1970s. For instance, the extent of canal irrigation in the Thar Desert was about 0.71×10^6 ha by the mid-1970s. Two decades later, the irrigated area increased to 2.17×10^6 ha, which is a tripling of extent (Tyagi, 2004).

Several climate modeling, water balance modeling, and observational studies have explored the effects of irrigation on the local climate and regional atmospheric circulation patterns, such as monsoon (e.g., Lee et al., 2009; Douglas et al., 2009; Biggs et al., 2008; Adegoke et al., 2003). The previous studies have an agreement that irrigation leads to decrease in sensible heat flux and increase in latent heat flux, which decrease the surface air temperature (i.e. irrigation cooling effect). A study of evapotranspiration and hydrological changes in the Aral Sea Drainage Basin in central Asia indicated that intense irrigation appeared to have considerably increased evapotranspiration and cooled this area (Shibuo et al., 2007). Climatic variables (temperature and humidity) related to irrigation practices have been considered as the important environmental factors for malaria transmission, especially in arid environments (Baeza et al., 2011; Keiser et al., 2005; Tyagi, 2004; Akhar and McMichael, 1996). In arid areas, people living in the proximity of irrigation infrastructure are potentially exposed to a higher risk of malaria due to changes in eco-hydrological and eco-climatological conditions that lead to increased vector abundance (Baeza et al., 2013).

We therefore explore the potential links between climate, irrigation, and malaria infection, as measured by annual parasite incidence (API), in two climatically distinct regions in northwestern and northeastern India, arid western Rajasthan and humid Arunachal Pradesh, respectively. These regions experienced significant changes in malaria API over a nearly decade

of surveillance. The bioclimatic differences between the regions set a stage for very different malaria transmission dynamics. In Arunachal Pradesh, malaria transmission is seasonal (peaks mid-year) and is driven by vector abundance, which is dependent on temperature, rainfall and humidity (Goswami et al., 2012). The primary vector is *Anopheles minimus*, with *An. dirus* and *An. fluviatilis* acting as secondary vectors (Nandi et al., 1993). In contrast, malaria epidemics in western Rajasthan were sporadic up until the 2000s when they shifted to a more seasonal pattern (Tyagi, 2004). Tyagi (2004) attributed malaria outbreaks prior to 2000 in western Rajasthan to a mix of vector activity with more varied breeding habitat, vector abundance, population migration, and the immune status of the population. The primary vector is *An. culicifacies*, which arrived in the wake of extensive canal and irrigation development in the 1980s. In non-irrigated villages the historically present vector, *An. stephensi*, is still responsible for low levels of malaria transmission (Tyagi and Yadav, 2001).

2. Data and Methods

The Indian subcontinent is located in a subtropical climate region where average temperature ranges 15-30 °C throughout the year. Most of the subcontinent falls within the temperature transmission window of malaria, which is between 16-34 °C (Mordecai et al., 2013). Thus, physical environmental factors, including temperature and other climate variables such as precipitation and evapotranspiration, might be important determinants for malaria parasite incidence in the subtropical region.

2.1. Study Areas

Western Rajasthan is located in the arid far west of the Indian subcontinent (the shaded areas in northwestern India in Fig. 1), and includes the Thar Desert in the western part of the region and semiarid steppes in the east. Arunachal Pradesh is located in far northeastern India (the shaded areas in northeastern India in Fig. 1) and has a humid subtropical climate. While the two regions have a wet monsoon season during boreal summer, Arunachal Pradesh is a much wetter environment: Arunachal Pradesh records 50-200 mm/month during the boreal spring and 150-400 mm/month during summer, while western Rajasthan records little precipitation for spring

(<10 mm/month) or summer (<100 mm/month) (Fig. 2a). The summer season is defined as June through September (JJAS) and the spring as March through May (MAM). Arunachal Pradesh has a more moderate summer temperature regime: the daily mean temperatures are around 19 °C, with the daily maximum of around 23 °C and the daily minimum of around 14 °C, while for western Rajasthan mean temperatures are around 31 °C, with the daily maximum of around 36 °C and the daily minimum of around 26 °C (Fig. 2b).

2.2. Malaria, Climate and Irrigation Datasets

As a measure of malaria infection, we use annually averaged malaria parasite incidence (API = (Number of cases/Population)*1000), which was compiled from 496 district-level malaria records (NMEP, 1996). We deleted the Churu district from the western Rajasthan dataset for the year 1995, because there was no API available. The district Changlang in Arunachal Pradesh was formed by a split between Changlang and Tirap in 1988/1989, and from 1989 onwards both districts are present in the data. Consequently, we discarded data in Changland and Tirap from 1986 to 1988 when the two districts were not separated. There was no API available for Tawang district in Arunachal Pradesh for the entire study period, so we did not include the district in the analysis. Thus, we used 11 districts for western Rajasthan, and 9 districts before 1989 and 10 districts from 1989 onwards for Arunachal Pradesh.

We use climate and irrigation variables in the two study areas, including precipitation, temperature, soil moisture, potential evapotranspiration (PET), irrigation schedule, and normalized difference vegetation index (NDVI). An index of irrigation schedule is calculated from the difference between PET and precipitation, and thus measures the amount of irrigation water needed to maintain crops. The vegetation index during the dry period in a wet-dry climate, such as India, could be an indicator of the greenness from irrigated crops (Lee et al., 2009). We also examine large-scale variables of SSTs in the Indian and Pacific Oceans. Regional- and large-scale climate variables are calculated during JJAS, which are the months of high malaria transmission in India (Bhattacharya et al., 2006), and irrigation variables are calculated during MAM, which are the dry pre-monsoon period in India.

Precipitation, temperature (daily minimum, mean, and maximum), and PET are derived from the Climatic Research Unit (CRU TS 3.1) (Mitchell et al., 2004). We use soil moisture

from the National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center (CPC) Soil Moisture v2 (Fan and Dool, 2004). With the advent of satellite remote sensing, it is now possible to obtain consistent global characteristics of vegetation information. NDVI observations are obtained from the NOAA Pathfinder Advanced Very High Resolution Radiometer (AVHRR) products (Tucker et al., 2005). As for large-scale climate variables, we extract regional SSTs from global high-resolution Hadley SST (HadISST) available through the Met Office, Hadley Center for Climate Research, which are compiled from satellite data (Rayner et al., 2003). We examine the climate and irrigation variables for 10 years from 1986 to 1995, which aligns with the availability of district-level malaria data in the two study regions. Spatial resolutions (longitude by latitude) of the physical environmental data sets are 0.5° by 0.5° for climate, soil moisture and NDVI data, and 1.0° by 1.0° for SST data. NDVI is converted from the original data (0.073° by 0.073°) to 0.5° by 0.5° .

2.3. Statistical Methods

Annual Parasite Incidence (API) is used from 496 district-level malaria observations. For climate and irrigation variables, we extract the district-level variables in the two study regions of India from the global high-resolution precipitation, temperatures, PET, soil moisture, and NDVI data at the geographical center of each district identified by using ARCGIS10.1 (ESRI, 2011).

For the linear regression analysis used in section 3.1, API from the district-level is interpolated to the grid-level at 5 minutes by 5 minutes (longitude by latitude). The gridded API data are required for the spatio-temporal analysis in the Grid Analysis and Display System (GrADS) (Doty, 1995) used in the study. Means of API are averaged over each grid-cell during 1986-1994. In the analysis of means and changes of API over India, data from 1995 are not included due to the relatively large number of missing values compared to other years. Changes of API are calculated using linear regression trends with time as an independent variable during the period. The slope coefficients of linear regression are estimated by the least squares method. To test if the API change over time is statistically significant, we calculate t -values by dividing the slope coefficients by standard errors at each grid.

To examine the overall relationships between malaria API and the regional climate and irrigation variables at the state-level, we aggregate API and the environmental variables over all

districts within each region by year. The aggregated variables facilitate examination of regional-level patterns and comparisons between the two climatically dissimilar regions. We investigate the associations of API with the environmental factors using plots with two Y variables (one for API and another for the environmental variables) and time along the X-axis. The visual relationships are supported by parametric and non-parametric correlation analyses.

The large-scale climate variables of SSTs in the Pacific and Indian Oceans are defined by the spatial correlation analysis of APIs in each region with summer SSTs in the tropical and subtropical Pacific and Indian Oceans. To examine the relations between the large-scale climate factors in the tropical western Pacific and regional climatic factors for malaria incidence in India, composite differences of mean precipitation and temperature are calculated in the Indian subcontinent by subtracting the mean values for the two lowest years of JJAS SST in tropical western Pacific from the two highest years during 1986-1995.

3. Results

3.1. Changes in Malaria APIs

The regions with highest malaria endemicity are shown in western, central, and far eastern India for 1986-1994 (Fig. 3a). During the period, API significantly increases in western Rajasthan and Arunachal Pradesh (Fig. 3b). Statistically insignificant regions are masked out and significant regions at the 10% level are shown in Fig. 3b. Spatial (Fig. 4) and temporal changes (Fig. 5) of APIs in the two study regions support increasing trends in APIs during the period of 1986-1995.

API ranges much higher in Arunachal Pradesh. Comparing the spatial and temporal changes of APIs in the two regions suggests that western Rajasthan experiences more variability and less endemicity than Arunachal Pradesh. Western Rajasthan experienced a small increase in 1990 and a marked increase in malaria rates in 1994 and 1995. The top two high APIs for western Rajasthan are observed in Jaisalmer and Barmer districts, which are located in the Thar Desert, during the last two years of study. High APIs in the last two years are also observed in Arunachal Pradesh. By use of a one-sided Grubbs' test for outliers (Grubbs, 1950), five outlying API observations are detected in western Rajasthan: 1990, 1994, and 1995 in Barmer district and 1994 and 1995 in Jaisalmer district. No significant outliers are detected for API in Arunachal

Pradesh. The extent of canal irrigation in the Thar Desert during the period of 1990-1994 (2.17×10^6 ha) increased by 63% compared to the previous period of 1985-1989 (1.33×10^6 ha) (Tyagi, 2004). In arid western Rajasthan, especially in the Thar Desert, the expansion of irrigation areas could provide new breeding habitat for *An. culicifacies* mosquitoes and consequently increase malaria risk.

3.2. Regional-Scale Climate Factors for APIs

To investigate the relationships between malaria API and regional climate factors we analyze precipitation, temperature (daily mean, maximum, and minimum), soil moisture, and PET in western Rajasthan and Arunachal Pradesh during the summer season (Table 1). Temperature and precipitation are known to be key factors in influencing the abundance of anopheline mosquitoes and consequently malaria transmission (Gilles and Warrell, 1993; Craig et al., 1999). In western Rajasthan, the inter-annual variability of API is positively and significantly correlated to that of JJAS precipitation ($r=0.72$; $p\text{-value}=0.02$), but there is a negative correlation between API and JJAS maximum temperature ($r=-0.55$; $p\text{-value}=0.10$, Fig. 6a). In Arunachal Pradesh, there is a positive correlation of API with JJAS temperature and a negative correlation with JJAS precipitation, but these correlations are not statistically significant (Fig. 6b). Thus, increases in precipitation could favor malaria incidence in the arid climate of northwestern India but have limited or negative impact in the humid climate of northeastern India.

The positive association of API with summer precipitation and negative association with temperatures in western Rajasthan are in correspondence with significant relationships of API with summer soil moisture ($r=0.78$; $p\text{-value}=0.01$) and PET ($r=-0.70$; $p\text{-value}=0.03$) (Fig. 6a). Higher values of soil moisture, caused by increasing precipitation and decreasing PET, would be associated with increases in cloudy/rainy days and decreasing temperature and could provide more favorable conditions for malaria incidence in this hot and arid climate region. Wetter summers are cooler and have less solar radiation to evaporate water from the land surface and plants. In Arunachal Pradesh, the relations between API and soil moisture (negative correlation) and PET (positive correlation) during the summer season are not statistically significant. All parametric and nonparametric correlation values of API with climate and irrigation variables in the two regions are presented in Tables 1a and 1b.

We assess the impacts upon correlation values of outlying observations in API and trends over time in API and environmental variables. The removal of five outlying API observations from western Rajasthan does not substantively change our findings with regard to the sign (direction of relationship) and statistical significance (strength of relationship) of correlation coefficients between APIs and the environmental predictors (see Supplementary material 1). Detrending time series of API and environmental variables alters strength and significance of association between API and explanatory variables in western Rajasthan, while direction of the association is consistent with correlations between variables that have not been detrended. For Arunachal Pradesh, the sign and strength of correlation by using detrending variables are consistent with the original relationship.

3.3. Irrigation Factors for APIs

In northwestern and northeastern India, variables that reflect irrigation conditions, including irrigation schedule, soil moisture, and NDVI during the dry pre-monsoon period (MAM), show different relationships with APIs in the two climatically dissimilar regions. During MAM, Arunachal Pradesh is a much wetter climate in comparison to western Rajasthan (Left figure in Fig. 2a). Western Rajasthan is characterized by greater aridity, as it has lower precipitation and higher levels of PET during spring. Consequently, irrigation water needs, as indicated by an irrigation schedule variable (PET – Precipitation) during MAM, is much higher for western Rajasthan (100 – 300 mm/month) than Arunachal Pradesh (-50 – +50 mm/month) which means little to no irrigation water is needed to grow crops (Fig. 7a). MAM soil moisture is much higher in Arunachal Pradesh (400 – 500 mm/month) than western Rajasthan (10 – 100 mm/month) (Fig. 7b). Arunachal Pradesh is much lushier as indicated by higher spring NDVI (Fig. 7c). A significant positive correlation ($r=0.67$; $p\text{-value}=0.04$) of API and MAM NDVI in western Rajasthan (Last figure in Fig. 6a) suggests that increasing surface moisture by increasing irrigation practices could provide more favorable conditions for malaria transmission in the arid climate region. There are positive relationships of API with other irrigation factors in western Rajasthan such as soil moisture and irrigation schedule during MAM (Table 1). In wetter Arunachal Pradesh, there is a negative correlation of API with MAM NDVI (Fig. 6b), but no significant relationships exist between API and any of the three irrigation-related variables.

3.4. Large-Scale Climate Factors for APIs

In order to examine the relationships of APIs with SSTs in the tropical Indian and Pacific Oceans, we calculate correlation coefficients of APIs with mean JJAS SST of each grid over the tropical oceans. APIs in both western Rajasthan and Arunachal Pradesh are significantly correlated with SSTs in the tropical western Pacific for JJAS (Figs. 8a and 8b). There are negative correlations between APIs in the both regions and SSTs in the northern Indian Ocean, but they are not statistically significant at the 5% level.

We use the spatial correlation patterns to select the domains of SST variables that are used as the large-scale climate factors for malaria API. SST in the tropical western Pacific for JJAS is averaged over 140°-190°E and 5°-20°N for western Rajasthan (right box in Fig. 8a), and over 145°-195°E and 10°-20°N for Arunachal Pradesh (right box in Fig. 8b). SST in northern Indian Ocean for JJAS is calculated over 65°-100°E and 5°-25°N for both land regions (left boxes in Figs. 8a and 8b). Consequently, the SST variables in northern Indian Ocean are the same for the two study regions but tropical western Pacific SST are different for the two regions. Time series of the area-averaged SST in the tropical western Pacific is highly correlated with APIs in western Rajasthan ($r=0.82$; $p\text{-value}=0.004$) and in Arunachal Pradesh ($r=0.89$; $p\text{-value}=0.001$). Abrupt increase in SSTs in tropical western Pacific in 1994 and 95 are consistent with those in APIs in the two study regions (Figs. 9a and 9b). The correlations of APIs with JJAS SST in the northern Indian Ocean are not statistically significant in either region ($r=-0.42$ for western Rajasthan; $r=-0.30$ for Arunachal Pradesh).

To examine the regional climatic conditions in India associated with the variability of SST in the tropical western Pacific, we calculate composite differences of JJAS precipitation and mean temperature in the Indian subcontinent between the two years of highest and of lowest JJAS SST in the tropical western Pacific. The highest and lowest years of SST for the composite analysis are selected from the time-series of SSTs in the tropical western Pacific. The selected years from the SST time-series are 1994 and 1995 for the two highest SST years and 1987 and 1992 for the two lowest years. During the years of high SST in the tropical western Pacific, the composite patterns show more summer rainfall and consequently decreasing surface air temperature in western Rajasthan (Figs. 10a and 10b). Conversely, less rainfall and resultant increasing temperature are observed in northeastern India.

Additionally, we examine a correlation between summer rainfall in arid western Rajasthan and SSTs in the Niño 3.4 region (170°W–120°W and 5°N–5°S), which has been used as an ENSO index. During the study period, JJAS precipitation in western Rajasthan is negatively correlated with SSTs in Niño 3.4 region ($r=-0.42$; $p\text{-value}=0.227$). The stronger positive correlation ($r=0.61$; $p\text{-value}=0.061$) has been observed between summer rainfall in western Rajasthan and SSTs in the tropical western Pacific (right box in Fig. 8a). In addition, we calculate a correlation of malaria API in western Rajasthan with SSTs in Niño 3.4. The correlation ($r=-0.10$) is much weaker than that with SSTs in the tropical western Pacific ($r=0.82$). The results suggest that the API variability in western Rajasthan during the study period could be explained more by the variability of SSTs in the tropical western Pacific, compared to those in the Niño 3.4 region. However, the malaria associations with the SST variabilities in the tropical oceans should be validated with longer time series of malaria API.

As mentioned in section 3.2, the different regional precipitation and temperature conditions are associated with malaria API in the climatically dissimilar regions. For the years of higher SST in the tropical western Pacific, wetter and cooler climates in northwestern India could result in more malaria incidence in arid western Rajasthan. During the same years, drier and warmer climates in northeastern India could also provide more favorable conditions for malaria incidence in humid Arunachal Pradesh.

4. Discussion and Conclusions

Malaria API in two climatically dissimilar regions in India is associated with different regional climate, irrigation, and transmission risk factors. The climate and hydrographic history associated with each region have created niches specific to different *Anopheles* species that translate into different malaria transmission dynamics. API in western Rajasthan is significantly correlated to summer moisture variables of precipitation, soil moisture and potential evapotranspiration, and spring irrigation activity as indicated by the vegetation index. Rainy summers in arid western Rajasthan are positively associated with API. Potential evapotranspiration in the arid climate region is negatively related to API, as high levels of evapotranspiration would inhibit mosquito development and decrease habitat space available for mosquito breeding and larvae. In arid western Rajasthan, especially in the Thar Desert, the

expansion and intensification of irrigation practices have provided new breeding habitat for *An. culicifacies* mosquitoes and could also initiate movement and clustering of people infected with malaria into the region. The association between malaria incidence and irrigation is supported by a strong positive correlation between API and spring irrigation indices in western Rajasthan.

We observed greater overall malaria incidence in humid Arunachal Pradesh, a region characterized by less inter-annual variability than outbreak-prone arid western Rajasthan. In Arunachal Pradesh, API is positively associated with temperature, but negatively related to precipitation during the boreal summer. The irrigation index as shown in spring vegetation activity is negatively related to API in the northeastern region of India. The results suggest that the relationships of malaria API with regional climate and irrigation factors are fundamentally different in the two (arid versus humid) study regions in India. The unique habitat requirements of the malaria vectors specific to each region are closely linked to the climatic and irrigation conditions. Malaria parasite incidences are significantly affected by summer moisture and spring irrigation conditions in the moisture-limited western Rajasthan. Spring irrigation could directly affect malaria transmission by providing breeding habitat for mosquitoes. Also, it might indirectly influence malaria by changing summer monsoon rainfall, because early Indian summer monsoon variability is partially associated with spring irrigation activities (Lee et al., 2009). However, while they are positively associated with summer temperature in the relatively moist Arunachal Pradesh, no environmental variables except summer SST in the western Pacific are significantly correlated with malaria in Arunachal Pradesh.

While this study focuses on inter-annual variation in API and its relationship to climate and irrigation variables, intra-annual API is different during the different months of the year in India (Bhattacharya et al., 2006). Monthly and seasonal variations of API in the two study regions could be differently affected by intra-annual variations of climate and irrigation practices. In order to examine the intra-annual relationships, monthly API and irrigation data are required. Often environmental variables, especially climate data, are not stationary with time (e.g., Kumar et al., 1999) and the correlation analysis we have performed here are no guarantee of stationarity. Therefore, the identified relationships in this study will have to be constantly monitored by using longer time series of high-resolution (district-level) malaria and environmental variables.

SSTs in the western Pacific during boreal summers are strongly and positively correlated with APIs in both western Rajasthan and Arunachal Pradesh. Increasing precipitation and

decreasing temperature during the years of high SST in tropical western Pacific appear to promote malaria infection in arid western Rajasthan. Conversely, decreasing precipitation and increasing temperature during the high SST years in the western Pacific provide favorable conditions for malaria in wetter Arunachal Pradesh. Thus, SST variability in the tropical ocean plays a significant role in controlling malaria parasite incidence by affecting regional climate conditions differently in northwestern and northeastern India. While we show the associations of the regional climate conditions in India with SSTs in the tropical western Pacific, the teleconnection mechanisms need further investigation using atmospheric circulation variables. In a recent study, SST in the tropical South Atlantic was shown to provide a basis for an early warning of anomalous hydrological conditions conducive to malaria epidemics four months later in India (Cash et al., 2013). Thus, the understandings of remote climate forcing of malaria epidemics at lead times are important to provide more accurate prediction of malaria risk in India.

Our study was limited to extrinsic environmental factors linked to malaria patterns in India, but unobserved intrinsic transmission factors are critical to a comprehensive understanding of malaria. Beyond climate and irrigation contributing to vector abundance, intrinsic variables incorporate risks associated with socioeconomic status, education, knowledge and use of malaria interventions (bed nets, repellents etc.), access to care and treatment, migration, surveillance bias, and political conflict (Yadav et al., 2014; Brooker et al., 2004; Parekh et al., 2007; Matthys et al., 2008; da Silva-Nunes et al., 2008). Any condition that increases the prevalence of malaria infections in the human population increases the likelihood of transmission events in the presence of a competent vector. Both extrinsic and intrinsic variables can alter the susceptibility of populations to malaria or affect the timing and magnitude of malaria epidemics. The intrinsic variables are not mutually exclusive and malaria epidemics are often caused by complex interactions with extrinsic factors (Kovats et al., 2003). Thus, both intrinsic and extrinsic (e.g. environmental factors like climate and irrigation variables) factors should be taken into account to fully characterize epidemic malaria in India.

Our findings shed light on the spatial and temporal variability of malaria risk in India, and could inform region-specific disease prevention strategies. The identified irrigation, regional and large-scale climatic variables in this study could be applied for improving malaria prediction model by utilizing the ecological and climatological conditions as potential predictors in multivariate regression framework (see Supplementary material 2: multivariate linear regression

analysis for API in arid western Rajasthan). Additionally, the identified underlying malaria-climate-irrigation linkages could be applied to estimate malaria incidence using general circulation model experiments with future climate scenarios, and could be used to estimate future populations at risk of malaria. While this study highlights the roles of changing climate and land use/cover in malaria incidence, extended temporal datasets are required to firmly establish the associations of climate, irrigation, vector abundance, and malaria. The further efforts could lead to a more robust understanding of the human health impacts of accelerating environmental change and inform decision-making in the land-use planning, environmental conservation, and public health policy realms (Myers et al., 2013).

Acknowledgements.

The study was supported by the Eberly College of Arts and Sciences Applied Computational Sciences Innovation Awards at West Virginia University. We wish to thank George Allez of the Center for Sustainability and the Global Environment (SAGE) at the University of Wisconsin-Madison for tirelessly digitizing the district level Indian malaria records. This study has been presented in the 2013 International Geographical Union (IGU) Regional Conference in Kyoto, Japan, partially supported by AAG IGU Travel Grant funded by NSF.

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Table:

Table 1. Correlation values of climate and irrigation factors with APIs in western Rajasthan and Arunachal Pradesh using (a) parametric Pearson and (b) non-parametric Spearman's rank correlation coefficients. Here ** and * represent that correlations are significant at $\alpha=0.05$ and 0.10 levels.

Figures:

Figure 1. Two study regions in northwestern (Western Rajasthan) and northeastern (Arunachal Pradesh) India.

Figure 2. (a) MAM (left) and JJAS (right) means of precipitation (mm/month) in India and (b) JJAS means of daily minimum (left), mean (center), and maximum (right) temperatures ($^{\circ}\text{C}$) in India.

Figure 3. (a) Means of Annual Parasite Incidence (API) of malaria in India for 1986-1994 (in unit of API case/ 1,000 population). (b) Changes of API in India for 1986-1994 (in unit of [API case/ 1,000 population)/ year]). Statistically significant regions at the 10% level are shown in Fig. 3b. The states of Rajasthan and Arunachal Pradesh are circled by red and blue, respectively. API data are compiled from 496 districts in India and then interpolated to 5 minutes by 5 minutes.

Figure 4. Changes of APIs at the districts in (left) western Rajasthan and (right) Arunachal Pradesh from 1986 to 1995.

Figure 5. Time series of aggregated (lines) and district APIs (circles) in (a) western Rajasthan and (b) Arunachal Pradesh from 1986 to 1995.

Figure 6. Time series of (a) western Rajasthan and (b) Arunachal Pradesh APIs (Y1 axis) with the regional-scale climate and irrigation (NDVI) variables (Y2 axis).

Figure 7. MAM means of (a) irrigation schedule variable (PET- precipitation; mm/month), (b) soil moisture (mm/month), and NDVI (unitless).

Figure 8. Correlation coefficients of APIs in (a) western Rajasthan and (b) Arunachal Pradesh with JJAS SST at each grid for 1986-1995. Significant regions at the 5% level are contoured. The boxes indicate the regions where SST variables for malaria incidence are calculated over.

Figure 9. Time series of (a) western Rajasthan and (b) Arunachal Pradesh APIs (Y1 axis) with the large-scale climate variable (JJAS SST in tropical western Pacific in Y2 axis).

Figure 10. Composite differences of (a) JJAS precipitation (mm/month) and (b) JJAS mean temperature ($^{\circ}\text{C}$) between the two years of highest (1994, 1995) and of lowest (1987, 1992) JJAS SST in tropical western Pacific.

Figure 1

Figure 2

(a)

(b)

Figure 3

Figure 4

(a)

(b)

Figure 5

(a)

(b)

Figure 6

Figure 7

Figure 8

(a)

(b)

Figure 9

(a)

(b)

Figure 10

Table. 1

(a) Pearson correlation

Environmental variables		API in western Rajasthan		API in Arunachal Pradesh	
		r-value	p-value	r-value	p-value
Regional-scale climate	JJAS precipitation	0.72**	0.02	-0.24	0.51
	JJAS mean temp	-0.39	0.26	0.40	0.25
	JJAS min temp	-0.03	0.93	0.36	0.31
	JJAS max temp	-0.55*	0.10	0.29	0.42
	JJAS soil moisture	0.78**	0.01	-0.36	0.30
	JJAS potential ET	-0.70**	0.02	0.12	0.74
Irrigation	MAM irrigation schedule	0.26	0.47	-0.12	0.74
	MAM soil moisture	0.53	0.12	-0.30	0.40
	MAM NDVI	0.67**	0.03	-0.31	0.38
Large-scale climate	JJAS SST in W. Pacific Ocean	0.82**	<0.01	0.89**	<0.01
	JJAS SST in N. Indian Ocean	-0.42	0.23	-0.30	0.39

(b) Spearman's rank correlation

Environmental variables		API in western Rajasthan		API in Arunachal Pradesh	
		rho-value	p-value	rho-value	p-value
Regional-scale climate	JJAS precipitation	0.59*	0.07	-0.35	0.33
	JJAS mean temp	-0.45	0.19	0.39	0.26
	JJAS min temp	-0.22	0.53	0.54	0.11
	JJAS max temp	-0.58*	0.08	0.22	0.53
	JJAS soil moisture	0.73**	0.02	-0.25	0.49
	JJAS potential ET	-0.62**	0.05	0.09	0.80
Irrigation	MAM irrigation schedule	0.31	0.38	-0.21	0.56
	MAM soil moisture	0.72**	0.02	-0.35	0.33
	MAM NDVI	0.58*	0.08	-0.21	0.56
Large-scale climate	JJAS SST in W. Pacific Ocean	0.45	0.19	0.82**	<0.01
	JJAS SST in N. Indian Ocean	-0.55**	0.01	-0.19	0.60