An Integrated Hydrological and Atmospheric Model to Predict Malaria Epidemics

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Abstract

The focus of this research is the integration of hydrological modeling with Regional Atmospheric Modeling System (RAMS) along with mosquito abundance and malaria parasite transmission studied in a GIS-based system applied to the Ixcan region of Guatemala. Approximately 35% of Guatemalan population lives in malaria areas. Results of field studies by the Medical Entomology Research and Training Unit-Guatemala (MERTU) and the center for health studies at (UVG) demonstrate that malaria incidence has increased in recent years. *P. falciparum* now accounts for as much as 20% of malaria infections at study sites.

Malaria transmission is strongly associated with environmental conditions, which control mosquito maturity and parasite development. Of particular importance are surface temperature, relative humidity, precipitation and wind speed. The Regional Atmospheric Modeling System is used to predict these variables which, in turn, are used in dynamic hydrological models to yield the parameters important to malaria transmission including surface wetness, mean water table depth, percent surface saturation and total surface runoff. The locations of saturated surface regions associated with mosquito breeding sites near populated regions, along with water temperature are then used to determine larvae development and mosquito abundance.

ASTER, LANDSAT and MODIS imagery are used to retrieve soil moisture, vegetation indices and land cover types. Pan-sharpened 1m spatial resolution IKONOS data has also been used to identify small mosquito breeding sites with an accuracy of 90%, as verified by ground observations. These layers of information, along with a 30m resolution Digital Elevation Model and field measurements of malaria incidence, larvae and mosquito counts were examined in a GIS system to identify the environmental parameters effective in mosquito distribution. The Genetic Algorithm for Rule Set Production (GARP) has been applied to the region using the parameters defined above to predict regions susceptible to malaria transmission

1. INTRODUCTION

Estimates of malaria transmission in Guatemala, measured as the number of cases per 1000 inhabitants per year (microscopically confirmed malaria febrile episode) have been available since the 1950s when the National Malaria Eradication Program and its passive surveillance system was established in the Guatemala.

In the Ixcan region, detailed malaria information has been gathered for 176 communities for the last 14 years. Malaria cases are recorded house-by-house in each community, and GPS coordinates have been recorded for every house. This data set allows us to identify clusters of communities with the highest/lowest malaria infection rates.

Malaria transmission is strongly associated with environmental conditions such as rainfall, temperature and humidity and with landscape

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features such as topography and land cover. We have utilized a combination of satellite-derived parameters and surface-based measurements/observations to develop a series of predictive models with the parameters necessary to support effective malaria elimination/control strategies.

2. Data

In the Ixcan region, (15° N to 16° N and 90° W to 89° W) detailed malaria information gathered for 26 communities for 7 months of April through October 2001 have been used to identify the distribution pattern of malaria. Malaria occurrences are recorded house-by-house in each community and GPS coordinates have been recorded for every house. This data set allows us to identify clusters of communities with the highest/lowest malaria infection rates.

Soil moisture is retrieved from the Moderate Resolution Imaging Spectroradiometer (MODIS 1km resolution level 1B) for April through October 2001 using Gilles et al. (1997) Triangle Method and monthly cloud frequency. The MODIS derived surface temperature and NDVI data set at 1 km resolution are made available by NASA Earth Observing System. National Center for Environmental Prediction (NCEP) reanalysis data set (Kalney et al. (1996)) including rainfall, wind direction and soil moisture are also used in this study to analyze the climatology and environmental characteristics of the study region.

Potential mosquito breeding sites are developed using MSAVI2, NDVI, TASSELED_CAP derived from LANDSAT , IKONOS, and 30 meter resolution Digital Elevation Model (DEM).

3. METHODOLOGY

3.1 Detection of Breeding Sites

Of critical importance is to determine the location of breeding sites near population centers. Mosquitoes have typical flight ranges of 1-3 km depending upon species. However, most mosquito breeding sites are sub-resolution scale for even the high spatial resolution satellites such as LANDSAT and the Advanced Spaceborne Thermal Emission and Reflectance Radiometer (ASTER), all of which have spatial resolutions of 15m in the visible channels. The small breeding sites, however, can be located in the new IKONOS satellite imagery that has panchromatic bands at 1m. Indeed, we have demonstrated in the Ixcan region of Guatemala that it is possible to positively

Figure 1.

locate small mosquito breeding sites using IKONOS imagery. Breeding sites were located, and the locations were transmitted to a ground-truth team who verified the sites using a GPS unit. An accuracy of 90% was achieved (see figure. 1). Houses, road intersections, breeding sites, trees, and vegetation covers are located within approximately 10m resolution. Unfortunately, IKONOS imagery is highly expensive and ground-truth teams generally are not available at all sites. Therefore, a major effort of this investigation is to determine to what degree the small mosquito breeding sites can be detected with lower resolution imagery available on LANDSAT and ASTER. NDVI (Normalized Vegetation Index), MSAVI2 (Modified Soil Adjustment Vegetation Index Qi et al. 1994) and Tasseled-Cap transformation for LANDSAT and IKONOS (James H. Horne) are also used to identify potential breeding sites.

3.2 Hydrological Modeling

We have used a Digital Elevation Model for terrain analysis to develop flow direction, flow accumulation, drainage line, catchment, and watershed delineations. This allows us to describe the principle water resource features of the landscape and the way that water moves from feature to feature.

We have utilized the TOPMODEL to model shallow subsurface flows. This hydrological model predicts catchment water discharge and regional spatial soil saturation patterns. There are four effective catchment parameters that are fitted from discharge predictions so that neither horizontal nor vertical soil parameters are required. A water table is assumed below the entire watershed. Parameters of particular importance are surface temperature, relative humidity, precipitation and wind speed. The Regional Atmospheric Modeling System (Described in section 3.3) is used to predict these variables which, in turn, are used in dynamic hydrological models to yield the parameters important to malaria transmission including surface wetness, mean water table depth, percent surface saturation and total surface runoff.

This hydrological approach identifies potential breeding habitats within a catchment accounting for topographic variability, soil moisture heterogeneity and runoff. The locations of small areas of surface wetness are predicted from percent surface saturation. Saturated surface regions are the potential mosquito breeding sites. These regions are compared with predictions generated from ASTER and/or MODIS imagery using the Gilles et al. (1997) Triangle Method.

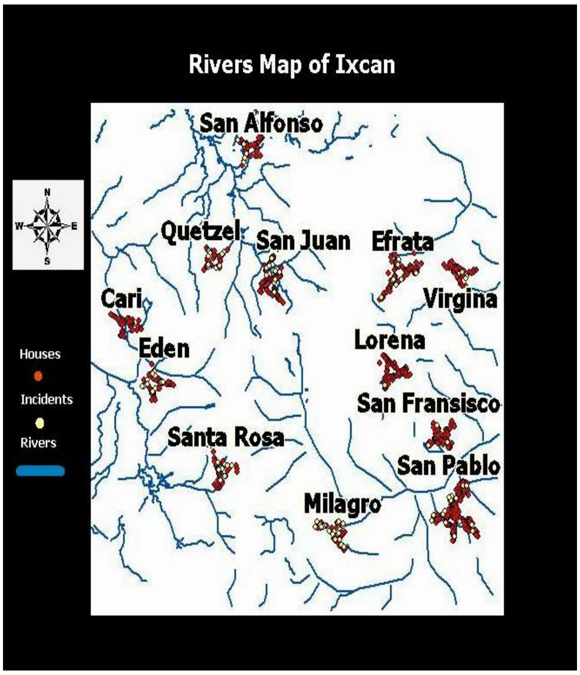

Figure 2. Houses geocoded for malaria investigation and malaria incidents shown on the river map.

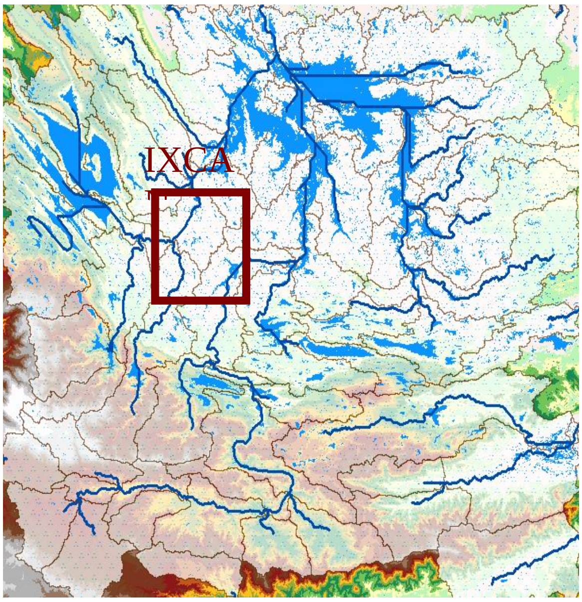

Figure 3. Inundation regions shown in blue and drainage lines overlayed on catchments and DEM layer. This map covers a larger area of 185 by 185 meters which includes IXCAN study area.

3.3 Regional Atmospheric Modeling System (RAMS)

RAMS uses finite difference methods for solving the various conservation equations governing atmospheric flow based on a polar stereographic grid in the horizontal and a terrain-following sigma-*z* coordinate system in the vertical (AXIS?). Atmospheric processes are represented in RAMS using schemes of varying complexity--it provides flexibility for choosing levels of sophistication for representing processes such as turbulence, cloud microphysics, radiative transfer and other processes. RAMS provides several techniques to handle top and lateral boundary conditions. Observational data and results from larger-domain models can be assimilated into the model using a nudging scheme. Here, values of predicted variables at model grid points are relaxed towards the values observed or predicted in large-scale models. The extent of influence of these external data on the model simulation may be adjusted via relaxation time scale applicable to the entire domain with weights whose values are function of grid location.

Land Surface Parameters: A major advantage of RAMS is its sophisticated Land-Ecosystem Atmosphere Feedback (LEAF-2) model to represent land surface processes. LEAF-2 accounts for energy and moisture transfers between atmosphere, soil, water, snow, and vegetation and allows for specification of multiple land use types at individual grid points. At the surface, RAMS uses a 30”-resolution global database to specify land use types and topography. However, RAMS also allows input of user-specified land use characteristics derived from other sources.

Precipitation: Cloud and precipitation processes can be represented in RAMS either through implicit convective parameterization schemes and the Kain-Fritsch scheme (Kain and Fritsch, 1993) or via explicit representation of cloud microphysics. Explicit representation of cloud microphysics allows for prediction of mixing ratios and number concentration of two categories cloud droplets, pristine ice, rain, snow, aggregates and hail. User-specified concentrations of cloud condensation nuclei (CCN) and giant cloud condensation nuclei (GCCN) are used to nucleate the two categories of cloud droplets. Explicit representation of cloud microphysics is more realistic and is essential for studies involving cloud-aerosol interactions.

Radiative Transfer: RAMS provides radiative transfer schemes of varying sophistication, from a scheme that accounts only for clear air radiative transfer to a two-stream technique that accounts for ice particle shape. However, none of these schemes currently accounts for radiative interactions of atmospheric aerosols. We have recently integrated a modified version of the sophisticated Fu-Liou radiative transfer scheme into RAMS, which encompasses radiative interactions of aerosols including smoke and transported dust. The Fu-Liou scheme is an important addition to RAMS since it provides accurate estimates of down-welling solar flux at the surface under both clear and aerosol-loaded atmospheric conditions, a crucial input for land-surface models. Proper estimates of surface-level solar flux will provide much better prediction of surface heat and moisture budgets.

3.4 Ecological Niche Modeling

Our ecological niche models are based on three principal suites of environmental data: (1) topography and landscape features, (2) remotely-sensed data (MODIS, AVHRR, IKONOS, ASTER, and LANDSAT), (3) Ground based measurements of temperature and humidity, and (4) malaria incidences. Ecological niches and potential geographic distributions are modeled using the machine-learning software application *Genetic Algorithm for Rule-set Prediction* (GARP), which develops a heterogeneous rule-set defining the distribution of the species in ecological space. GARP relates ecological characteristics of a species' geographic occurrence to those of points randomly sampled from the study region. The result is a set of decision rules that best summarize those factors associated with the species' presence. This rule set constitutes a model of the ecological niche of the species.

First, GARP is used to interpolate at fine scales between mosquito breeding sites to produce detailed maps of breeding sites that are not biased by access considerations in sampling. Second, and more challenging, we explore the applicability of GARP to the challenge of predicting malaria outbreaks and mosquito distributions from one month to the next. Here, we take occurrence data and satellite imagery from one month and use GARP to build models of the ecological conditions under which mosquitoes reached high populations or malaria outbreaks occurred. The rule set associated with this model then is projected to the satellite imagery to predict high mosquito populations or malaria outbreaks in the next year.

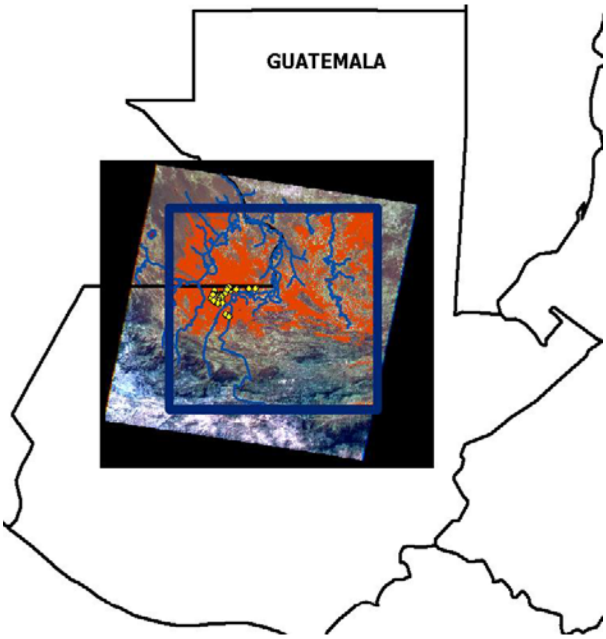

Figure 4. Distribution of malaria in ecological space using Genetic Algorithm for Rule-Set Prediction (GARP)

5. CONCLUSIONS

Soil moisture, surface temperature, normalized vegetation index retrieval and cloud frequency from low resolution data such as MODIS are useful to identify the pattern of the environmental characteristics of a region.
Cloud frequency retrieval could be used as an estimate for precipitation rate.
Tasseled-Cap transformation, NDVI, MSAVI & topographical analysis are useful tools to

identify potential mosquito breeding sites and small water ponds.

Genetic Algorithm Models can be used to determine the possible distribution of mosquito breeding sites.

Modeled surface wetness allows us for real time monitoring and forecasting of floodwater species at high resolution.

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