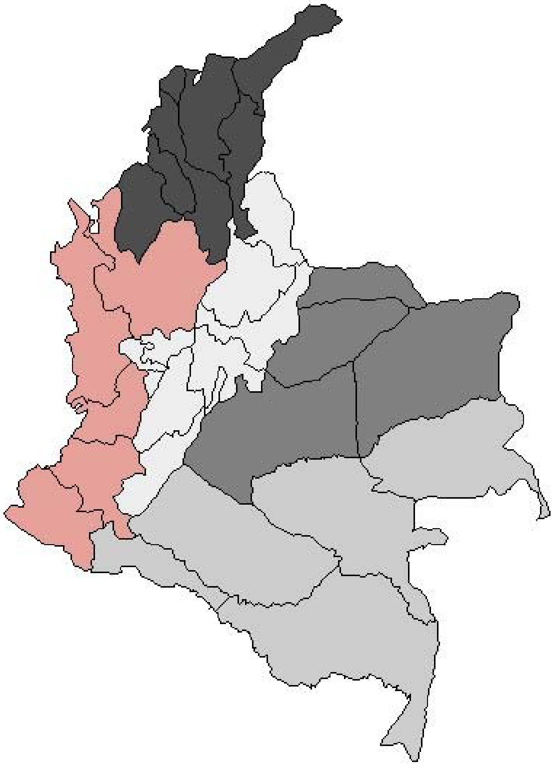
Final Report on Activities of the Integrated National Adaptation Pilot Project (INAP)



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Introduction

This report summarizes activities conducted by the International Research Institute for Climate and Society, in collaboration with Colombia's National Institute of Health and the National Institute of Hydrology, Meteorology, and Environmental Studies, in the design and development of an early warning system framework to facilitate National Integrated Surveillance and Control System. Though the collaboration has lasted five years, this report focused on developments since the last report, issued in May of 2010.

Background

Climate change is considered to be a major global environmental problem that could have significant effects on human health. One of its potential ecologically-mediated impacts is the change in the incidence and the spatial distribution of climate-sensitive vector-borne diseases, including malaria. Changes in climatic conditions associated with long-term climate change, as well as those associated with more short-term fluctuations such as the El Niño-Southern Oscillation, could influence the behavior of vectors, their geographical distribution, and the development rate at which pathogens mature.

This is particularly true in Colombia, where malaria has already reemerged as a significant public health burden. Malaria incidence during epidemic years has increased from less than 15 positive cases per 10,000 inhabitants in 1964, to 58 per 10,000 in 1983, to almost 165 per 10,000 in 1998. More recently, Colombia's Ministry of Social Protection calculated that 85 percent of Colombia's rural territory has adequate climatic, geographic, and epidemiologic characteristics for malaria transmission; it also reported that more than 25 million Colombians were at risk of contracting the disease (Ministry of Social Protection 2003).

The incidence of malaria in Colombia has continued to rise despite a wide range of interventions in both vector control and treatment. To curb this, Colombia has proposed a very ambitious adaptation strategy to mitigate the possible adverse effects of climate change on human health: the National Integrated Surveillance and Control System (ISCS), which is part of the Integrated National Adaptation Pilot Project, first initiated by the country in 2006.

The National Integrated Surveillance and Control System is based on five linked components: (i) an early warning system (EWS) framework; (ii) a platform of climate forecasts, monitoring and analysis of scenarios; (iii) epidemiological surveillance and control activities; (iv) entomological surveillance and control activities; and (v) improvement of the activities for early diagnosis and treatment of primary cases. The major phases of the implementation of this adaptation strategy include: the design of the early warning system, the strengthening of institutional capacity, and the implementation of the knowledge management, monitoring, and evaluation systems.

Role of the IRI

For the last five years, the International Research Institute for Climate and Society (IRI) of Columbia University has worked closely with Colombia's National Institute of Health (INS) as well as the National Institute of Hydrology, Meteorology, and Environmental Studies (IDEAM) in the design and development of the EWS framework of the ISCS. Through the development of predictive models that use climate variables and other potential predictors, this EWS will allow for the early detection and timely intervention of malaria epidemics. The proposed EWS will make use of both statistical and dynamical (biological or process-based) models.

It is worth mentioning that because malaria is a very localized problem in Colombia, any control program would need to incorporate very local targets for interventions. An EWS in support of such a program would need to be able to identify outbreaks as soon after infection as possible.

To date, the collaboration between IRI, INS, and IDEAM has involved:

- capacity building on the impact of climate change on public health
- data quality control and the development of data sets of malaria incidence
- analysis for statistical models
- analysis for dynamical models
- validation and intercomparison of satellite rainfall estimates over Colombia
- vulnerability analysis

These activities were detailed in two earlier communications, issued in May of 2010.

The current report, the final communication of the project, addresses more recent progress, including the development of a range of malaria forecasting models:

- an improvement of a previously proposed dynamical model for malaria transmission
- a statistical model to isolate the effects of climate on malaria transmission
- a multi-model ensemble approach to simulate transmission dynamics

The report concludes with a brief summary on overall progress and a series of recommendations for the future, including guidelines for the development and implementation of an EWS for malaria in Colombia.

Recent Activities

The current project developed statistical and dynamical models to forecast the incidence of malaria in the five pilot regions identified by the INS. While statistical models attempt to formalize the stochastic relationships between the variables with probability distributions, dynamical models take into the account the interactions between vector life cycles, sporogonic cycles, and human disease cycles, under the influence of external factors.

Statistical and dynamical models are also being merged in order to create a multi-model ensemble. Ensemble forecasting is a form of Monte Carlo analysis in which multiple numerical predictions are conducted using slightly different initial conditions that are all plausible given the past and current set of observations, or measurements. The current work employs all these methods in order to understand and forecast malaria incidence in Colombia.

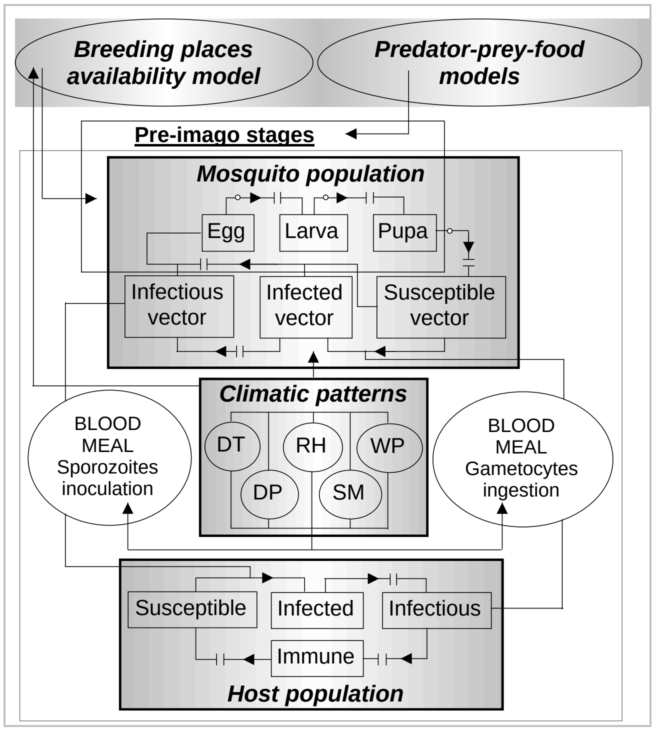
1. Dynamical Model: *Work was conducted to improve a dynamical model that describes the complexity of malaria transmission in the pilot regions of Colombia*.

Our analysis and implementation of dynamical models follow a long history of experimentation with malaria transmission models, the first of which was developed nearly 100 years ago. In the time since then, scientists have worked to develop increasingly intricate dynamical models that could capture the complexity of malaria transmission.

Dynamical tools can be used to understand the role that climatic and non-climatic factors play in malaria transmission; compare simulation outputs with actual malaria morbidity profiles; assess the effects of changes in climate and in socioeconomic conditions on malaria transmission; simulate the impact of control interventions; conduct stability analyses; and create an interactive learning environment.

To accurately characterize the transmission dynamics in the pilot areas in Colombia, a team led by Daniel Ruiz – jointly appointed to the IRI and to the Escuela de Ingeniería de Antioquia in Colombia – worked to improve a previously developed and published dynamical model: the overall malaria model proposed by Ruiz et al. (2006), whose schematic diagram is depicted in Figure 1. The comprehensive tool has three linking components that can be simulated separately. These components are: the human host population, the mosquito population, and the climate patterns. As the schematic diagram shows, climate strongly affects the interaction between populations, the vector ecology, and the availability of breeding sites.

Figure 1: Schematic diagram of the dynamical model for malaria transmission.



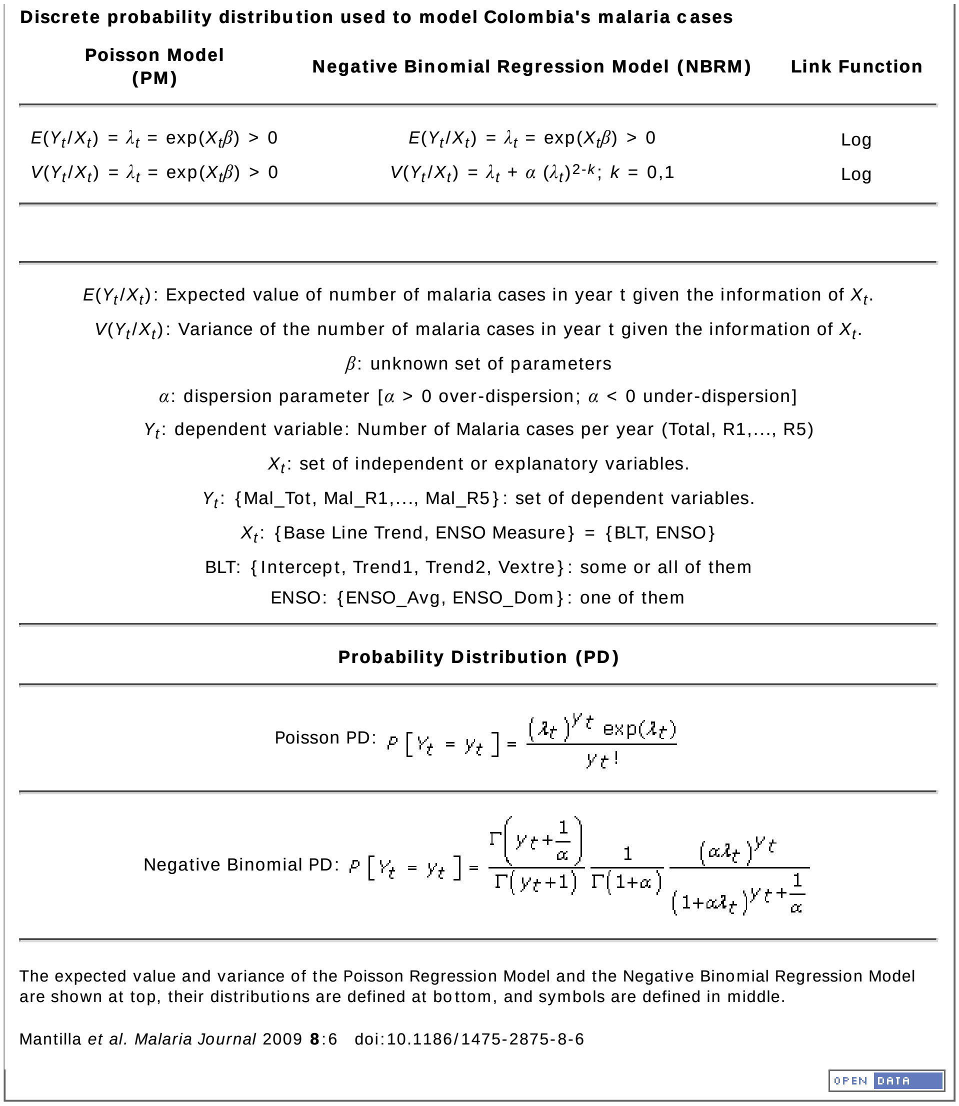
This tool was used to integrate the local climatic variables with non-climatic factors in order to simulate malaria transmission dynamics in each of the pilot sites of the INAP project. Simulations included retrospective experiments (base scenarios, changes in initial conditions, local settings, sensitivity analyses, and uncertainties) of at least 8-year simulation periods, corresponding to the time horizon that spans from the first epidemiological week of 2000 to the 52nd epidemiological week of 2008. These preliminary simulation results suggest that the correlation coefficients between the *Plasmodium falciparum* malaria prevalence, simulated by the improved dynamical tool, and the actual malaria morbidity profiles observed in the selected pilot sites could reach values as high as 0.592, when local climatic, entomological and socioeconomic conditions are incorporated in the simulation process. The mean square errors could reach, in turn, values as low as 1E-05.

2. Statistical Analysis: *Using historical climate data and annual malaria case number data from 1960 to 2006, statistical analyses were developed to isolate the effects of climate in each of Colombia's five contrasting geographical regions. These analyses can be used to develop statistical models.*

A link between malaria and year-to-year-climate variability, coupled with some ability to predict climate variations, can extend the lead time possible in organized malaria early warning systems beyond what can be done on the basis of real-time rainfall monitoring alone. To characterize this, the team explored statistical relationships between climate variability and malaria incidence in Colombia.

Table 1 describes the general models considered in this study and the way the variables are used to estimate the model parameters. Poisson regression models and Negative Binomial regression models are the baseline models used to test the influence of ENSO on Colombia's malaria cases. The follow predictors were used: annual indices of the ENSO state (sea surface temperature [SST] in the tropical Pacific Ocean) and time reference indices keyed to two major malaria trends during the study period.

Two ENSO indices, two time-reference indices, and one dummy variable were chosen as candidate predictors. The analysis was conducted using the five geographical regions to match the similar aggregation used by the National Institute of Health for its official reports.



Discrete probability distribution used to model Colombia's malaria cases

Poisson Model (PM)	**Negative Binomial Regression Model (NBRM)**	**Link Function**
$E(Y_t/X_t) = \lambda_t = \exp(X_t\beta) > 0$	$E(Y_t/X_t) = \lambda_t = \exp(X_t\beta) > 0$	Log
$V(Y_t/X_t) = \lambda_t = \exp(X_t\beta) > 0$	$V(Y_t/X_t) = \lambda_t + \alpha\,(\lambda_t)^{2-k};\ k = 0,1$	Log

$E(Y_t/X_t)$: Expected value of number of malaria cases in year t given the information of X_t.

$V(Y_t/X_t)$: Variance of the number of malaria cases in year t given the information of X_t.

β: unknown set of parameters

α: dispersion parameter [$\alpha > 0$ over-dispersion; $\alpha < 0$ under-dispersion]

Y_t: dependent variable: Number of Malaria cases per year (Total, R1,..., R5)

X_t: set of independent or explanatory variables.

Y_t: {Mal_Tot, Mal_R1,..., Mal_R5}: set of dependent variables.

X_t: {Base Line Trend, ENSO Measure} = {BLT, ENSO}

BLT: {Intercept, Trend1, Trend2, Vextre}: some or all of them

ENSO: {ENSO_Avg, ENSO_Dom}: one of them

Probability Distribution (PD)

Poisson PD: $P\left[Y_t = y_t\right] = \dfrac{(\lambda_t)^{y_t}\exp(\lambda_t)}{y_t!}$

Negative Binomial PD: $P\left[Y_t = y_t\right] = \dfrac{\Gamma\left(y_t+\frac{1}{\alpha}\right)}{\Gamma(y_t+1)}\,\dfrac{1}{\Gamma(1+\alpha)}\,\dfrac{(\alpha\lambda_t)^{y_t}}{(1+\alpha\lambda_t)^{y_t+\frac{1}{\alpha}}}$

The expected value and variance of the Poisson Regression Model and the Negative Binomial Regression Model are shown at top, their distributions are defined at bottom, and symbols are defined in middle.

Mantilla *et al. Malaria Journal* 2009 **8**:6 doi:10.1186/1475-2875-8-6

Table 1: describes the general models used in the statistical analysis.

To facilitate this project, data sets of malaria incidence and two climatic variables (temperature and rainfall) were developed for four Colombia municipalities. Though data set development was challenging, missing entries in the daily datasets of precipitation and temperature were filled using a stochastic daily weather generator.

The results show that year-to-year climate variability associated with ENSO causes interannual variability in malaria case numbers, while changes in population and institutional control policy result in more gradual trends.

Ultimately, probabilistic forecasts of the ENSO state could be used to form probability forecasts of temperature and precipitation, which in turn could lead to predict malaria levels, together with their uncertainties, throughout Colombia.

3. Multi-Model Ensemble: *A collaborative research project was also conducted to design and implement a multi-model ensemble approach to malaria transmission.*

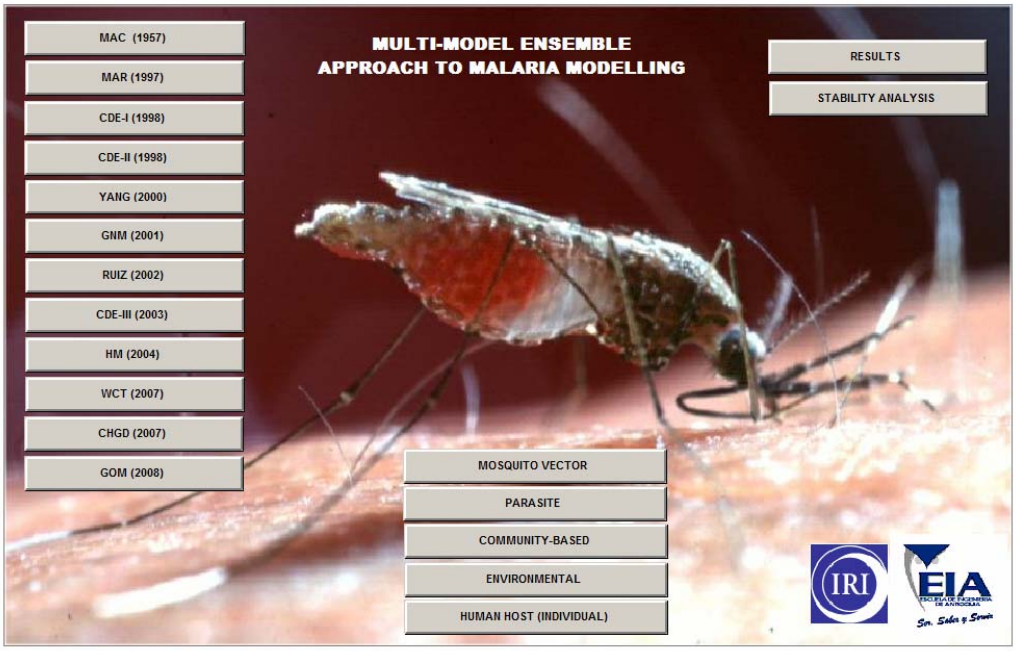
Background on Multi-Model Ensembles. Ensemble forecasting is a numerical prediction method that is used to generate a representative sample of possible future states of a dynamic system. This approach has been widely used to represent uncertainty in seasonal climate forecasting, where it has been shown to be an effective means of improving model predictions as well as demonstrating the level of uncertainty associated with model outputs.

Instead of using individual models in isolation, the team seeks to gain more useful insights by developing ensembles of different models, where biases in one model are compensated for by biases in other models, and where each model may be rerun using a different set of initial conditions. In this way, the combined outputs, represented as probability distributions, may offer useful information to effectively guide decision-makers in risk assessment and choice of control interventions.

Multi-Model Framework in Support of Malaria Surveillance and Control. Given the complexity of malaria transmission and the need for mathematical models for predicting the impact of interventions, a team led by Daniel Ruiz took steps to create an ensemble framework of various mathematical models to aid in the forecasting of malaria epidemics in pilot regions in Colombia. See Figure 2. Twelve process-based models were studied and included in a single multi-model ensemble. Five tools were initially applied in the pilot sites where the ISCS is being implemented. Activities included the characterization of local eco-epidemiological settings and numerical simulations.

Characteristics such as general profile (population at risk, natural resources, economic activities), climatic conditions (climatology, long-term trends), entomology (primary and secondary vectors, breeding sites, feeding frequencies, preferences), malaria situation (annual cycles of malaria incidence, stability conditions), and non-climatic factors (including control campaigns) were analyzed to assess local conditions. The tool will be implemented in the foreseeable future to explore the role that both climate and non-climate factors play in fluctuations and trends in malaria incidence, and to offer useful information to effectively guide decision-makers in risk assessment, malaria control investments, and a choice of interventions.

Figure 2. Main control panel of the malaria multi-model ensemble



The stock-flow models in the multi-model ensemble, not shown here, represent the systems of coupled differential equations of the implemented dynamical models and the major components, level variables and endogenous variables of each mathematical tool. The major exogenous variables are divided into five major groups: community-based, parasite, individual human host, mosquito vector, and environmental variables. The value of these variables was gathered from published literature and/or local data, or measured directly from field records or mosquito life-table studies.

In this way, the approach makes use of dynamical models that employ the established biological mechanism of the transmission cycle of malaria parasites, to integrate climatic variables with demographic, epidemiological, and entomological data routinely collected in malaria-prone areas. The system includes climate forecasting capability, statistical models, eco-epidemiological mathematical models, and other tools to support campaigns and mitigation plans aimed at reducing human health impacts of sudden malaria outbreaks. Global forecasting models are incorporated to estimate future climatic conditions with a lead-time of no less than four to six months.

The strategy uses these predictions to prevent concomitant health effects of the warm phase of the ENSO, as well as non-ENSO climate variability. Eco-epidemiological models are used to:

- evaluate spatial and temporal risks
- estimate the time of occurrence and severity of outbreaks
- analyze major confounders of the overall driving factors
- investigate the current decision-making process
- provide quantitative goals for effective interventions adapted to the specific ecological circumstances of each endemic area
- pose and answer "what if" questions
- help decision makers learn about current and future scenarios

Incorporating Model Information into an EWS for Malaria

Early warning systems provide alerts for malaria epidemics at the interannual, annual, and seasonal timescales.. Colombia's EWS can make use of information from the dynamical model proposed by Ruiz et al., the set of transmission models studied by our group, the statistical model developed, and from the multi-model ensemble described above. In this way, Colombia's Integrated Surveillance and Control System will include climatic forecasting capability, statistical models, eco-epidemiological mathematical models, and other tools to support efforts to reduce the human health impacts of climate variability and change.

A Framework for the Way Forward

Model information should be incorporated into an EWS that is simple to operate and sufficiently flexible so as to take account of evolving conditions. Recommendations on the development of this EWS are based on a framework of five integrated components. These are:

1. vulnerability assessments and monitoring
2. seasonal climate forecasting
3. environmental monitoring
4. sentinel case surveillance
5. planning, preparedness, and response

Vulnerability Assessment and Monitoring

Vulnerability monitoring does not indicate when an epidemic will occur, but gives an indication of the changes that raise the "epidemic potential" and increase the risk of severe disease outcome should an epidemic occurs. To ensure that accurate vulnerability assessment is in place, inter-sectoral collaboration with food security, drought monitoring, livestock and water resource management services is encouraged.

Seasonal Climate Forecasting

The information available from seasonal climate forecasts may allow control services to prepare for preventative interventions, procure effective drug supplies, raise community awareness, and educate communities on personal protection prior to the onset of the critical season and 3-6 months prior to the peak malaria season.

Environmental/Climate Monitoring

The availability of routine information on environmental/climatic variables pertinent to malaria transmission, such as rainfall, temperatures, humidity, vegetation status, and flooding can provide control services with useful indicators of changes in epidemic risk.

In addition, additional analyses that could shed light on the climate-malaria relationship and thus inform an EWS for malaria are:

1. multiple regression of malaria, using both rainfall and temperature predictors
2. exploration of the relationships between ENSO and climate variables (rainfall and temperature) in each municipality, based on a longer time period

Both of these analyses would require the procurement of longer time series. In addition, the incorporation of further socioeconomic data could better suit the data to on-the-ground vulnerability.

Sentinel Case Surveillance and Early Detection

Development of good sentinel case surveillance systems is a prerequisite for an effective and responsive health service and, in the case of epidemic malaria, an essential means to detect any unusual increase in the number of cases.

Planning, Preparedness, and Response

Control plans should be developed based on vulnerability assessments and monitoring of epidemic-prone regions and the communities at risk. Early warning indicators and their interpretation should be agreed upon and the preventative control options they trigger identified and costed.

Summary and Recommendations

Because malaria is a disease that is strongly dependent on local conditions in Colombia, the EWS in support of the control program must be able to identify outbreaks as soon after infection as possible. Through the development of predictive models that use climate variables and other potential predictors, this EWS will allow for the early detection and timely intervention of malaria epidemics.

To facilitate the development of such an EWS, researchers at the IRI have worked to develop statistical and dynamical models. These models use different methods to characterize the transmission dynamics in the pilot areas in Colombia. The statistical model specifically isolates the effects of climate on malaria transmission in each of Colombia's five contrasting geographical regions.

Researchers have also developed a multi-model ensemble to explore the role that both climate and non-climate factors play in fluctuations and trends in malaria incidence, and to offer useful information to effectively guide decision-makers in risk assessment, malaria control investments, and a choice of interventions. The combined outputs of these models, represented as probability distributions, may offer useful information to effectively guide decision-makers in risk assessment and choice of control interventions with regards to changing risk of malaria epidemics.

These efforts build on earlier efforts conducted by researchers at the IRI, which include:

- capacity building on the impact of climate change on public health
- data quality control and the development of data sets of malaria incidence
- analysis for statistical models
- analysis for dynamical models
- validation and intercomparison of satellite rainfall estimates over Colombia
- vulnerability analysis

After five years of work on this topic, the IRI offers a number of recommendations regarding, in general, the development of the EWS. These recommendations include:

1. Intersectoral collaboration with food security, drought monitoring, livestock and water resource management services is encouraged, in order to facilitate effective vulnerability assessments.
2. Seasonal forecasts should be used to guide preparation and preparedness.
3. Routine information on geographical, environmental, and climatic variables should be incorporated into the EWS in such a way to facilitate decision-making.
4. The development of a sentinel case surveillance system is essential.
5. Control plans should respond to the previous four levels of the framework; indicators and their interpretation should be agreed upon and the preventative control options they trigger identified and costed ahead of any future epidemics.
6. Both control plans and EWS must be specific to local settings, taking into account particular local environmental, socioeconomic, and institutional

conditions in order to allow decision-makers to properly respond to the challenges at hand.

7. The sharing of data, information and capacity (at local, state, national and international levels) is necessary for improving malaria and other climate sensitive diseases monitoring and surveillance systems, which the IPCC Fourth Assessment Report termed the most elementary public health adaptation.
8. Strengthening the ground based observing systems in support of improving health outcomes especially for the development of malaria – climate sensitive disease early waning and response systems is critical.
9. Weather and climate research should continue being merged in order to create a seamless prediction system and to provide tools relevant to health decisions such as the development of monitoring and prediction products and services on all timescales. These need to inform disease risk mapping (in space and in time), epidemic and trend prediction, as well as intervention impact assessment.
10. Institutional mechanisms that link outputs and responsible actors (National Institute of Health, IDEAM, DNP, etc.) to the recommendations above are required and a clear framework for activities is critical to continue working on this national adaption project.

After the first experimentation-validation process of malaria transmission models conducted by the Escuela de Ingeniería de Antioquia in Colombia and our group, the IRI recommends:

11. Quantifying or qualifying the demographic and socioeconomic conditions in each of the selected pilot sites and creating a database of local exogenous variables and parameters. Our current level of understanding of non-climatic factors and confounders, in particular, is very limited and the information required for their quantification is disperse or scarce.
12. Extending the climatic and epidemiological time series, as well as the simulation time horizons, which now are restricted to the time horizon 2000 - 2008. Longer, homogeneous and continuous historical records are required for an effective experimentation and validation process.
13. Weather station data (ground truth records), in particular, should be provided in a timely manner. Under the current institutional arrangements climate data are received and processed every eight to twelve months, exceeding the lead-time of four to six months proposed for an early prediction and detection of malaria outbreaks.
14. Updating the annual cycles of climate variables and long-term trends in climatic conditions every 5 to 10 years. Climate seasonal forecasts, which are based upon historical annual cycles, are being included in dynamical models to estimate short-term future epidemiological conditions with a lead-time of three to six months (one to two seasons ahead). Long-term trends in local climatic conditions, in turn, are used to estimate medium-term malaria

morbidity profiles. Both approaches require up-to-date analyses of local historical climatic conditions.

15. Reprocessing the historical time series of malaria positive cases, in order to provide continuous and homogenous epidemiological records. Almost all available time series exhibit null records or gaps that affect the correlation analysis between the observed malaria incidence and the simulated disease prevalence.
16. Studying and implementing the MAC, SimulMal and WCT models given their simplicities, flexibilities, and levels of skill. The final simulation results of these transmission models showed to be acceptable for the purpose of setting up the EWS in the selected pilot sites of the Colombian ISCS.
17. Conducting multiple numerical simulations with the available tools (i.e. rerunning the models for different set of initial conditions, parameters and uncertainties)and building the EWS framework with both statistical and process-based models.
18. Assessing the level of skill of the malaria transmission models, in particular their simulation outputs for the proposed short-term climate scenarios (in our case, for the target seasons December, 2009 through February, 2010 and March, 2010 through May, 2010). Experts at the Colombian National Institute of Health should analyze the actual malaria morbidity profiles observed over the predicted timespan and compare those incidences with the monthly *Plasmodium falciparum* malaria prevalence suggested by the WCT and SimulMal dynamical models.
19. Studying, in depth, the proposed multi-model ensemble platform, the individual simulation platforms, the Microsoft Excel version of the WCT tool, and/or the on-line version of the WCT model, in order to evaluate their strengths, weaknesses, capabilities, and constraints.
20. Strengthening the local institutional capacity in each of the pilot sites and improving their current understanding of the key factors driving the final malaria incidence. The recently-created Simulating Malaria Transmission Dynamics (SMTD) online course could be used to study from the basics of the General Systems Theory to the actual experimentation-validation process of malaria transmission models.

Relevant Publications

Mantilla, G., H. Oliveros, and A.G. Barnston. 2009. The role of ENSO in understanding changes in Colombia's annual malaria burden by region, 1960–2006. *Malaria Journal*, 8:6 (8 January 2009)

Connor, S.J., and G.C. Mantilla. 2008. Integration of seasonal forecasts into early warning systems for climate-sensitive diseases such as malaria and dengue. In: Seasonal Forecasts, Climatic Change, and Human Health [Madeleine C. Thomson, Ricardo Garcia-Herrera and Martin Beniston, eds.] Geneva, Switzerland: Springer.

Ruiz, D., G. Poveda, I.D. Velez, M.L. Quiñones, G.L. Rúa, L.V. Velásquez, and J.S. Zuluaga. 2006. Modelling entomological-climatic interactions of Plasmodium falciparum malaria transmission in two Colombian endemic-regions: contributions to a National Malaria Early Warning System. Malaria Journal, 5:66 (1 August 2006)

Ruiz, D., S.J. Connor, and M.C. Thomson. 2008. A multimodel framework in support of malaria surveillance and control. In: Seasonal Forecasts, Climatic Change, and Human Health [Madeleine C. Thomson, Ricardo Garcia-Herrera and Martin Beniston, eds.] Geneva, Switzerland: Springer.