Analysis of impacts of climate variability on malaria transmission in Sri Lanka and the potential for an early warning system

Foundation for Environment, Climate and Technology, SRI LANKA

Report sponsored by MacArthur Foundation under a grant to the University of Peradeniya

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Citation: Zubair, L., Connor, S.J., Ward, N., Galapaththy, G.N.L., Mahanama, S., Faizal, H.M., Yahiya, Z., Siriwardhana, M., Tennakoon, M., Chandimal, J., Razick, S., Nawarathna, B., Shaman, J., Ndiaye, O. and Yang, H. Analysis of Impacts of Climate Variability on Malaria Transmission and the Development of Early Warning System. Project Report: Foundation for Environment, Climate and Technology, Digana Village, November 2011.

Website:
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The preparation of this document was supported by a grant from the John D. and Catherine T. MacArthur Foundation to the University of Peradeniya to launch a new Master's in Development Practice Programme based on a model of rigorous, inter-disciplinary training and the curriculum recommended by the International Commission on Education for Sustainable Development Practice.

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Summary

This is the report of the FECT contributions to the collaborative project that was led by the International Research Institute for Climate and Society (IRI) under the Climate Variability and Human Health joint program of the National Oceanic and Atmospheric Agency (NOAA) in association with National Science Foundation, Environmental Protection Agency, and Electric Power Research Institute. The complementary effort led by the International Water Management Institute (IWMI) is being reported separately.

This project set goals of bringing together a multi-disciplinary, multi-national and multi-institutional team to address the relationship between climate and malaria in aggregate terms for Sri Lanka, and in detail for the *Uva* Province to help develop early warning systems. The project was undertaken in partnership with Sri Lanka's Anti-Malaria Campaign (AMC) and the Foundation for Environment, Climate and Technology (FECT), Sri Lanka. Overall, we have accomplished the projected outcomes in spite of several setbacks.

Project Initiation Workshop: A successful project initiation workshop brought together relevant officials of the AMC and *Uva* Provincial Health and Resource Management Authorities, the Sri Lanka Department of Meteorology, the World Health Organization, NOAA, IWMI and IRI and academics from Sri Lankan Universities in December of 2003.

Database Development: Obtaining, digitizing and undertaking quality control of Sri Lanka's rich data sets took longer than anticipated. These databases are unique in terms of quality, density and duration. We have used these data to characterize climatologies, climate variability, decadal changes and climate change at fine scales (10 km). We characterized the seasonal variation of malaria at District, Sub-District and village scale for *Uva* Province. Gridded data sets for rainfall, maximum and minimum temperature and day and night relative humidity were used to develop estimates at the sub-district scale. Rainfall monitoring systems and prediction system were implemented at fine scales.

Climate and Malaria Relationships: Important relationships between climate and malaria variability have been identified. (a) The seasonality of malaria is bimodal with the seasonal peaks in malaria following two months after the rainfall peaks. (b) Temperature modulates the seasonality with higher values during cooler months. (c) Regions to the lee-side of the monsoon winds have lower malaria incidence during the South-West and North-East monsoons. (d) In some regions, malaria transmission is modulated by stream flow rather than rainfall.

Climate and Malaria Epidemics: Epidemics have been preceded by drought conditions. Epidemics coincided frequently during El Nino episodes up to 1927. This relationship has been affected by epochal changes in the ENSO-rainfall and ENSO-stream flow relationships over Sri Lanka.

Epochal Variation in Geography of Epidemics: Malaria epidemics were frequent in the West of the island during the turn of the 19th Century. Since then, the occurrence has been more preponderant in the East and North of the island. There is evidence that changes in climate have coincided with changes in this distribution. This is important as the rate of temperature change in Sri Lanka was identified at 1.7 ^{o}C/100 years – a rate which is considerably larger than the global average rate.

Monsoon, Topography and Climate: The monsoons depress malaria incidence in the windward side (excessive rainfall) and the leeward side (excessive temperature) of the central mountain massif that runs North-South. This influence of monsoon leads to an explanation of the preferential incidence in the South-East and North-West.

Malaria Incidence and Climatic Variables (Rainfall, Relative Humidity and Temperature): We have quantified the probabilistic nature of the relationship between malaria incidence and climatic variables. The probabilistic relationships can be used with the monitored and predicted climate to interpret malaria risk.

Malaria Risk Prediction: During the course of the project malaria risk predictions were provided to the AMC by IWMI based on seasonality and recent history. The quantifications of relationships can be incorporated into the early warning system that has been established by IWMI.
Climatic Suitability for Malaria Transmission: We have combined these probabilistic estimates to generate “climatic suitability” for malaria transmission maps. The climatic suitability maps identify the role of climate in modulating the spatial and seasonal distribution of malaria.

Dissemination*:* We have submitted 5 project reports to NOAA; published 6 peer-reviewed papers in journals and books; submitted 5 for review and another 7 are in a draft form with a few more in the pipeline. This work was presented on 8 occasions in US, and 6 occasions in Sri Lanka, Kenya and Maldives. A summary flyer was produced (Included in the Appendix). The work was presented in-depth in Sri Lanka at the project conclusion workshop (at IWMI) and the training workshop (at the Post-Graduate Institute for Science) in September 2007.

Education*:* Two FECT staff members completed undergraduate programs and two followed post-graduate programs.

Training: A training workshop was held at the end of the project in Sri Lanka. Two AMC officers were sent to the IRI for training for two weeks with funding from the Global Fund on Aids, Tuberculosis and Malaria (see letters in the Appendices). The involvement of FECT and AMC staff in all stages of the project resulted in training for researchers in climatic, hydrological and malaria analysis.

Institutional Relationships: We have been able to establish a relationship with IWMI through this project leading to institutional visits, exchange of products and further collaborative proposals. The partnership with the Anti-Malaria Campaign has been extensive with many meetings, two workshops, and frequent visits of IRI personnel. The AMC officer managing the malaria control program visited IRI in the early phase.

Capacity Building: The Foundation for Environment, Climate and Technology, has established capacity to research and education on climate and health related topics. Project personnel have been able to present their work at international Ecohealth conferences in Mexico and UK. Follow up proposals were submitted to IDRC and WHO of which a project on Dengue has been funded already.

All the outcomes anticipated in our proposal have been delivered in large measure. This project has provided a unique demonstration of the use of practical new tools for climate variability and human health for risk predictions.

A. Acknowledgements

This project was conducted with a grant from the Climate Variability and Human Health program of NOAA which was led by IRI and included FECT as the major regional collaborator. The program manager Juli Trtanj helped initiate this project and supported our work during the initial years. Aurelia Micko assisted with the program management and provided a comprehensive presentation as the commencement workshop. We are thankful to them for their unstinting support, courtesy and understanding.

At FECT, Zeenas Yahiya and Janaki Chandimala supported this effort throughout the project. Manjula Siriwardhana, Upamala Tennakoon, Siraj Razick, Badra Nawarathna, Yoosuf Ashraj, Champika Jayatillake, Amal Tillakaratne, Amila Karunaratna and Ranmalee Bandara contributed over shorter periods. Vidhura Ralapanawe assisted us in the management of data bases, development of project presentation material such as posters and brochures and the project website.

The partnership with the Anti-Malaria Campaign of Sri Lanka (AMC) has been extensive. Particular thanks are due to the Directors of the AMC, Dr. R.R.M.L. Siyamabalagoda and Dr. Rabindra Abeyasinghe for all the support that was provided including participation in the project conclusion workshop. H.M. Faizal, Regional Malaria Officer in the *Uva* Province, supported us in hosting our visits, enduring numerous queries, arranging interactions with his staff and Provincial health officials and presenting at the project conclusion workshop. We are also thankful to Regional Malaria Officers, Drs. Devika Perera, P. Kusumawathie and S.Bandara, for interactions in their respective districts. We also thank the other Regional Malaria Officers who participated through the project inception and conclusion workshops.

Our work was supported by the Natural Resources Management Services (NRMS) from 2003-2004. We are particularly grateful to the Directors of NRMS, H.M. Manthrithillake, R. Herath and C.M. Madduma Bandara for their support. We thank A. Amarasekera, K.B. Jayasundera, P. Renuka and S.B. Rajakaruna for their assistance. The support of the Executive Director of the Mahaweli Authority of Sri Lanka's (MASL) River Basin Division, Eng. J.A.S.A. Jayasinghe, and the Director of the Headworks Division, Eng. Nimal Wickramaratne were indispensable since 2004. Messers. H. Herath Banda and A. Batcha of the MASL Headworks division and their staff have supported us at the FECT office in many ways. Mr. Kalyana Samarakoon of the Mahaweli Authority shared hydrological data with us.

We thank the Director-General of the Sri Lanka Department of Meteorology, G.H.P. Dharmaratne for his support particularly for addressing the project inception workshop, support in data acquisition and providing departmental support and participation in the project conclusion workshops. Messers. Lalith Chandrapala, S.B. Basnayake, G.B. Samarasinghe, K.R. Abeyasinghe, Ananda Perera and KHMS Premalal of the Department of Meteorology have assisted us. Dr. B.V.R. Punyawardene, agro-meteorologist at the Sri Lanka Department of Agriculture, assisted us in data collection.

We have obtained assistance at the University of Peradeniya for training programs for staff, obtaining meteorological data from observations and library records and support in the conduct of the final workshop. We thank Prof. T.D.M.A Samuel, Prof. P. Wickramagamage, Prof. Lakshman Dissanayake, Prof. Parakarama Karunaratne, Prof. Manel Wijesundera, Drs. U.R. Ratnayake, Rupika Rajakaruna, and Champika Bandara, for their assistance.

The Director-General of the IRI Stephen Zebiak has supported the commitment of IRI personnel to this project. Ann Binder and Lori Scally contributed to the implementation of this grant and its financial management. Jason Rodriguez, Rise Rullon, Tricia Ramsey, and Francesco Fiondella assisted with the documentation. Benno Blumenthal, Michael Bell, John del Corral, Remi Cousins and Emily Grover assisted with data management and analysis. Ousmane Ndiaye contributed to the work on downscaling. Columbia University students Stacey Hirsh, Hyemin Yang, Lindsay Kaye Warren, Lady Vanessa Reyes, Nelun Fernando, Syd Partridge, Joseph Simonson, Arron Lyans, Daniel Bader, Sarah Wishnek and Shaky Sherpa participated in this project.

We are grateful to Sarith Mahanama in the Global Modeling and Assimilation Office of NASA/GSFC who led the development of a fine scale land surface model for Sri Lanka with contributions from Rolf

Riechle and Randal Koster. We thank Dilip Hensman from the World Health Organization in Sri Lanka for participating in the project workshops and assisting the GIS work.

We record our appreciation to all the project team members from IWMI and their partners for the collaboration. The acting Director-General of IWMI, David Molden, supported this project starting from the proposal to the participation in the project conclusion workshop. Chalotte Fraiture, Theme Leader for Basin Water Management and Julie Van Der Bliek, Director of the Global Research Division assisted in the transition of the project. We thank them for their hospitality during our visits. We also thank the IWMI Principal Investigators, the late Dr. Felix Amerasinghe and Dr. Priyanie Amerasinghe for their role in ensuring a productive, mutual beneficial and enjoyable collaboration. Olivier Briet played an important role in this collaboration.

Finally, the preparation of this document was supported by a grant from the John D. and Catherine T. MacArthur Foundation to the University of Peradeniya to launch a new Master's in Development Practice Programme based on a model of rigorous, inter-disciplinary training and the curriculum recommended by the International Commission on Education for Sustainable Development Practice.

B. Project Team

Investigators

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Upamala Tennakoon, (GIS operations)
Zeenas Yahiya (Documentation and Administration)
Janaki Chandimala (Hydro meteorological Analysis)
Manjula Siriwardhana (Climate Impact on Malaria) - (IWMI)

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Vidhura Ralapanawe (Data Management and Web Support)
Badra Nawarathna (Rain fall monitoring)
Amal Thilakaratne (Data Management)
Amila Karunaratne (Web Management)
Champika Jayatillake (Data Management)
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Michael Neil Ward (Climate Scientist and Statistician)
Lareef Zubair (Climate and Adaptation Scientist, Environmental Engineer)

Columbia University, USA (IRI)

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Marc Stieglitz (Hydrologist, Presently at Georgia Institute of Technology)
Mark Cane (Climate and Environmental Scientist)

Anti-Malaria Campaign, Ministry of Health, Sri Lanka (AMC)

Gawrie NL Galappaththy (AMC – Consultant Physician)
DM Gunawardena (Disease Control Manager, On Leave at National Malaria Control Program, Eritrea and Uganda)
H.M. Faizal, Regional Malaria Officer (RMO), Moneragala District, Uva Province

International Water Management Institute, Sri Lanka (IWMI)

Felix Amerasinghe (Ecologist and Entomologist)
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Lal Muthuwatta (Mathematical Modeler and GIS Analyst)

University of Sri Jayawardhenapura / University of Kelaniya, Sri Lanka

AR Wickremasinghe (Medical Doctor, Epidemiologist and Biostatistician)

Collaborators

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Michael Bell (IRI data library)
Ann Binder (Project Administration)
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John Del Corral (IRI data library)
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Emily Grover-Kopec (IRI data library)
Ousmane Ndiaye (Downscaling)
Jian-Hua Qian (Regional Modeling)
Lori Scally (Project Administration)

Columbia University, USA

- Stacey Hirsh (Senior, Earth Institute Internship)
- Hyemin Yang (IRI Summer Intern - 2005, CICAR Summer Intern - 2006)
- Lindsay Kaye Warren (Senior Thesis)
- Lady Vanessa Reyes (Senior Thesis)
- Nelun Fernando (Thesis, Masters in Climate and Society)
- Syd Partridge (Summer Intern, Climate and Society Masters Course)
- Joseph Simonson (Sophomore, Earth Institute Summer Intern)
- Arron Lyans (Intern, Climate and Society Masters)
- Daniel Bader (Intern, Climate and Society Masters)
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- Senarath Bandara, RMO, Kurunegala District, North-Western Province

National Aeronautical and Space Agency, Goddard Space Flight Centre,

- Sarith Mahanama (Land Surface Modeling)

International Water Management Institute, Sri Lanka (IWMI)

- Gayathree Jayasinghe (Biometrician)
- Deeptha Wijerathna (Agricultural Economist)
- Markandu Anputhas (Biometrician)
- Susitha Wanigaratne (Intern)

Plate 1: FECT Staff Members outside the inaugural workshop of the Climate and Malaria project at Passara, Uva Province on December 8, 2003.
Left to Right: M.R.A. Siraj, I. Bandara, L. Zubair, S.B. Rajakaruna, Z. Yahiya, U. Tennakoon and J. Chandimala. Passara is in the highlands overlooking the plains of Moneragala which is in the background.

C. Proposed Work Plan and Work Accomplished

The planned activities are extracted from the table included in the joint proposal. Note, that while the proposal was originally for 3 years, we completed work with a no-cost extension of an additional year.

Year 1

Activity	1	2	3	4	5	6	7	8	9	10	11	12
Workshop in Colombo	■											
Data collection- *Uva* province	■	■	■	■	■	■						
Data collection- Sri Lanka	■	■	■	■	■	■	■	■	■	■	■	■
Hydrological modeling				■	■	■	■	■	■	■	■	■
Downscaling climate forecasts	■	■	■	■	■	■	■	■	■	■	■	■

Year 2

Activity	1	2	3	4	5	6	7	8	9	10	11	12
Climate & malaria relationships	■	■	■	■	■	■	■	■				
Development of statistical model (IRI/IWMI)	■	■	■	■	■	■	■	■	■			
Hydrological modeling (IRI)	■	■	■	■	■	■	■	■	■	■	■	
Development & establishment of early warning system					■	■	■	■	■	■	■	■

Year 3

Activity	1	2	3	4	5	6	7	8	9	10	11	12
Malaria risk mapping (IWMI/IRI)	■	■	■	■	■	■	■	■	■	■	■	■
Economic evaluation (IWMI)				■	■	■	■	■	■	■		
Forecast skill survey (IWMI)				■	■	■	■	■	■	■	■	■
International workshop (IWMI/IRI)										■		
Publications and report writing					■	■	■	■	■	■	■	■

The report from IWMI shall contain aspects not reported here including the operationalization of the early warning system, its economic evaluation and forecast skill survey.

MAIN REPORT

We describe our work in the sequence identified in the methodology in the proposal. FECT had major responsibility along with IRI. These include:-

- Project Inception Workshop
- Data Collection
- Distribution of Malaria
- Climate Analysis
- Climate Monitoring
- Climate Predictions
- Hydrological Modeling
- Vulnerability Analysis
- Climate and Malaria Relationships in Sri Lanka
- Climate and Malaria Relationships in *Uva* Province
- Predictive Malaria Risk Mapping
- Workshops
- Publications and Dissemination
- Outcomes
- References

An appendix that provides the annual summaries of progress, the details of project visits and meetings, details of the inception, conclusion and training workshops, and the posters are included at the end of the report.

Plate 2: An abandoned gem pit in South-Eastern Uva Province has been left open leaving it as a site for mosquito breeding. In the background is new gem pit with excavated earth creating more breeding sites. This is compounded by additional breeding sites created by cattle, leaving hoof prints that collect temporary pools of water. Malaria control using larvivorous fish is being attempted by the Regional Malaria Officer (H.M. Faizal), who is seen looking for the fish.

1. Project Inception Workshop

Background

We collaborated with International Water Management Institution (IWMI) and Anti-Malaria Campaign (AMC) in the conduct of a project inception workshop in Sri Lanka during December 2003. The workshop was held in the provincial capital of the *Uva* Province that is to be the region of interest. This workshop was successful in bringing together all stakeholders in the *Uva* province as well as at the national level. The Agenda and List of Participants are included in the Appendix. The agencies that were represented at the highest levels were the AMC Head Quarters and all Regional Malaria Offices in Sri Lanka, the Natural Resources Management Services of the *Mahaweli* Authority, *Uva* Management Training Institute, *Uva* Provincial Directorate of Health, and the Sri Lanka Department of Meteorology. Ms. Aurelia Micko of National Oceanic and Atmospheric Administration – Office of Global Program (NOAA/OGP) attended this meeting and provided an overview of progress in climate and health activities globally. Relevant prior studies were presented and discussed.

Summary

The workshop participants emphasized that malaria in Sri Lanka is not related to weather (climate) alone, and that rural development (housing), land-use, hydrological interventions (such as irrigation), and above all malaria control interventions (parasite and vector) are factors to take into account when trying to attribute malaria epidemiology. Also, the vector component of the malaria transmission system should not be ignored. Participants emphasized that the suitability of sites for *Anopheles culicifacies* breeding varies according to their environmental conditions; therefore breeding relates differently to rainfall in different areas. In the dry zone, vector breeding may occur shortly after the onset of the *Maha* rainy season (September to December), whereas in the wet zone, drought during the usual rainy seasons may be conducive to vector breeding. Therefore, in time series analysis, the spatial component should not be ignored. We learnt that the AMC has excellent malaria records from the seventies onwards, but that older data has to be sought in the archives of AMC regional offices in *Kurunegala*, *Anuradhapura* and *Hambantota*.

There was agreement on the need for and utility of an early warning system and that this early warning system should be operational through the year. Participants also identified the need for a mechanism to coordinate and disseminate information for work related to climate and health among the different sectors.

2. Data Collection

Data Collection - *Uva* Province

Case data on Malaria

Uva Province consists of two districts, *Badulla* and *Monaragala*. Government institutions such as hospitals maintain monthly records of the number of examined patients (blood films) and slide-results. Before 1995, few cases were recorded at village spatial resolution. Therefore it was decided to restrict the temporal window for the high spatial resolution {*Grama Niladhari* (GN) or Village Officer - GN level} analysis to the period after 1995.

Meteorological and Hydrological data

The data collection and archiving in the *Uva* Province of hydrological and climatic data on a monthly scale [1]is being undertaken in Sri Lanka. Monthly data have been collected as follows:

- Monthly Rainfall for 18 stations for varying periods
- Monthly (Mean, Minimum and Maximum) Temperature for 5 stations
- Stream flow data for 10 stations[2]

Environmental data

A digital elevation model at a resolution of 90 meters[3] generated by the National Aeronautics and Space Administration (NASA) Shuttle Radar Topography Mission was obtained from the U.S. Geological Survey (USGS) websites.

Plate 3: The "Malaria Laboratory" at Buttala Hospital in the Uva Province in January 2006.
All patients who are suspected of having malaria provide blood samples which are then examined on a slide by the technician (left) to identify the presence of the parasite. These results are tabulated daily and then collected by the regional malaria officer (right).

[1] Monthly scale meteorology and hydrological data were selected for this study instead using daily or weekly, because of the availability of the data.

[2] 10 stations were selected for the stream flow data analysis, because for the *Uva* Province, there were only 10 stations which practiced stream flow data collection at the time of this study.

[3] At the time of this study, there was 90 m resolution of digital elevation model exist. Today there are much more advanced resolutions are practicing by NASA.

Socio-economic and Demographic data

Village (GN level) level population and Socio-economic data from 1997 to 2003, and provincial wise surveys have been acquired from the *Uva* Provincial Council, and missing data have been filled.

Data Collection – Island Wide (Sri Lanka)

Case Data on Malaria

Monthly positive malaria case data at District resolution have been digitized for the 1960 – 1972 period. For 1972 – 2003, malaria species-wise data have been entered at sub-district resolution.

Climate and Hydrological Data

Monthly data for 180 rainfall stations, 130 stream flow stations and 50 temperature stations have been compiled. Quality control[4] of parts of these data sets has been completed. We have filled gaps in our rainfall records in the *Uva* Province using the mathematical principles for calculating missing rainfall (i.e. Arithmetic method, Normal ration method and Inverse distance squared). Foundation for Environment, Climate and Technology (FECT) has collected daily rainfall data for the *Uva*. Climatological mapping of the data has been completed: Temperature (Minimum, Maximum and Mean) at 1 km resolution, Wind at 8 km, Solar Radiation at 20 km, and Rainfall at 10 km been completed. Based on the density of the available data, the resolution used for each parameter was varied.

Environmental data

We have obtained the 90m resolution Shuttle Radar Topography Mission (SRTM)[5] (elevation) data for Sri Lanka and Normalized Difference Vegetation Index (NDVI)[6] at a resolution of 8km was extended from 1981-2005 and was compared with rainfall, temperature and El-Nino Southern Oscillation (ENSO)[7] indices.

Socio-economic and Demographic data

Demographic data have been obtained from the Department of Census and Statistics and interpolated.

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[4] **Data quality control** – It is a process of controlling the usage of data with known quality measurement for an application or a process. This process is usually done after a Data quality assurance process, which consists of discovery of data inconsistency and correction. (Refer to annex for more description)

[5] **Shuttle Radar Topography Mission** (**SRTM**) **–** It is an international research effort that obtained digital elevation models on a near-global scale from 56° S to 60° N, to generate the most complete high-resolution digital topographic database of Earth prior to the release of the ASTER GDEM in 2009. (Refer to annex for more description)

[6] **Normalized Difference Vegetation Index** (**NDVI**) – It is a simple graphical indicator that can be used to analyze remote sensing measurements, typically but not necessarily from a space platform, and assess whether the target being observed contains live green vegetation or not. (Refer to annex for more description)

[7] **El-Nino Southern Oscillation indices (ENSO) -** It is a quasiperiodic climate pattern that occurs across the tropical Pacific Ocean roughly every five years. It is characterized by variations in the temperature of the surface of the tropical eastern Pacific Ocean. Warming or cooling of the ocean known as *El Niño* and *La Niña*, respectively. Air surface pressure in the tropical western Pacific is the *Southern Oscillation*. The two variations are coupled: the warm oceanic phase, El Niño, accompanies high air surface pressure in the western Pacific, while the cold phase, La Niña, accompanies low air surface pressure in the western Pacific.[2][3] Mechanisms that cause the oscillation remain under study. (Refer to annex for more description)

3. Distribution of Malaria

We have compiled a data base that allows spatio-temporal analysis of the study. Some examples of annual and monthly mean estimates are shown below, and fine scale estimates along with hydrological features are provided in the maps (figure 1).

Malaria incidence by District

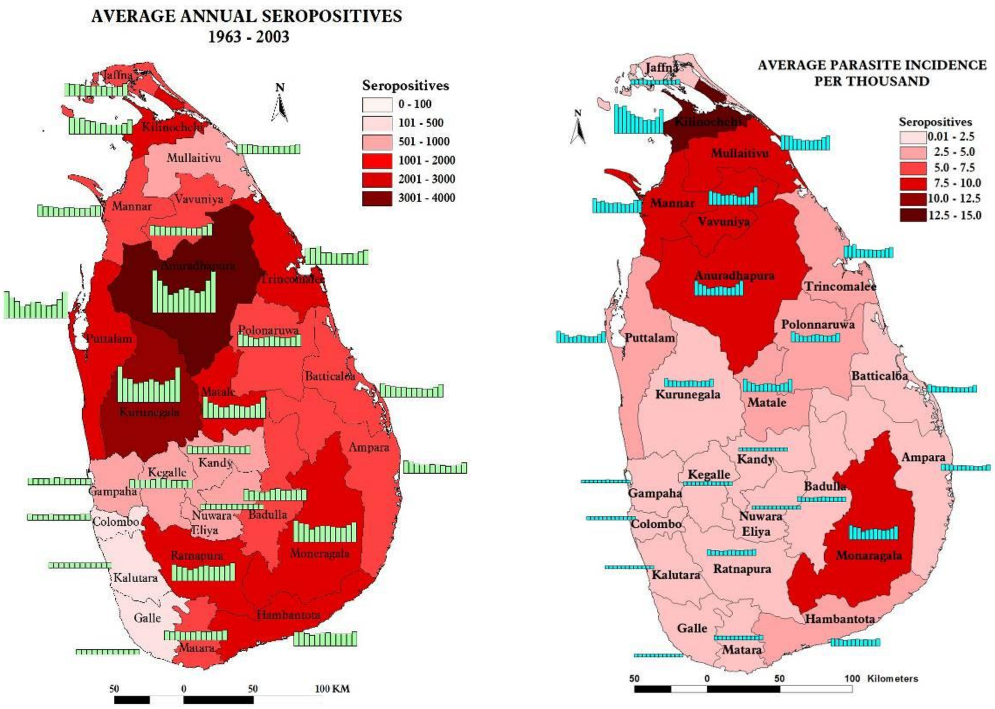


Figure 1: The maps of average regional distribution of malaria incidence for Sri Lanka.
Left: Average annual seropositives (1963 – 2003)
Right: Average Parasite Incidence per thousand
The bar graphs show the monthly variation from January to December for each district.

District wise malaria data were used to construct an average monthly distribution on malaria incidence in total, and for the *Plasmodium vivax* and *Plasmodium falciparum* instances separately (figure 2). District wise malaria maps were produced, because of the availability of the district wise malaria data at the initial phase of the study.

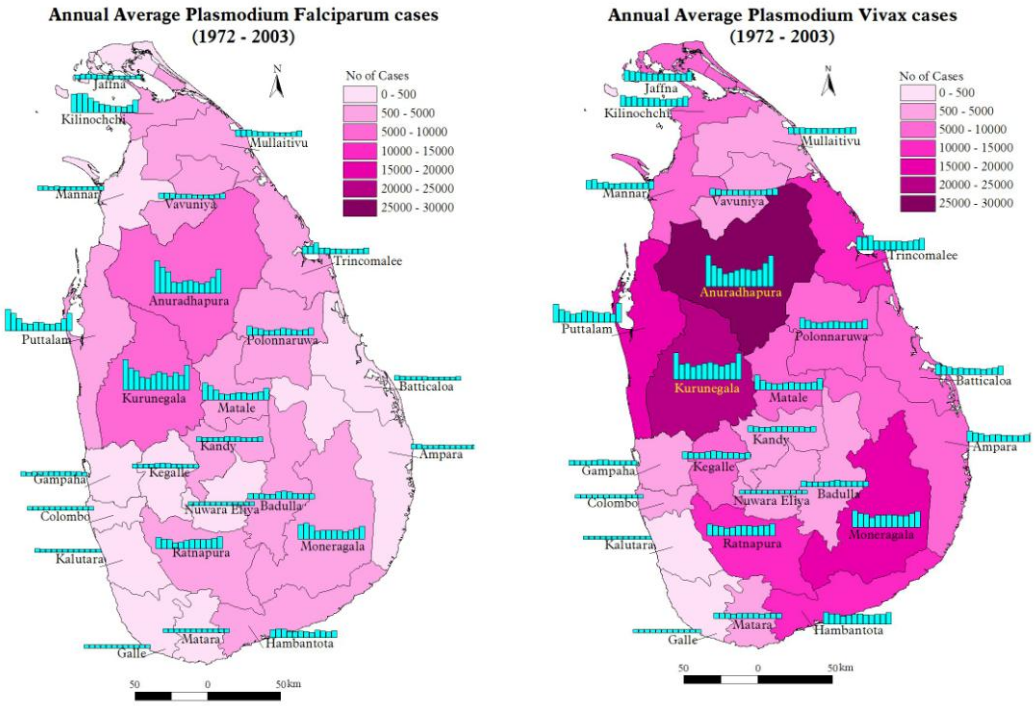


Figure 2: Annual Average Cases of Malaria due to P. falicparum and P. vivax (FECT/AMC)
Left: P. falicparum, Right: P. Vivax.
Bar charts show the monthly means from January to December.

Plate 3: Maps at the Regional Malaria Office at Moneragala, Uva Province being pointed out by the Regional Malaria Officer in 2005.

Plate 3 shows maps which were available at Regional Malaria Office (RMO) at *Moneragala*, *Uva* Province. These include maps on land use, river networks and road networks in addition to malaria incidence. The data collected from the hospitals had been mapped at the Regional Malaria Office in *Moneragala* using Geographic Information System (GIS)[8] which was not working during the early part of the project. The GIS and email capability at the RMO office was updated and in-house training was provided to a technician at FECT.

[8] **Geographic Information System (GIS)** – It is a system designed to capture, store, manipulate, analyze, manage, and present all types of geographically referenced data. In the simplest terms, GIS is the merging of cartography, statistical analysis, and database technology. (Refer to annex for more description)

Malaria incidence by Village for *Moneragala* District

Figure 3 shows the map, which illustrates the annual incidence of malaria by Divisional Secretariats in the *Moneragala* district for 2000. There are few DS which observed 1000 – 2000 annual malaria cases. In figure 4, group of maps show the year by year variation of malaria incidence in *Moneragala* from 1995 to 2002 at village resolution. However in 2002 annual malaria incidences were recorded at a range of 0 – 100 and the record was minimum compared to other years.

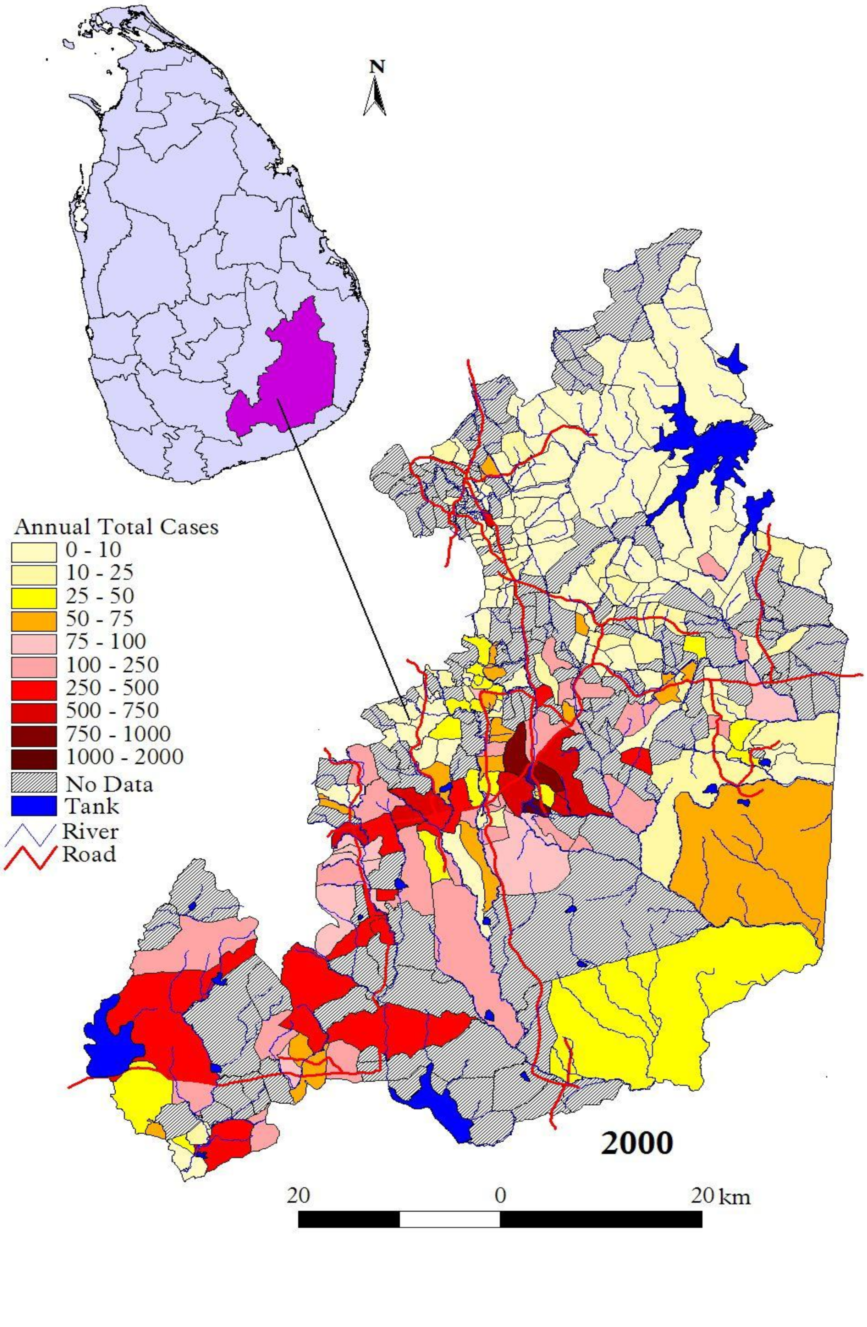


Figure 3: Map which shows annual incidence of malaria by DS division in the Moneragala district for 2000. The map is provided along with the principal roads, reservoirs and streams.

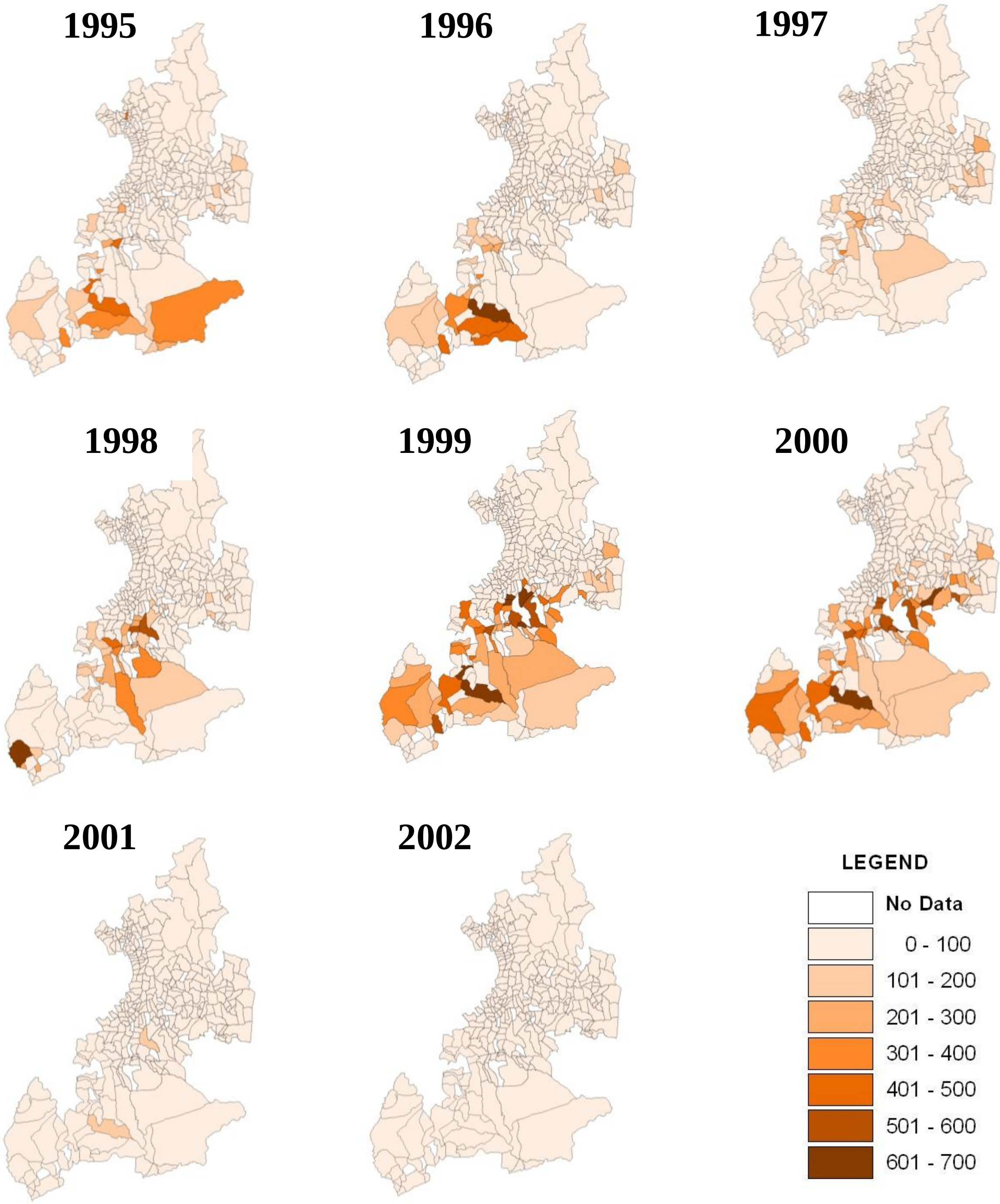


Figure 4: Maps showing the year-by-year variation of malaria incidence in Moneragala from 1995 to 2002 at village resolution.

4. Climate Analysis

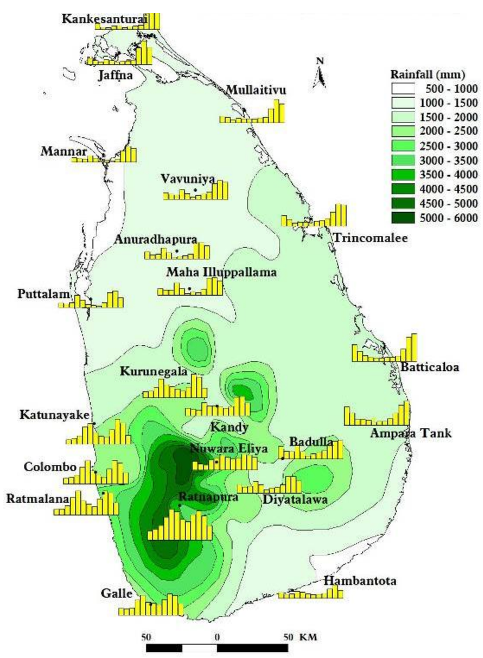
Rainfall, stream flow, temperature and relative humidity have been identified as the key meteorological variables that influence malaria transmission. The large-scale climate phenomenon ENSO and drought and flood conditions were also implicated in malaria transmission previously (Bouma and Van Der Kaay, 1996).

Quality control work on the climatic data sets was undertaken. These data were used to develop rainfall, temperature (mean, maximum and minimum), relative humidity, evaporation, solar radiation and NDVI climatologies. We conducted base line analysis on rainfall, temperature, evaporation and addressed the specific ways in which ENSO affects the environmental conditions in Sri Lanka. Both the climatologies and the ENSO influences are subject to decadal and epochal changes including climate change, which we have investigated. We have also estimated the spatial and temporal with a focus at the decadal variations of climatic trends in Sri Lanka (Zubair et al., 2004d). The warming trends in temperature were found to be several times the global average. The rainfall trends were stable but there were significant declines in the hills during the summer seasons.

Climatological Analysis

We have constructed monthly, seasonal and annual climatologies at resolution as high as permitted by the data, because there is a need for grid data for multiple reasons of this study. The dense network of rainfall stations allows for a high-resolution climatology of rainfall. We developed an interpolation technique that incorporates elevation for reconstructing regional temperature. The computation of solar radiation climatology was based on direct measurements of solar radiation and the use of daily sunshine hours to estimate regional radiation.

Climatology



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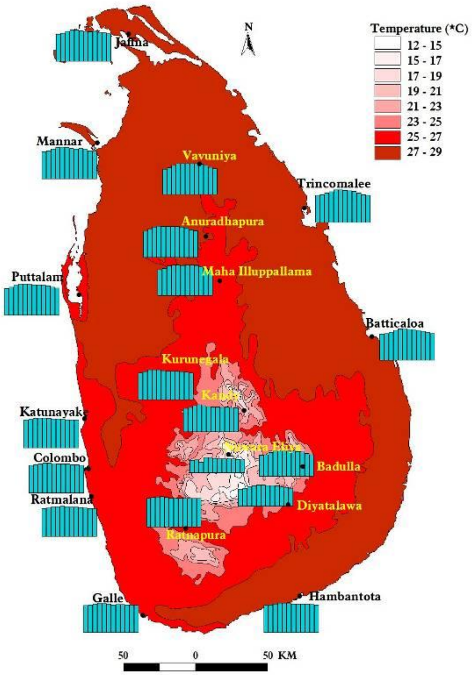
Climatology of Rainfall

The island receives on average 1,800 mm of rainfall annually (figure 5). The rainfall pattern has a bimodal seasonality with peaks in November and May. The western and eastern hill slopes receive increased rainfall from May to October and December to February respectively. The storms and cyclones bring rain to the North-East around November.

Figure 5: Map of the average annual rainfall observed at 179 stations from 1960 to 1990
The bar charts show the monthly means from January to December for the main stations



Climatology of Mean Temperature

The mean annual island-wide temperature is around 27°C with lower temperatures in the mountains that rise to 2,500 meters. Temperature drops during December and January and increases from April to September. The mean daily range is approximately 6°C. Figure 6 illustrates the mean annual temperature classes for Sri Lanka.

Figure 6: Map of the annual mean temperature averaged from observations at 37 stations from 1960 to 1990
The bar charts show the monthly means from January to December for the main stations

For Rainfall interpolation we simply used an inverse distance procedure as there were adequate rainfall stations (300) particularly in the hilly areas. We have a more limited set of temperature data and the interpolation has to take account of topographic changes. We developed a precise temperature interpolation procedure using topography which leads to better interpolations as shown in the following figure 7.

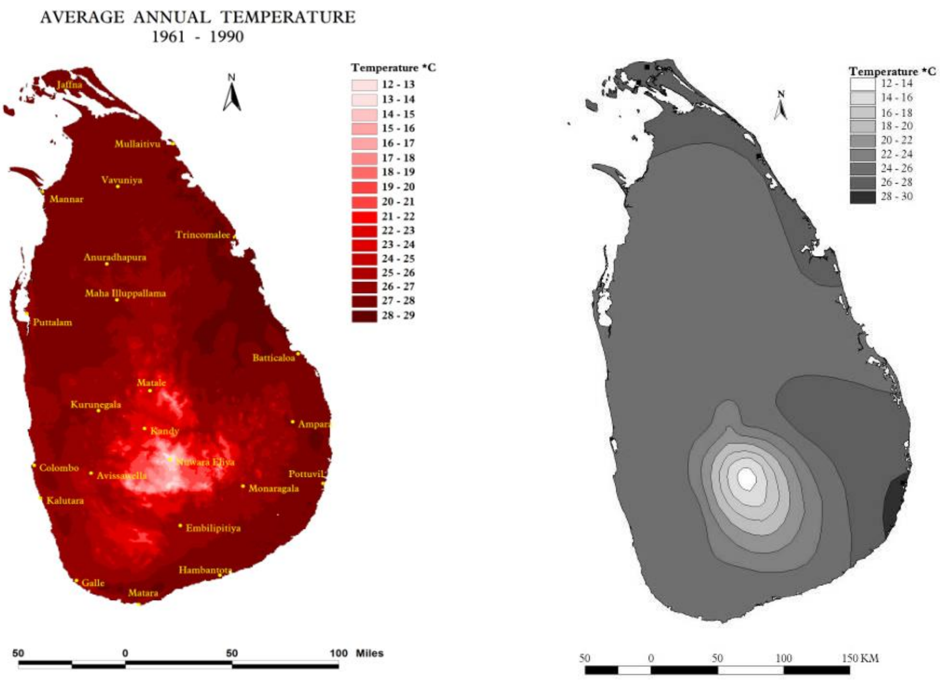


Figure 7: Left: Simple spatial interpolation of the annual average station temperature for the whole island.
Right: Topographically informed annual average temperature climatology map for Sri Lanka.

Climate Variability Analysis

The influences of global modes of climatic variability such as ENSO and Indian Ocean Dipole [9]on the Sri Lanka climate were characterized (Zubair et al., 2008, Zubair and Ropelewski, 2006), and hydrology (Chandimala and Zubair, 2007; Zubair and Chandimala, 2006) have been systematically investigated.

Epochal Analysis

We have shown that there is epochal variability in how the ENSO influences affect rainfall and stream flow in Sri Lanka coinciding with the epochal changes in Malaria-ENSO relationships in the 1940's (Zubair and Chandimala, 2006) during the summer. This is a key finding which shall shape any climate based early warning system. We also showed that the relationship between Sri Lanka rainfall and ENSO during the fall has strengthened (Zubair and Ropelewski, 2006).

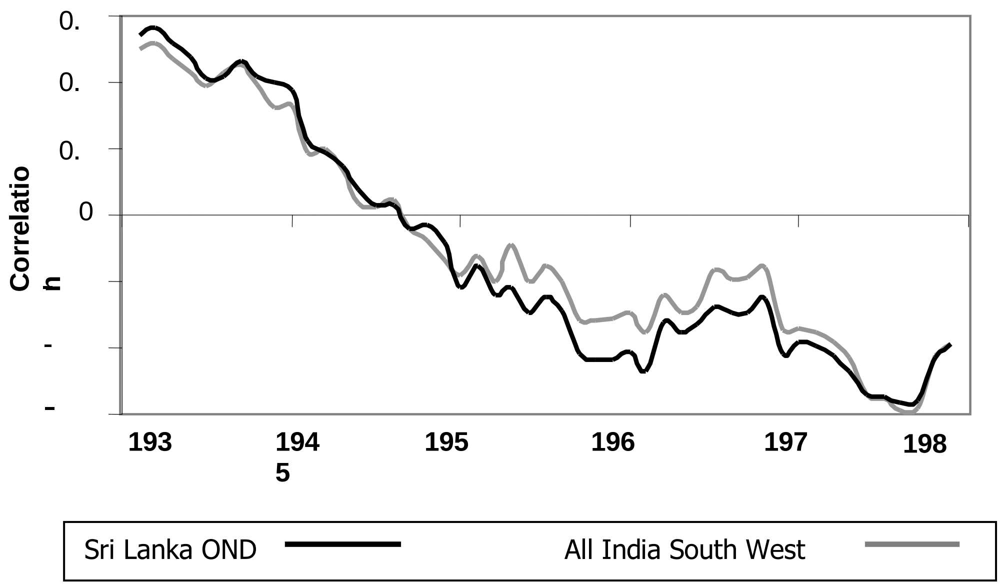


Figure 8: The 21-year sliding window correlation between the concurrent April to September stream flow, catchment rainfall and NINO3.4 is shown as a function of the central year of the window for the Kelani catchment. The 95% significance level is 0.42. This figure shows a dramatic reversal in ENSO relationships around 1940's reminiscent of an epochal change.

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9 **Indian Ocean Dipole** – It is a coupled ocean-atmosphere phenomenon in the Indian Ocean. It is normally characterized by anomalous cooling of SST in the south eastern equatorial Indian Ocean and anomalous warming of SST in the western equatorial Indian Ocean. Associated with these changes the normal convection situated over the eastern Indian Ocean warm pool shifts to the west and brings heavy rainfall over the east Africa and severe droughts/forest fires over the Indonesian region. (Refer to annex for more description).

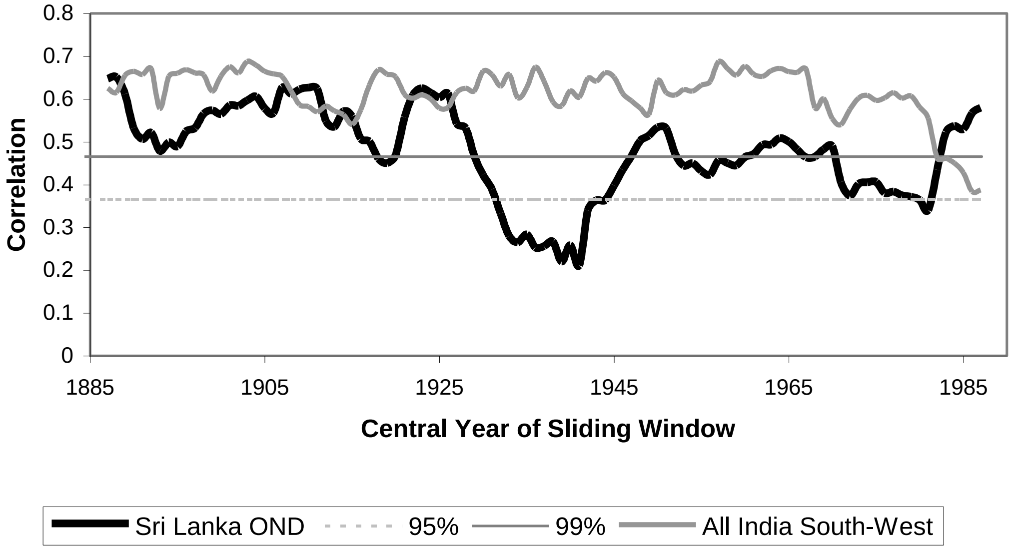

Figure 9: Sliding correlations with a 31-year window of NINO3 with simultaneous Sri Lankan, October to December rainfall is shown.
A similar sliding correlation of All-India South-West Monsoon rainfall and simultaneous NINO3 is also shown with its sign changed to positive to facilitate comparison. Correlation values at 0.36 and 0.46 are significant at 95% and 99% levels and these thresholds are shown. This figure shows dramatic changes in how ENSO influenced the rainfall in Sri Lanka during the 1930's and then again after 1980.

Climate Change Analysis

We have undertaken analysis of changes in rainfall, temperature (i.e. minimum, maximum, mean) and stream flow. Figure 10 shows the variation of mean annual temperature in Sri Lanka.

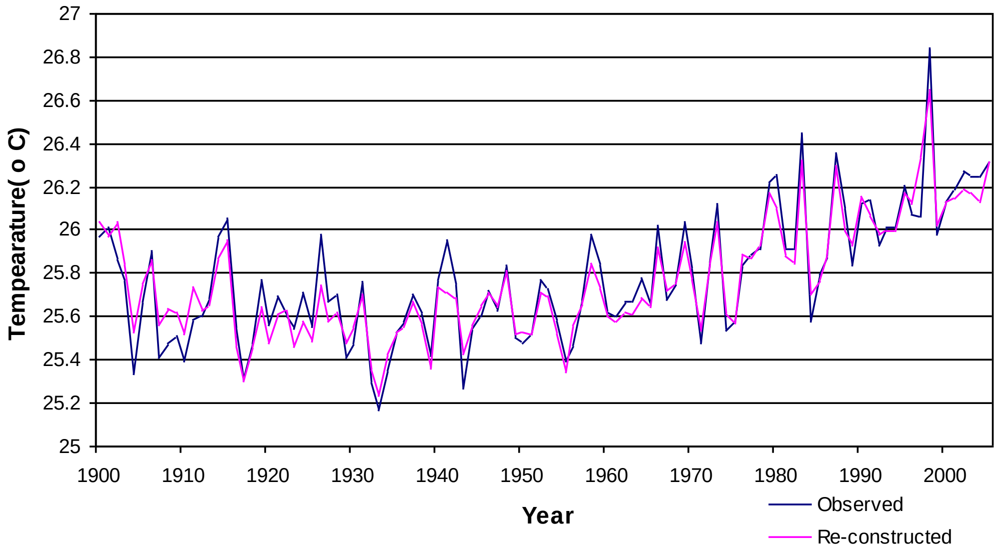

Figure 10: Mean annual temperature in Sri Lanka.
The line in red shows the estimated mean based on quality controlled data. The blue line shows the mean of the observations. The trends since 1960 have been characterized regionally and seasonally for mean, minimum, maximum temperature and rainfall.

5. Climate Monitoring

Provision of timely malaria risk assessments based on rainfall requires a near-real-time estimation of rainfall and associated variables. Figure 11 illustrates the online resource for malaria managers to obtain rainfall estimates in near real time in multiple formats at fine scales. We developed methodologies for estimating rainfall in near real time initially based on satellite estimates as made available by the NOAA Climate Prediction Center (CPC) (figure 12).

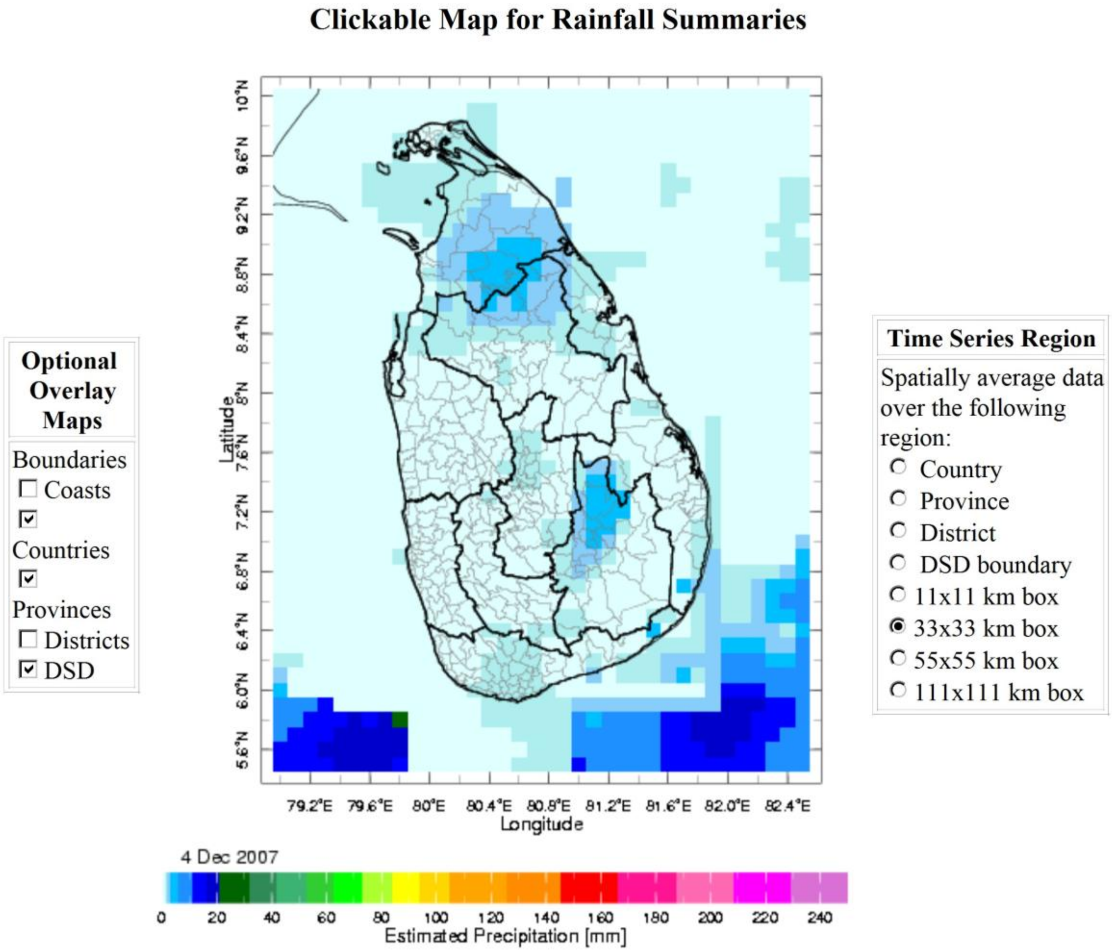

Figure 11: Rainfall Monitoring for Sri Lanka (IRI/FECT).
An online resource for malaria managers to obtain rainfall estimates in near real time in multiple formats at fine scales was developed with data from NOAA CPC. This site is accessible at: http://www.climate.lk/monitoring_index.php?pagename=monitoring

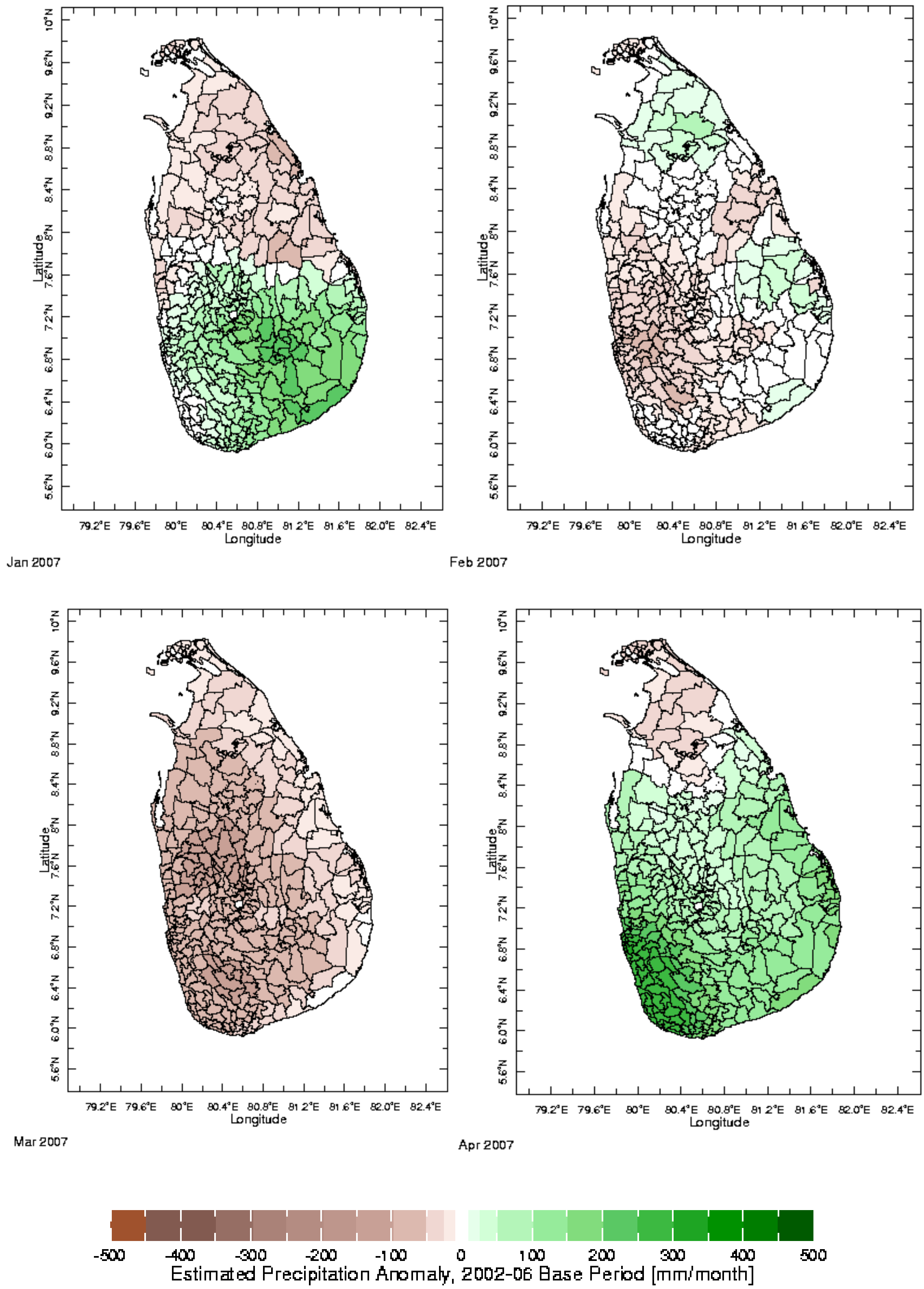

Figure 12: Fine-scale monitoring of rainfall anomalies at fine spatial scales has been developed using observed rainfall and satellite estimates. The departures from mean values are estimated for each sub-district unit. Shown in this set of figures are estimates for January to April 2007.

6. Vulnerability Analysis

In addition, year to year variation in risk due to climatic, environmental and ecological factors, the vulnerability of the people in question, and their exposure to malaria plays a determinative role in whether the malaria risk is translated into actual incidence. Usually estimating vulnerability is more challenging than estimating hazard due to the paucity of relevant data. We have reported on preliminary analyses.

A variety of vulnerability factors may be considered such as education, house types, distance to water bodies, economic status and occupation types. While some analyses have been carried out on these factors, it is the correlation of malaria incidence with cattle density that stands out for both Badulla and Moneragala districts (figure 13).

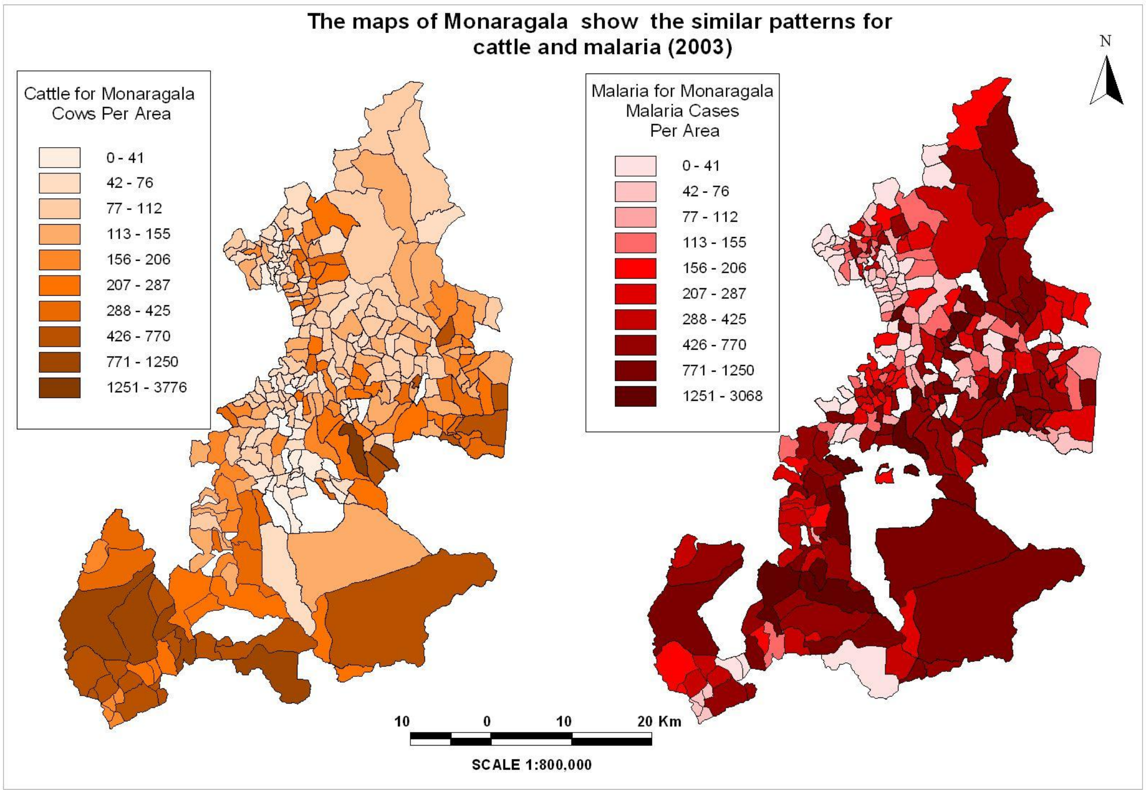

Figure 13: Left: Density of cattle in Moneragala District
Right: Incidence of Malaria in Moneragala District

7. Downscaling Climate Predictions

Figure 14 and 15 show what we have refined and archived downscaled statistical rainfall predictions for Sri Lanka for the October to December season for the period 1960 to 2000 at a resolution of 10 km* (Zubair *et al*., 2004b). FECT collaboratively works with Dr. Joshua Qian of the IRI to develop a regional climate model focused on Sri Lanka (Qian and Zubair, 2009). This work complements the statistical downscaling as it enables the investigation of key mechanisms.

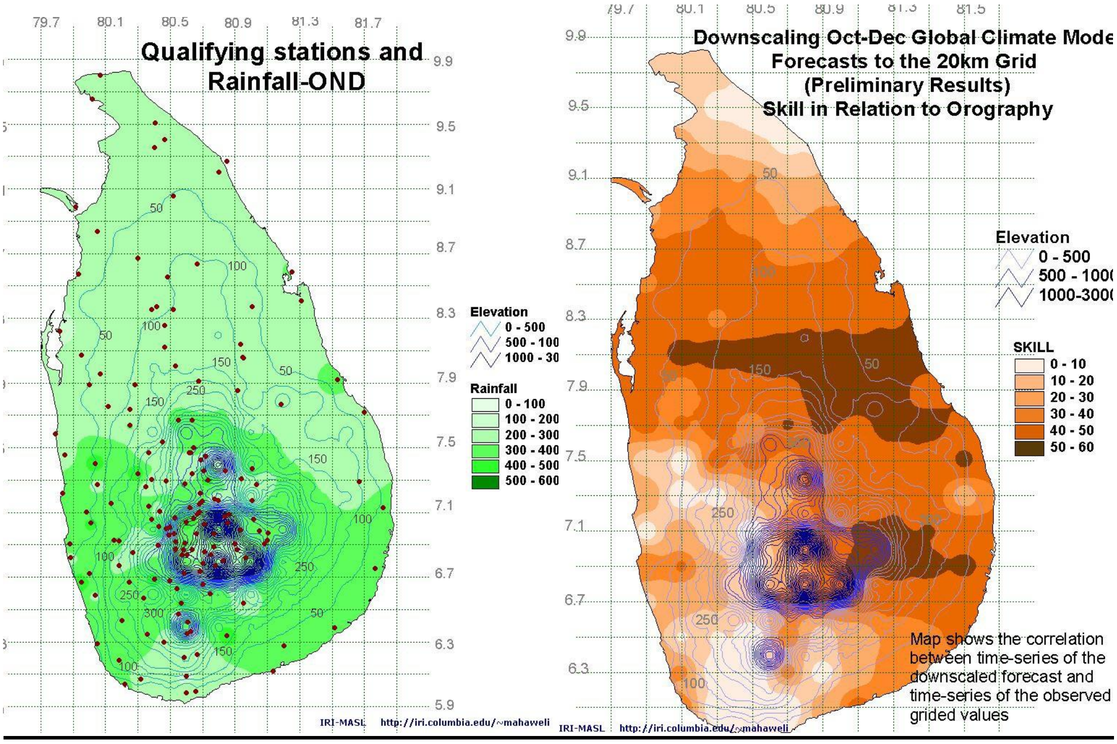

Figure 14: Left: Map showing the stations used for the mean rainfall during October to December. The 20-km grid and the topographic contours are shown
Right: Map of the correlation between time-series of the downscaled forecast and time series of the observed gridded value. The skill of the downscaling scheme that was shown is represented as a correlation score at right. The correlation skill ranges up to 0.6. The topographic contours are shown as well

* Based on the density of the stations, the specific mentioned resolutions were selected for the study

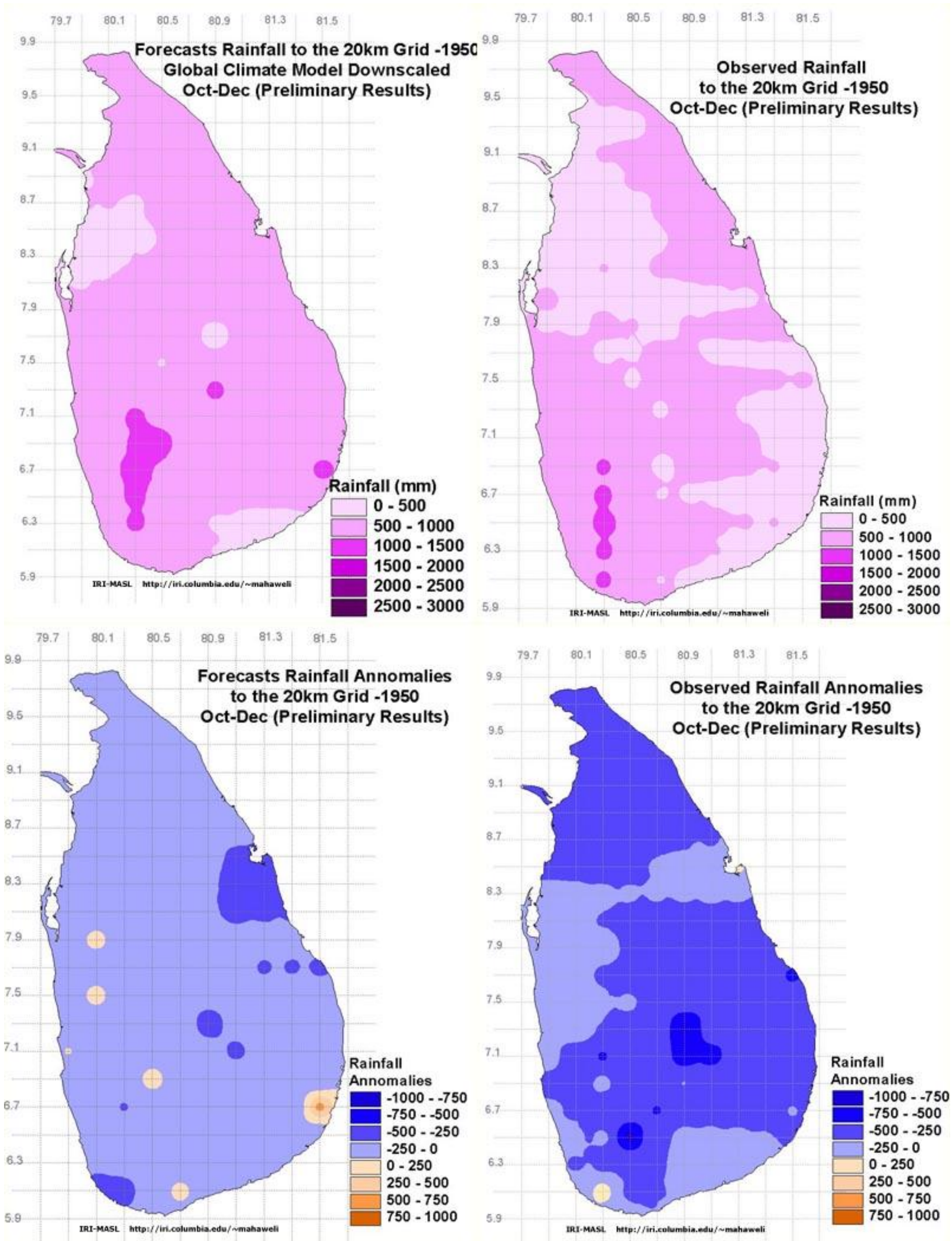

Figure 15: Example of downscaled rainfall predictions for Sri Lanka for October to December season in 1950 (left) and Corresponding Observations (right).
Predictions and Observations are shown as Top row: Total Rainfall, Bottom row: Rainfall Anomalies.

8. Hydrological Modeling

We generated in-situ seasonal stream flow predictions for Sri Lanka, and implemented a state of the art land surface model in collaboration with the Land Surface Modeling group at NASA Goddard Space Flight Center (GSFC).

Seasonal Stream flow Predictions

While model based predictions are useful in generating fine scale results, in-situ predictions of variables such as stream flow may be obtained using statistical relationships between sea surface temperature which is a primary driver of climate and the stream flow histories. Our work on stream flow analysis for Sri Lanka has included diagnostics of stream flow variability and modeling of stream flow from rainfall (Chandimala and Zubair, 2006) providing the potential for future seasonal predictions of stream flow from global sea surface temperatures using canonical correlation analysis[10]. Figure 16 shows the variation of observed and predicted stream flow of the Yala {agricultural season (April to September)} season using the above mentioned principal for the time duration of 1960s to 1990s.

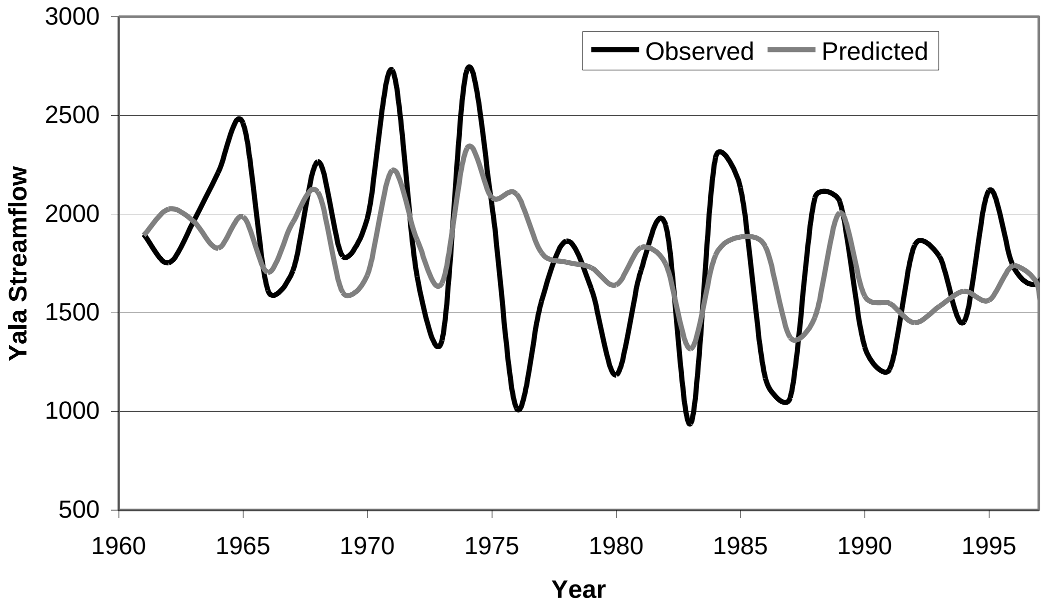

Figure 16: The prediction of the Yala season (April to September) stream flow at Glencourse stream flow in cross-validated mode based on the leading principal component of the sea surface temperatures in the Indian and Pacific Oceans (Chandimala and Zubair, 2006).

Catchment Land Surface Modeling

The hydrological work is motivated by reports of relationships between malaria incidences variations in stream flow and soil moisture. We have progressed well with our hydrological modeling work resulting

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[10] **Canonical correlation analysis** - is a way of making sense of cross-covariance matrices. If we have two sets of variables, $x_1, \ldots, x_n$ and $y_1, \ldots, y_m$, and there are correlations among the variables, then canonical correlation analysis will enable us to find linear combinations of the x's and the y's which have maximum correlation with each other. (Refer to annex for more description)

in the generation of stream flow and soil moisture estimates. A state of the art Land Surface Model[11] (LSM) was implemented with the support of the NASA-Goddard Space Flight Centre-Global Modeling and Assimilation Office Land Surface Modeling Group (Mahanama *et al.*, 2008). This model is implemented at present using a Digital Elevation Model (DEM)[12] at a 1-km resolution with parameters based on the Hydro-IK ensemble of the USGS. The meteorological forcings are obtained from the European Center for Medium range Weather Forecasts (ECMWF) re-analyses data set which has been adjusted to obtain realistic hydrology. Thereafter it was nudged further with the 0.25 degree monthly rainfall and temperature observations over Sri Lanka. Tests show good performance in the simulation of monthly rainfall.

This model is capable of generating the stream flow estimates that are needed at the fine scales required to capture the spatial variations in malaria incidence in Sri Lanka. The model diurnal temperature climatology compared well with observations at 17 stations. The stream flow estimates were compared with observations at 10 stations in different rivers and these were of adequate quality. The stream flow prediction and observation for one station (Peradeniya) is shown in figure 17(Mahanama et al., 2008).

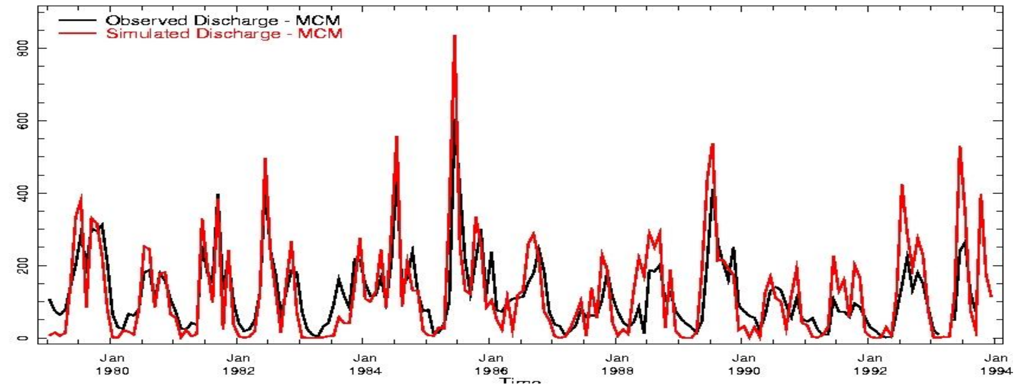

Figure 17: Observed and Simulated Discharge at Peradeniya on the Mahaweli River which is to the upstream of the Mahaweli. The simulation shows good fidelity to the observed records.

Malaria incidence has been related to river margin pooling as well as pooling due to rainfall in depressions. If accurate soil moisture estimates are available it shall be possible to estimate the distribution of inundated areas which are favorable for larvae survivorship. The Land Surface Model has now been developed well enough to generate soil moisture. The seasonal soil moisture pattern is generated by the model implemented on 768 tiles over Sri Lanka. This model can be refined further to obtain soil moisture estimates at DS levels.

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[11] **Land Surface Model** – Land surface models are used to provide a boundary condition to hydrological models, representing the interactions between the land surface and the atmosphere. (Refer to annex for more description)

[12] **Digital Elevation Model (DEM)** – It is a digital model or 3-D representation of a terrain's surface. Commonly for a planet (including Earth), moon, or asteroid which is created from terrain elevation data. (Refer to annex for more description)

Plate 4: H.M. Faizal, Regional Malaria Officer, Moneragala District, in front of potential mosquito breeding sites in his district in January 2006. Stagnant water bodies created by open-pit gem mining (background) and cattle hoof depressions (foreground) create conditions for mosquito breeding. Larvivorous fish varieties were deployed at this pit as a control measure. Soil moisture mapping enables us to identify locations where there shall be at least a film of water on the surface.

Top-model Implementation

The basic top-model Land Surface Model (LSM) formulation which does not consider energy budgets is a simpler option for hydrological modeling than the catchment LSM. Two small catchments for model calibration on two tributaries of the Mahaweli, one in the *Uva* Province and one in a Mahaweli sub-catchment in the Central Province were selected for model calibration based on the availability of diurnal (daily) stream flow data. Figure 18 illustrates a map of the *Uva* site, Upper *Uma Oya* or *Bomurella* catchment.

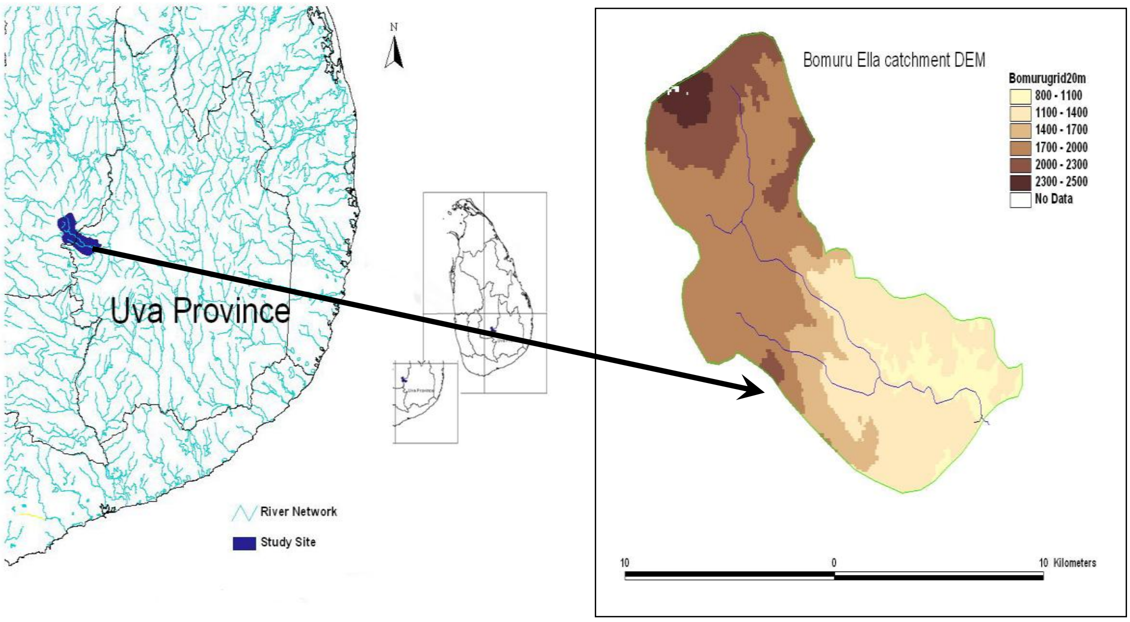

Figure 18: The location of the site, the river network is shown in the top panel.
At bottom, the digital elevation model of the upper Uma Oya catchment of the Mahaweli river that was used in the calibration.

It is important to model the diurnal variation correctly in order to reproduce environmental conditions. To this end, we were fortunate in obtaining the support of Mr. *Kalyana Samarakoon* of the Mahaweli

Authority of Sri Lanka (MASL), who has been collecting diurnal data on stream flow for a study of sedimentation in the *Uma Oya* tributary of the Mahaweli River that flows into the *Uva* Province; and Prof. Samuel, who directs the Solar Research Laboratory at the University of Peradeniya, who has recorded diurnal solar radiation, humidity and wind profiles for *Talawakelle* for several years for studies on agro-meteorological impacts on tea production. Other data needed such as solar radiation, wind, topography and land surface have been approximated.

9. Climate and Malaria Relationships

We undertook an analysis of the relationships of malaria incidence with hydro-meteorological variables such as rainfall, stream flow, temperature and relative humidity and analyzed the seasonality, trends, spatial distribution and statistical relationships between malaria epidemics and rainfall, and stream flow anomalies. These are described below.

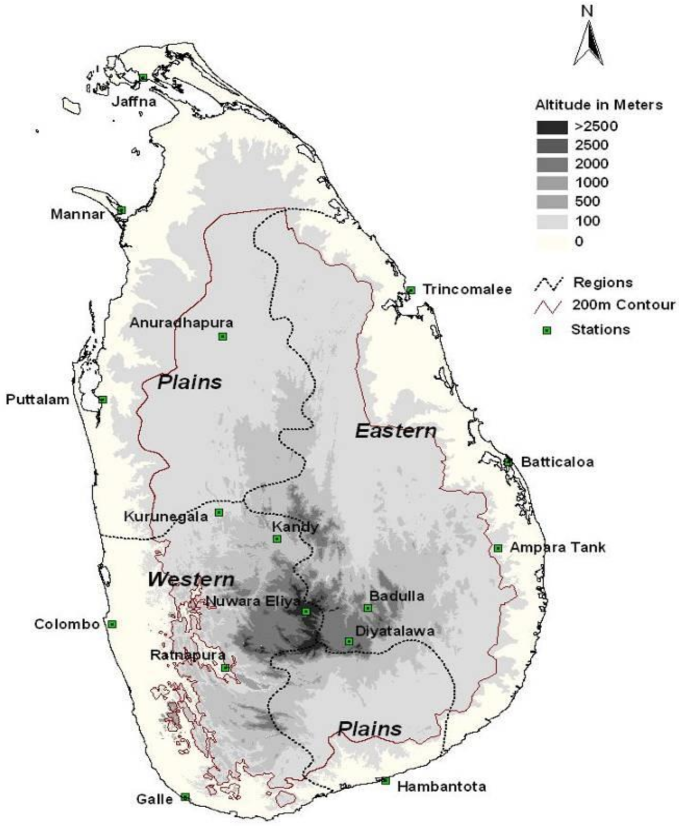

Figure 19: The regionalization of Sri Lanka used in our analysis is shown along with the topography and Department of Meteorology rainfall stations.
The 200 m contour that separates the low areas from the hilly areas is indicated as thin contours.

The regional character of the malaria distribution is brought out in relation to topography by considering the four climatically homogenous regions – Eastern, Western, Northern and Southern Plains (figure 19). The Eastern and Western regions are further subdivided into the Eastern and Western coasts and hills. This classification makes sense from the point of view of the monsoonal wind directions (North-Easterly and Westerly) which lead to enhancement of rainfall on the Eastern and Western hill slopes during the respective monsoon seasons.

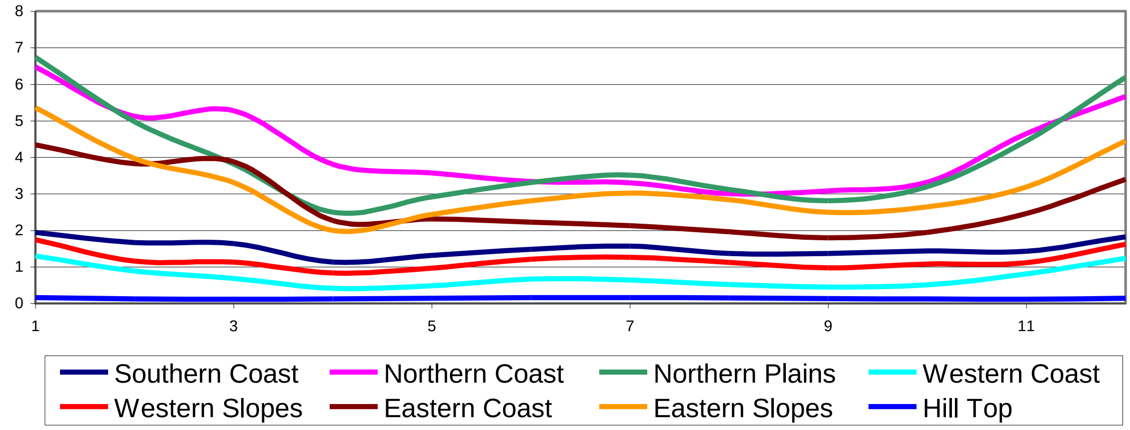

Figure 20: The monthly average malaria incidence in the different climatically homogenous regions for January to December over a recent 40 year period.
Clear differences in the different regions are seen.

Rainfall climate as well as malaria incidence in Sri Lanka is largely bimodal (figure 20). The agricultural seasons Yala (April to September) and Maha (October to December) capture the bimodality of rainfall with rainfall during the early part of the season followed by dry period towards the end. Malaria incidence follows two months after the rainy season and it is possible to use the agricultural seasons to capture the two main modes of malaria incidence.

Seasonal maps for both seasons show similarities and some important differences (Figure 21). Overall the Maha incidence is largely greater than the Yala incidence. The malaria incidence is particularly enhanced in Maha in the regions to the North, whereas regions to the South have comparable malaria incidence in both seasons.

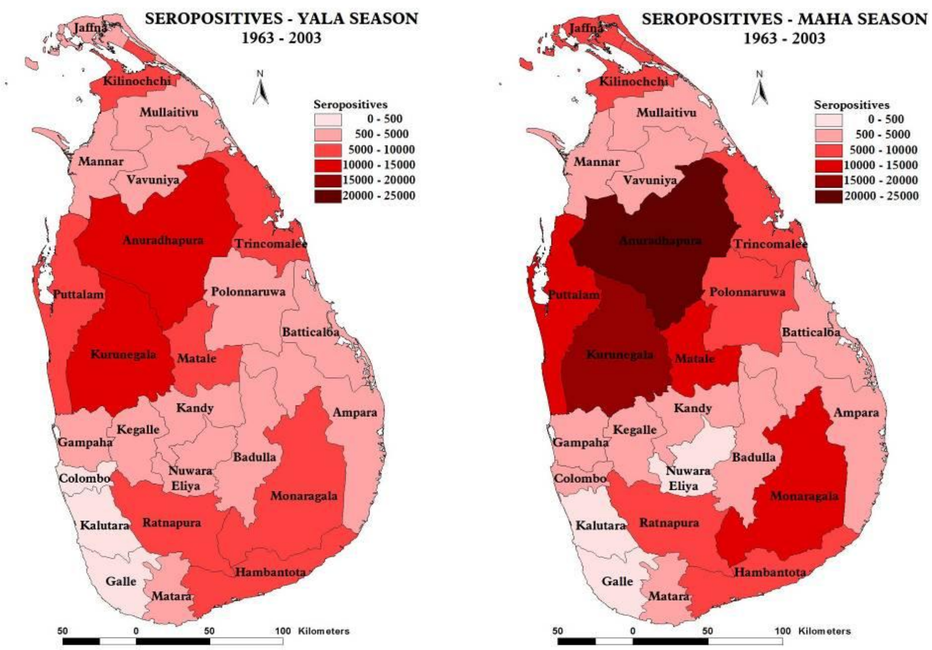

Figure 21: The regional distribution of malaria incidence show during Yala (April to September) and Maha (October to December).

Inter-Annual Variation of Malaria Incidence and El Nino

Previous work (Bouma and Van Der Kaay, 1996) suggested a strong link between malaria epidemics in Sri Lanka and El Nino events which were observed during 1880 to 1945. The above analysis shows that the validity of this claim relies on a particular designation of El Nino episodes; the use of contemporary definitions of El Nino episodes results in a weaker result than previously reported. In addition, this relationship does not hold after 1950 as it did prior to 1950.

The table 1 summarizes the occurrences of epidemics in relation to El Nino years based on contemporary data. The disparity of likelihood of epidemics during El Nino years and that during non-El Nino years was not statistically significant.

Table 1: Epidemic years in Sri Lanka in relation to the El Nino years between the time periods of 1861 and 1999.

	Epidemic years	Non-epidemic years	Total
El Nino years	**7**	**26**	**33**
Non-Nino years	**13**	**92**	**105**
Total	**20**	**118**	**138**

We investigated whether this breakdown was due to an epochal change in the relationship of ENSO and rainfall over Sri Lanka that occurred around 1950 (Zubair and Chandimala, 2007). The insecticide based control program put in place in the early fifties may also have played an important role in disturbing the "natural" relationship between epidemics in malaria and climate variation.

The particulars of El Nino relationships with Sri Lankan rainfall are complex and dependent on spatial and epochal details. Indeed, the El Nino's influences have come in different flavors in different years as also has been the case with the character of the epidemics. A more comprehensive analysis of El Nino events, its impacts on climate, and the relationship with morbidity and mortality were published (Zubair et al., 2008, Zubair and Ropelewski, 2006). Bouma and Van Der Kaay, 1996 proposed that ENSO forecasts could serve as an early warning system for Sri Lanka. We examine this relationship by plotting the mean annual ENSO index (NINO34) in relation to years in which there were epidemics (figure 22).

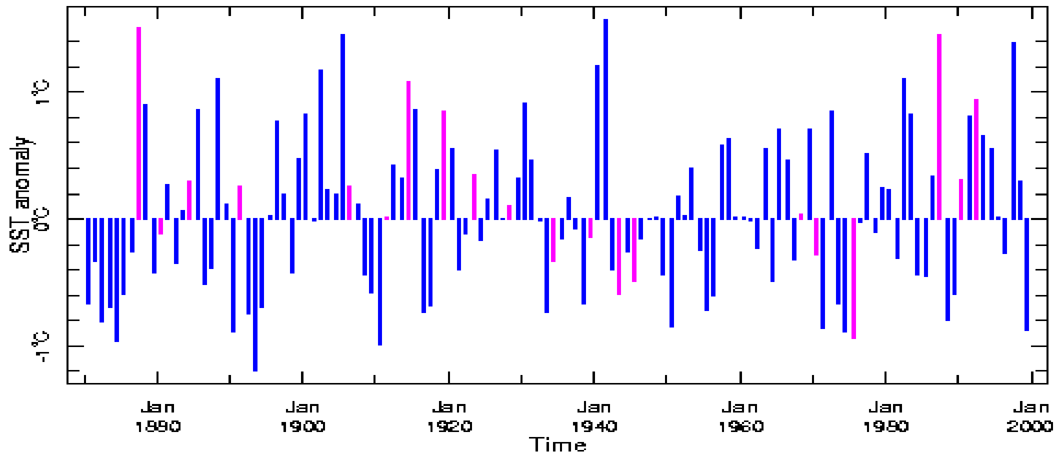

Figure 22: Epidemic years are identified in red on a time series of annual NINO34 which is an index of ENSO. NINO34 values above 0.5 may be taken as El Niño events. It is plausible that even if the value is not about 0.5 in a particular year, it may well have been above this value for part of the year. The years in which epidemics occurred are marked in red. This figure shows that usually Epidemics occurred during periods of warm ENSO indices up to 1930's and after 1980's. In the intervening period, epidemics were more likely if at all during cold ENSO events.

The epidemic years (red bars) did not coincide with "El Niño years" in a statistical significant manner. In addition, any such relationship is inverted from 1940-1980. We are not convinced that the control program put in place in the early fifties led to the disturbing of this relationship.

Our analysis shows that the use of El Nino episodes to predict malaria episodes as suggested previously requires an explanation as to why the relationships inverted from 1940 to 1980. Rainfall, stream flow and temperature are influenced by ENSO phenomenon. An examination of the monthly rainfall patterns during different ENSO extremes is shown in figure 23 a), 23 b) and 23 c) for the period before 1945, between 1945 and 1985, and after 1985, respectively.

ENSO and Malaria Incidence

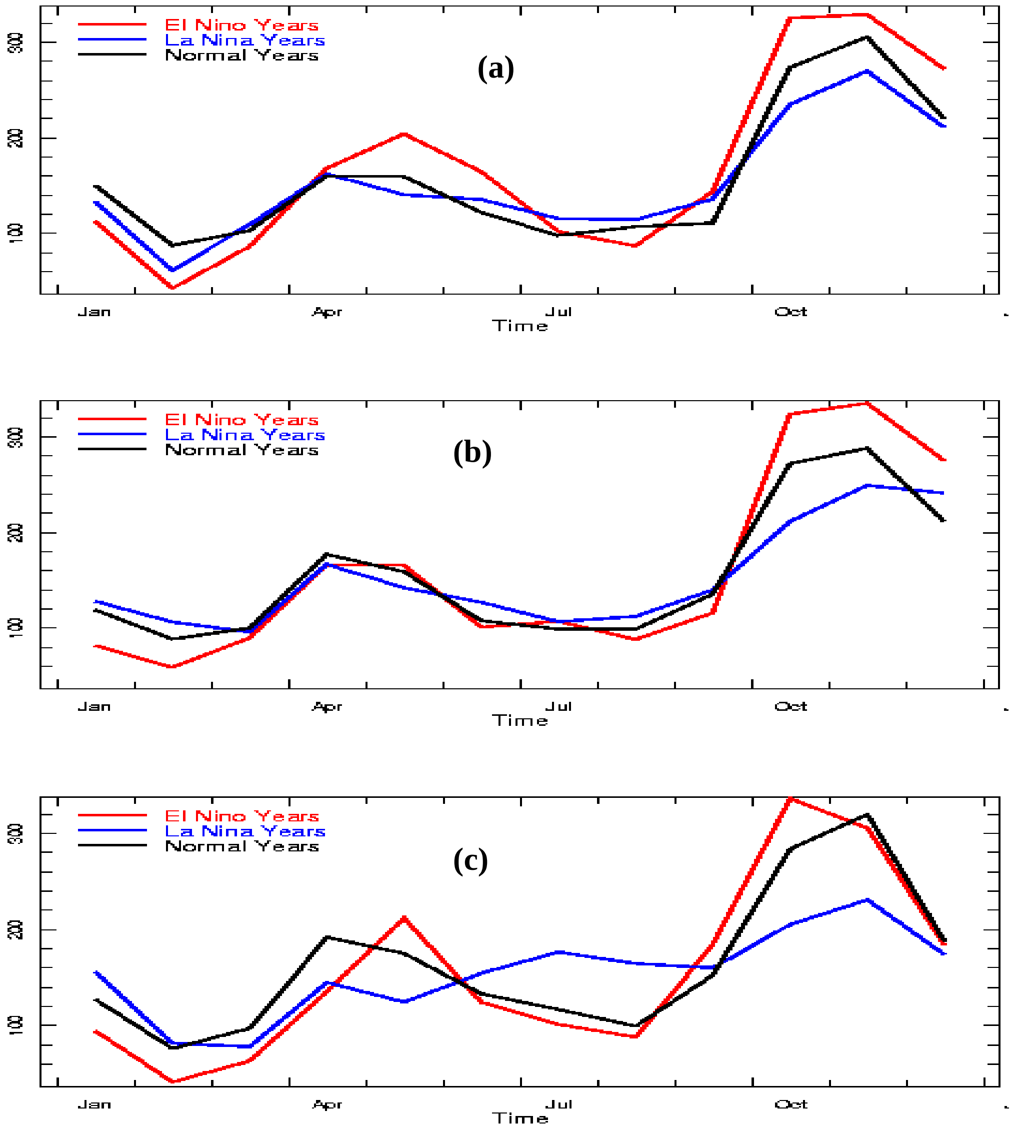

Figure 23: a) Monthly average rainfall in Sri Lanka from 1869 to 1945 during all years, during El Niño years and during La Niña years. b) Monthly average rainfall in Sri Lanka from 1946 to 1985 during all years, during El Niño years and during La Niña years. c) Monthly average rainfall in Sri Lanka from 1986 to 2003 during all years, during El Niño years and during La Niña years.

This analysis shows that rainfall during El Nino events was enhanced during wet periods and diminished during dry periods prior to 1945 and after 1985. This is in keeping with the patterns expected during high morbidity years. These dramatic changes may be due to an epochal change in the relationship of ENSO and rainfall over Sri Lanka that occurred around 1940 (Zubair and Chandimala, 2006) and around 1980 (Zubair and Ropelewski, 2006).

Relationships between Stream flow and Malaria Incidence

Previous works cite the relationship between epidemics and variations in stream flow (e.g. Visvalingam, 1961). We have constructed composites of stream flow for epidemic years for the *Kelani* River which is located in south-west. The pattern of malaria dynamics is known to differ in this region when compared with that in the rest of the island. The prevalence in this region has also been reduced in recent decades. However, this is a basin with long records that had been the locus of severe epidemics before 1950.

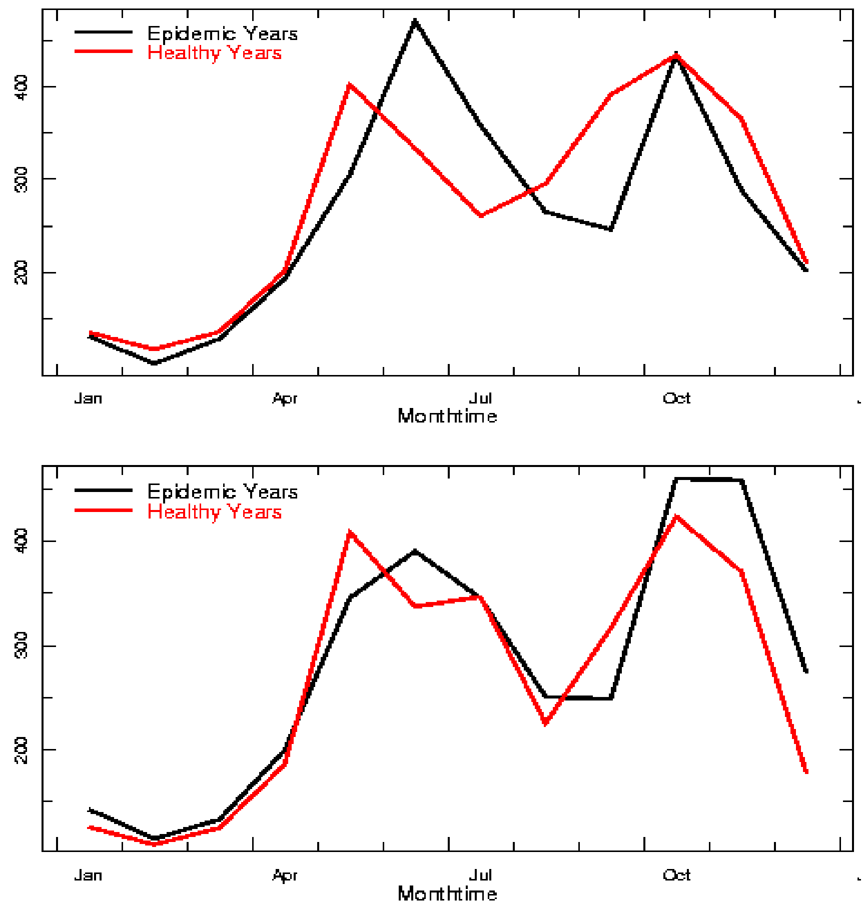

Figure 24: The average stream flow in the Kelani River during peak epidemic years (black line) and years in which there was the least malaria (red line) are compared for the year before the epidemic (top) and the year of the epidemic (bottom).

There is a deficit in stream flow during the October to December season preceding an epidemic year (figure 24). Such a deficit was also found in the records of the *Gin Ganga* River in the South-West (figure 25). Further work shall examine such diagnostic for other rivers. Such a deficit if confirmed is a potential precursor of malaria risk. Our work is ongoing and we shall seek to understand the island-wide variation of stream flow and its relationship to epidemicity and report on it (Zubair *et al.*, 2005e).

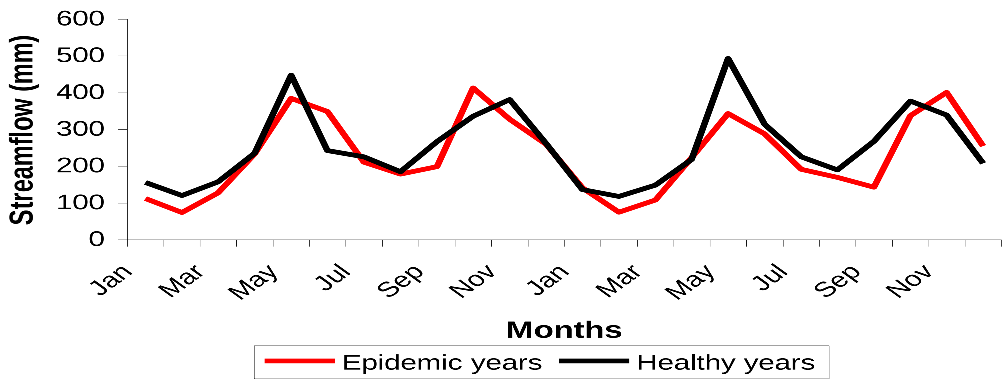

Figure 25: The average stream flow in Gin Ganga River during years in peak epidemic years (red line) and years in which there was the least malaria (black line) are compared starting before the epidemic into the year where the epidemic was reported.

In general, the rainfall and stream flow during years of high malaria incidence may be characterized as higher flows during wet seasons and lower flows during the dry seasons. Extended dry periods leading up to September have lead to increased malaria risk.

Plate 5: Menik Ganga (river) which is often a locus for malaria outbreaks in the Uva province in January 2006 when the river has its seasonal high flow. During dry seasons, the stream flow declines leaving pools in the riverbed favorable for mosquito breeding.

Epochal Change in Incidence and Distribution of Malaria

An examination of the historical record shows that the incidence of malaria is seen to have undergone dramatic changes in prevalence during the 1930's, 1960's, 1980's and 2000's (figure 26).

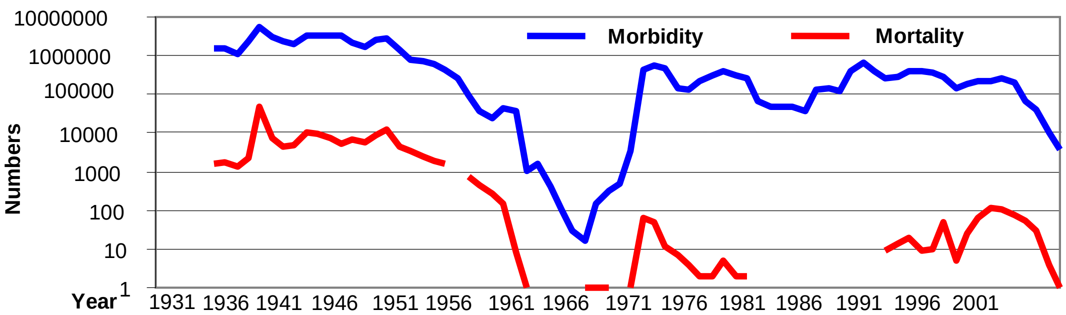

Figure 26: Annual island-wide morbidity and mortality due to Malaria from 1931 to 2002.

There have also been dramatic changes in the regional prevalence of epidemics as shown in the maps in figure 27. These changes have coincided with changes in the control program. For instance, in the 1930's environmental control programs were in use and thereafter in 1947 *Dichlorodiphenyltrichloroethane* (DDT) was used widely resulting in the near elimination of malaria around the late 1960's. After the re-emergence of malaria in 1968 Malathion was sprayed and DDT was phased out. Other insecticides including Fenitrothion and Lambda-cyhalothrin were sprayed thereafter. The introduction of Artemesinin based insecticides has again led to a dramatic drop in malaria incidence after 2000.

Environmental factors are also important contributors to malaria control. For instance, larviciding of stagnant pools with diesel and construction of buffer dams to prevent pooling were undertaken in the first half of the century as control measures. People without acquired immunity who were from non-malarious regions were resettled in malarious regions during large land settlement projects in malarious areas from 1950's such as the *Gal Oya* scheme in the South-East to the Mahaweli Development scheme in the 1980's. Of late, environmental control has re-emerged as a means of vector control. In all this however, the epochal change in climate may also be implicated in changes in the intensity and distribution of malaria.

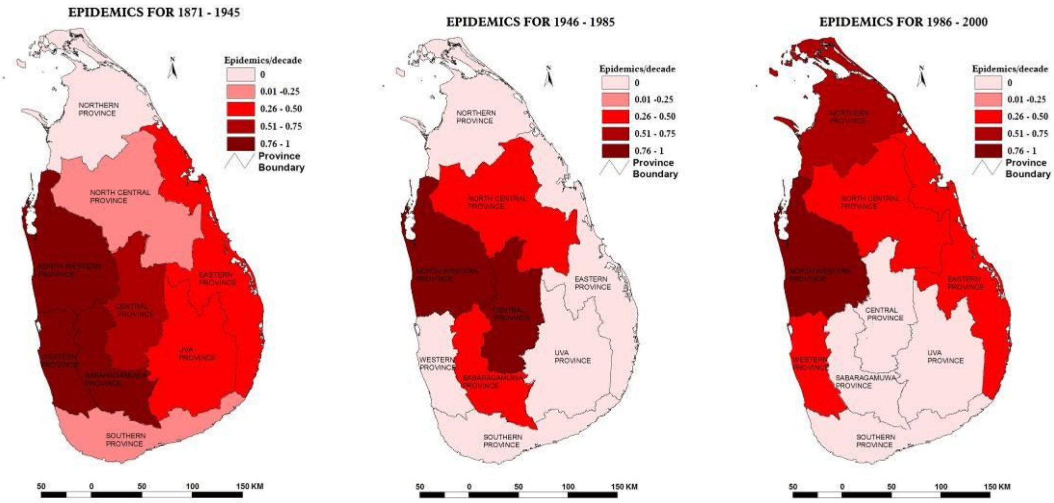

Figure 27: The relative spatial frequency of epidemics in three epochs (from L-R 1871-1945, 1946-1986, 1986-2000) period. The prevalence of epidemics has shifted from the Western and Sabaragamuwa Provinces to North-East. The relationship between malaria epidemics and El Niño which broke down from 1946 to 1986 re-emerged after 1986.

10. Climate and Malaria Relationships in *Uva*

Even though Sri Lanka's climate does not vary by much compared to many other parts of the world, the spatial and seasonal variations results in important consequences for malaria risk. We report on preliminary climatological analysis of mean monthly malaria incidence, rainfall and temperature for districts in *Uva* (*Badulla* and *Moneragala*) and those close by (*Nuwara Eliya*, *Hambantota*, *Batticaloa*). We have also undertaken investigations of inter-annual variability. The incidence of malaria is characterized both by a robust mean annual cycle even though there are strong epidemic type behavior in certain years. This robust mean annual cycle is driven by the contrasting seasonality of rainfall and temperature in the 5 districts (figure 28, 29 and 30).

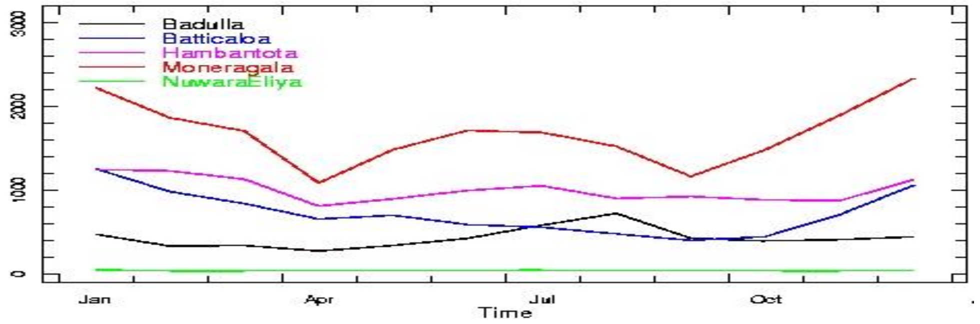

Figure 28: The relative variation of the mean annual cycle for malaria morbidity (positive blood tests) in Sri Lanka. Morbidity is bimodal for all districts excluding Batticaloa. Batticaloa experiences only the Maha maximum.

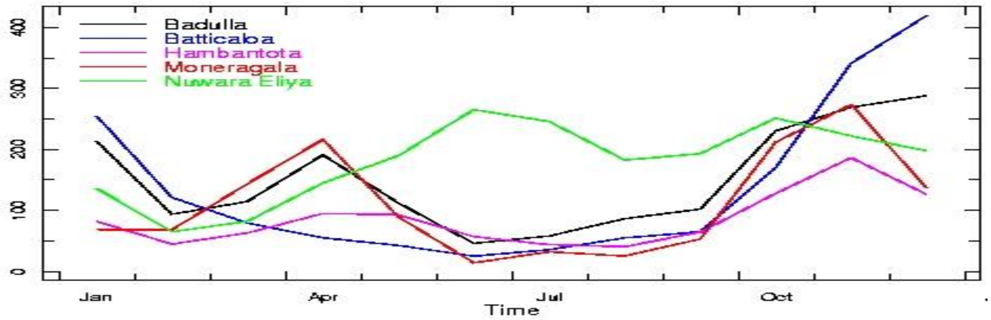

Figure 29: The mean annual cycle for rainfall (mm) in Sri Lanka. Rainfall is bimodal for all districts excluding Batticaloa. Peaks occur during both Maha and Yala. Batticaloa experiences only the Maha maximum.

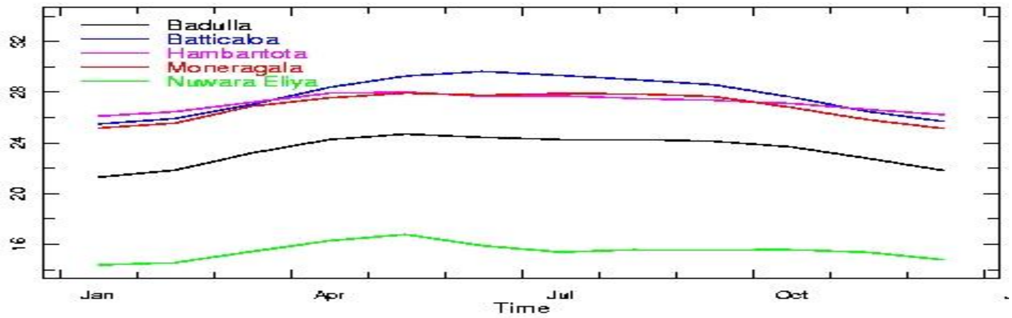

Figure 30: The mean annual cycle for temperature (°C) in Sri Lanka. Maximum temperatures occur during the boreal summer (May-June), while minimum temperatures occur during the boreal winter (December-January).

Badulla District:

The Badulla District which is in the highlands of the Uva Province shows a seasonal peak in malaria incidence around August. The peak in August in unlike that found in many other districts where the December/January peak is dominant (see covered area in the graph). There is considerable spatial variability of mean temperatures within the district. The malaria peaks follow rainfall peaks by 4 months in the summer and are coincident with the rainfall peaks in winter.

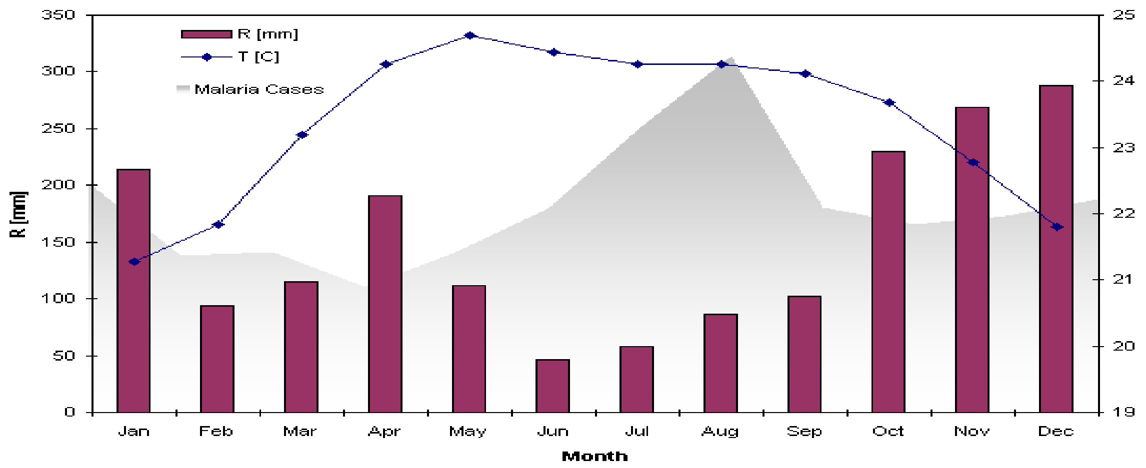

Figure 31: The mean values for Malaria cases, total rainfall and mean daily temperatures from January to December computed for the 1971-2001 period for the Badulla District. Note, that the rainfall and temperature seasonality that is shown represent point measurements in the capital of the Badulla district.

The *Badulla* District which is in the highlands of the *Uva* Province shows a seasonal peak in malaria incidence around August (figure 31). The major peak in August is unusual for Sri Lanka as usually the December/January peak is dominant (figure 31). The mean temperature varies considerably within the district. The malaria peaks follow rainfall peaks by 4 months in the summer and are coincident with the rainfall peaks in winter.

Moneragala District:

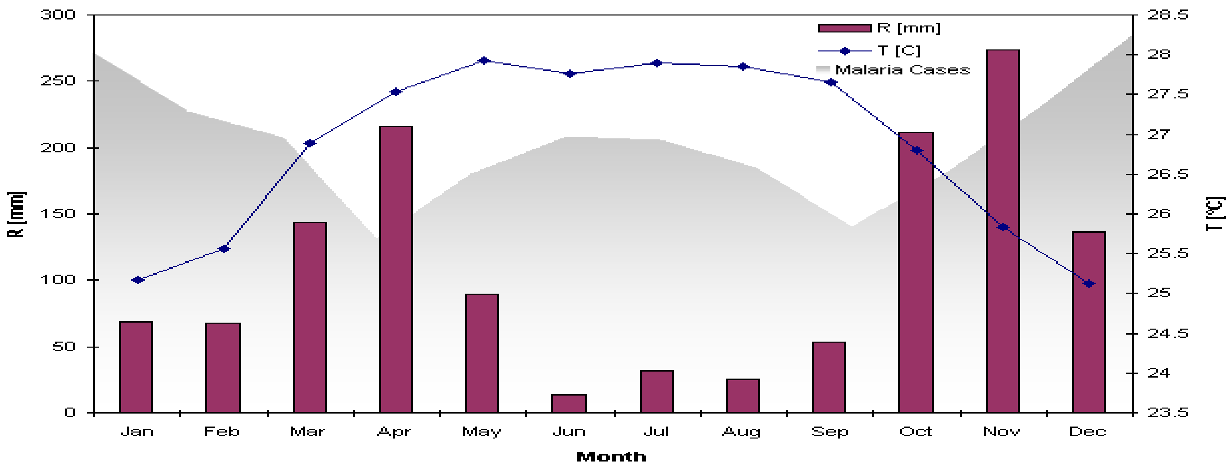

Figure 32: The mean values for Malaria cases, total rainfall and mean daily temperatures from January to December computed for the 1971-2001 period for the Moneragala District.

The *Moneragala* District comprises the lowlands of the *Uva* Province and is one of the most malarious regions in Sri Lanka. The seasonal peaks in both December/January and June/July/August are both significant (figure 32). The malaria peaks follow the rainfall peaks by 1-2 months.

11. Predictive Malaria Risk Mapping

Given our findings of sharp spatial variability in the distribution of malaria, and observations along these lines from Regional Malaria Officers, it was important to undertake analysis at scales finer than the district scale. The availability of digitized village-level data is limited to about 10 years for only a few districts. The spatial variability at the village scale appears to be governed by vulnerability factors rather than climate. Thus, we undertook the analysis at sub-district scales that are used by the Ministry of Health agencies (figure 33). Each of these sub-districts is assigned a Medical Officer of Health (MOH). Data for the 220 odd MOH divisions are available from 1971. There have been several changes in MOH divisions that have to be considered in the analysis.

We incorporated the geometries for the MOH sub-divisions after appropriate modifications into our analysis tools. We also needed to undertake various data management techniques to develop climatic data sets (Rainfall, Day and Night Relative Humidity, Temperature; Mean, Minimum and Maximum) at these regional scales. Thereafter we developed probabilistic relationships between malaria and climate which were used in the first instance to predict seasonality as a test for its utility. We found that many features in the distribution of malaria could be explained. We also tested hypothesis regarding the relationship between drought and malaria at this time scale.

Malaria at MOH sub-district scales

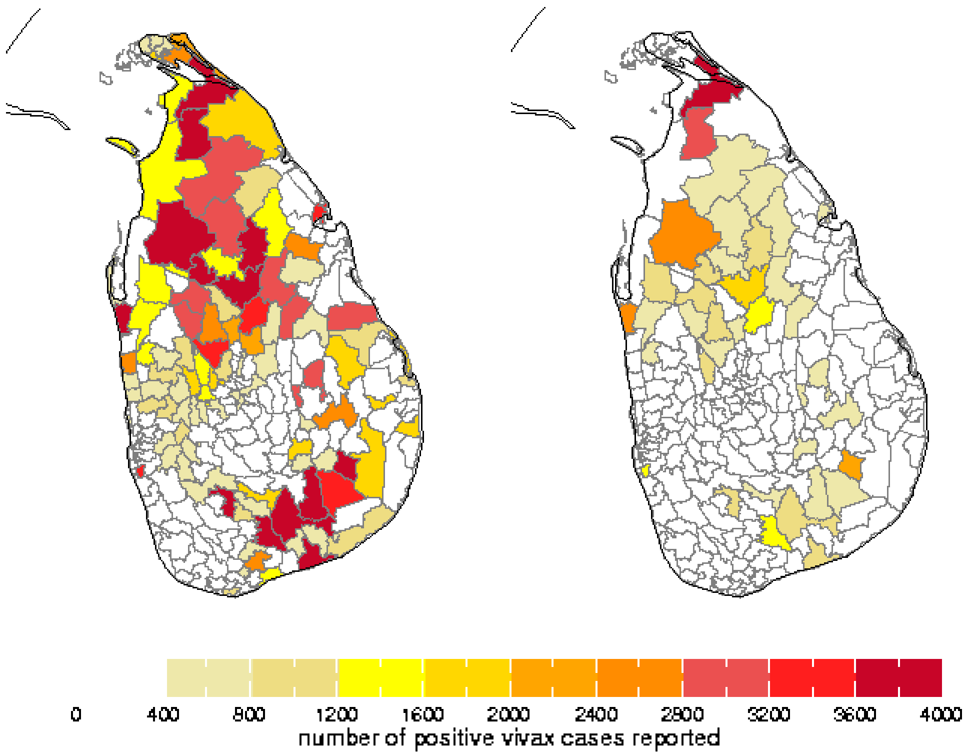

Figure 33: : Maps showing the average malaria incidence by Ministry of Health sub-districts (MOH) was represented as the annual average for the Plasmodium Vivax (left) and Plasmodium Falciparum (right).
The malaria numbers are based on laboratory confirmed incidence data obtained from the Sri Lanka Anti-Malaria Campaign (AMC) for the period from 1963-2003.

Rainfall Malaria Relationships at MOH sub-district scales

An analysis of the relationship between the June-August malaria incidence and the rainfall just prior to this season is shown in the top-left graph in figure 34. Malaria incidence exceeds 50 cases per thousand only when the rainfall is between 25 and 175 mm. This range is further narrowed when the wetter and drier sub-districts are separated. In the dry sub-districts, the incidence is high from 25-100 mm whereas the high transmission in the wet districts prevails when the rainfall is from 100-175 mm. Similar association of malaria incidence is evident with monthly means of daily minimum and maximum temperature and relative humidity. Malaria incidence exceeded 50 cases per 1000 only when the minimum temperature was in the range from 18 to 26.5°C, the maximum temperature was in the range of 28-35°C and the night-time relative humidity ranged between 70 and 90% (top right graph on figure 34). There is a narrower range of climatic conditions that lead to the highest transmission.

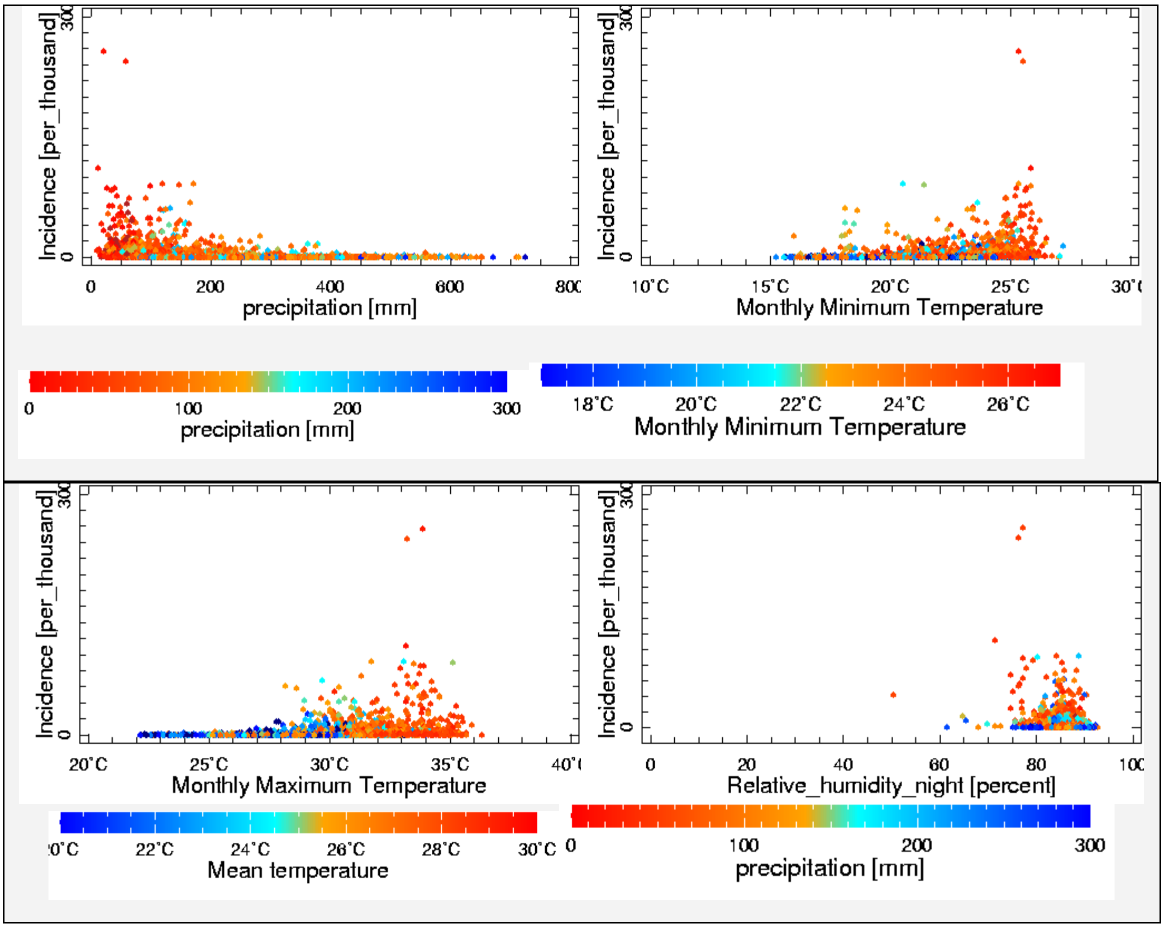

Figure 34: Seasonal average malaria incidence in the sub-districts from 1972-2003 as a function of rainfall, temperature and relative humidity (IRI/FECT/AMC).
Top Left: Average malaria incidence from June-August is shown as a function of the average April-June rainfall. The color of each dot indicates the average temperature as given in the scale bar.
Similarly, Top Right: June-August incidence as a function of minimum temperature colored by rainfall.
Bottom Left: June-August incidence as a function of maximum temperature colored by rainfall.
Bottom Right: June-August incidence as a function of relative humidity colored by min. temperature.

Climatic Suitability at MOH sub-district scales

Climatic Suitability for Malaria Transmission

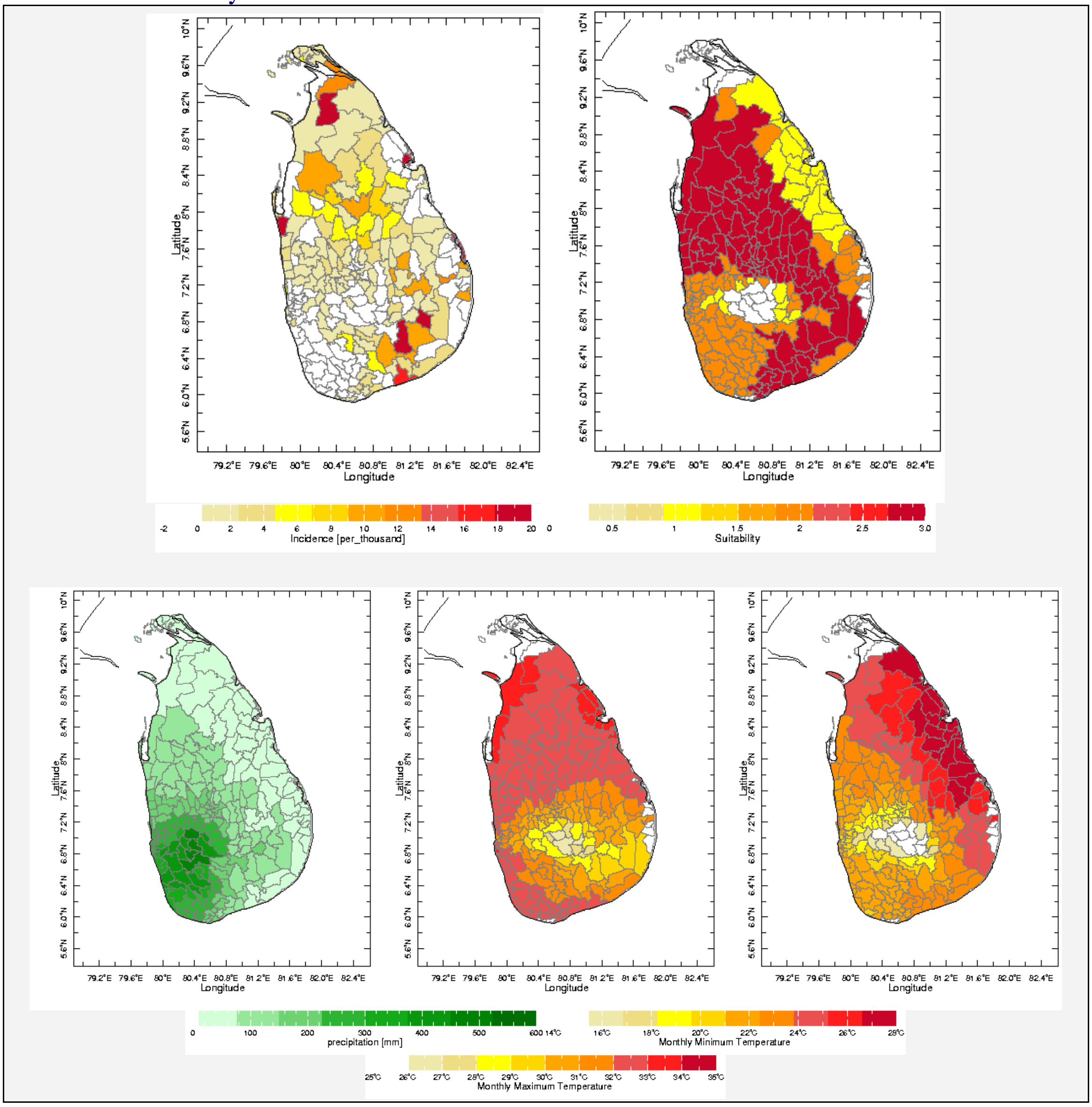

Figure 35: Maps showing climate suitability for the malaria transmission
Top left: Monthly mean malaria incidence (cases per thousand) during June-August.
Top right: climatic suitability defined as a combination of thresholds on precipitation (60-200 mm), minimum (20-26°C) and maximum (28-34°C) temperature. A value of 3 (red) means that all conditions, on precipitation, minimum and maximum temperature, are met.
Bottom: Monthly mean precipitation, minimum and maximum temperature during June-August.

We undertook an exercise in identifying climatic suitability for average June-August malaria transmission based on average rainfall, and minimum and maximum temperature that are within the ranges that provide incidence greater than 50 cases/ 1000 historically (figure 35). The number of different variables (see lower panel of figure 35) that fell within these ranges were added. The resulting distribution is shown at top-right map of the figure 35. This methodology leads to a geographic pattern that replicates the high incidence in North-West and South-East regions shown at top-left.

Incorporating Vulnerability Information and Disease Control History

Although, the large scale geography of malaria incidence can be explained in terms of climate, there are sharp spatial contrasts in the distribution of malaria at finer scales that may be influenced more by other factors. Some of this variation may be explained by considering the local distribution of river systems. Proximity to streams, irrigation systems and abandoned gem pits, have an influence on malaria incidence. Vulnerability to malaria has a geographic aspect and adverse risk factors such as type of housing, economic activity and age distribution. The influence of control measures has to be taken account of in risk prediction. Note that climate can also have an influence on the exposure (e.g. irrigation practices) and on vulnerability (susceptibility is enhanced due to malnutrition during droughts) and on control programs (e.g. distribution of bed nets).

A conceptual framework for using climate information that integrates vulnerability assessment and monitoring, predictions, climate and environmental monitoring, sentinel site surveillance and incorporation into disease control activities has been proposed. Vulnerability assessment has to be conducted to delineate the geographic location of the epidemic prone populations along with other demographic and socio-economic characteristics that lead to susceptibility. Climate monitoring and seasonal forecasts can be used to anticipate disease risk, if the relationship between climate and disease is understood. Early detection and warning can be undertaken through disease surveillance, entomological monitoring (which provides a lead time of weeks), monitoring climatic and environmental variables (which gives a months lead time) and the use of seasonal predictions of climatic and environmental variables up to 3 months ahead (which gives a lead time of up to 4 months). The longer lead times are achieved at the cost of accuracy and greater uncertainty but all of these predictions are useful for different disease control decisions.

Testing Hypothesis on Influences of Seasonal Drought on Malaria Incidence

We took advantage of the availability of high-resolution data sets to check two hypotheses regarding the role of rainfall in malaria transmission. According to Gill (1935), the deficiency of rainfall during the spring leads to malaria incidence in the wet parts of the island and the excess of rainfall leads to epidemics in the dry part of the country. An example of these tests is shown in the correlation maps that follow in figure 36. This analysis shows seasonal variations. The high correlation of the rainfall to the North of the island supports the hypothesis that, excess rainfall in October to December leads to malaria incidence (figure 36) with the relationship being inverted in the South. The relationship of the rainfall in the preceding dry season (July to September) has an even more complicated relationship with malaria incidence from November to February. This analysis points to the need for detailed spatial consideration.

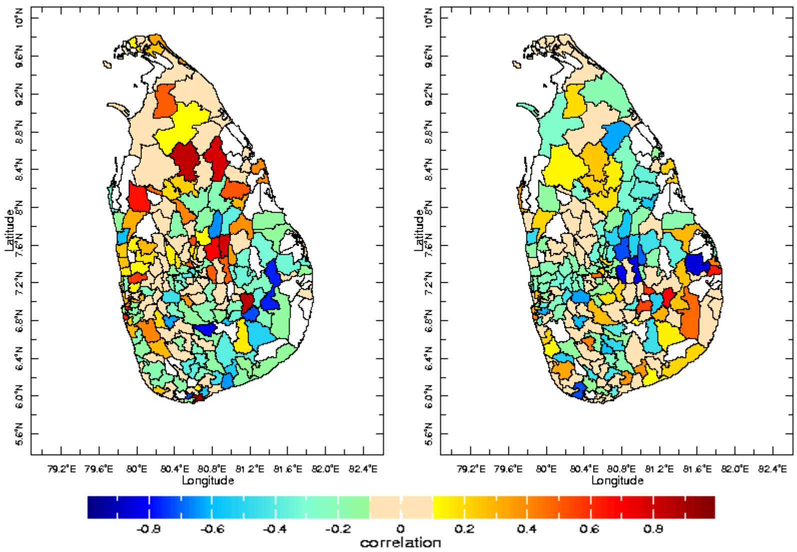

Figure 36: Left - Correlation between October to December Rain and November to February Cases (Pv)
Right - Correlation between July to September Rain and November to February Cases (Pv).
The correlation is based on data sets that are available for 1972-2003.

Climate Change and Malaria Incidence

While this project focused on Climate Variability, we also undertook preliminary analysis of climate change impacts using our annual island-wide data for malaria morbidity and mortality that goes up to 1911. We also constructed annual time series for rainfall, temperature; minimum, maximum and mean and relative humidity; day and night time.

An examination of the relationship between rainfall, temperature and malaria incidence shows that higher morbidity prevailed during periods of lower temperature (figure 37). The relationship with rainfall was not as clear cut.

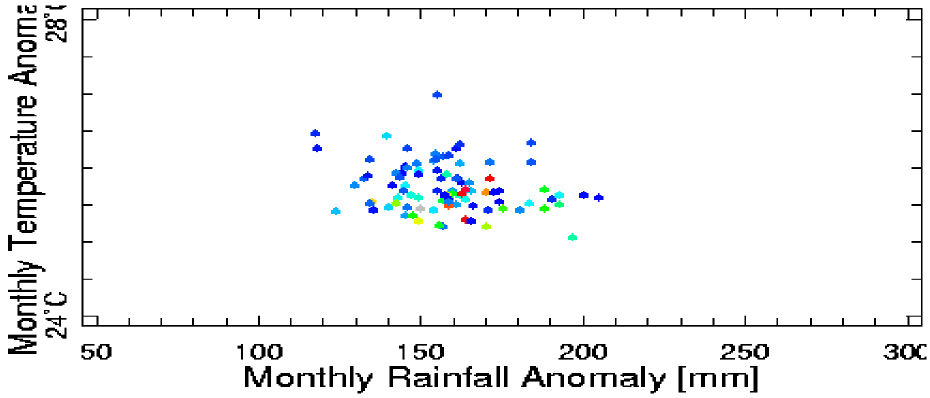

Figure 37: The annual malaria incidence is plotted as a function of the annual rainfall anomaly and the mean annual temperature.

The annual temperature may be plotted with incidence represented by the color as in the figure 38 below. Figure 38 shows the epidemics that coincided with lower temperatures. The association of higher incidence with lower temperatures is fairly robust at diurnal, seasonal and inter-annual time scales.

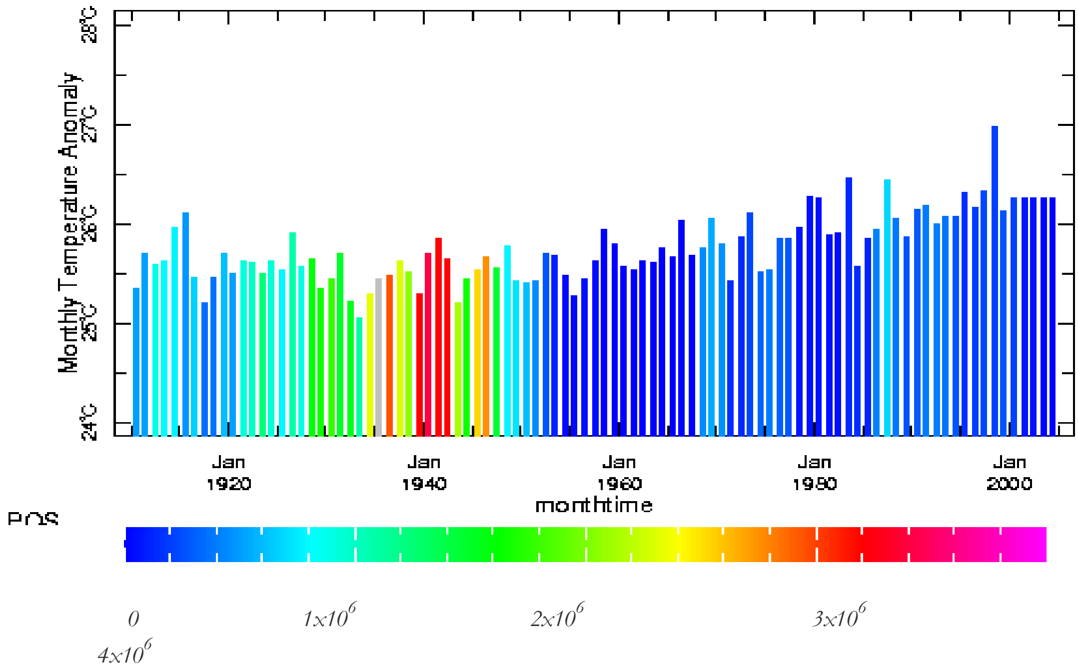

Figure 38: Annual Sri Lankan average temperature is plotted from 1911 to 2005.
The bar representing each year is colored based on the number of cases as shown in the scale bar.

12. Conclusion Workshops

Project Conclusion Workshop

This project completion workshop for the stakeholders was conducted successfully at the headquarters of the International Water Management Institute (IWMI) on September 17, 2007 with the participation of those who were involved with the project. The International Research Institute for Climate and Society (IRI), Anti-Malaria Campaign of the Ministry of Health (AMC), the Sri Lanka Department of Meteorology (MET), World Health Organization (WHO – Sri Lanka), and the Mahaweli Authority of Sri Lanka (MASL), along with officials of the Ministry of Health participated. This was an opportunity to have discussions regarding the progress of the project. The program fitted quite well with presentations on the experience of Malaria Early Warning Systems (MEWS) globally, from Steve Connor, with a presentation on the specific needs in Sri Lanka from the Director of the Anti-Malaria Campaign and presentations of the work at IRI and IWMI and their respective partners. There was an extended period for discussion, feedback and follow up of the workshop participants.

A persistence based forecast system was put in place at IWMI for two years. They have also undertaken work on vulnerability analysis and economic assessment of the value of MEWS. FECT and IRI have established linkages between rainfall, temperature and malaria incidence, undertaken vulnerability studies, rainfall and temperature monitoring at fine scales, downscaled climate predictions and hydrological simulations to generate soil moisture and stream-flow.

The outcomes include a revival of the collaboration between the different partners, good understanding of the potential for MEWS and the limitations, and an acknowledgement of the continuing need for climate informed MEWS even as there is a drop in the case load. And the focus now is on publication and operationalization of the project outputs. Further details on this workshop such as announcement, agenda and participants are provided in the Appendix.

Training Workshop

A workshop at the Post-Graduate Institute of Science, University of Peradeniya on September 21, 2007 was targeted at dissemination and interaction with researchers and younger scientists. This workshop provided the opportunity to bring together related research on insecticide resistance, vector control, investigations of recent outbreaks and the specifics of the situation in the *Uva*, and to provide an in-depth account of the methodological issues involved in the research.

The workshop was well supported by the Anti-Malaria Campaign with extensive participation. The Acting Director provided the keynote address, and also underlined the continuing need for an early warning system and outlined the specific needs in such a system. The Epidemiologists and Regional Malaria Officers provided their experience which enriched the discussions. The University academics contributed in areas of entomology and parasitology. The workshop was also an occasion to meet with Dr. R. Siyambalagoda who had stepped down as Director of the Anti-Malaria Campaign.

Overall, this was a successful meeting that supplemented the stakeholders meeting and it enabled us to build a more comprehensive partnership with the climate and malaria community in Sri Lanka. After the meeting, we were able to meet with the two Regional Malaria Officers who were due to visit IRI in November 2007 for further collaborations. Further details on this workshop such as announcement, agenda and participants are provided in the Appendix.

13. Publication and Dissemination

Publications

This work led to many findings which should be disseminated to the disease control and public health community in the US, Sri Lanka and elsewhere. We have published 8 papers in peer-reviewed international journals and one chapter in a WHO publication. We have 8 paper published and more than 8 reports that can be published.

In Journals and Books

- L. Zubair, M. Siriwardhana, J. Chandimala and Z. Yahiya, 2008, *International Journal of Climatology*, Predictability of Sri Lanka rainfall based on ENSO, 28 (1) : 91-101.
- L. Zubair and J. Chandimala, December 2007, *Journal of Hydrometeorology*, Epochal Changes in ENSO-streamflow relationships in Sri Lanka, 7(6):1237-1246.
- J. Chandimala and L. Zubair, March 2007, *Journal of Hydrology*, ENSO based predictions for Water Resources Management in Sri Lanka, 335 (3-4), 303-312.
- S. Mahanama, R. Koster, Rolf Riehl and L. Zubair, 2008, On the predictability of seasonal streamflow from soil moisture, *Advances in Water Resources.* 31 (3): 1333-1343
- B. Lyon, L. Zubair, V. Ralapanawe and Z. Yahiya, 2009, Fine scale evaluation of drought hazard for tropical climates, *Journal of Applied Meteorology and Climatology*.
- Zubair, L., G. Galapaththy, H. Yang, J. Chandimala, Z. Yahiya, P. Amerasinghe, MN Ward, SJ Connor, Epochal Changes in the Association between El Niño and Malaria in Sri Lanka, 2008, *Malaria Journal*. 7:140
- L. Zubair and Chet Ropelewski, 2006: The strengthening relationship between ENSO and the North-East Monsoon over Southern India and Sri Lanka, *Journal of Climate*, 19 (8): 1567–1575.
- L. Zubair (2004), *Empowering the Vulnerable*, TIEMPO magazine, University of East Anglia, Volume 52.
- L. Zubair (2004), Weather, Climate Variability and Climate Change, Workshop Report, Synthesis Workshop on Climate Variability, Climate Change and Health in Small-Island States, Bandos Island, Maldives, 1-4 December 2003, pages 13-14, World Health Organization, Bandos, Maldives.

Technical Reports

- Zubair, L., M. Siriwardhana, H. Yang, J. Chandimala, Z. Yahiya, U. Tennakoon, S. Partridge, A. Giannini, MN Ward., S. J. Connor, (2008) *Seasonality and Spatial Variation of Malaria in Sri Lanka in relation to Climate.*
- Zubair, L., O. Ndiaye, N. Ward, R. Perera and J. Chandimala (2008), Statistical Downscaling from a GCM at fine resolutions in a monsoon climate.
- H.M. Faizal, J. Simonson, Z. Yahiya, J. Chandimala, A. Giannini, Zubair, L., (2008) *Climate and Malaria in South-Eastern Sri Lanka.*
- P.H.D. Kusumawathie, A. Giannini, Z. Yahiya, J. Chandimala, Zubair, L., (2008) *Climate and Malaria in Central Sri Lanka*.
- B. Nawarathna, L. Zubair, M. Bell, J. Del Corral., J. Chandimala, (2008) Calibration of Satellite Rainfall Estimates for Sri Lanka.
- Chandimala, J. and L. Zubair, (2008) Topography based interpolation of Surface Temperature.
- M. Bell, J. Del Corral, B. Blumenthal, B. E. Grover-Kopec, Nawarathna, J. Chandimala, S.J. Connor, N.Ward, L. Zubair, (2008) *Rainfall Monitoring for Malaria Early warning for Sri Lanka.*
- Zubair, L., M. Siriwardhana, H. Yang, J. Chandimala, Z. Yahiya, U. Tennakoon, S. Partridge, A. Giannini, S. J. Connor, (2008) *Spatial and Inter-Annual Variation of Malaria in Sri Lanka in relation to Climate.*
- L. Zubair, Heli Bulathsinhala, M. Siriwardhana, J. Chandimala, U. Tennakoon and Z. Yahiya, 2007, Climate Change Trends from Quality Evaluated Surface Temperature Data in Sri Lanka.

Peer Reviewed Conference Proceedings

- Chandimala and L. Zubair (2004), *Predictability of Streamflow and Rainfall in the Kelani river basin in Sri Lanka using ENSO*, International Conference on Sustainable Water Resources Management in the Changing Environment of the Monsoon Region, United Nations University, Colombo, Sri Lanka.
- L. Zubair (2004c) Downscaling of Sri Lanka's Maha Rainfall from a GCM and Indian Ocean Dipole and ENSO influences, International Conference on Sustainable Water Resources Management in the Changing Environment of the Monsoon Region, United Nations University, Colombo, Sri Lanka.
- L. Zubair, U. Tennakoon and M. Siriwardhana (2004d), Climate Change Assessments for Sri Lanka from Quality Evaluated Data, International Conference on Sustainable Water Resources Management in the Changing Environment of the Monsoon Region, United Nations University, Colombo, Sri Lanka.

Reports

- July 2007: Joseph Simonson, REU report to the National Science Foundation, Analysis of the Impacts of Rainfall and Mean Temperature on Malaria Morbidity in Southeastern Sri Lanka, Supervisor, L. Zubair.
- Jun 2006: M. Siriwardhana, H. Yang, U. Tennakoon, and L. Zubair, Monthly maps of average malaria incidence in Sri Lanka by district.
- Jun 2006: U. Tennakoon, M. Siriwardhana, Z. Yahiya, Yoosuf Ashraj, Siraj Razick, H.M. Faizal and L. Zubair, *Spatial Atlas of Malaria Incidence in the Uva Province*.
- May 2006: Stacey Hirsh, Vidhura Ralapanawe, J. Chandimala and L. Zubair, *Characterization of Climate Influences on NDVI over Sri Lanka*.
- Nov 2005: J. Chandimala and L. Zubair, Land surface model implementation for a catchment in the Uva.
- January 2004: Zeenasy Yahiya and L. Zubair (2004), *Climate and Malaria Project Initiation Workshop Report*, Foundation for Environment, Climate and Technology, Digana Vilalge.

Dissemination

This work was disseminated through conferences, meetings and workshops in Sri Lanka, the US, Kenya and Maldives. The posters that have been presented are assembled into the appendix of this report. We also disseminated the content via two workshops at the International Water Management Institute and the University of Peradeniya. Other disseminations events are listed below.

Conference Proceedings and Abstracts

- December 2006: Chandimala J., Hirsh S., Ralapanawa V., Zubair L., Vegetation Mapping and its Application in Drought Disaster Identification. *International Conference on Humid Tropical Ecosystems: Changes, Challenges, Opportunities*, UNESCO and Sri Lanka National Science Foundation. Kandy, 4th-9th December, Kandy, Sri Lanka
- August 2006: Topographically informed interpolation of temperature in Sri Lanka, J. Chandimala, U. Tennakoon, M. Siriwardhana, L. Zubair, *Third Annual Sessions of the GIS society of Sri Lanka*, Central Environment Authority, Battaramulla, Sri Lanka.
- February 2006: L. Zubair, Using Climate Information for River Basin Management in Sri Lanka, *Invited Presentation*, *Annual Meeting of the American Meteorological Society*, Atlanta, February 2, 2006.
- July 2005: L. Zubair, Climate Risk Management: Case Studies in Public Health, Natural Disasters and Renewable Energy, *Biennial Conference of the Association of Environmental Engineering and Science Professors*, Clarkson University, Potsdam, New York, July 23-27.
- June 2006, Chandimala J., Siriwardhana, M., and Zubair L., Topographically informed high resolution temperature estimates for Sri Lanka, *Sri Lanka Association for Advancement of Science, 62nd annual sessions*, 2006 (under review)
- June 2006, Siriwardhana M, Chandimala J, Zubair L., ENSO influences on mean temperature of Sri Lanka, *Sri Lanka Association for Advancement of Science, 62nd annual sessions*, 2006 (under review)

- March 2006: L. Zubair, Progress in Developing a Climate based Malaria Early Warning System in Sri Lanka, *Climate Predictions and Applications Sciences Workshop*, Tucson, Arizona, 21-24 March 2006.
- November 2005: Neil Ward, James Hansen, Sankar Arumugam, Dan Osgood, L. Zubair, Casey Brown, Ashok Mishra, Decision System Research and Tool Development at the IRI, *U.S. Climate Change Science Program Workshop*, "Climate Science in Support of Decisionmaking," Arlington, Virginia. November 14-16, 2005.
- L. Zubair, J. Qian, N. Ward, O. Ndiaye, J. Chandimala, R.Perera, V. Ralapanawe and B. Blumenthal (2004b), Complementary Dynamical and Statistical Downscaling from a GCM: Maha rainfall over Sri Lanka, Annual Meeting of the American Geophysical Union, San Francisco.

Presentations

This listing does not include the project conclusion and training workshop which are documented in the appendix.

- March 2007: Sarith Mahanama, L. Zubair, J. Chandimala, Soil Moisture Memory and Predictability of Seasonal Streamflow in Sri Lanka, *International Conference on Mitigation Of The Risk Of Natural Hazards*, University of Peradeniya, Sri Lanka, March 27, 2007.
- March 2007: L. Zubair, Fine-scale hydro-climatic information for malaria epidemic prediction", *Greater Horn Of African Climate Outlook Forum and Malaria Outlook Forum*, Nairobi, Kenya. March 5-10, 2007.
- February 2007: L. Zubair, Developing a Suite of Climate Information for Applications in Sri Lanka, Invited Lecture Earth System Science Interdisciplinary Center (ESSIC), University of Maryland, College Park, Maryland. February 16, 2007.
- December 2006: L. Zubair, Sarith Mahanama, J. Chandimala and Neil Ward, *Hydro-climatological Simulation over Sri Lanka Using Global Reanalyses,* American Geophysical Union Annual Conference, San Francisco. Poster
- June 2006: L. Zubair, Progress in Developing a Climate based Malaria Early Warning System in Sri Lanka, *Foundation for Environment, Climate and Technology*, Kandy, Sri Lanka, 1 June 2006.
- January 2006: L. Zubair, Advances in Climate for River Basin Management, *Mahaweli Authority of Sri Lanka*, Headworks Adminstration and Operations Management Division, Digana, Sri Lanka, January 4, 2006.
- November 2005: L. Zubair, Predictability of Climate around Sri Lanka and its Applications, *Global Modeling and Assimilation Office, National Aeronautical and Space Agency*, Maryland.

Posters

The majority of the posters that were prepared by FECT and IRI are listed below and included as a supplement to this report. They are categorized following the methodology section as:

Malaria and Dengue Incidence

- Climate and Health : Malaria and Dengue in Sri Lanka
- Annual and Monthly Average Distribution of Malaria in Sri Lanka
- Dengue Incidence in Sri Lanka
- Annual and Monthly Malaria (Pv) Incidence at MOH Scale in Sri Lanka

Climatology

- Rainfall Climatology of Sri Lanka
- Temperature Climatology of Sri Lanka
- Climate Calendar of Sri Lanka

Climate Monitoring

- Rainfall Monitoring for Early Warning for *Uva* Province and Sri Lanka
- Validation of Satellite Rainfall Estimates over Sri Lanka

Climate Predictions

- IRI Seasonal Climate Forecasts for Sri Lanka
- High Resolution Climate Prediction for Sri Lanka
- High Resolution Dynamical Downscaling for Sri Lanka

Hydrological Modeling

- Predictability of Stream flow in Sri Lanka using Global Climate Information

Vulnerability to Malaria

- Vulnerability to Malaria in *Badulla* District, *Uva* Province in Sri Lanka

Climate and Malaria Relationships

- Analysis of Association of El Nino and Malaria Epidemics in Sri Lanka
- Analysis of the Impacts of Rainfall and Mean Temperature on Malaria Morbidity in Southeastern Sri Lanka.

14. Outcomes

Here is a comparison of the outputs from the project as opposed to what we have accomplished:

Extract from the Project Proposal:

The specific outcomes expected from this project:

1. A methodology to convey the modulation of disease transmission by climate variability.
2. An understanding of the historical relationships between malaria transmission, meteorological and environmental factors in Sri Lanka.
3. A detailed understanding of the interaction between climate variability and malaria transmission in the *Uva* Province of Sri Lanka.
4. An evaluation of the use of a hydrological model based on digital elevation maps and meteorological data to forecast hydrological parameters of epidemiological significance in a tropical setting.
5. A methodology to forecast disease epidemics a season in advance spatially, using climate predictions, remotely sensed environmental data and spatial analytic techniques.
6. An archive of climatic, hydrological, entomological, epidemiological data and tailored climate forecasts for a specific location at a high resolution.
7. An evaluation of the skill of malaria risk mapping technology and the identification of the measures needed to improve its skill.
8. An evaluation of the effectiveness of risk-maps in malaria control planning.
9. An economic analysis of the various costs associated with malaria incidence, household costs and disease-control costs and the costs of incorporating climate variability information into malaria risk maps.
10. Documentation on the incorporation of climate variability into malaria risk mapping technology.
11. Dissemination of these results to other areas of low to moderate endemicity.
12. Establishment of a working relationship and exchange of scientific products between IWMI and the IRI.

Delivery compared with Expected Outcomes:

All of the above outcomes have been delivered in large measure. The outcomes related to items 1-6 have been documented in this report. The outcomes related to Items 7-9 are being reported exclusively in the report from IWMI. While many outcomes related to Items 10-12 are being reported here, residual work shall continue, particularly turning reports into publications.

15. References

Note: Additional References cited under section 13 on Publications.

Bouma MJ and Van der Kaay HJ (1996) The El Niño Southern Oscillation and the historic malaria epidemics on the Indian subcontinent and Sri Lanka: an early warning system for future epidemics? *Tropical Medicine and International Health.* **1**, 86-96.

Briercliffe R (1935). The Ceylon Malaria epidemic, 1933. *Report by the Director of Sanitary Services.* Sessional Paper XXII,-1935, Ceylon Government Press.

Gill CA (1936). Some points in the epidemiology of malaria arising out of the study of the malaria epidemics in Ceylon in 1934-35. *Transactions of the Royal Society of Tropical Medicine and Hygiene XXIX* : 427-466.

Ministry of Health (2001), A Five Year strategic plan for Roll Back Malaria in Sri Lanka, 2001-2005, Ministry of Health, Colombo, Sri Lanka, 138

Visvalingam T. (1961) A review of the problem and control of malaria in Ceylon, *Journal of the Ceylon Public Health Association* **2**, 43-99.

Foundation for Environment, Climate and Technology,
C/o Maintenance Office, Mahaweli Authority of Sri Lanka,
Digana Village, Rajawella, Sri Lanka
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