Environmental factors and population dynamics as determinants of meningococcal meningitis epidemics in the Sahel: an investigation of NASA and NOAA products

**NASA-Roses: 1 Yr Feasibility Study**
**Sept 1, 2009 - Aug 31, 2010, no cost extension till April 30, 2011**

**IRI:** S. Trzaska (PI), M. Thomson, M. Madajewicz, T. Dinku, P. Ceccato, L. Cibrelus,

**CIESIN:** S. Adamo (Co-PI), M. Levy, G. Yetman, SA

**GISS:** J. Perlwitz, R. Miller

**JPL:** O. Kalashnikova

**Collaborators:** C. Perez (EI, IRI, GISS), J. del Corral (IRI), M. Bell (IRI), P. Diggle (U. Lancaster, UK), M. Stanton (U. Lancaster, UK)

NASA Public Health Program Review, Sept 14-16, 2011, Santa Fe, NM
Meningococcal Meningitis – a few facts

- Bacterial meningitis
- Human to human transmitted
- High rate of asymptomatic carriers (10-20% of general population)

Pathogenesis
- Respiratory acquisition
- Colonization of the nasopharynx
- Penetration the respiratory mucosa and entrance into the bloodstream

- If untreated fatality rates > 50%, and 10% despite treatment
- 10-20% of survivors develop severe neurological sequelae
Meningococcal Meningitis – a few facts

- Highest prevalence in Subsaharan Africa => Meningitis belt
- Highly seasonal
- Identified since 1963 (Lapeyssonie, 1963)
- Population at risk each year >450 million, 25 countries
- Largest recorded outbreak, in 1996: 250,000 cases, approx. 25,000 deaths and at least 50,000 persons suffered permanent disability
- The burden is estimated to be more than $11 million/year in diagnostic, tests and case treatment costs.
- Additional burden at the household level in Burkina Faso: $90/case – 34% annual GDP/capita – and up to $154 more when permanent disability occurred.

Yet, no efficient preventive treatment exist.
Control Strategies

- **Current control**: reactive vaccination, polysaccharide vaccine

- **Future control**
  - Preventive vaccination Men A conjugate vaccine
  - Reactive vaccination for other strains and/or in places where MenA not implemented

**CHALLENGES:**
- Timely vaccination to optimize the control of the epidemics
- Vaccination campaign 2-3 weeks after alert threshold

<table>
<thead>
<tr>
<th>Incidence cases / 100 000 pop./wk</th>
<th>Number of Cases</th>
<th>Number of Cases</th>
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<tr>
<td>wk1</td>
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<td>wk20</td>
<td>0</td>
<td>160</td>
</tr>
</tbody>
</table>

NASA Public Health Program Review, Sept 14-16, 2011, Santa Fe, NM
Proposed MenA conjugate vaccine introduction

Need for improved risk assessment for next 10 years

2009/10  2012  2011  > 2013

KEY
- Meningitis belt country
- Hyperendemic country
- Non-meningitis belt country

Country Name
2009 Population

Meningitis Vaccine Project
Stake-holders and decisions

- WHO – Global Alert and Response
  National Public Health Ministries and Services
  Meningitis Vaccine Project
  **MERIT**

- Decisions:
  - Short term, within season (2-3 weeks): which district to vaccinate
    ➔ to reduce operational delays, to decide whether vaccinate (UCAR)
  - Seasonal, before the season: how bad is the season going to be
    ➔ enhance surveillance, capacity building
  - Annual
    ➔ vaccine production, stockpile (ICG)
  - Decadal
    ➔ changes in Meningitis Belt

*Changes in the areas of MM epidemics risk in Africa between 1950-79 and 1980-1999 periods, Cuevas et al. 2007*
Hypothetical decision tree adding an “alert+” action threshold

- Routine Surveillance
  - < alert: Surveillance
  - ≥ alert < epidemic: Network epidemic?
    - YES: Vaccinate
    - NO: Susceptible population?
      - YES: Vaccinate
      - NO: Timing?
        - YES: Vaccinate
        - NO: Event?
          - YES: Vaccinate
          - NO: Surveillance

Courtesy S. Hugonnet (WHO) and R. Novak (CDC)
Specificity/timeliness trade-off (REQUIRES 5/100,000 IN DISTRICT):

*include neighboring districts in epidemic*

<table>
<thead>
<tr>
<th>Neighbors in epidemic cutpoint for action</th>
<th>Specificity</th>
<th>Lower CL for specificity</th>
<th>Upper CL for specificity</th>
<th>Mean improvement in timeliness (weeks)</th>
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<tr>
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<tr>
<td>10</td>
<td>100</td>
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<td>0</td>
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<tr>
<td>Ignore neighbors</td>
<td>100</td>
<td>0.9951</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

Courtesy S. Hugonnet (WHO) and R. Novak (CDC)
Causes of meningitis epidemics still poorly understood

- Known Risk Factors

  - Individual and population risk factors
    - Age-related acquisition of bactericidal antibodies
    - Underlying immune defects (i.e., asplenia, genetics)
    - Crowding
    - Smoke exposure
    - Upper respiratory tract infections

  - Climatic conditions (dry season)
    - Excessively dry & hot season
    - Dust storms

  - Immunological susceptibility
    - Introduction of a novel, virulent strain
    - Waning herd immunity
    - Large population movements

Courtesy CDC

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IMPACT OF THE ENVIRONMENT

- On the pathway of infection
- Indirect

1. Enhancing bacterial survival via iron content of dust
2. High dust levels affecting human behaviour, including crowding and reduced ventilation (e.g. blocking windows)
3. (More controversially) serving as carriers for bacteria

Pharyngeal carrier

Respiratory droplets (meningococci) → Survival of meningococci in droplets

Susceptible host → Damage to mucosa facilitating colonisation

Pharyngeal carrier → Damage to mucosa facilitating invasion

Case → Influence on the immune response

Courtesy Brian Greenwood
Climate features in the Meningitis Belt/Sahel

Schematic meridional cross section of atmospheric circulations over West Africa. (*Haywood et al., 2008*).
Project Objectives

Statistical model, forecasting the likelihood of epidemic threshold to be crossed (or not) at a given district at different time leads (before, at the beginning and during the season)

Using environmental and demographic predictors

- Detect the optimal combination of predictors at different time lags
- Evaluate model’s skill (capacity to predict past epidemics and their timing)
- Demonstrate that different decision can be made based on the available forecasts

- Meningitis data for Niger: weekly district level, 1086-May 2008, QC
Using multiple source information information for predicting meningitis risk

**Environmental factors**
- Dust (concentration, particle size...) from in-situ observation, Satellite (MISR), Models (global and regional) and dust forecasts
- Weather and Climate Conditions - wind, humidity, temperature, rainfall - in situ (Met Station), Satellite (TRMM), NCEP Reanalysis
- Seasonal forecasts (ECHAM4.5)

**Epidemiological state of the population at the district level based on:**
- Past history of epidemics
- Past history of immunization
- Migration paths
- Seasonality

**Population factors:**
- Population density
- Population stratification: gender, Age, Rural-urban
- Mobility

**Generalized Linear Model to predict crossing alert/epidemic threshold**
- For each district and at country level
- At different lead-times: seasonal, monthly, 2 weeks and simultaneous
- Probability based on historical model performance

**Skill assessment**

**Outputs**
- Build GIS based predictive tool using models and predictors selected in the project to provide risk maps at district and country level at different lead-times

→ Extract relevant climate information

**Related research**
- Quantify the relationship dust-meningitis
- Quantify the relationships between atmospheric conditions (wind, temperature, humidity...) and meningitis
- Validate dust products
- Validate seasonal forecast models
- Assess the usefulness of satellite and model data for predictive purposes
- Investigate a range of statistical models, predictors and lead-times and select most appropriate
Project participants and their responsibilities

IRI:
- analysis of relationships between atmospheric conditions & dust and meningitis, analysis of their predictability; construction and evaluation of the model - S. Trzaska, L. Cibrelus;
- advisory role on the use of satellite data - P. Ceccato, T. Dinku;
- advisory role on links between environmental conditions and meningitis and on general statistical model - M. Thomson;
- advisory role on the evaluation of decision improvement processes - M. Madajewicz

CIESIN:
- population mapping by age structure, urban/rural distribution, population mobility, georeferenced datasets, construction of predictive model - S. Adamo, G. Yetman);
- advisory role on data integration and model construction – M. Levy;

GISS:
- aerosols simulation – J. Perlwitz
- advisory role on validation and interpretation of model results – R. Miller

JPL:
- MISR data and related technical expertise - O. Kalashnikova
Where we are now...

- Important effort of data collection, archiving & tool development
- Dust products validation & assessment of relevance for meningitis prediction
- Assessment of predictability of meningitis based on environmental and epidemiological information
- Analysis of spatial characteristics of meningitis outbreaks
Data Collected

Epi
• Meningitis data in Niger, weekly, district, 1986-May 2008
• Weekly alert/epi status & weekly case number at country level for the belt 2002-present, from WHO Weekly Epidemiological Reports

Pop
• CIESIN Gridded Population data (GRUMP/SEDAC)
  • pop density
  • urban /rural
  • age structure
• Literature review of migration patterns and data; some data gathered

Dust
• Aeronet data from 16 stations across Africa N of equator
• Visibility data from Niamey
• MISR Aerosol data
• TOMMS OMI
• Outputs from model simulation of mineral dust (regional and global)

Climate
• Temperature, wind data from NCEP reanalysis
• TRMM rainfall estimates
• IRI Seasonal Forecast Outputs
Climate and Meningitis in Africa

Epidemics of meningitis occur worldwide. The “meningitis belt” in the Sahel region of Africa experiences the greatest incidence of the disease. Epidemics occur throughout the “belt” in annual cycles and coincide with periods of very low humidity and dusty conditions and disappear at the onset of the rainy season, suggesting that these environmental factors may play an important role in the disease.

Datasets and variables

- Aerosol Measurements at Banizoumbou
- CESM
- GISS
- GISS, ACERON
- GLDAS
- Global Dust
- Men_Niger (restricted)

Documents

- Overview an outline showing subset datasets of this dataset

Descriptions and relevant bibliography on project accessible portal
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<th>Variable category</th>
<th>Variable name</th>
<th>Source of the data</th>
<th>Origin of the data</th>
<th>Type of variable</th>
<th>Computation of the variable</th>
<th>Time resolution</th>
<th>Spatial resolution</th>
<th>Time coverage</th>
<th>Spatial coverage</th>
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<td>Incidence of</td>
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<td>WHO routine surveillance</td>
<td>Count</td>
<td>Derived from the number of meningitis cases</td>
<td>Week</td>
<td>District</td>
<td>Dec 1985 - May 2008</td>
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<td>District</td>
<td>Dec 1985 - May 2008</td>
<td>All districts, Niger</td>
<td></td>
</tr>
</tbody>
</table>

| | Satellite | MISR, NASA | Continuous | Daily | 0.25x0.25 | Apr 2000-Apr 2009 | Africa north of the Equator Longitude: [74.875W, 64.875E]; Latitude: [0.125N, 34.875N] |
| | AOD\(\text{\textsuperscript{440}}\), AOT\(\text{\textsuperscript{10}}\) | Satellite | AERONET, NASA | Continuous | Daily | Single point | Oct 1995-June 2009 | Banizoumbou, Niger |
| | Satellite | MISR, NASA | Continuous | Daily | 0.25x0.25 | Apr 2000-Apr 2009 | Longitud: [74.875W, 64.875E]; Latitude: [0.125N, 34.875N] |
| | Dust fraction: Total, large, medium, small | Satellite | MISR, NASA | Continuous | Daily | 0.25x0.25 | Apr 2000-Apr 2009 | Longitude: [74.875W, 64.875E]; Latitude: [0.125N, 34.875N] |
| | Dust surface concentration | Model | Mineral Dust aerosol model GISS, NASA: Global Climate Model E | Continuous | Hourly and Monthly | Horizontal: 144x90 grid cells (2.5°x2°) Vertical: Total over troposphere | 1984-2009 | Global |
| Climate | Visibility | Ground | Met Station | Continuous | Daily | Single point | 1995-2009 | Niamey, Niger |
| Wind | Wind speed | Model | Seasonal forecast | Continuous | Daily and monthly | Vertical: near surface (2m, 10m) and Plevels (925, 950, 850 etc) Horizontal: ECHAM 4.5 T42: 2.5°x2.5° | 1948-present (last week for daily, last month for monthly) |
| | Model | NCEP/NCAR Reanalysis | Continuous | Daily and monthly | Vertical: 1 “diagnostic” or “near-surface” (also “top”) variables: one level, specified (surface, 2m, 10m etc) 2 “intrinsic” variables: across the atmospheric depth, on specified Pressure levels (950hPa, 500hPa, sea level pressure) or total atmospheric column Horizontal: 1 diagnostic “ variables : 1.875° (long)x2.5° (lat), 2 “intrinsic” variables 2.5°x2.5° | 1948-present (last week for daily, last month for monthly) |
| | Wind direction | Model | Seasonal forecast | Categorical | Daily and monthly | Vertical: near surface (2m, 10m) and Plevels (925, 950, 850 etc) Horizontal: ECHAM 4.5 T42: 2.5°x2.5° | 1948-present (last week for daily, last month for monthly) |
| | Model | NCEP/NCAR Reanalysis | Categorical | Daily and monthly | Vertical: 1 “diagnostic” or “near-surface” (also “top”) variables: one level, specified (surface, 2m, 10m etc) 2 “intrinsic” variables: across the atmospheric depth, on specified Pressure levels (950hPa, 500hPa, sea level pressure) or total atmospheric column Horizontal: 1 diagnostic “ variables : 1.875° (long)x2.5° (lat), 2 “intrinsic” variables 2.5°x2.5° | 1948-present (last week for daily, last month for monthly) |
| Humidity | Dew point | Ground | Met Station | Continuous | (unitless) ordered (1.) to (137231.) | Single point | (unitless) ordered (1.) to (137231.) | Niamey, Niger |
Some issues/solutions

Spatial scale
• Extract information at district level
• Specific tool in IRI Data Library

Time resolution
• Weeks: Monday to Sunday
• Calendar done for 1986-2008
• DL extracts weekly averages according to this calendar

<table>
<thead>
<tr>
<th>Year</th>
<th>Starting Week</th>
<th>Ending Week</th>
<th>Number of Weeks</th>
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<td>01/02/88</td>
<td>52</td>
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</table>
Some issues (cont.)

Pop Data

Population

Graphs by District

S. Adamo
Dust products validation & assessment of relevance for meningitis prediction

- MISR (2000-2009)
- TOMMS-OMI (1997-2008)
- Regional model (NMMB/BSC-Dust, 1979-2008)
- Global model (NASA GISS ModelE, 1979-2008)
Dust - time series validation

Synthesis of linear correlation analysis
of daily data from different sources for 16 AERONET locations

Linear correlation coefficient

Pairs of time series

non-significant correlation
significant correlation (p=0.05)
significant correlation median
Seasonal cycles (weekly, national)
Assessment of predictability of meningitis based on environmental and epidemiological information

- Seasonal & weekly scale
- National & district scale
Annual attack rates in Niger

NATIONAL SCALE

Log (incidence JAN-MARCH) ~ Log (early season Climate)

\[ R^2 = 0.35, \text{ RMSE}=0.77, \]
\[ CV \ R^2=0.2, \text{ CV RMSE}=0.87 \]

DISTRICT SCALE

Log (incidence JAN-MARCH) ~ Humidity (DEC)

Log (incidence JAN-MARCH) ~ Min Surface Temperature (FEB)

with M. Stanton (U. Lancaster)
Weeklly incidence in Niger

MODELS
- three types of models were fitted to the data:
  - a linear model
  - a model with a fixed seasonal cycle
  - a dynamic linear model, with a varying season cycle
- several forms of the climate variables:
  - single week lagged climate anomalies
  - lagged climate anomalies averaged over the previous four weeks to account for the cumulative affects of climate on the disease
  - the information about incidence levels in previous weeks

RESULTS
- national scale
  - several climate variables with significant correlation but none stood out
  - best results obtained when previous week(s) incidence included
  - only small improvement when adding climate variables
- district level
  - Similar conclusions to national scale
- dynamic linear model yielded similar results as the model with fixed seasonal cycle

with M. Stanton (U. Lancaster)
Analysis of spatial characteristics of epidemic outbreaks in Niger
Spatial distribution of recorded epidemics

- Highest epidemic numbers along southern border
- Approx southward gradient
- Other variables show similar structures
Stepwise multiple linear regression

Different combinations of potential predictors at district level

- Population and geography:
  Pop=\[\log_{10}(\text{pop density}), \log_{10}(\text{pop}), \text{percentage urban}, \text{latitude(centroid)}, \text{longitude(centroid)}\]

- Annual means of climate variables:
  Clim_ann=\[\text{meanU}_\text{ann}, \text{meanV}_\text{ann}, \text{meanT}_\text{ann}, \text{mean SpecHum}_\text{ann}\]

- Dry season means of climate variables (Jan-Apr):
  Clim_dry=\[\text{meanU}_d, \text{meanV}_d, \text{meanT}_d, \text{mean SpecHum}_d\]

- Wet season means of climate variables (Jul_Sept):
  Clim_wet=\[\text{meanU}_w, \text{meanV}_w, \text{meanT}_w, \text{mean SpecHum}_w\]

- Combinations:
  Pop & Annual, Dry, Wet means
  All
Crossvalidated multiple linear regression

Nbr_epid = f(Twet, log10(pop), Vdry, Udry)

- Extend this analysis to Burkina Faso & Mali and the whole belt
- Include mobility indicators (incl. road network)
- Investigate spatial characteristics of the epidemic onset (first district) & relationships with demographic/geographic characteristics (incl. migration patterns and roads)
## Meningitis thresholds in Niger

<table>
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<tr>
<th>Epid threshold</th>
<th>Alert+ epid</th>
<th>Epid +no non epid</th>
</tr>
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<tbody>
<tr>
<td>Nbr yr.distr inc&gt;10 epid</td>
<td>223</td>
<td>363</td>
</tr>
<tr>
<td>Nbr yr.distr 5&lt;inc&lt;10 alert, no epid</td>
<td>140</td>
<td>835</td>
</tr>
<tr>
<td>Nbr yr.distr inc&lt;10 all non epid</td>
<td>612</td>
<td>X</td>
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<tr>
<td>Nbr yr.distr inc&gt;15 epid</td>
<td>149</td>
<td>363</td>
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<tr>
<td>Nbr yr.distr 5&lt;inc&lt;15 alert, no epid</td>
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<td>835</td>
</tr>
<tr>
<td>Nbr yr.distr inc&lt;15 all non epid</td>
<td>686</td>
<td>X</td>
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</table>

- Approx. 61% (41%) of yr.distr that cross alert threshold, cross the epidemic threshold=10 (15 resp.)
- Approx. 20% (30%) of yr.distr that do not reach the epidemic threshold=10 (resp.15) cross the threshold=5 cases/100,000
- The spatial differentiation is less sharp when the threshold=15 is used, as if the higher threshold was crossed less frequently in the South, with no impact of the threshold in the other regions.
Using multiple source information information for predicting meningitis risk

Environmental factors
- Dust (concentration, particle size...) from in-situ observation, Satellite (MISR), Models (global and regional) and dust forecasts
- Weather and Climate Conditions - wind, humidity, temperature, rainfall - in situ (Met Station), Satellite (TRMM), NCEP Reanalysis
- Seasonal forecasts (ECHAM4.5)

Epidemiological state of the population at the district level based on:
- Past history of epidemics
- Past history of immunization
- Migration paths
- Seasonality

Population factors:
- Population density
- Population stratification: gender, Age, Rural-urban
- Mobility

Generalized Linear Model to predict crossing alert/epidemic threshold
- For each district and at country level
- At different lead-times: seasonal, monthly, 2 weeks and simultaneous
- Probability based on historical model performance

Skill assessment

GIS based maps to display the probability of alert/epidemic threshold
- For each district and at country level
- At different lead-times

Outputs
- Build GIS based predictive tool using models and predictors selected in the project to provide risk maps at district and country level at different lead-times

Extract relevant climate information ✔

Related research
- Quantify the relationship dust-meningitis ✔
- Quantify the relationships between atmospheric conditions (wind, temperature, humidity...) and meningitis ✔
- Validate dust products ✔
- Validate seasonal forecast models ✗
- Assess the usefulness of satellite and model data for predictive purposes ✔
- Investigate a range of statistical models, predictors and lead-times and select most appropriate ✔

NASA Public Health Program Review, Sept 14-16, 2011, Santa Fe, NM
 Outputs

- Annotated Database & Tools, publicly available
  - original model simulations e.g. BSC regional reanalysis
  - U Lancaster

- Contribution to MERIT, link to WHO
  - evolution of project following this interaction

- Publications

Published:

Submitted

In preparation
5. S. Trzaska, 2012: ‘Intraseasonal characteristics of the dry season in the Sahel’
Publications (cont.)

Presentations


- S. Trzaska: 'End-to-end and interdisciplinary approach to climate research at the International Research Institute for Climate and Society: Investigating the role of climate in epidemic outbreaks of Meningococcal Meningitis in the Sahel.', seminar at the Addis Ababa University, Dept of Physics, November 23, 2010.


- S. Trzaska 2010: ‘A pilot project to monitor dust in West Africa’ presentation ate the 2nd annual MenAfriCar consortium meeting, January 20-22nd 2010, Addis Ababa, Ethiopia;

Dust and Climate monitoring

Instruments installed Feb-March 2011
Meningitis Belt
Sites of dust and climate monitoring