An online mineral dust forecast model from meso to global scales: description, validation and applications

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GISS Lunch Seminar Series
October 20th, 2010

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- Motivation

- Model description

- Model validation

- An application: long term simulations in support of meningitis studies in Sub-Saharan Africa
Mineral dust interactions with meteorology and climate

Anthropogenic forcing?

climate

atmospheric dynamics & physics

surface wind & turbulence

Sources, Vegetation, Soil humidity, cohesion

dust emission

dust transport

Radiation

Cloud microphysics

Ocean fertilization

Snow/ice albedo modification

dust deposition

Human disturbances: e.g. agriculture
Dust transport is a global phenomenon. However, dust emission is a threshold phenomenon, sporadic and spatially heterogeneous, that is locally controlled on small spatial and temporal scales.
NMMb/BSC-Dust

GOALS

✓ Implement a common ‘on-line’ dust module for regional and global domains

✓ Global dust forecasts up to 7-8 days at sub-synoptic resolutions and nested regional domains at high resolution (5-10 km).

✓ Intermediate complexity dust emission scheme

✓ Include new high resolution databases for soil textures and vegetation fraction.

✓ Update deposition schemes

✓ Radiative feedbacks between dust and meteorology
NCEP Nonhydrostatic *Multiscale* Model on B grid (NMM-b) (Zavisa Janjic)

- Further evolution of WRF NMM (Nonhydrostatic Mesoscale Model)
- Intended for wide range of spatial and temporal scales, from meso to global, and from weather to climate
- The nonhydrostatic option as an add–on nonhydrostatic module
- Global lat-lon, regular grid; Regional rotated lat-lon
- Arakawa B grid (in contrast to the WRF-NMM E grid) and Pressure-sigma hybrid
NCEP Nonhydrostatic *Multiscale* Model on B grid (NMM-b) 
(Zavisa Janjic)

 nghiêm NCEP’s WRF NMM “standard” physical package (more options will be available)

- Mellor-Yamada-Janjic (MYJ) level 2.5 turbulence closure for the treatment of turbulence in the planetary boundary layer (PBL) and in the free atmosphere (Janjic, 2001)
- Surface layer scheme based on the Monin-Obukhov similarity theory (Monin and Obukhov, 1954) with introduced viscous sublayer over land and water (Zilitinkevich, 1965; Janjic, 1994)
- The NCEP NOAH land surface model (Ek et al., 2003) or the LISS model by Janjic
- The GFDL longwave and shortwave radiation (Fels and Schwarzkopf, 1975; Lacis and Hansen, 1974) UPGRADED
- Ferrier gridscale clouds and microphysics (Ferrier et al., 2002)

严禁 Recent upgrades

- New Eulerian tracer advection scheme (Janjic)
- Gravity wave drag (Janjic)
- RRTM radiation with aerosols (implemented by C. Perez)

严禁 Regional version planned to replace the WRF NMM as the NOAA/NCEP regional operational forecasting model for North America (NAM) this year
dust sources

Based on USGS-wrf vegetation/surface type

19: Barren or sparsely vegetated (1)
8: Shrubland (0.3)

P: probability to have accumulated sediments in the grid (Ginoux et al., 2001)

Best fit with the sources identified by Prospero et al. 2000

\[ P = \left( \frac{Z_{\text{max}} - Z_{i}}{Z_{\text{max}} - Z_{\text{min}}} \right)^5 \]
Soil texture classes according STASGO-FAO 1km database are converted to 4 parent soil size classes. They are used to calculate *horizontal flux*.
Modes of particle motion

- Creep or rolling motion of the largest particles (> 500 um)
- Saltation or horizontal motion of large soil grains (sand) (50-500um)
- Suspension of dust (after sandblasting or saltation bombardment) (0.1-50 um)

Movie from the COMET program at http://meted.ucar.edu/ of the University Corporation for Atmospheric Research (UCAR)
dust emission I

H: Horizontal dust flux

\[ H = c_s \frac{\rho_a}{g} u^* \sum_{i=1}^{4} (1 + \frac{u_{t_i}^*}{u^*})\left(1 - \frac{u_{t_i}^{*2}}{u^*2}\right)s_i \quad \text{for } u^* > u_{t_i}^* \]

White (1979)

- \(c_s\): constant
- \(s_i\): relative surface area of each soil particle fraction
- \(\rho_a\): air density
- \(g\): gravitational constant
- \(u^*\): friction velocity
- \(u_{t_i}^*\): threshold friction velocity

\[ u_{t_i}^* = u_{tsd}^*(D) \frac{f_h}{f_e} \]

Iversen and White (1982)

- \(f_e\): Drag partition correction
- \(f_h\): Soil moisture effects.

Marticorena and Bergametti (1995)

Fecan et al. (1999)
**dust emission II**

<table>
<thead>
<tr>
<th>Symbol/Expression</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F$</td>
<td>Vertical dust flux</td>
</tr>
<tr>
<td>$F = \alpha H$</td>
<td></td>
</tr>
<tr>
<td>$\alpha = \sum_{i=1}^{4} m_i \alpha_i$</td>
<td>Vertical to horizontal flux ratio (Tegen et al. 2002)</td>
</tr>
<tr>
<td>$F_k = \sum_{i=1}^{3} F_i M_{i,j}$</td>
<td>We assume tri-modal size distribution of emitted dust in source regions (D’Almeida, 1987)</td>
</tr>
<tr>
<td>$F_k = CS(1-V)\alpha H \sum_{i=1}^{3} M_i M_{i,k}$</td>
<td>Emitted dust in 3 source modes is distributed over 8 size transport bins (Zender et al., 2003)</td>
</tr>
</tbody>
</table>

- **C**: Tuning parameter
- **S**: Preferential source probability
- **V**: Vegetation fraction
- **$\alpha$**: Vertical to horizontal flux ratio
Advection and diffusion

- Eulerian advection; conservative, positive definite, monotone
  - Crank-Nicholson for vertical advection
  - Modified Adams-Bashforth for horizontal advection

- Vertical diffusion in the PBL and in the free atmosphere is handled by the NMMb surface layer scheme and by the boundary layer parameterization scheme (Janjic 1996a, 1996b, 2002a, 2002b)

- The lateral diffusion is formulated following the Smagorinsky’s non-linear approach (Janjic, 1990).
Sedimentation and dry deposition

• Terminal velocity of aerosol:

\[ v_{gk} = \frac{d_k^2 g (\rho_k - \rho_a) C_c}{18 \nu} \]

  - k: aerosol size bin number
  - dk: aerosol diameter
  - \( \rho_k \): aerosol density
  - \( \rho \): density of air
  - g: gravitational constant
  - \( \nu \): dynamic viscosity of air
  - Cc: Cunningham correction factor

• Dry deposition velocity (Zhang et al. 2001):

\[ v_{dk} = v_{gk} + \frac{1}{(R_a + R_s)} \]

\[ R_a = \frac{\Psi(\zeta_2) - \Psi(\zeta_1) + \varphi(0) \ln\left(\frac{z_1}{z_2}\right)}{\kappa u^*} \]

\[ R_s = \frac{1}{3u^*(E_B + E_{IM} + E_{IN})} \]

  - Aerodynamic resistance (z2 from viscous sublayer over land and ocean)
  - Surface resistance (brownian diff., impaction, interception)
Scavenging from grid scale clouds

- Grid scale clouds (NMMb incorporates Ferrier microphysics for grid scale clouds)

\[ F^w_k (L) = F^w_k (L - 1) (1 - \alpha_w f_{evp} (L)) + \Delta F^w_k (L) \]

- In-cloud and below cloud scavenging for rain
  - In cloud is proportional to auto conversion of cloud water to rain

\[ \Delta F^w_k |_{in} = \epsilon_k \left( f_{liq} \frac{P_{CR}}{QW} + f_{ice} \frac{P_{IR}}{QI} \right) M_k \]

  - Below cloud scavenging (Slinn, 1984) includes directional Interception, inertial Impaction and brownian diffusion

\[ \Delta F^w_k |_{sub} = \frac{cP_l E^l_k (d_k, D)}{D} M_k \]

- Below cloud scavenging for snow

\[ \Delta S_k |_{sub} = \frac{r P_s E^s_k (d_k, \lambda)}{D_m} M_k \]
Convective scavenging and mixing

- Convective clouds (NMMb incorporates BMJ convective adjustment for convective clouds)
  - deep convective clouds
    - Dust mixing follows the postconvective moisture redistribution.
      \[\Delta T = (T_{ref} - T^m) \frac{\Delta t}{\tau/F(E)}\]
      \[\Delta q = (q_{ref} - q^m) \frac{\Delta t}{\tau/F(E)}\]
    - In-cloud scavenging is proportional to the release of moisture from the cloud
      \[\Delta F_{kw}|_{in} = -\varepsilon_k \frac{DQ_{tot}}{Q_{tot}} M_k\]
    - Below cloud scavenging is performed following Slinn 1984 assuming a typical raindrop diameter for convective clouds.
  - shallow convective clouds (no precipitation)
    - Dust is mixed homogeneously within the cloud
Dust and Radiation

- RRTM with aerosol implemented. Aerosol climatologies are available.

- Map shows effects on NMMb incoming shortwave at the surface of aerosol climatology (sea-salt, om, bc and so4) and forecasted dust

Surface concentration of forecasted dust
AEROCOM Year 2000: surface concentration
AEROCOM Year 2000: optical depth
AEROCOM Year 2000: deposition
Regional simulation 0.25°x0.25° for 2006 vs AERONET AOD daily averages

Mediterranean
Regional simulation 0.25°x0.25° for 2006 vs AERONET AOD daily averages

**El_Arenosillo : AOD for 2006 - NMMb/BSC-Dust vs AERONET**

**Granada : AOD for 2006 - NMMb/BSC-Dust vs AERONET**

**Caceres : AOD for 2006 - NMMb/BSC-Dust vs AERONET**

Iberian Peninsula
Regional simulation 0.25°x0.25° for 2006 vs AERONET AOD daily averages

Eastern Sub-tropical Atlantic
Regional simulation 0.25°×0.25° for 2006 vs AERONET AOD daily averages

Blida: AOD for 2006 - NMMb/BSC-Dust vs AERONET

North Africa

Ilorin: AOD for 2006 - NMMb/BSC-Dust vs AERONET

Sahel

Namaey: AOD for 2006 - NMMb/BSC-Dust vs AERONET
Regional simulation 0.25°x0.25° for 2006 vs AERONET AOD daily averages

Middle East

Dhabi : AOD for 2006 - NMMb/BSC-Dust vs AERONET

Hamim : AOD for 2006 - NMMb/BSC-Dust vs AERONET

Solar_Village : AOD for 2006 - NMMb/BSC-Dust vs AERONET
An Ill Wind, Bringing Meningitis

An affordable, effective vaccine in the works could change that

OUAGADOUGOU, BURKINA FASO; RAMBO, MALI; GENEVA, SWITZERLAND—The dust is inescapable, buffeting your eyes, clogging your nose, penetrating into your lungs, and making breathing nigh-impossible. In March, on the road to Koumbanggan, some 109 km west of Ouagadougou, the landscape is moonscaped. In the creased bottom of a hollowed-out dust-cloud, eerily distinguishable from their surroundings, fashioned bricks from the mud. The bricks will dry quickly in the baking heat, which tops 40°C each day.

It is the dry season in Burkina Faso. And with the dust and the heat, dry wind, known as the harmattan, that blasts across the Sahara, come meningococcal meningitis epidemics, caused by the bacterium Neisseria meningitidis. What, exactly, about these conditions triggers the epidemics remains mysterious, but they conspire to spread the disease, hitting Burkina Faso every year and engulfing the entire "meningitis belt," which runs from Djibouti in the east to Senegal and The Gambia in the west, every 6 to 12 years.

The last big one, in 1996-97, sickened hundreds of thousands and killed more than 20,000 in 10 countries. In 2007, the death toll climbed alarmingly high again, prompting the World Health Organization (WHO) to warn that another huge epidemic was likely in 2008. But this season turned out to be relatively quiet, with some 940 cases in Burkina Faso and 27,000 across the entire belt. As always, the epidemics in Burkina Faso stopped suddenly with the first rains in May, as the population in this country, one of the poorest in the world, breathe for the inevitable onslaught next year.

Koumbanggan district officially passed the epidemic threshold in mid-March, and scarce supplies of the meningitis vaccine were made available to try to curb the epidemic's spread. At a rudimentary health center there, hundreds of people—mostly women and children—queue up for vaccinations, seeking shade by the buildings or under a scrawny tree. Most have been waiting patiently for hours, but some occasionally surge to the front of the line only to be pushed back by the men in charge of crowd control.

At best, the reactive vaccination strategy, as it is called, is a "Band-Aid," says Rosamund Lewis, a physician and meningitis expert at the GAVI Alliance (formerly the Global Alliance for Vaccines and Immunization). The reason is that the vaccine being used, a 1967s design using a polysaccharide from the bacterium's coat and still the only affordable one in Africa, doesn't work very well. Although this vaccine prevents those carrying the bacterium from getting sick, it doesn't stop them from passing it on to others; immunity lasts only a few years and the vaccine has minimal effect on children under age 2. Because of these limitations, WHO has long recommended that it be used only to control epidemics, not to prevent them—"a strategy that has its critics. "The epidemic is sometimes over by the time vaccine arrives," concedes William Perez, a Colombian-born epidemiologist who heads Epidemic Readiness and Interventions at WHO and who nonetheless supports the strategy for lack of a cost-effective alternative.

F. Marc LeFèvre wants to change that. He is heading an innovative public-private partnership known as the Meningitis Vaccine...
Meningococcal meningitis key facts

- Bacterial form of meningitis, a serious infection of the thin lining that surrounds the brain and spinal cord
- Direct transmission, person to person, respiratory droplets
- 12 serogroups. 4 in Africa: A, C, W135, X
- Highest rates of the disease in the so-called “meningitis belt” in sub-Saharan Africa stretches from Senegal in the west to Ethiopia in the east (80 % of the global burden)
- 21 countries and 300 million people at risk
- 700 000 cases in the past 10 years, 10-50 % fatality rates, 10-20 % of survivors suffer permanent brain damage
- Meningococcal polysaccharide vaccines are available for reactive vaccination
- A new meningococcal conjugate A vaccine developed specifically for Africa should be available by the end of 2010
Climate and dust

Seasonality of MM outbreaks related to climate dynamics in the region

Sultan et al.
Risk factors for meningitis outbreaks in sub-saharan Africa

**Climate**
- humidity
- dust
- wind speed
- temperature
- rainfall
- ....

**Health factors**
- number of years since last meningitis outbreak
- on-going outbreak in a neighboring district
- vaccine coverage
- number of years since last immunization campaign
- type of circulating serogroup
- ....

**Social and demographic**
- population density
- proportion of children under 15 years old
- main religious celebrations
- transhumance season
- ....
Temporal and spatial scales

Decadal/regional scale

- Could climate variability at these scales explain past meningitis large scale waves (8-12 years)?
- What will happen on the coming decades?

Interannual/sub-regional scale

- Prediction 1 year ahead for vaccine production planning?
- Seasonal forecasts are available but skills for the dry season must be assessed

Operational/district scale

- Adding climate criteria in the reactive vaccination decision process at the district scale?
Reactive vaccination

- Polysaccharide vaccines
- Poorly immunogenic in children < 2yr
- Immunity short lived
- Does not protect from carriage
- Routine immunization not feasible in the Belt
- Limited supply, affordability

**CHALLENGE:**

Timely vaccination to optimize the control of the epidemics
Dust & Meningitis: hypothesis

Possible mechanisms by which the dust could influence the development of the disease

1. Irritation and disruption of the epithelial lining of the upper respiratory tract, allowing bacterial penetration

2. Enhancing bacterial survival via iron content of dust

3. High dust levels affecting human behaviour, including crowding and reduced ventilation (e.g. blocking windows)

4. (More controversially) serving as carriers for bacteria

People caught in a dust storm in Mali

FESEM image showing the morphology and particle size of a typical airborne diatome from the Chad Basin (Moreno et al., 2006)
Ongoing work

- 30 year simulation (February 1979- March 2010) within a domain that covers Northern Africa, Middle East and Europe
- Resolution of the model was set to 0.5º x 0.5º
- The simulation was reinitialized every 24 hours with Reanalysis-2 for atmosphere and GLDAS for soil.
- 3 hourly output of climate (humidity, temperature, winds, precipitation) and dust respirable concentrations

- Comparison with weekly cases at district levels in Niger

Goals:
- understand the influence of climate and dust on epidemics
- Build statistical predictive tool to help reactive WHO vaccination strategy
Preliminary results for Niger
1986-2008 weekly cases vs climate and dust

Precipitation vs cases

Wind direction vs cases
Lagged scatter plots from t to t-12 weeks
Absolute humidity vs cases
Lagged scatter plots from t to t-12 weeks
Temperature vs cases
Lagged scatter plots from t to t-12 weeks
Dust concentration vs cases
On-going projects

**NASA ROSES:**
*Towards improved control of meningitis outbreaks in sub-Saharan Africa*
PI: S. Trzaska

**NIEHS:** *The role of airborne dust and climate in meningococcal meningitis outbreaks in the Sahel*
PI: S. Trzaska

Dust measurements of concentration and composition
2 stations: Niger and Ghana

**FRAMEWORK:** Meningitis Environmental Risk Information Technologies (MERIT)

**2010**

**CCI:** *Atmospheric aerosol impacts on health in sub-Saharan Africa*
PI’s: C. Pérez Garcia-Pando, S. Trzaska

Additional dust measurements of concentration and composition in Senegal