NOAA Air Resources Lab
HYPLIT and Satellite Observations:
Volcanic Ash Forecasting and Other Applications

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Cooperative Institute for Climate and Satellites,
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4th Annual CICS-MD Science Meeting
Rick Artz, Ariel Stein, Glenn Rolph, Barbara Stunder, Mark Cohen, Fantine Ngan,
Tianfeng Chai, Roland Draxler, Daniel Tong
Justin Seiglaff, Michael Pavolonis, Jaime Kibler,
Outline

• Overview NOAA ARL
• Overview HYSPLIT Atmospheric Transport and Dispersion Modeling
• Model development and evaluation (Fantine Ngan)
• HYSPLIT Model use of Satellite Data
  Volcanic Ash
  Smoke
  Dust
• Use of Satellite data for PM2.5 forecasts (Daniel Tong, Tianfeng Chai)
Research Areas

ARL Locations
www.arl.noaa.gov

College Park, MD
Idaho Falls, ID
Las Vegas, NV
Oak Ridge, TN
80 People, 30 in Maryland

Atmospheric Transport and Dispersion
- Modeling
- Decision support tools
- Tracer studies

Air Quality
- Ozone and fine particulate matter
- Ecosystem relevant air pollution
- Mercury
- Nutrients

Climate
- Climate Observations
- Analysis of change and variability

Support for DOE, NASA, DOD, DHS, WMO

Boundary Layer
- Boundary-layer characterization
- Prediction
Atmospheric Transport and Dispersion Modeling Research & Applications

- Emergency Response
  - Radiological releases
  - Chemical releases
  - Volcanic eruptions

- Air Quality
  - Wildfire smoke & wind-blown dust forecasting
  - Global pollutant transport (mercury)
  - Source-receptor analysis

- Model Evaluation
  - Data Archive of Tracer Experiments and Meteorology
  - Meteorological data assimilation (WRF)

- Decision Support
  - Dispersion model training
  - Real-time Environmental Applications and Display sYstem (READY)
What is the HYSPLIT model?

- Air Parcel Trajectory Model
- *also an* Atmospheric Fate and Transport Model
- Simulates the 3-D dispersion of materials emitted to the air
- Can also simulate:
  - Wet and Dry Deposition
  - Chemical Transformations
  - Radioactive Decay
  - Gravitational settling
Running HYSPLIT On-Line

https://www.ready.noaa.gov/HYSPLIT_traj.php

More than 3000 registered users worldwide
HYSDPLIT Inputs and Outputs

**Forecasting**
Source – current location
Output – future location

**Source Attribution**
Source – current location
Output – possible past locations

OR

Source – possible past locations
Output – current location

HYSDPLIT Inverse Modeling – Tianfeng Chai (Poster)
Fantine Ngan

Tracer Experiment data - ASCOT
Atmospheric Studies in Complex Terrain

- Mid-September 1980
- Study transport and diffusion of pollutant associated with nocturnal drainage flows
- Five releases on a different night at Anderson Creek Valley in Northern California

Data archive of tracer experiments at: http://www.arl.noaa.gov/DATEM.php

**Comparison for ASCOT**

**Model Development : verification**

**Evaluation Statistic**

\[
\text{Rank} = R^2 + 1 - \left| \frac{FB}{2} \right| + \frac{FMS}{100} + \left(1 - \frac{KSP}{100}\right)
\]
Volcanic Eruption

Sources of Information:
- Satellites
- Volcano Observatories
- Pilot Reports

Thermal energy + Kinetic energy

Potential energy

Augustine Volcano
30 Jan 2006

Estimate Mass of Ash from Plume Height.

Image courtesy of AVO/USGS. Photographer: McGimsey, Game
9 Volcanic Ash Advisory Centers World Wide
The Weekly Volcanic Activity Report is a cooperative project between the Smithsonian's Global Volcanism Program and the US Geological Survey's Volcano Hazards Program. Updated by 2300 UTC every Wednesday, notices of volcanic activity posted on these pages are preliminary and subject to change as events are studied in more detail. This is not a comprehensive list of all of Earth's volcanoes erupting during the week, but rather a summary of activity at volcanoes that meet criteria discussed in detail in the "Criteria and Disclaimers" section. Carefully reviewed, detailed reports on various volcanoes are published monthly in the Bulletin of the Global Volcanism Network.

### Activity for the week of 11 November-17 November 2015

<table>
<thead>
<tr>
<th>Name</th>
<th>Location</th>
<th>Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuego</td>
<td>Guatemala</td>
<td>New</td>
</tr>
<tr>
<td>Rinjani</td>
<td>Lombok Island (Indonesia)</td>
<td>New</td>
</tr>
<tr>
<td>Yasur</td>
<td>Vanuatu</td>
<td>New</td>
</tr>
<tr>
<td>Chipoi</td>
<td>Kuril Islands (Russia)</td>
<td>Ongoing</td>
</tr>
<tr>
<td>Colima</td>
<td>Mexico</td>
<td>Ongoing</td>
</tr>
<tr>
<td>Cotopaxi</td>
<td>Ecuador</td>
<td>Ongoing</td>
</tr>
<tr>
<td>Dukono</td>
<td>Halmahera (Indonesia)</td>
<td>Ongoing</td>
</tr>
<tr>
<td>Karangetang</td>
<td>Siau Island (Indonesia)</td>
<td>Ongoing</td>
</tr>
<tr>
<td>Karymsky</td>
<td>Eastern Kamchatka (Russia)</td>
<td>Ongoing</td>
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<tr>
<td>Kilauea</td>
<td>Hawaiian Islands (USA)</td>
<td>Ongoing</td>
</tr>
<tr>
<td>Lokon-Fmpung</td>
<td>Sulawesi (Indonesia)</td>
<td>Ongoing</td>
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<tr>
<td>Nevado del Ruiz</td>
<td>Colombia</td>
<td>Ongoing</td>
</tr>
<tr>
<td>Popocatepetl</td>
<td>Mexico</td>
<td>Ongoing</td>
</tr>
<tr>
<td>Sheveluch</td>
<td>Central Kamchatka (Russia)</td>
<td>Ongoing</td>
</tr>
<tr>
<td>Shishaldin</td>
<td>Fox Islands (USA)</td>
<td>Ongoing</td>
</tr>
<tr>
<td>Sinabung</td>
<td>Indonesia</td>
<td>Ongoing</td>
</tr>
<tr>
<td>Tungurahua</td>
<td>Ecuador</td>
<td>Ongoing</td>
</tr>
<tr>
<td>Ubinas</td>
<td>Peru</td>
<td>Ongoing</td>
</tr>
</tbody>
</table>
Passive IR sensors
Pavolonis et. al.
JGR- Atmospheres
2015 V120, p7813

http://volcano.ssec.wisc.edu
VERIFICATION

Data from CALIOP instrument aboard CALIPSO
(Cloud-Aerosol Lidar with Orthogonal Polarization)

Data obtained from the NASA Langley Research Center Atmospheric Science Data Center
https://www-calipso.larc.nasa.gov
Case study: Kasatochi, Alaska, August, 2008

- CALIOP
  - LIDAR instrument

- MODIS
  - Passive IR

- Eruption (km)
  - E1
  - E2
  - E3

- Time 1
  - 2
  - 3
  - 4
  - 5

- RT1

- 00 UTC Aug. 7
- 00 Aug. 8
- 00 Aug. 9
- 00 Aug. 10
- 00 UTC Aug. 11
Compare output generated using different source terms

Source term at vent
08/08
05:00 UTC

Source term T1
08/08
14:00 UTC

Source term T2
08/09
01:00 UTC

Source term T3
08/09
13:00 UTC
Verification statistics

Retrieval = hit + miss
Model = hit + false alarm
Overlap = hit
Total = hit + miss + false alarm

CSI = overlap / total \quad 0.0 \text{ to } 1.0
POD = overlap / retrieval \quad 0.0 \text{ to } 1.0
FAR = false alarm / model \quad 0.0 \text{ to } 1.0

Threshold = 0.1 \text{ g/m}^2
but otherwise statistics are binary (yes/no)
and independent of mass loading value.

CSI = \text{Critical success index}
POD = \text{Probability of detection}
FAR = \text{False alarm ratio}
Mass loading (g/m$^2$) valid at Time 4

Cylindrical source initialized at vent.

Initialized from satellite retrieval at Time 1.

Satellite retrieval
KSP = maximum (|CDFA − CDFB|)
Height of ash at Time 1

Cylindrical initialization, model particle positions color-coded by height.

Orange solid line = track of CALIOP

Model particle positions (red) and CALIOP backscatter

The lidar data was obtained from the NASA Langley Research Center Atmospheric Science Data Center.
The lidar data was obtained from the NASA Langley Research Center Atmospheric Science Data Center.
Vertical plume structure at Time 4
Model cylindrical initialization at vent.

Standard footprint plot.
Model particle positions color-coded by height.

Vertical cross-section along red line on plot at left.
Model particle positions (magenta).
Satellite-retrieved top heights (black).
Loop from 165 to 151 degrees longitude.
Volcanic Ash Summary:
Satellite retrievals of mass loading reduce uncertainty in forecast.

Sources initiated at observed position performed well.

HYSPLIT predictions of vertical structure of the ash cloud agree well with lidar profiles and top heights retrieved from passive IR measurements.
NAQFC is one of the major gateways to disseminate NOAA satellite observations and model prediction of air quality to the public.
HYSPLIT  Smoke forecasting

NOAA Hazard Mapping System Fire and Smoke Product and ground reports

U.S. Fire Service Blue Sky - PM2.5 emissions and heat release BlueSky (http://www.airfire.org/bluesky/) (Larkin et al., 2008, O'Neill et al. 2008)

HYSPLIT

https://ready.arl.noaa.gov/smoke_verifyhms.php
HYSPLIT Dust forecasting

- Emission algorithm
- Dust source locations based on land use
OR
- Dust source locations defined on a monthly basis based upon climatology of MODIS Deep-Blue AOD values.


TOMS aerosol index for April 2001
Black dots- daily HYSPLIT particle positions at 0600 UTC
NAQFC PM$_{2.5}$ Forecasts with AOD assimilation

<table>
<thead>
<tr>
<th>Cases</th>
<th>12Z</th>
<th>17Z</th>
<th>18Z</th>
<th>20Z</th>
<th>00Z*</th>
<th>06Z*</th>
</tr>
</thead>
<tbody>
<tr>
<td>C0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>C1</td>
<td>-</td>
<td>Terra total AOD</td>
<td>-</td>
<td>Aqua total AOD</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>C2</td>
<td>PM$_{2.5}$</td>
<td>-</td>
<td>PM$_{2.5}$</td>
<td>-</td>
<td>PM$_{2.5}$</td>
<td>PM$_{2.5}$</td>
</tr>
<tr>
<td>C3</td>
<td>PM$_{2.5}$</td>
<td>Terra total AOD</td>
<td>PM$_{2.5}$</td>
<td>Aqua total AOD</td>
<td>PM$_{2.5}$</td>
<td>PM$_{2.5}$</td>
</tr>
</tbody>
</table>

AIRNow surface station measurements

Hour 0: 12 Z 7/1, 2011

7/19, 2011

7/20, 2011
### Emission Challenges

<table>
<thead>
<tr>
<th>Emission Challenges</th>
<th>Existing or Proposed Solutions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Huge number of emission sources</td>
<td>NEIs and SMOKE-like Emission Processing</td>
</tr>
<tr>
<td>2. Gap between NEIs and forecast years</td>
<td>Emission forecasting capability</td>
</tr>
<tr>
<td>3. Weather effects on emissions</td>
<td>Inline emission modeling (snow/ice, precip., drought, etc)</td>
</tr>
<tr>
<td>4. Major Socio-economic Events (Recession, Fracking, Disasters);</td>
<td>Emission data assimilation capability</td>
</tr>
<tr>
<td>5. Missing natural Sources (Fire, Dust, Volcano, Lightning, Marine, etc)</td>
<td>Process-based emission models</td>
</tr>
</tbody>
</table>

Many volcanos are found in remote, hard to monitor areas. Ash and SO2 are often injected to the tropopause or even stratosphere.

**Real-time Earth observations are key to tackle these issues**
EXTRA SLIDES
**Indirect Method**
Location of vent.
Plume Height.
Time of eruption.

**Direct Method**
Satellite Retrieval at T1, T2, T3

**Source Term**
Initial Position and Amount of Ash

**Meteorological data from a meteorological model**
GDAS 1° 3 hourly
ECMWF 1.5° 6 hourly

**HYSPLIT**
Future position and mass of ash.

**HYSPLIT**
Satellite Retrievals at times 2,3,4...

**Compare**
• An independent HYSPLIT simulation at each time segment (t), at each possible release location is run with unit source;
• A Transfer Coefficient Matrix (TCM) is then built to correspond with observations.
• Source terms are solved by minimizing a cost function built to measure the differences between model simulations and observations, following a general 4D-variational data assimilation approach.

\[
\mathcal{F} = \frac{1}{2} \sum_{t=1}^{T} \sum_{k=1}^{K} \frac{(q_{kt} - q_{kt}^b)^2}{\sigma_{kt}^2} + \frac{1}{2} \sum_{s=1}^{S} \sum_{i=1}^{I} \sum_{j=1}^{J} \frac{(l_{ij}^m - l_{ij}^o)^2}{\epsilon_{ij}^2} + \mathcal{F}_{other}
\]

\(\text{e.g. Satellite volcanic ash mass loading at point (i, j), time } s\)
Meteorological data drives the HYSPLIT model

- HYSPLIT uses specially formatted meteorological data to estimate the transport and dispersion of atmospheric constituents.

- Both Forecast and Archived met data can be used.

- NOAA Air Resources Laboratory converts meteorological model outputs (e.g., from NOAA weather models) to this HYSPLIT format, and makes them available freely via the web.

- Numerous North American and Global datasets (primarily NOAA-based) are available to run HYSPLIT.

- The HYSPLIT suite also includes conversion programs to convert other meteorological model output to the correct format (WRF, ECMWF, MM5, RAMS, etc.).
Decreased MER by a factor of 100
- To match model mass loadings to retrievals
- Model MER=$1.0 \times 10^{11}$ g/hour
Mass loading (g/m²) valid at Time 1

- Line source initialized at vent.
- Cylindrical source initialized at vent.
- Satellite retrieval

Color bar applies to all.
Solid line is retrieval footprint (plots on left).
Summary of this research on Kasatochi, 2008 ...

- Quantitative source term, which is needed for quantitative results
  - At vent
    - MER algorithm (Mastin, 2009) and an estimate of fine ash fraction
      will give uncertain results without any mass adjustment from satellite
      retrievals
    - Cylindrical source initialization tended to be better than linear source
    - Inverse modeling produced reasonable results but needs to be tested
      with more eruptions
  - Downwind
    - Initializing HYSPLIT from satellite-retrieved-products and assuming an
      ash cloud thickness gave roughly comparable results as the cylindrical
      source initialized at the vent

- HYSPLIT was able to simulate the height and thickness of the ash cloud layer(s)
  reasonably well compared to lidar data

- The HYSPLIT top heights agreed reasonably well with retrieved top heights,
  although HYSPLIT also showed a very complex vertical structure in parts of the
  ash cloud

For more on this work, see the poster by Crawford et al.
More on dispersion model verification

Above binary (yes/no) statistics are for mass loadings above some threshold.

Draxler (2006) developed a “rank” score to compare point-to-point concentration values.
• Correlation coefficient (scatter)
• Fractional bias
• CSI (aka Figure of Merit in Space or Threat Score) (spatial coverage)
• Kolmogorov-Smirnov Parameter (unpaired cumulative distribution)

Satellite Retrieval at 2008 08 08 13:40 UTC
Model output one hour average 2008 08 08 13 - 14 UTC
GDAS 1degree
-----------------------------------
96098 Unaveraged data points for processing
0.28 Correlation coefficient (P=99%)
66.75 Root mean square error
13.27 Average bias [(C-M)/N]
1.24 Fractional bias [2B/(C+M)]
51.94 False Alarm Rate [fa/(fa+hit)]
54.98 Probability of Detection [hit/(hit+miss)]
34.48 Threat Score [hit/(fa+hit+miss)]
14.48 Measured 95-th percentile
11.80 Measured 90-th percentile
6.24 Measured 75-th percentile
2.43 Measured 50-th percentile

Example stats from Kasatochi
Valid 14 UTC August 8, 2008

### Data Archive of Tracer Experiments and Meteorology (DATEM)

http://www.arl.noaa.gov/DATEM.php

Near ground-level releases of tracer gases

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Number of tracer releases</th>
<th>Sampler distance from release</th>
<th>Meteorology</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACURATE (March, 1982-Sept. 1983)</td>
<td>near-continuous</td>
<td>300 - 1100 km</td>
<td>NARR</td>
</tr>
<tr>
<td>ANATEX_GGW (1987)</td>
<td>33 (every 2.5 days)</td>
<td>500 - 3000 km</td>
<td>NARR</td>
</tr>
<tr>
<td>ANATEX_STC (1987)</td>
<td>33 (every 2.5 days)</td>
<td>500 – 2000 km</td>
<td>NARR</td>
</tr>
<tr>
<td>ASCOT (1980)</td>
<td>10</td>
<td>~10 km</td>
<td>WRF</td>
</tr>
<tr>
<td>CAPTEX (1983)</td>
<td>6</td>
<td>300 – 1100 km</td>
<td>WRF and NARR</td>
</tr>
<tr>
<td>ETEX</td>
<td>1</td>
<td>200 – 1500 km</td>
<td>Reanalysis</td>
</tr>
<tr>
<td>INEL74 (Jan- May, 1974)</td>
<td>near-continuous</td>
<td>~1200-1800 km</td>
<td>Reanalysis</td>
</tr>
<tr>
<td>METREX_8h_MDVA (Nov 83 – Dec 84)</td>
<td>~ 275</td>
<td>&lt; 50 km</td>
<td>MM5</td>
</tr>
<tr>
<td>METREX_8h_MtVern on (Nov 83 – Dec 84)</td>
<td>~ 275</td>
<td>&lt; 50 km</td>
<td>MM5</td>
</tr>
<tr>
<td>OKC80 (1980)</td>
<td>2</td>
<td>100, 600 km</td>
<td>NARR</td>
</tr>
<tr>
<td>SRP76 (March 1975 – Sept. 1977)</td>
<td>near-continuous</td>
<td>&lt; 150 km</td>
<td>Reanalysis</td>
</tr>
</tbody>
</table>
Volcanic Eruption

Ash is of concern to aviation

Large amounts of \( \text{SO}_2 \)

Potential energy

Thermal energy + Kinetic energy

Augustine Volcano
30 Jan 2006

• Wind can increase entrainment of air.
• Condensation of vapor releases extra heat.
• Temperature stratification of atmosphere
• Particle fallout and thermal disequilibrium removes heat.

Estimate Mass of Ash from Plume Height.

\[ \dot{M} = \dot{V} \times \text{DRE} \]  (Total mass – all grain sizes.

Ash > 63\( \mu \text{m} \) will fall out quickly.

\[ M_{63} \approx 0.01 \text{ to } 0.5 \]

Aggregation Processes

How is mass distributed in the eruption column?

Data has a large amount of scatter:
50% of measurements can be expected to be within a factor of 4 of the calculated value.

Empirical fits to data

\[ H \propto \dot{V}^{0.25} \]  Theoretical.

Mastin: \[ H = 2.00\dot{V}^{0.241} \]

Sparks: \[ H = 1.67\dot{V}^{0.259} \]

Image courtesy of AVO/USGS. Photographer: McGimsey, Game
HYSPLIT4: Basic Equations

- **Mean Trajectory Equation**
  - \( P'(t+\Delta t) = P(t) + V(P,t) \Delta t \)
  - \( P(t+\Delta t) = P(t) + 0.5 \left[ V(P,t) + V(P',t+\Delta t) \right] \Delta t \)

- **Turbulent Trajectory Equation**
  - \( P_{\text{final}}(t+\Delta t) = P_{\text{mean}}(t+\Delta t) + U'(t+\Delta t) \Delta t \)

- **Turbulent Velocity**
  - \( U'(t+\Delta t) = R(\Delta t) U'(t) + U'' (1-R(\Delta t)^2)^{0.5} \)

- \( U'(t) \) at the previous time
  - \( R(\Delta t) = \exp (-\Delta t / T_{Li}) \) autocorrelation
  - \( T_{Li} \) Lagrangian time scale

- \( U'' = \sigma_u \lambda \)
  - \( \lambda \) Gaussian random number
  - \( \sigma_u \) velocity standard deviation

Air Resources Laboratory
**HYSPLIT Inverse Modeling**

- An independent HYSPLIT simulation at each time segment (t), at each possible release height (k) is run with unit source;
- A *Transfer Coefficient Matrix (TCM)* is then built to correspond with the available satellite mass loading observations. Mass loadings are obtained by integrating from surface to ash cloud top or for a fixed cloud depth;
- Source terms are solved by minimizing a cost function built to measure the differences between model simulations and observations, following a general 4D-variational data assimilation approach.

\[
F = \frac{1}{2} \sum_{t=1}^{T} \sum_{k=1}^{K} \frac{(q_{kt} - q_{kt}^b)^2}{\sigma_{kt}^2} + \frac{1}{2} \sum_{s=1}^{S} \sum_{i=1}^{I} \sum_{j=1}^{J} \frac{(l_{ijs}^m - l_{ijs}^o)^2}{\epsilon_{ijs}^2} + F_{other}
\]

*Satellite volcanic ash mass loading at point (i, j), time s*