An Overview of the HYSPLIT Modeling System for Trajectory and Dispersion Applications

http://www.arl.noaa.gov/ready/hysplit4.html

Roland.Draxler@noaa.gov

- Trajectory computation method
- Simulating plume dispersion
- Air concentrations / deposition
- Example calculations
- Verification
Integration Methods

- **Eulerian**
  - Local derivative
  - Solve over the entire domain
  - Ideal for multiple sources
  - Easily handles complex chemistry
  - Problems with artificial diffusion

- **Lagrangian - HYSPLIT**
  - Total derivative
  - Solve only along the trajectory
  - Ideal for single point sources
  - Implicit linearity for chemistry
  - Non-linear solutions available
  - Not as efficient for multiple sources
HYSPLIT Model Features

- Predictor-corrector advection scheme; forward or backward integration
- Linear spatial & temporal interpolation of meteorology (external off-line)
- Converters available ARW, ECMWF, RAMS, MM5, NMM, GFS, …
- Vertical mixing based upon SL similarity, BL Ri, or TKE
- Horizontal mixing based upon velocity deformation, SL similarity, or TKE
- Mixing coefficients converted to velocity variances for dispersion
- Dispersion computed using 3D particles, puffs, or both simultaneously
- Modelled particle distributions (puffs) can be either Top-Hat or Gaussian
- Air concentration from particles-in-cell or at a point from puffs
- Multiple simultaneous meteorology and concentration grids
- Latitude-Longitude or Conformal projections supported for meteorology
- Nested meteorology grids use most recent and finest spatial resolution
- Non-linear chemistry modules using a hybrid Lagrangian-Eulerian exchange
- Standard graphical output in Postscript, Shapefiles, or Google Earth (kml)
- Distribution: PC and Mac executables, and UNIX (LINUX) source
HYSPLIT Model Development History

- 1.0 – 1982: rawinsonde data with day/night (on/off) mixing
- 2.0 – 1988: rawinsonde data with continuous vertical diffusivity
- 3.0 – 1992: meteorological model fields with surface layer module
- 4.0 – 1997: multiple meteorological fields, combined particle-puff
- 4.0 – 1998: switch from NCAR to Postscript graphics
- 4.1 – 1999: isotropic turbulence for short-range simulations
- 4.2 – 1999: terrain compression of sigma & use of polynomial
- 4.3 – 2000: revised vertical auto-correlation for dispersion
- 4.4 – 2001: dynamic array allocation and support lat-lon grids
- 4.5 – 2002: ensemble, matrix, and source attribution options
- 4.6 – 2003: non-homogeneous turbulence correction, dust storm
- 4.7 – 2004: velocity variance, TKE, new short-range equations
- 4.8 – 2006: staggered WRF grids, turbulence ensemble, urban TKE
- 4.9 – 2009: incorporated global Eulerian model (grid-in-plume)
Computation of a Single Particle Trajectory

- Position computed from average velocity at the initial position (P) and first-guess position (P'):

\[
P(t+dt) = P(t) + 0.5 \left[ V(P(t)) + V(P'(t+dt)) \right] dt \\
P'(t+dt) = P(t) + V(P(t)) dt
\]

- The integration time step is variable: \( V_{\text{max}} dt < 0.75 \)
- The meteorological data remain on its native horizontal coordinate system
- Meteorological data are interpolated to an internal terrain-following sigma coordinate system:

\[
s = \frac{(Z_{\text{top}} - Z_{\text{msl}})}{(Z_{\text{top}} - Z_{\text{gl}})}
\]
Representation of a Plume using Trajectories

- A single trajectory cannot properly represent the growth of a pollutant cloud when the wind field varies in space and height.
- The simulation must be conducted using many pollutant particles.
- In the illustration on the right, new trajectories are started every 4-h at 10, 100, and 200 m AGL to represent the boundary layer transport.
- It looks like a plume because wind speed and direction varies with height in the boundary layer.
Trajectory based Plume Simulation Options

- **Particle**: a point mass of contaminant. A fixed number is released with mean and random motion.

- **Puff**: a 3-D cylinder with a growing concentration distribution in the vertical and horizontal. Puffs may split if they become too large.

- **Hybrid**: a circular 2-D object (planar mass, having zero depth), in which the horizontal contaminant has a “puff” distribution and in the vertical functions as a particle.
Central Position of Particles and Puffs

3D-Particles (5000)

Position from mean wind + turbulence

3D-Puffs (500)

Position from mean wind
Horizontal Distribution for a Single Puff

**Top Hat**
- Top-Hat Distribution
- Uniform over 1.54 sigma

**Gaussian**
- Gaussian Distribution
- Shown over 3 sigma
Computational Approach

3D-Particles

3d-particle positions are adjusted by the component turbulent velocities:

\[
X(t+dt) = X_{\text{mean}}(t+dt) + U'(t+dt) \, dt
\]

\[
U'(t+dt) = R(dt) \, U'(t) + U''(1-R(dt)^2)^{0.5}
\]

\[
R(dt) = \exp\left(-\frac{dt}{T_L}\right)
\]

\[
U'' = (s_u) \, (\text{Gaussian Random Number})
\]

The growth of 3D-puffs is based upon the turbulence:

\[
d s_h^2/dt = 2^{0.5} \, s_u
\]

\[
s_u = (K_x / T_L)^{0.5}
\]

The second moment of the 3D-particles gives the puff distribution:

\[
s_h^2 = (X_i-X_m)^2
\]
Air Concentration

5000 Particles

500 Puffs
Summary of Air Concentration Equations

- Each particle is assigned a pollutant mass
- Concentration is simply the mass sum / volume
- Volume may be defined as the …
  - size of the concentration grid cell for particles
  - the volumetric distribution of the puff

3D particle: \[ dC = q \left( dx \ dy \ dz \right)^{-1} \]
Hybrid Top-Hat: \[ dC = q \left( \pi r^2 \ dz \right)^{-1} \]
Hybrid Gaussian: \[ dC = q \left( 2 \pi s^2 \ dz \right)^{-1} \exp\left(-x^2 / 2s^2\right) \]
Puff Top Hat: \[ dC = q \left( \pi r^2 \ dzp \right)^{-1} \]
Puff Gaussian: \[ dC = q \left( 2 \pi s^2 \ dzp \right)^{-1} \exp\left(-x^2 / 2s^2\right) \]
Sensitivity to Particle Number - Why Puff Dispersion?

- A puff simulation models the growth of the particle distribution, the particle standard deviation
- Requires fewer puffs than particles to represent distribution
- Puff growth uses the same turbulence parameters as particle method
- The Puff-Particle Hybrid method
  - Fewer puffs required for horizontal distribution
  - Vertical shears captured more accurately by particles

500 3D-particles
HYPLIT Default Deposition Configuration

- **Dwet+dry = M \left[ 1 - \exp (-\Delta t \{ \beta_{\text{dry}} + \beta_{\text{gas}} + \beta_{\text{inc}} + \beta_{\text{bel}} \} ) \right]**

- **Dry Deposition**
  - $\beta_{\text{dry}} = \frac{V_d}{\Delta Z_p}$
  - $V_d$ user defined; $V_d = V_g$; Resistance method
  - $V_g$ gravitational settling (Stokes equation)

- **Cloud Layer Definition**
  - Cloud bottom: 80% Rh
  - Cloud top: 60% Rh

- **Particle Wet Deposition**
  - Within cloud: $\beta_{\text{inc}} = \frac{V_{\text{inc}}}{\Delta Z_p}$; $V_{\text{inc}} = S \cdot P$; $S = 3.2 \times 10^5$
  - Below cloud: $\beta_{\text{bel}} = 5 \times 10^{-5} \text{ s}^{-1}$

- **Gaseous Wet Deposition**
  - $\beta_{\text{gas}} = \frac{V_{\text{gas}}}{\Delta Z}$; $V_{\text{gas}} = H \cdot R \cdot T \cdot P \times 10^3$
China April 2001
Particle Distribution and TOMS Aerosol Index

April 7th 0600 UTC  
April 14th 0600 UTC
US PM$_{10}$ Measurements from China Event

- First arrival in BL over the US around April 16$^{th}$
- Model indicated spotty spatial distribution
- Arrival over eastern US between 19$^{th}$ and 22$^{nd}$
- Predicted concentrations too high (in part because deposition was turned off)
Wild Fire Smoke Verification
http://www.arl.noaa.gov/smoke
Local Scale Verification
Washington D.C. - Metropolitan Tracer Experiment

- **Tracer releases**
  - Rockville, Mt. Vernon, Lorton
  - every 36-h at 2 locations

- **Sampling**
  - 3 locations at 8-h
  - 93 locations monthly

- **Duration all 1984**

- **Meteorology**
  - ECMWF ERA-40

![Graph showing concentration vs. distance for METREX Monthly 1984 (PMCH and PDCH).]
Objective Verification for Sensitivity Testing

• The final model performance ranking is defined as the sum:
  \[ R^2 + \{1-|FB/2|\} + \text{FMS}/100 + \{1-\text{KS}/100\} \]

• where
  – the correlation (R) represents the scatter
  – the fractional bias (FB) is the mean difference between paired predictions and measurements and yields a normalized measure of the prediction bias in concentration units
  – the Figure-of-Merit-in-Space (FMS) is defined as the percentage of overlap between measured and predicted areas and is computed as the intersection over the union of predicted and measured concentrations
  – the Kolomogorov-Smirnov (KS) parameter is the maximum difference between the unpaired measured and calculated cumulative distributions

• The best model ranking result would be 4.0
Data Archive of Tracer Experiments and Meteorology

http://www.arl.noaa.gov/datem/results.html

<table>
<thead>
<tr>
<th>EXPERIMENT</th>
<th>Average</th>
<th>Paired</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACURATE</td>
<td>3.25</td>
<td>1.77</td>
</tr>
<tr>
<td>ANATEX GGW</td>
<td>3.48</td>
<td>1.84</td>
</tr>
<tr>
<td>ANATEX STC</td>
<td>2.66</td>
<td>1.63</td>
</tr>
<tr>
<td>CAPTEX</td>
<td>3.24</td>
<td>1.63</td>
</tr>
<tr>
<td>¹ETEX</td>
<td>2.37</td>
<td>1.55</td>
</tr>
<tr>
<td>¹INEL74</td>
<td>1.71</td>
<td>1.37</td>
</tr>
<tr>
<td>METREX (t1)</td>
<td>2.81</td>
<td>1.77</td>
</tr>
<tr>
<td>METREX (t2)</td>
<td>2.27</td>
<td>1.58</td>
</tr>
<tr>
<td>OKC80</td>
<td>2.50</td>
<td>1.73</td>
</tr>
</tbody>
</table>

North American Regional Reanalysis: http://nomads.ncdc.noaa.gov

¹NCAR/NCEP 2.5 degree reanalysis
### Verification Example for ANATEX

<table>
<thead>
<tr>
<th>Metric</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data points after temporal averaging</td>
<td>76</td>
</tr>
<tr>
<td>Percentile input for zero measured</td>
<td>0.00</td>
</tr>
<tr>
<td>Zero measured concentration value</td>
<td>0.00</td>
</tr>
<tr>
<td>Correlation coefficient (P=99%)</td>
<td>0.97</td>
</tr>
<tr>
<td>T-value (</td>
<td>Slope</td>
</tr>
<tr>
<td>Average measured concentration</td>
<td>16.34</td>
</tr>
<tr>
<td>Average calculated concentration</td>
<td>22.43</td>
</tr>
<tr>
<td>Ratio of calculated/measured</td>
<td>1.37</td>
</tr>
<tr>
<td>Normalized mean square error</td>
<td>19.17</td>
</tr>
<tr>
<td>Number of pairs analyzed</td>
<td>76</td>
</tr>
<tr>
<td>Average bias [(C-M)/N]</td>
<td>6.09</td>
</tr>
<tr>
<td>Factor exceeding [(N(C&gt;M))/N-0.5]</td>
<td>-30.26</td>
</tr>
<tr>
<td>Lo 99% confidence interval</td>
<td>-19.58</td>
</tr>
<tr>
<td>Hi 99% confidence interval</td>
<td>31.76</td>
</tr>
<tr>
<td>Fractional bias [2B/(C+M)]</td>
<td>0.31</td>
</tr>
<tr>
<td>Fig of merit in space (%)</td>
<td>100.00</td>
</tr>
<tr>
<td>Measured 95-th percentile</td>
<td>40.61</td>
</tr>
<tr>
<td>Measured 90-th percentile</td>
<td>34.92</td>
</tr>
<tr>
<td>Measured 75-th percentile</td>
<td>11.30</td>
</tr>
<tr>
<td>Measured 50-th percentile</td>
<td>6.82</td>
</tr>
<tr>
<td>Calculated 95-th percentile</td>
<td>38.38</td>
</tr>
<tr>
<td>Calculated 90-th percentile</td>
<td>20.72</td>
</tr>
<tr>
<td>Calculated 75-th percentile</td>
<td>8.38</td>
</tr>
<tr>
<td>Calculated 50-th percentile</td>
<td>4.16</td>
</tr>
<tr>
<td>Kolmogorov-Smirnov Parameter</td>
<td>30.00</td>
</tr>
<tr>
<td>Final rank (C,FB,FMS,KSP)</td>
<td>3.48</td>
</tr>
</tbody>
</table>
What’s in the pipeline for version 4.9 …

- Web interactive verification linked to DATEM
- Integrated global model for background contributions
- Chemical (CAMEO) and radiological effects database (web)
- GIS-like map background layers for graphical display (pc)
- Model physics ensemble (pc/unix)
  - meteorology and turbulence already in existing version
- Completely revised user’s guide with examples