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

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

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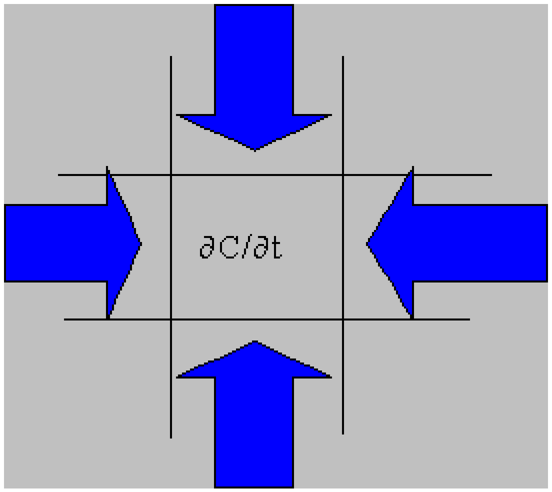
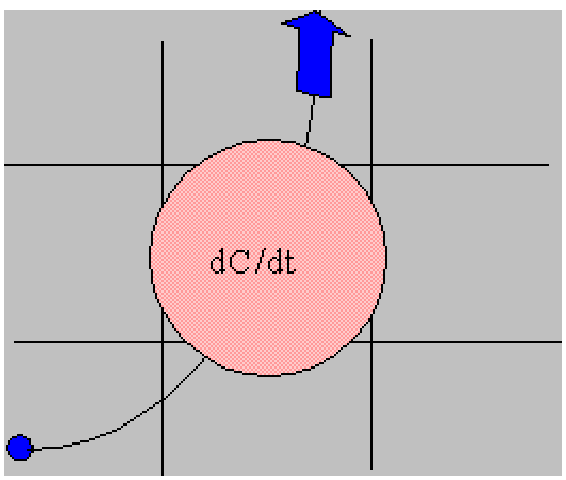
- Trajectory computation method
- Simulating plume dispersion
- Air concentrations / deposition
- Example calculations
- Verification

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'):

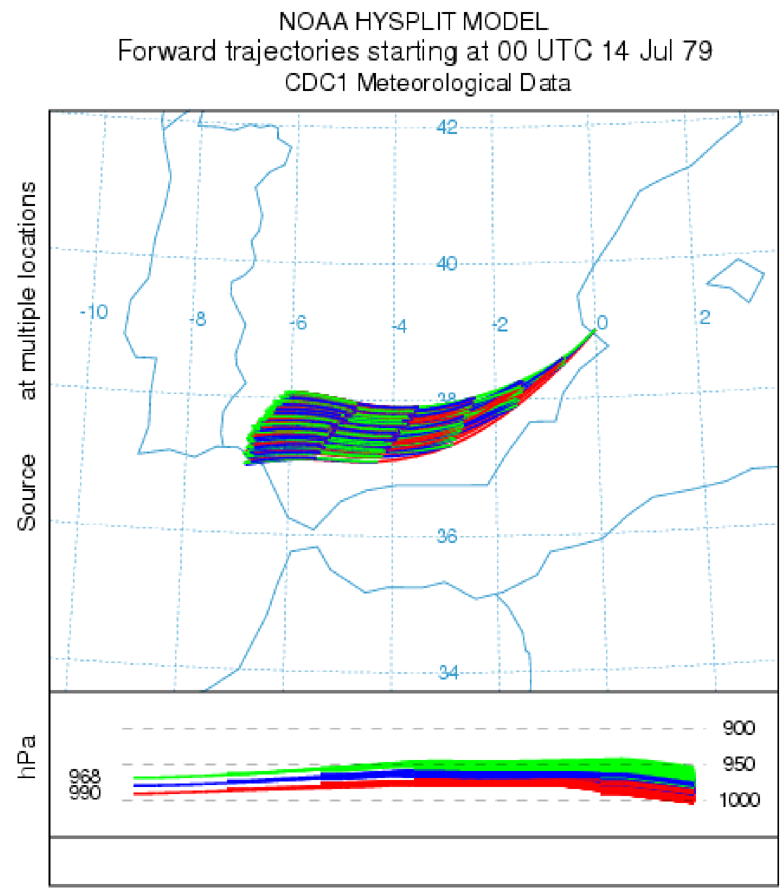
  P(t+dt) = P(t) + 0.5 [V(P{t}) + V(P'{t+dt})] dt
  P'(t+dt) = P(t) + V(P{t}) dt

- The integration time step is variable: V_{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:

  $s = (Z_{top} - Z_{msl}) / (Z_{top} - Z_{gl})$

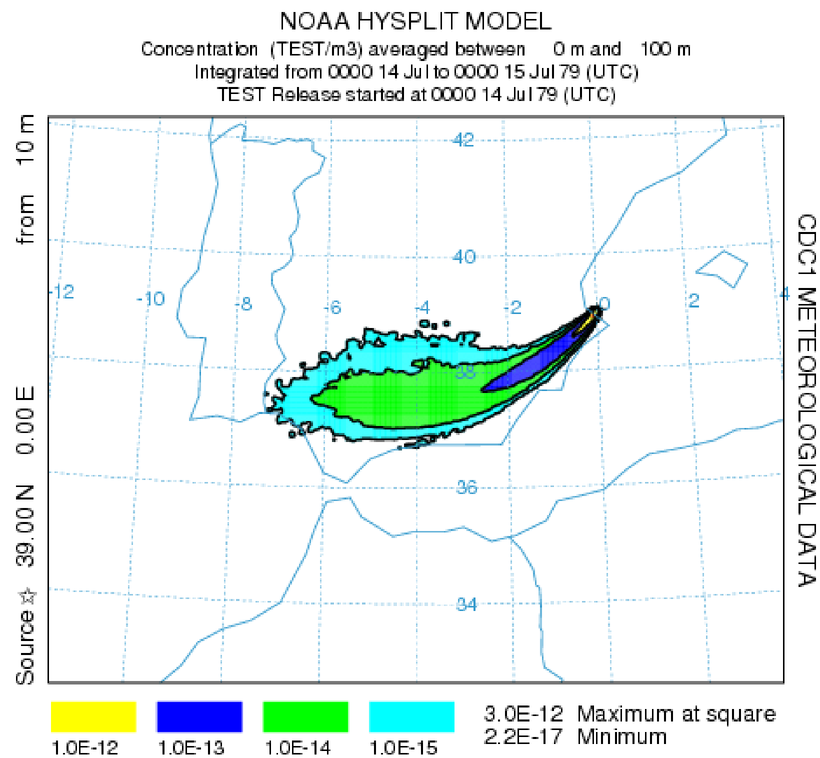
Representation of a Plume using Trajectories

- 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

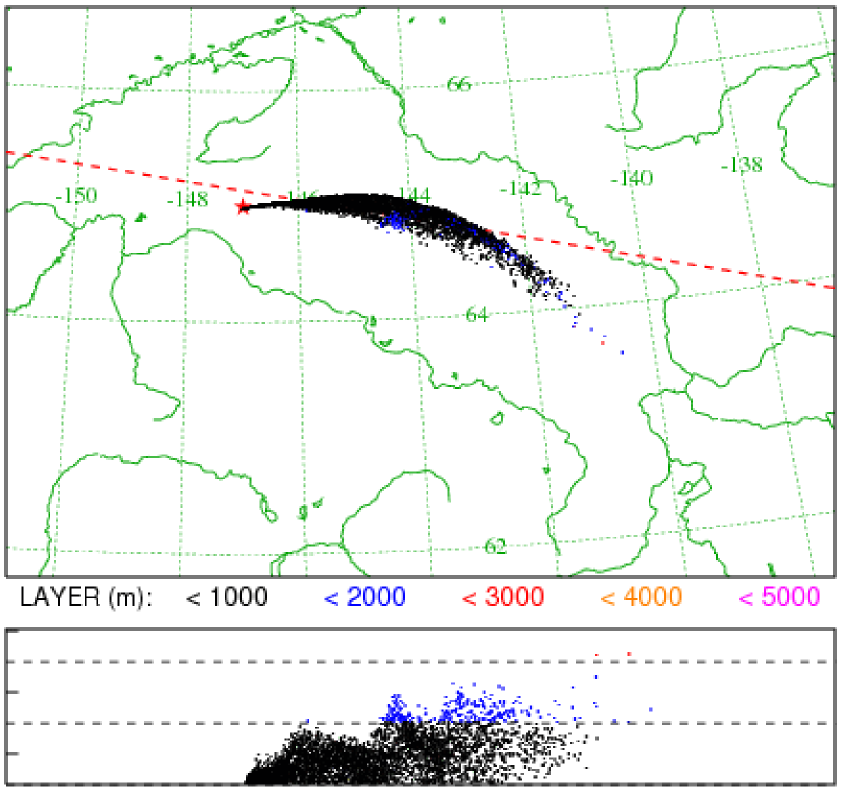
- **Particle**: a point mass of contaminant. A fixed number is released with mean and random motion.
- **Puff**: a 3-D cylinder with a growing concentration distribution in the vertical and horizontal. Puffs may split if they become too large.
- **Hybrid**: a circular 2-D object (planar mass, having 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

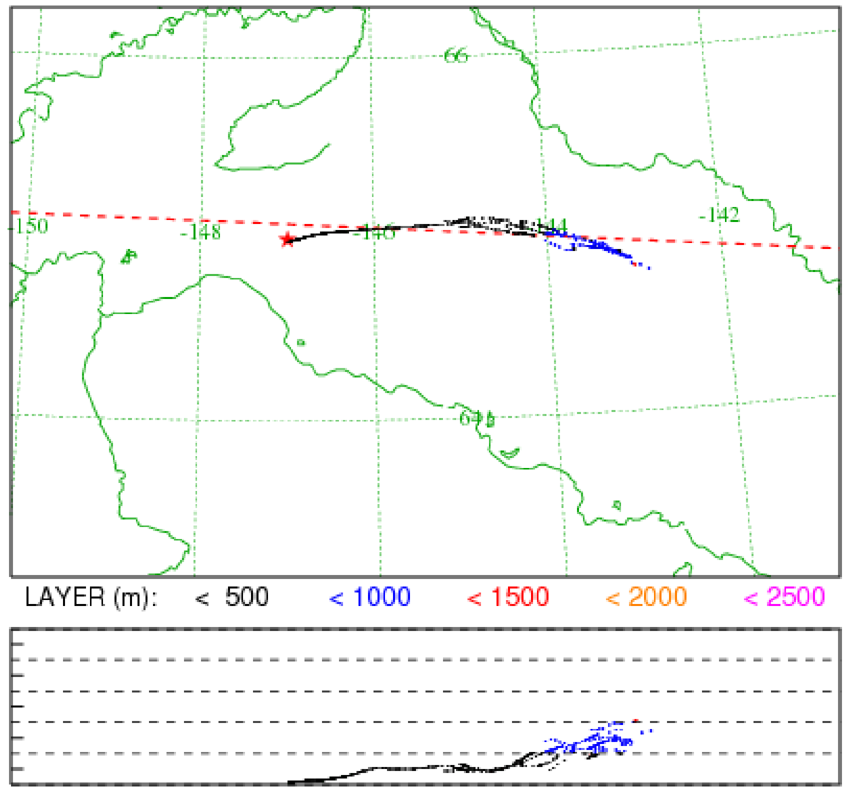
3D-Particles (5000)

Position from mean wind +turblence



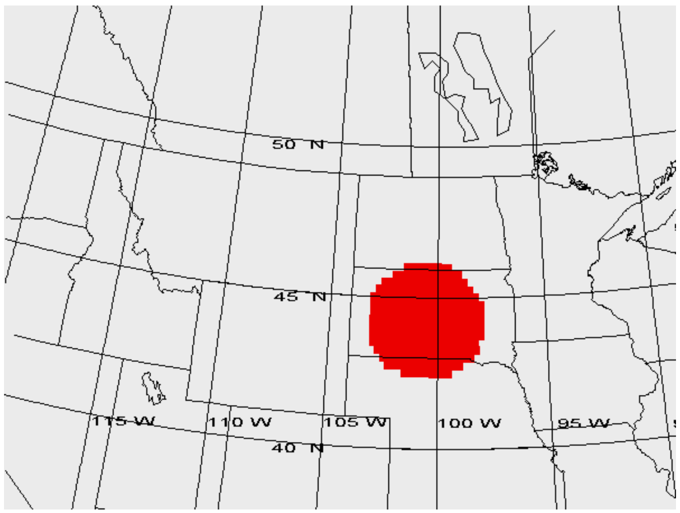
3D-Puffs (500)

Position from mean wind



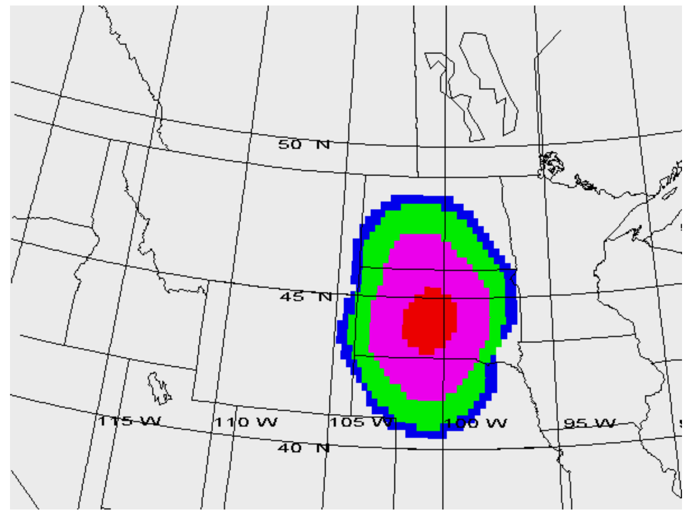
Horizontal Distribution for a Single Puff

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:

$X(t+dt) = X_{mean}(t+dt) + U'(t+dt)\ dt$

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

$R(dt) = \exp(-dt/T_{Lx})$

$U'' = (s_u)$ (Gaussian Random Number)

Puffs

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

$ds_h/dt = 2^{0.5}\ s_u$

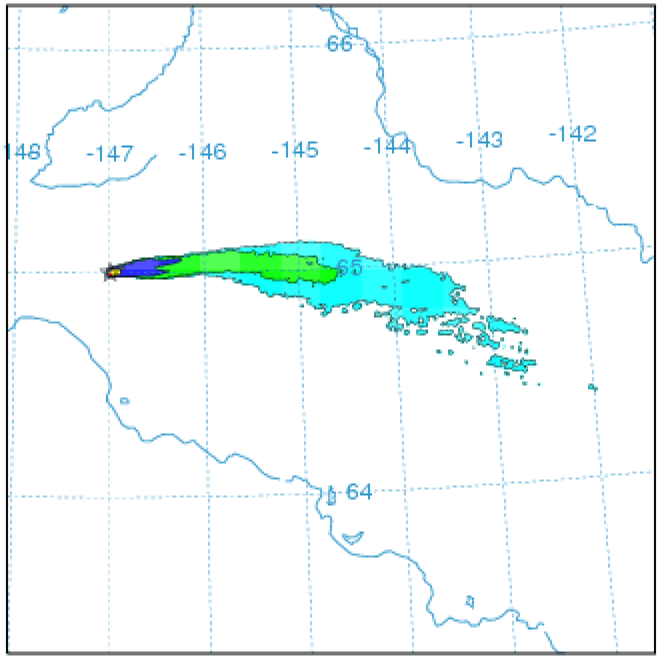
$s_u = (K_x\ /\ T_L)^{0.5}$

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

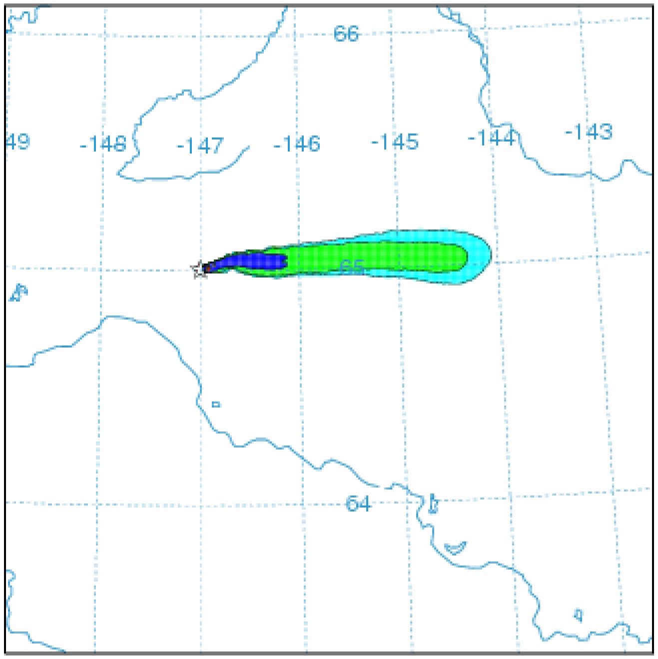
$s_h^2 = (X_i-X_m)^2$

Air Concentration

5000 Particles



500 Puffs



Summary of Air Concentration Equations

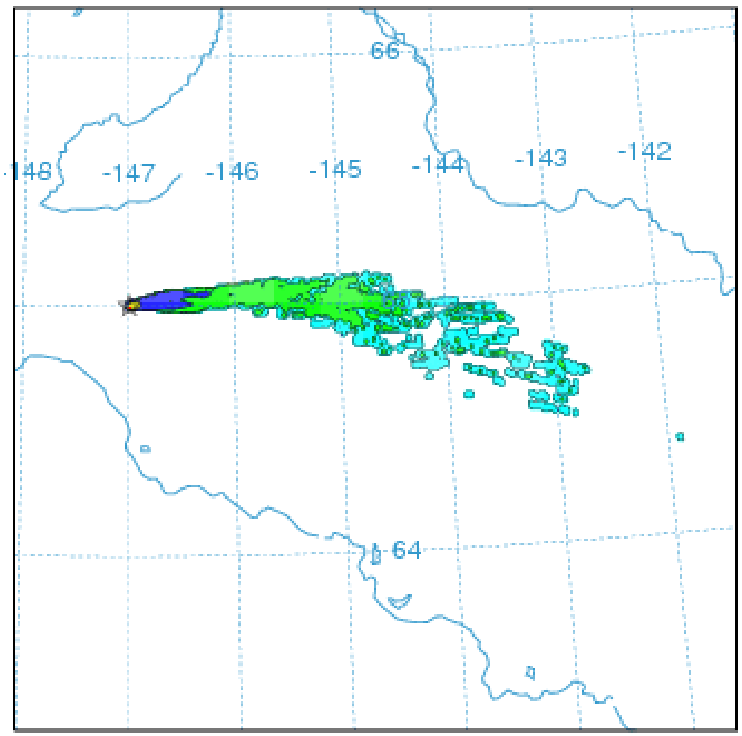
- Each particle is assigned a pollutant mass
- Concentration is simply the mass sum / volume
- Volume may be defined as the …
  - size of the concentration grid cell for particles
  - the volumetric distribution of the puff

3D particle:	$dC = q\,(dx\ dy\ dz)^{-1}$
Hybrid Top-Hat:	$dC = q\,(pi\ r^2\ dz)^{-1}$
Hybrid Gaussian:	$dC = q\,(2\ pi\ s^2\ dz)^{-1}\ exp(-x^2 / 2s^2)$
Puff Top Hat:	$dC = q\,(pi\ r^2\ dzp)^{-1}$
Puff Gaussian:	$dC = q\,(2\ pi\ s^2\ dzp)^{-1}\ exp(-x^2 / 2s^2)$

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



HYSPLIT Default Deposition Configuration

- **Dwet+dry = M [1 - exp (-Δt { βdry + βgas + βinc + βbel })]**

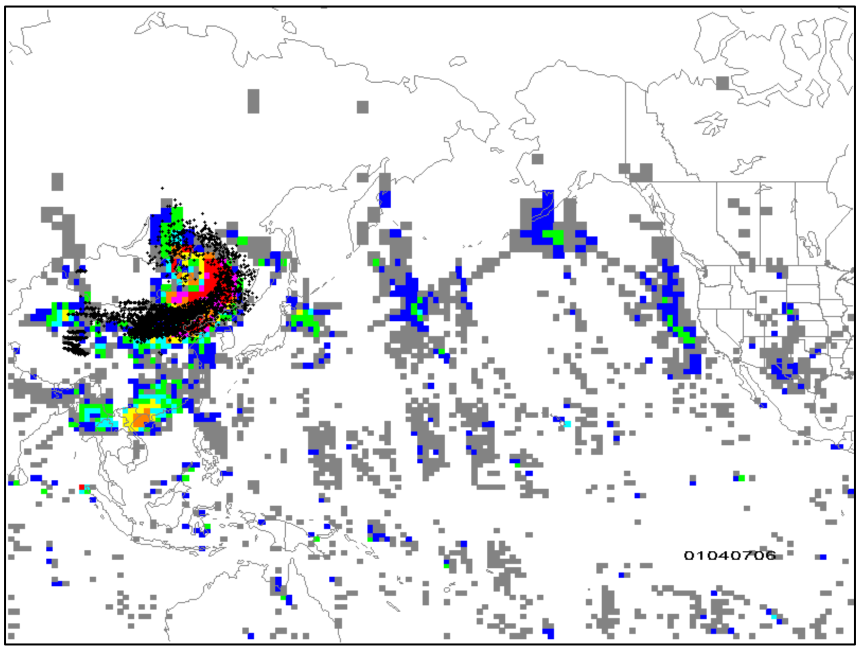
- **Dry Deposition**
  - βdry = Vd / ΔZp
  - Vd user defined; Vd = Vg; Resistance method
  - Vg gravitational settling (Stokes equation)

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

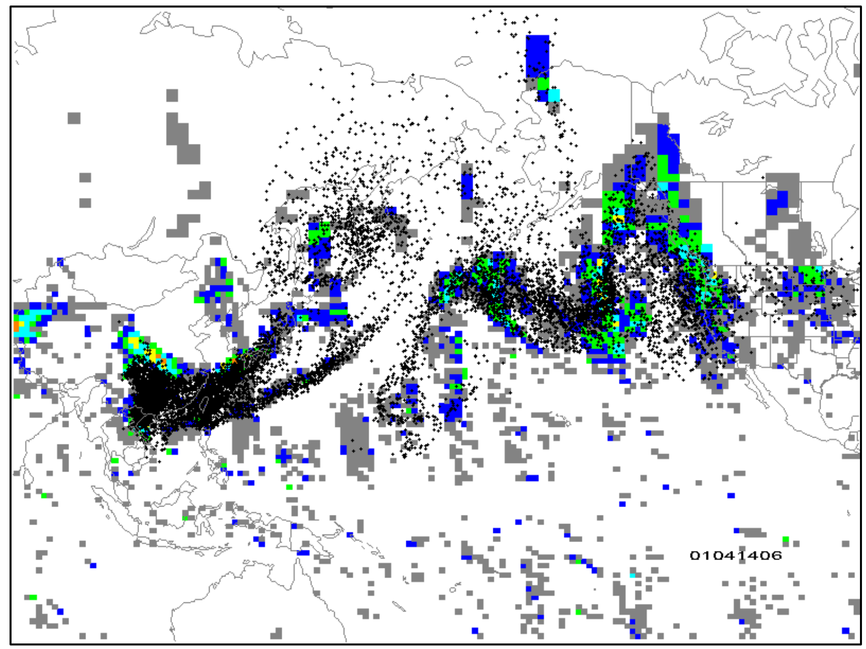
- **Particle Wet Deposition**
  - Within cloud: βinc = Vinc / ΔZp; Vinc = S P; $S=3.2 \times 10^5$
  - Below cloud: βbel = 5×10^{-5} s^{-1}

- **Gaseous Wet Deposition**
  - βgas = Vgas / ΔZ; Vgas = H R T P 10^3

China April 2001
Particle Distribution and TOMS Aerosol Index



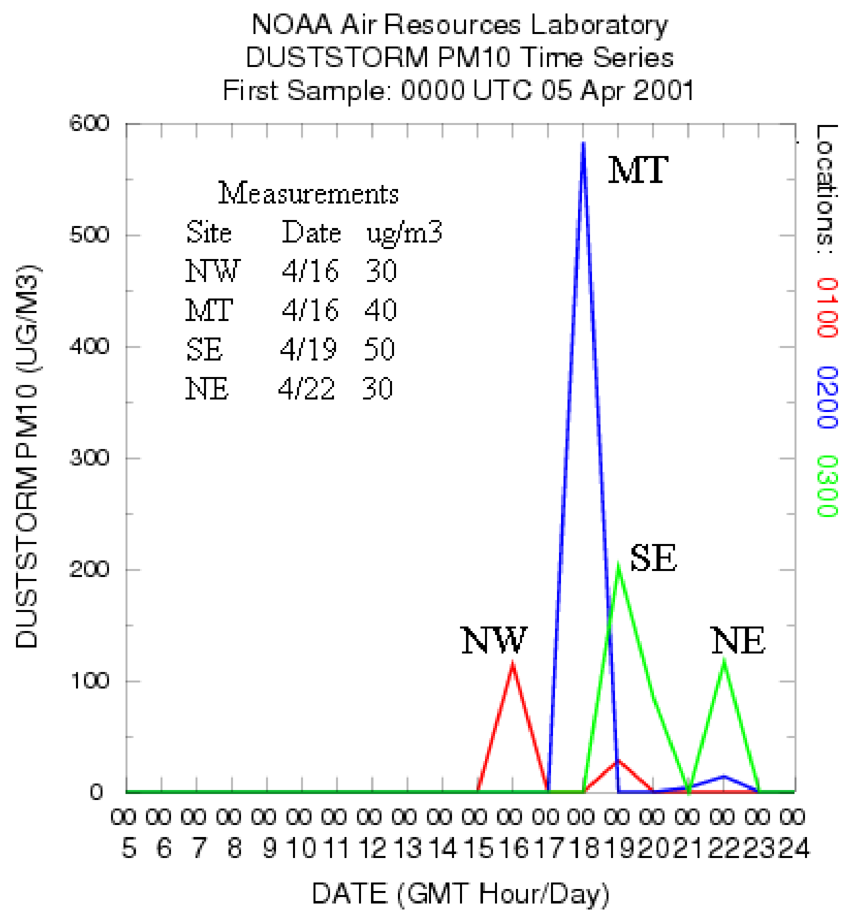
April 7th 0600 UTC



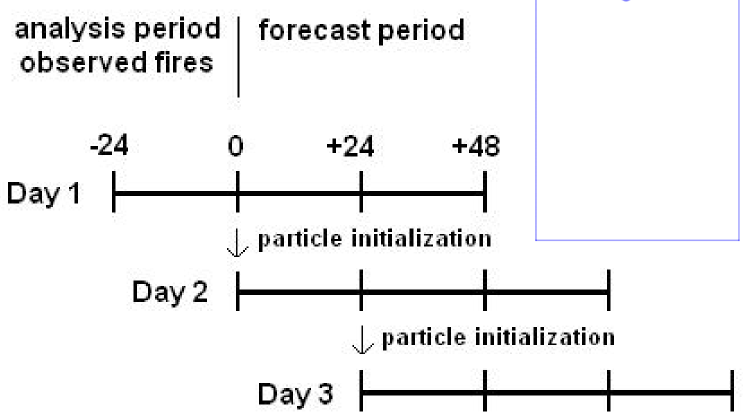
April 14th 0600 UTC

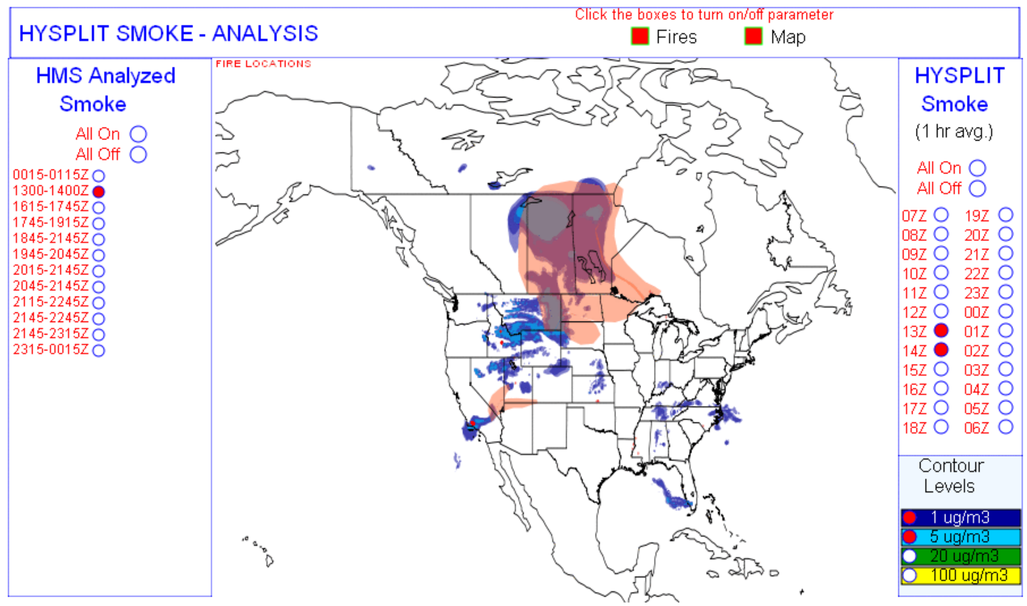
US PM_{10} Measurements from China Event

- First arrival in BL over the US around April 16th
- Model indicated spotty spatial distribution
- Arrival over eastern US between 19th and 22nd
- Predicted concentrations too high (in part because deposition was turned off)



Wild Fire Smoke Verification
http://www.arl.noaa.gov/smoke

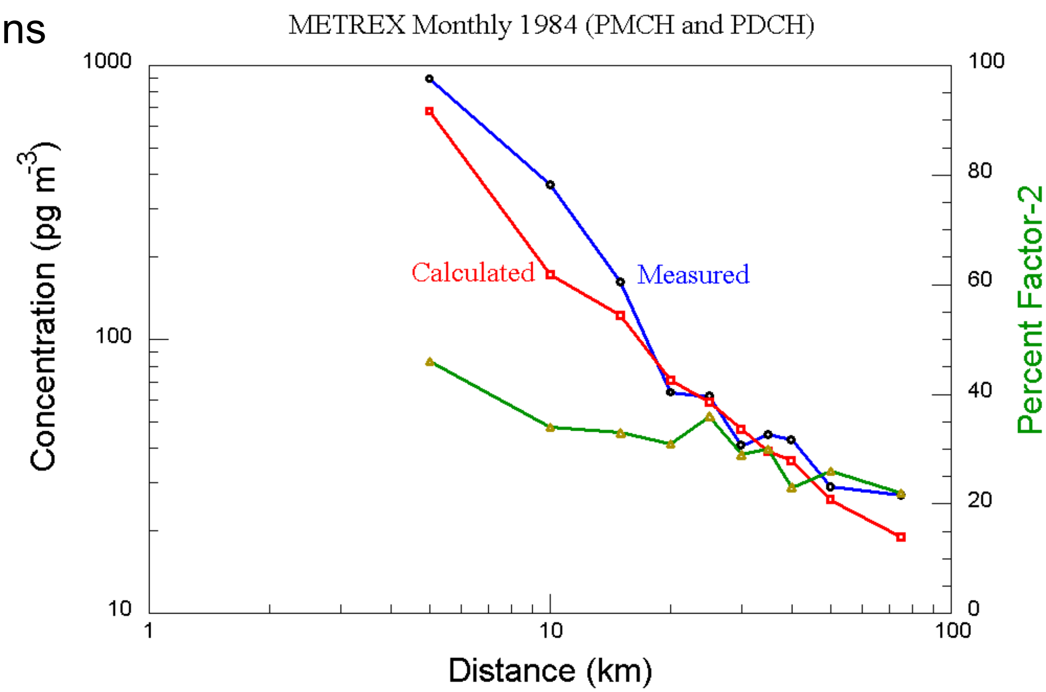




Local Scale Verification

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



Objective Verification for Sensitivity Testing

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

- 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

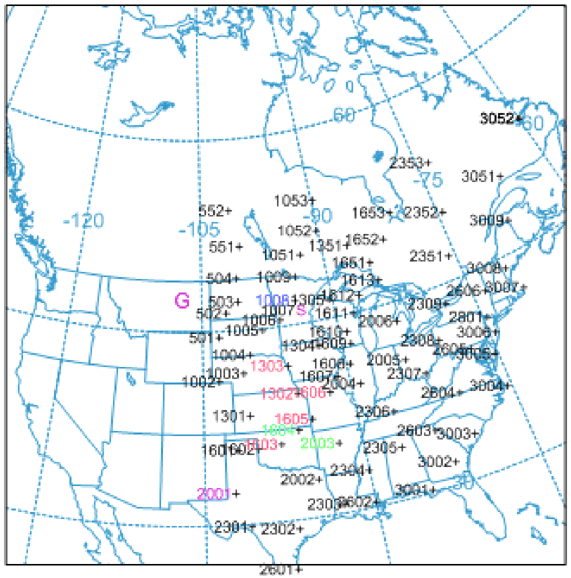
http://www.arl.noaa.gov/datem/results.html

EXPERIMENT	Average	Paired
ACURATE	3.25	1.77
ANATEX GGW	3.48	1.84
ANATEX STC	2.66	1.63
CAPTEX	3.24	1.63
[1]ETEX	2.37	1.55
[1]INEL74	1.71	1.37
METREX (t1)	2.81	1.77
METREX (t2)	2.27	1.58
OKC80	2.50	1.73

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

[1]NCAR/NCEP 2.5 degree reanalysis

Verification Example for ANATEX



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    76 Data points after temporal averaging
  0.00 Percentile input for zero measured
  0.00 Zero measured concentration value

  0.97 Correlation coefficient (P=99%)
 33.16 T-value (|Slope|/Standard Error)
 16.34 Average measured concentration
 22.43 Average calculated concentration
  1.37 Ratio of calculated/measured
 19.17 Normalized mean square error
    76 Number of pairs analyzed

  6.09 Average bias [(C-M)/N]
-19.58 Lo 99 % confidence interval
 31.76 Hi 99 % confidence interval
  0.31 Fractional bias [2B/(C+M)]

100.00 Fig of merit in space (%)

-30.26 Factor exceeding [N(C>M)/N-0.5]
 55.26 Percent C/M ± 2
 85.53 Percent C/M ± 5
100.00 Percent M>0 and C>0
  0.00 Percent M>0 and C=0
  0.00 Percent M=0 and C>0

 40.61 Measured   95-th percentile
 34.92 Measured   90-th percentile
 11.30 Measured   75-th percentile
  6.82 Measured   50-th percentile

 38.38 Calculated 95-th percentile
 20.72 Calculated 90-th percentile
  8.38 Calculated 75-th percentile
  4.16 Calculated 50-th percentile

 30.00 Kolmogorov-Smirnov Parameter

  3.48 Final rank (C,FB,FMS,KSP)
```

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