The NOAA HYSPLIT Atmospheric Transport and Dispersion Model: Recent Updates and Nuclear Applications

Mark Cohen[1], Tianfeng Chai[1,2], Alice Crawford[1], Hyun Cheol Kim[1,2], Chris Loughner[1], Todd McKinney[1,3], Fantine Ngan[1,2], Allison Ring[1,2], Sonny Zinn[1,4]

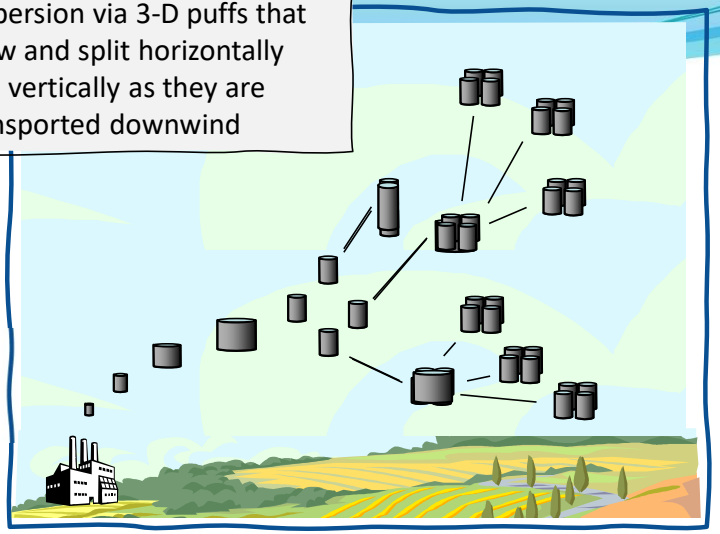
1. NOAA Air Resources Laboratory (U.S. Dept of Commerce, Oceanic and Atmospheric Research)
2. University of Maryland, Cooperative Institute for Climate and Satellites (CISESS)
3. University of Alabama, Huntsville
4. Earth Resources Technology, Inc.

2021 International MACCS Users Group (IMUG) Meeting
September 20-22, 2021 (Virtual)

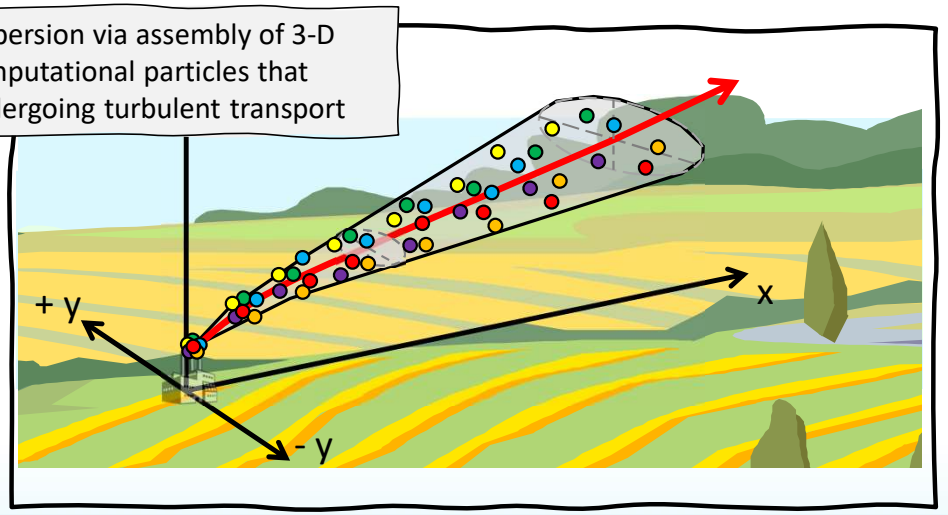
HYSPLIT Model

- **Continuous development** at NOAA Air Resources Laboratory (ARL) for more than 40 years
- ARL HYSPLIT **modeling group** (~10 scientists)
- **Trajectories** and **Dispersion**
- **Forward** and **Backward**
- **3-D Dispersion (generally > ~1 km)**:
  - Puffs (top-hat or Gaussian)
  - "Particles" (i.e., computational points)
  - Eulerian grid
- **Dry** and **Wet deposition**
- **Chemical** and **Radiological Transformations**
- **Simulation Modes:**
  - Run online (READY)
  - Download – run via Graphical User Interface
  - Download – run via command line and scripts
  - Windows, Mac, Linux
- **Users:**
  - Emergency response & science at NOAA
  - Emergency response & science - other agencies (e.g., MACCS)
  - Scientific community: e.g., Stein et al. 2015 ~ 3000 citations

Dispersion via 3-D puffs that grow and split horizontally and vertically as they are transported downwind

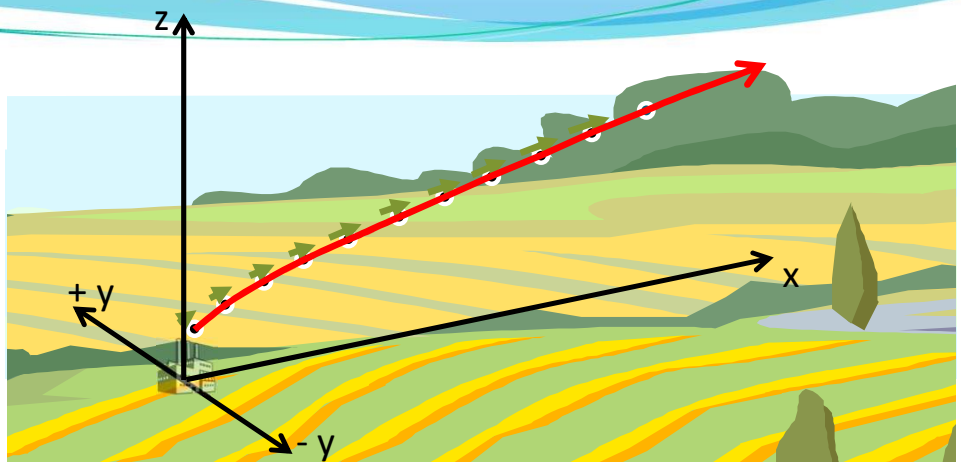


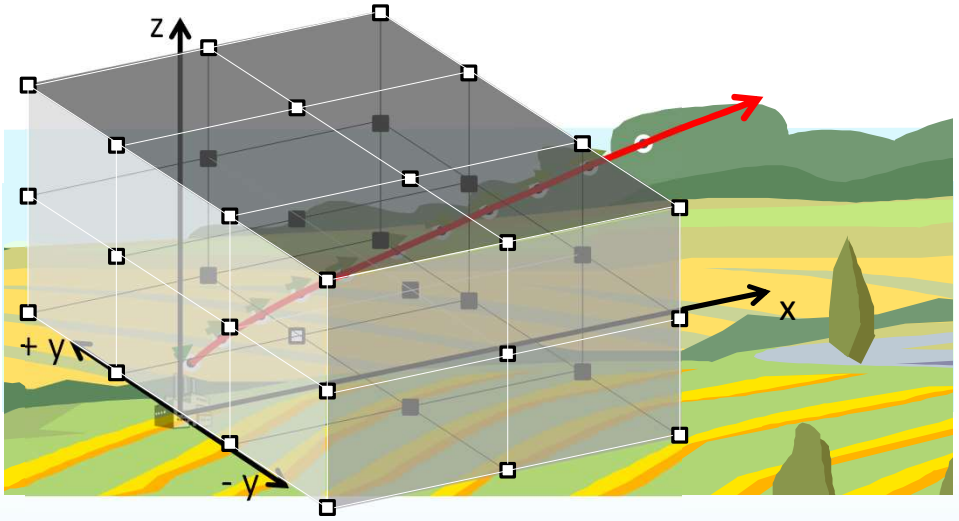
Dispersion via assembly of 3-D computational particles that undergoing turbulent transport



Met Data for HYSPLIT: Overview

- HYSPLIT is driven by gridded meteorological data, required as an "input"
  - Data must be supplied in ARL Packed Format
  - Conversion programs exist to convert most met model output data to ARL Packed Format
  - There is also an inline version of HYSPLIT embedded within the WRF meteorological model
- NOAA has several forecast and reanalysis datasets in HYSPLIT format
  - CONUS+ grids (e.g., 3 km HRRR; 12 km NAM)
  - CONUS+ 27km WRF reanalysis
  - Global grids (e.g., 0.25 deg GFS)
- HYSPLIT interpolates spatially and temporally to estimate meteorological variables at any given point in the simulation domain
- Can have multiple meteorological grids during the same simulation (e.g., local, regional and global), and HYSPLIT will use the finest grid at any location
- Ability to treat complex terrain? Largely depends on resolution / capability of meteorological model output used to drive HYSPLIT



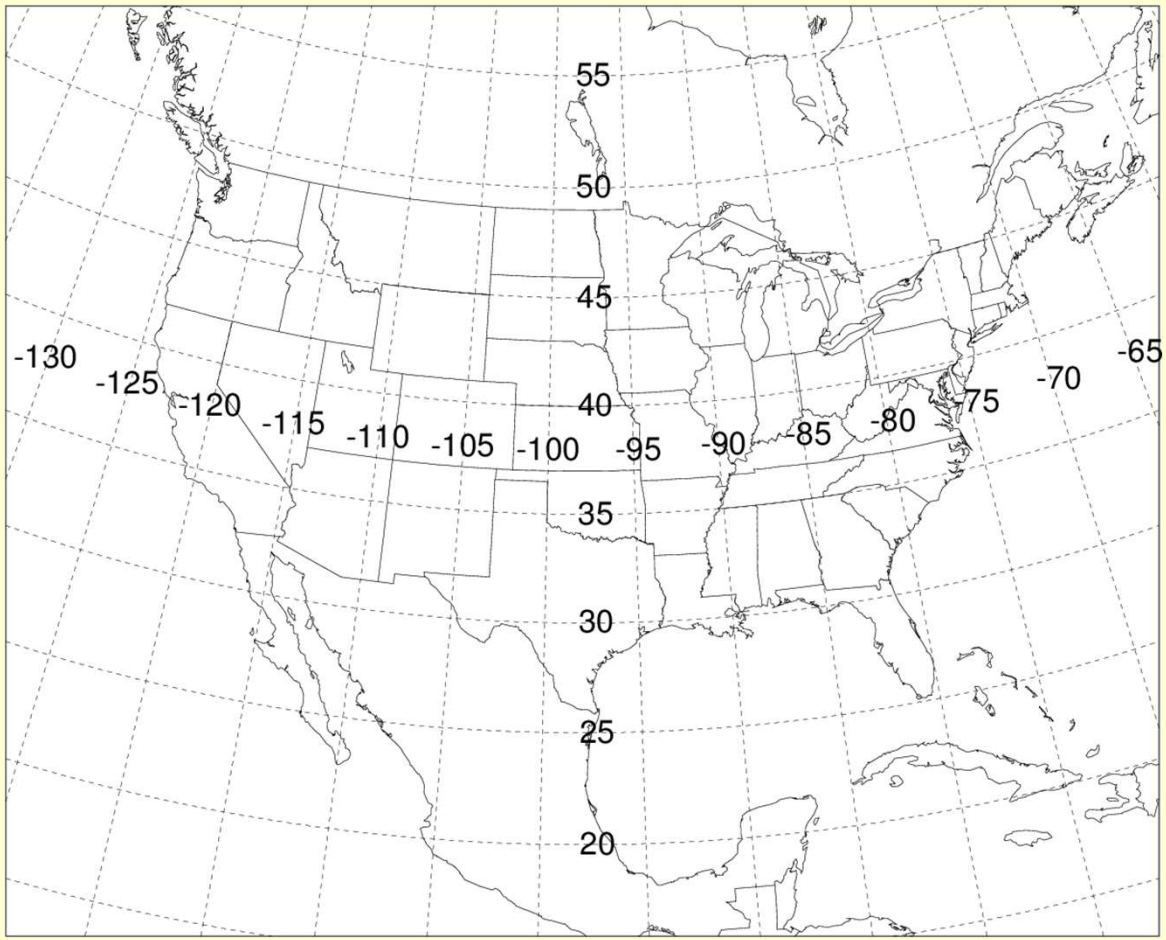


Selected Meteorological Datasets Available from NOAA ARL Archives* (~100 TB)

(https://ready.arl.noaa.gov/archives.php)

	Dataset	Horizontal Resolution (km- approx.)	Full-grid dimensions	Temporal resolution (hrs)	Vertical Levels	Period of each file	Size of each file (GB)	Total size for one month of data (GB)	Availability
Continental U.S. and surrounding regions	HRRR-3km	3	1799 x 1059	1	37	¼ day	3.2	390	Jun 2015 -> present
	NAMS-12km Hybrid	CONUS - 12 Alaska - 12 Hawaii – 2		1	40	1 day	1.0 0.64 0.71	30 19 21	2010 -> present
	NAM-12km	12	614 x 428	3	27	1 day	0.395	12	May 2007 -> present
	WRF-ARW-27km	27	216 x 174	1	35	1 day	0.210	6.4	1980 -> present
	NARR-32km	32	309 x 237	3	24	1 month	2.8	2.8	1979 -> 2019
	EDAS-40km	40	185 x 129	3	27	½ month	0.6	1.2	2004 -> 2018
Global	GFS - 0.25°	27	1440 x 721	3	56	1 day	2.7	82	Jun 2019 -> present
	GDAS - 0.5°	55	720 x 361	3	56	1 day	0.468	14	Sep 2007 -> Jun 2019
	GDAS - 1°	111	360 x 181	3	24	1 week	0.571	2.5	Dec 2004 -> present
	Global Reanalysis - 2.5°	278	144 x 73	6	18	1 month	0.11	0.11	1948 -> present

Domain of WRF-ARW-27km met data set



Horizontal spacing ~27 km

35 vertical levels

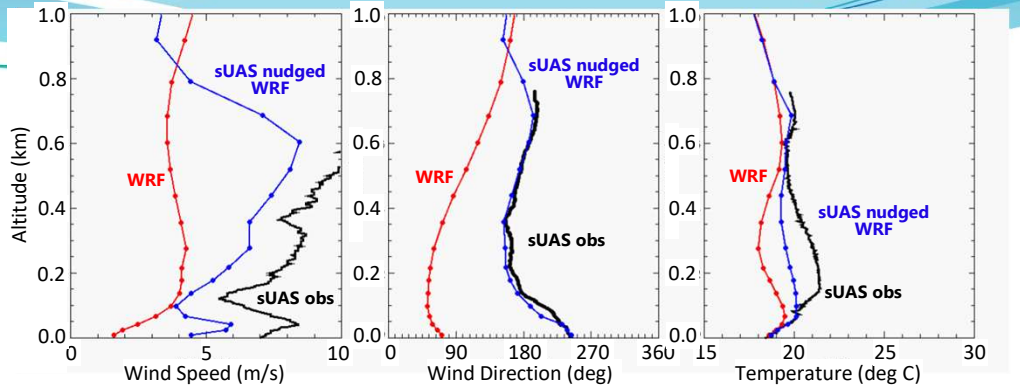
Data every hour

Each file is for one day

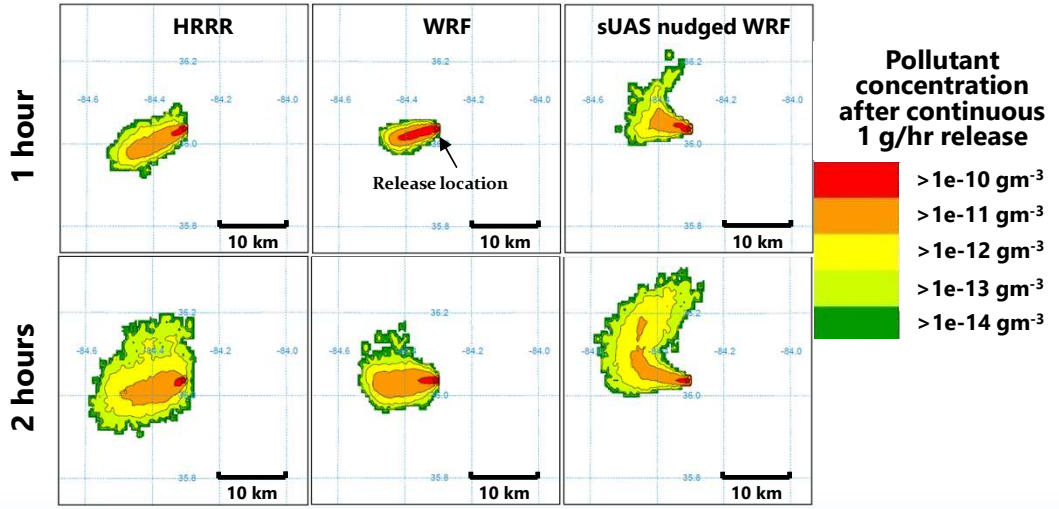
(~210 MB per file)

Met Data for HYSPLIT: New

- Time-averaged WRF-27km reanalysis in addition to snap-shot dataset
- Ensemble met data sets to produce ensemble dispersion products
  - HREF: High Resolution Ensemble Forecast
  - GEFS: Global Ensemble Forecast System
- Drone-based met measurements, i.e., from small uncrewed aircraft systems (sUAS)
- ***Emerging:*** Evaluating met data sets for dispersion applications
- ***Emerging:*** High-resolution simulations in urban environments
  - Supported by high-resolution urban meteorological measurement mesonets, e.g., DC-Net (new Lidar on top of Hoover Building)



1 km profiles of wind speed (left), wind direction, (middle), and temperature (right) collected via sUAS observation (black), WRF model (red), and sUAS-data nudged WRF model (blue).

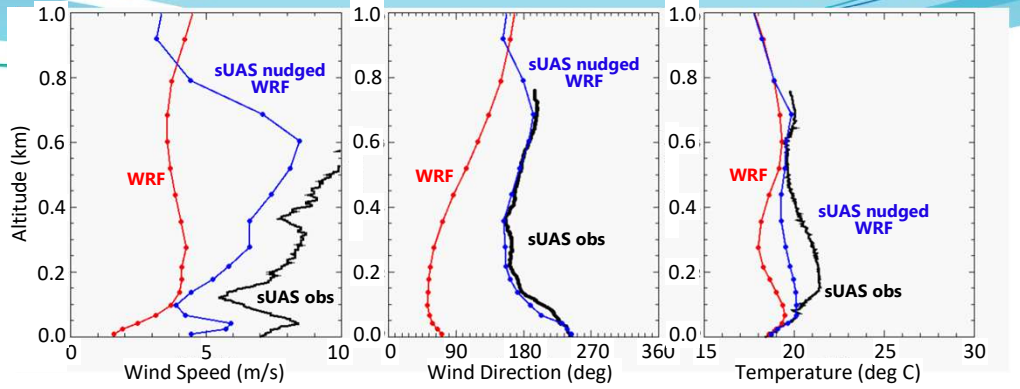


HYSPLIT-simulated pollutant concentrations 1 hour (top) & 2 hours (bottom) after release (1 g hr^{-1}) using HRRR (left), WRF, (middle), sUAS-nudged WRF (right).

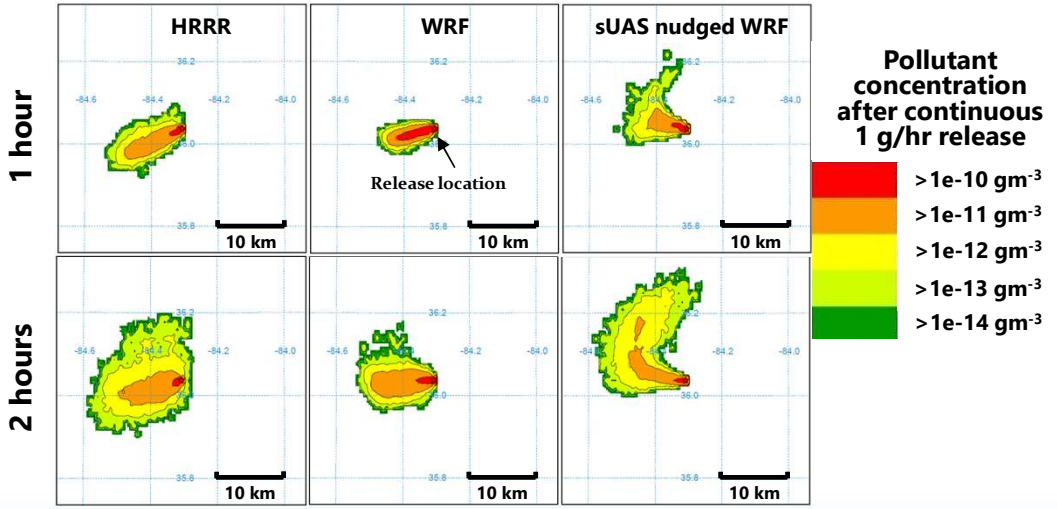
Small Uncrewed Aircraft System (sUAS) – "Drone" Data Assimilation

Meteomatics Meteodrone SSE

- Vertical profiles of temperature, moisture, and wind (u,v) were collected by NOAA ARL ATDD via a Meteomatics Meteodrone SSE (sUAS) (0 – 700m agl)
- System continuously looks for new sUAS data and automatically converts to HYSPLIT format files; met data from other NWS forecast data products appended at heights above sUAS profile
- sUAS data also used to nudge new WRF simulation in local region → reduced the discontinuity between drone-only & existing NWP domain → improved modeled wind speed, wind direction, and temperature.
- User specifies whether HYSPLIT uses:
  - Existing NWP data product (e.g., 3 km HRRR);
  - sUAS data + existing NWP model;
  - sUAS-nudged WRF + existing NWP model.



1 km profiles of wind speed (left), wind direction, (middle), and temperature (right) collected via sUAS observation (black), WRF model (red), and sUAS-data nudged WRF model (blue).



HYSPLIT-simulated pollutant concentrations 1 hour (top) & 2 hours (bottom) after release (1 g hr^{-1}) using HRRR (left), WRF, (middle), sUAS-nudged WRF (right).

HYSPLIT Resolution Overview

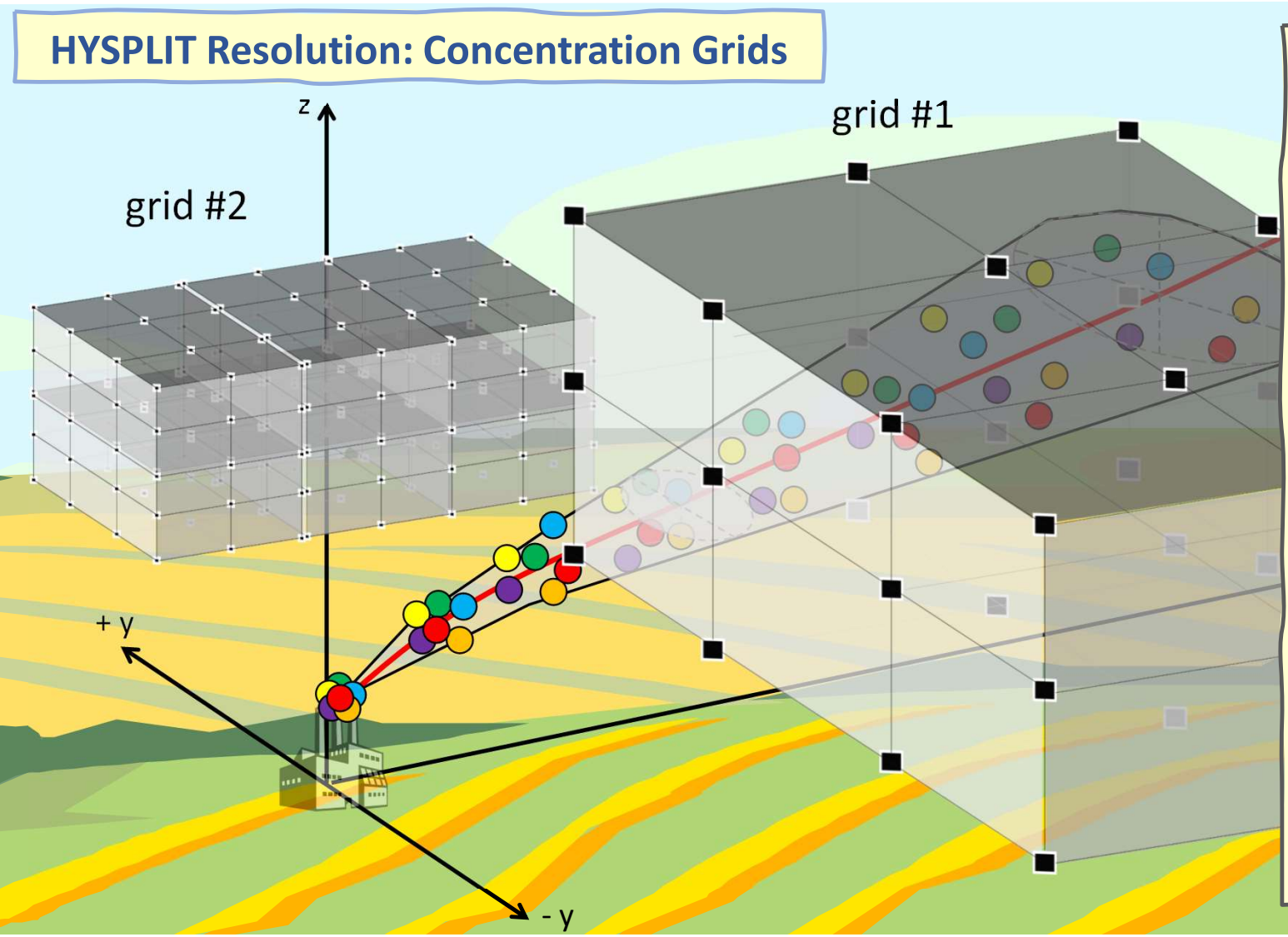
+ New

- HYSPLIT is driven by gridded meteorological data, generally supplied as an "input"
  - This gridded met data will have a temporal and spatial resolution that will affect the accuracy of the transport and dispersion simulation
  - HYSPLIT interpolates in time and space between met model data grid points to try to estimate the met data at any location/time in the simulation domain
- HYSPLIT simulations will have one or more concentration grids that are specified by the user
  - These conc grids each have their own user-defined temporal, horizontal, and vertical resolution
  - Resolution of the conc grids are independent and completely separate from the resolution of the met data grids
  - Note – the same concentration grids are also used to track deposition

- Minimum time step in HYSPLIT is 1 minute
  - this governs transport & dispersion; deposition; and concentration outputs
  - 3 m/sec wind → 180 meters in 1 minute
  - Interpolation routine in output algorithm fills in space between starting and ending position to avoid leap-frogging over concentration grid squares
  - But, no met data finer than 1 minute is used
  - In most cases, we do not have met data with temporal resolution of less than 1 minute… (*exception:* HYSPLIT in-line with WRF)

- We are considering decreasing the minimum time step down to 1 second; this may offer some advantages for very near-field simulations

HYSPLIT Resolution: Concentration Grids



You can define more than one grid, each with its own specifications.

Depending on where the grid is and which way the wind is blowing during the simulation, you might not get any computational point particles in the grid, and all concentrations in the grid will be zero.

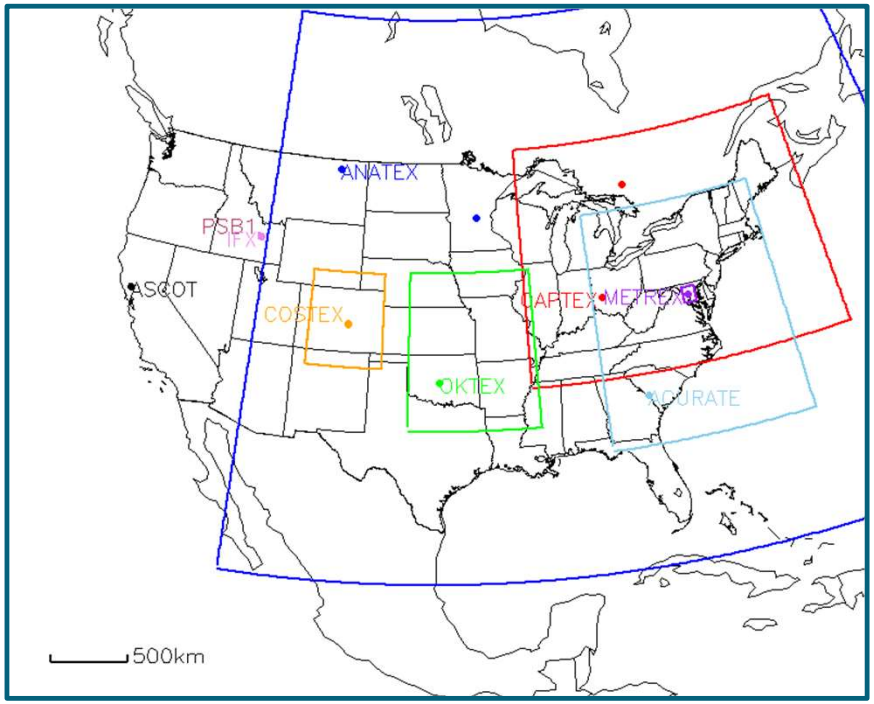
If a grid has very fine spacing, you might need to increase the number of computational point particles released in the simulation.

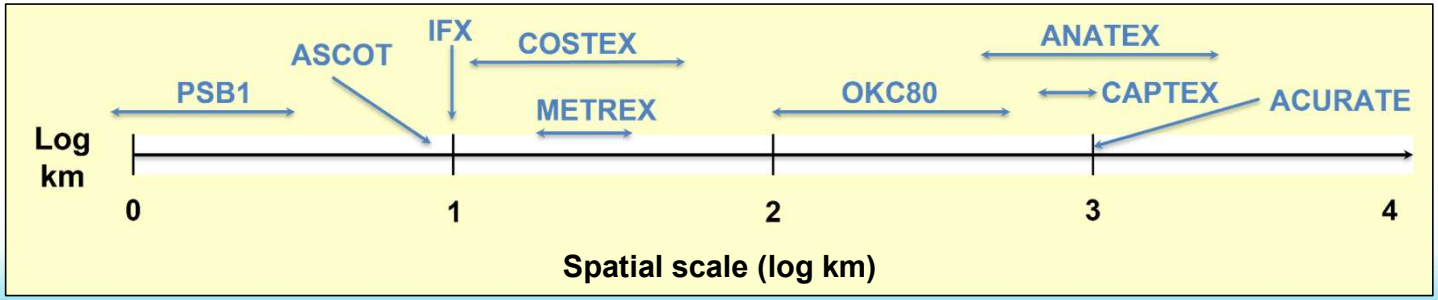
The particles are “discrete” and if there are too few of them, you aren’t really representing the continuous plume, and you can get very blotchy results.

HYSPLIT Model Evaluation + Improvement with Tracers

- **Intentional Tracers**
  - Past tracer experiments → DATEM system

Experiments	Range (km)	Range (log km)
ACURATE	1000	3.0
ANATEX	500-2800	2.7-3.4
CAPTEX	800-1000	2.9-3.0
OKC80	100-600	2.0-2.8
METREX	20-30	1.3-1.5
COSTEX	10-50	1-1.7
IFX	10	1
ASCOT	10	1
PSB1	0.2-3.2	-0.7-0.5

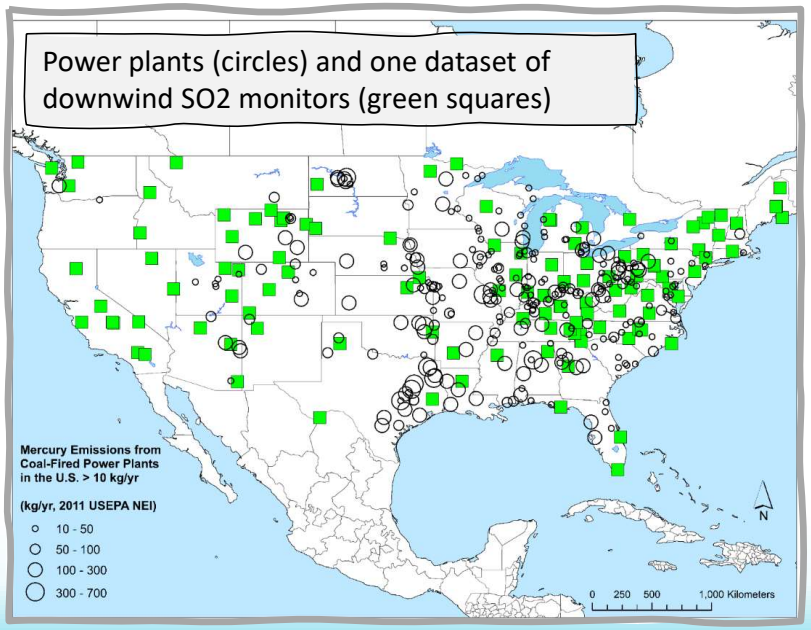




HYSPLIT Model Evaluation + Improvement with Tracers: New

- **Intentional Tracers**
  - New analysis of past tracer experiments
  - Additional past tracer experiments being collected and added to DATEM when possible
  - High-altitude balloons
  - New tracer expts? → maybe, but resource intensive…
  - *Upcoming:* In-situ drone-based chemical measurements within plumes (with Brian Gullett, USEPA)
- **Tracers of Opportunity**
  - Situations where emissions relatively well known and downwind measurements exist (or can be taken)
    - E.g., SO_2 and CO_2 emissions from power plants, where emissions data measured via Continuous Emissions Monitoring Systems (CEMS), coupled with downwind SO_2 and CO_2 measurements

Tracked, high-altitude balloons circling the earth (Todd McKinney, Univ of Alabama, Huntsville)



Reanalysis of previous tracer experiments

Summary of three sets of HYSPLIT simulations

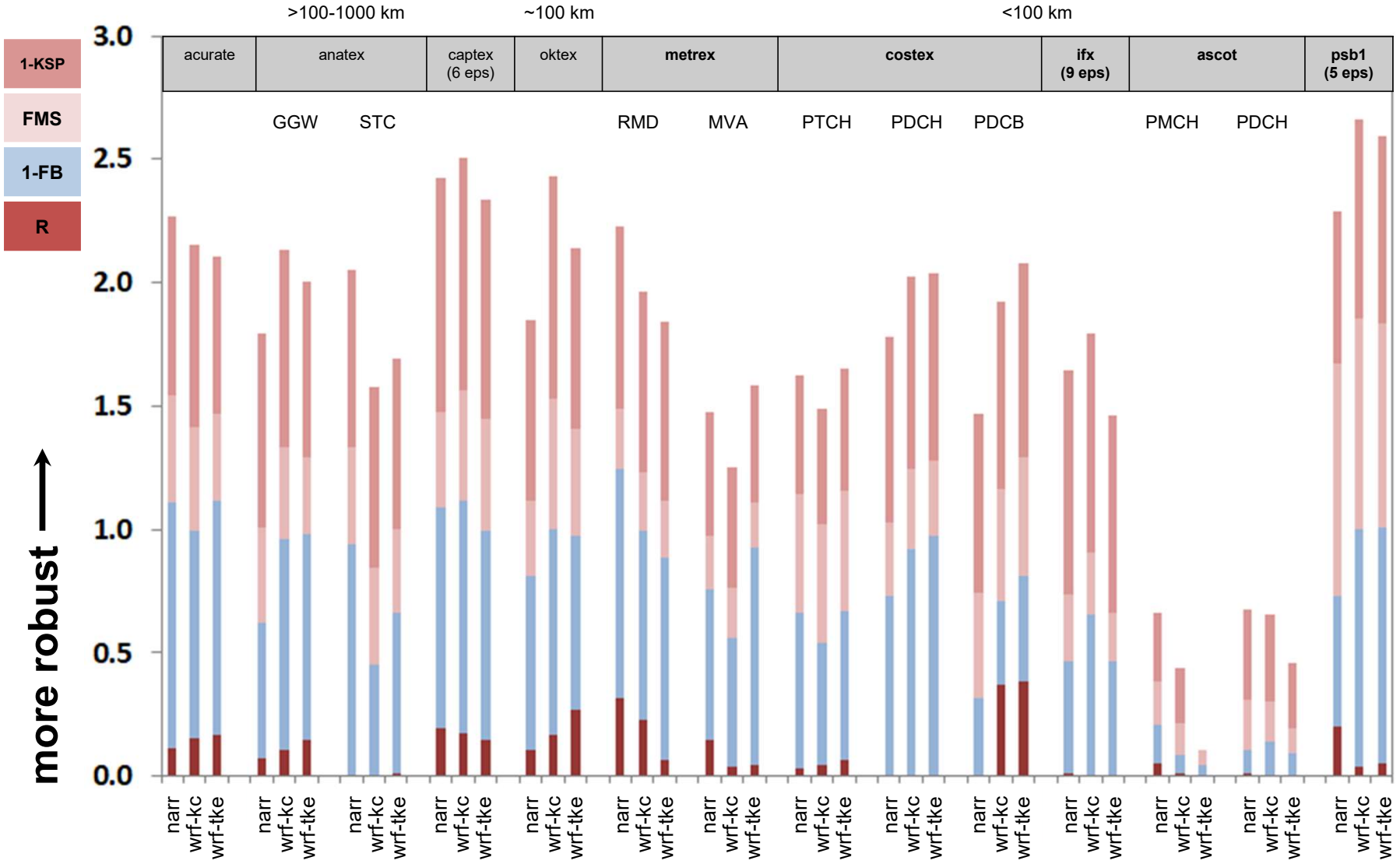
name	Met data	Model wind	HYSPLIT PBL stability (KBLS)	HYSPLIT mixing (KBLT)
narr	NARR	Instantaneous wind	Wind/Temp profiles	TKE
wrf-kc	WRF	Instantaneous wind	Heat/momentum flux	Kantha-Clayson
wrf-tke	WRF	Time-averaged wind	Heat/momentum flux	TKE

Statistical Rank

Rank, a cumulative statistical score (range between 0-4) (Draxler, 2006))

$$Rank = R^2 + 1 - \left|\frac{FB}{2}\right| + \frac{FMS}{100} + \left(1 - \frac{KSP}{100}\right)$$

R – correlation coefficient, FB – fractional bias,
FMS – figure of merit in space, KSP – Kolmogorov-Smirnov parameter


>100-1000 km
~100 km
<100 km
1-KSP
FMS
1-FB
R
more robust
3.0
2.5
2.0
1.5
1.0
0.5
0.0
acurate
anatex
captex (6 eps)
oktex
metrex
costex
ifx (9 eps)
ascot
psb1 (5 eps)
GGW
STC
RMD
MVA
PTCH
PDCH
PDCB
PMCH
PDCH
narr
wrf-kc
wrf-tke

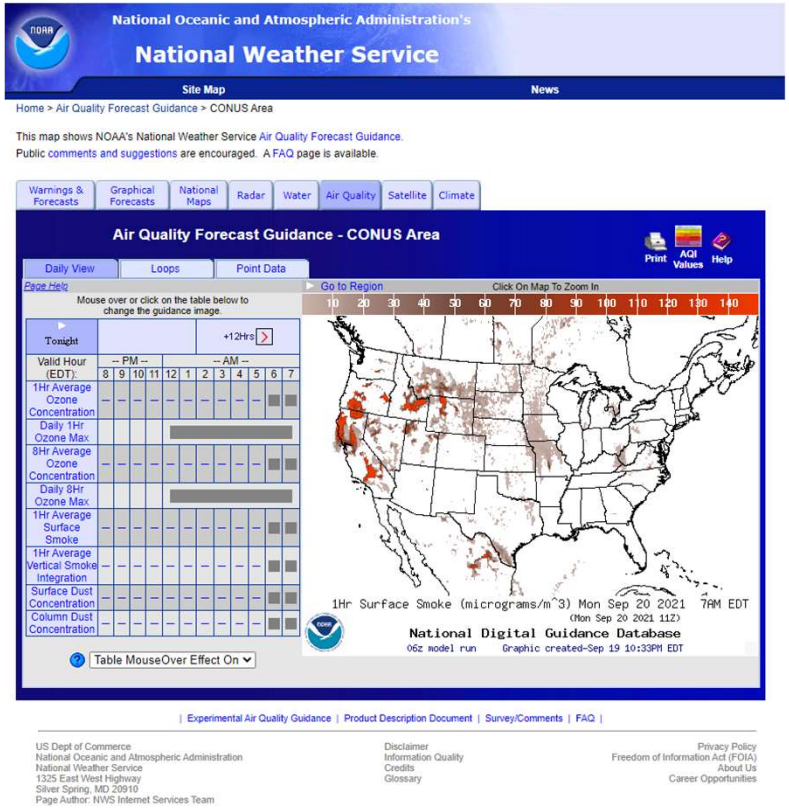
Emergency Response Overview

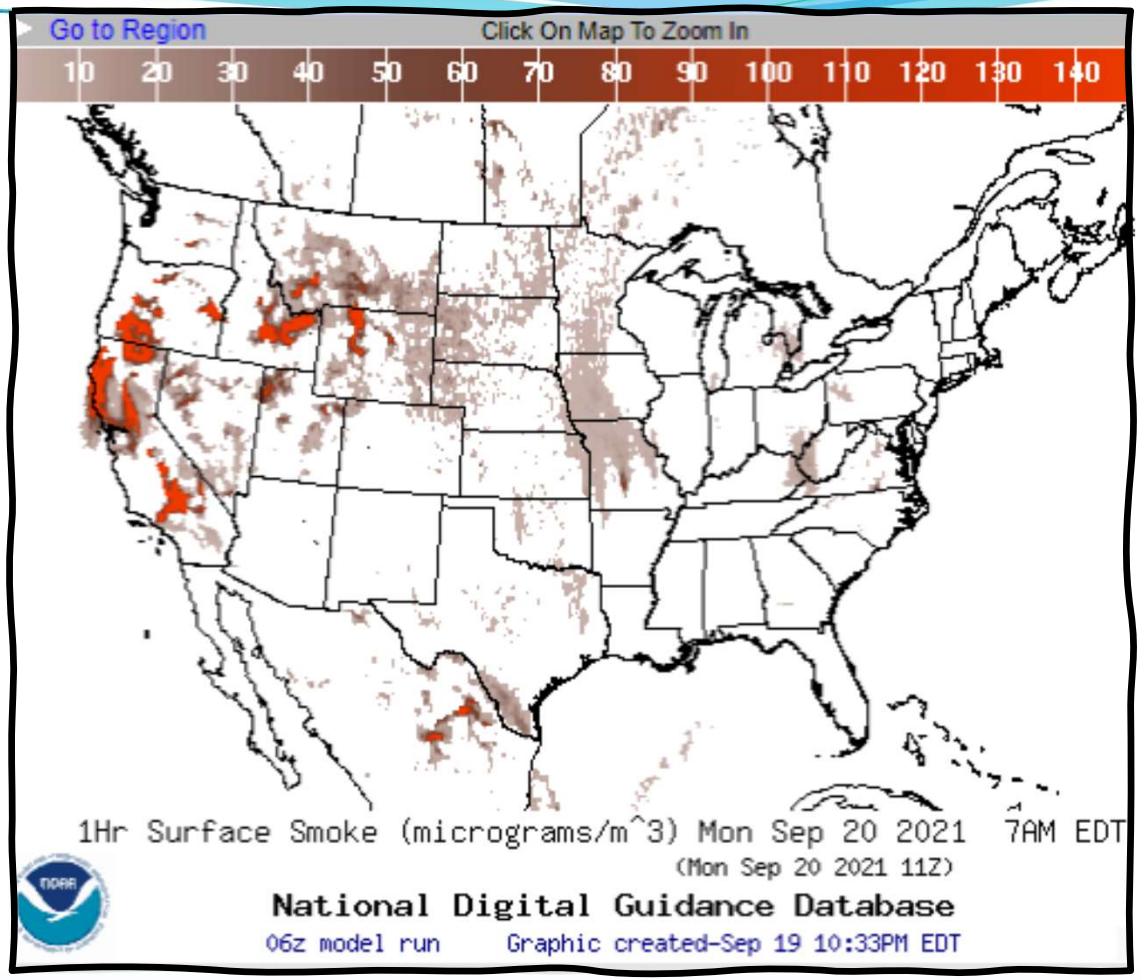
- **Nuclear**
  - Regional Specialized Meteorological Center (RSMC) (description; products)
  - ***New:*** Transfer Coefficient Matrix approaches
  - ***New:*** use of HYSPLIT with MACCS
- **Volcanoes**
  - Washington Volcanic Ash Advisory Center (VAAC) provides warnings to civilian aircraft
  - ***New:*** (a) satellite-based plume adjustment methodologies; (b) ensemble-based, quantitative, probabilistic forecasts
- **Wildfires**
  - NOAA operational wildfire forecast system
  - ***New:*** alternative plume rise algorithms; ***New:*** emissions estimation methodologies; ***New:*** ensemble forecast approaches:

    Li, Y., et al. (2020). Ensemble PM2.5 forecasting during the 2018 Camp Fire event using the HYSPLIT transport and dispersion model. *Journal of Geophysical Research: Atmospheres*, *125*, e2020JD032768. https://doi.org/10.1029/2020JD032768
- **Industrial / Transportation Accidents**
  - NWS-HYSPLIT: at NOAA Weather Forecast Offices to support local emergency response to release of toxic chemicals
  - ***New:*** ensemble-based dispersion forecasts
- **Locust Migration**
  - ***New:*** Collaboration with UN Food and Agriculture Organization (Keith Cressman) to create HYSPLIT-based tools to forecast locust migration based on airborne paths, coupled with daily take-off and landing times

Example: Wildfire Smoke Forecasts

https://airquality.weather.gov/sectors/conus.php





NOAA ARL Nuclear Emergency Assistance Applications

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

- RSMC applications
- CTBTO backtracking support
- Other radioactivity applications

RSMC – products for nuclear environmental emergency response

ready.noaa.gov/rsmc2-bin/jntrsmc.pl

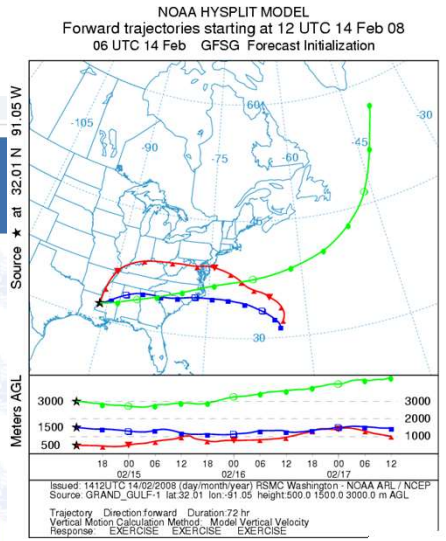
REGIONAL SPECIALIZED METEOROLOGICAL CENTER (RSMC)

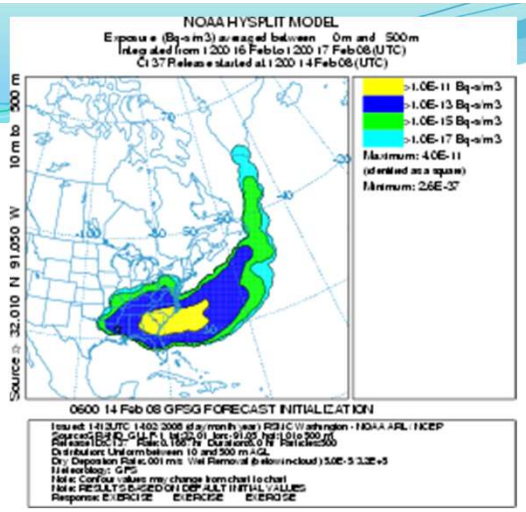
TRANSPORT MODEL PRODUCTS

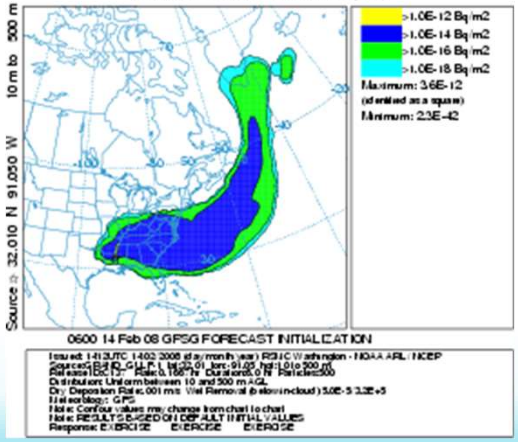
The following are current (as of the date indicated in the table) operational RSMC products as established by **The World Meteorological Organization (WMO)** for the provision of transport model products for environmental emergency response. To view a product click on the text link or click on one or more checkboxes and then click on the **Request checked boxes** button at the bottom of the form. Details on the model products can be found in **WMO/TD-No. 778**. The lead RSMCs are highlighted in yellow shading. To ensure the latest update, refresh/reload your browser.

For all (current and past) model results, click on the link titled, "**All Products**" in the first column of each RSMC.
"**No archive**" is displayed if no additional products are available.

RSMC TIME OF MODEL RUN (YYYYMMDDCC_HHMM)	MODEL PARAMETERS	JOINT STATEMENT	VIEW PRODUCTS	TRAJECTORIES	TIME PERIOD 1 +24 HRS	TIME PERIOD 2 +48 HRS	TIME PERIOD 3 +72 HRS
Washington Unavailable	Cover (Postscript)	Region III/IV	Check All / Uncheck All	Trajectories (traj.txt)	Exposure / Deposition	Exposure / Deposition	Exposure / Deposition



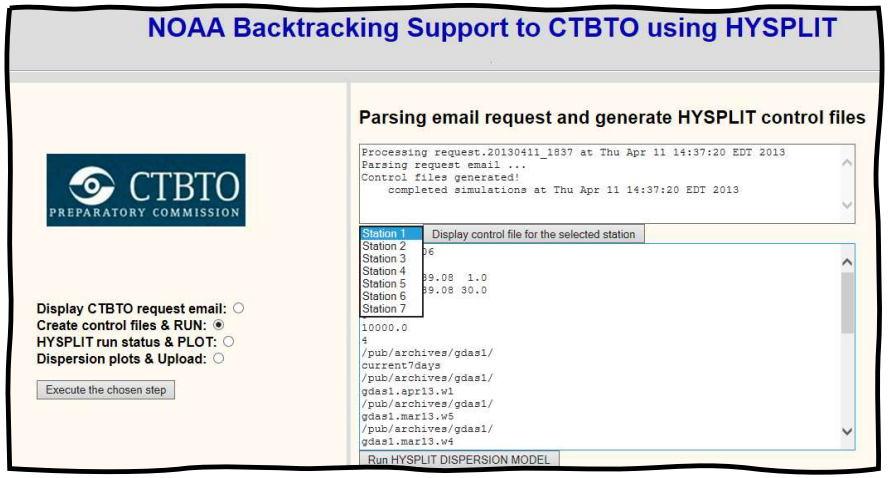


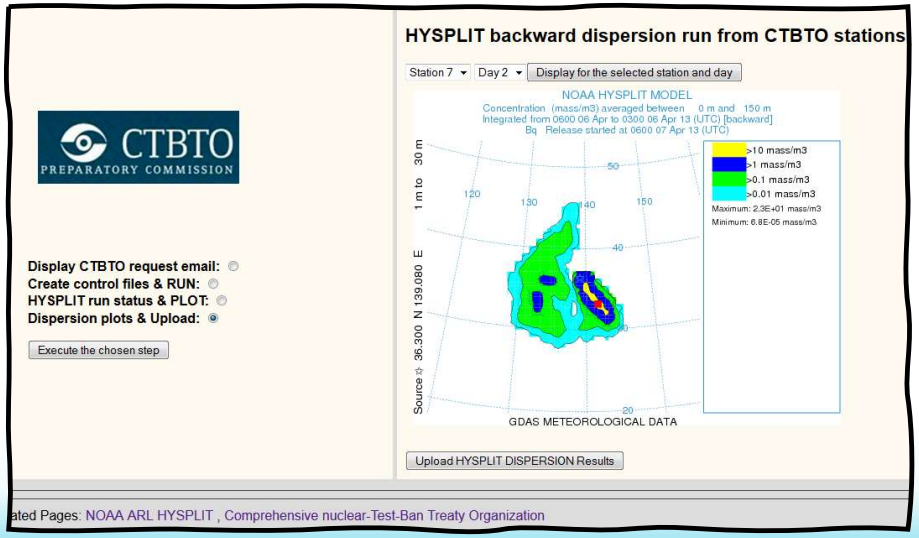


- Time of arrival products are also available
- RSMC TCM products are being developed

Source Estimation via Inversions of Observations

- **Nuclear – CTBTO (Comprehensive Nuclear Test Ban Treaty Organization)**
  - On-demand backward dispersion results are sent to CTBTO for their source term estimation (location and strength)
  - Such measurement-based backward runs can be adapted to estimate source terms in other radioactivity emergence response problems.





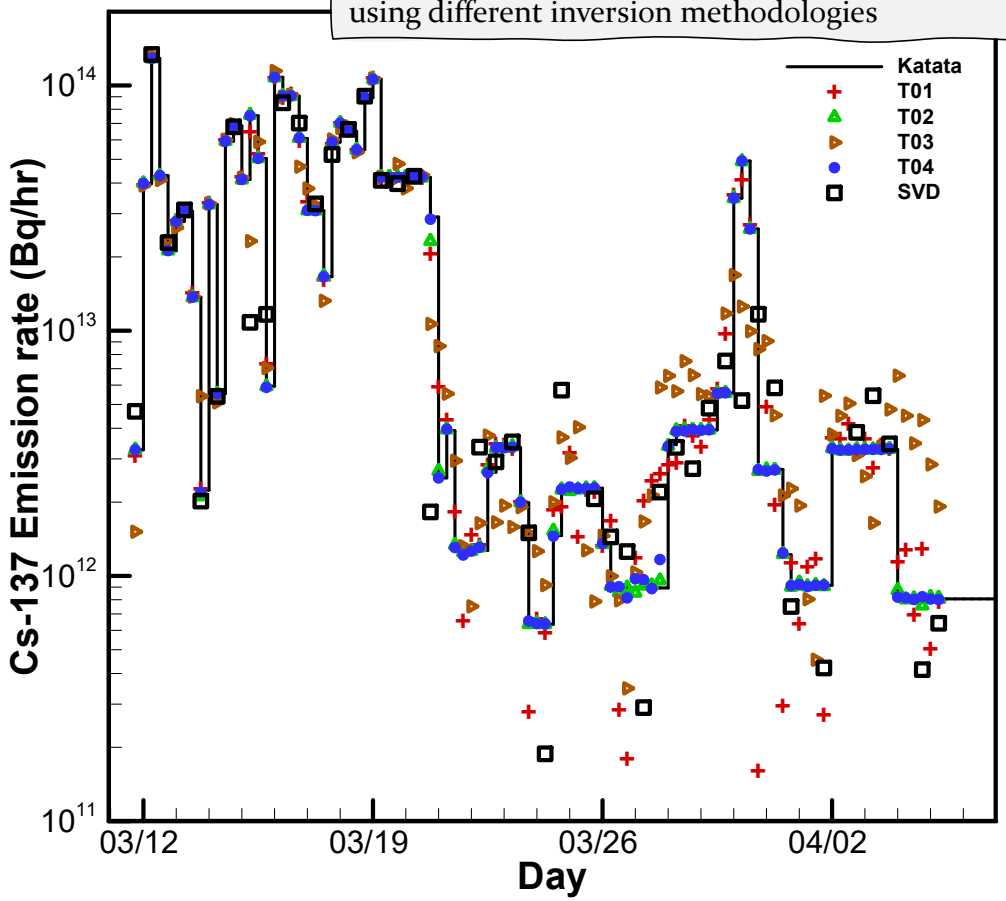
Source Estimation via Inversions of Observations

- **Nuclear - Fukushima**

Chai et al. (2015). Source term estimation using air concentration measurements and a Lagrangian dispersion model -- Experiments with pseudo and real cesium-137 observations from the Fukushima nuclear accident. *Atmos Envr* **106**:241-251 http://dx.doi.org/10.1016/j.atmosenv.2015.01.070

- Emission inversion has been built based on a Lagrangian model and a cost function.
- Cs-137 releases from Fukushima accident were recovered using global measurements.
- Using ln(c) differences in the cost function is better than using concentrations.
- Inversion is not sensitive to observational errors or different first guesses.
- A temporal smoothness penalty can remove artificial variability from the results.

Fukushima emissions estimated from observations using different inversion methodologies

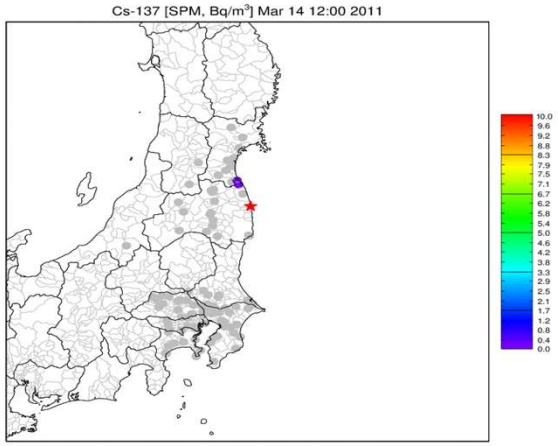


Source Estimation via Inversions of Observations: New

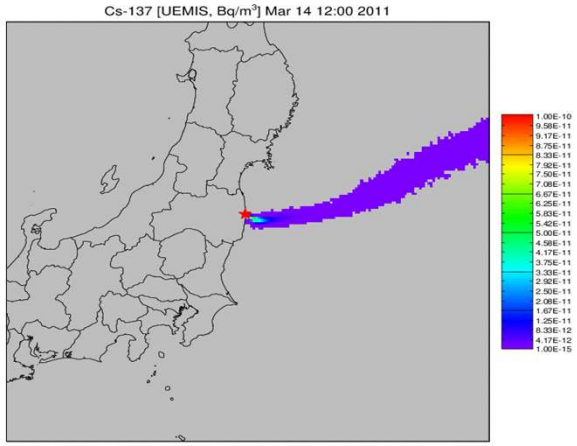
- **Nuclear**

Kim H., Chai, T., et al. (2021): HYSPLIT-based Emissions Inverse Modeling System (HEIMS) (in preparation)

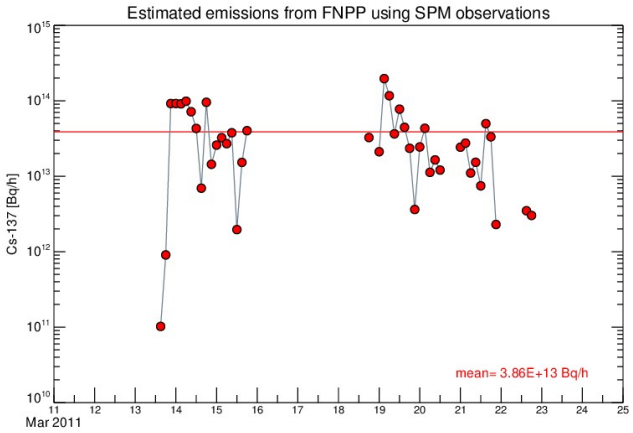
- New quasi-operational system being developed in collaboration with Korean Institute of Nuclear Safety (KINS)
- Being tested against Fukushima data



Cs-137 concentrations (SPM monitors)



Unit emission simulation (HYSPLIT)



Estimated Cs-137 emissions (HEIMS)

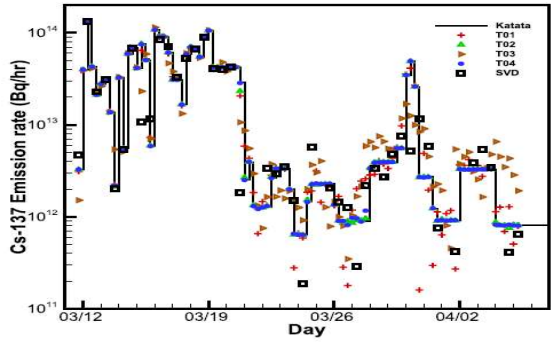


Fig. 5. Cs-137 release estimates from twin experiments T01-04 and solution using singular value decomposition (SVD). Cs-137 release estimates by Katata et al. (2014) are shown for comparison.

Previous results (Chai et al. 2015)

Source Estimation via Inversions of Observations: New (other)

- **Wildfires**
  - Kim, H. C., Chai, T., Stein, A., and Kondragunta, S. (2020): Inverse modeling of fire emissions constrained by smoke plume transport using HYSPLIT dispersion model and geostationary satellite observations, *Atmos. Chem. Phys*., **20**, 10259–10277, https://doi.org/10.5194/acp-20-10259-2020
- **Volcanoes**
  - Ongoing work in collaboration with NOAA NESDIS to estimate volcanic ash and SO_2 emissions from inversions of satellite observations and downwind concentration measurements. (Crawford, A., Ring, A., Chai, T., Pavolonis, M, et al. – *in preparation*)
- **Greenhouse Gases**
  - New project using HYSPLIT-based inversions to estimate GHG emissions in urban areas (Loughner, C. , et al. – *in preparation*)
- **Point-Sources**
  - Inversion of aircraft measurements downwind of power plants to estimate SO_2, NO_x, and CO_2 emissions (Chai, T., Ren, X., et al – *in preparation*)
- **Re-incorporation of STILT features into HYSPLIT**
  - Loughner, C., Fasoli, B., Stein, A., and Lin, J. (2021). Incorporating Features from the Stochastic Time-Inverted Lagrangian Transport (STILT) Model into the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) Model: A Unified Dispersion Model for Time-Forward and Time-Reversed Applications. *Journal of the American Meteorological Society* **60**(6): 799-810. https://doi.org/10.1175/JAMC-D-20-0158.1

Model physics – selected recent updates

- **Random numbers – turbulence treatments**
  - (2019) - Changed how turbulent velocity is initialized. New namelist variable VINIT = 1 (default) initializes turbulent velocity by drawing from distribution; VINIT = 0 initializes turbulent velocity to zero
- **Random numbers – non dispersion procedures**
  - (2020) new KRAND options for more user control over initial seeds for random number generation
- **Model vertical structures**
  - (2020) - Increased compatibility with WRF hybrid vertical coordinate system
  - (2021) - More user control over model vertical levels
- **Buoyancy-driven plume-rise algorithms**
  - Existing: Briggs (based on point source observations)
  - (2020) - New for wildfires: Sofiev
  - (2022) - Upcoming for wildfires: Freitas
- **Dust emissions**
  - (2022) – Upcoming: FENGSHA algorithm

Model features – selected recent updates

- **more functionality for polar concentration grids**
  - (2018) - Now works with puffs as well as particles
- **HYSPTEST program**
  - (2019) - Pre-processing program to test inputs and configuration to diagnose common errors
- **Center-of-Mass Trajectory option**
  - (2020) - Trajectory created based on center-of-mass of emitted computational particles (CMTFN)
- **Python post-processing graphics programs**
  - (2020) - Python versions have increased functionality, e.g., different map backgrounds, zooming features
- **SVG graphics outputs – as an alternative to postscript**
  - (2021) - Workaround for increasingly difficult Ghostscript / Ghostview compatibility issues
- **Density estimation via Gaussian Mixture Models**
  - (2020) Crawford, A: The Use of Gaussian Mixture Models with Atmospheric Lagrangian Particle Dispersion Models for Density Estimation and Feature Identification. *Atmosphere* **11**:1369. doi:10.3390/atmos11121369

HYSPLIT Tips

- **CONTROL file**: Look at this file if you are having a problem – sometimes you can see obvious errors
- **GUI**: When you are using the GUI, most input and output files will be in **`hysplit\working\`**
- **Scripts**: usually create a new working directory, e.g., **`hysplit\working_nuclear\`**
- **Met File(s)**: Correct directory and name; encompass time & spatial domain of your desired simulation
- **Ascii text**: CONTROL, SETUP.CFG, MESSAGE, TDUMP files (trajectory output files), scripts
- **Binary**: Met data files, CDUMP files (concentration output files)
- **Options**: Not all available from GUI; can type executable name from command line to see options
- **Met data archives**: https://www.ready.noaa.gov/archives.php
- **Many other HYSPLIT programs** in the HYSPLIT exec directory (e.g., met data analysis programs); some are available in the GUI, but not all
- **Graphics**: HYSPLIT has some graphical capabilities – including some new Python and SVG graphics – but you can also display your model outputs using other graphics platforms (Google Earth, GIS, Python, Matlab...)
- **Numerical Experiments**:
  - Do you have enough particles in your simulation? Increase the number and see if your answers change. Keep increasing until the answers level off. The finer the grid you use, the more particles you need.
  - Do the same simulation with different met data sets to evaluate sensitivity to met data uncertainties
  - And you can do other sensitivity tests for other parameters

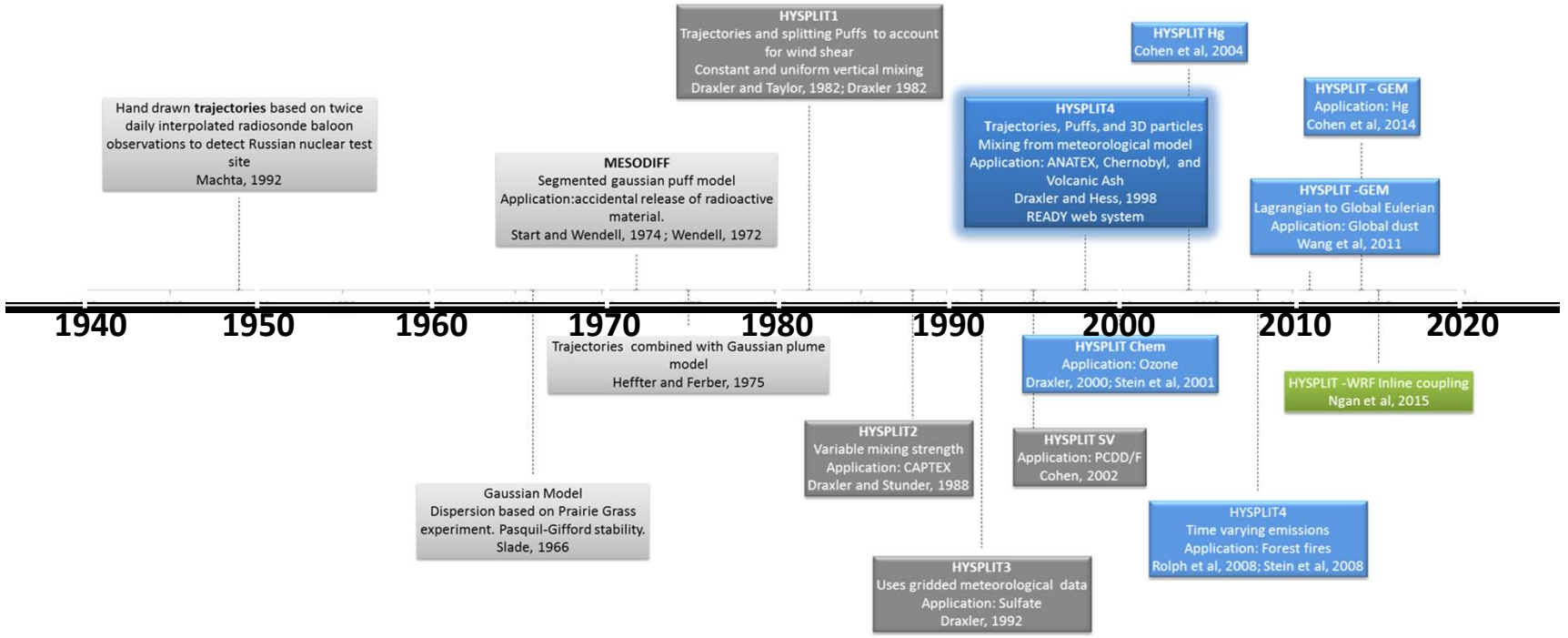
HYSPLIT Documentation and Learning Resources

- HYSPLIT Tutorial: detailed instructions on using the GUI + example scripts; can be run online or downloaded to local computer
- The GUI is a great way to learn HYSPLIT
  - even experienced users use it when trying something new
  - can create a run in the GUI, and then look at associated input/output files to tell you how to to create a script to do similar simulations
  - you can do some relatively complicated procedures (e.g., trajectory clustering)
- HYSPLIT Users Guide: online (and also in hysplit/documents directory)
- Download HYSPLIT and other resources: https://www.ready.noaa.gov/HYSPLIT.php
- HYSPLIT Cheat Sheet
- Model Overview: https://www.arl.noaa.gov/hysplit/hysplit/
- Equations: https://www.arl.noaa.gov/wp_arl/wp-content/uploads/documents/reports/arl-224.pdf
- HYSPLIT Forum: https://hysplitbbs.arl.noaa.gov/
- HYSPLIT FAQ's: https://www.arl.noaa.gov/hysplit/hysplit-frequently-asked-questions-faqs/
- Recent HYSPLIT Training Workshop: https://www.ready.noaa.gov/register/HYSPLIT_hyagenda.php
- Stein et al., 2015: NOAA's HYSPLIT atmospheric transport and dispersion modeling system, *Bull. Amer. Meteor. Soc.*, **96**, 2059-2077, http://dx.doi.org/10.1175/BAMS-D-14-00110.1
- Rolph et al., 2017: Real-time Environmental Applications and Display sYstem: READY. *Environmental Modelling & Software*, 95, 210-228, https://doi.org/10.1016/j.envsoft.2017.06.025

Thanks for your interest

Extra Slides

History of the HYSPLIT model



Early Model History

Version

1.0 - 1979 rawinsonde data with day/night (on/off) mixing

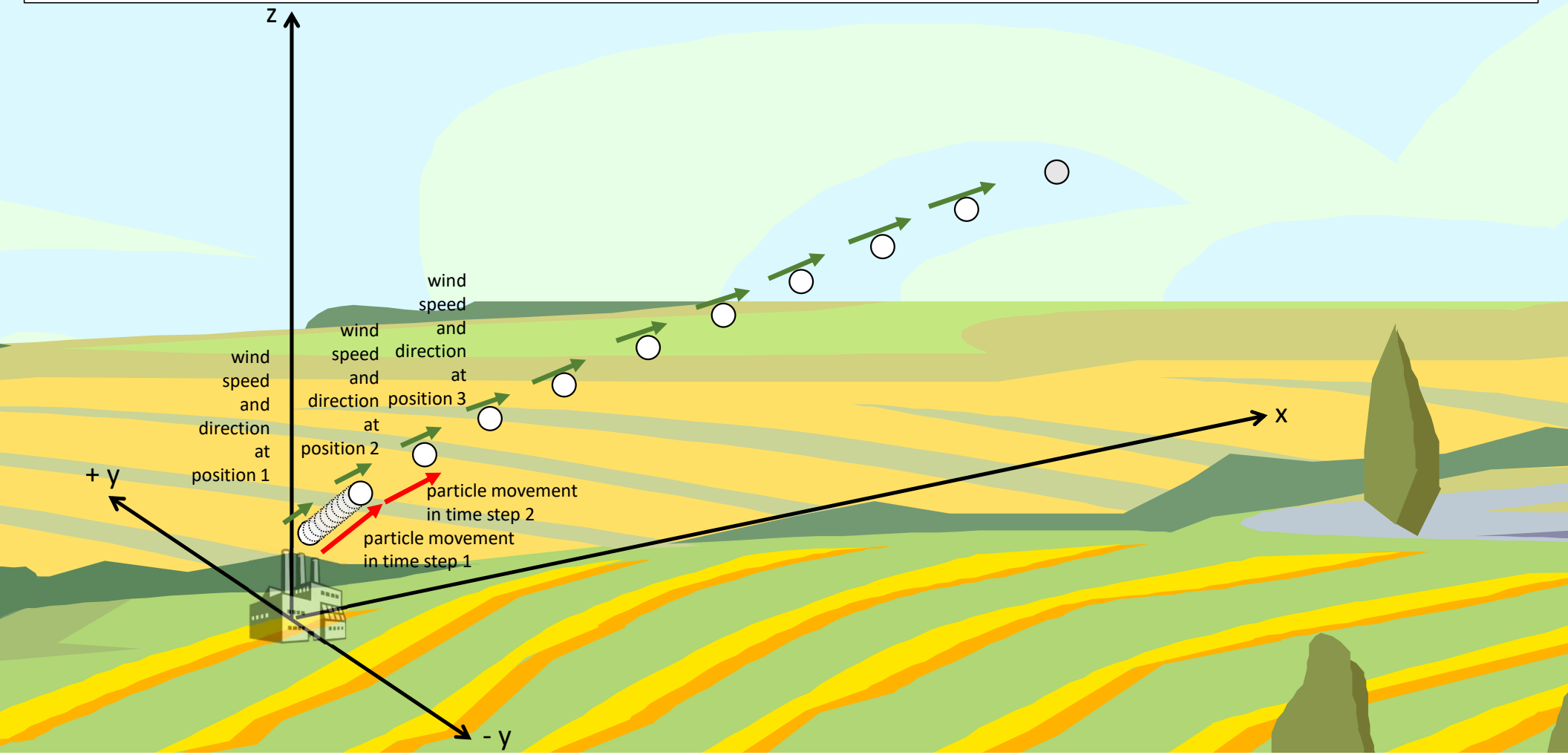
2.0 - 1983 rawinsonde data with continuous vertical diffusivity

3.0 - 1987 model gridded fields with surface layer interpolation

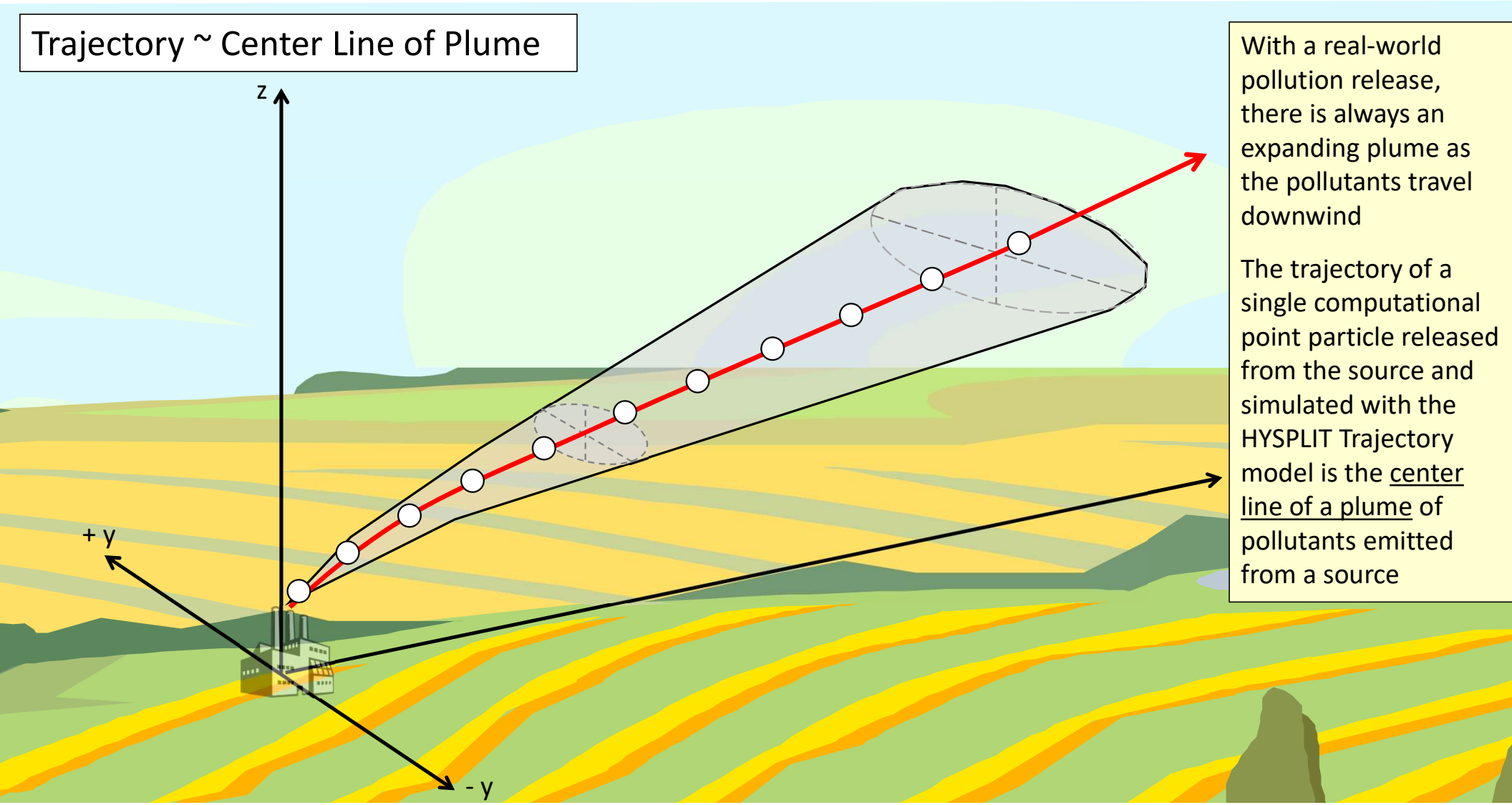
4.0 - 1996 multiple meteorological fields & combined particle-puff (NOAA Tech Memo ERL ARL-224)

- 4.0 - 8/1998 - switch from NCAR to PostScript graphics for PC
- 4.1 - 7/1999 - isotropic turbulence for short-range simulations
- 4.2 - 12/1999 - terrain compression of sigma and use of polynomial
- 4.3 - 3/2000 - revised vertical auto-correlation for dispersion
- 4.4 - 4/2001 - dynamic array allocation and support of lat-lon grids
- 4.5 - 9/2002 - ensemble, matrix, and source attribution options
- 4.6 - 6/2003 - non-homogeneous turbulence correction and dust storm
- 4.7 - 1/2004 - velocity variance, TKE, new short-range equations
- 4.8 - 2006 - CMAQ compatibility, expanded ensemble options, plume rise, Google Earth, trajectory clustering, staggered grids

At its core, the HYSPLIT model just transports “particles” as they are blown along by the wind



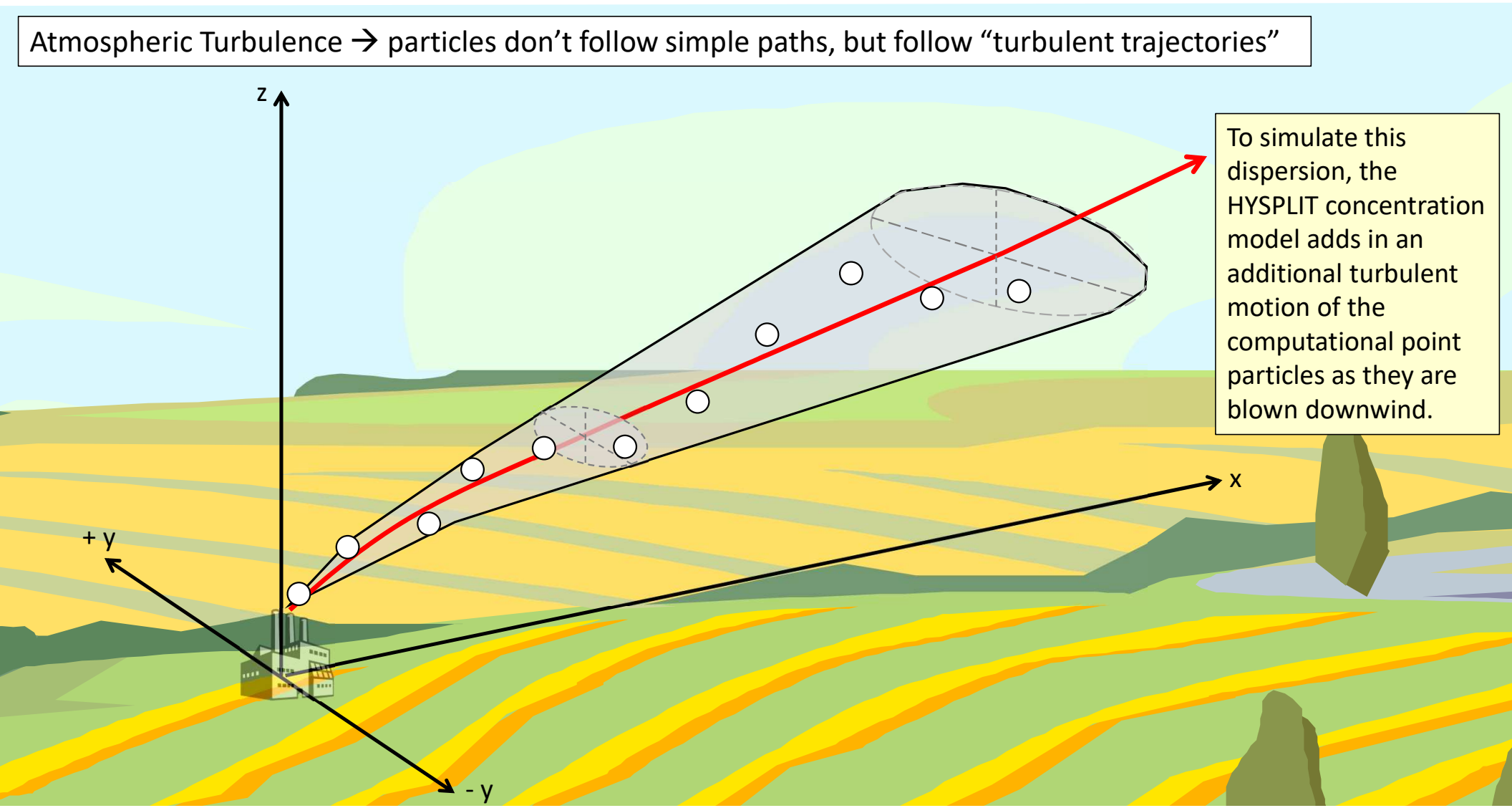
Trajectory ~ Center Line of Plume



With a real-world pollution release, there is always an expanding plume as the pollutants travel downwind

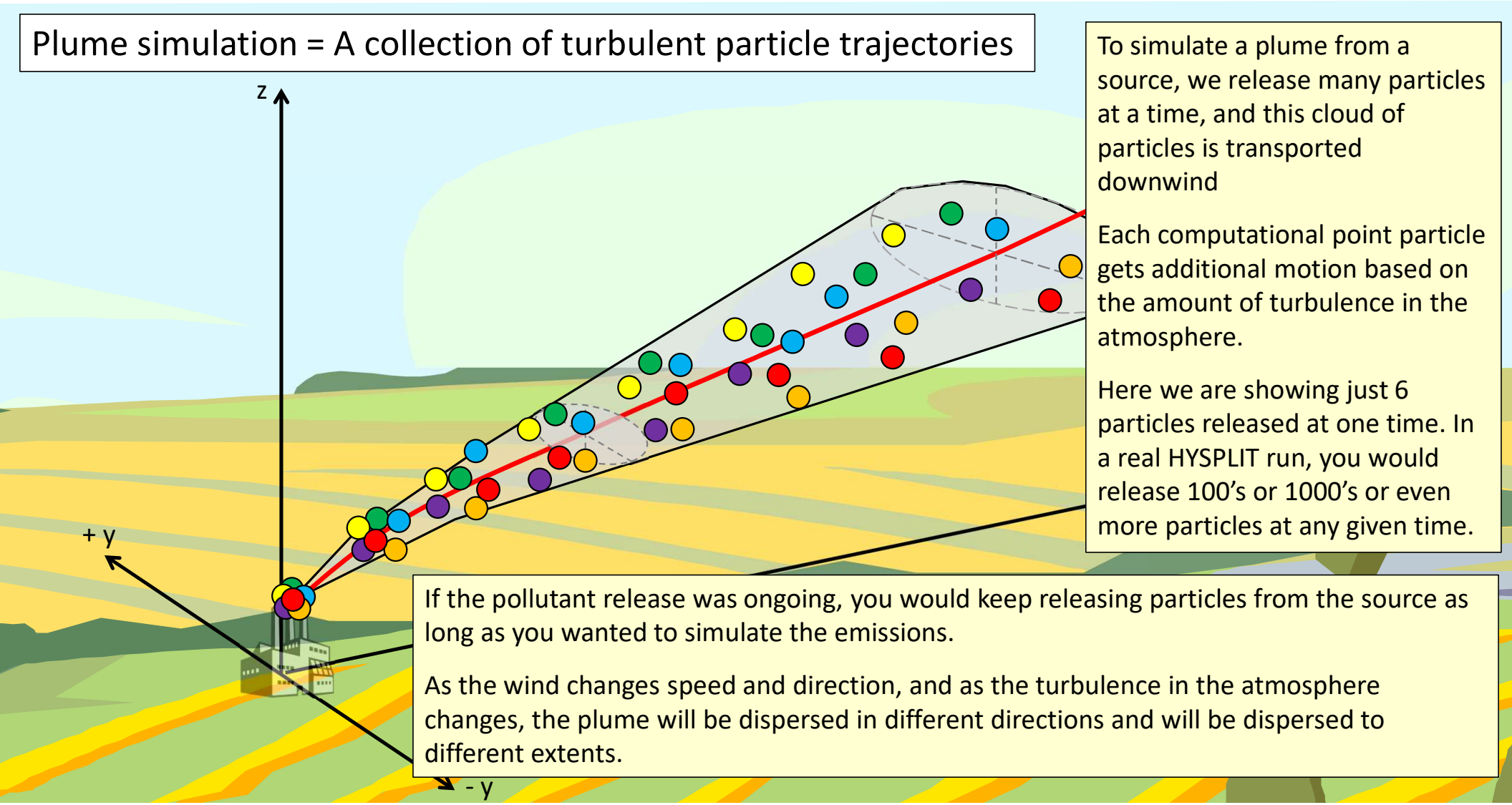
The trajectory of a single computational point particle released from the source and simulated with the HYSPLIT Trajectory model is the center line of a plume of pollutants emitted from a source

Atmospheric Turbulence → particles don't follow simple paths, but follow "turbulent trajectories"



To simulate this dispersion, the HYSPLIT concentration model adds in an additional turbulent motion of the computational point particles as they are blown downwind.

Plume simulation = A collection of turbulent particle trajectories



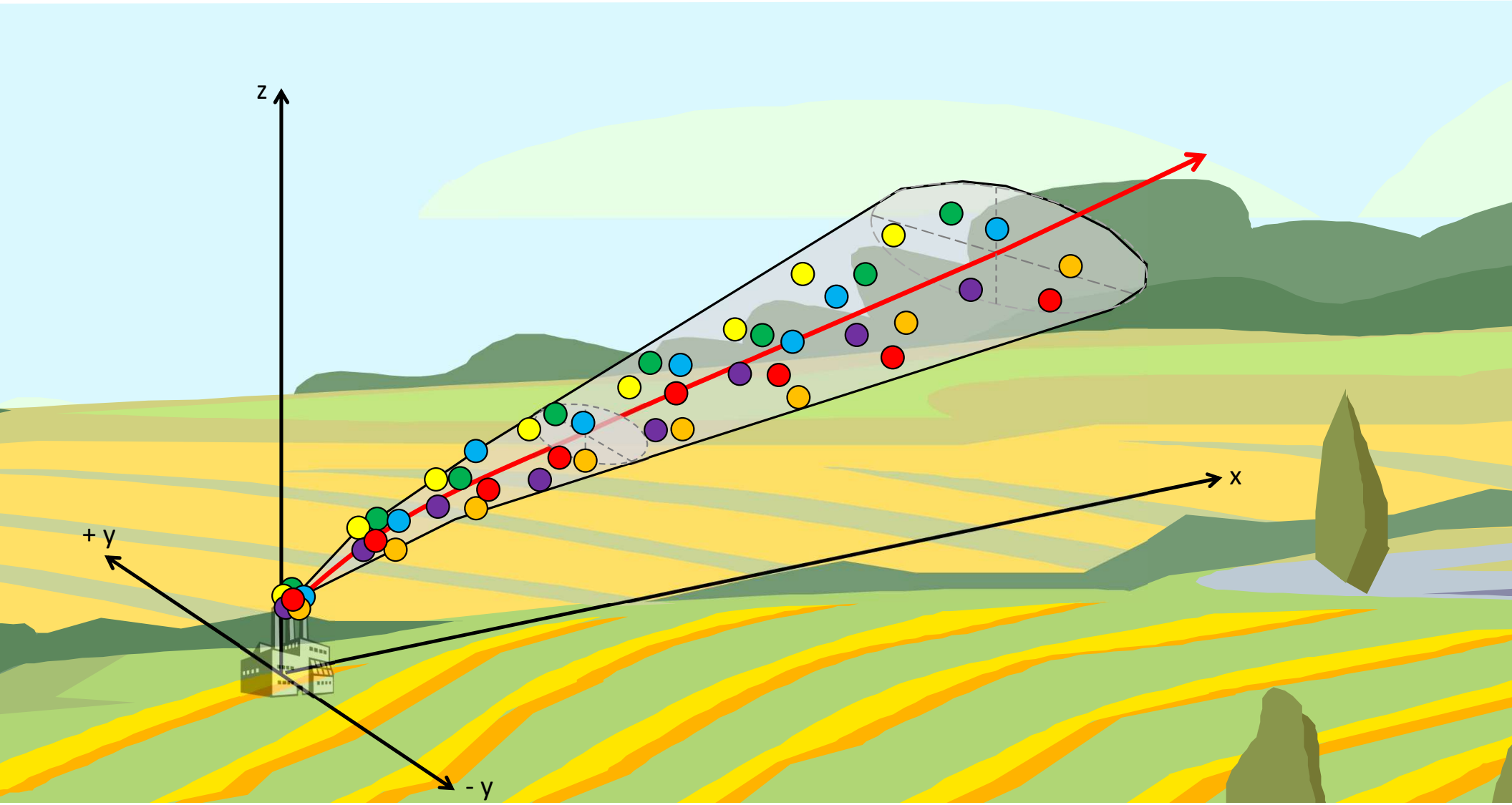
To simulate a plume from a source, we release many particles at a time, and this cloud of particles is transported downwind

Each computational point particle gets additional motion based on the amount of turbulence in the atmosphere.

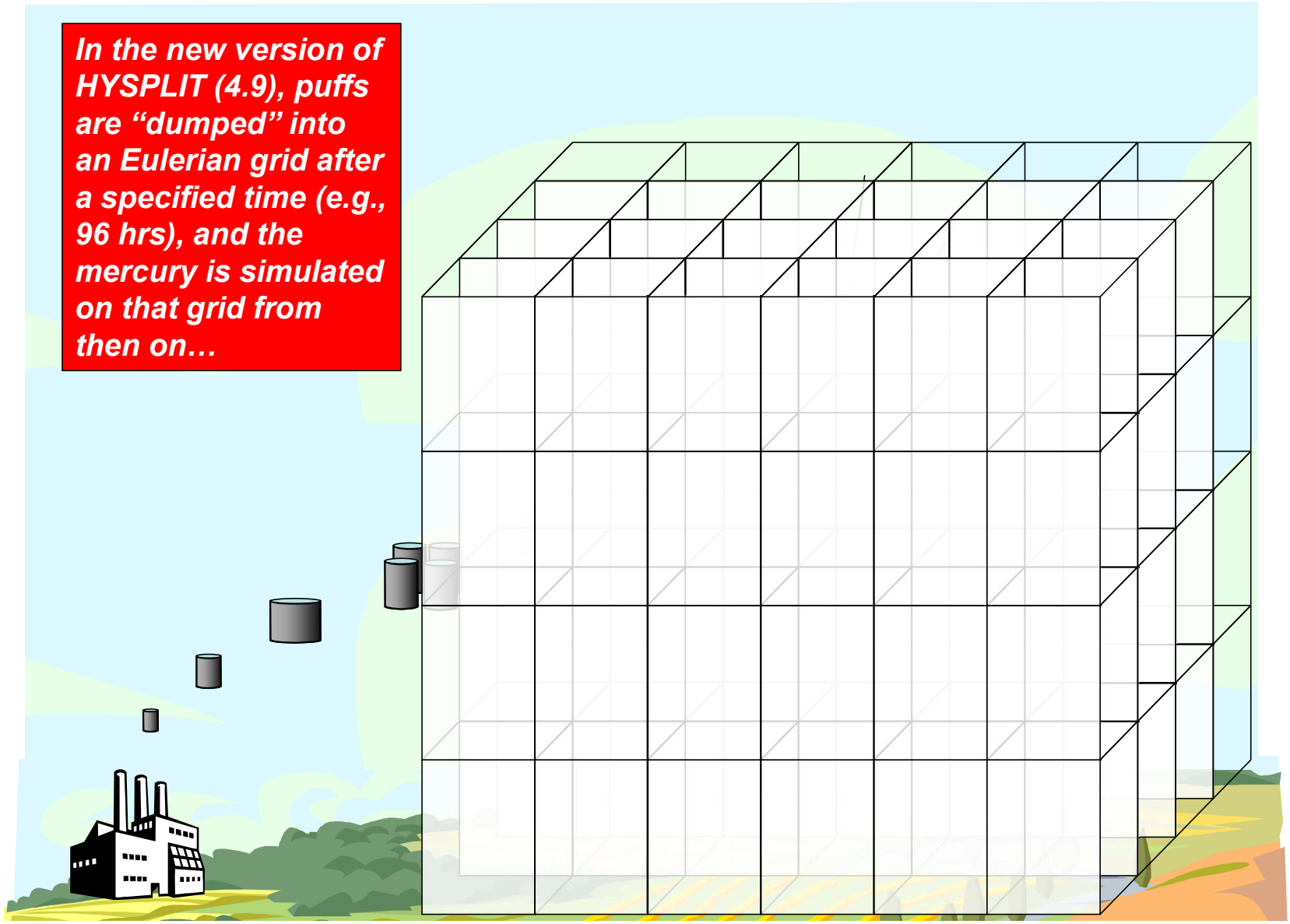
Here we are showing just 6 particles released at one time. In a real HYSPLIT run, you would release 100's or 1000's or even more particles at any given time.

If the pollutant release was ongoing, you would keep releasing particles from the source as long as you wanted to simulate the emissions.

As the wind changes speed and direction, and as the turbulence in the atmosphere changes, the plume will be dispersed in different directions and will be dispersed to different extents.


z
x
+ y
- y

In the new version of HYSPLIT (4.9), puffs are "dumped" into an Eulerian grid after a specified time (e.g., 96 hrs), and the mercury is simulated on that grid from then on…



Experiment	Release and location	Tracer	Study period	Emission Duration
ACURATE	Savannah River Plant, SC	KR85	1982 Mar – 1983 Oct	1-hr, daily
ANATEX	Glasgow, MT	PTCH	1987 Jan – Feb	3-hr, every 2.5 days
	St. Cloud, MN	PDCH		
CAPTEX	Six episodes 4 at Dayton, Ohio 2 at Sudbury, Ontario, Canada	PMCH	1983 Sep – Oct	3-hr
OKC80	Oklahoma City, OK	PMCH	1980 Jul	3-hr
METREX	Rockville, MD	PMCH	1984 Jan – 1985 Jan	6-hr, every 36 hours
	Vernon, VA	PDCH		
COSTEX	Colorado Springs, CO	PTCH	2010 Oct	10-40 min, multiple times a day
		PDCH		
		PDCB		
IFX	Nine episodes Idaho Fall, ID	SF6	1981 Jul	8-hr
ASCOT	Anderson Creek valley, CA	PMCH	1980 Sep	1-hr
		PDCH		
PSB1	Five episodes Idaho Fall, ID	SF6	2013 Oct	2.5 hr

What do HYSPLIT *Computational Point Particles* actually represent?

- A small parcel of air that contain one or more pollutants
- Each *Computational Point Particle* (parcel) contains a vast multitude of actual pollutant entities
  - molecules (in gas phase)
  - and/or atmospheric pollutant particles
- Amount of actual pollutant associated with a *Computational Point Particle* is determined by the emissions rate divided by the number of *Computational Point Particles* released in the simulation. Both of these parameters are set by the user.
- Example: NO_2 emissions from a power plant.
  - Suppose there is a power plant that emits 1000 pounds of NO_2 per hour
  - Suppose we do a simulation that releases 500 *Computational Point Particles* per hour
  - You can calculate that there are 1.2×10^{25} NO_2 molecules per HYSPLIT *Computational Point Particle*
  - *With the same emission rate, if you release 5000 Computational Point Particles per hour, there will 10x less NO_2 molecules per particle, e.g., 1.2×10^{24}*

Details of Calculation for NO_2 Emissions Example:

$$1000 \left[\frac{\text{pounds } NO_2}{\text{hour}} \right] * \frac{1}{500} \left[\frac{\text{hour}}{\text{HYSPLIT particles}} \right] * 454 \left[\frac{\text{grams } NO_2}{\text{pound } NO_2} \right]$$

$$* \frac{1}{46} \left[\frac{\text{mole } NO_2}{\text{grams } NO_2} \right] * 6.022 \times 10^{23} \left[\frac{\text{molecules } NO_2}{\text{mole } NO_2} \right] = 1.2 \times 10^{25} \left[\frac{\text{molecules } NO_2}{\text{HYSPLIT particle}} \right]$$

What do HYSPLIT *Computational Point Particles* actually represent?

- A small parcel of air that contain one or more pollutants
- Each *Computational Point Particle* (parcel) contains a vast multitude of actual pollutant entities
  - molecules (in gas phase)
  - and/or atmospheric pollutant particles
- Amount of actual pollutant associated with a *Computational Point Particle* is determined by the emissions rate divided by the number of *Computational Point Particles* released in the simulation. Both of these parameters are set by the user.
- Example: particulate emissions from a fire.
  - Suppose there is a fire that is emitting 1000 pounds per hour of particulate (smoke), that the average particle size is 5 µm diameter, and the average particle density is 1 g/cm^3
  - Suppose we do a simulation that releases 500 computational point particles per hour
  - You can calculate that there are 1.4×10^{13} smoke particles per HYSPLIT computational point particle

Details of Calculation for Smoke Emissions Example:

$$\frac{1000\left[\frac{\text{pounds smoke}}{\text{hour}}\right] * 454\left[\frac{\text{grams smoke}}{\text{pound smoke}}\right] * 1.0 \times 10^{-6}\left[\frac{\text{m}^3}{\text{cm}^3}\right]}{500\left[\frac{\text{HYSPLIT particles}}{\text{hour}}\right] * \left[\frac{\frac{4}{3}\pi\left[2.5 \times 10^{-6}\ \text{meters}\right]^3}{\text{smoke particle}}\right] * 1\left[\frac{\text{gram smoke}}{\text{cm}^3\ \text{smoke}}\right]} = 1.4 \times 10^{13}\left[\frac{\text{smoke particles}}{\text{HYSPLIT particle}}\right]$$

Many programs in the HYSPLIT exec directory (e.g., met data analysis programs); some in GUI, but not all

Some of the most commonly-used programs are underlined in red

```
C:\Users\Mark\hysplit\working>dir ..\exec /w
 Volume in drive C is OS
 Volume Serial Number is 74AE-B69A

 Directory of C:\Users\Mark\hysplit\exec

[.]                 [..]                accudiv.exe         add_data.exe        add_grid.exe        add_miss.exe
add_time.exe        add_velv.exe        afwa2arl.exe        amps2arl.exe        arl2grad.exe        arl2meds.exe
arw2arl.exe         asc2par.exe         ascii2shp.exe       autoview.exe        avn2arl.exe         avn2gbl.exe
boxplots.exe        c2array.exe         c2datem.exe         catps2ps.exe        chk_data.exe        chk_file.exe
chk_index.exe       chk_rec.exe         chk_times.exe       clusend.exe         cluslist.exe        clusmem.exe
clusplot.exe        cluster.exe         cmp3arl.exe         con2arcv.exe        con2asc.exe         con2ctbt.exe
con2dose.exe        con2grad.exe        con2rem.exe         con2srs.exe         con2stn.exe         conappend.exe
conavgpd.exe        conc2cdf.exe        concacc.exe         concadd.exe         concplot.exe        concplot.py
concrop.exe         concsum.exe         condecay.exe        conedit.exe         conhavrg.exe        coninfo.exe
conlight.exe        conmask.exe         conmaxpd.exe        conmaxv.exe         conmerge.exe        conprob.exe
conpuff.exe         conread.exe         constats.exe        content.exe         contour.exe         coversheet.exe
dat2arl.exe         dat2cntl.exe        data_avrg.exe       data_del.exe        data_year.exe       datecol.exe
datesmry.exe        dbf2txt.exe         display.exe         dustbdy.exe         dustedit.exe        ecm2arl.exe
edit_flux.exe       edit_head.exe       edit_index.exe      edit_miss.exe       edit_null.exe       ensperc.exe
ensplots.exe        eta04arl.exe        eta12arl.exe        eta40arl.exe        filedates.exe       file_copy.exe
file_merge.exe      findgrib.exe        fires.exe           firew.exe           gelabel.exe         gen2xml.exe
gfs2arl.exe         goes2ems.exe        grad2arl.exe        grib2arl.exe        gridplot.exe        gridxy2ll.exe
hur2arl.exe         hycs_ens.exe        hycs_gem.exe        hycs_grs.exe        hycs_ier.exe        hycs_so2.exe
hycs_std.exe        hycs_var.exe        hysptest.exe        hyts_ens.exe        hyts_std.exe        inventory.exe
isochron.exe        jma2arl.exe         kma2arl.exe         latlon.exe          lbfgsb.exe          macc2date.exe
matrix.exe          meds2arl.exe        mergextr.exe        merglist.exe        metdates.exe        metlatlon.exe
metpoint.exe        mm5toarl.exe        nam12arl.exe        nam40arl.exe        nams2arl.exe        narr2arl.exe
ncr2arl.exe         nuctree.exe         par2asc.exe         par2conc.exe        parhplot.exe        parmerge.exe
paro2n.exe          parshift.exe        parsplot.exe        parvplot.exe        parxplot.exe        pNA05.exe
pNA15.exe           pNA45.exe           pole2merc.exe       poleplot.exe        profile.exe         profile_orig.exe
Readme_exec.txt     rec_copy.exe        rec_insert.exe      rec_merge.exe       rsmp2arl.exe        rsms2arl.exe
run_mpi.sh          scatter.exe         setpoint.exe        showgrid.exe        snd2arl.exe         stabplot.exe
stat2grid.exe       statmain.exe        stn2arl.exe         stn2ge.exe          stn2par.exe         tcmsum.exe
tcsolve.exe         testnuc.exe         timeplot.exe        timeplus.exe        toaplot.py          trajfind.exe
trajfreq.exe        trajfrmt.exe        trajgrad.exe        trajmean.exe        trajmerg.exe        trajplot.exe
trajplot.py         txt2dbf.exe         unpacker.exe        unpacker.txt        var2datem.exe       velvar.exe
viewer.exe          vmixing.exe         vmsmerge.exe        vmsread.exe         volcplot.exe        wget.exe
win3plot.exe        wincpick.exe        wincplot(1).exe     wincplot.exe        wintplot(1).exe     wintplot.exe
xtrct_grid.exe      xtrct_stn.exe       xtrct_time.exe      zcoord.exe          zip.exe
             201 File(s)    195,372,732 bytes
```

```
C:\Users\Mark\hysplit\working>..\exec\trajplot
 USAGE: trajplot -[options (default)]
   -a[GIS output: (0)-none 1-GENERATE_points 3-KML 4-partial_KML 5-GENERATE_lines]
   -A[KML options: 0-none 1-no extra overlays 2-no endpoints 3-Both 1&2]
   -e[End hour to plot: #, (all) ]
   -f[Frames: (0)-all files on one  1-one per file]
   -g[Circle overlay: ( )-auto, #circ(4), #circ:dist_km]
   -h[Hold map at center lat-lon: (source point), lat:lon]
   -i[Input files: name1+name2+... or +listfile or (tdump)]
   -j[Map background file: (arlmap) or shapefiles.<(txt)|process suffix>]
   -k[Kolor: 0-B&W, (1)-Color, N:colortraj1,...colortrajN]
      1=red,2=blue,3=green,4=cyan,5=magenta,6=yellow,7=olive
   -l[Label interval: ... -12, -6, 0, (6), 12, ... hrs
      <0=with respect to traj start, >0=synoptic times)]
   -L[LatLonLabels: none=0 auto=(1) set=2:value(tenths)]
   -m[Map proj: (0)-Auto 1-Polar 2-Lambert 3-Merc 4-CylEqu]
   -o[Output file name: (trajplot.ps)]
   -p[Process file name suffix: (ps) or process ID]
   -s[Symbol at trajectory origin: 0-no (1)-yes]
   -v[Vertical: 0-pressure (1)-agl, 2-theta 3-meteo 4-none]
   -z[Zoom factor:  0-least zoom, (50), 100-most zoom]

 NOTE: leave no space between option and value
```

EXAMPLE: **trajplot -itdump.txt -oFIRE -a3 -A3**

- Not all program options available from GUI
- More options from scripts
- Type executable name from command line to see options
- At left: trajplot (the program that plots trajectories)

Locust Migration Forecasting

- With United Nations *Food and Agriculture Organization* (FAO)
- Predicts paths of locust swarms; provides *early warnings* to affected communities
- Desert locust upsurge in East Africa and Middle East: ~10x greater than normal
- Caused by climate-change perturbations in rain patterns
- Locusts are “lazy fliers” & follow the wind, in a swarm; so HYSPLIT Atmospheric *Trajectory* Model is suitable
- 15-day forecasts, driven by NOAA Global Forecast System
- Single swarm, batch, and source-region simulations: https://locusts.arl.noaa.gov:8443/