NOAA's HYSPLIT atmospheric transport and dispersion modeling system: history, applications, and new developments.

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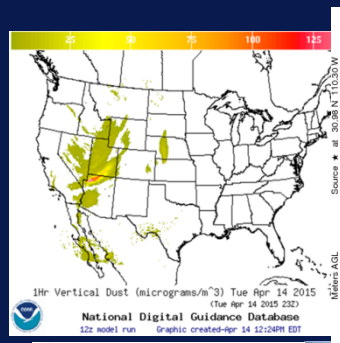
2016 INTERNATIONAL MACCS USER GROUP (IMUG) MEETING

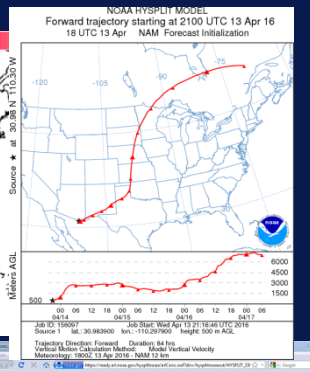
Background

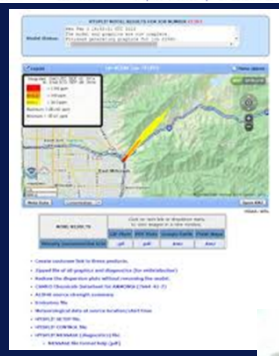
- The accidental or intentional release of chemical, biological, or nuclear agents or the eruption of volcanic ash can have significant health, safety, national security, economic, and ecological implications.
- We want to understand and predict how, where, and when harmful materials are atmospherically transported and deposited
- 65+ years of research experience

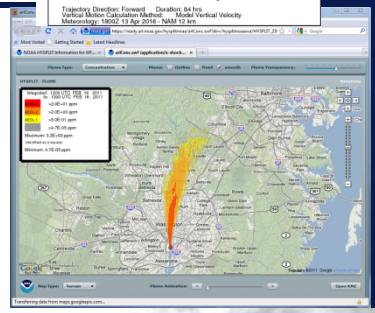
NOAA's responsibilities require Atmospheric Transport and Dispersion predictions

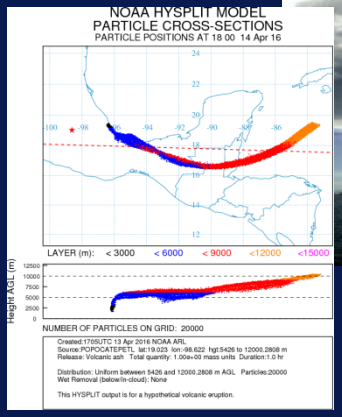
- NOAA operates two of nine Volcanic Ash Advisory Centers in support of International Civil Aviation Organization
- NOAA operates a Regional Specialized Meteorological Center (RSMC) to support World Meteorological Organization (WMO)
- Local National Weather Service's Weather Forecast Offices (WFO) provide dispersion predictions to local emergency managers
- Consequence assessment support for DOE's Idaho National Laboratory and Nevada National Security Site.
- Modeling support to Nuclear Regulatory Commission (NRC) for their MELCOR Accident Consequence Code System (MACCS)
- ARL continuously develops and updates NOAA's operational model for dispersion applications



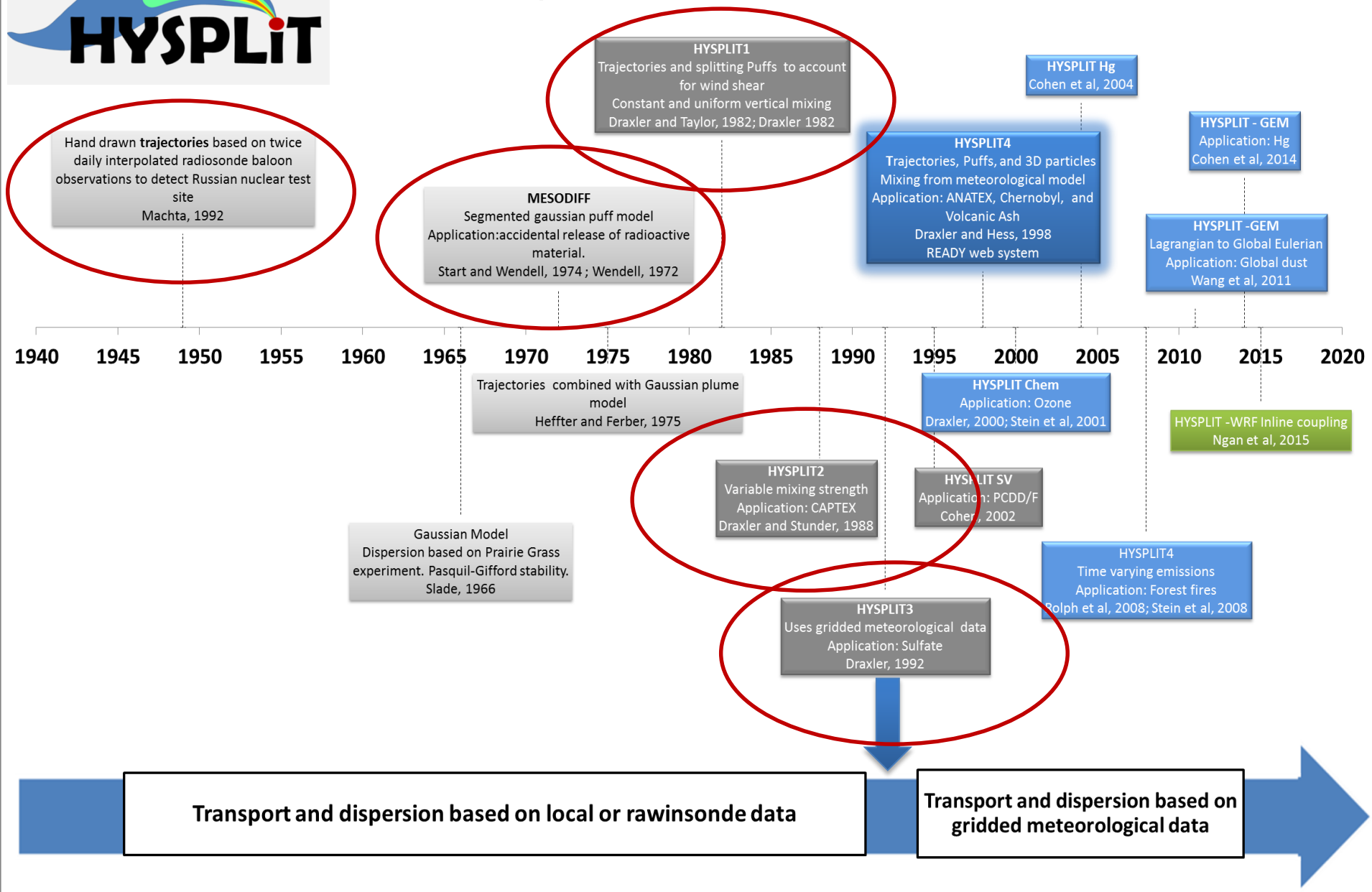








History of the HYSPLIT model



HYSPLIT 4

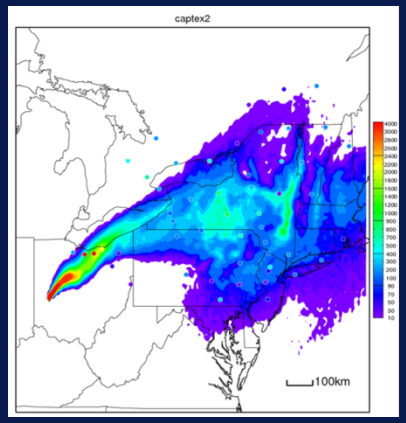
- Automated method of simultaneously using multiple meteorological grids
- Pre-processors for many different meteorological models (WRF, RAMS, MM5, ECMWF) to convert data to the ARL format, in addition to the archives of existing NOAA models
- Multiple parameterizations to estimate the stability from gradients of meteorological variables
- Multiple options to convert stability into dispersion values (diffusivity profiles, turbulent kinetic energy, velocity variance)
- Modeling the turbulent particle motion directly (3D) or the change in the statistic of the particle distribution (puffs)

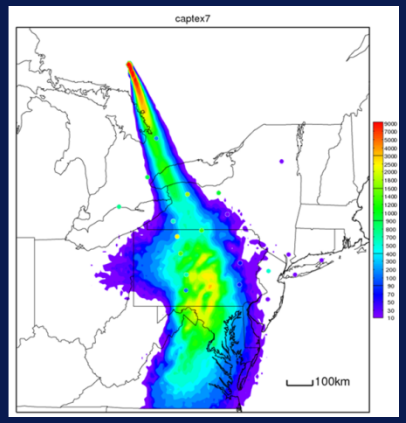
- **Version 4 of HYSPLIT has been the basis for the construction of essentially all model applications for the last 15 years**

Model Evaluation

Data Archive of Tracer Experiments and Meteorology (DATEM)

- **Approach**
  - North American Regional Reanalysis (NARR) and several with WRF runs
  - Creating new WRF
  - Common statistical evaluation protocols
- **Accomplishments**
  - Web access to run HYSPLIT for each experiment
  - Standardized model change testing in conjunction with version control

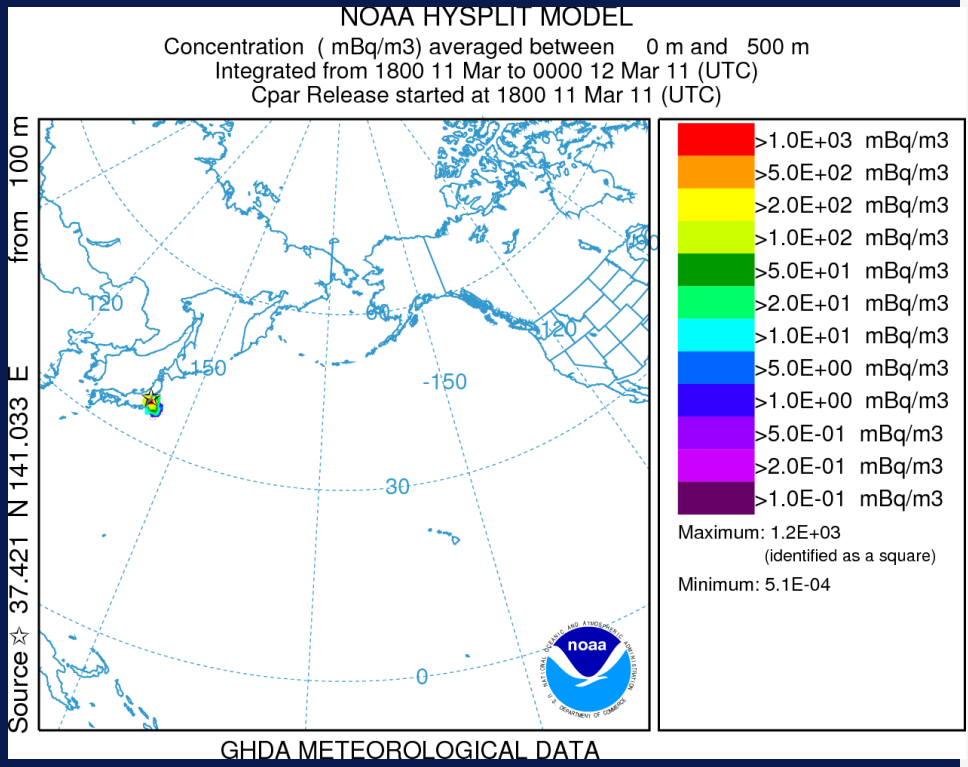




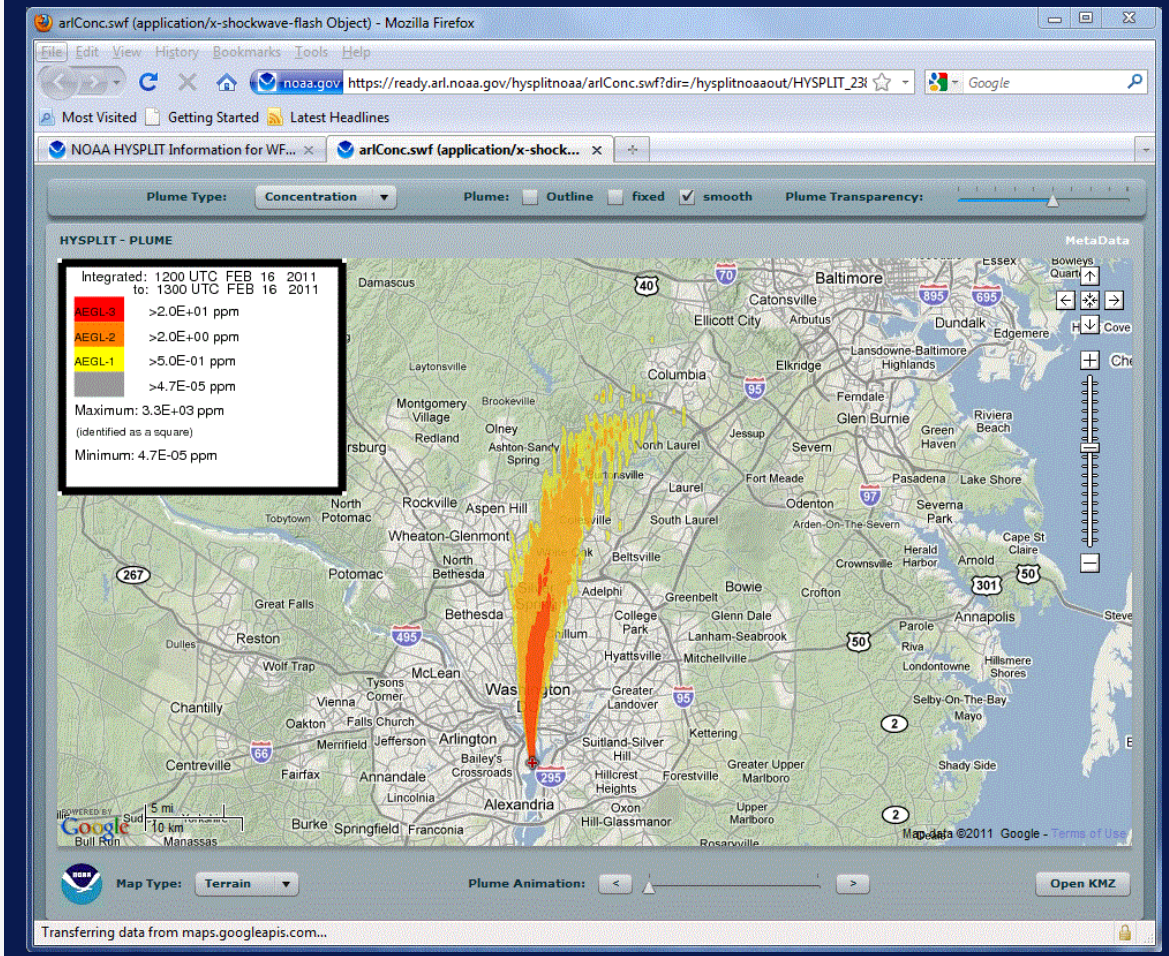
- **Cross Appalachian Tracer Experiment (CAPTEX)** Dayton, OH, and Sudbury, ONT, Sep., Oct., 1983
- **Atlantic Coast Unique Regional Atmospheric Tracer Experiment (ACURATE),** Savannah River Plant, SC, Spring 1982 – Summer 1983
- **Across North America Tracer Experiment (ANATEX)**, Glasgow, MT, and St. Cloud, MN, January through March 1987
- **Oklahoma Tracer Experiment**, Norman, OK, July, 08 1980
- **Metropolitan Tracer Experiment (METREX)** , Washington, DC, January – December 1984
- **European Tracer Experiment (ETEX)**, Rennes, France, October 23, 1994
- **Savannah River Plant Experiment** , Aiken, SC, Aug. 1975 through Sep. 1977
- **Atmospheric Studies in Complex Terrain (ASCOT)** , California, September 12-25, 1980
- **Colorado Springs Tracer Experiment (COSTEX)**, October 18, 21, 23, 2010
- **Sagebrush, Idaho, 2013**.

Emergency Response
Nuclear accidents

- **Background**
  - Lack of communication between countries after Chernobyl accident 1986
- **Approaches**
  - Comprehensive Test Ban Treaty Organization (CTBTO) - WMO Backtracking Response System - US Dep. Of State and NOAA MOA
  - Regional Specialized Meteorological Centers (RSMC) – WMO - NWS and OAR
- **Applications**
  - Fukushima-Daiichi power plant accident 2011.
  - NRC/ARL MOU integrate the HYSPLIT code into MELCOR Accident Consequence Code System (MACCS) as an alternate ATD model
  - EPA/ARL modeling support and training
  - HYSPLIT installed in Australia and China



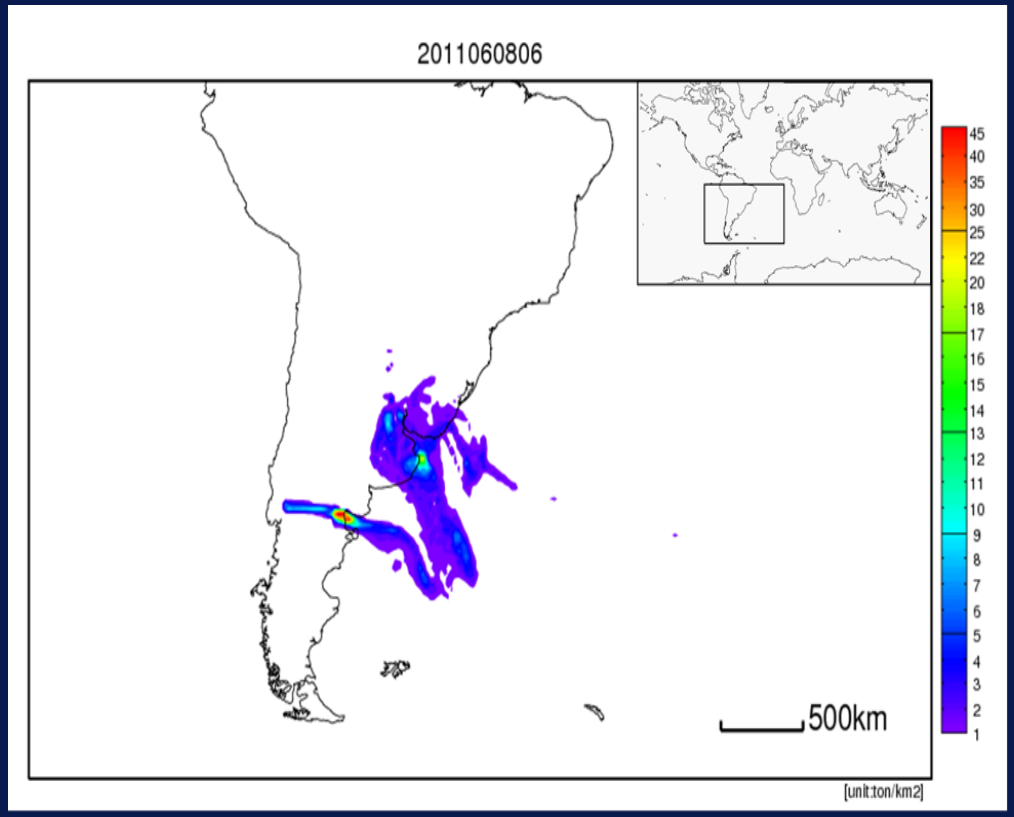
Emergency Response
Chemical Releases



- **Background**
  - Post 9/11 applications for forecast offices centrally run
- **Approaches**
  - Link to Computer-Aided Management of Emergency Operations (CAMEO) chemicals data
  - Collaboration with Office of Response and Restoration (OR&R) to include Areal Locations of Hazardous Atmospheres (ALOHA) source model
- **Applications**
  - Incorporating real-time chemical plume modeling capability through the web for WFOs

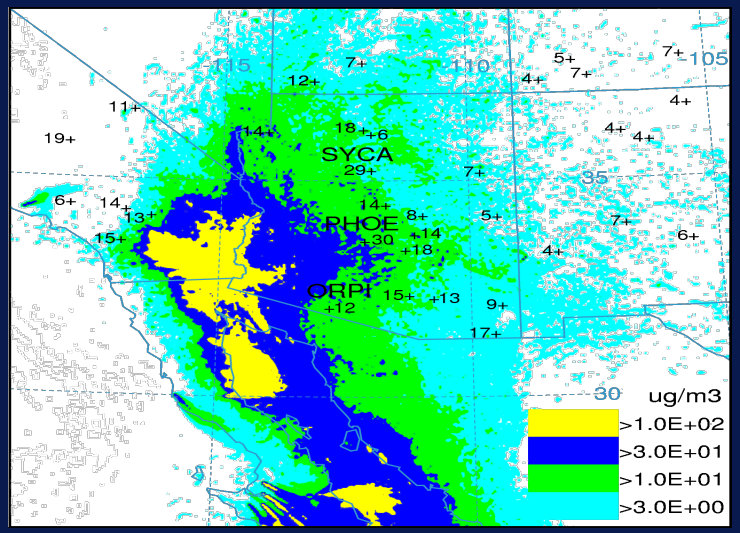
Emergency Response

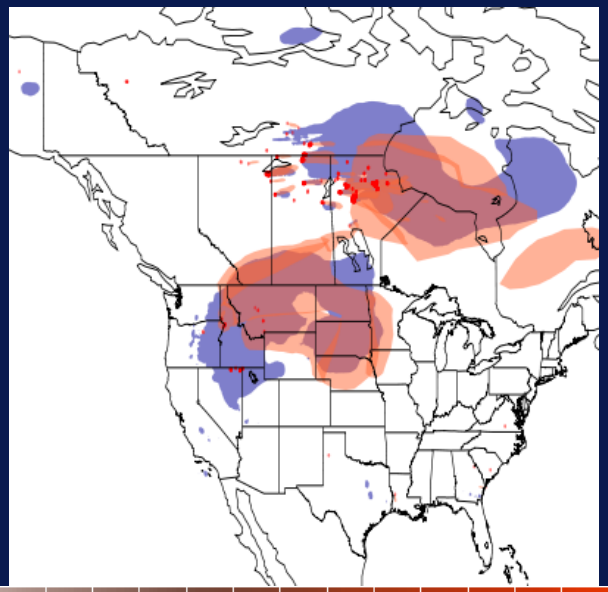
Volcanic Eruptions (Alice Crawford's poster)

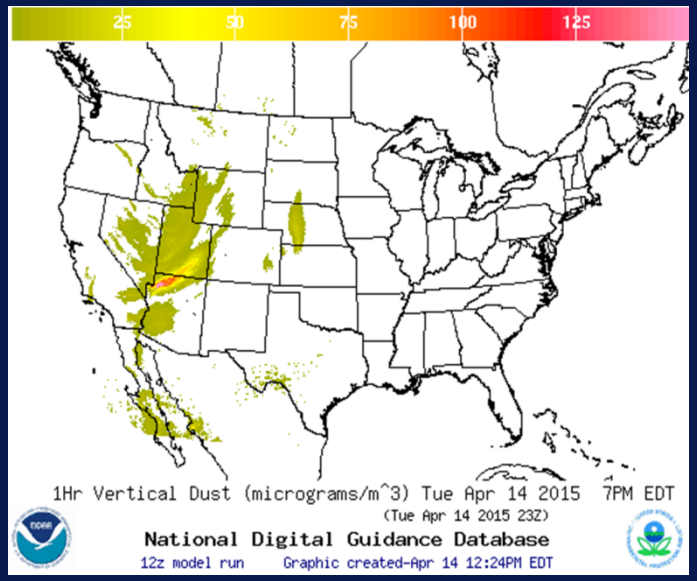


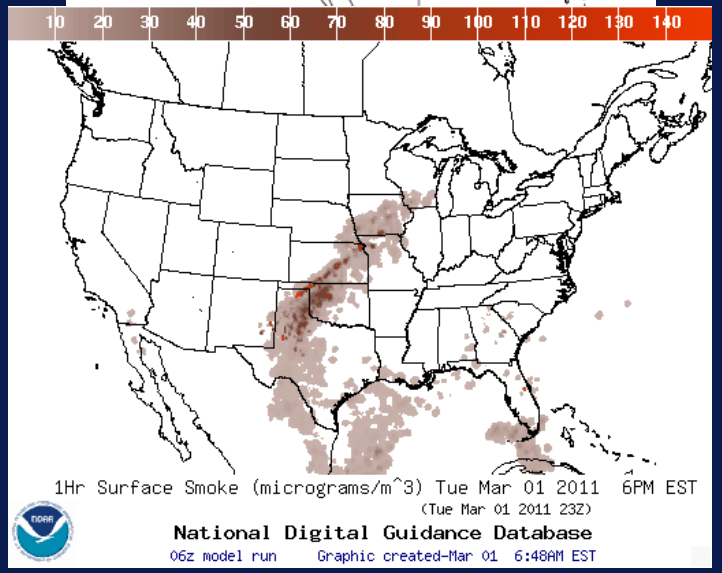
- **Background**
  - Mt. St. Helens – forecast trajectories to the USGS
  - Mt. Redoubt – KLM encounter
- **Approaches**
  - Source term uncertainty (mass, particle size, height)
  - Quantitative air concentration
  - Assimilation of satellite data
- **Applications**
  - International Civil Aviation Organization – FAA - Washington Volcanic Ash Advisory Center (NCEP and NESDIS)
  - HYSPLIT installed in Australia, New Zealand, Argentina, and AFWA

Forecasting Transport of Dust and Smoke









NOAA/NWS Air Quality Forecast Guidance

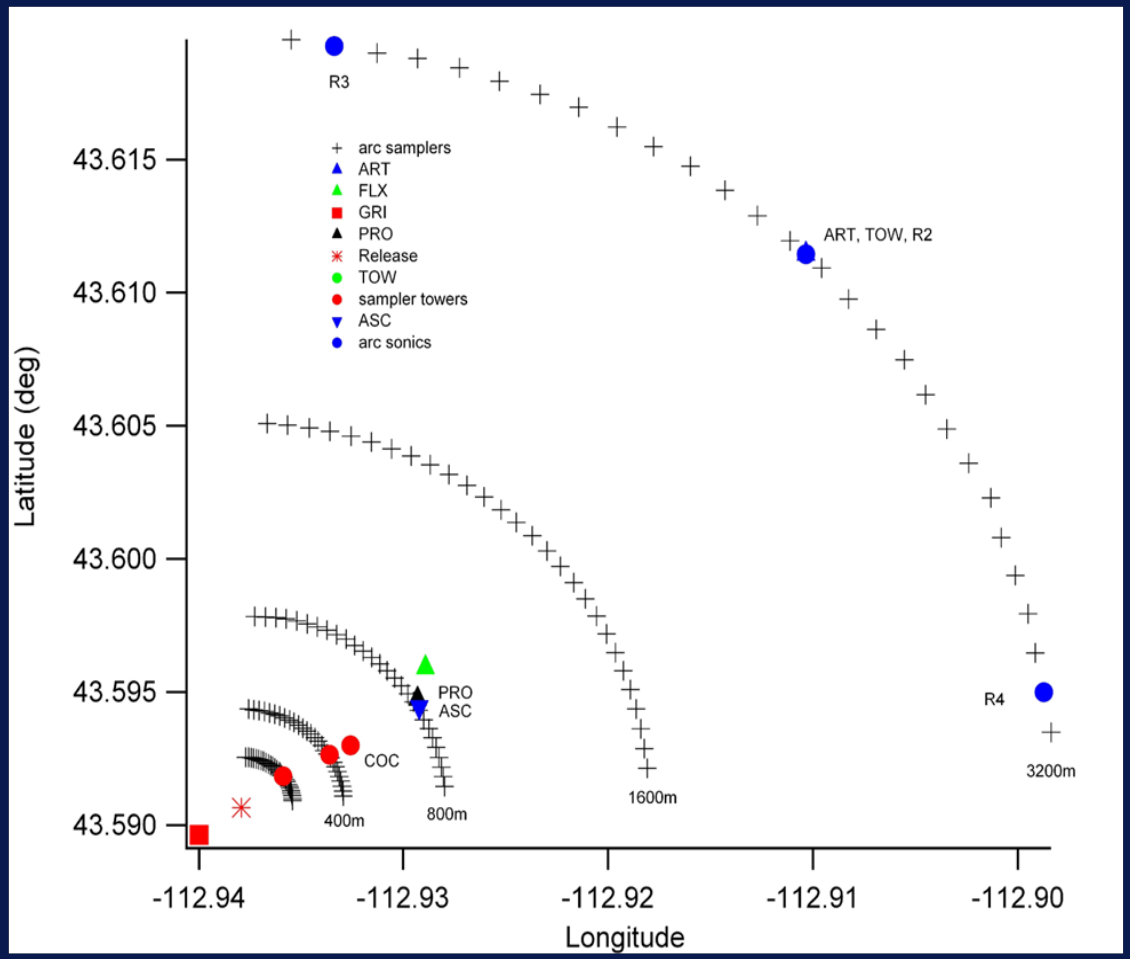
Inline versus Offline

Comparison of inline and offline approaches

	Inline HYSPLIT	Offline HYSPLIT
Source of met. input	WRF-ARW	Varying met. data (WRF, MM5, NARR, etc); Need conversion programs for each
Met. input frequency	The meteorology is used at WRF's time step, which could be seconds. No temporal interpolation .	WRF's output (hourly or in minute intervals) interpolated to the HYSPLIT time step.
Vertical grid	Using WRF's terrain-following hydrostatic vertical coordinate. No vertical interpolation.	A terrain-following coordinate using a equation between height & model level; then interpolating data to HYSPLIT's layers
Horizontal grid	Following WRF's grid configuration.	Same as the meteorological data grid.
Disk usage	Dispersion output and WRF output based on users' request.	Large cost of data storage if high temporal resolution data are needed.
Multiple simulations	Requires repeating the meteorological simulation.	Only one meteorological simulation is required.

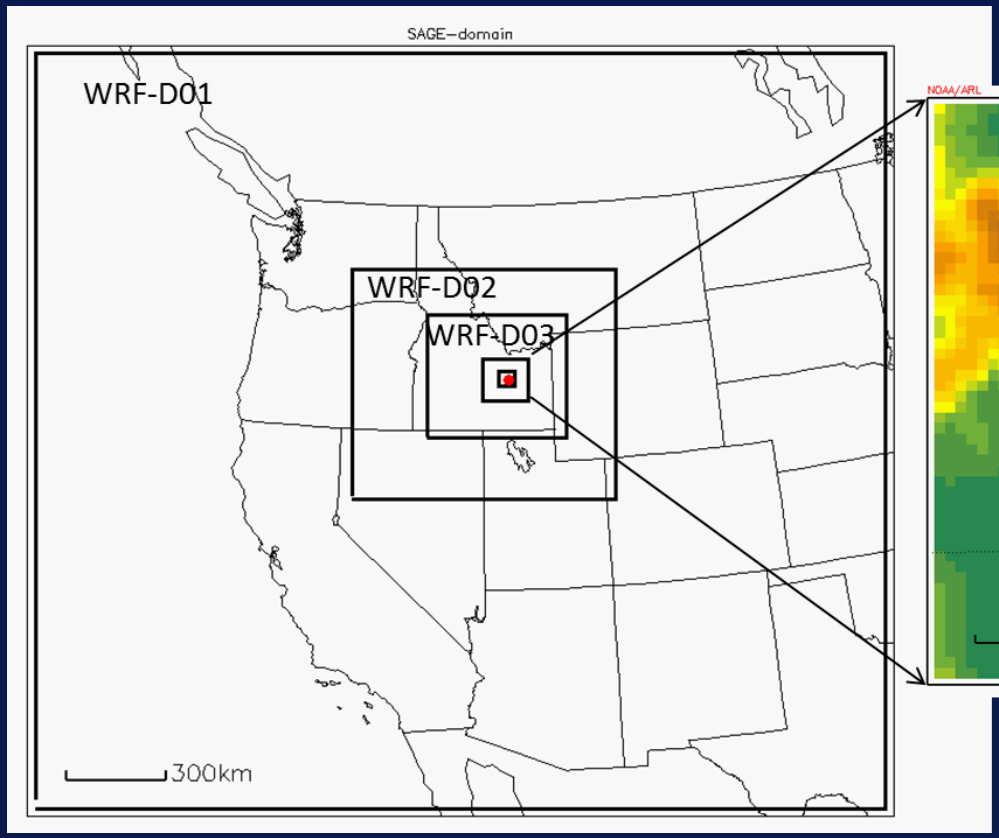
Sagebrush tracer experiment

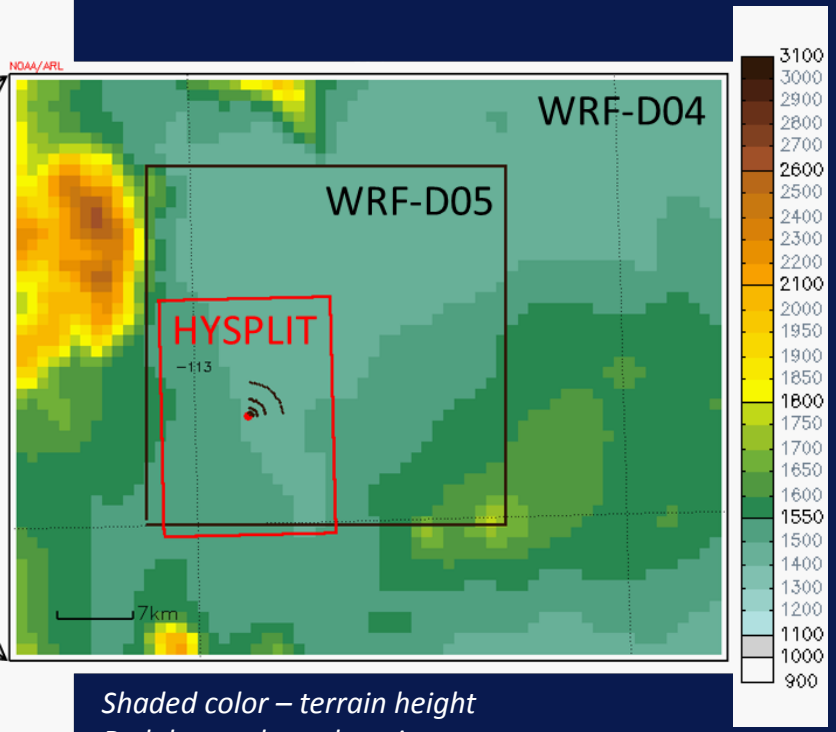
Conducted by ARL's Field Research Division



from NOAA Technical Memorandum OAR ARL-268

HYSPLIT simulation of Sagebrush experiment





Shaded color – terrain height
Red dot – release location
Small black dots – sampling network

- Horizontal grid: 27km, 9km, 3km, 1km and 333m
- Vertical coordinate: 33 layers with the 1st mid-layer at around 8m and 20 layers included below 850 hPa.
- Simulation period: 2013/10/07 00UTC – 10/08 00UTC

HYSPLIT model configuration

- Tracer: SF_6
- Sampling network: 10-minute interval for 2 hours
- Release location: Idaho National Laboratory
- Release time: 1930 UTC on 7th October 2013
- Release duration: 2.5 hours
- Release rate: 35748 g/hr with 250,000 particles
- HYSPLIT grid: ~11 m (horizontal)
  50 m (vertical)
- WRF data frequency: 5-minute for offline
  using WRF time-step for inline

Statistical metrics

$$Rank = R^2 + 1 - \left|\frac{FB}{2}\right| + \frac{FMS}{100} + \left(1 - \frac{KSP}{100}\right)$$ (Draxler 2006)

Correlation coefficient (R)

$$R = \frac{\sum(M_i - \overline{M})(P_i - \overline{P})}{\sqrt{\sum(M_i - \overline{M})^2 \sum(P_i - \overline{P})^2}}$$

Fractional bias (FB)

$$FB = 2\frac{(\overline{P} - \overline{M})}{(\overline{P} + \overline{M})}$$

Figure of merit in space (FMS; %)

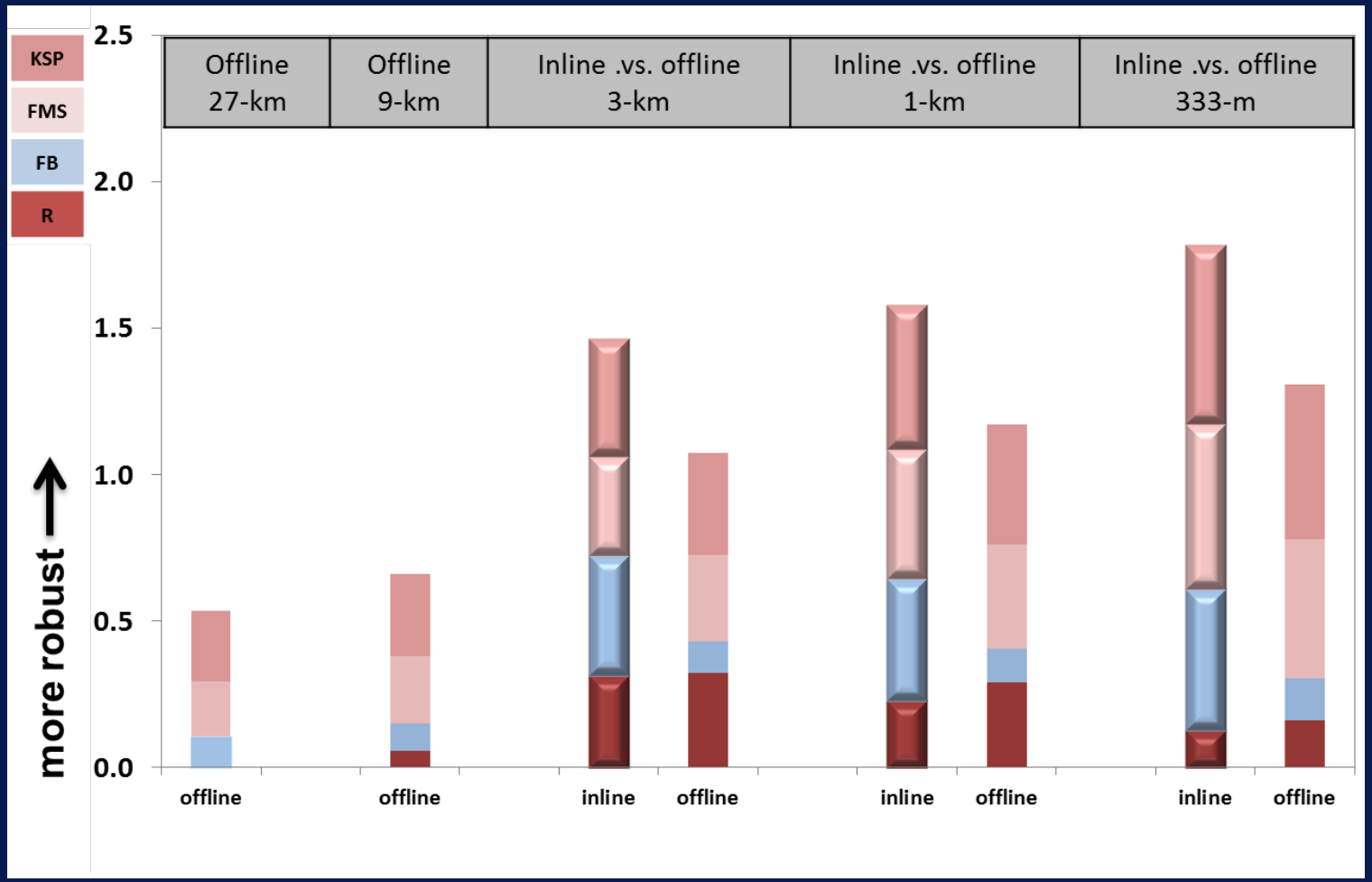
$$= 100\frac{N_p \cap N_m}{N_p \cup N_m}$$

Kolmogorov-Smirnov parameter (KSP; %)

$$= Max|D(M_k) - D(P_k)|$$

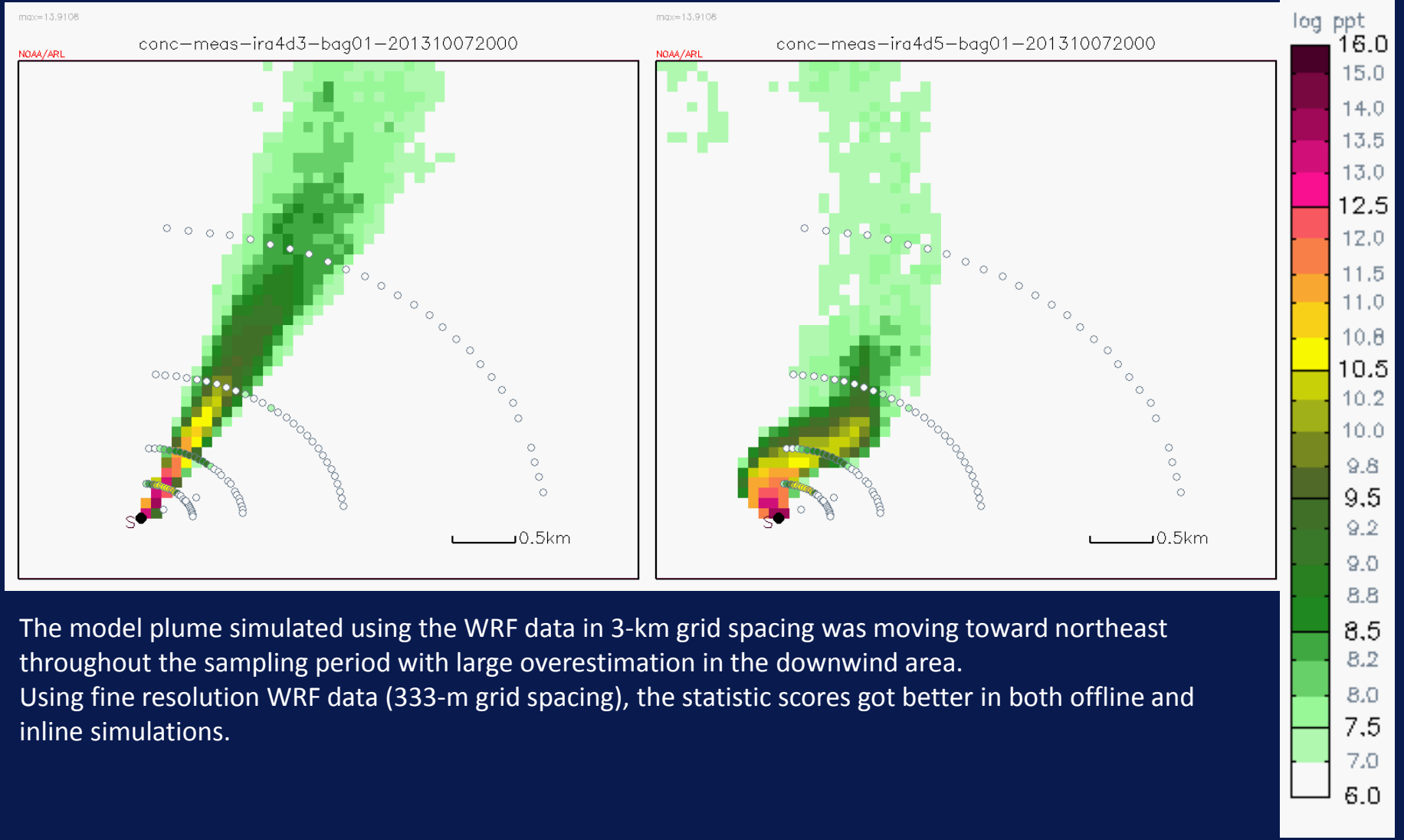
NOTE: "M" – measured tracer concentrations
"P" – predicted tracer concentrations
N is number of samples and "D" is the cumulative distribution

Dispersion results using different grid spacing and coupling approaches (inline and offline)



Inline HYSPLIT showed significant improvement compared to the offline approach for the Sagebrush case. The fractional bias of the inline plume was much lower than that of the offline plume calculated with different meteorological model resolutions.

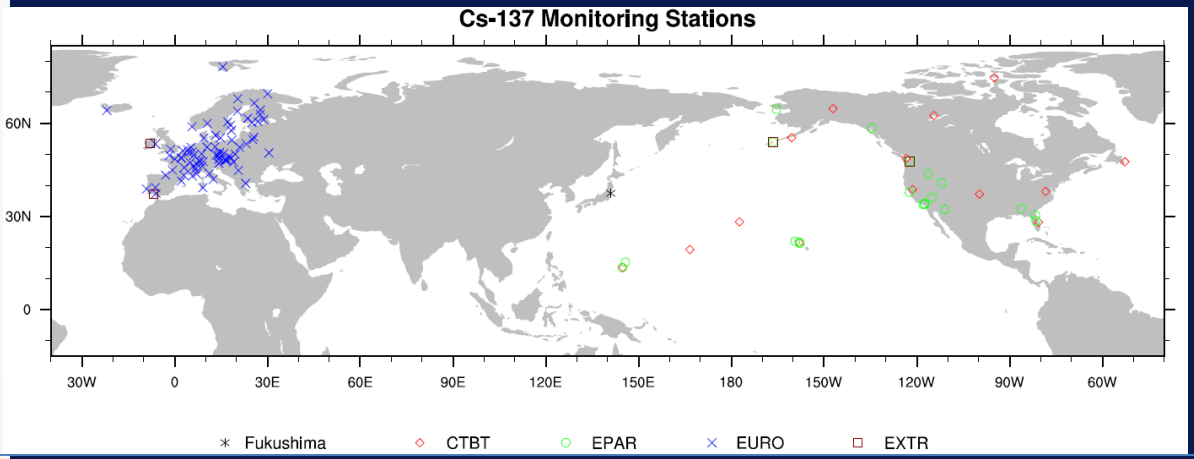
Inline dispersion results using WRF 3-km and 333-m grid spacing

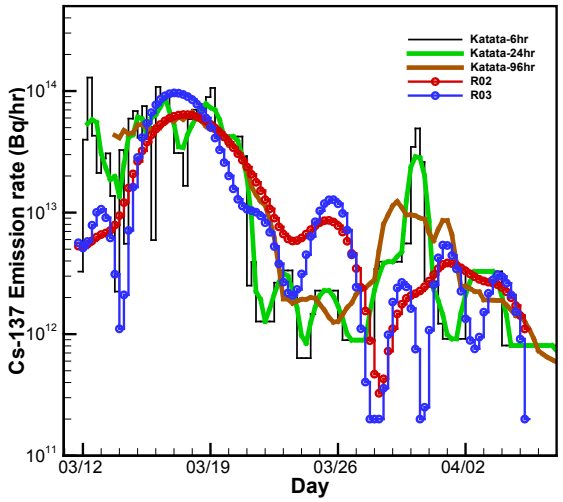


The model plume simulated using the WRF data in 3-km grid spacing was moving toward northeast throughout the sampling period with large overestimation in the downwind area.
Using fine resolution WRF data (333-m grid spacing), the statistic scores got better in both offline and inline simulations.

Inverse modeling

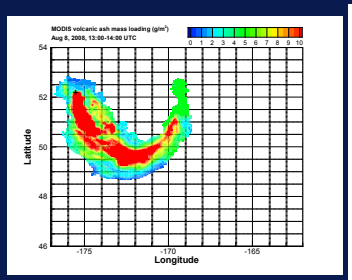
1. Fukushima source term estimation

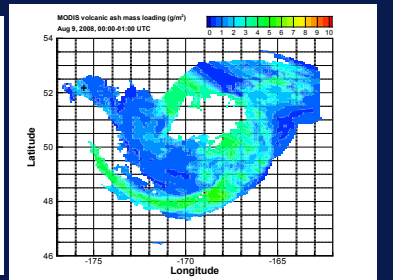


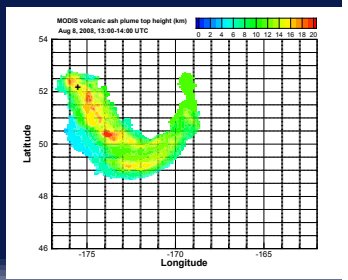


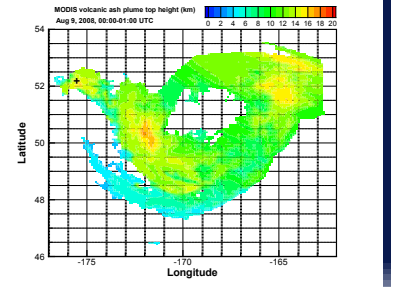
Ref: Source term estimation using air concentration measurements and a Lagrangian dispersion model–Experiments with pseudo and real cesium-137, T Chai, R Draxler, A Stein – Atmos. Environ., 2015

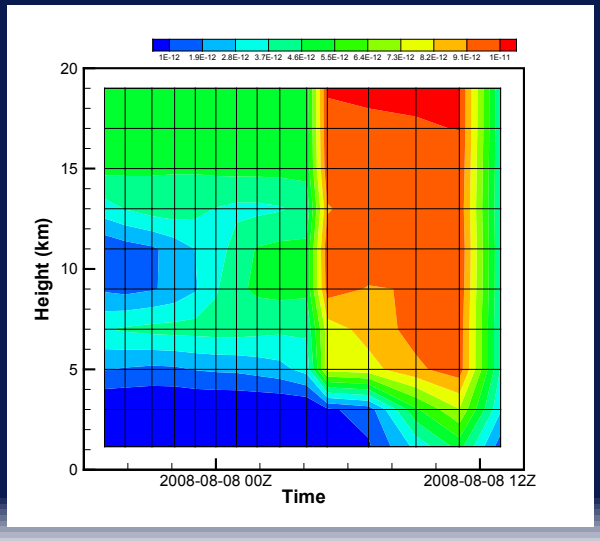
2. Volcanic ash application - Kasatochi eruption

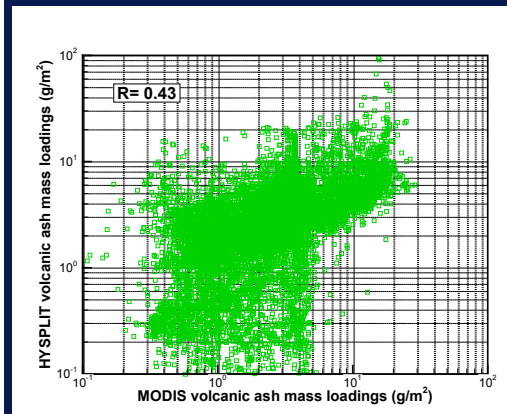






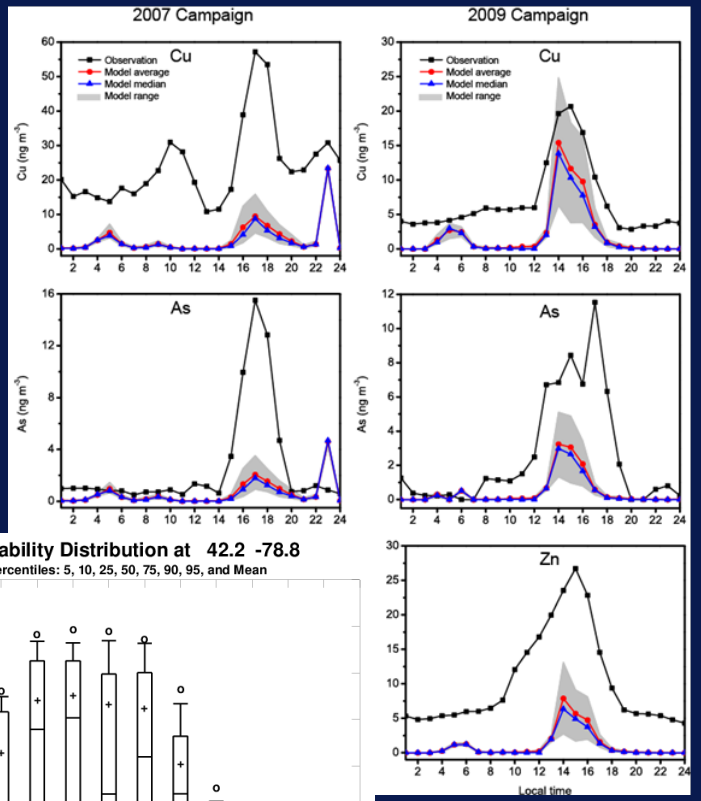


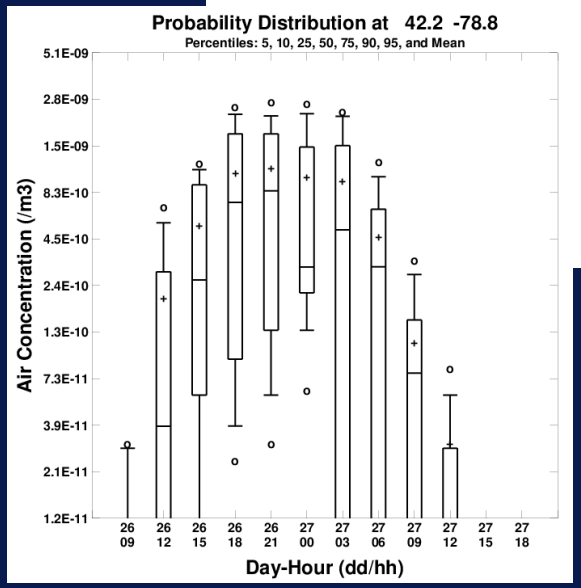




Dispersion Model Ensembles

- Increasingly attractive approach to study atmospheric transport in the lower troposphere to improve plume simulations and assess their uncertainty
- HYSPLIT has a built-in capability to produce different simulation ensembles
- Studying ways of determining the optimum number of multi-model members and/or individual model physical features to vary is the primary difficulty to overcome when constructing ensembles

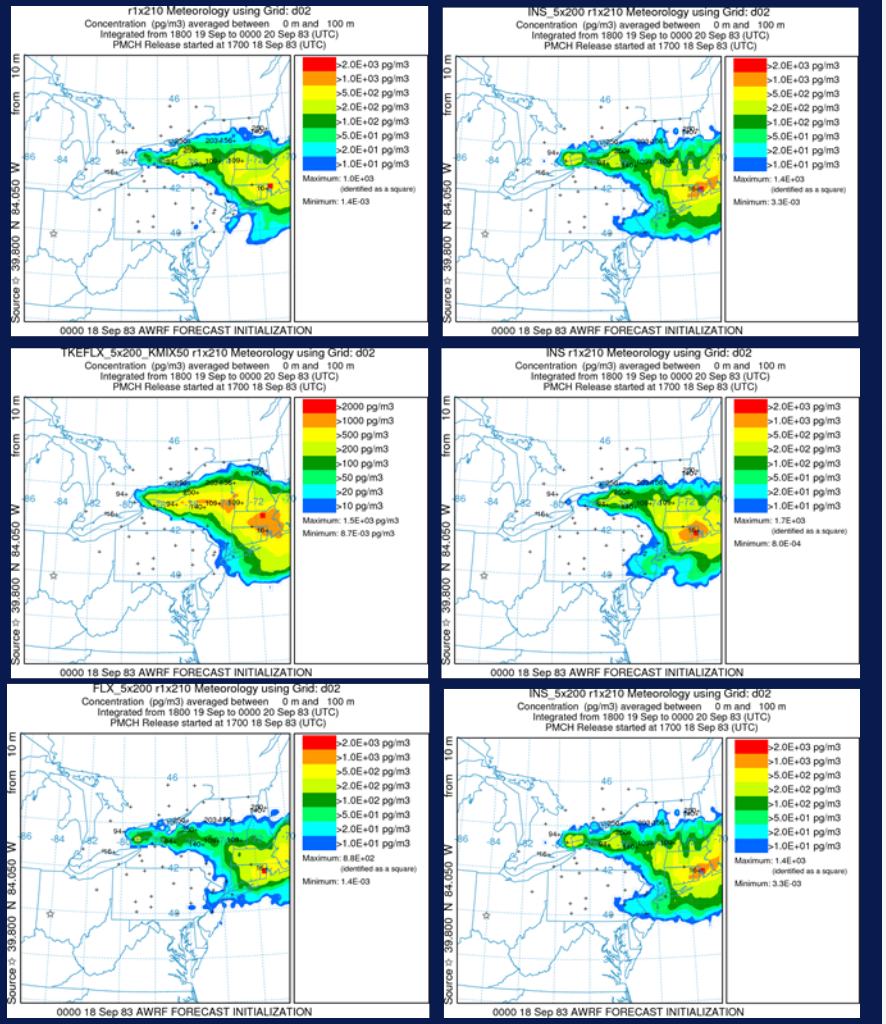




Dispersion Model Ensembles

Standard with the HYSPLIT distribution

- HYSPLIT has a built-in capability to produce three different simulation ensembles:
  - "Meteorological Grid" ensemble, created by slightly offsetting the meteorological data to test the sensitivity of the advection calculation to the gradients in the meteorological data fields
  - "Turbulence" ensemble, represents the uncertainty in the concentration calculation arising from the model's characterization of the random motions created by atmospheric turbulence
  - "Physics" ensemble, built by varying key physical model parameters and model options within the dispersion model



CAPTEX #2 Ensemble Performance

- Shown at right are the RANKS by member for the WRF ensemble, the HYSPLIT physics and meteorological data ensembles
- The largest range in performance is for the meteorological grid ensemble
- The best performing member came from the WRF ensemble
- In no case did the all member ensemble mean performance exceed that of the best member!

Member	WRF	Physics	Grid
1	3.1	2.9	2.9
2	3.0	2.7	3.0
3	3.2	2.7	2.9
4	3.0	2.7	2.8
5	2.8	2.8	2.9
6	2.6	2.8	2.8
7	2.8	2.6	2.9
8	3.1	2.8	3.0
9	3.1	2.8	2.9
10	3.0	3.1	1.5
11	3.0	2.8	1.7
12	3.5	2.6	1.5
13	3.3	3.1	1.5
14	3.1	2.6	1.6
15	3.0	2.9	
16	2.7	2.9	
17	2.9	3.0	
18	2.6	2.8	
19	2.7	2.8	
20	3.0	2.9	
21	3.0		
22	3.4		
23	3.2		
24	2.6		
Mean	**3.1**	**3.1**	**2.9**

Dispersion Model Ensembles
Evaluation Procedures

- Issues
  - Determining the optimum number of multi-model members and/or individual model physical features to vary is the primary difficulty to overcome when constructing ensembles
  - In general, any ensemble might contain redundant information that overemphasizes certain transport and dispersion features suggests using a reduced ensemble over an “all-member” mean
  - Reducing member redundancy reduces the chance that the mean result is biased toward an unrepresentative group of members
- Including Observations
  - Minimize Mean Square Error {accuracy – diversity}
  - Optimal use of reduced ensemble is to improve forecasts
  - Can be applied in a sequence of data assimilation – forecast cycles

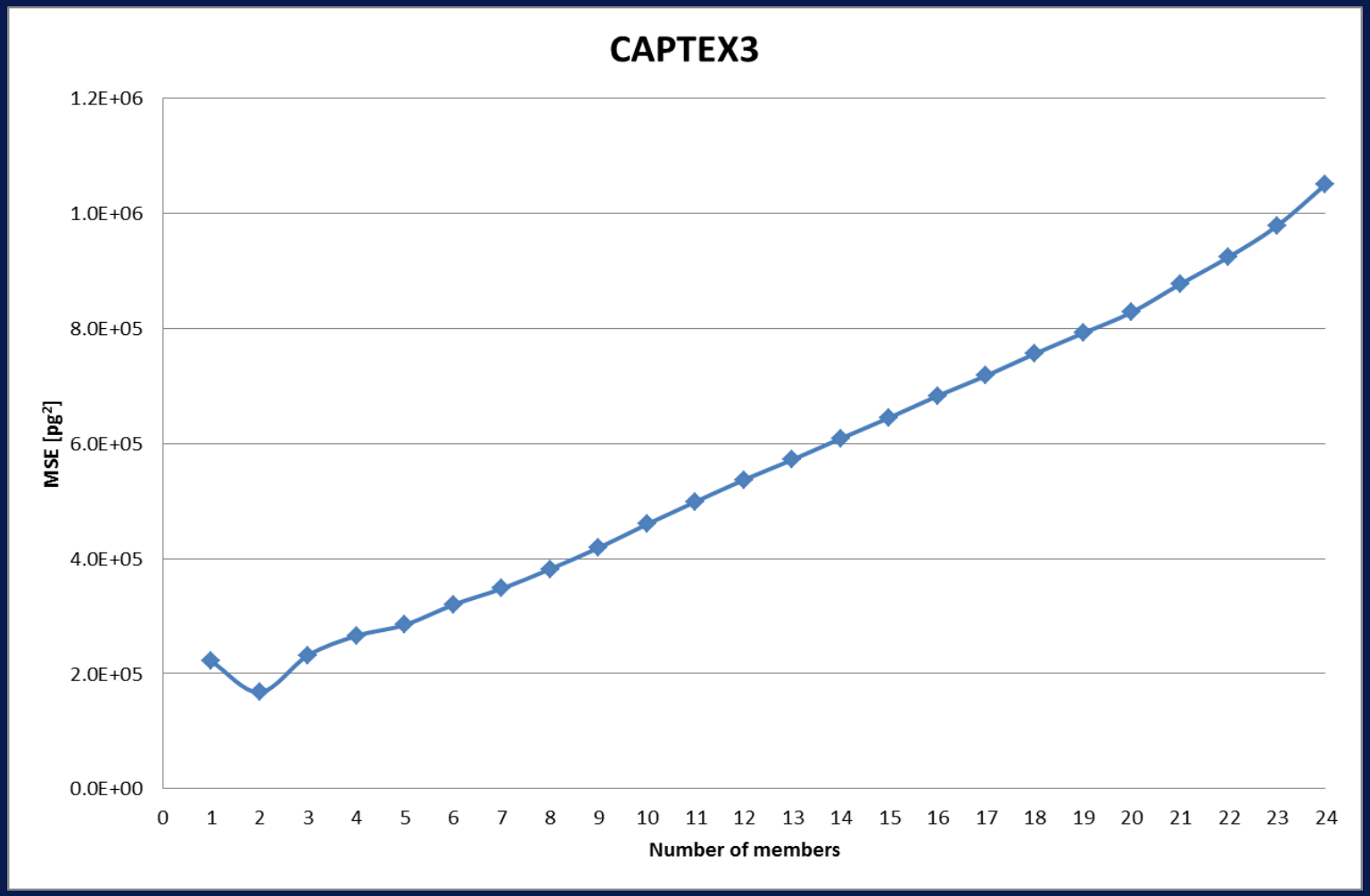
Dispersion Model Ensembles

Reduction Techniques

- Solazzo and Galmarini (2014) demonstrated that an ensemble can be reduced by optimizing the skills of the mean taken among all the possible subsets of ensemble members.
- Calculate the average of all the possible model combinations composed by an increasing number of sub ensemble members up to 24 and estimate their MSE
- if M is the total number of ensemble members (i.e. 24) and n is the number of sub ensemble members, then the number of possible combinations is given by M!/(n!*(M-n)!). 276 pairs, 2024 trios, 10626 quartets….

Dispersion Model Ensembles

Reduction using the Minimum MSE



Dispersion Model Ensembles

Reduction Results

	Full Ensemble	Reduced ensemble minimizing MSE (Ensemble member #)
Rank		
Captex-1	2.43	2.76 (5,18)
Captex-2	3.06	3.49 (12,13,23)
Captex-3	1.79	1.93 (13,23)
Captex-4	2.36	2.37 (9,13)
Captex-5	2.65	2.80 (12,18)
Captex-7	2.50	2.99 (14,12)

Relevance

- 3,500+ registered users from US and overseas from government, private sector, and academia.
- READY HYSPLIT web site usage:
  - Average 60,000+ simulations/month. 1,000,000+ in 2014.
  - Meteograms in READY: ~10,000/day !!!!!
- Training & outreach :
  - Annual onsite HYSPLIT workshop
  - Offsite national and international training
  - Web forum with 3,000+ subscribers: 700+ questions answered.
- HYSPLIT peer literature reference:
  - 800+ references to Draxler and Hess, 1998. Source: Web of Science
  - 12,500 citations to HYSPLIT google scholar
  - 76 references to HYSPLIT BAMS Stein et al, 2015 (published in December, 2015)

READY - Real-time Environmental Applications and Display sYstem