Atmospheric Transport and Dispersion

Mark Cohen

ARL scientists perform activities to understand the main processes that drive the transport and dispersion of harmful substances in the atmosphere, to improve the quality of our modeling tools, and to assess the uncertainties and applicability of those tools.

Background & Motivation

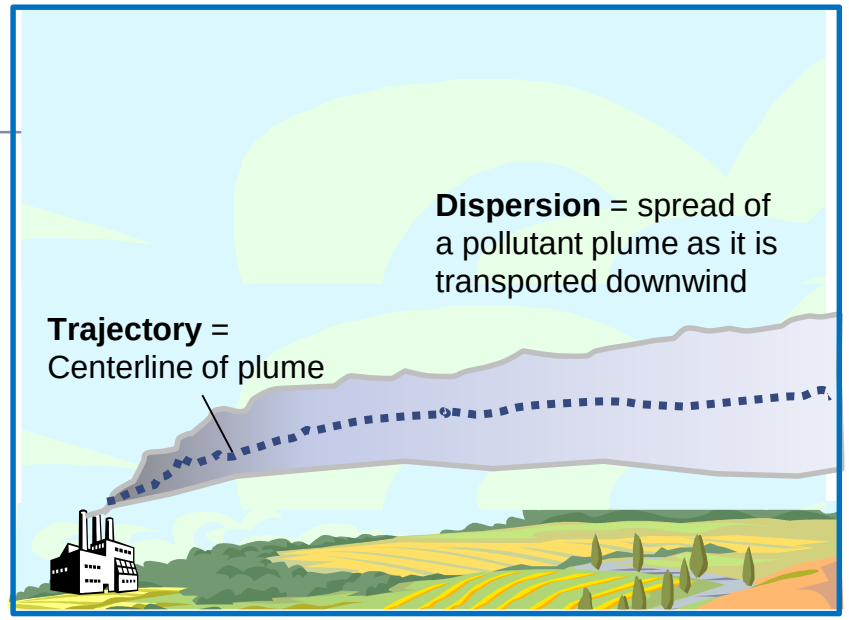
- Atmospheric transport and dispersion modeling is critical for emergency response and assessment for pollutants released to the air
- A key focal point of our R&D is the HYSPLIT model – under continuous development at NOAA ARL for more than 40 years
- Simulations to estimate impacts from emitted pollutants
- Simulations to estimate emissions based on observations

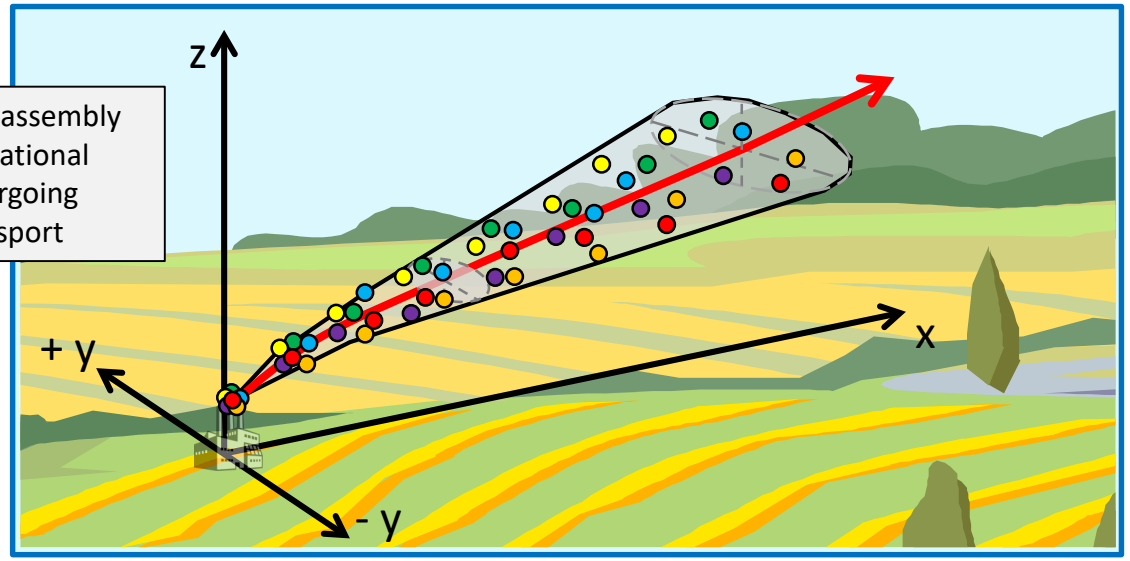
A plume of air pollutants emitted from an industrial fire in Deer Park, Texas, March 2019.

AP Photo: David J. Philip

HYSPLIT Model

- **Continuous development** at ARL for more than 40 years
- ARL HYSPLIT **modeling group** (7-10 scientists)
- **Trajectories** and **Dispersion**
- **Forward** and **Backward**
- **3-D Dispersion (generally > ~1 km)**:
  - "Particles" (i.e., computational points)
  - Puffs (top-hat or Gaussian)
  - Eulerian grid
- **Dry** and **Wet deposition**
- **Chemical** and **Radiological Transformations**
- **Ways to run HYSPLIT:**
  - 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 at other agencies
  - Scientific community: e.g., Stein et al. 2015 ~ 3000 citations





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

Relevance to NOAA OAR goals

Make Forecasts Better

- *Design tools and processes to forecast high-impact weather, water, climate, ocean, and ecosystem events*

  -- OAR Strategy 2020-2026

- *Transition science that meets users' current and future needs*

  -- OAR Strategy 2020-2026

- *Develop Interdisciplinary Earth system models*

  -- OAR Strategy 2020-2026

- *Improve weather & climate predictions by increasing our understanding of Planetary Boundary Layer (PBL) processes*

  -- OAR Implementation Plan 2021-2026

Detect Changes in the Atmosphere

- *Produce, analyze, and interpret observation records to understand the Earth system and inform the public*

  -- OAR Strategy 2020-2026

- *Optimize the greenhouse gases (GHG) observing system… to accurately track GHG [emissions]… and direct feedback to mitigation of emissions.*

  -- OAR Implementation Plan 2021-2026

Pre-Recorded Presentations

- Nuclear Applications and Emergency Response - *Tianfeng Chai*
- Wildfire Applications and Emergency Response - *HyunCheol Kim*
- Volcano Applications and Emergency Response - *Alice Crawford*
- Chemical Applications and Emergency Response - *Sonny Zinn*
- Model Evaluation / Improvement with Tracers - *Fantine Ngan*
- Source Estimation using Inversions - *Chris Loughner*

Atmospheric Transport and Dispersion: *Overview*

Emergency Response & Longer-Term Assessments

Emissions

- Industrial Accidents and Processes
- Wildfires and Prescribed Burns
- Volcanoes
- Nuclear Incidents
- Tracers – Intentional and Opportunistic
- Locust Migration

Meteorology

(forecast and analysis)

- NOAA NWS (e.g., HRRR, NAM, GFS)
- ARL (e.g., WRF)
- External (e.g., MERRA, ECMWF)
- Ensembles (e.g., HREF, GEFS)
- Data assimilation

HYSPLIT Model

- Pre-processing systems
- Trajectories
- Dispersion
- Post-processing systems
- Code management
- Training

Observations

- Surface, Towers, Mobile, UAS, Aircraft, Satellite and other remote
- Ambient concentrations and fluxes
- ARL, NOAA, external partners
- Method development

Consequence Assessment

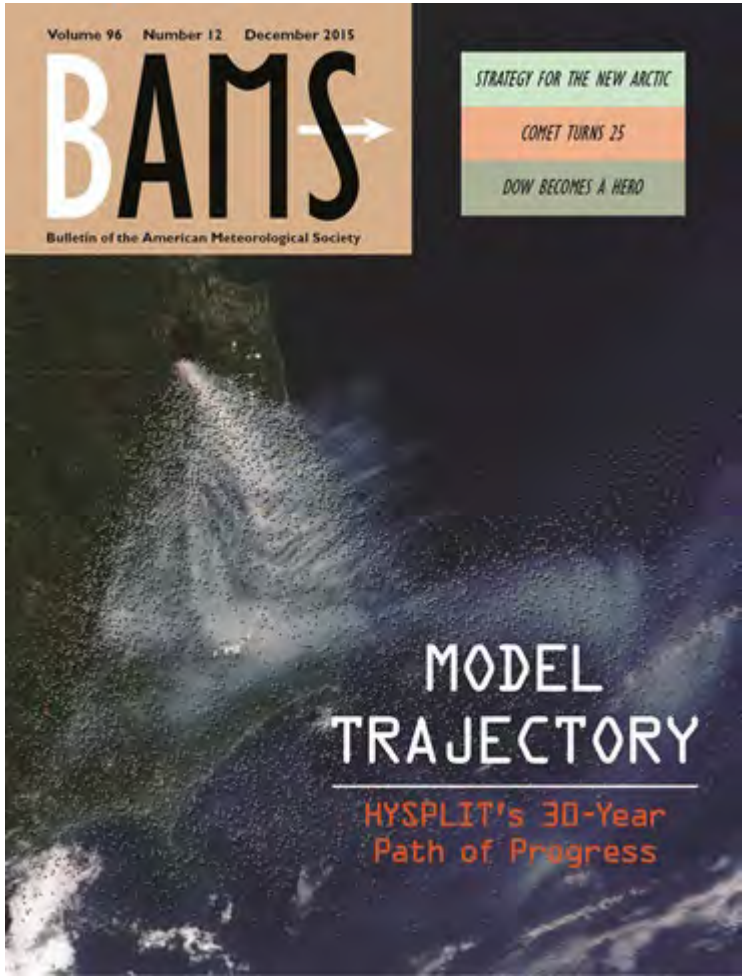
- NWS Weather Forecast Offices
- Wildfire smoke forecasts at NOAA and external partners
- VAACs - Volcanic Ash Advisory Centers
- RSMC - Regional Specialized Meteorological Center
- CTBTO - Comprehensive Test Ban Treaty Organization
- FAO - U.N. Food & Agricultural Organization
- Widespread use at other agencies and in the research community

Pre-Recorded Presentations

Observation-Based Inversions to Estimate Emissions

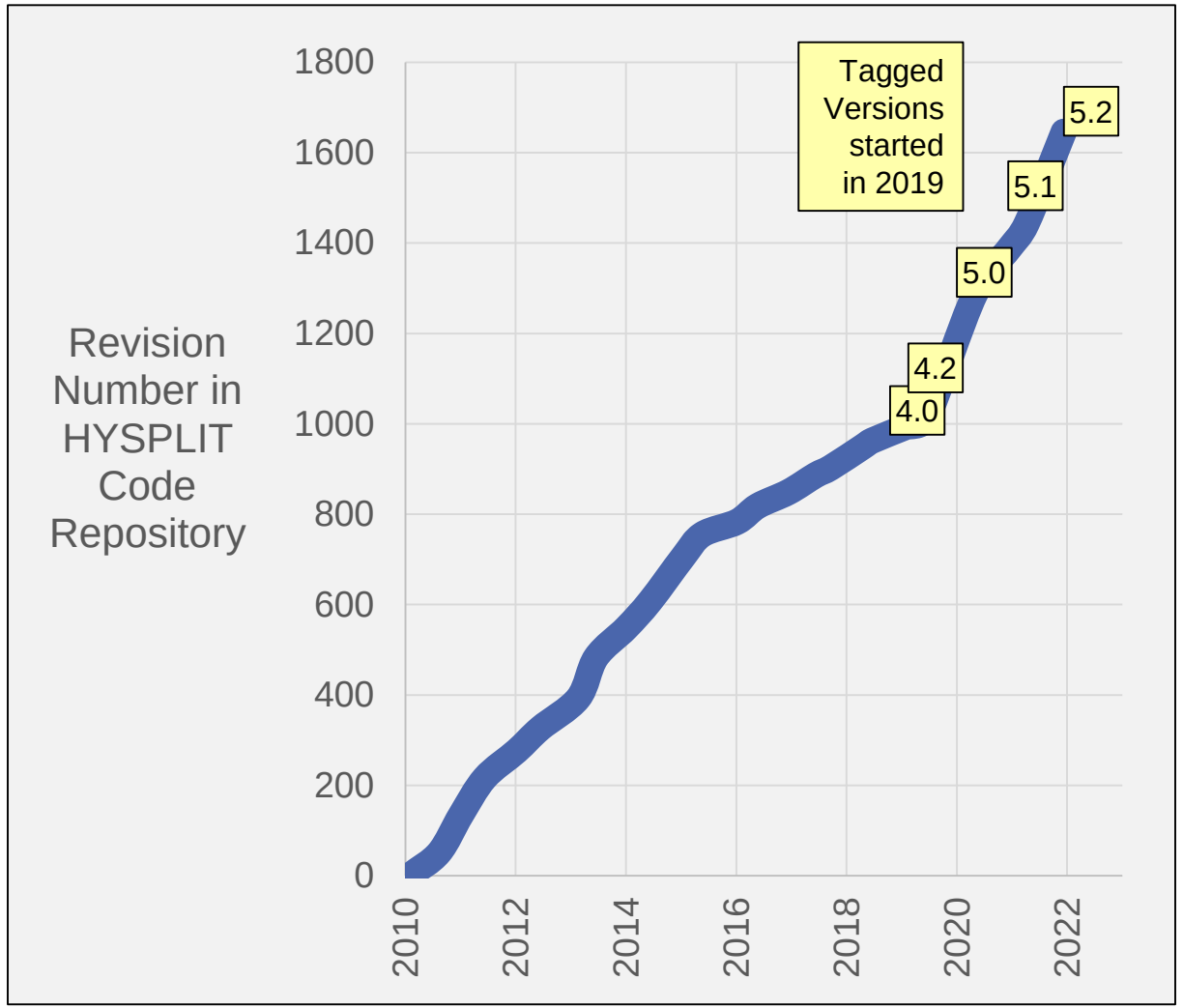
Overarching Goals with the HYSPLIT Model

- Understand, quantify, and reduce uncertainties
  - Evaluate the modeling system by comparison with observations
  - Investigate hypotheses to improve model inputs, physics and parameterizations
- Support and improve model applications
  - Transition modeling tools to operational environments at NOAA and at external partners
  - Balance complexity, flexibility, and ease-of-use
  - Help model users in their application of the model and interpretation of model results



Code Maintenance and Improvement

- Version control system, including the *trunk*, *development*, and several *experimental* branches (1600+ tracked revised versions just in *trunk*)
- *Tagged Versions* started in 2019 to benchmark major-milestone releases
- New features and capabilities, but maintain *backward compatibility*
- Significant testing, e.g., new *unit-testing* procedures
- Extensive user base serves as alerting system for bugs and additional ideas for code improvement
- Studies of code optimization to increase speed
- Graphics improvements (Python, SVG, probabilistic)



Recent Updates (selected examples)

New HYSPLIT physics

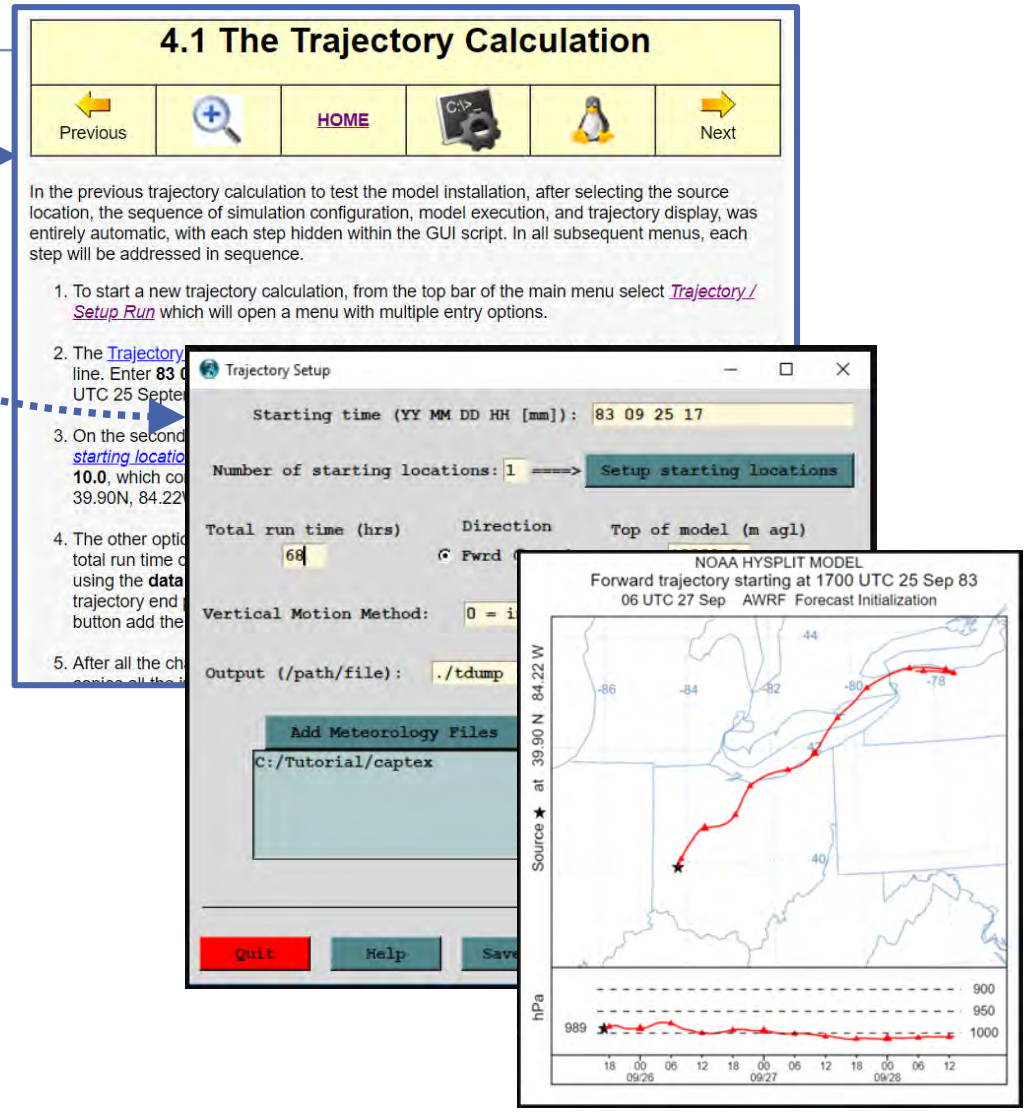
- **STILT dispersion schemes**
  - (2020) –numerous additional physics options from the HYSPLIT-based *Stochastic Time-Inverted Lagrangian Transport Model* were incorporated, involving vertical interpolation and Lagrangian time scale, mixed-layer convection and turbulence, and other dispersion algorithms
- **Random numbers – turbulence treatments**
  - (2019) – Options in turbulent velocity initialization (VINIT)
  - (2020) – Options for random number generation (KRAND)
- **Buoyancy-driven plume-rise algorithms**
  - Existing: Briggs (based on point source observations)
  - (2020) - New for wildfires: Sofiev
  - (2022) – *Upcoming for wildfires:* Freitas scheme
- **Dust emissions**
  - (2022) – *Upcoming:* FENGSHA algorithm
- **Nuclear simulations**
  - (2016-17) - simulate radionuclide daughter products
- **Deposition**
  - (2017) – time interpolation for deposition
- **Weather balloons trajectory functionality**
  - (2018) – to forecast weather balloon landing locations

New HYSPLIT features

- **more functionality for polar concentration grids**
  - (2018) - Now works with puffs as well as particles
- **HYSPTEST program**
  - (2019) - Tests inputs and configs to diagnose common errors
- **Center-of-Mass Trajectory option**
  - (2020) - Center-of-Mass trajectories (CMTFN)
- **Python post-processing graphics programs**
  - (2020) – including new map backgrounds, zooming features
- **SVG graphics outputs – as an alternative to postscript**
  - (2021) – avoids 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
- **Additional meteorological data conversion programs**
  - (2017-21) – e.g., ECMWF, ERA5, MERRA, CESM, AER
- **Higher resolution land cover, roughness length, and terrain datasets**
  - (2020) – 0.1° and 0.5° datasets added to supplement 1° dataset

Training & Education

- Self-guided Tutorial
- Graphical User Interface (GUI)
- Extensive documentation and help resources
- Annual “Hands-On” HYSPLIT Workshop – now virtual, with ~300+ attendees each year
- Additional trainings for different user groups
- HYSPLIT Forum (Wiki) – 1000’s of posted questions and answers
- Numerous collaboration with students, including several internships per year and other assistance



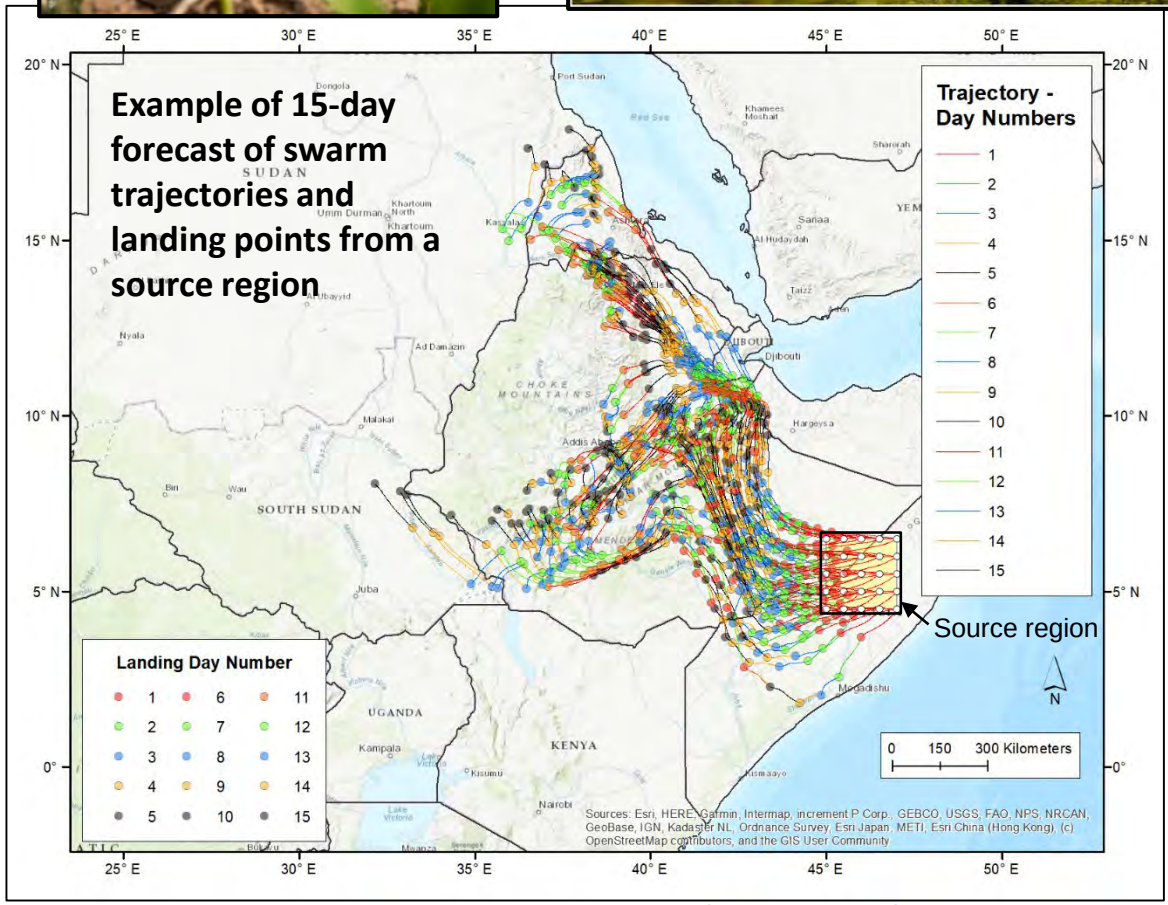
Accomplishments

- Operational Implementations
  - NOAA NWS (National Weather Service) - HYSPLIT for Weather Forecast Offices
  - RSMC (WMO Regional Specialized Meteorological Center) for nuclear emergencies
  - CTBTO (Comprehensive Test Ban Treaty Organization) for detection of clandestine nuclear tests
  - VAAC (Volcanic Ash Advisory Centers) (Wash D.C. and Anchorage)
  - NOAA Smoke Forecast System
  - Locust Migration Forecast System for U.N. Food and Agriculture Organization
- Code Maintenance and Improvements (e.g., new model physics features, new graphics)
- Platform Enhancements (e.g., new architecture for web applications, implemented for Volcanoes and Locusts)
- Collaboration within ARL
  - WRF / HYSPLIT for Western Divisions (SORD, FRD)
  - Assimilation of ATDD-collected Drone data into HYSPLIT emergency response simulations
- Collaboration with other NOAA and external users (training, support, requested enhancements)

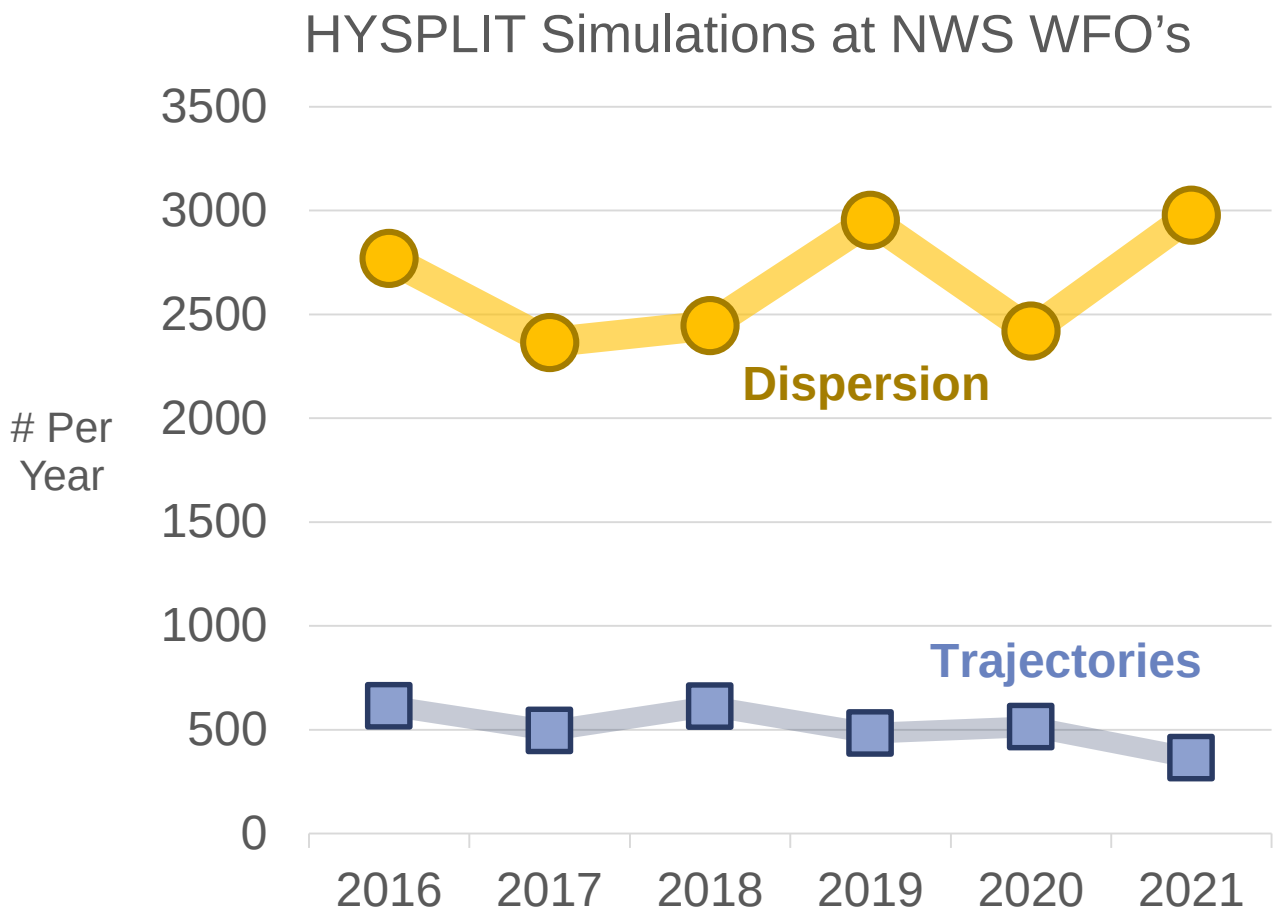
Locust Migration Forecasting

…not included in pre-recorded presentations

- With UN *Food and Agriculture Organization* (FAO)
- Predicts paths of airborne locust swarms
- Daily takeoffs and landings
- Provides *early warnings* to affected communities
- Desert locust upsurge in East Africa and Middle East: ~10x greater than normal for the last two years, *but now appears to be subsiding*
- Caused by climate-change effects on rain patterns
- Locusts are “lazy fliers” & follow the wind, in a swarm, so HYSPLIT *Trajectory* Model is suitable
- 15-day forecasts, using NOAA Global Forecast System
- Single swarm, batch, and source-region simulations: https://locusts.arl.noaa.gov:8443/

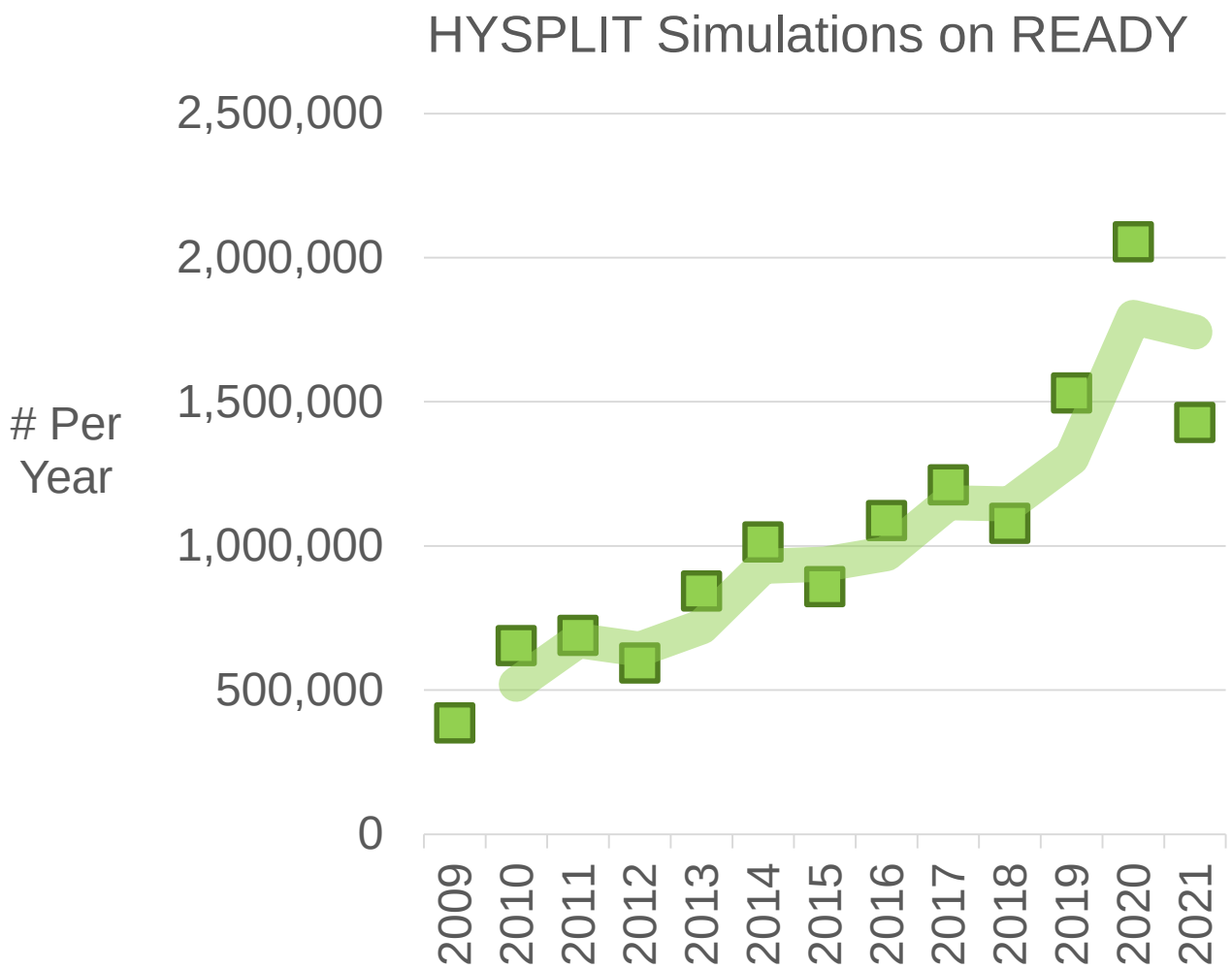


WFO’s use NWS HYSPLIT for emergency response



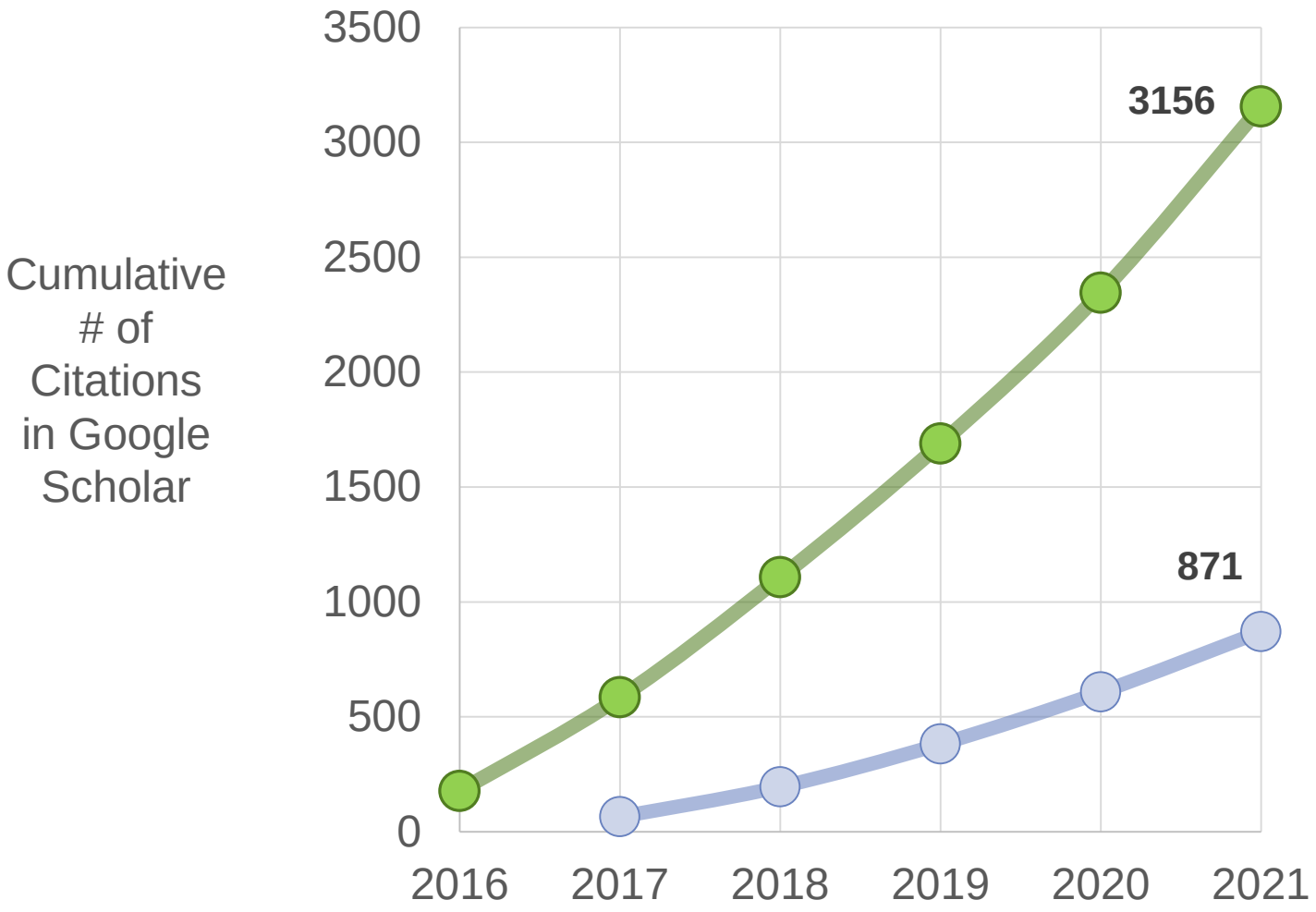
Fire at the Chem-Tool factory
in Rockton, IL, June 2021
(images from CNN and Best World News).

READY is Extensively Used



- Graph at left shows just the yearly on-line HYSPLIT simulations
- … does not include on-line uses for examining meteorological data
- … does not include simulations carried out by users after downloading and installing model on their local computers

Extensive use of HYSPLIT by the research community



A. Stein, R. Draxler, G. Rolph, B. Stunder, M. Cohen, and F. Ngan (2015). NOAA's HYSPLIT Atmospheric Transport and Dispersion Modeling System. *Bulletin of the American Meteorological Society*, 96: 2059 doi: 10.1175/BAMS-D-14-00110.1

G. Rolph, A. Stein, and B. Stunder (2017). Real-time Environmental Applications and Display sYstem: READY. *Envr. Modelling and Software* 95: 210 doi: 10.1016/j.envsoft.2017.06.025

+ ~80 other publications by ARL ATD group scientists from 2016-2021

Future Plans

Objective	Applications
Extend inversions of observations to improve emission estimates	Particularly for greenhouse gases, volcanoes, nuclear, wildfires
Extend use of ensembles to provide probabilistic forecasts	Particularly with volcanic, chemical and wildfire applications
Expand use of Transfer Coefficient Matrix approach to allow efficient updating of forecasts with new data	Particularly with nuclear and volcanic applications
Continue to evaluate and improve model physics	Extend use of *Tracers of Opportunity* to improve understanding of dispersion
Continue to evaluate & improve meteorological data	Evaluate impact of meteorological uncertainties on dispersion simulations
Increase model resolution	Extend and improve meteorological and dispersion simulations on urban scales
Continue to make model code more robust and efficient	Modernize READY / Numerical optimization / Extend unit & other testing schemes
Continue to improve model features and usability	Improve graphics / Increased engagement with WFO and other model users

Collaborations (a sampling)

Atmospheric Transport and Dispersion: *Questions?*

Emergency Response & Longer-Term Assessments

Emissions

- Industrial Accidents and Processes
- Wildfires and Prescribed Burns
- Volcanoes
- Nuclear Incidents
- Tracers – Intentional and Opportunistic
- Locust Migration

Meteorology

(forecast and analysis)

- NOAA NWS (e.g., HRRR, NAM, GFS)
- ARL (e.g., WRF)
- External (e.g., MERRA, ECMWF)
- Ensembles (e.g., HREF, GEFS)
- Data assimilation

HYSPLIT Model

- Pre-processing systems
- Trajectories
- Dispersion
- Post-processing systems
- Code management
- Training

Observations

- Surface, Towers, Mobile, UAS, Aircraft, Satellite and other remote
- Ambient concentrations and fluxes
- ARL, NOAA, external partners
- Method development

Consequence Assessment

- NWS Weather Forecast Offices
- Wildfire smoke forecasts at NOAA and external partners
- VAACs - Volcanic Ash Advisory Centers
- RSMC - Regional Specialized Meteorological Center
- CTBTO - Comprehensive Test Ban Treaty Organization
- FAO - U.N. Food & Agricultural Organization
- Widespread use at other agencies and in the research community

Pre-Recorded Presentations

Observation-Based Inversions to Estimate Emissions