Survey of Evolutionary and Probabilistic Approaches for Source Term Estimation

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Outline

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- Common components of source term estimation (STE)
- Probabilistic approach using Bayesian inference
  - Example: Algeciras accidental release
- Optimization using Genetic Algorithms
  - Example: Redoubt volcano release
- Summary

Source Term Estimation Problem

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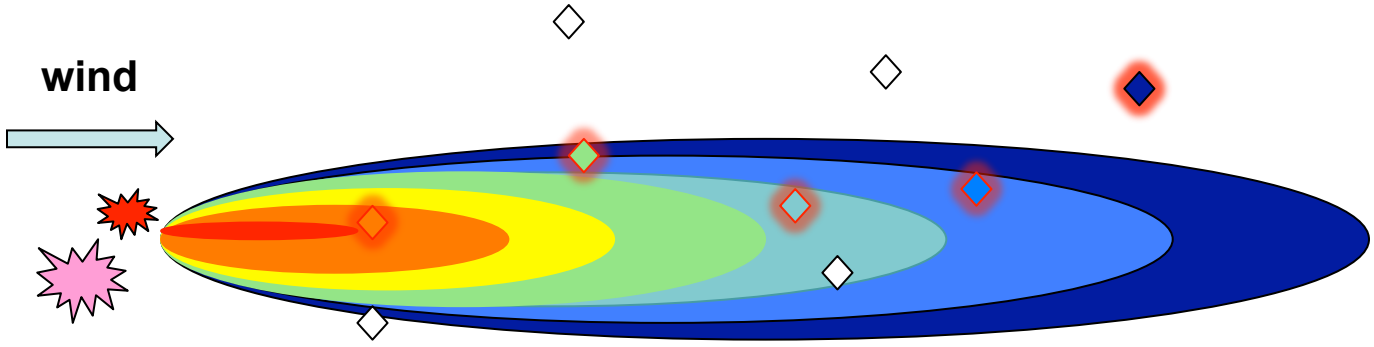
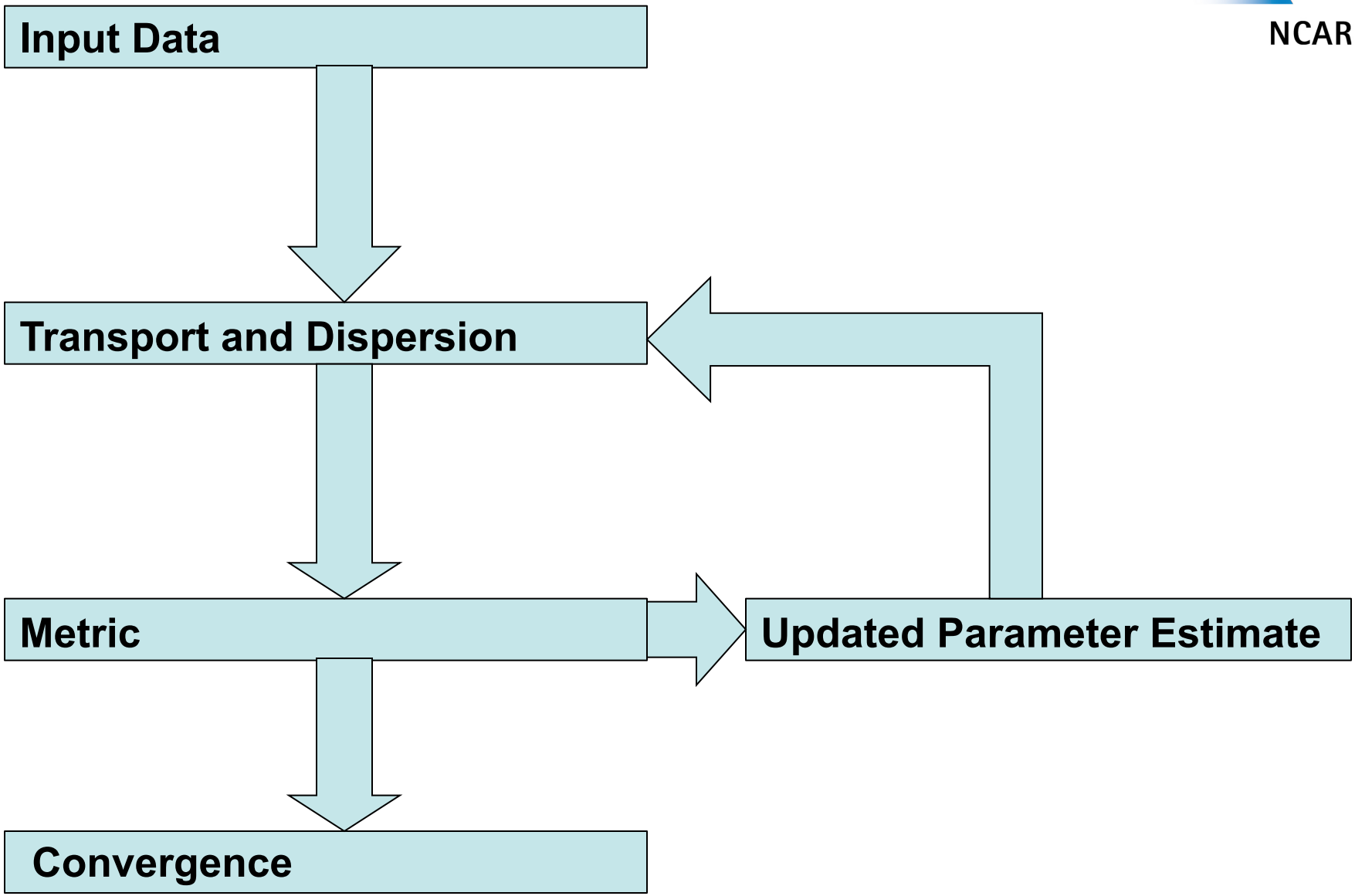
Requirements for STE methodology:

- **Effective (quantitative & accurate)**
- **Efficient (within time constraints)**
- **Flexible (adaptable, multiple data types)**
- **Robust (operational use)**
- **Quantifies uncertainty (probabilistic)**



Source Term Estimation Process



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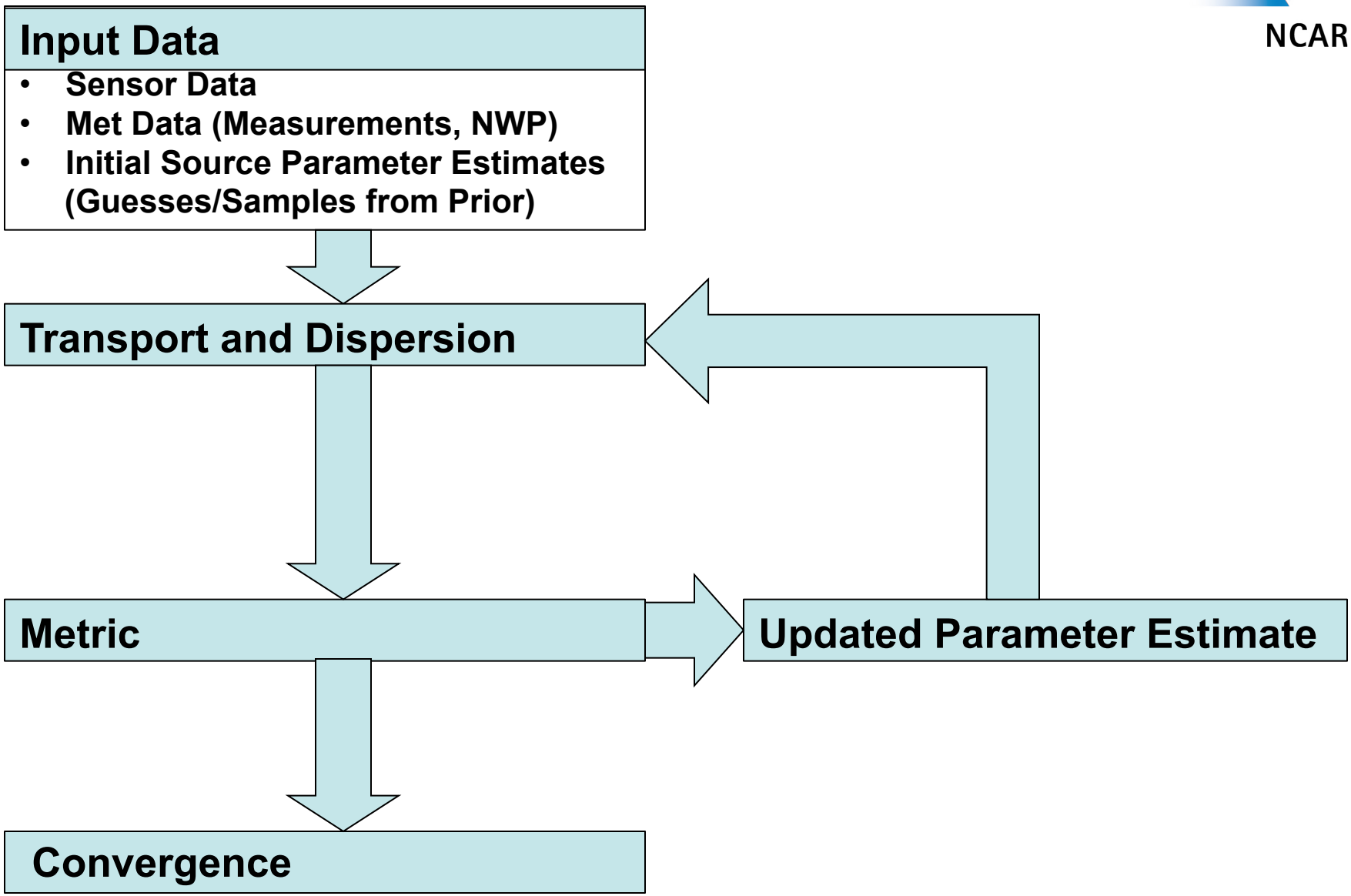
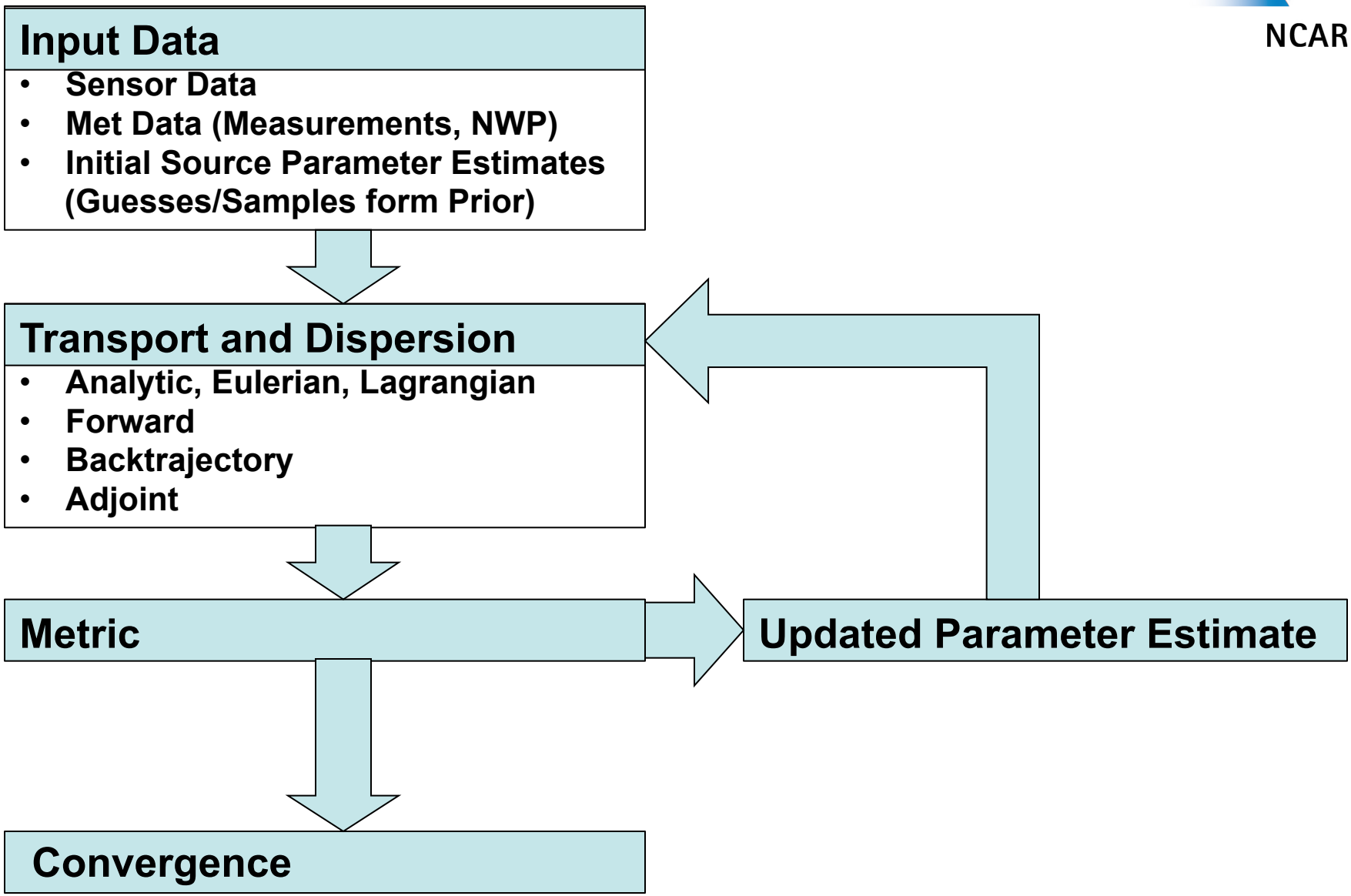
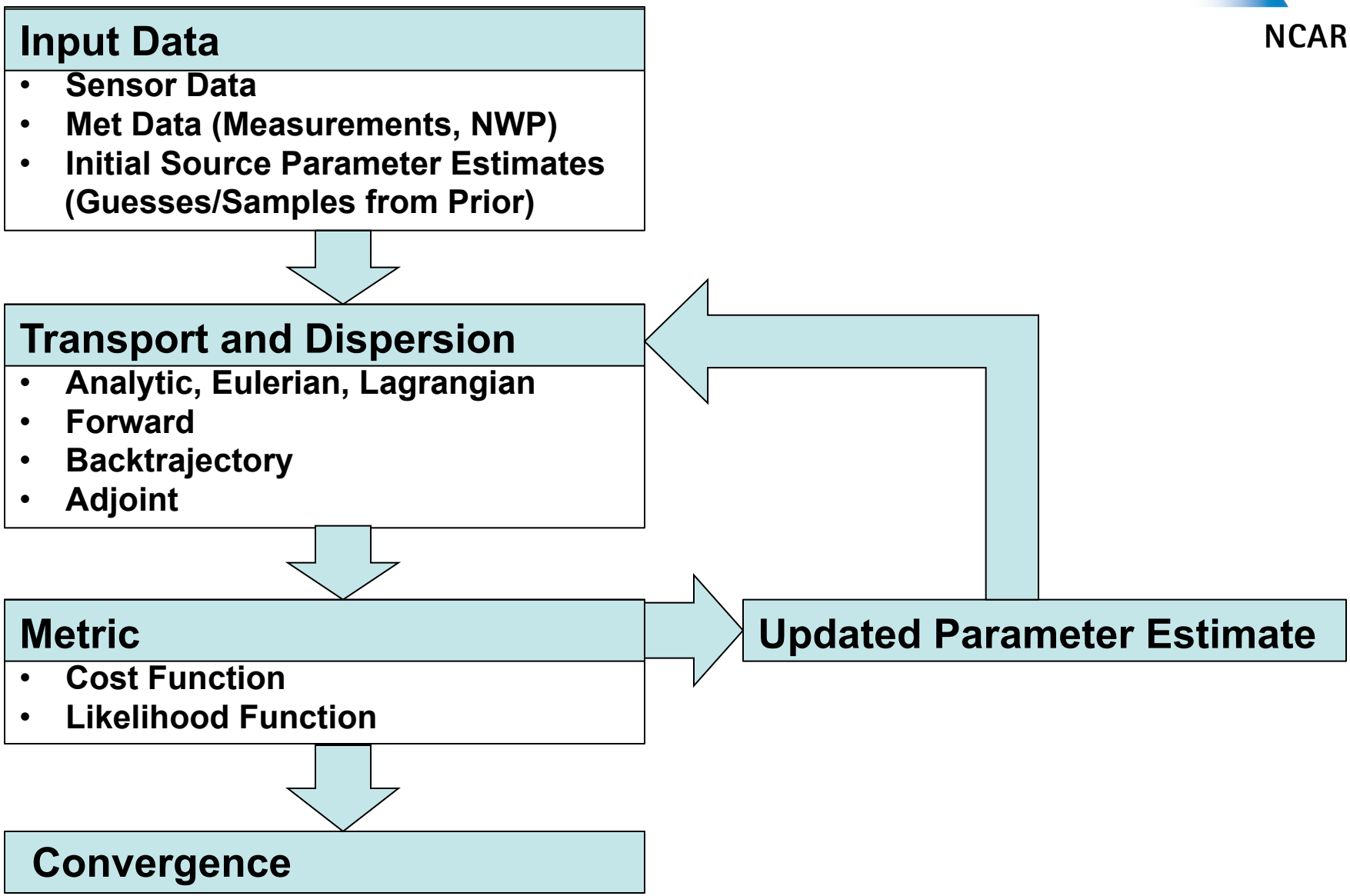


Source Term Estimation Process



Source Term Estimation Process



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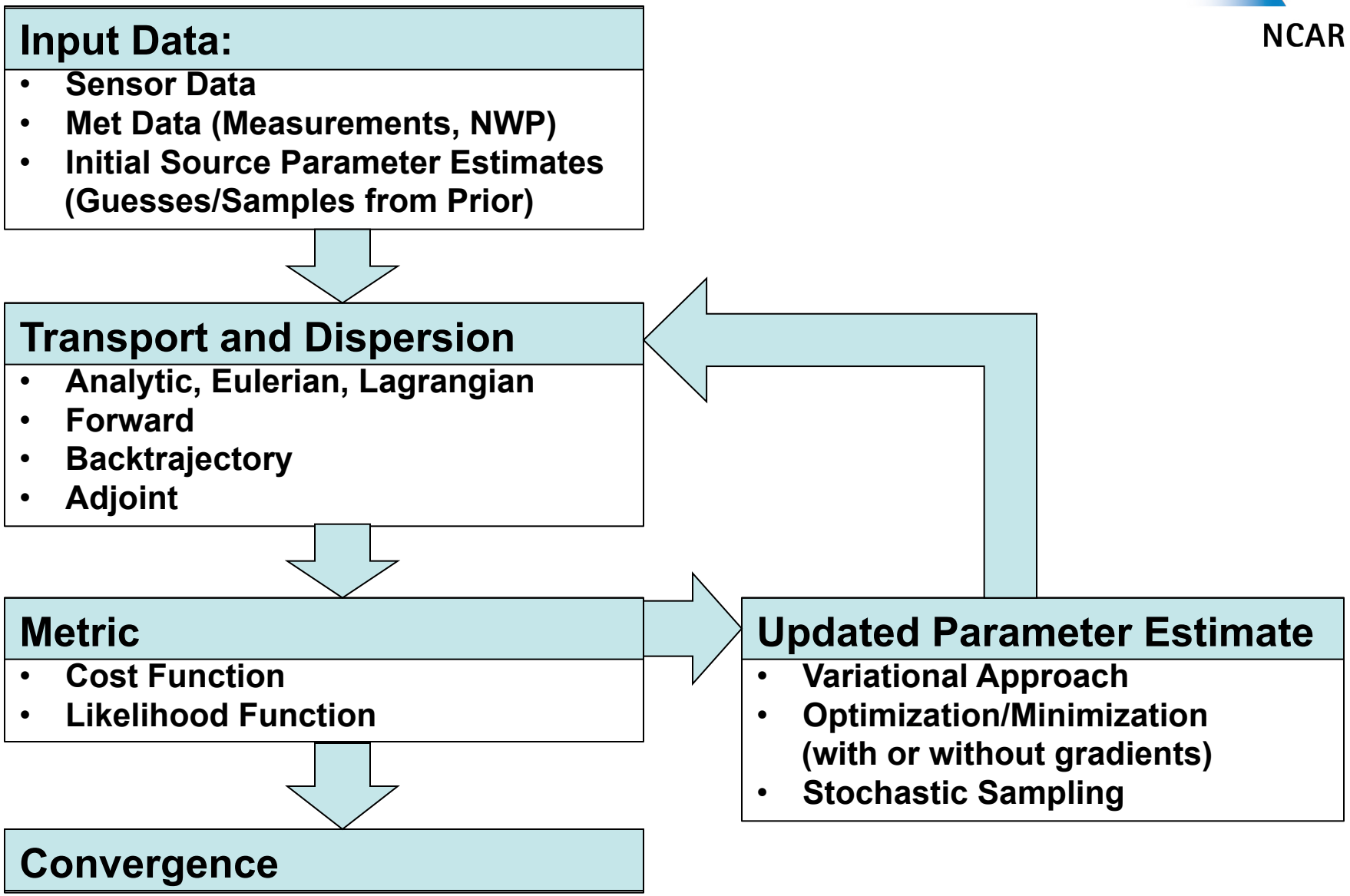
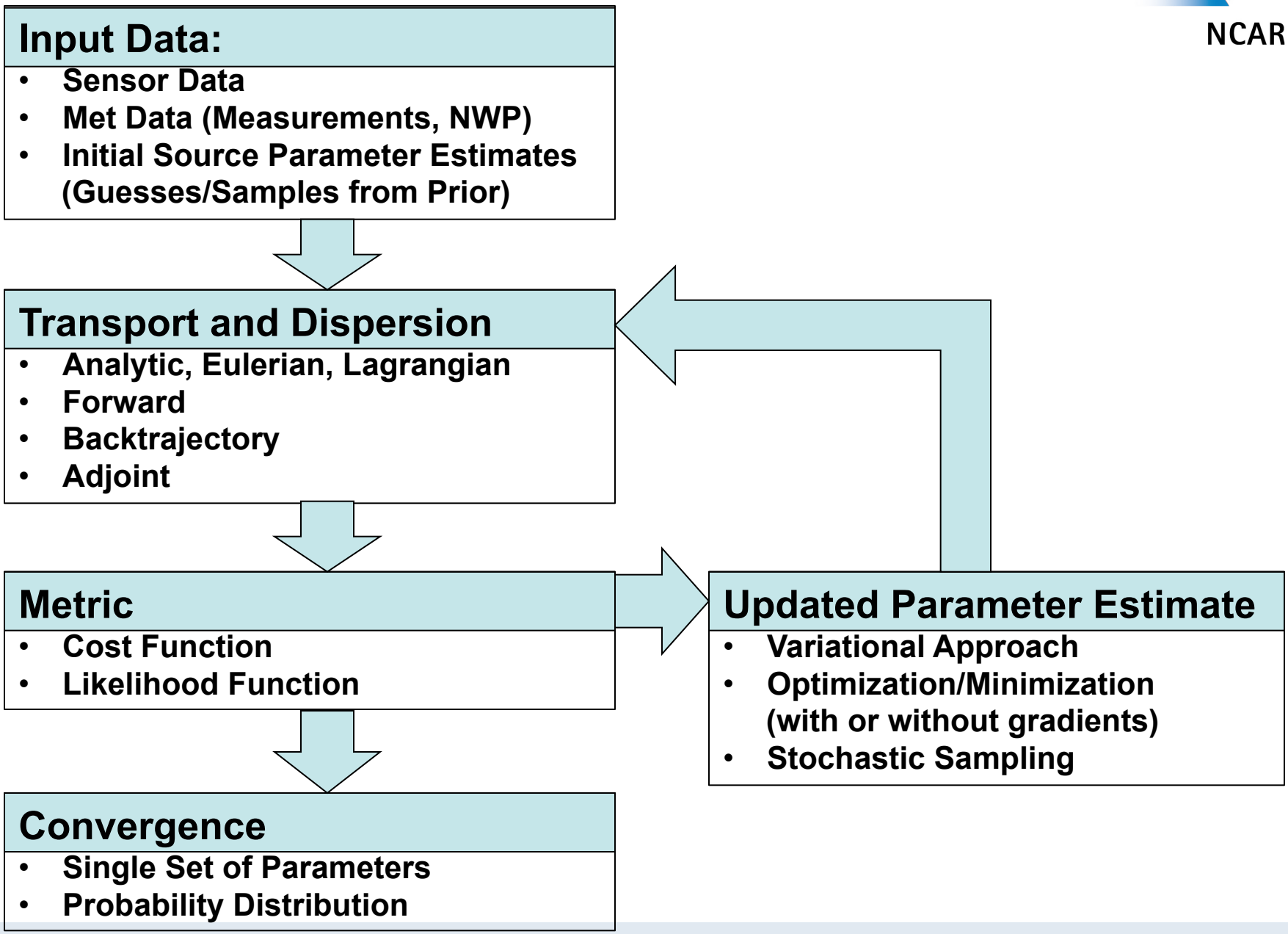


Source Term Estimation Process



Source Term Estimation

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PROBABILISTIC APPROACH USING BAYESIAN INFERENCE WITH STOCHASTIC SAMPLING

Input Data:
- Sensor Data
- Met Data (Measurements, NWP)
- Initial Source Parameter Estimates (Guesses/Samples from Prior)

Transport and Dispersion
- Analytic, Eulerian, Lagrangian
- Forward
- Backtrajectory
- Adjoint

Metric
- Cost Function
- Likelihood Function

Updated Parameter Estimate
- Variational Approach
- Optimization/Minimization (with or without gradients)
- Stochastic Sampling

Convergence
- Single Set of Parameters
- Probability Distribution

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OPTIMIZATION APPROACH USING GENETIC ALGORITHM

Outline

- Common components of source term estimation (STE)
- **Probabilistic approach using Bayesian inference**
  - **Example: Algeciras accidental release**
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  - Redoubt volcano release
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Models and Observations are Coupled Through Bayesian Inference

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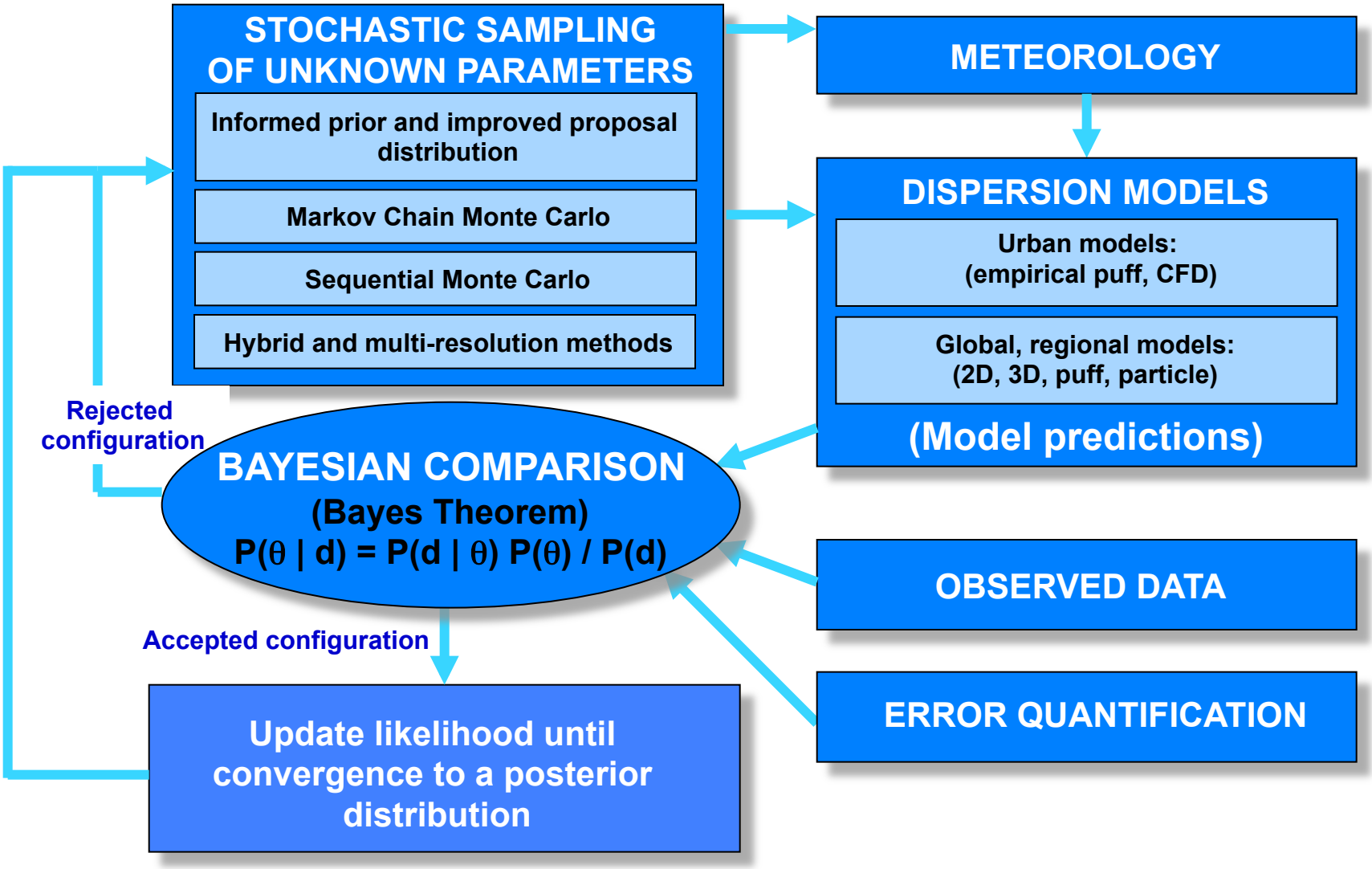

Algeciras Accidental Release

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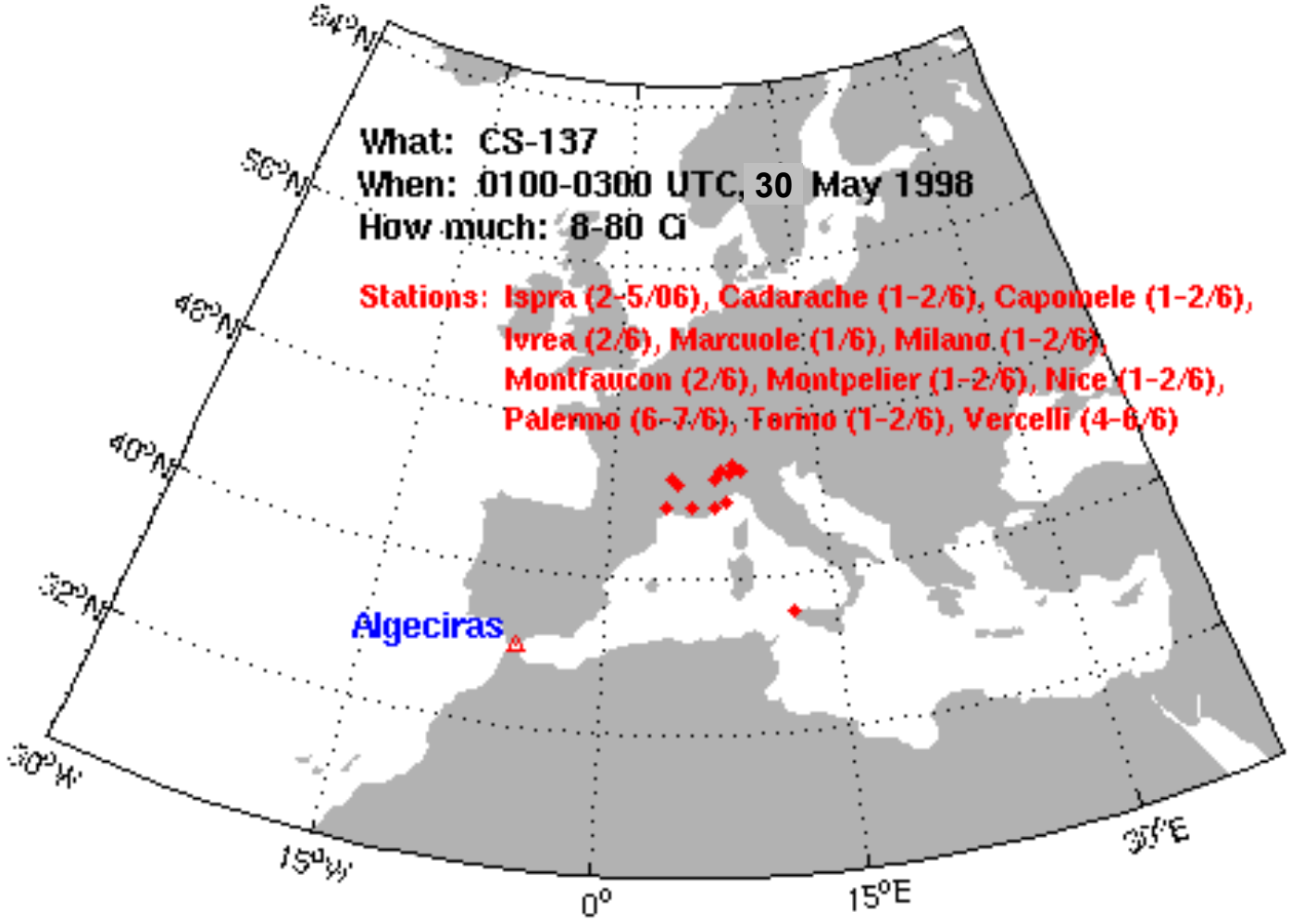

Simulation Set-up and Assumptions

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- Surface point source
- Time and duration of the release
  (0130-0200 UTC, May 30, 1998)
- Sampling box (next slide)
- 11 stations for 17 observations
  (9 on 06/02/1998 + 8 on 06/03/1998)
- Zero concentrations not used

Prediction of Source Location Using Three Markov Chains

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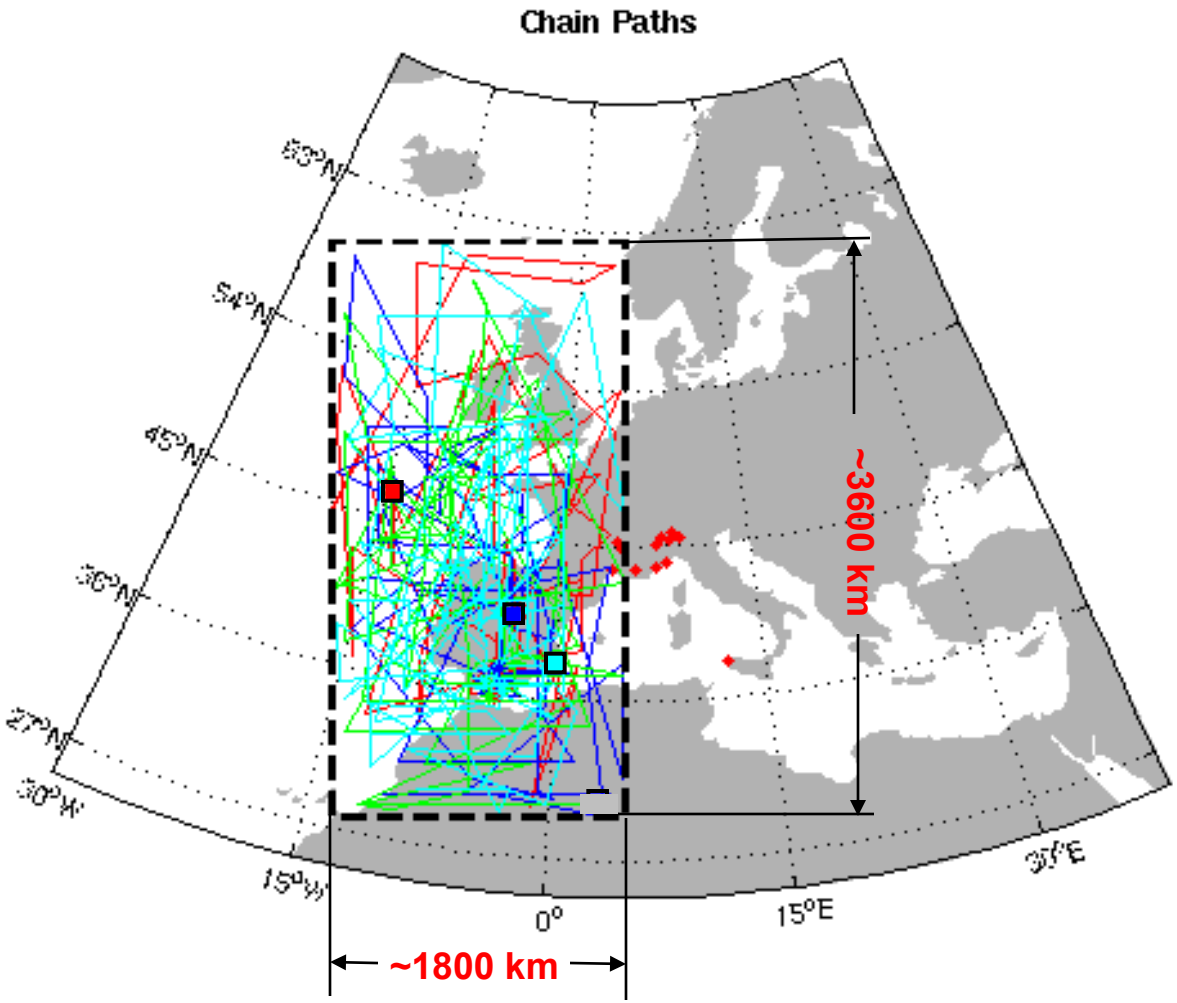
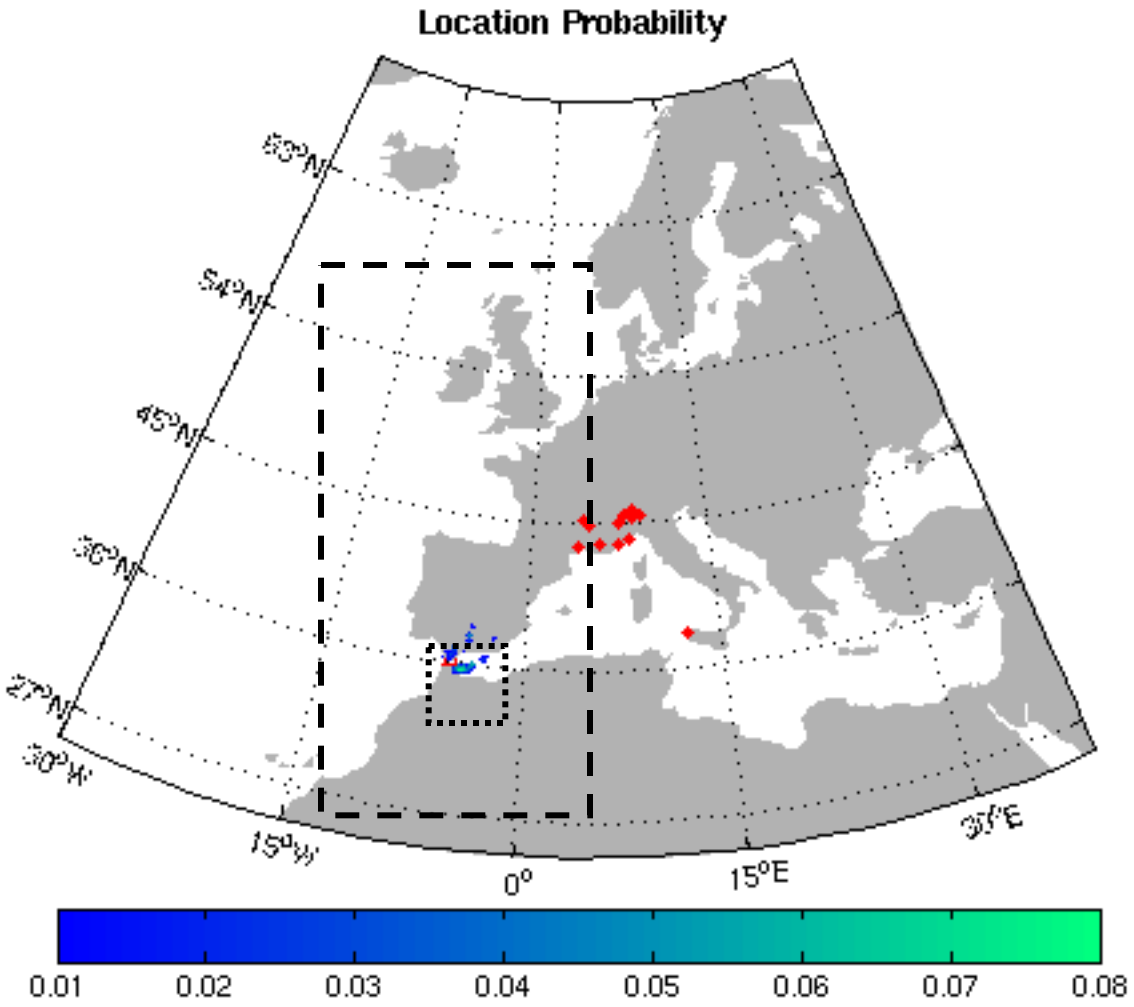


Probability Contours for Source Location Using Three Markov Chains



Location and Release Rate Probability Densities

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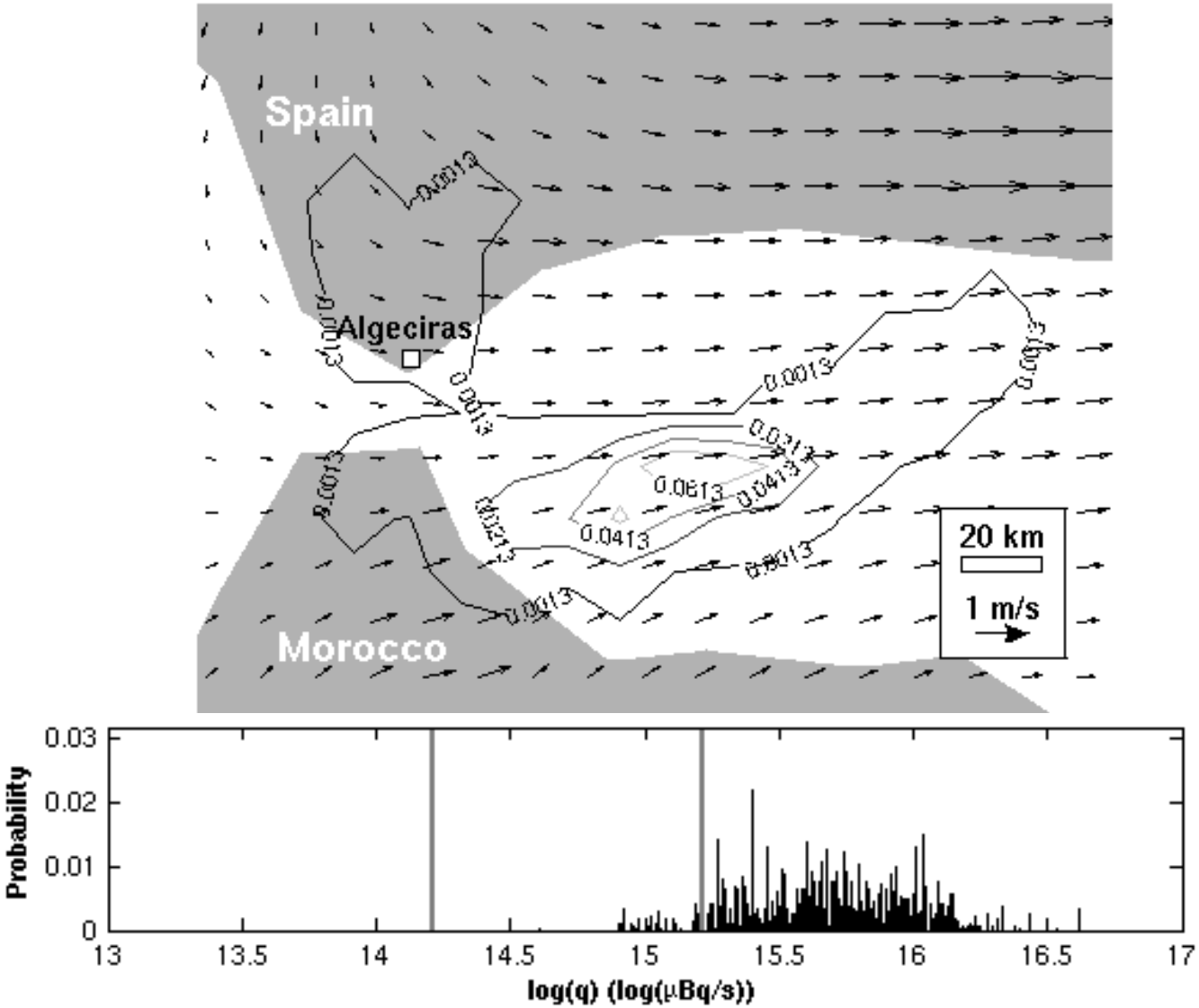

Plume Prediction
After Several Hours (@ 1200 UTC)

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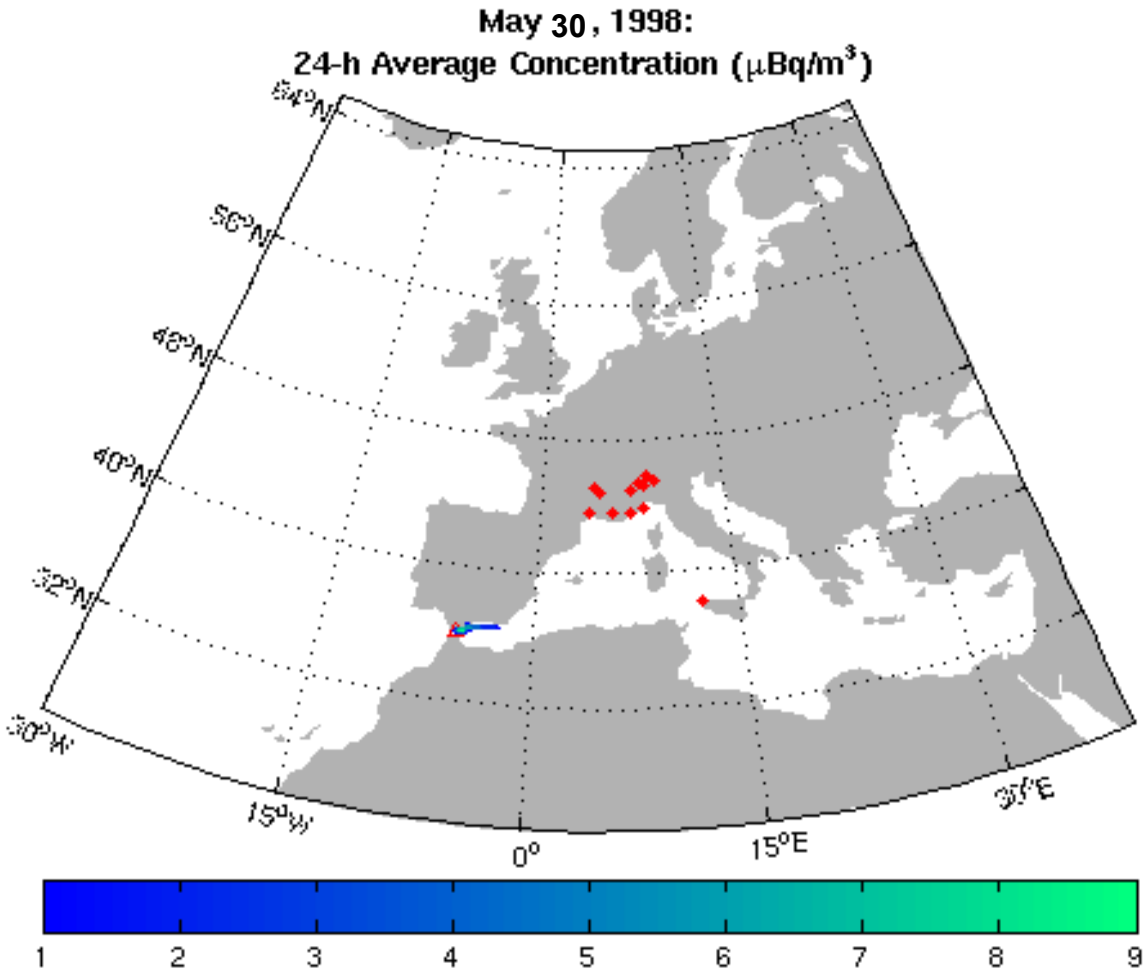
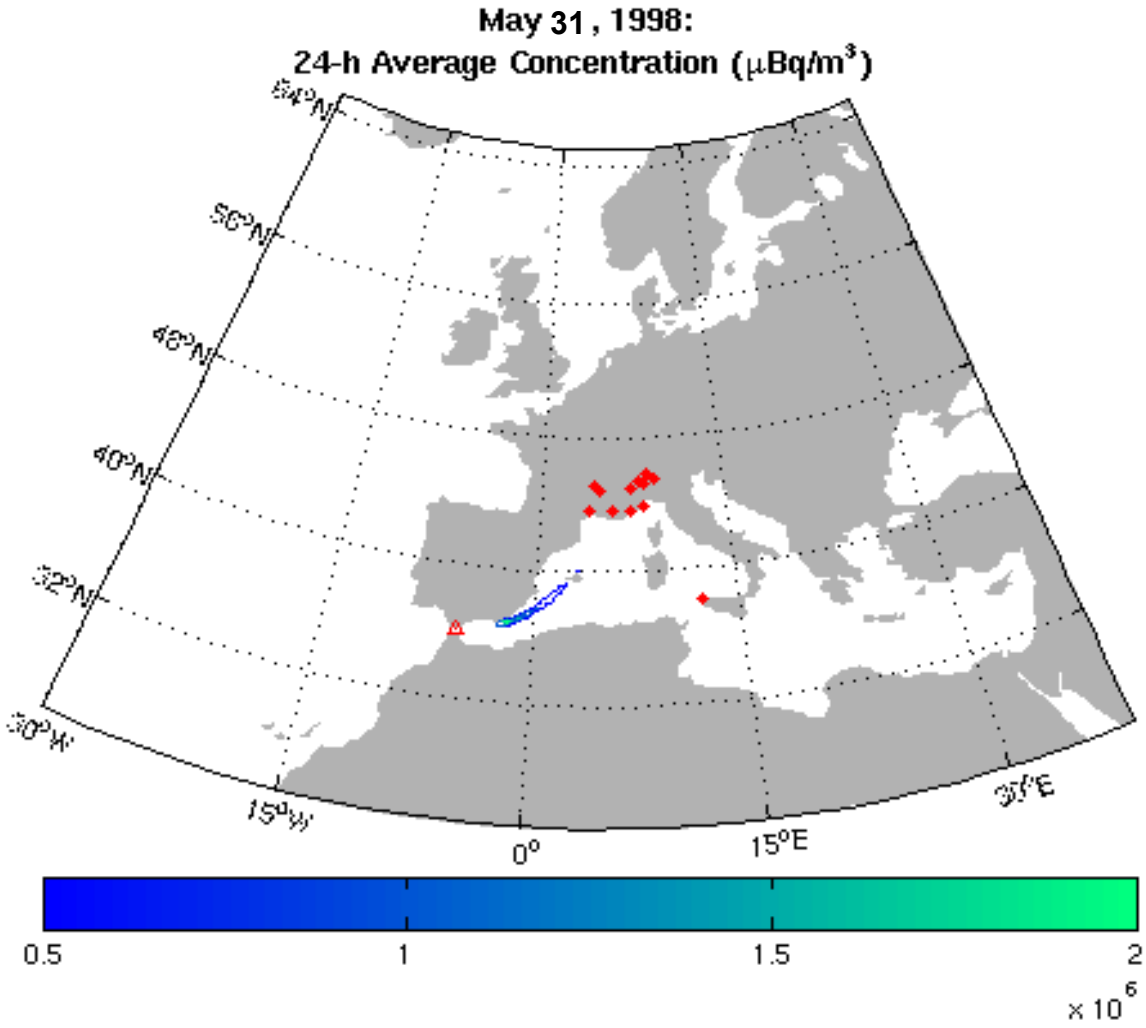


Prediction plume after 1 day



Prediction plume after 2 days

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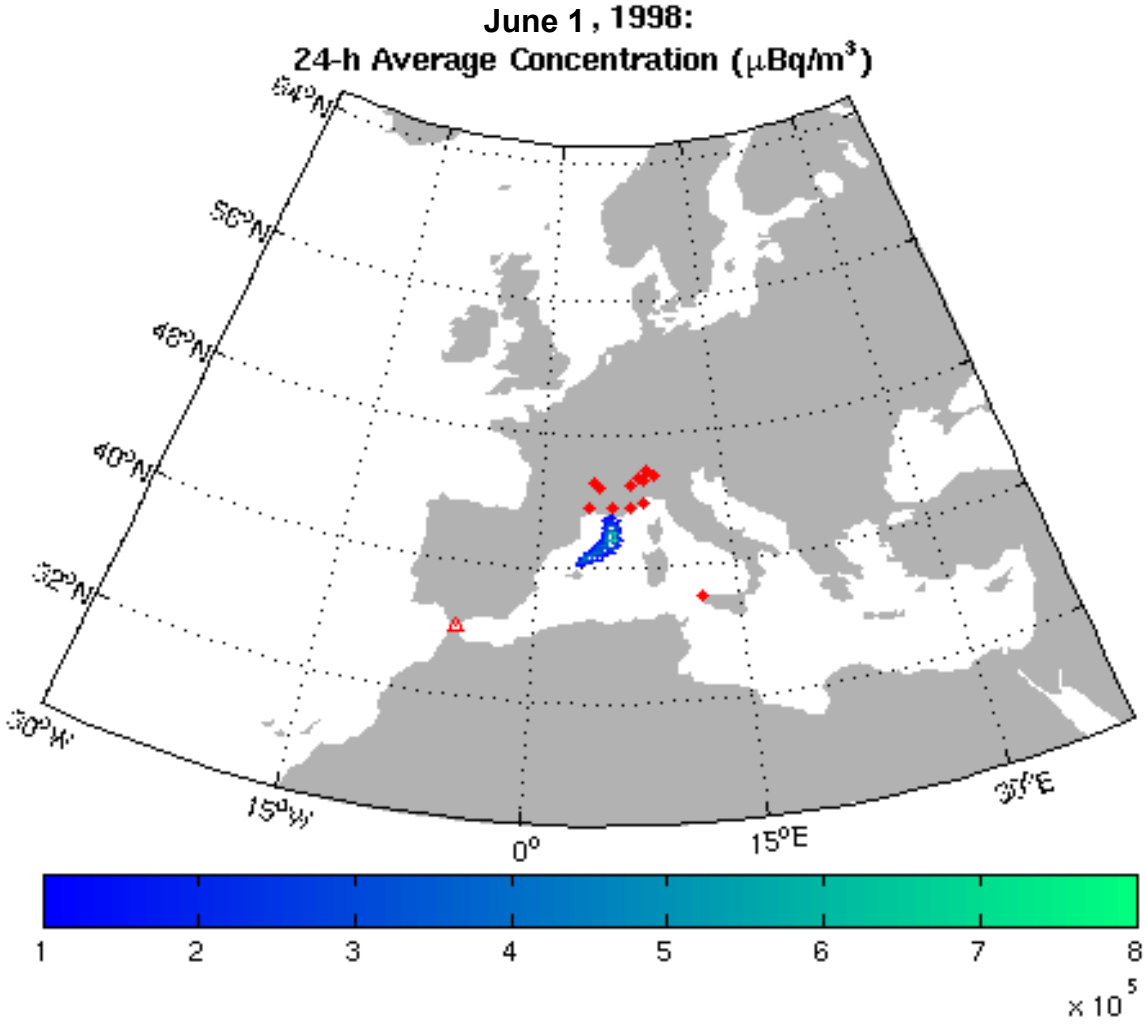

Prediction plume after 3 day

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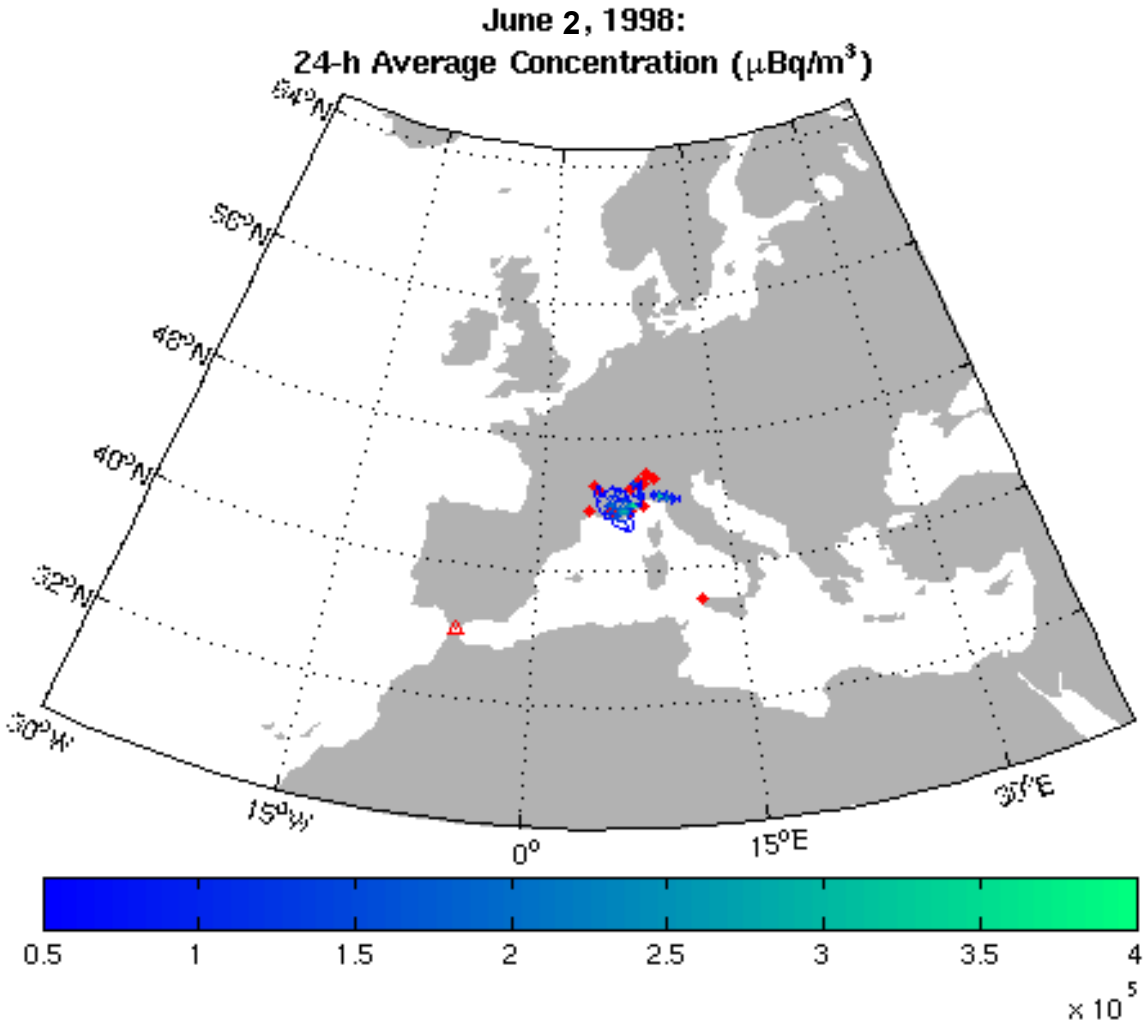

Prediction plume after 5 day

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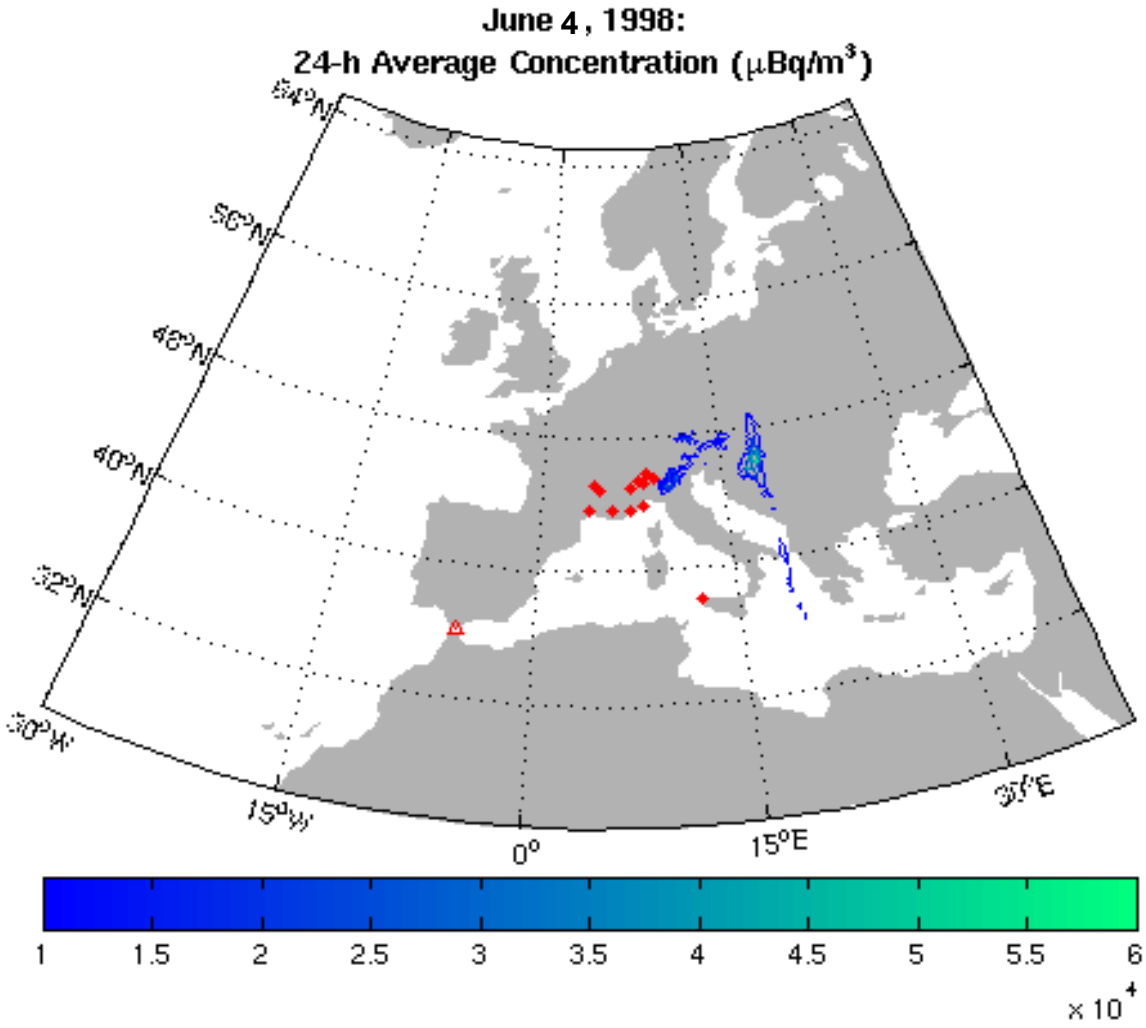

Prediction plume after 6 day

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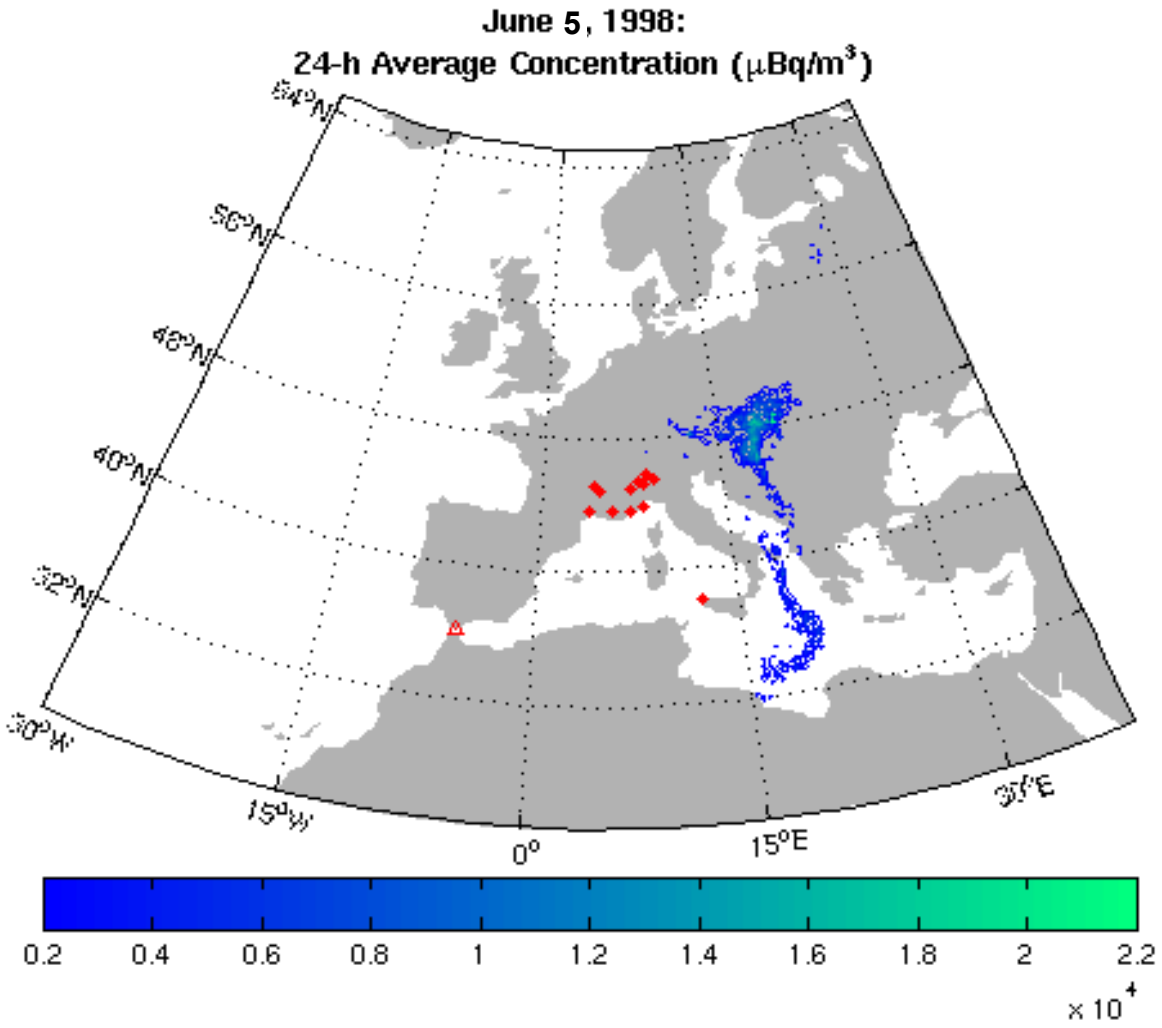

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Genetic Algorithm

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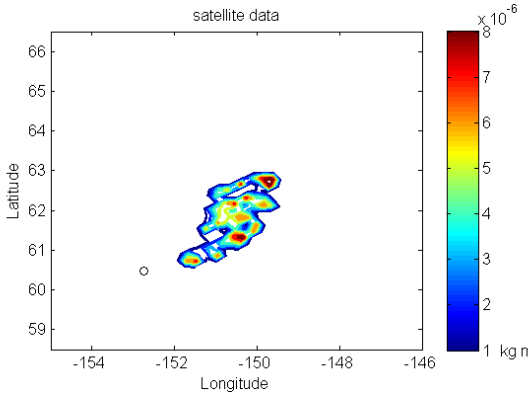

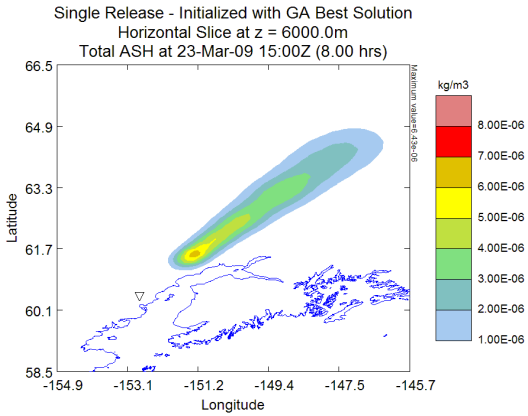

$$\text{cost function} = \frac{\sqrt{\sum_{s=1}^{TS}\left[O_s - C_s\right]^2}}{\sqrt{\sum_{s=1}^{TS}\left[O_s\right]}\sqrt{\sum_{s=1}^{TS}\left[C_s\right]}}$$

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Redoubt Volcano Eruption

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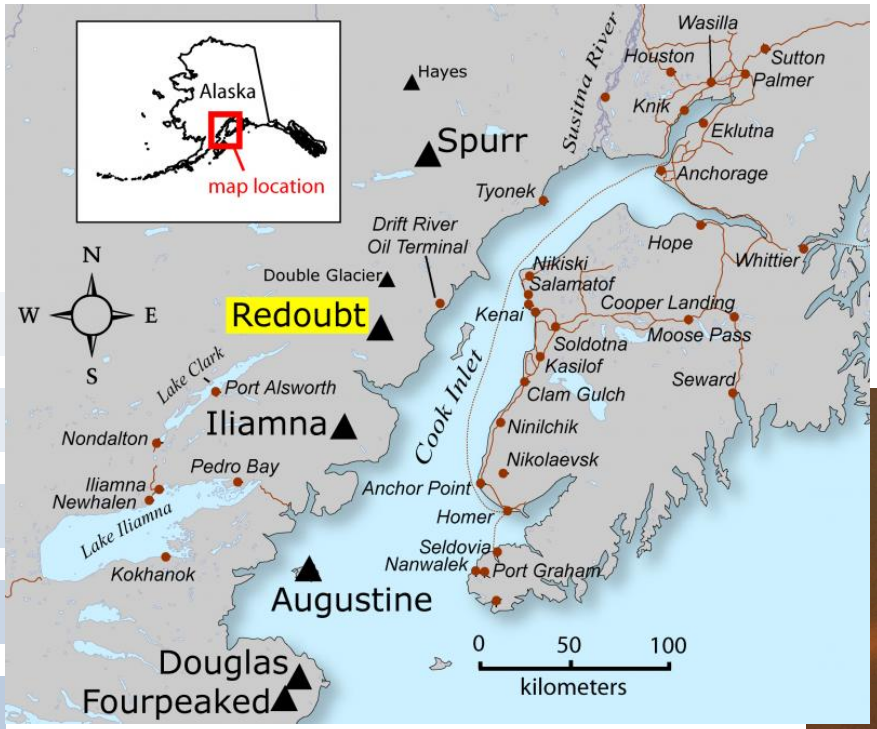
March 23, 2009 Eruption



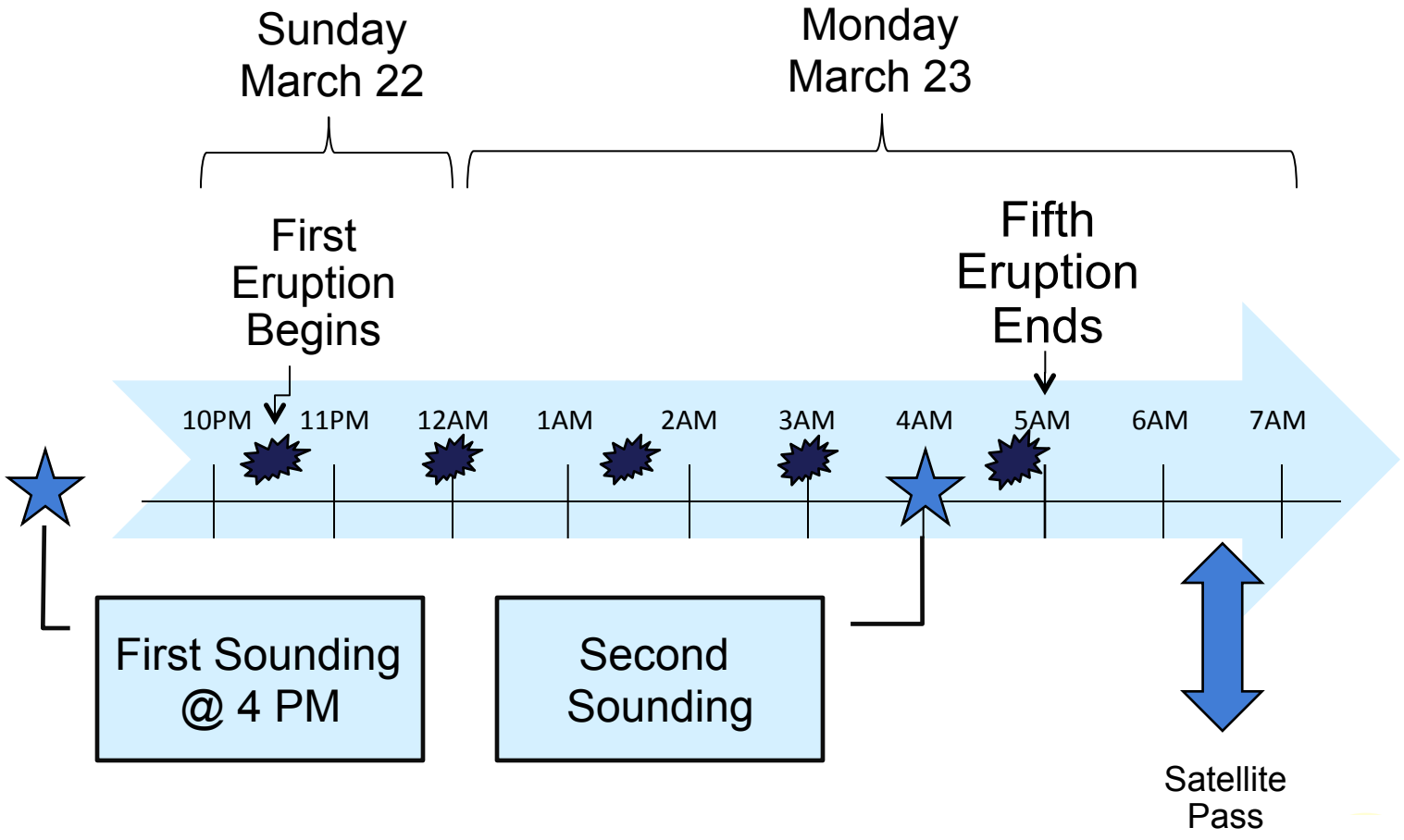
http://www.avo.alaska.edu/image.php?id=15524

Coordinates: 60°29′ N 152°44′ W
Elevation: 3108 meters (10,197 ft.)
Volcano Type: Stratovolcano

The Alaska Volcano Observatory (AVO) observed eleven major explosive events during the first week, and a total of 19 events over the 14 day explosive eruptive period in March and early April.

http://www.avo.alaska.edu/volcanoes/volcimage.php?volcname=Redoubt

Eruption Timeline



Satellite Data

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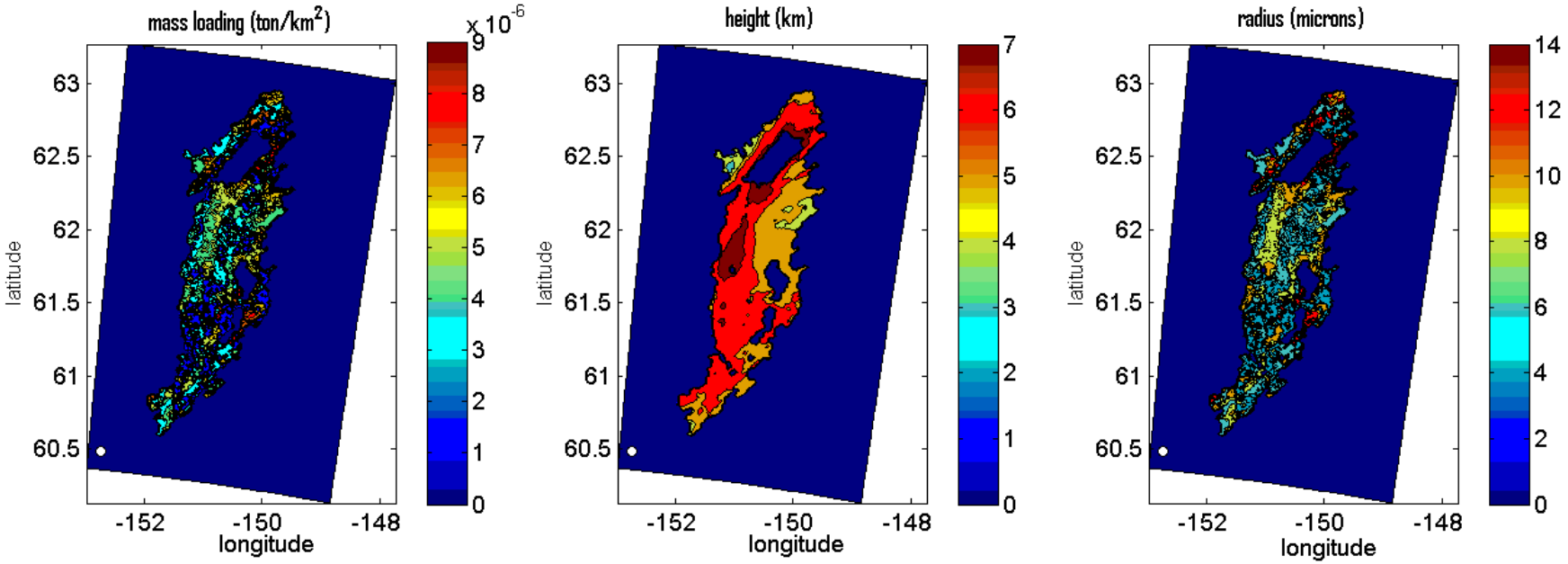
GOES-11 satellite provided data for use with the GA



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Single Uniform Release Results

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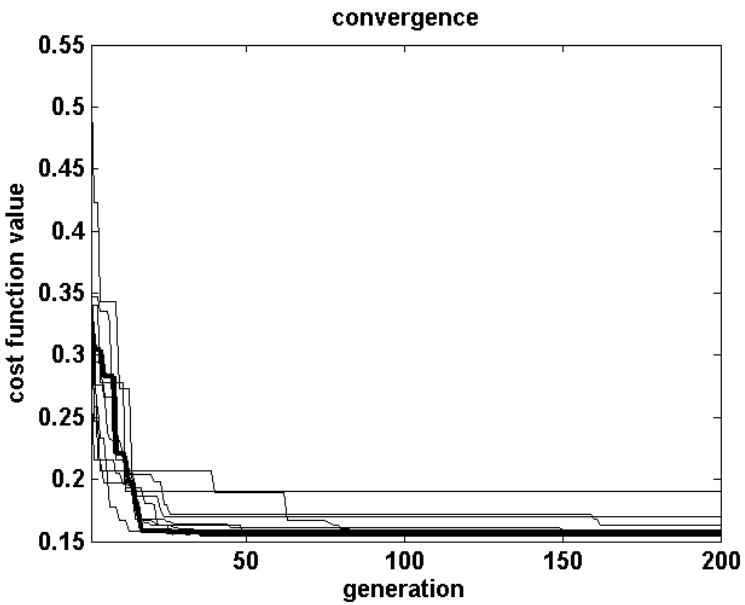
Ten Runs



Population	**64**
Generations	**200**
Mutation Rate	**20%**
Selection	**50%**

	Wind direction (°)	Wind speed (m s-1)	Emission Rate (kg s-1)	Cost Function Value
Run 1	215.7	16.4	$6.8x10^4$	0.1631
Run 2	213.0	23.8	$1.1x10^5$	0.1589
Run 3	214.0	18.0	$6.4x10^4$	0.1592
Run 4	*213.2*	*23.7*	*$9.7x10^4$*	*0.1593*
Run 5	**213.3**	**19.3**	**$8.0x10^4$**	**0.1555**
Run 6	212.4	21.2	$1.0x10^5$	0.1594
Run 7	213.5	21.8	$9.1x10^4$	0.1567
Run 8	213.0	29.3	$1.5x10^5$	0.1701
Run 9	211.8	34.7	$2.3x10^5$	0.1903
Run 10	213.7	24.0	$9.9x10^4$	0.1587
Mean	**213.4**	**23.2**	**$1.1x10^5$**	**0.1631**
STD	**1.0**	**5.4**	**$4.8x10^4$**	**0.0104**

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Single Uniform Release: GA Initialized Best Solution

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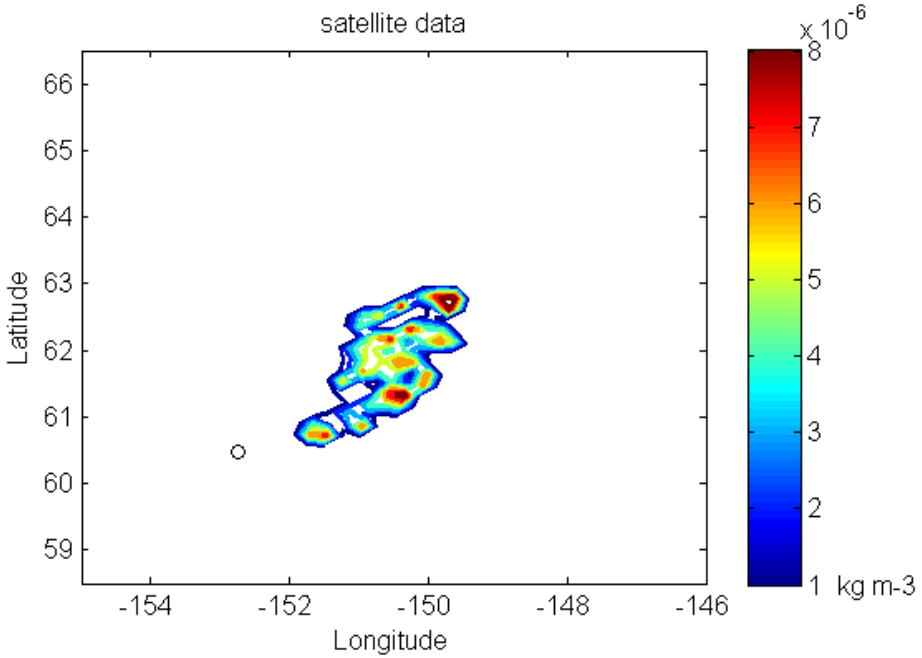
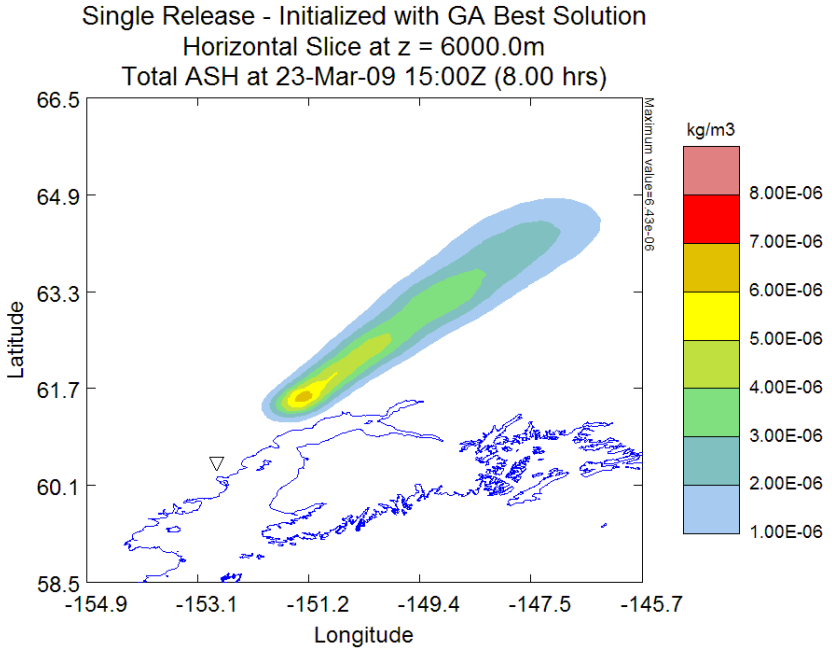
Emission Rate	Total Mass Emitted	Wind Direction	Wind Speed
8.0×10^4 kg/s	2.6×10^9 kg	213.3°	19.3 m/s





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Summary

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How to achieve effectiveness and efficiency while dealing with complexity and uncertainty?

Both algorithms are effective but require significant computational expense.

Bayesian approach:

- **Provides probabilistic solution**
- **Flexible framework**

Delle Monache et al. “Bayesian Inference and Markov Chain Monte Carlo Sampling to Reconstruct a Contaminant Source on a Continental Scale,” J. Appl. Meteor. and Climatol., 47, 2600–2613.

Genetic Algorithm approach:

- **Efficient exploration of parameter space**
- **Single best solution, but also probabilistic**

Schmehl et al. “A Genetic Algorithm Variational Approach to Data Assimilation and Application to Volcanic Emissions,” accepted for publication in Atmospheric Environment.