



AOMSUC-15 2025 FYSUC

THE 15TH ASIA-OCEANIA METEOROLOGICAL SATELLITE USERS' CONFERENCE (AOMSUC-15)
2025 FENGYUN SATELLITE USER CONFERENCE (2025 FYSUC)

Using EnKF Data Assimilation to Improve Predictions of Volcanic Ash Dispersion

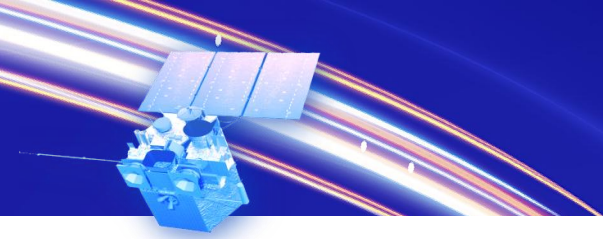
Reporter: ZHANG Yiran

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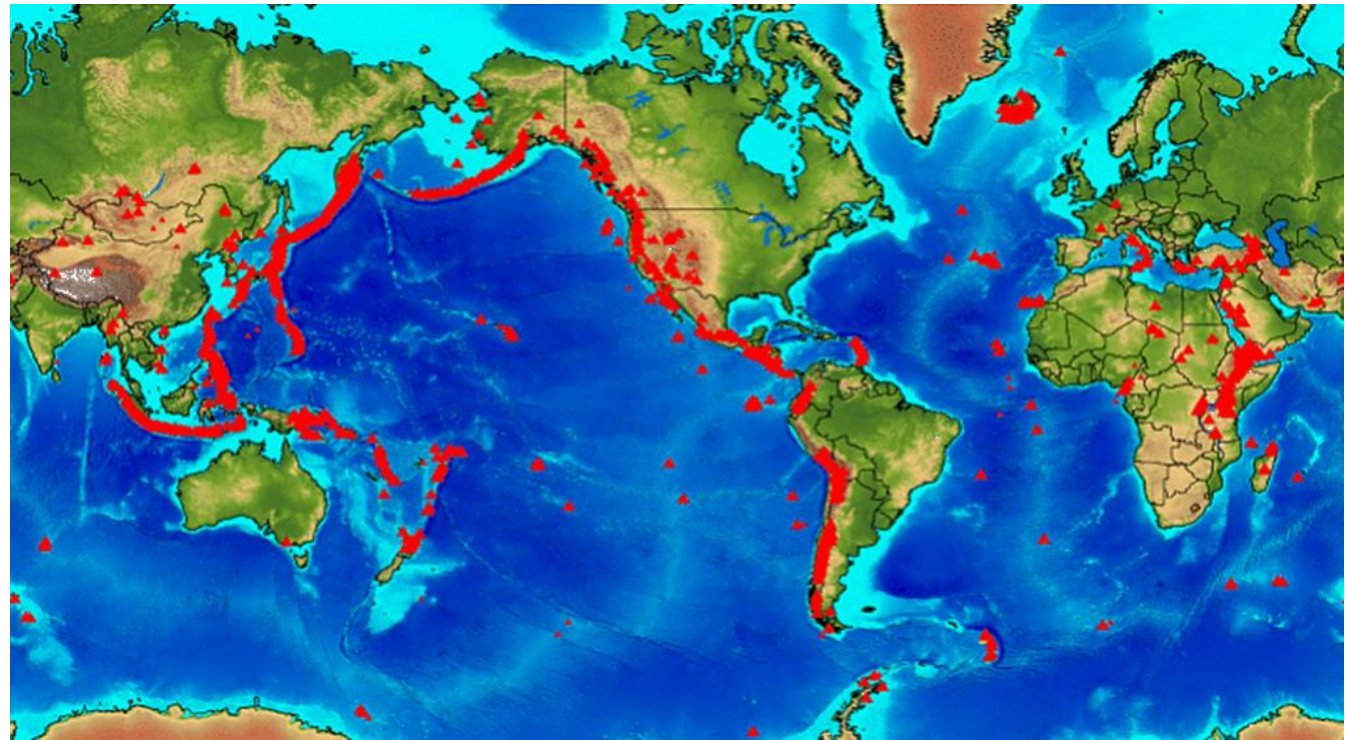


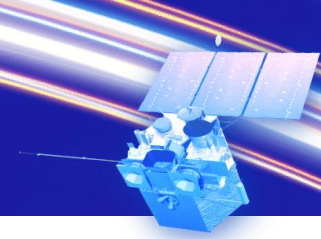
• 1. Introduction

large-scale eruptions have significant impacts on both aviation and the climate environment.

In terms of **aviation safety**, silicate particles in volcanic ash can cause serious engine failures.

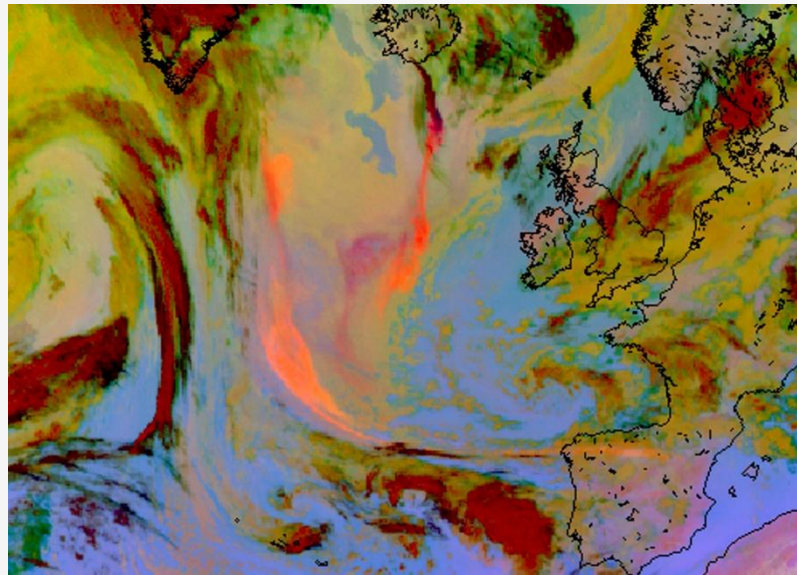
In terms of **environment**, fine ash and aerosols can alter solar radiation and contribute to climate effects.



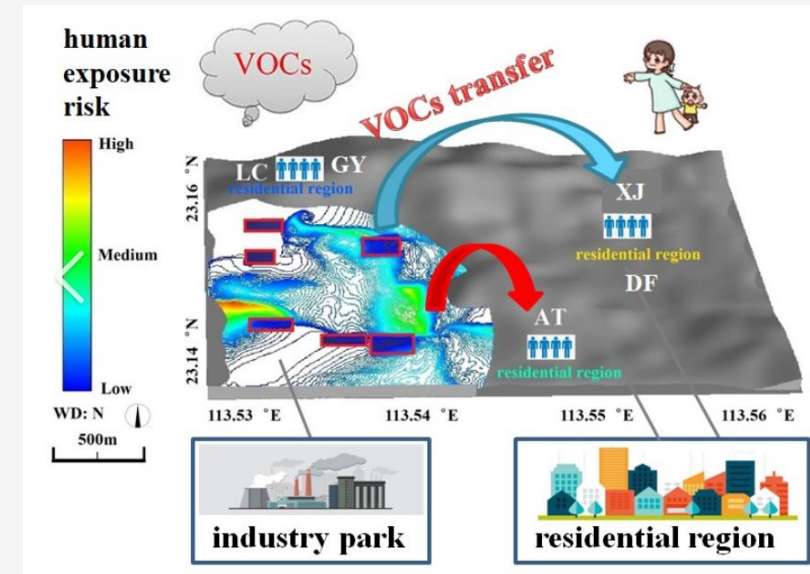


• 1. Introduction

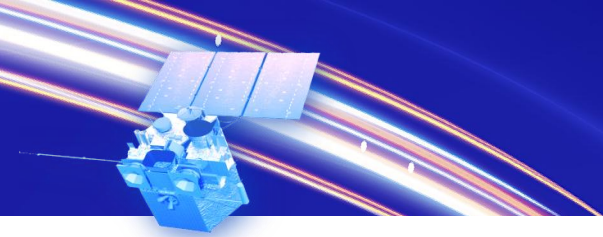
Two approaches for
monitoring & forecasting volcanic ash
dispersion



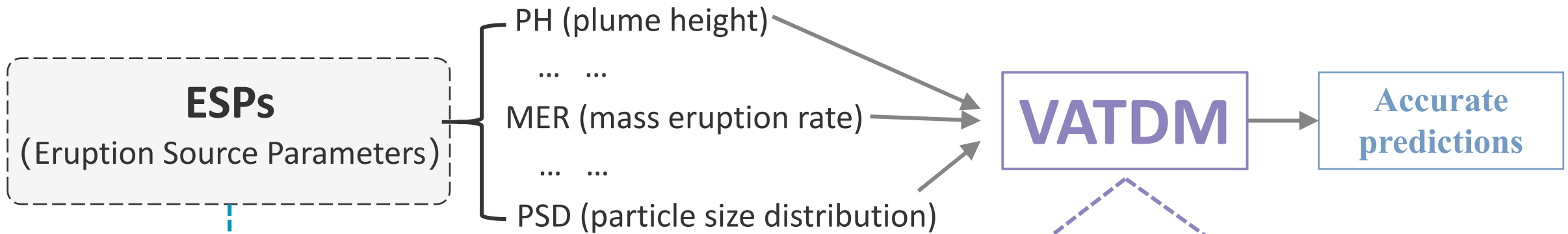
Remote sensing data can retrieve parameters such as the spatial extent, height, and mass loading of volcanic ash in near real time.



Volcanic Ash Transport and Dispersion Models (VATDMs) simulate the atmospheric transport of fine ash and aerosols.



• 1. Introduction



Difficult to obtain timely

Depends on empirical relationship

$$H = 25.9 + 6.64 \log_{10}(V) \quad [1]$$

Eruption type	Example (Date as M/D/Y)	H (km) above vent	D (h)	$\dot{M}$ (kg/s)	V (km ³)	m_{63}
Mafic, standard (M0)	Cerro Negro, Nicaragua, 4/13/1992	7	60	1×10^5	0.01	0.05
Small (M1)	Etna, Italy, 7/19–24/2001	2	100	5×10^3	0.001	0.02
Medium (M2)	Cerro Negro, Nicaragua, 4/9–13/1992	7	60	1×10^5	0.01	0.05

[2]

Eulerian models

Lagrangian models

FALL3D



- [1] Mastin, L., Pavolonis, M., Engwell, S., Clarkson, R., Witham, C., Brock, G., Lisk, I., Guffanti, M., Tupper, A., & Schneider, D. (2022). Progress in protecting air travel from volcanic ash clouds. *Bulletin of Volcanology*, 84(1), 9. <https://doi.org/10.1007/s00445-021-01511-x>
- [2] Mastin, L. G., Guffanti, M., Servranckx, R., Webley, P., Barsotti, S., Dean, K., Durant, A., Ewert, J. W., Neri, A., & Rose, W. I. (2009). A multidisciplinary effort to assign realistic source parameters to models of volcanic ash-cloud transport and dispersion during eruptions. *Journal of Volcanology and Geothermal Research*, 186(1-2), 10-21. <https://doi.org/10.1016/j.jvolgeores.2009.10.013>



Satellite-Based

Infrared: 11 μm and 12 μm channels detect volcanic ash. 7.3 μm and 8.7 μm channels detect SO_2 .

Ultraviolet: 280 nm and 340 nm channels measure SO_2 .



Airborne/UAV-Based

Suitable for PSD and concentration measurements, allowing safe and close-range plume monitoring.



plume

Spread cloud

Ash cloud information from remote sensing

Combine

VATDM

01

02

Data Insertion^[1]

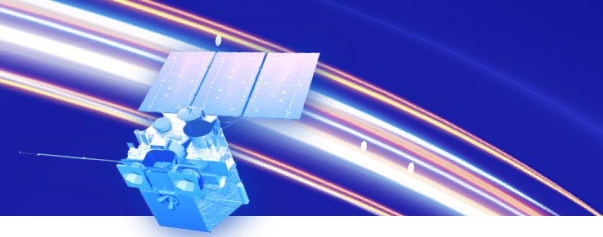
Satellite-retrieved ash parameters serve as “virtual sources” in dispersion models.

Inverse Modeling^[2]

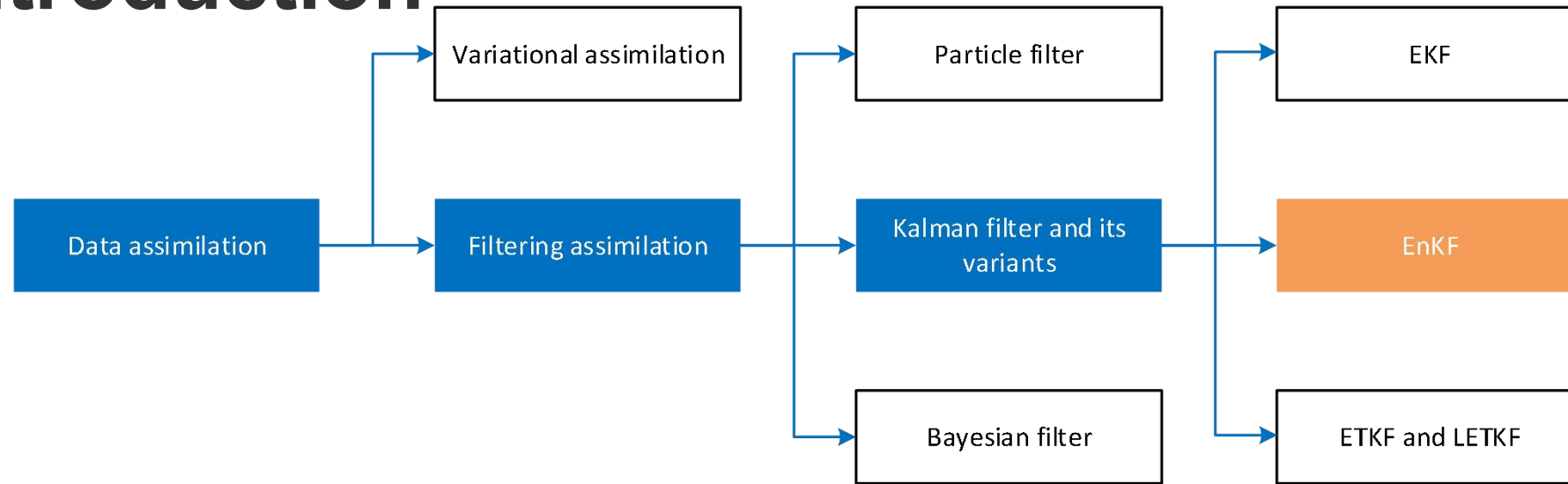
A cost function minimizes the deviation between model results and observations to optimize source parameters.

[1] CHAI T, Improving volcanic ash predictions with the HYSPLIT dispersion model by assimilating MODIS [J]. Atmospheric Chemistry and Physics, 2017, 17(4): 2865-79.

[2] CRAWFORD A M. Initializing HYSPLIT with satellite observations of volcanic [J]. Journal of Geophysical Research: Atmospheres, 2016, 121(18): 10,786-10,803.

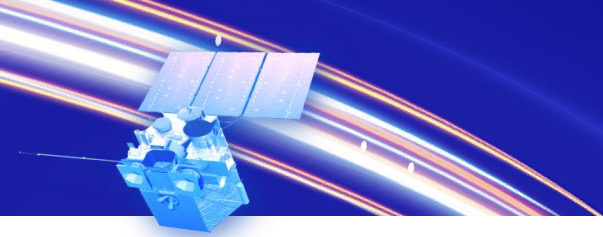


• 1. Introduction



Data Assimilation

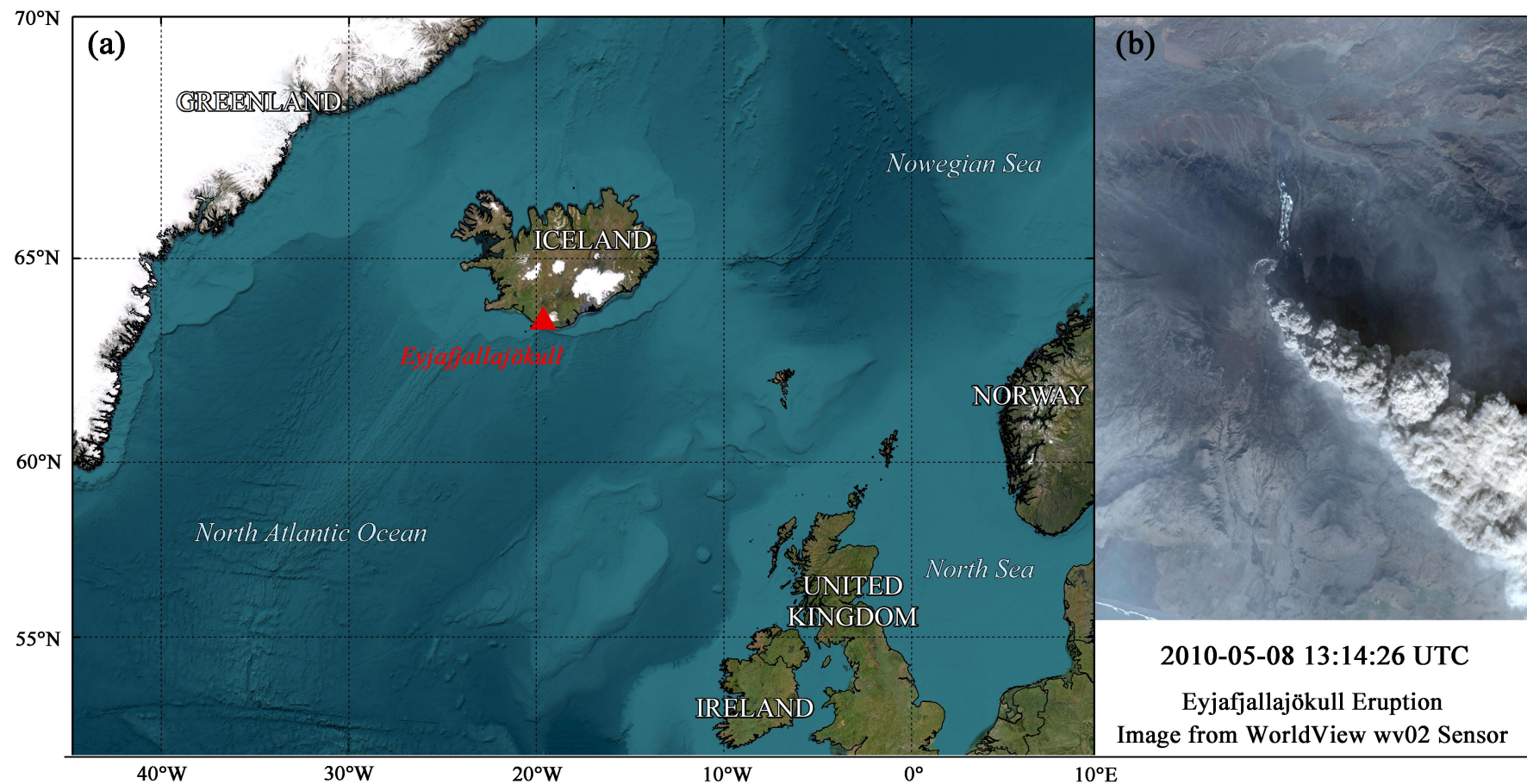
- **EKF and UKF:** Have been demonstrated in practice but are computationally expensive when coupled with FEMs.
- **ETKF AND LETKF:** Deterministic updates may overlook observation errors, limiting satellite data assimilation.
- **EnKF:** Uses ensemble means to represent complex covariance matrices, avoiding linearization and high computation of other KF approaches.

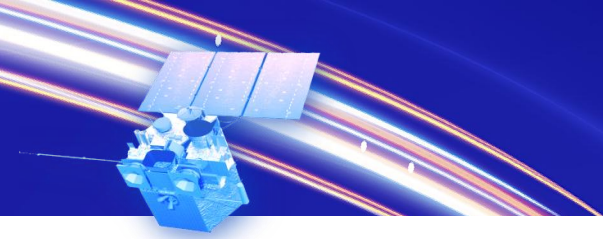


• 2. Data and Model

Data

1. MSG-SEVIRI
2. CALIPSO
3. GDAS

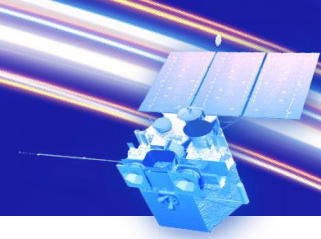




• 2. Data and Model

HYSPLIT is one of the most extensively used systems for computing simple air parcel trajectories and complex transport, dispersion, chemical transformation, and deposition simulations. In this study, the initial run time of the model was set to 17:00 UTC on May 5, 2010. The eruption source was located at 63.63°N and 19.63°W, with a crater altitude of 1666m above sea level.

Parameter	HYSPLIT Parameter Setting Description	Unit/Data type
Simulation Time	Start and end time of the simulation	Time (Hours)
Starting Location	Location of the volcanic ash source point	Longitude, Latitude (Degrees)
Dispersion Parameters	The influence of meteorological conditions on horizontal and vertical dispersion	Numerical (e.g., atmosphere stability)
Source Strength	The intensity or emission rate of the source	g/s or kg/h
Mixing Layer Height	The height to which pollutants disperse upwards	Meter (m)
Dispersion Type	The type of dispersion used by the model	Type (Gaussian/ Lagrangian)
Particle number	The number of simulated particles	Numerical



• 3. Forecasting Experiment I

Initializing HYSPLIT from eruption source

The volcanic mass eruption rate (MER) and particle size distribution (m31) vary with time and eruption intensity. Based on aerial and airborne LiDAR observations, as well as the empirical relationship provided by Mastin et al., the plume height of the Eyjafjallajökull eruption ranged approximately from 4 to 8.5 km.

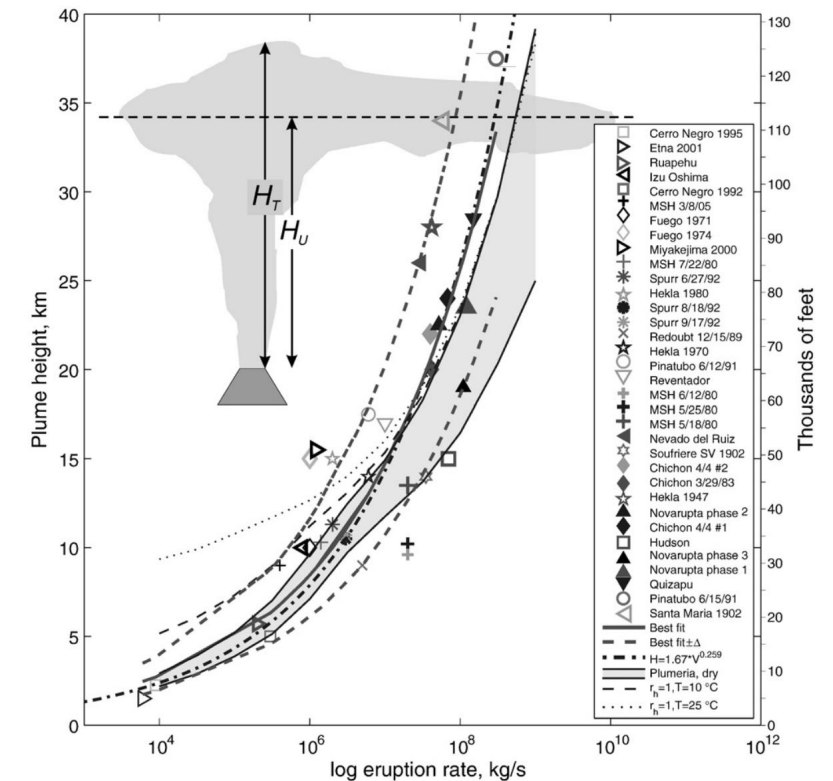
MER: $7 \times 10^4 \text{ kg s}^{-1} \sim 8 \times 10^5 \text{ kg s}^{-1}$

MER_f: $2.8 \times 10^3 \text{ kg s}^{-1} \sim 2.3 \times 10^5 \text{ kg s}^{-1}$

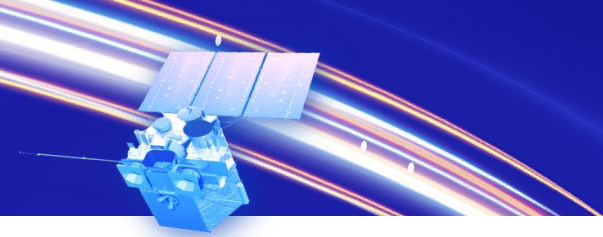


$3.8 \times 10^4 \text{ kg s}^{-1}$

Plume height above the vent versus mass eruption rate^[1]

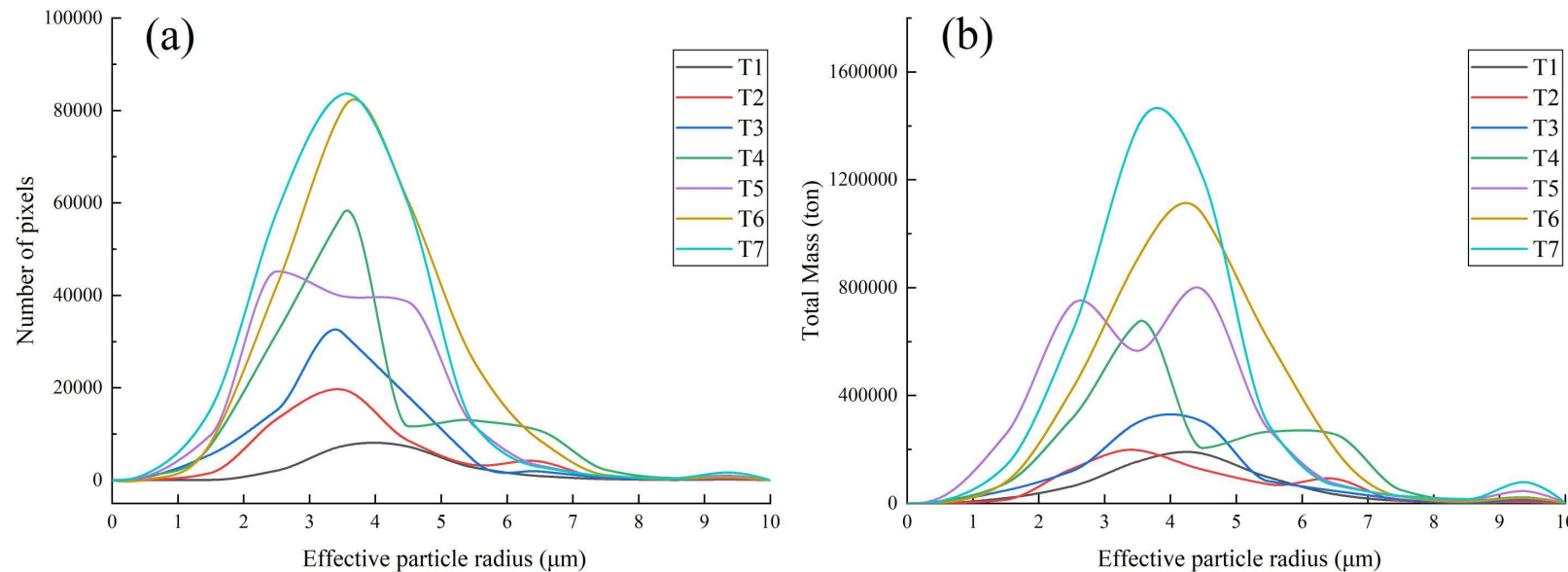


[1] Mastin, L. G., Guffanti, M., Servranckx, R., Webley, P., Barsotti, S., Dean, K., Durant, A., Ewert, J. W., Neri, A., & Rose, W. I. (2009). A multidisciplinary effort to assign realistic source parameters to models of volcanic ash-cloud transport and dispersion during eruptions. *Journal of Volcanology and Geothermal Research*, 186(1-2), 10-21. <https://doi.org/10.1016/j.jvolgeores.2009.10.013>



• 3. Forecasting Experiment II

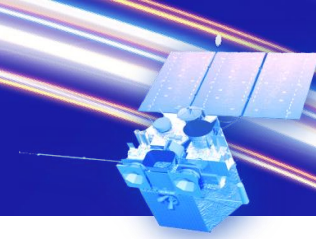
Initializing HYSPLIT from satellite retrievals



(a) Number of pixels and (b) total mass of effective particle radius obtained from satellite retrievals at T1-T7

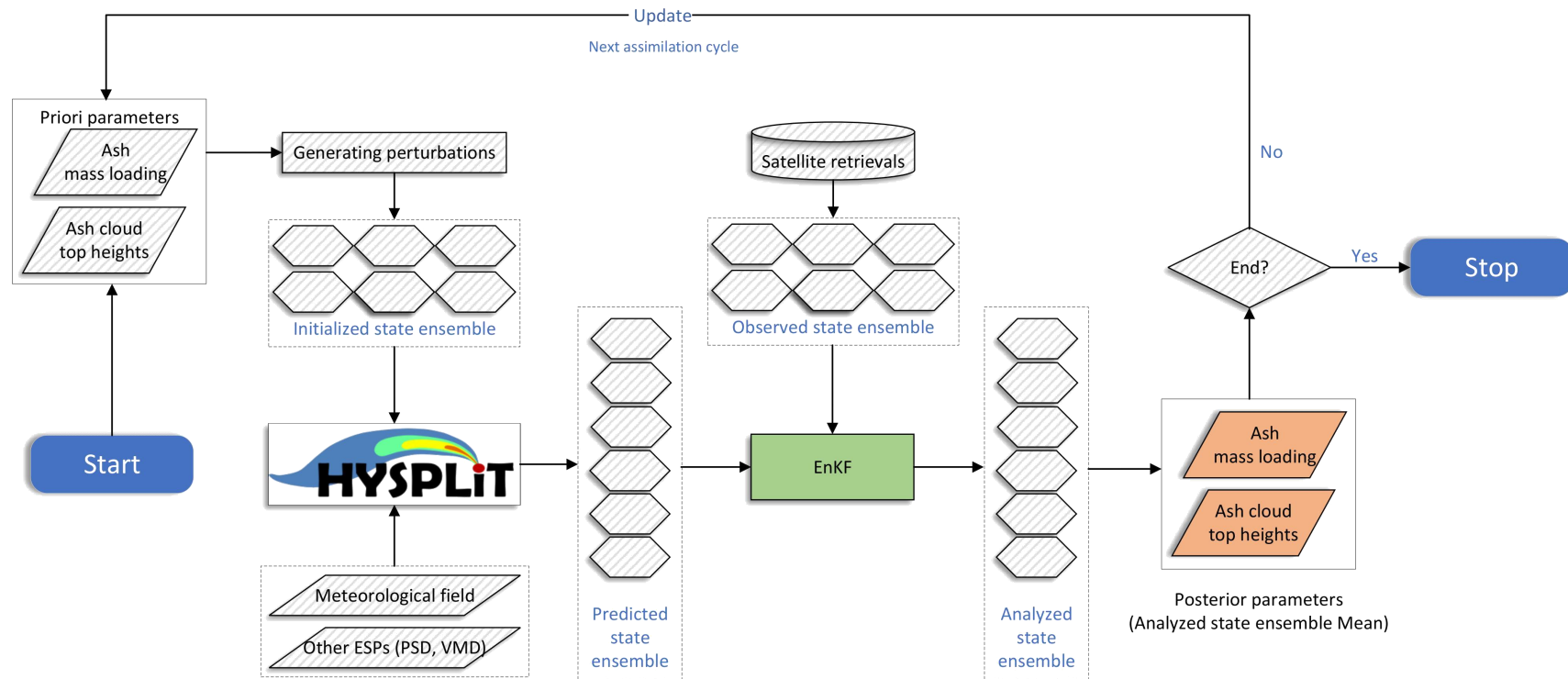
The output concentration grid of HYSPLIT was set to the same resolution as the satellite retrievals. The effective particle radius of the volcanic ash cloud from satellite retrievals ranged from 0 to 16 μm.

The cloud top height, column mass loading, latitude and longitude of the volcanic ash cloud obtained from satellite retrievals were used as inputs for the HYSPLIT model. All the particles were released at the height of the retrieval.



• 3. Forecasting Experiment III

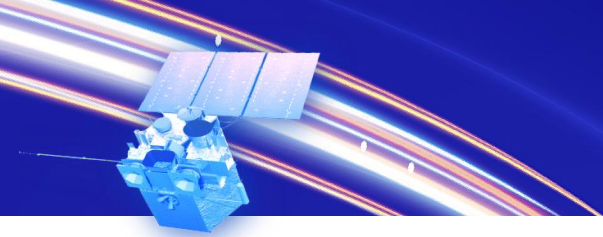
EnKF_HYSPLIT



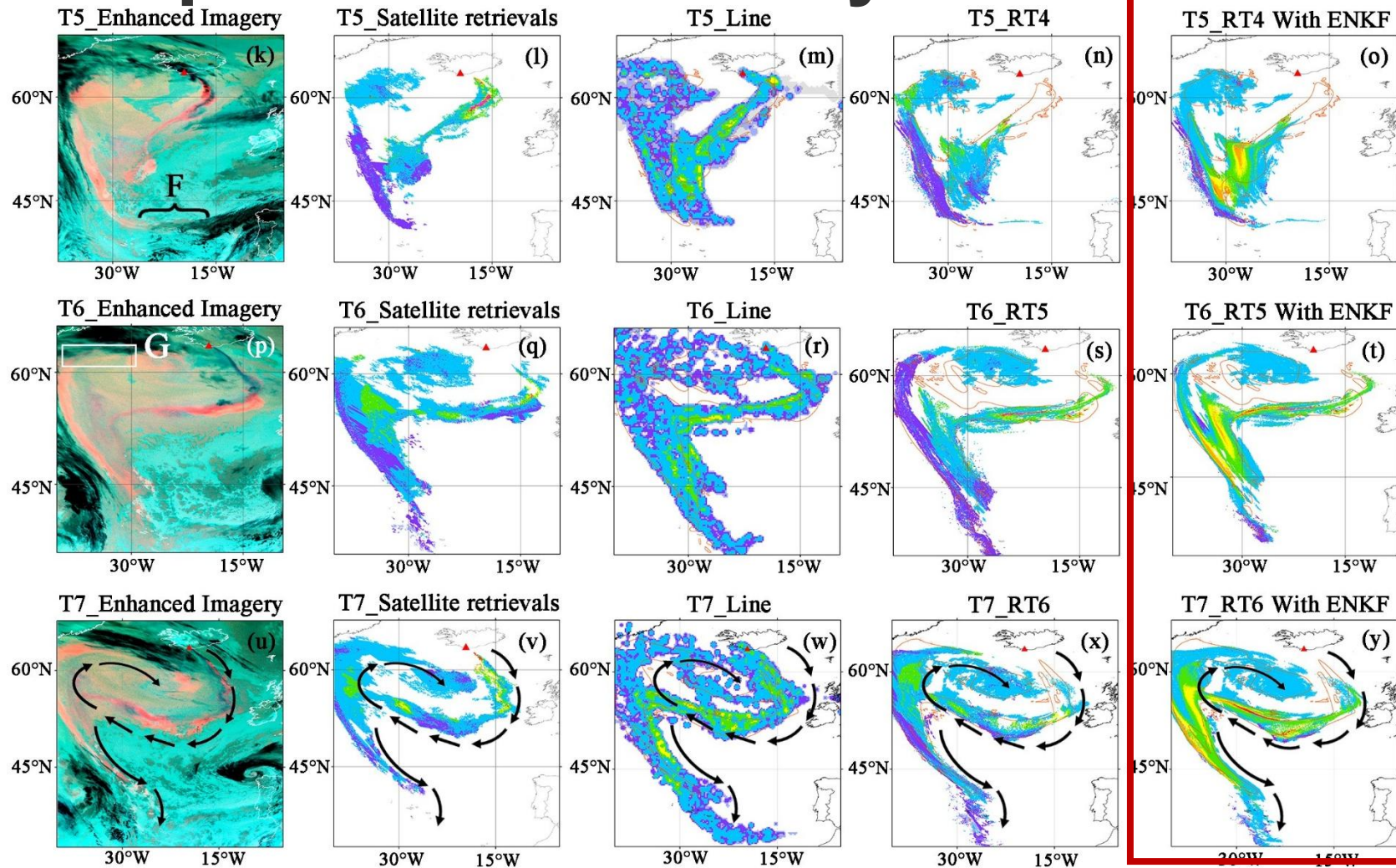
Step 1: Independently perturb each pixel value in the satellite observation data and input the perturbed datasets into HYSPLIT.

Step 2: Apply the EnKF algorithm to assimilate the simulated results with the satellite observations (ensemble of observation states).

Step 3: Use the updated analysis ensemble as new observation data for the next assimilation cycle.



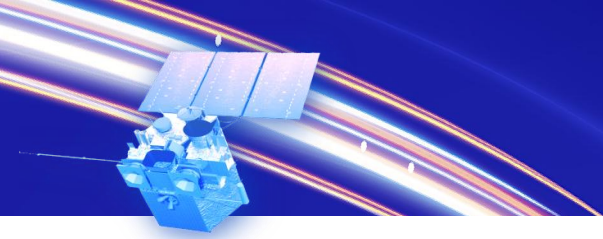
• 4.1 Spatial Extent Analysis



◆ Experiment I shows more false predictions

◆ Experiment II exhibits significant improvement

◆ Experiment III produces the most accurate simulation results



• 4.2 Comparative Statistics

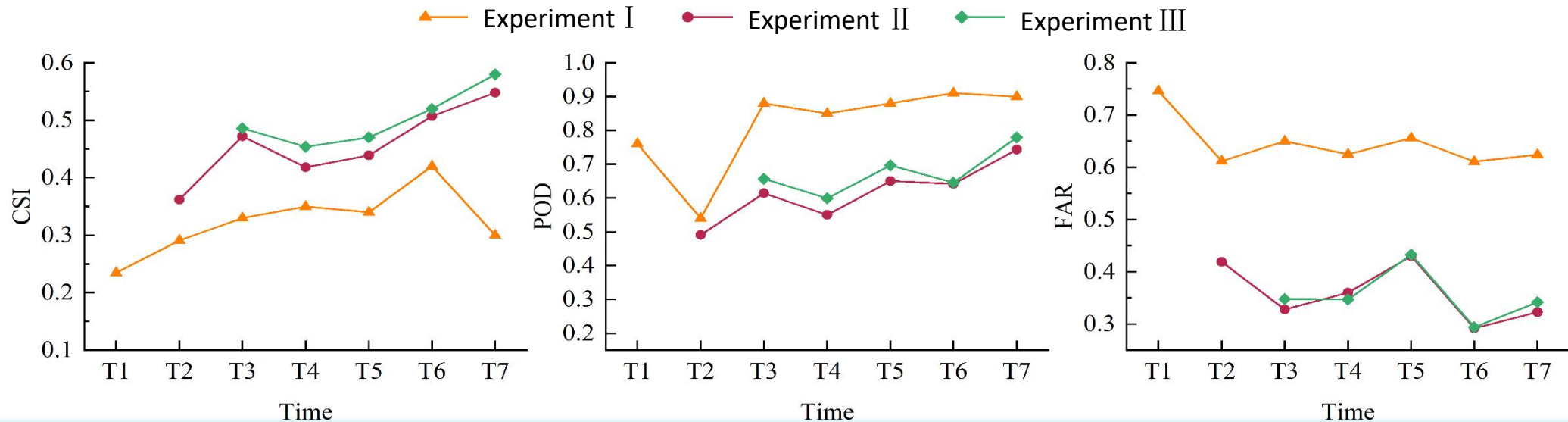
$$\text{CSI} = \frac{n_{\text{hit}}}{n_{\text{hit}} + n_{\text{miss}} + n_{\text{fa}}}$$

Forecast accuracy

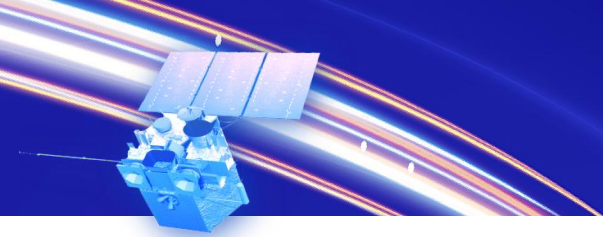
$$\text{POD} = \frac{n_{\text{hit}}}{n_{\text{miss}} + n_{\text{hit}}}$$

$$\text{FAR} = \frac{n_{\text{fa}}}{n_{\text{fa}} + n_{\text{hit}}}$$

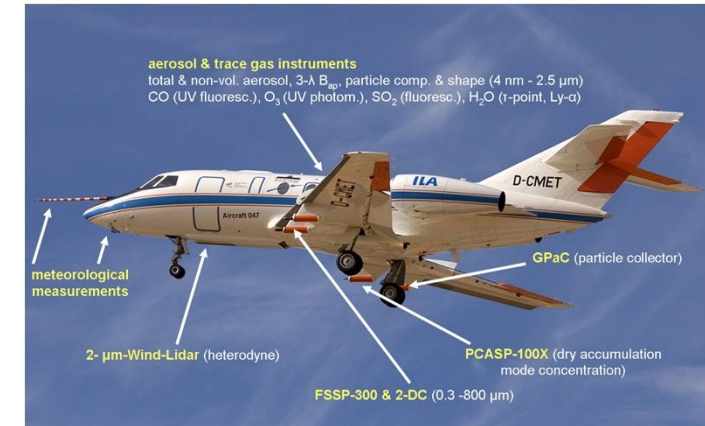
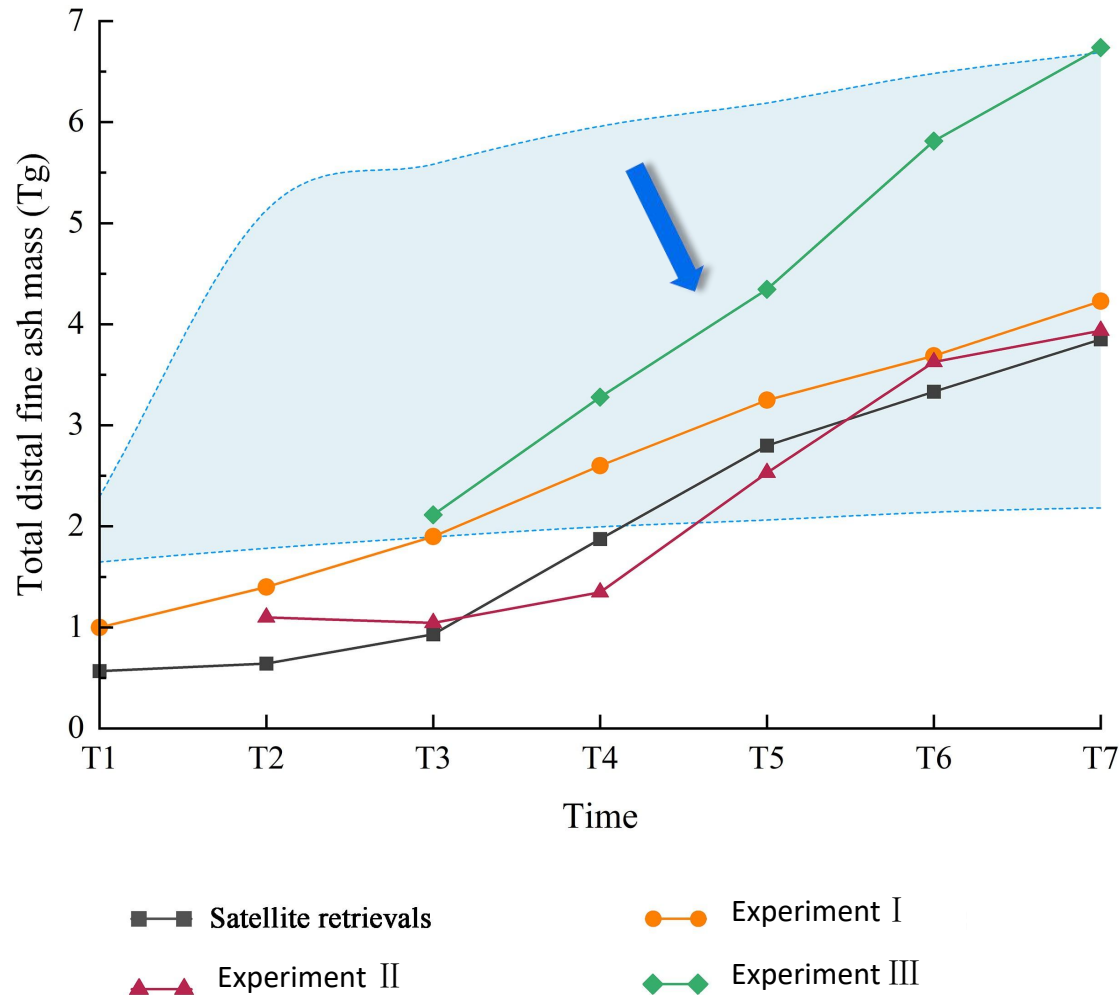
Forecast accuracy



Data assimilation can not only correct the false alarms produced by HYSPLIT model but also effectively reduce the accumulated negative effects due to the satellite retrieval errors, continuously improving forecast accuracy.

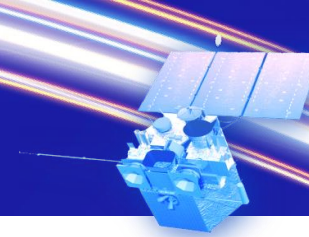


• 4.3 Mass Loading

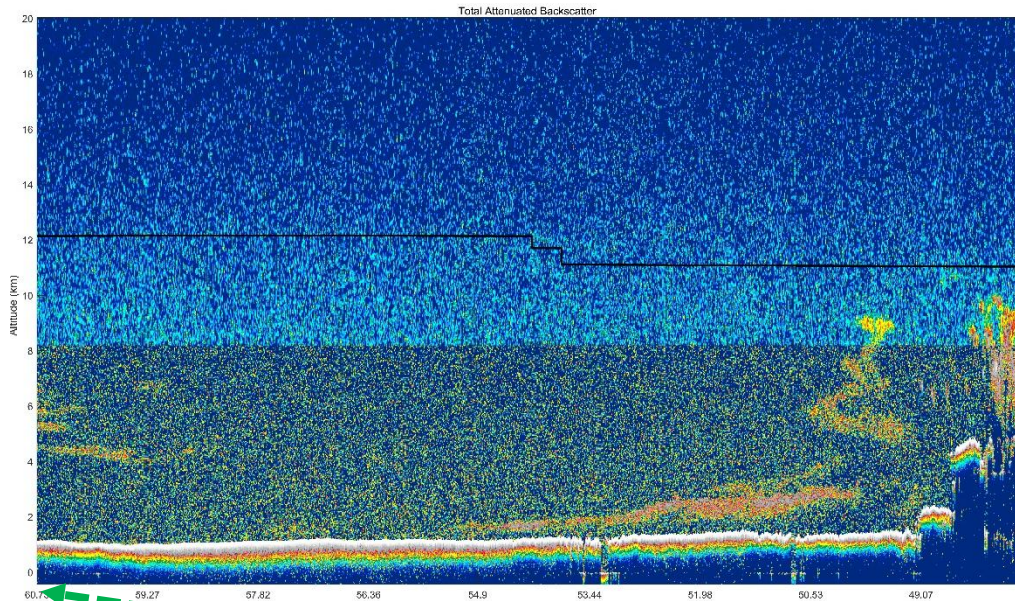


◆ Total eruption mass range × fine ash fraction
= “true” mass (blue shaded area)

Data assimilation can marginally improve the accuracy of volcanic ash mass prediction, and to some extent **compensate for the errors from satellite data and retrieval algorithms.**

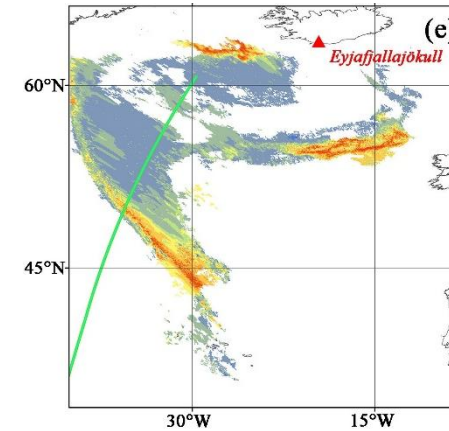


• 4.4 Cloud Top Height

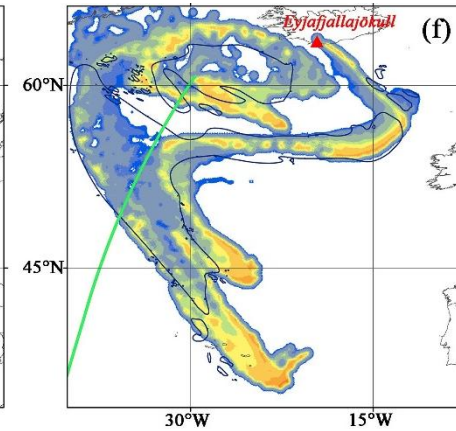


The overall height distribution in Experiment III shows a decreasing trend without abnormally high or low values, maintaining the highest consistency with satellite observations across multiple time steps.

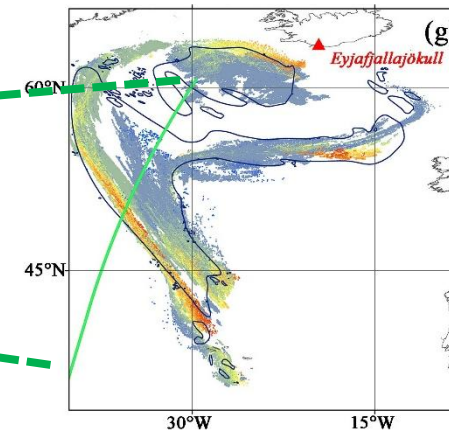
T6_Satellite Retrievals



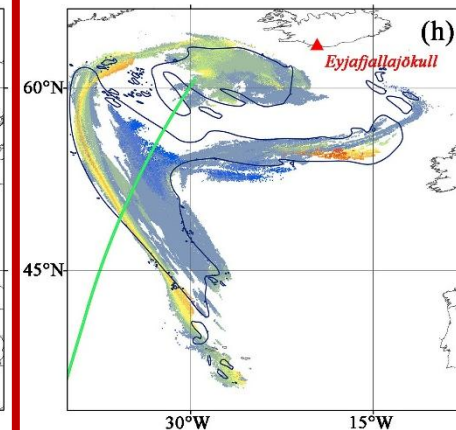
Experiment I (T6_Line)



Experiment II (T6_RT5)



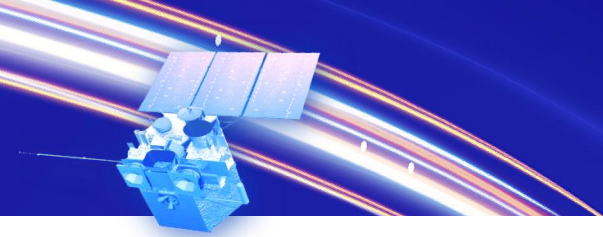
Experiment III (T6_RT5 With EnKF)



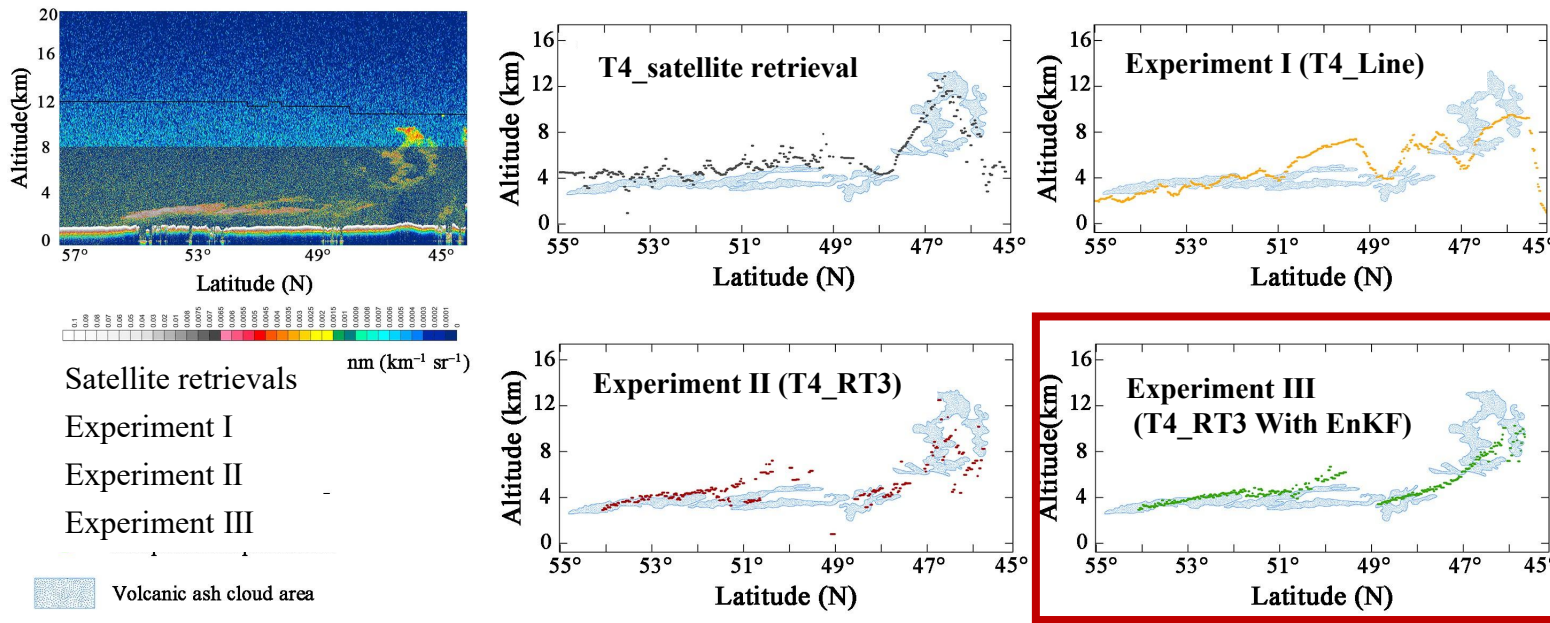
CALIOP Lidar trajectory

Ash cloud top height [km]

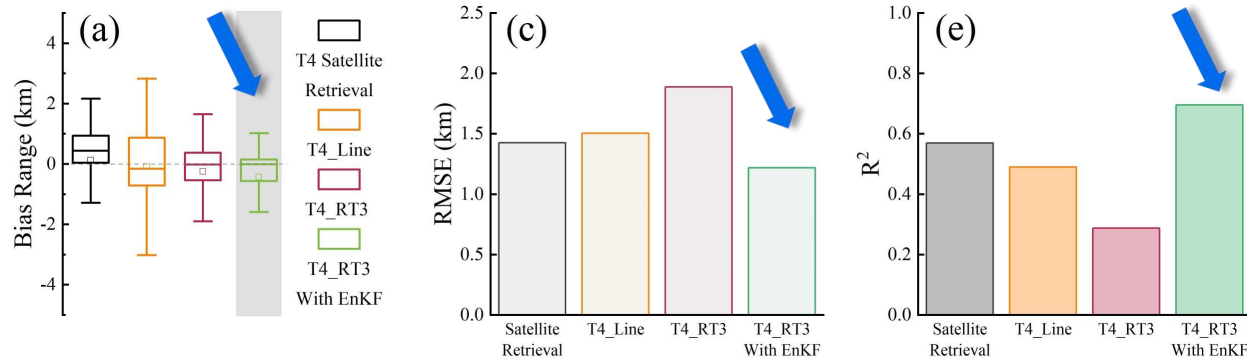
0 5 10 15 20



• 4.4 Cloud Top Height

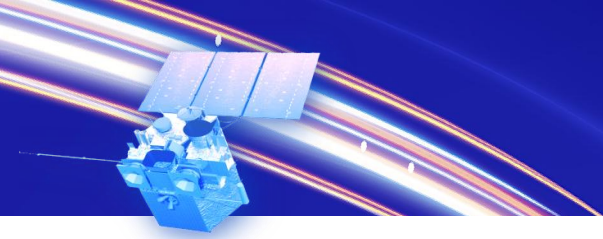


◆ EnKF assimilation improves forecast accuracy and enhances the model's ability to capture height trends.

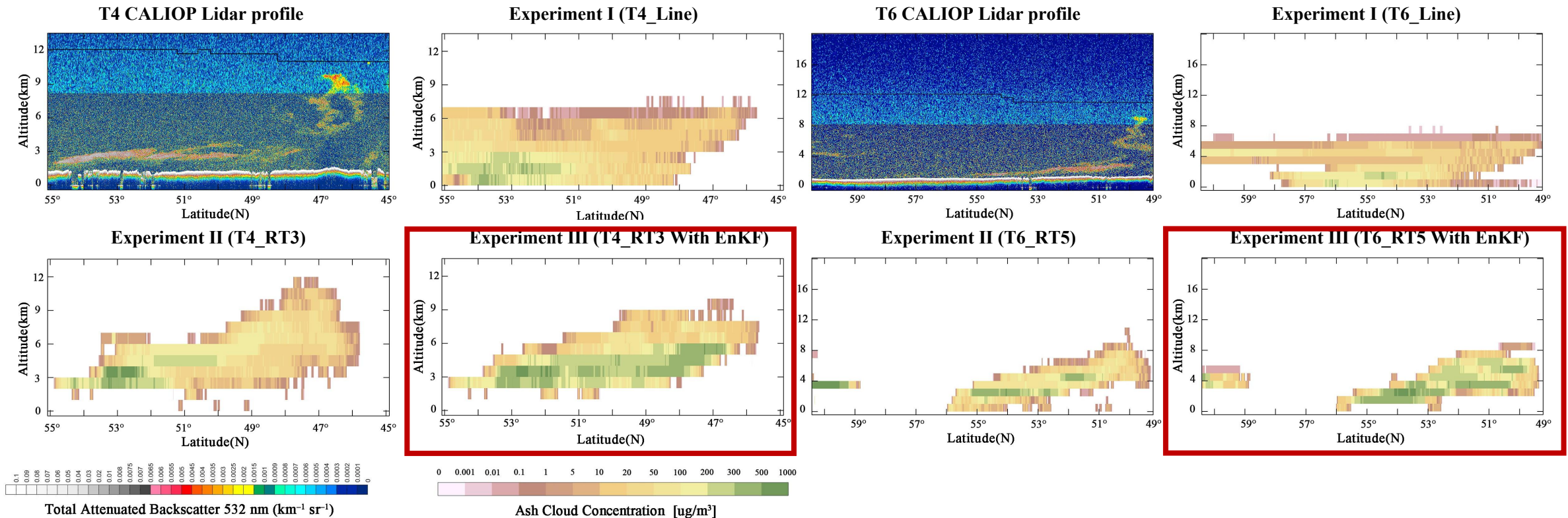


Smallest bias range,
Lowest RMSE
Highest R^2

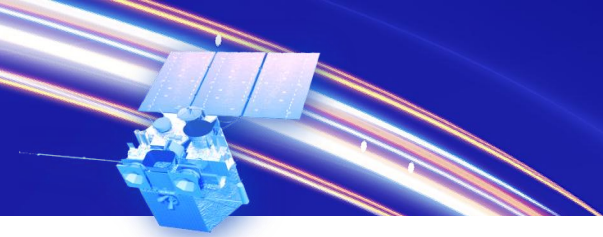
Experiment III shows the best match between predicted and lidar-observed ash cloud top heights.



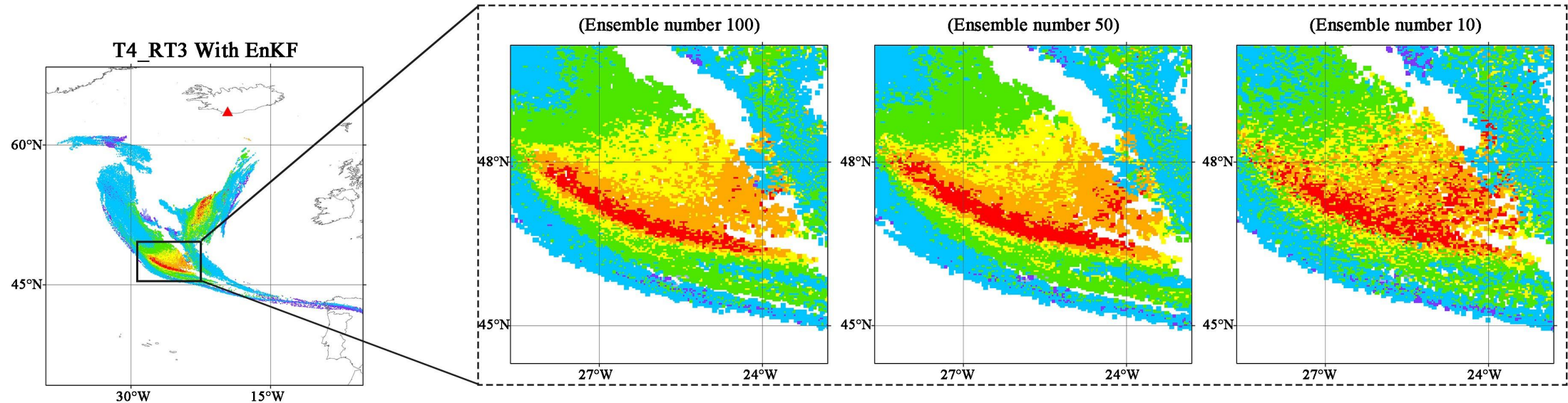
• 4.5 Vertical Concentration Distribution



- ◆ Experiment I performs poorly in predicting ash concentration.
- ◆ The vertical variation of ash concentration in Experiment III matches the CALIOP profile better than in Experiment II.

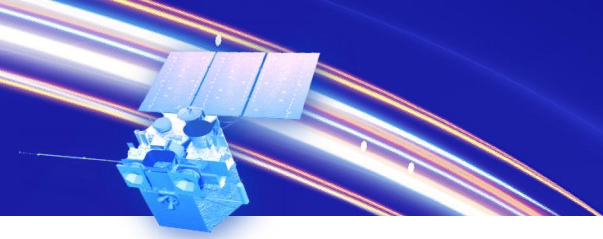


• 5.1 Impact of Ensemble Number

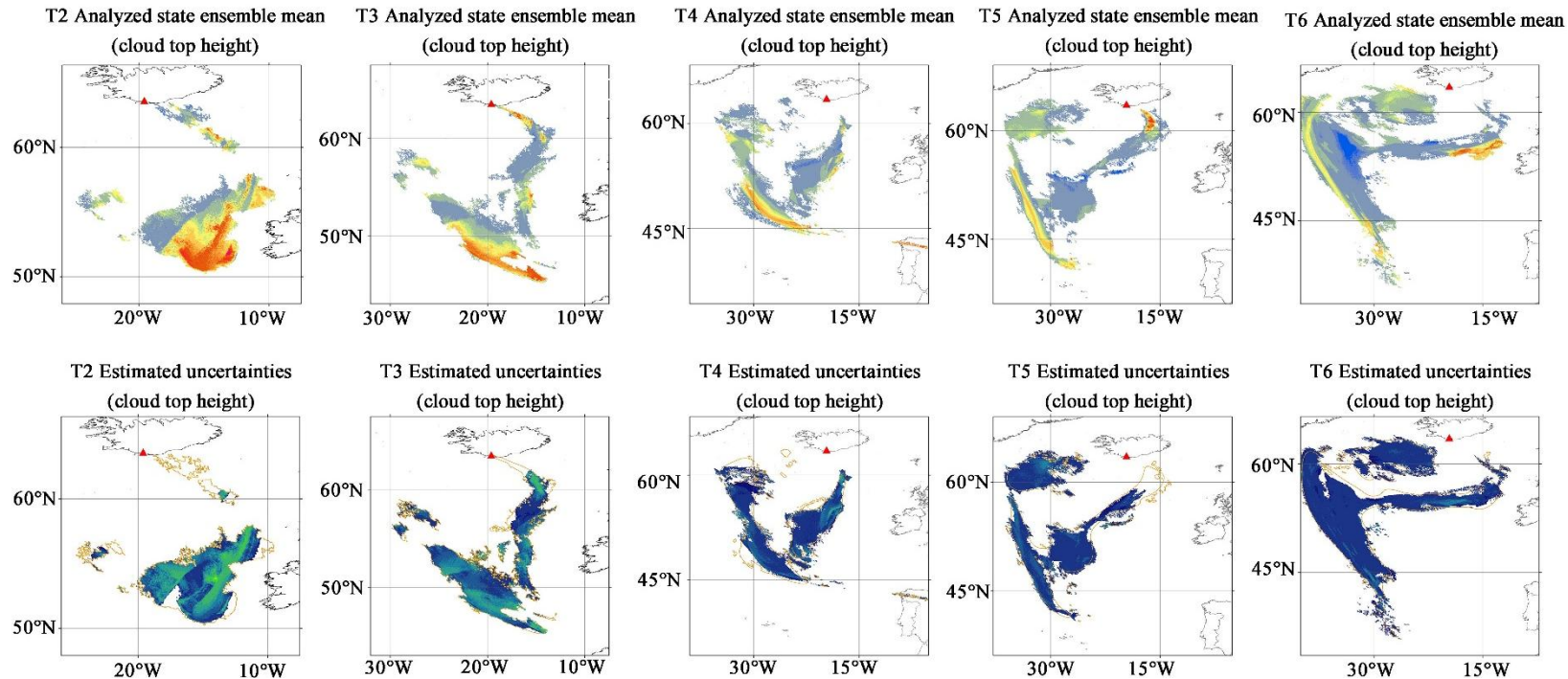


Increasing Ensemble Number

- ◆ As the number of ensemble members increases, the spatial distribution of mass loading becomes smoother, the uncertainty of the EnKF ensemble decreases significantly, and the model stability is improved.



• 5.2 Uncertainty Analysis of EnKF



The data assimilation process can gradually decrease the uncertainties of prediction, further improving accuracy and stability.

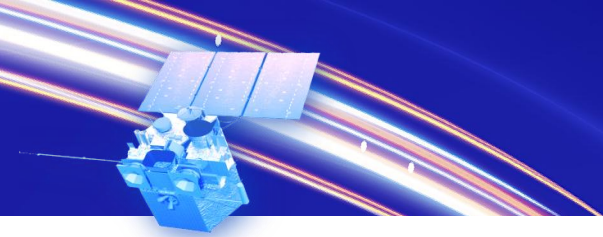
Spatial characteristics

Ensemble mean $\uparrow \rightarrow$ uncertainty $\uparrow$

Pixel number $\uparrow \rightarrow$ uncertainty $\downarrow$.

Temporal characteristics

The uncertainty is **much higher** in the early stage of assimilation than in the later stage.



• 6. Conclusions

01

Due to the lack of accurate ESP estimates, forecasts based on eruption source initialization often generated significant errors.

02

Using satellite retrievals to drive HYSPLIT for ash predictions can compensate for model simulation errors, but the prediction results may still have significant uncertainty.

03

Data assimilation can improve predictions of volcanic ash dispersion, but it also has certain limitations especially in accurately demonstrating 3-D spatial characteristic and ash concentration of volcanic ash plume.

04

The EnKF assimilation technique leverages the complementary advantages of model predictions and satellite retrievals. During the assimilation process, forecasts are optimized by the continuous adjustment and updating of model parameters.