Volcano Model-Data Fusion

DATA

+ Direct observation, good error estimates

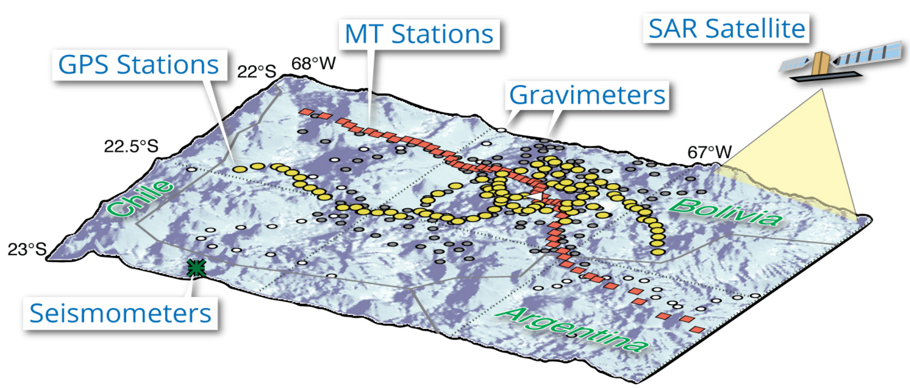
- Gaps, incomplete coverage

MODELS

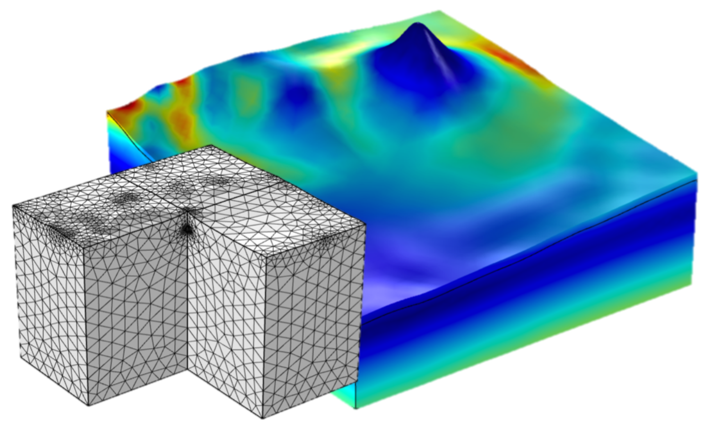
+ Knowledge of system evolution

- Poor error estimates

Central Andes | PLUTONS project



Pritchard & Gregg, Elements (2016)



Zhan & Gregg, JVGR (2017)

Volcano Model-Data Fusion

MODEL-DATA FUSION

- The data improves the model's performance by adjusting unknown model parameters or variables and correcting the model's trajectory.
- The model improves data targets by constraining gaps in our observations.

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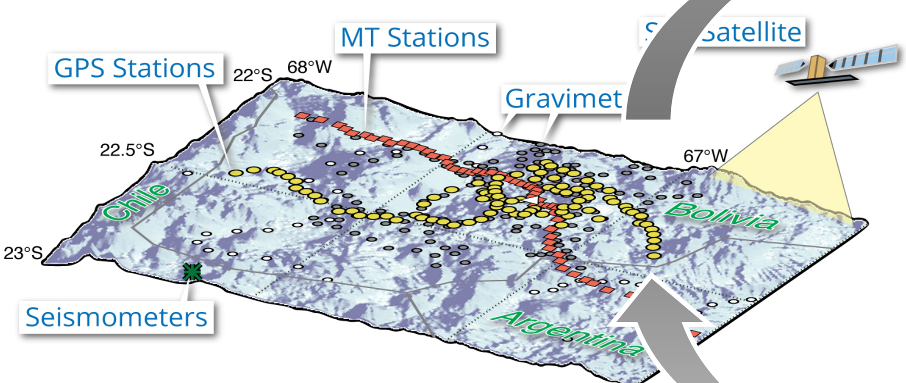

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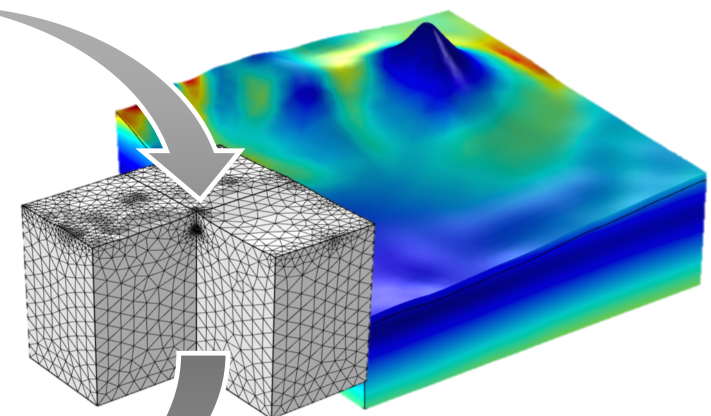
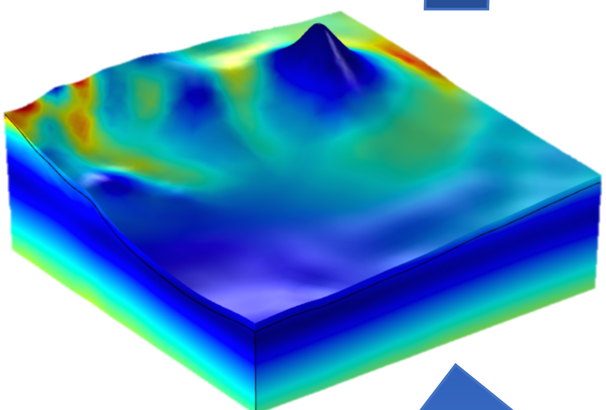


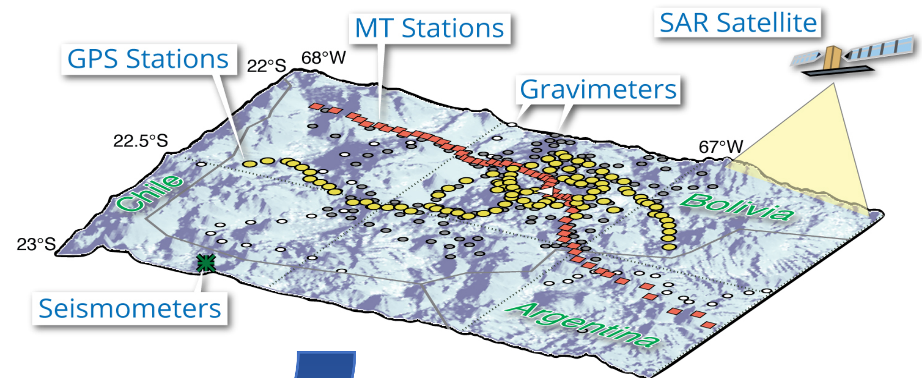
Zhan & Gregg, JVGR (2017)

The Goal: A forecast-correction method using observations

Time-forward models
FORECAST



Observational inputs
CORRECT



after Williams (2009)

Sequential Data Assimilation – A brief history leading up to EnKF

Modern Data Assimilation

1700's
Instruments developed to collect meteorological information (T, P, precip)

1854
FitzRoy appointed British Chief of Board of Trade and charges ships with collection of weather data at sea

1941
Kolmogorov develops statistical interpolation of data

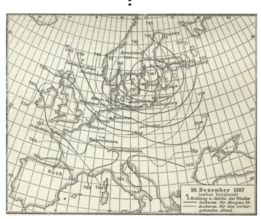
1966
Schmidt develops the Extended Kalman Filter for nonlinear systems

1996
Segall group adapts the Extended Kalman Filter for geodetic applications (Segall and Matthews, 1996)

1700 | 1800 | 1900 | 1950 | 1990 | 2000

T. Bayes 1701-1761

1835
Electrical telegraph invented allowing the rapid transfer of meteorological data



Weather map from 1887

1922
Richardson publishes first attempt at numerical weather forecasting

1946 – 50s
Monte Carlo method was invented by Stanislaw Ulam and developed with von Neumann

1960
Kalman publishes *"A new approach to linear filtering and prediction problems"*

"Big Data"

1994
Evensen develops the Ensemble Kalman Filter (EnKF) using MCMC methods

2016
EnKF adapted for volcanology (Gregg and Pettijohn, 2016)

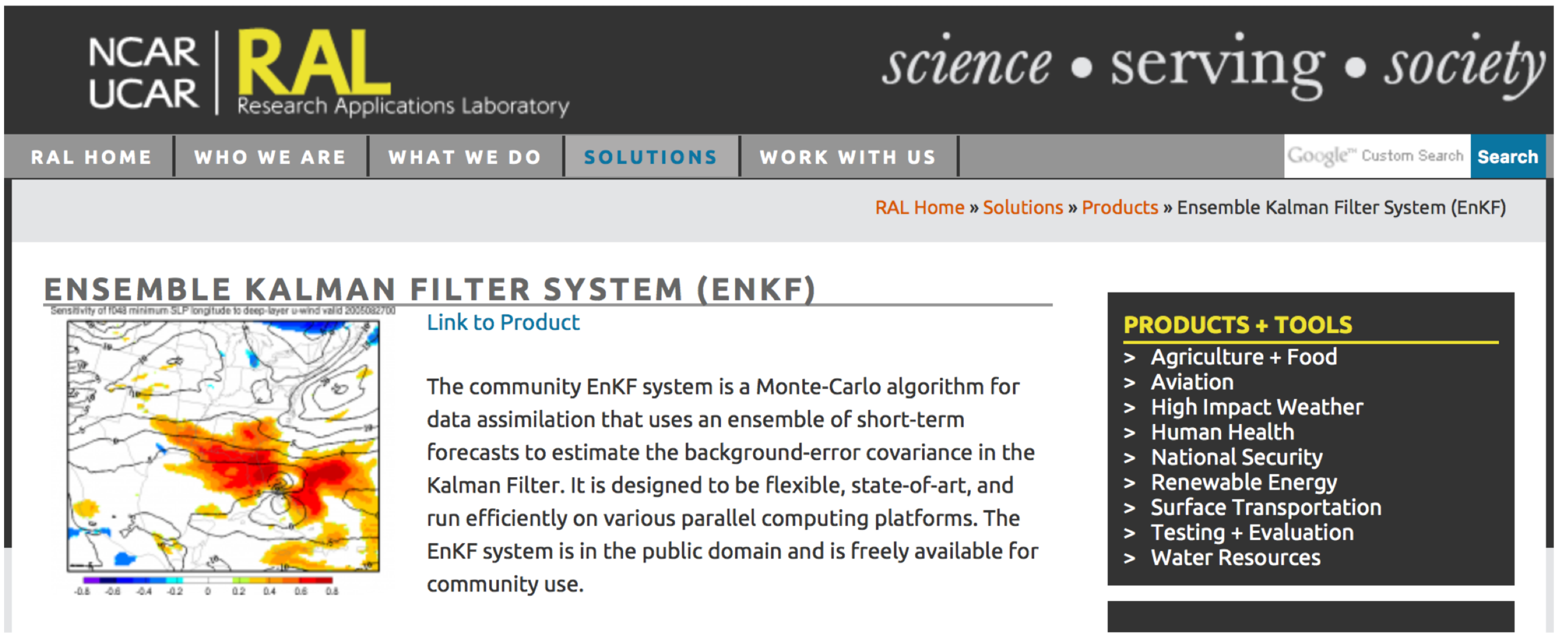
Early 2000's
UCAR / NCAR adopts EnKF for Global Climate modeling community

Comparison of Kalman Filtering Approaches

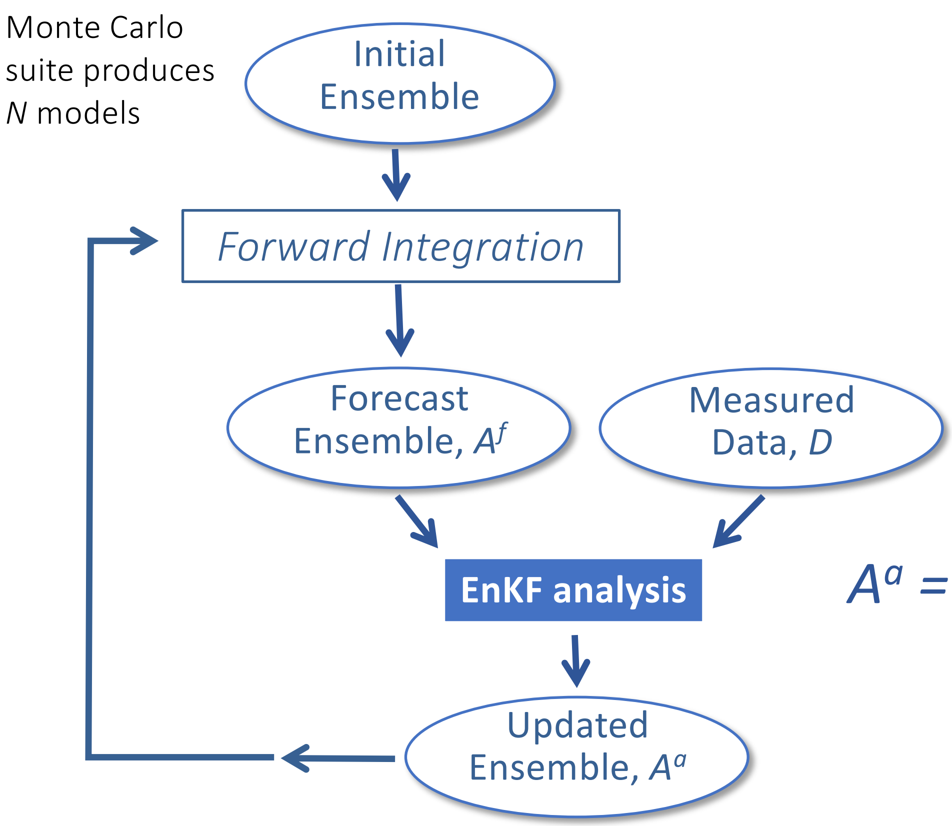
	Linearity	Computational load	Model independent?
Kalman Filter (KF) *Kalman (1960)*	**Linear**	high	NO
Extended Kalman Filter (EKF) *Schmidt (1966); Kalman and Schmidt (1968)* → Segall and Matthews (1996)	**Quasi-Linear** uses PDEs to linearize the model	>> KF	NO
Unscented Kalman Filter (UKF) *Julier & Uhlmann (2004)* → Fournier, Freymueller, Cervelli (2009)	**Non-linear** NL transformations for covariance matrix	2-3 x EKF	NO
Ensemble Kalman Filter (EnKF) *Evensen (1994)* → Gregg and Pettijohn (2016), etc.	**Non-linear** uses MCMC methods for covariance matrix	<< KF	YES

Why EnKF?

EnKF is the standard / state-of-the-art technique for data assimilation used in **climate and weather forecasting** and has been adopted by NCAR and UCAR.



Ensemble Kalman Filter (EnKF) - Markov Chain Monte Carlo Approach



EnKF Workflow

Gregg and Pettijohn (2016)

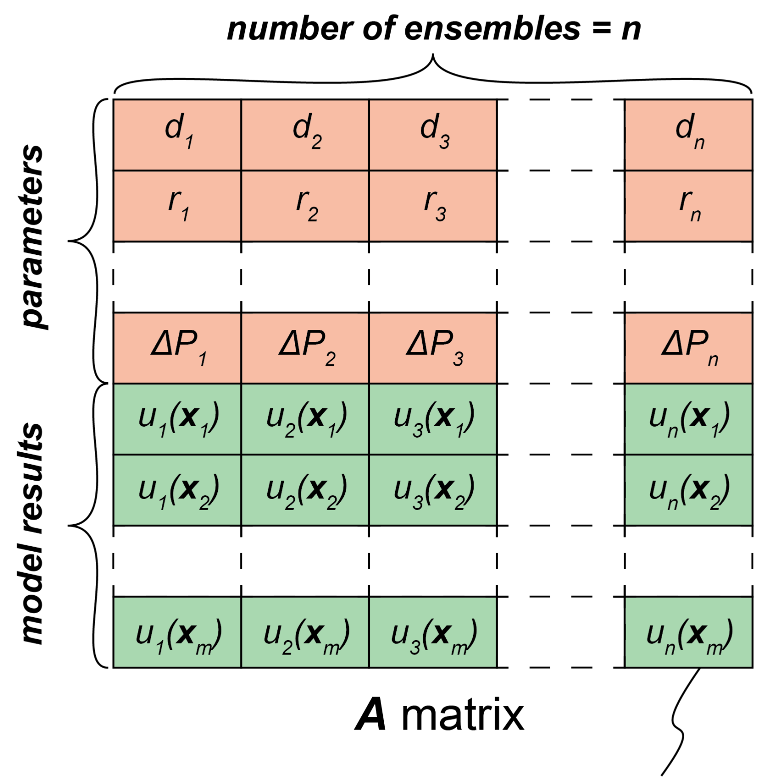
based on Evensen (1994)

$$A^a = A^f + \underbrace{X H^T (H X H^T + C)^{-1}}_{\text{Kalman Gain}} (D - H A^f)$$

A^f model forecast
A^a updated model
H model operator matrix
D data
C data covariance matrix
X ensemble covariance matrix

Ensemble Kalman Filter (EnKF) - Markov Chain Monte Carlo Approach

$$A_a = A + \underbrace{P_e H^T (H P_e H^T + R_e)^{-1}}_{K\ =\ \text{“Kalman gain”}} (D - H A)$$

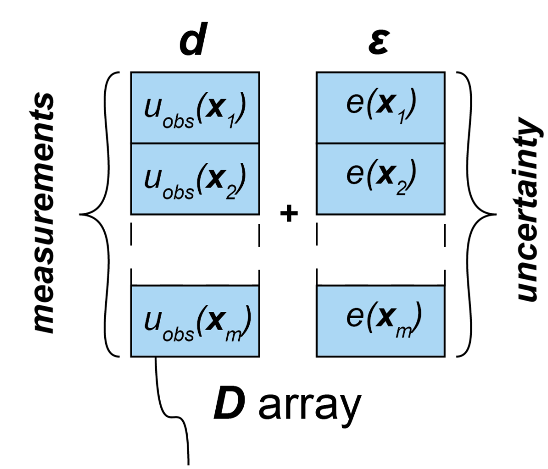


P_e = covariance of A

R_e = covariance of ε

P_e ~ inf, K = 1

R_e ~ inf, K = 0



e.g., Mogi: u(x) = f(x, d, r, ΔP)

e.g., GPS motion at x