

# Atmospheric data assimilation using the LMD Mars GCM with an ensemble Kalman Filter

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## Data Assimilation

Data assimilation is a technology widely used in geosciences, especially meteorology and weather forecast. It enables to **optimally reconstruct a best estimate of the atmospheric state** by combining various instrumental **observations** and theoretical information provided by a **model**. In Earth atmosphere science, it is systematically used to provide climatologies derived from space-based observations.

The purpose of this work is to develop a data assimilation chain by coupling the Laboratoire de Météorologie Dynamique (LMD) Mars GCM with the Local Ensemble Transform Kalman Filter (LETKF) [1] assimilation framework of the University of Maryland.

LETKF is an ensemble-based method that propagates covariance thanks to the forecast model (i.e. the GCM). Therefore, it does not need the development of an adjoint model, as opposed to variational methods.

$x$ atmospheric state vector	$H$ observational operator
$P$ atmospheric covariance matrix	$M$ forward model
$y^o$ vector of observations	$R$ error covariance matrix of observations

### Forecast step

$$\forall i \in \{1, 2, \dots, N\} \quad x_n^{b(i)} = M_{t_{n-1}, t_n}(x_{n-1}^{a(i)})$$

### Analysis step - mean state

$$\bar{x}_n^a = \bar{x}_n^b + P_n^a H_n^T R_n^{-1} (y_n^o - H_n \bar{x}_n^b)$$

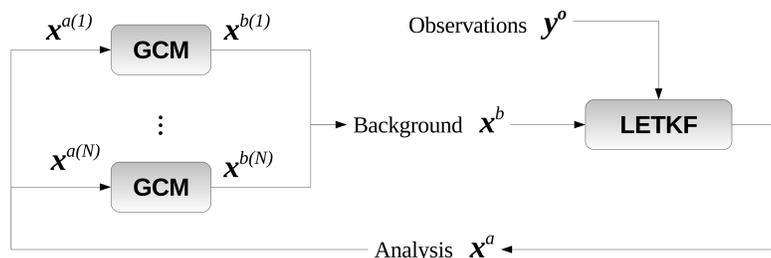
### Covariance estimation

$$P_n^b = \frac{1}{N-1} \sum_{i=1}^N (x_n^{b(i)} - \bar{x}_n^b)(x_n^{b(i)} - \bar{x}_n^b)^T$$

### Analysis step - covariance

$$P_n^a = [(P_n^b)^{-1} + H_n^T R_n^{-1} H_n]^{-1}$$

$$= (I + P_n^b H_n^T R_n^{-1} H_n)^{-1} P_n^b$$



### Backtrack trace gases

One main objective of the ExoMars Trace Gas Orbiter (TGO) is to detect the presence and origin of trace gas in the Martian atmosphere. Data assimilation with observations from the Atmospheric Chemistry Suite (ACS) on board TGO can reconstruct 4D meteorological fields and in particular winds, (that are not observed by instruments) to **backtrack trace gases and locate their sources**. It can also provide "real-time" atmospheric properties for retrieval by other TGO instruments.

### Climatology Reanalysis

The reconstruction of atmospheric fields is *per se* a strong motivation. It provides a best estimate of the known atmosphere and could be seen as a useful tool for atmospheric science community.

We will assimilate and combine vertical profiles of **temperature** from **Planetary Fourier Spectrometer on board ESA Mars Express** and **temperature, dust and water ice** from **Mars Climate Sounder on board NASA Mars Reconnaissance Orbiter**.

By doing so, we can take advantage of both Mars Express irregular, eccentric orbit with a strong dispersion in local time and systematic mapping of Mars Reconnaissance Orbiter sun-synchronous orbit.

### weather forecast on Mars: WHY?

#### Mission support

In the future, an operational data assimilation chain could help to characterize the local conditions for Entry, Descent & Landing of probes and daily operations of landers and rovers on the Martian ground.

### Improve atmospheric model

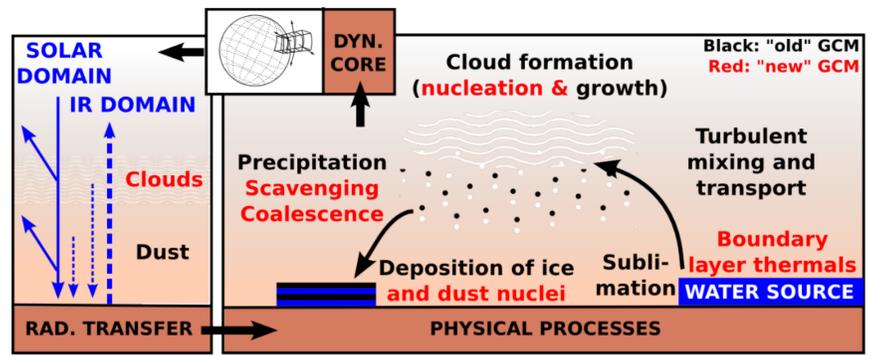
Data assimilation can point out disagreements between model and observations. As an **optimization problem**, it is a very powerful tool to estimate GCM parameters or characterize instrumental errors.

For instance, a lot of assumptions are made in the modeling of airborne dust and water-ice clouds. We could bring a new level of assessment to the GCM and refine values of **model parameters**.

## Global Climate Model

The forward model used is the Mars General Circulation Model (GCM) developed at Laboratoire de Météorologie Dynamique (LMD) [6]. It includes:

- Subgrid scale convection using a thermal plume model [7]
- Radiative effects of airborne dust and water ice clouds [8,9]
- Semi-interactive airborne dust, guided by dust scenarios for 7 Martian Years [9]
- Microphysics of water ice clouds [10]
- A photochemistry model [11]
- An extension to the thermosphere up to 600 km [12]



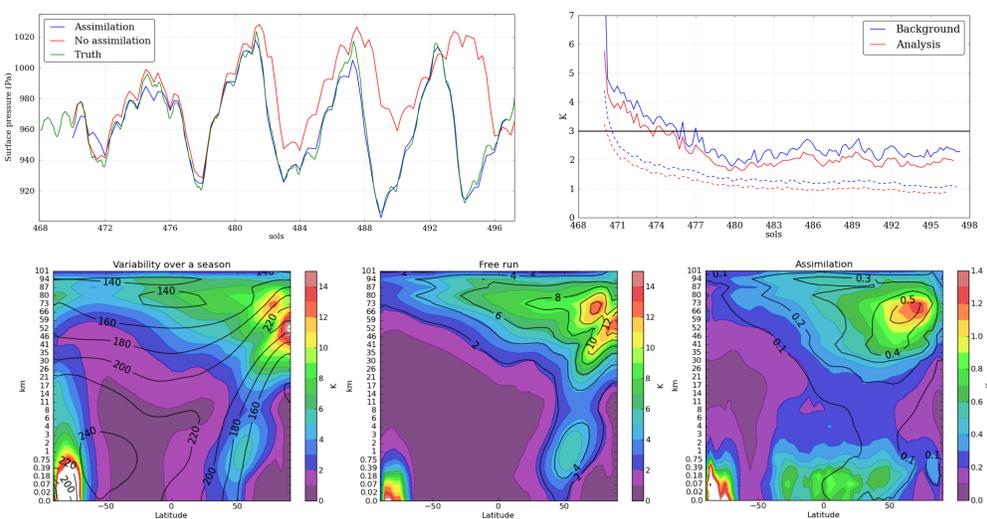
Overview of some meaningful processes recently developed or added in the LMD GCM (courtesy of J.-B. Madeleine)

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## Illustrative example

This is an illustration of Martian assimilation, similar to the study of [3]. We use **locations of observations from instrument MCS** during month 9 ( $L_s=240^\circ-270^\circ$ ) for MY 29 and **temperatures generated from the model itself with an additive noise**. This is only a classic study case to show the correct utilization of the data assimilation chain and not an innovative work in comparisons to other Martian data assimilation systems [2,3,4,5].



**Top left:** Surface pressure at Longitude  $0^\circ$  and Latitude  $70^\circ N$  from an assimilation run, a free run without assimilation, and the reference truth from which temperature data were generated. The amplitude and phase of the strong and chaotic baroclinic waves are well reconstructed.  
**Top right:** Ensemble spread of this assimilation run (dashed), and root mean square error with the reference truth (solid) of temperature, for both background and analysis atmospheric fields. The horizontal line is for the observation error of  $3K$ .  
**Bottom left:** Zonal and time average of temperature (contoured) and temperature standard deviation (shaded) over this season.  
**Bottom middle:** Zonal and time average of temperature ensemble spread (contoured) and RMSE with truth reference run (shaded) for an ensemble of 20 members freely evolving. Similarities with previous plot are an illustration of the ergodicity of the system..  
**Bottom right:** As previous, but for the analysis of an assimilation. The stronger the intrinsic variability of the system, the stronger the mean square error and ensemble spread.