Planetary atmospheres modeling at LMD

Ehouarn Millour, Francois Forget
and/for the LMD team

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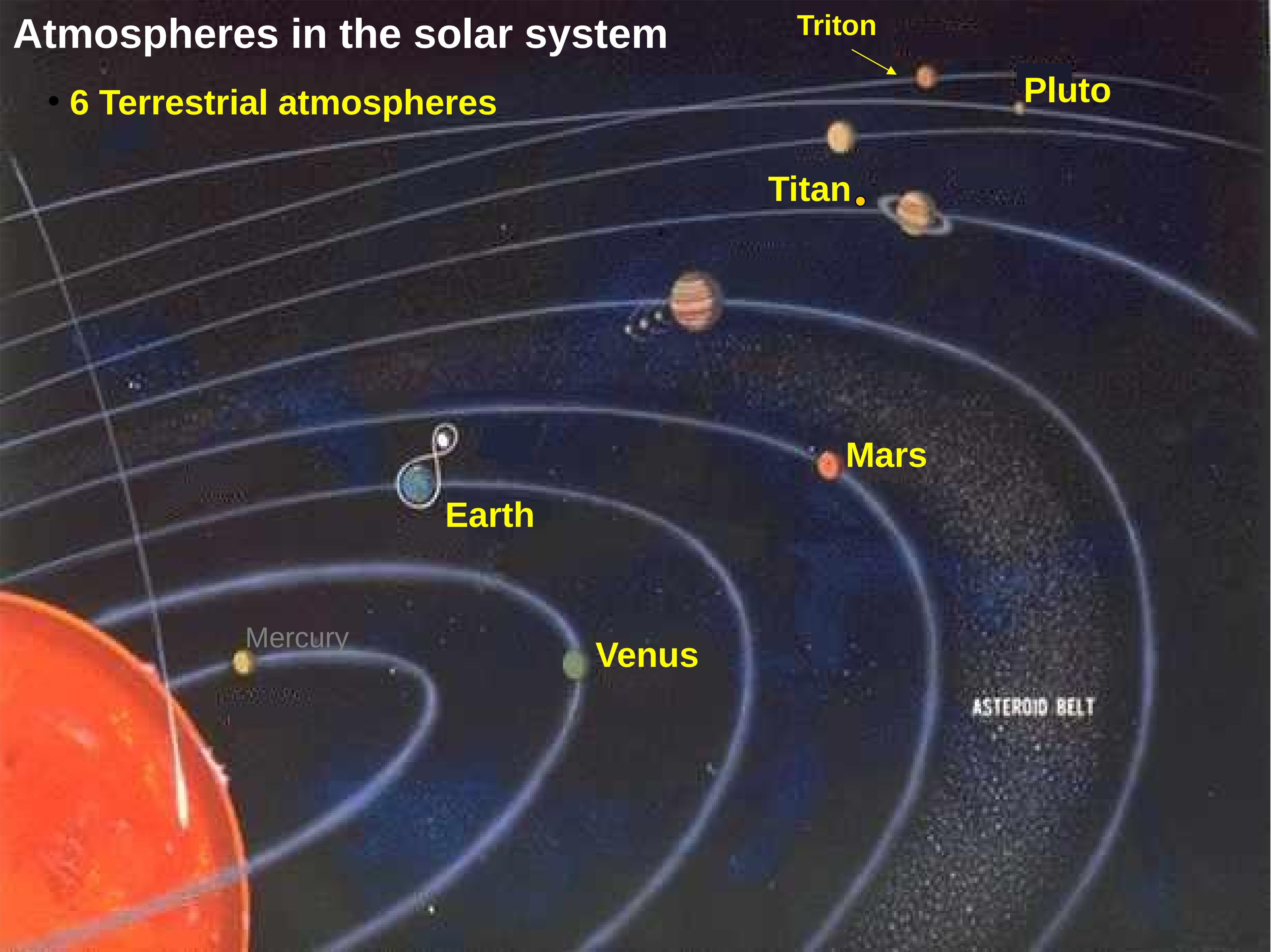
IPSL, Paris, France

CPS, Kobe, 28/03/2018

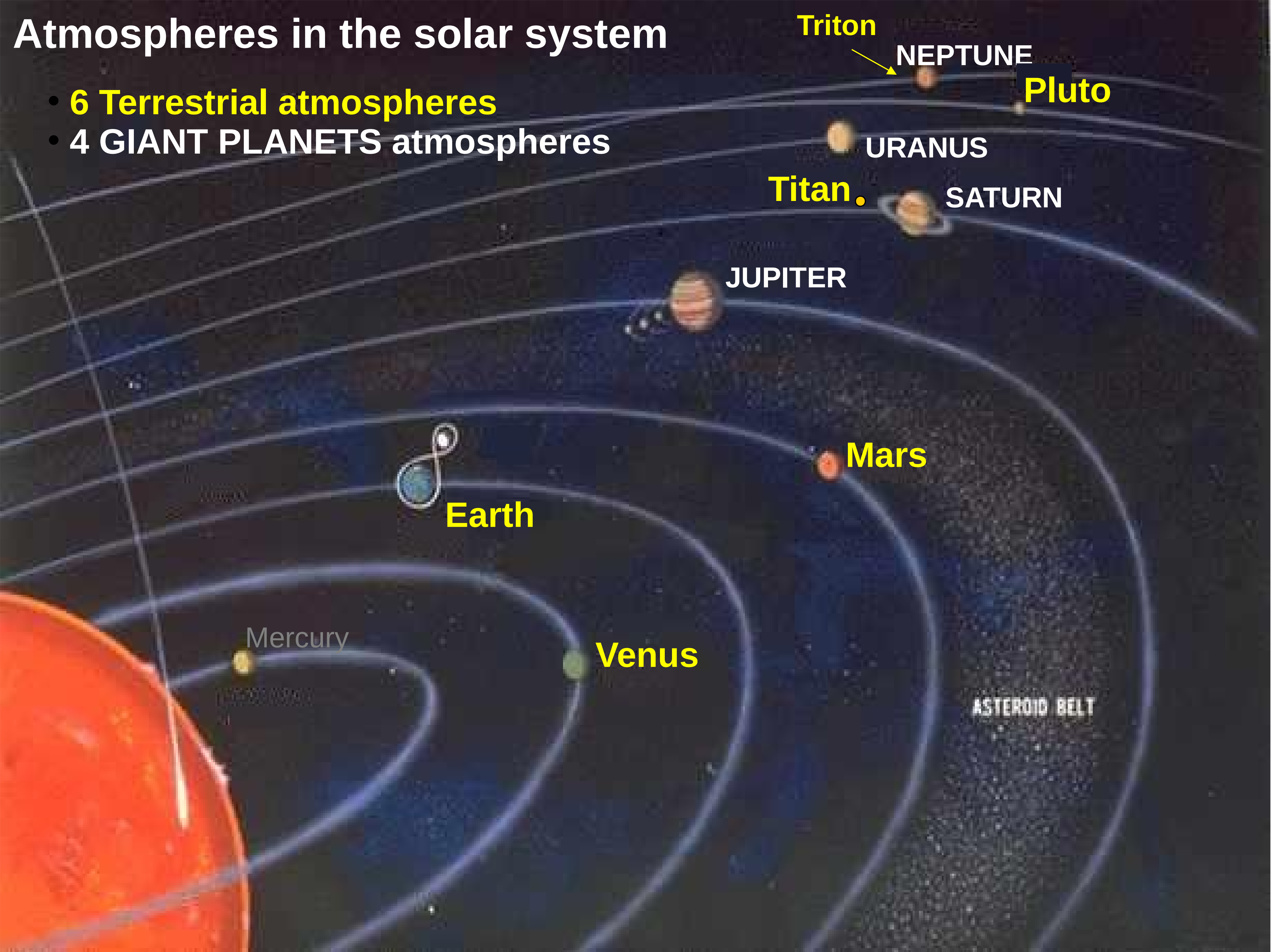
Atmospheres in the solar system

- 6 Terrestrial atmospheres

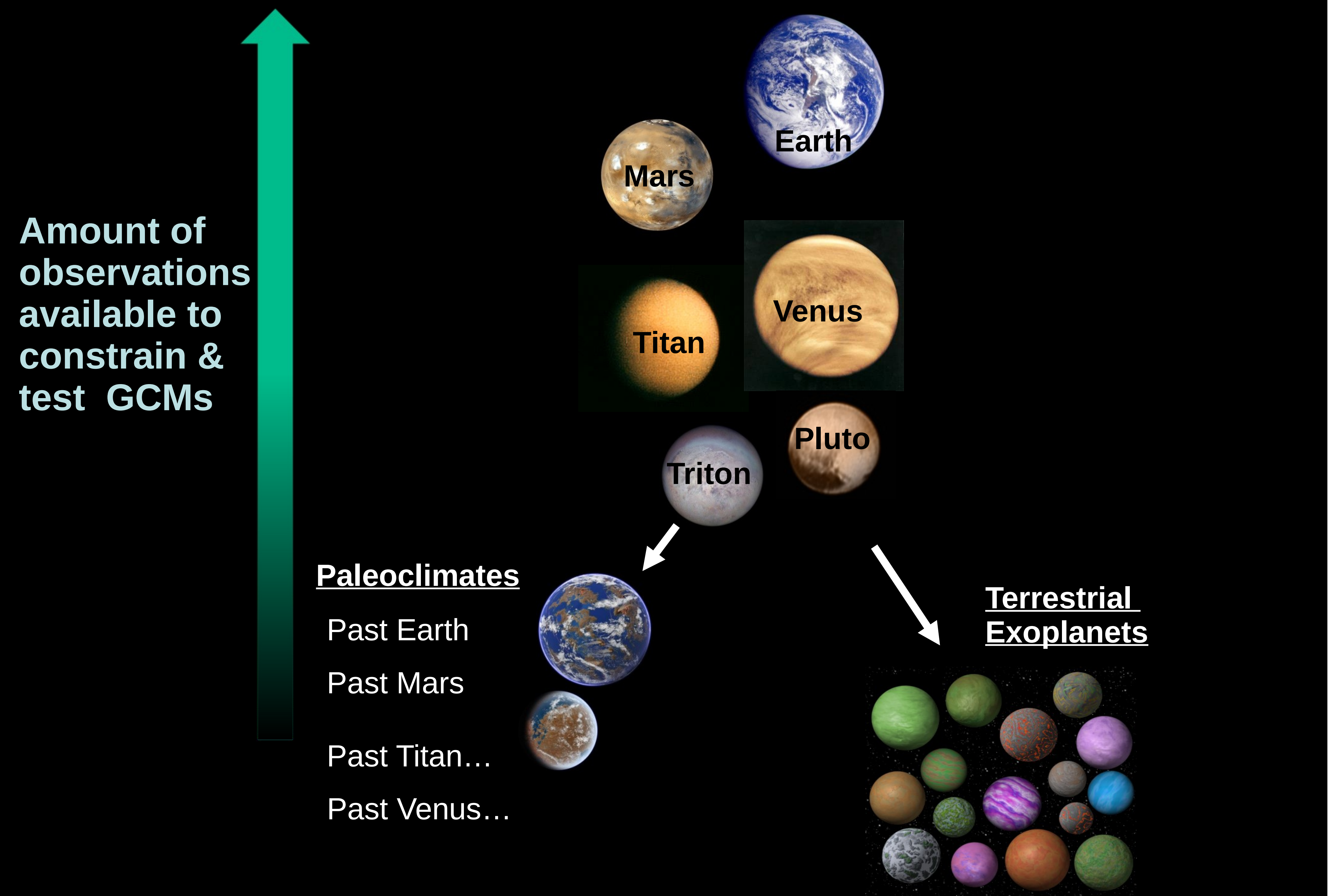


Atmospheres in the solar system

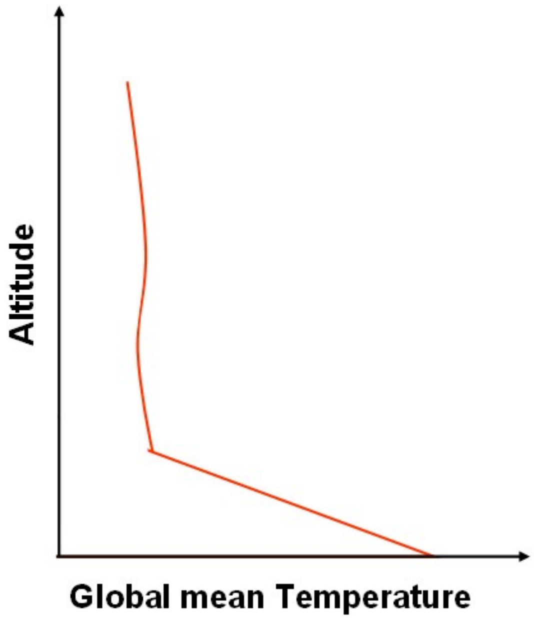
- 6 Terrestrial atmospheres
- 4 GIANT PLANETS atmospheres

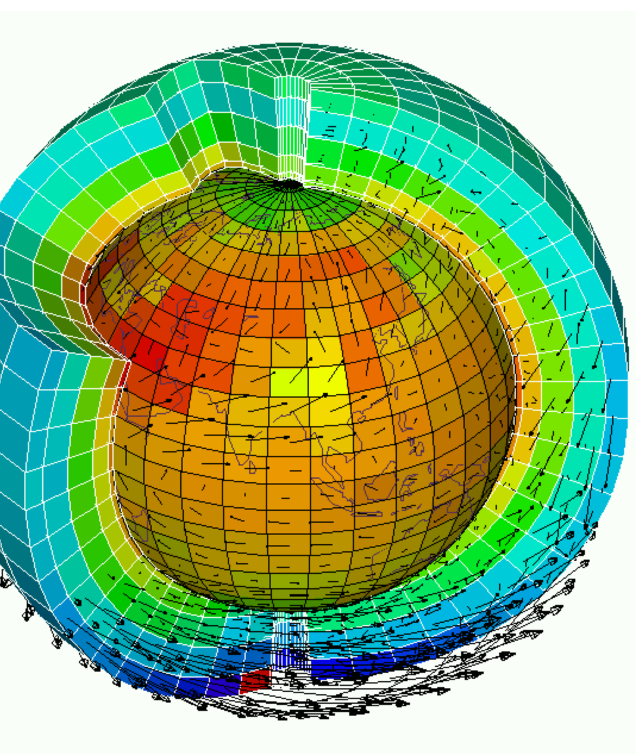


Terrestrial atmospheres to Model



A hierarchy of models for planetary climatology





1. 1D global radiative convective models

   Great to explore a wide range of possible climates; *(e.g. Kasting et al. 1993)*

2. 2D Energy balance models…

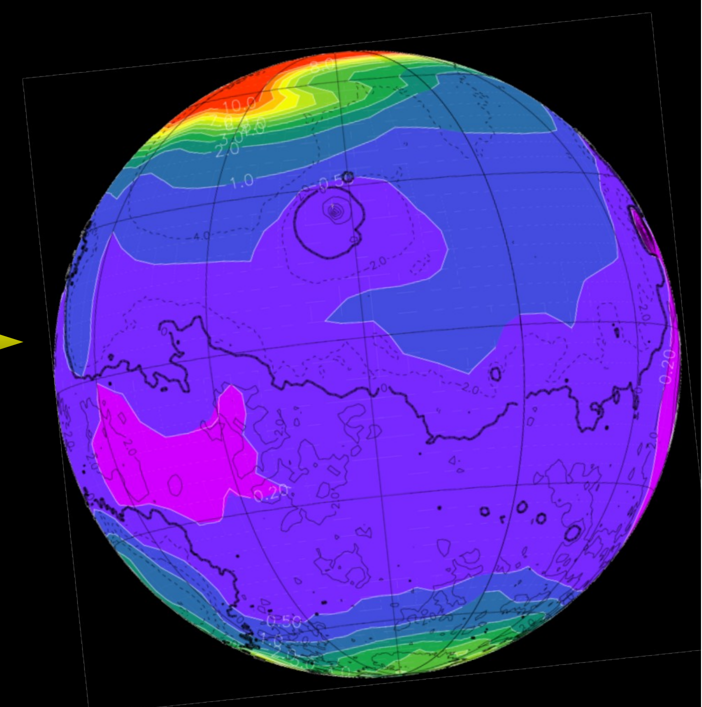
3. Theoretical 3D General Circulation model with simplified forcing: used to explore and analyse the possible atmospheric circulation regime *(e.g., Read 2011, Kaspi & Showman 2015, etc)*

4. Full Global Climate Models aiming at building "virtual" planets.

Ambitious Global Climate Models : Building “virtual” planets behaving like the real ones, on the basis of universal equations

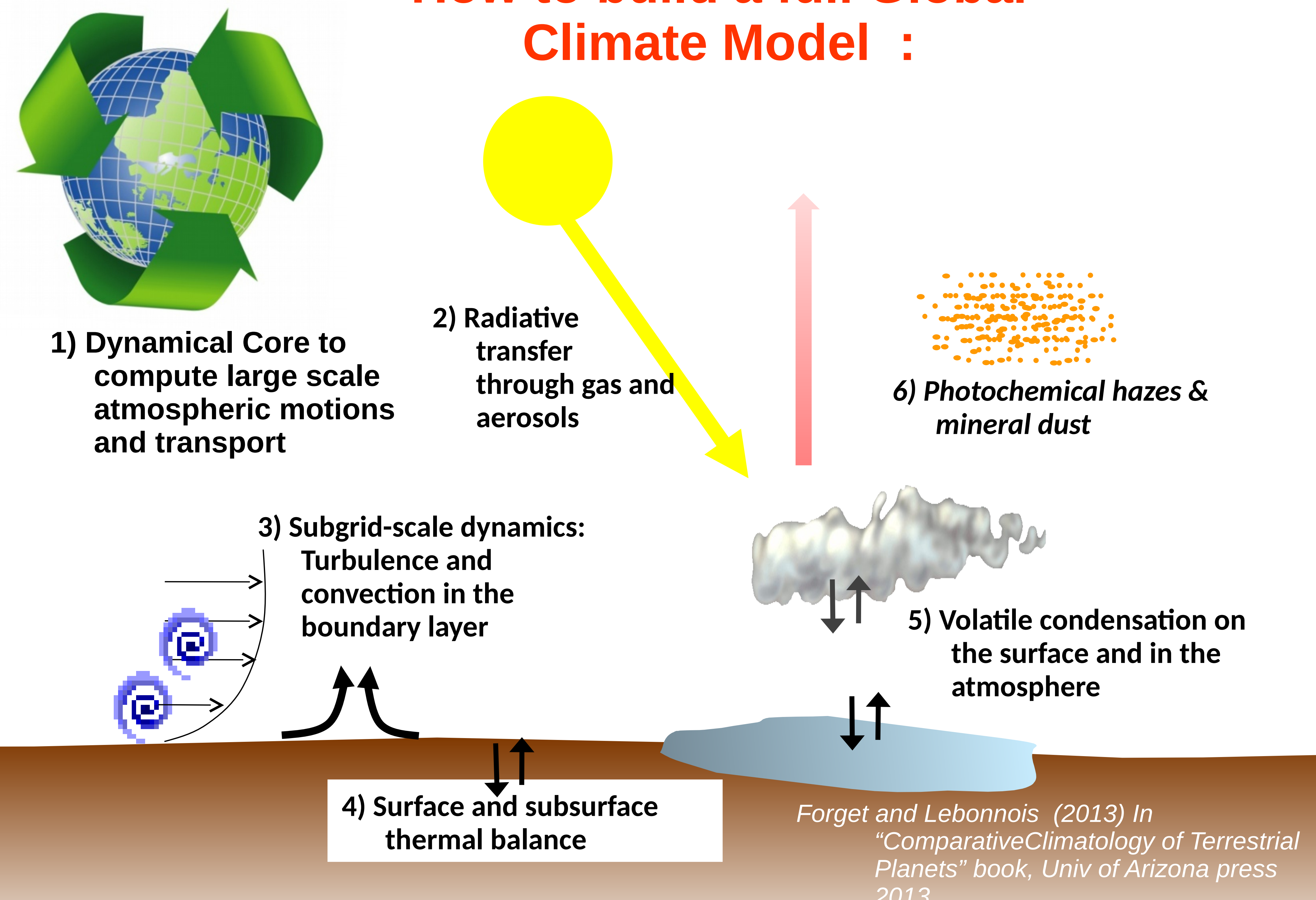
Observations

Reality



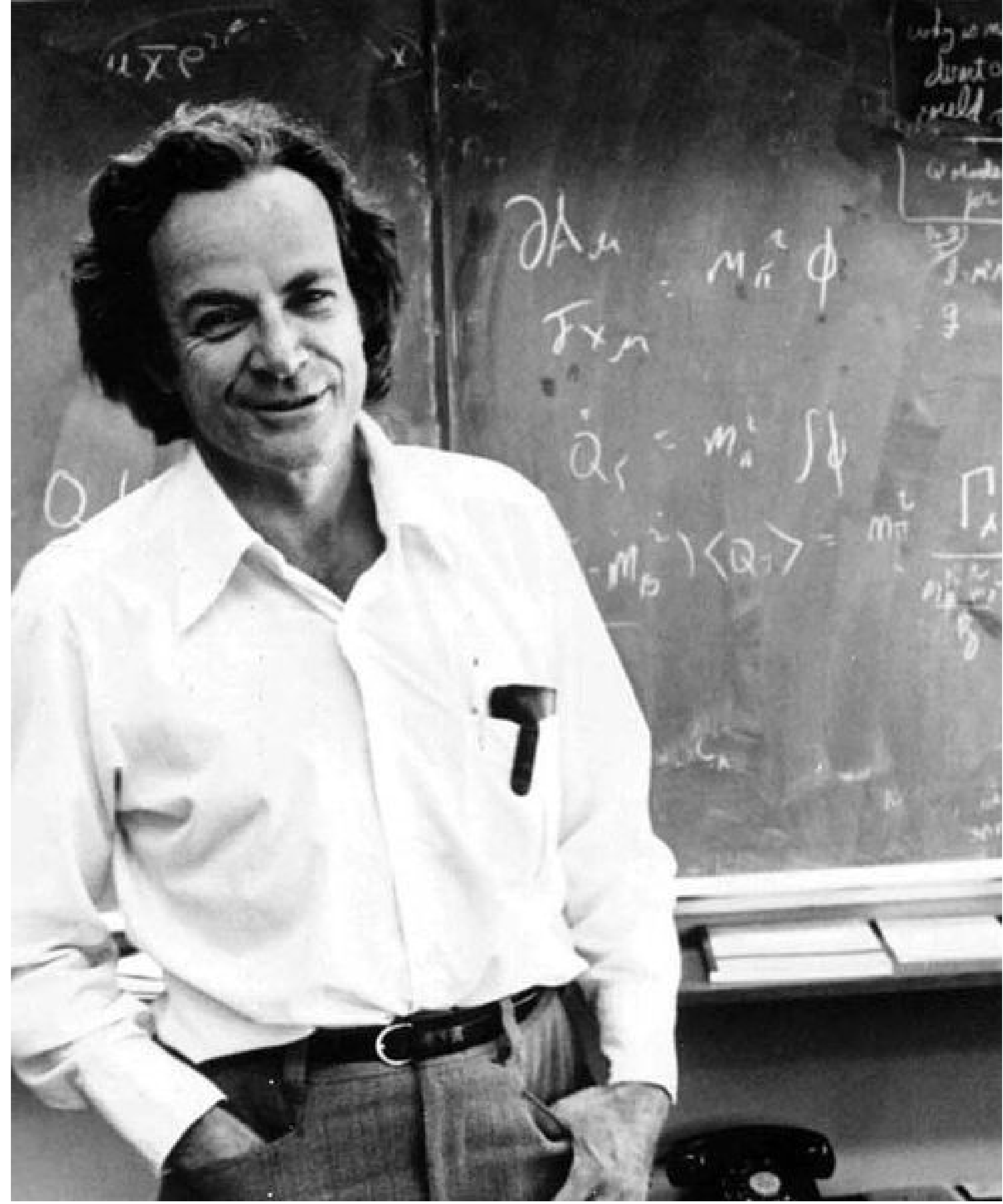
Models

How to build a full Global Climate Model :

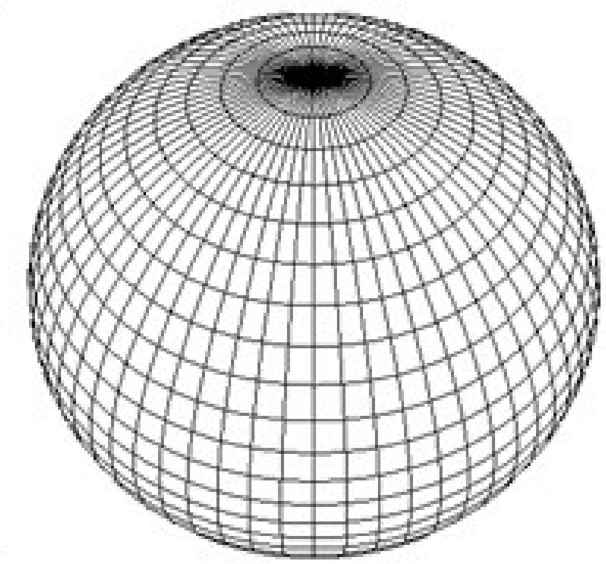


"What I cannot create, I do not understand"

Richard Feynman



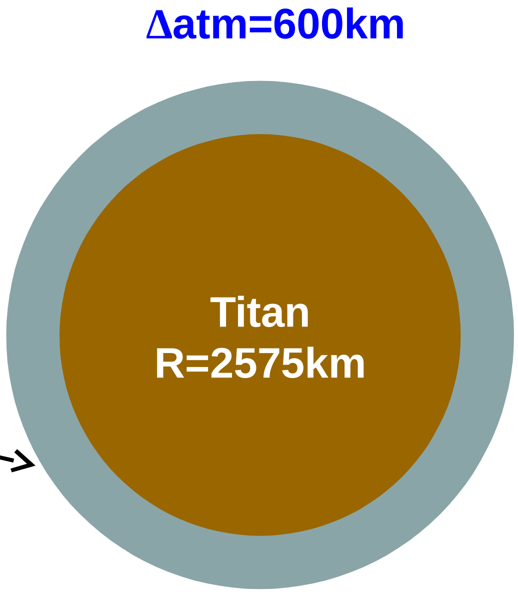
LMDZ : a 3D "dynamical core" to compute the primitive equations of meteorology :



⇒ to compute large scale atmospheric motions and transport

- Uses "finite volumes/differences schemes" (grid point model)
- Initially developed for the Earth, but equations are universal and simplifications made are valid on most planets

- Exceptions:
  - Assumption that air specific heat Cp is constant : not valid on Venus *(Lebonnois et al. 2010)*
  - Assumption that air Molecular mass is constant : not valid in Mars polar night *(Forget et al. 2005)*
  - "Thin layer approximation" : may not be valid on Titan *(Hirtzig et al. 2010)*



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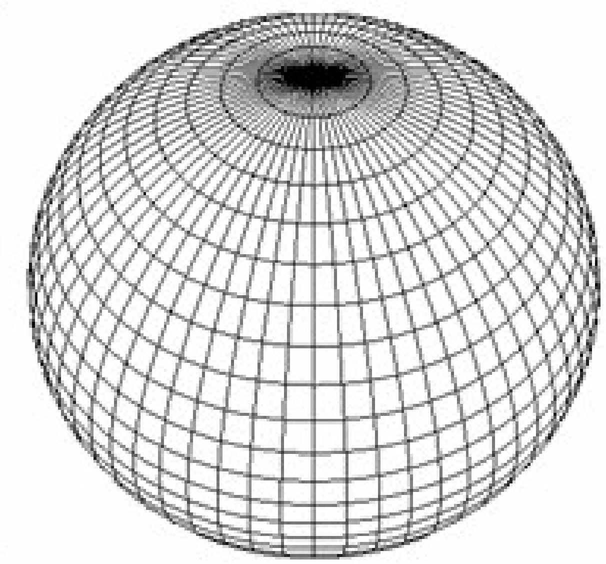


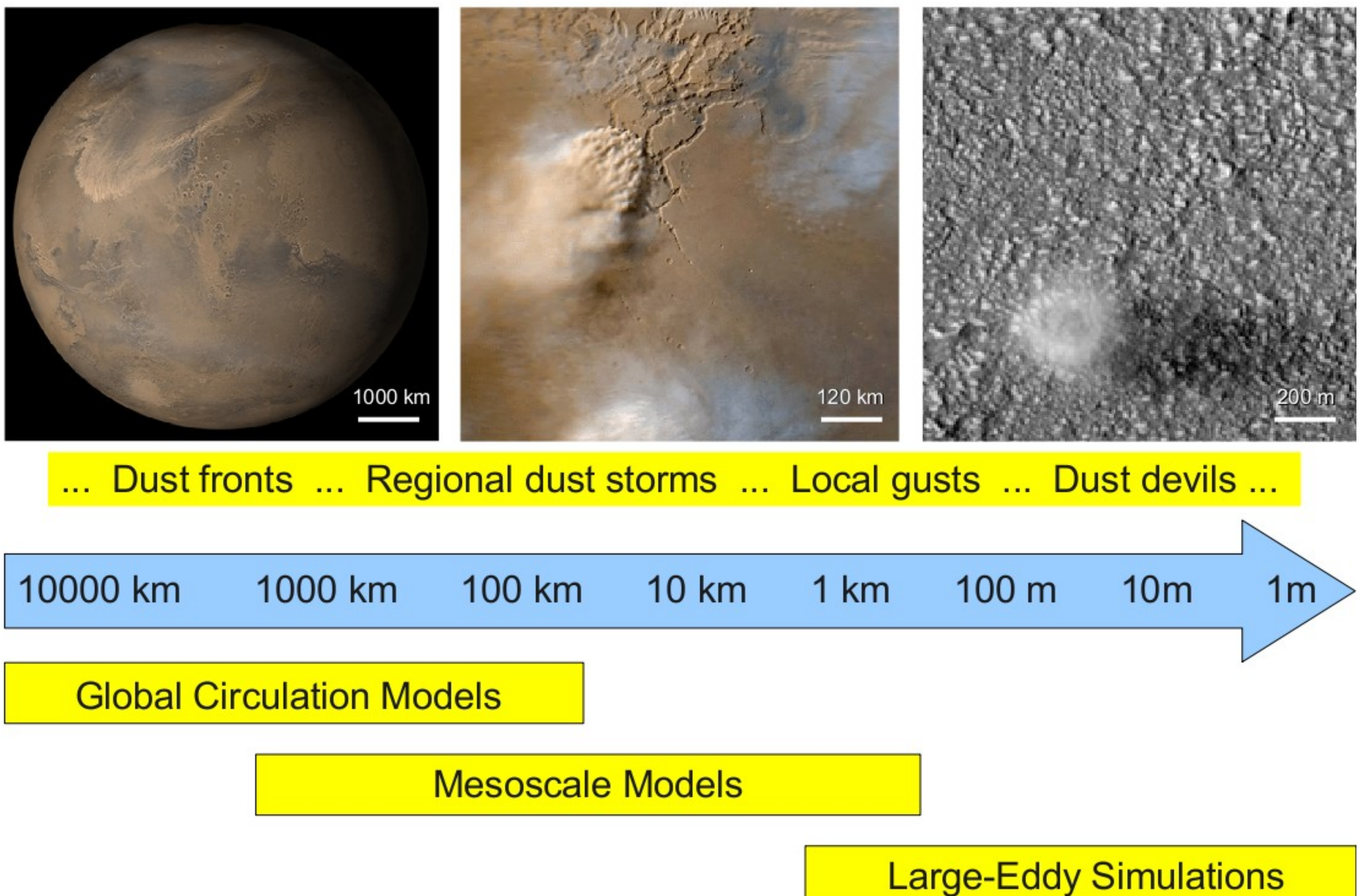
⇒ to compute large scale atmospheric motions and transport

- Uses “finite volumes/differences schemes” (grid point model)
- Initially developed for the Earth, but equations are universal and simplifications made are valid on most planets

=> which moreover must be coupled to a physics package appropriate to the studied planet

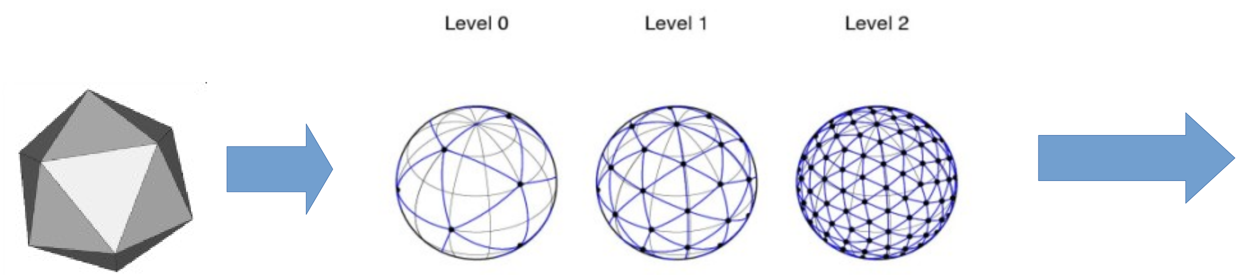
A suite of dynamical cores

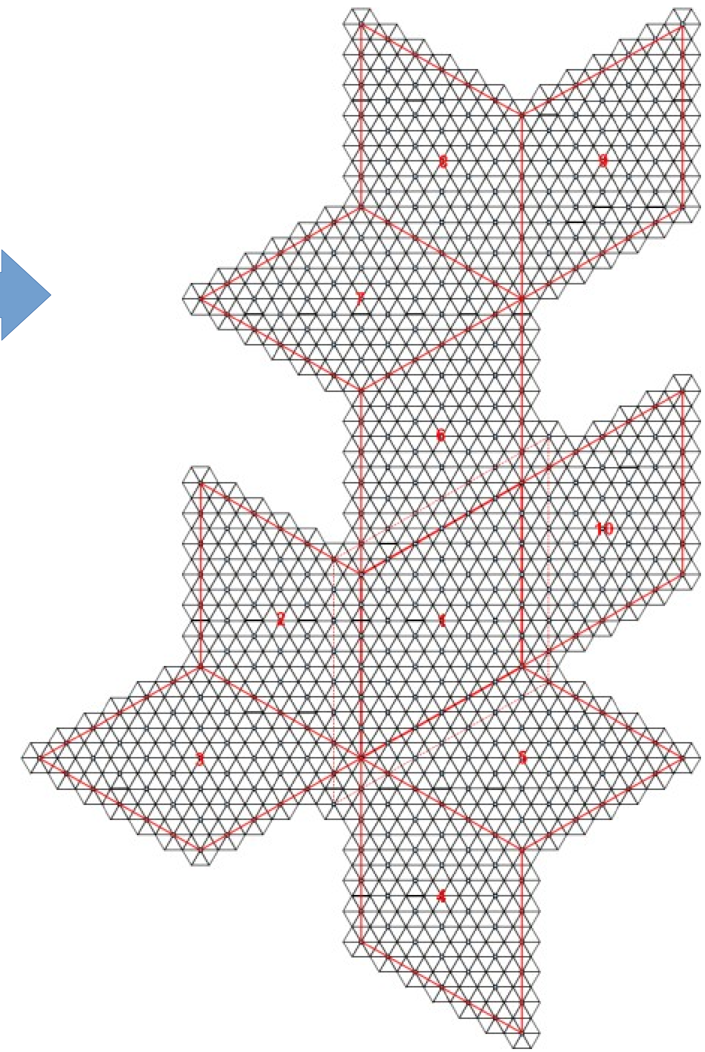
- To study finer-resolution phenomena, e.g. on Mars, coupling of our physics package with limited area model WRF was necessary (Spiga, 2009)



A suite of dynamical cores

- To be able to do high resolution global runs (e.g. for giant gas planets) and alleviate the “pole problem”, switching to a new icosahedral grid core (Dynamico) is necessary





Parallelism & HPC

- Implementation on semi-structured grid
  - 10 regular rhombus tiles, hexagons paved
  - Regular memory access, domain easy to cut up
- 1 MPI parallelism level (horizontal)
- 2 OpenMP parallelism level (horizontal & vertical)
- 99.7 vectorized (~60% peak perf. On SX8)

The Mars Climate Database (MCD version 5.3)

E. Millour[1], F. Forget[1], A. Spiga[1], M. Vals[1] , V. Zakharov[1] , T. Navarro[1] , L. Montabone[1,2], F. Lefèvre[3], F. Montmessin[3], J.-Y. Chaufray[3], M.A. López-Valverde[4], F. González-Galindo[4], S.R. Lewis[5], P.L. Read[6], M.-C. Desjean[7] , F. Cipriani[8] and the MCD/GCM development team

[1]Laboratoire de Météorologie Dynamique, IPSL, France

[2]Space Science Institute, Boulder, USA

[3]Laboratoire Atmosphères, Milieux, Observations Spatiales, IPSL, France

[4]Instituto de Astrofísica de Andalucía, Spain

[5]Department of Physics and Astronomy, The Open University, UK

[6]Atmospheric, Oceanic & Planetary Physics, University of Oxford, UK

[7]Centre National d'Etudes Spatiales, France

[8]European Space Agency, Netherlands

What is the Mars Climate Database ?

- The Mars Climate Database (MCD) is a database **derived from Global Climate Model** (GCM) **simulations**, using the LMD-GCM.
- The MCD is intended to be useful for engineering applications (e.g. Entry Descent & Landing studies) and scientific work which require accurate knowledge of the Martian atmosphere (e.g. Analysis of observations).
- The MCD is freely available, either via light online access (http://www-mars.lmd.jussieu.fr) for moderate needs, or a full version which includes advanced post-processing software (Fortran subroutine call_mcd; examples of C, C++, IDL, MATLAB, SCILAB, Python interfaces are provided).
- MCD v4.x and v5.x () have been distributed to more than 350 teams around the world. v5.3 was released in July 2017

MCD contents & main features

- The MCD provides mean values and statistics of main meteorological variables: **pressure**, **atmospheric density**, **temperature**, **winds**.
- Other variables included in the MCD:
  - Surface temperature and pressure
  - Thermal and solar radiative fluxes
  - CO_2 ice cover
  - Dust column opacity and mass mixing ratio
  - Dust effective radius and dust deposition rate
  - [H_2O] vapour and [H_2O] ice columns and mixing ratio
  - Water ice effective radius
  - [CO_2], [CO], [O], [O_2], [O_3] [N_2], [Ar], [H], [H_2], [He], [electrons] mixing ratios
  - Air specific heat capacity, viscosity and reduced gas constant r
  - Convective PBL height, typical updraft and downdraft velocities in PBL
  - Surface heat stress and surface sensible heat flux

Water cycle model

Chemistry model

Thermosphere model

Ionosphere model

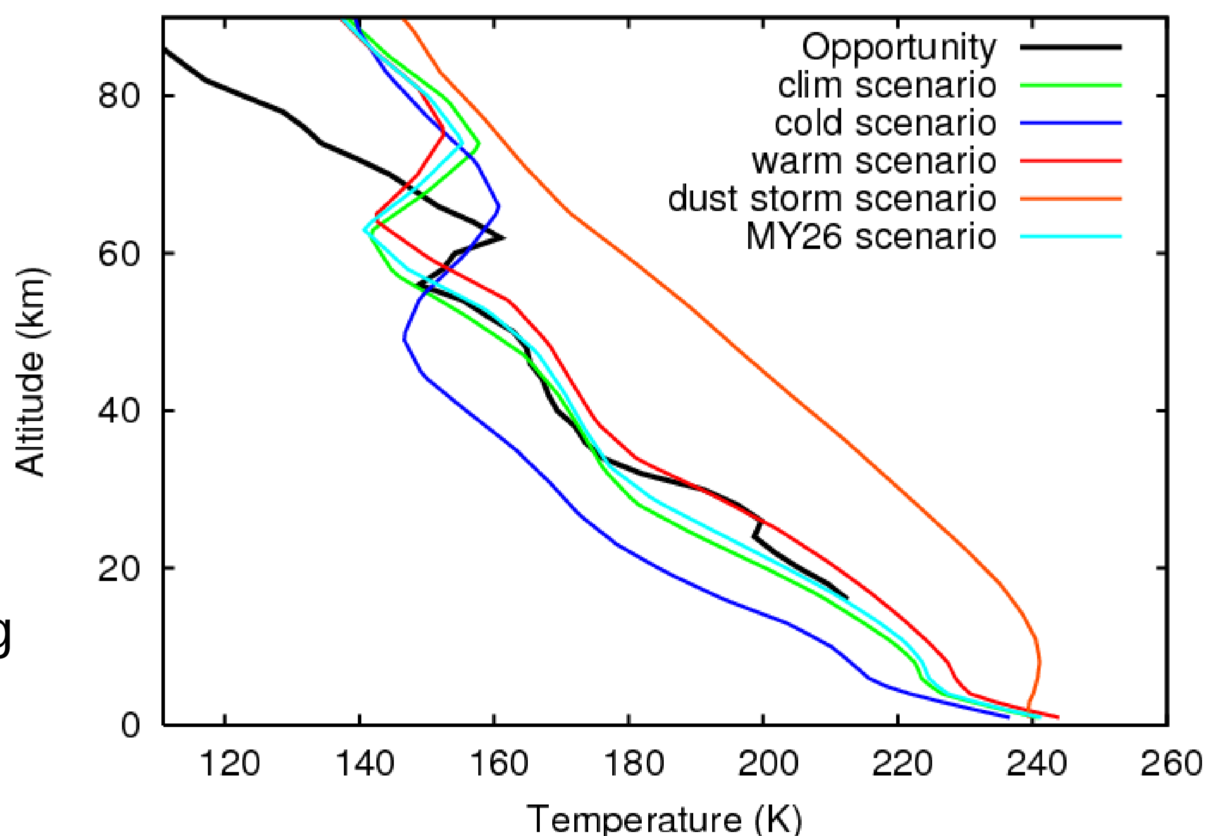
MCD contents & main features

- The dust load of the Martian atmosphere is highly variable; the MCD includes 4 synthetic dust scenarios to bracket reality, topped by 3 EUV scenarios to account for the Sun's 11 year cycle.
- Real-case Mars Years 24 to 32 scenarios (including EUV input) are also provided.

- **Climatology**: "Best guess" scenario for a typical Mars year
- **Cold**: very clear sky
- **Warm**: dusty atmosphere
- **Dust Storm**: severe global dust storm

- Opportunity landed during a local dust storm in MY26

Opportunity entry profile
(retrieved by P. Withers)



MCD contents & main features

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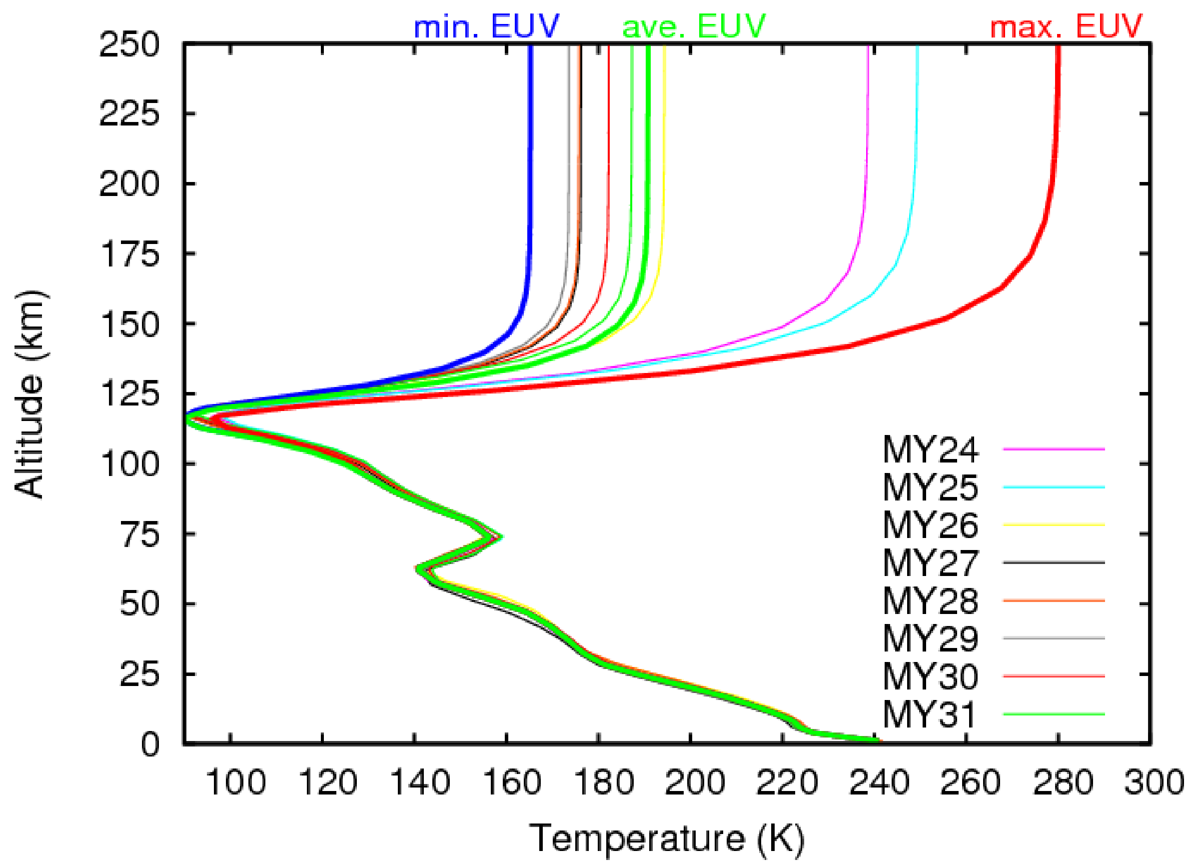
- Real-case Mars Years 24 to 32 scenarios (including EUV input) are also provided.

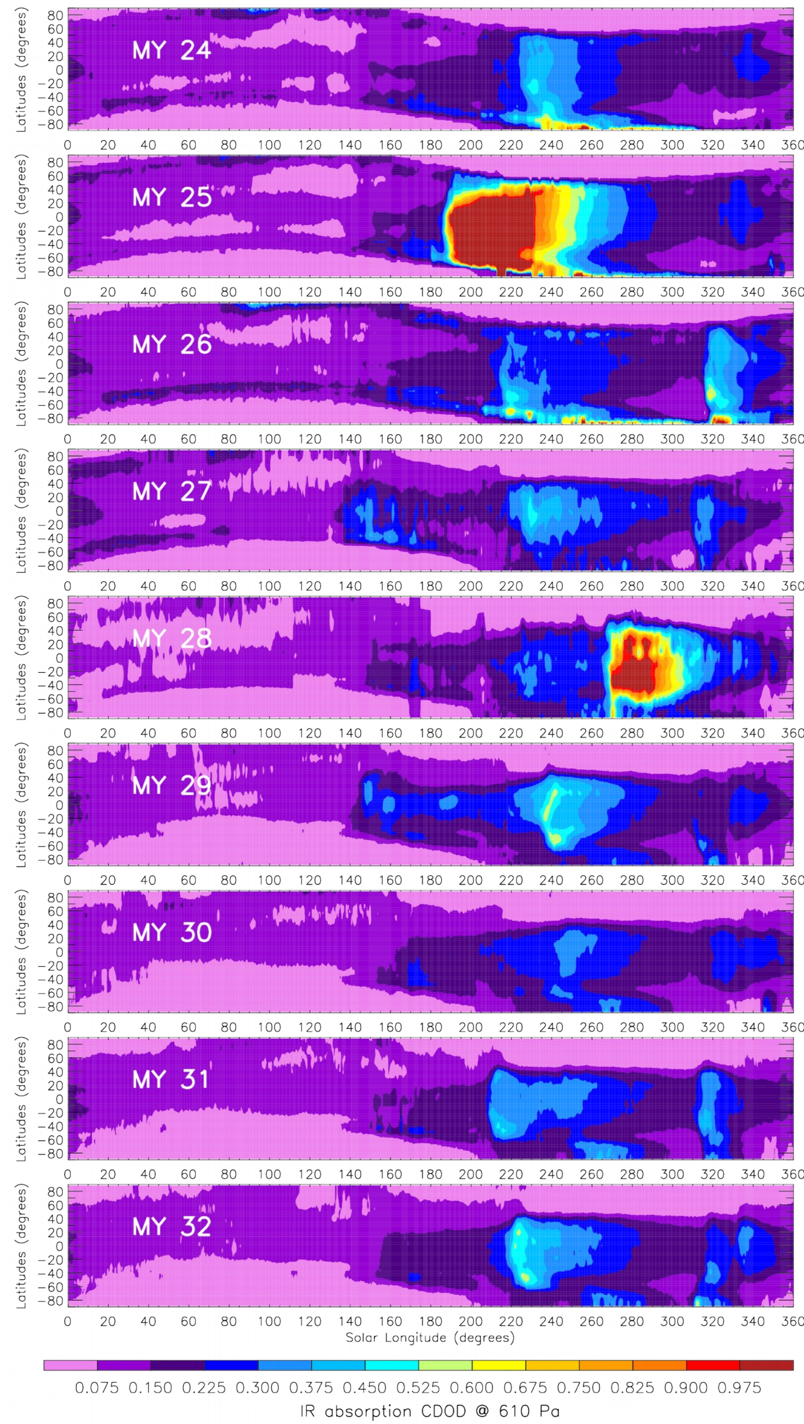
• **EUV input** matters in the thermosphere (above ~250km)

• **minimum** and **maximum EUV input** (revised in MCDv5.3) bracket recent solar cycle cases.
(NB: current solar cycle is quite weak)



MCD v5.3 dust scenarios

- We have access to dust scenarios for last 9 Mars years (Montabone et al., 2015).
- **Combining** all "non-global dust storm" years (MY 24, 26, 27, 29, 30, 31), we can generate a **mean Mars year dust scenario and climatology**.
- Also used to design cold and warm scenarios
- Moreover, specific simulations for each of the MY years are also provided.



MCD contents & main features

- The MCD enables to reconstruct realistic conditions using:

  - day-to-day variability of main variables

  - adding random small scale perturbations as vertical gravity waves (of user specified wavelength)

  - adding random large scale perturbations (extracted from EOFs of individual GCM runs)

- The MCD provides a high resolution mode based on 32 pix./deg. MOLA topography (where GCM resolution is 5.625° x 3.75°) combined to Viking Lander 1 pressure records, which yields:

  - high resolution surface pressure

  - reconstructed high resolution atmospheric temperature, using an empirical scheme validated using high resolution GCM runs.

Validation of the MCD climatology

- Ongoing work
- Available measurements are the best way to evaluate and validate the MCD, e.g.:

  - **Surface temperatures**, **atmospheric temperatures** and **water vapour** can be compared to **TES** values.

  - **Atmospheric temperatures** and **water ice** can be compared to **MCS** values.

  - **Atmospheric temperatures** can be compared to **MGS** and **Mars Express Radio Occultations**.

  - **Surface pressures** can be compared to **Viking Lander**, **Pathfinder, Phoenix** and **MSL** measurements.

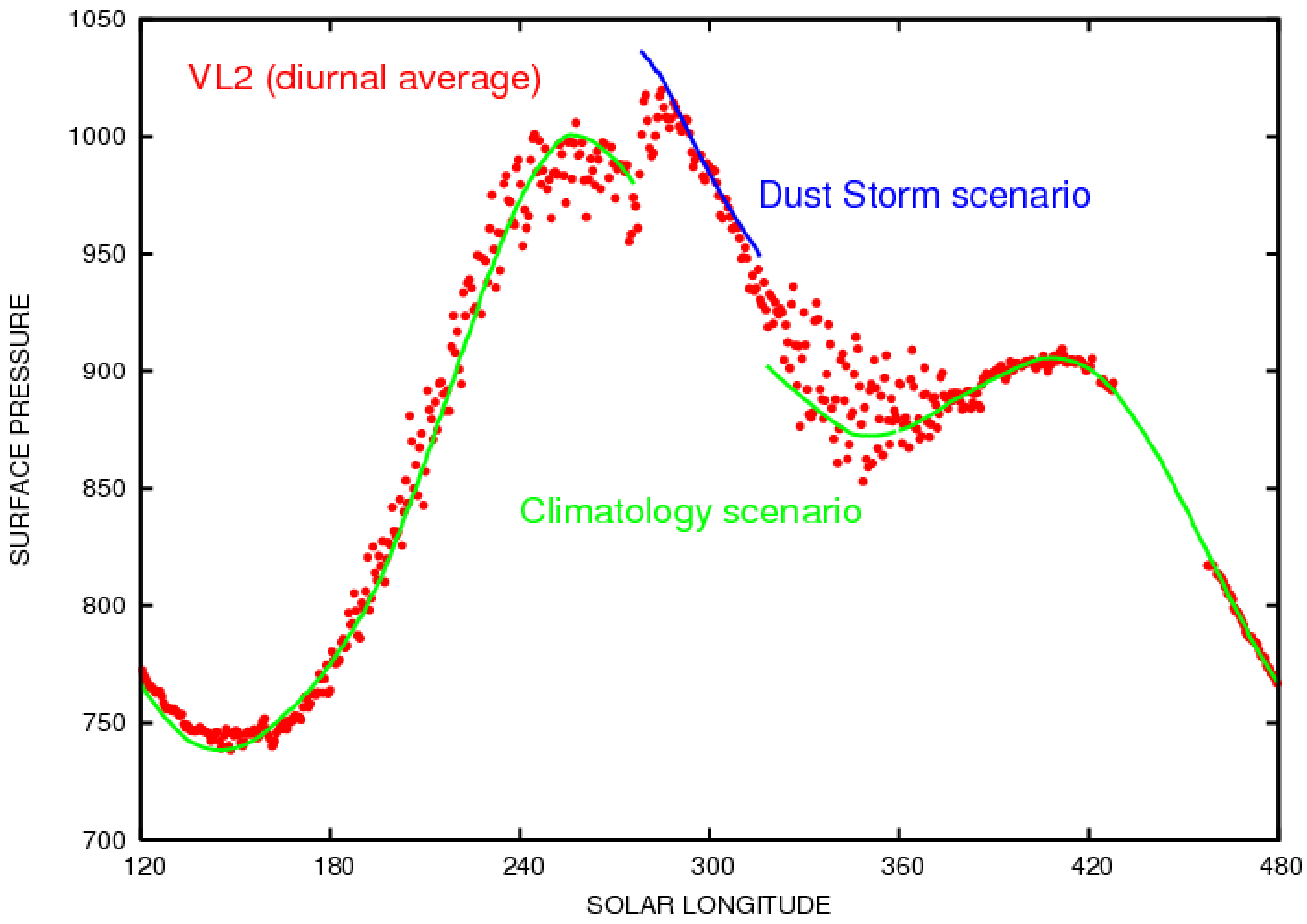
  - **...**

Surface Pressure

Viking Landers

Mars Years 12-13

MCDv5.3 validation – Viking Lander 2 pressure (Mars Year 12-13)



- Change in global behavior due to dust storm is well captured by MCD scenarios.

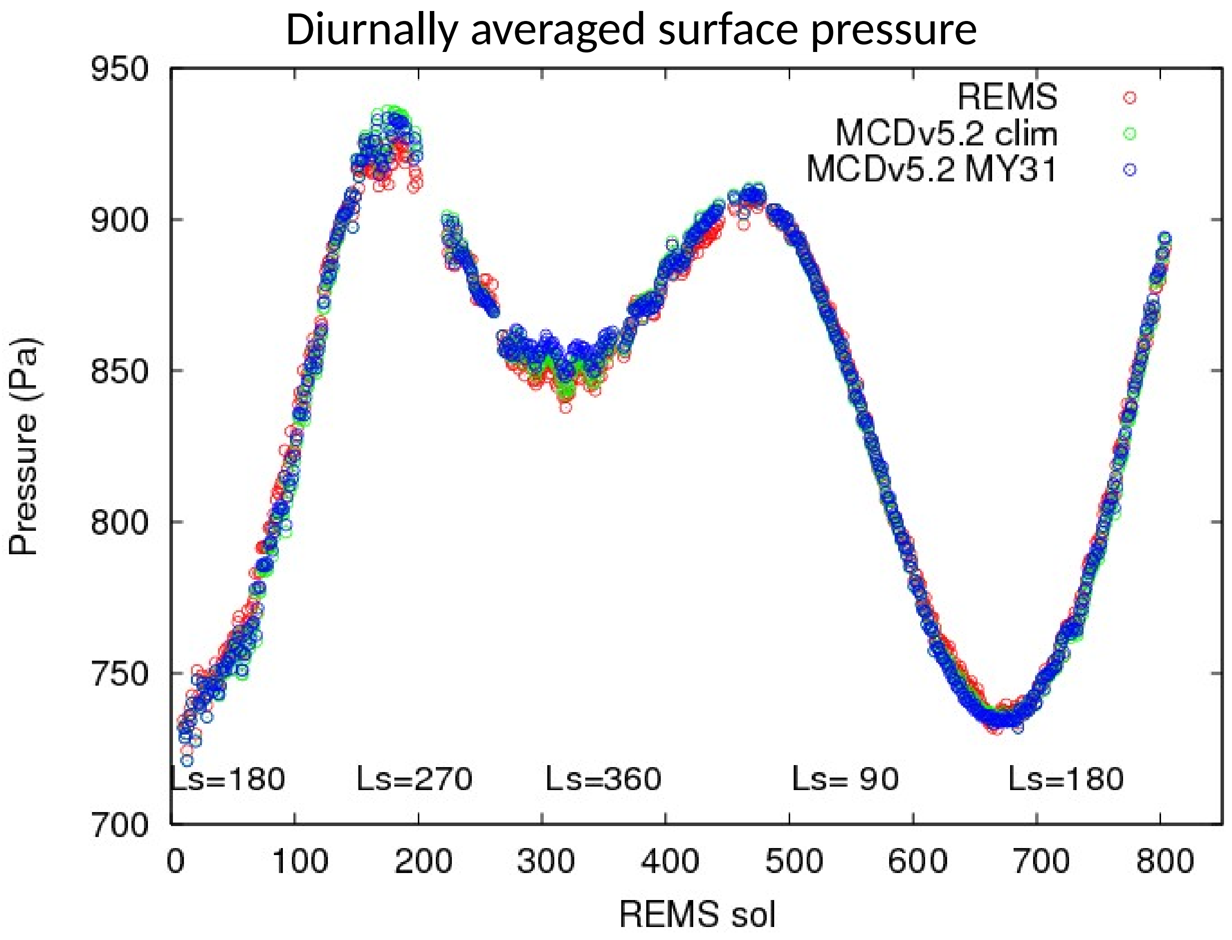
Surface Pressure

REMS onboard Curiosity

Mars Year 31-32

REMS pressure measurements

- Ongoing measurements since Curiosity landing in Mars Year 31.



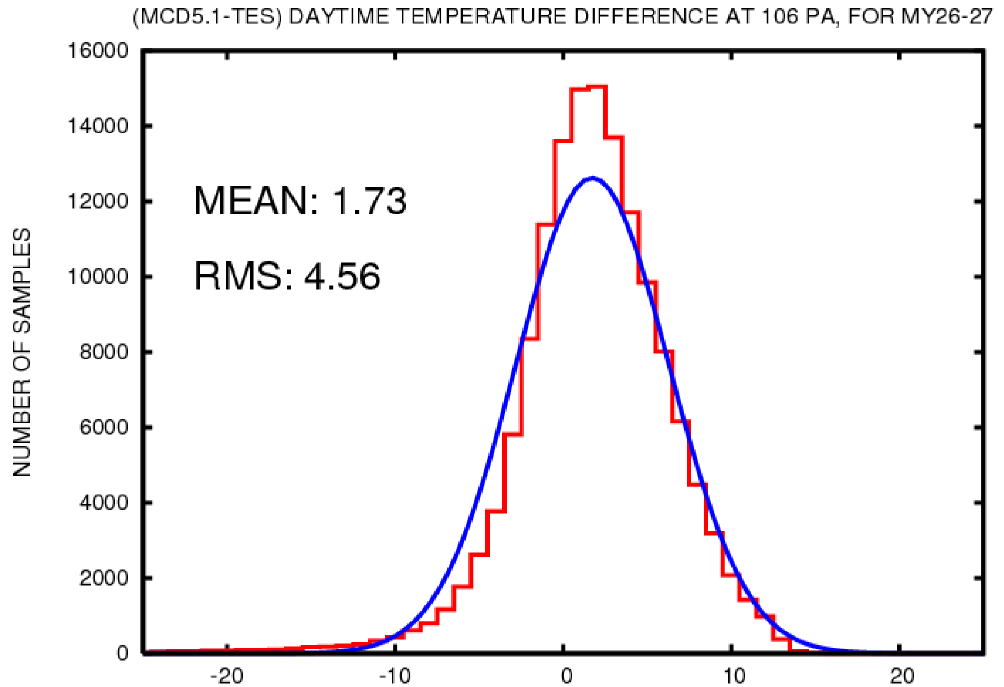
- Good representativeness of MCDv5.2 clim and MY31 scenarios of the seasonal evolution of the Martian CO2 cycle

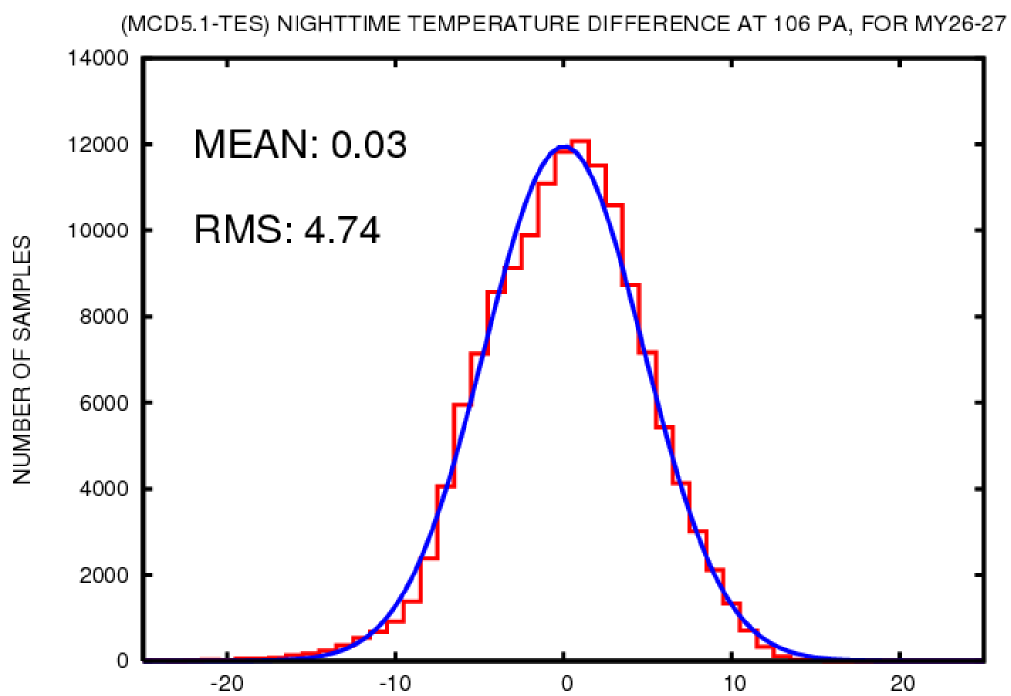
Atmospheric Temperature

TES onboard MGS

Mars Years 24-27

(2am-2pm measurements)

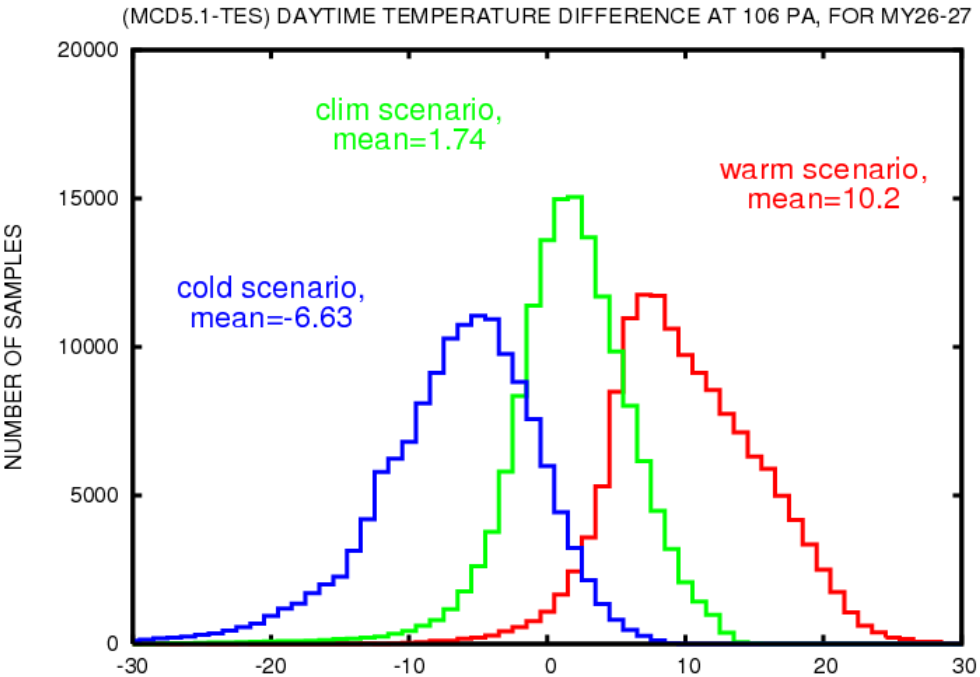




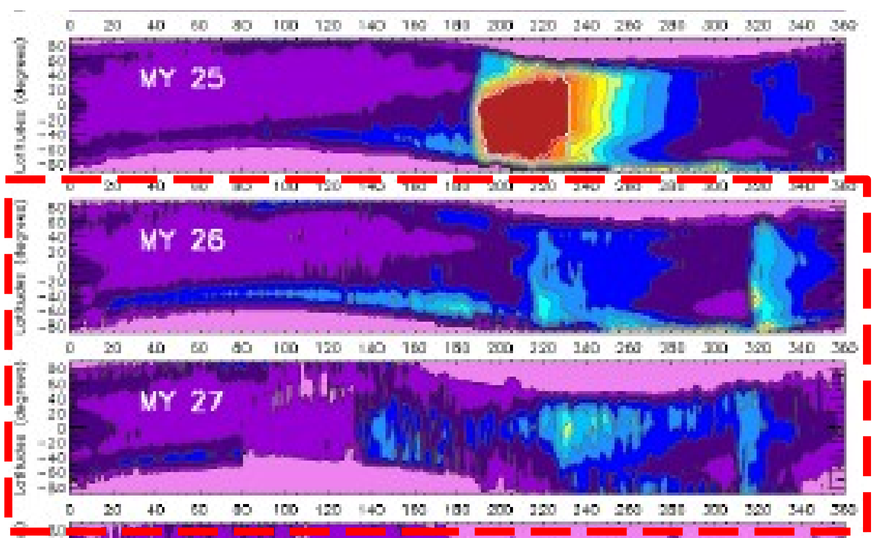
Distributions of **atmospheric temperature differences**, at 106 Pa, between MCDv5.3 (climatology) and TES onboard MGS (MY 26-27) daytime (2pm) and nighttime (2am) measurements.

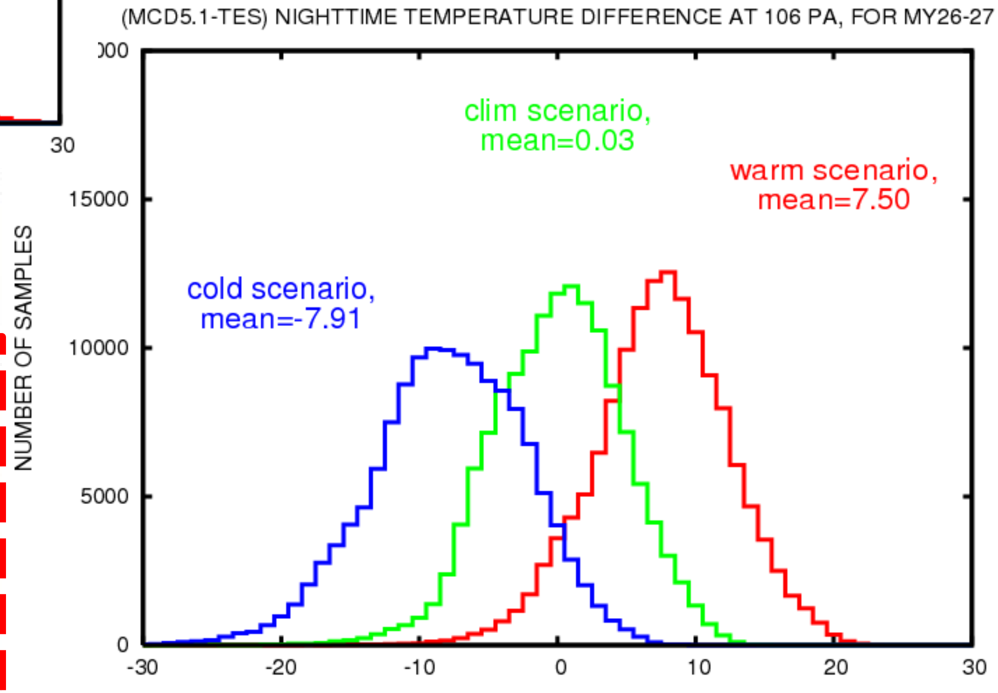
- Statistics computed for:
  - Pressure: 106 Pa
  - MY26: 0 < Ls < 360
  - MY27: 0 < Ls < 85
  - -50 < latitude < 50
  - Bins of 1K

Bracketing TES with MCDv5.3 scenarios

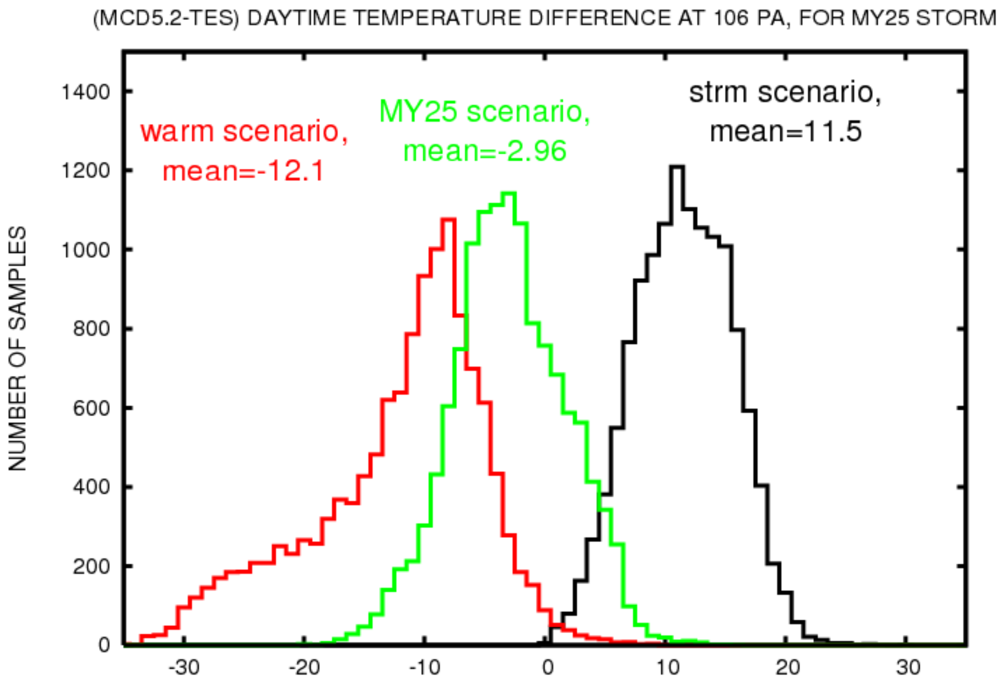


during regular martian years (e.g. MY26-27)

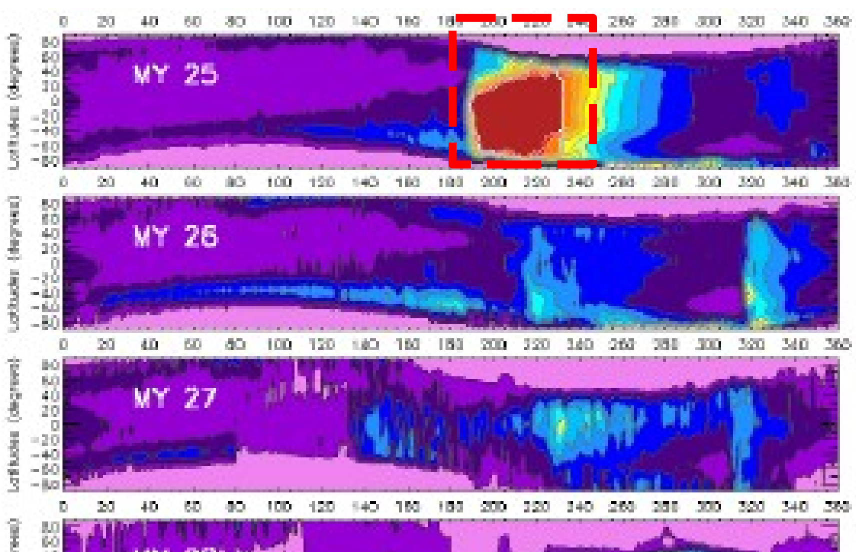


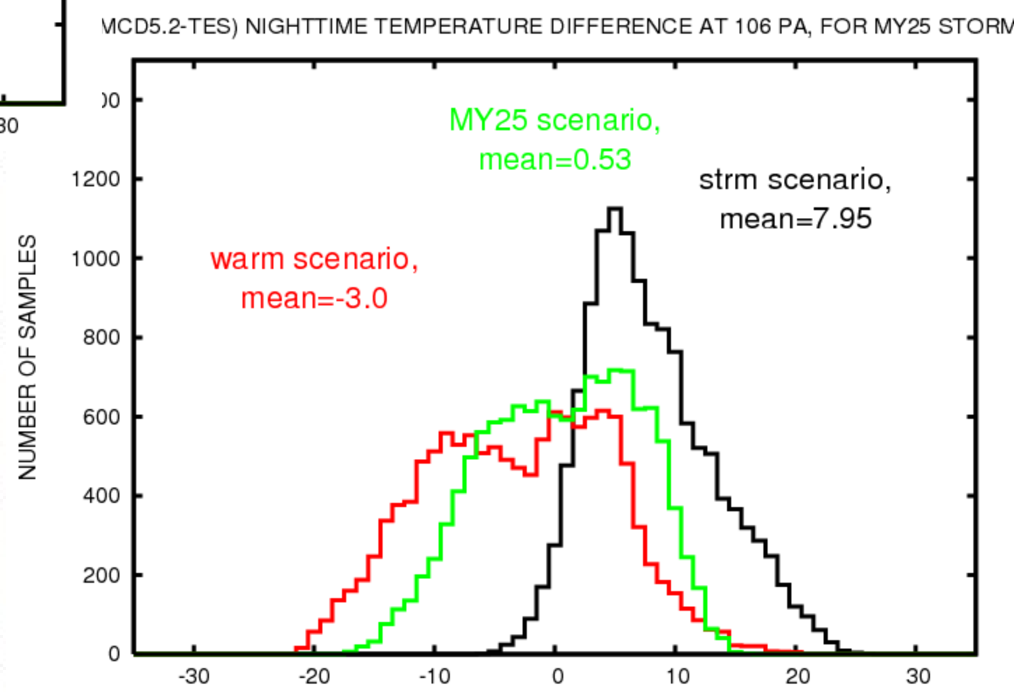


Bracketing TES with MCDv5.3 scenarios



during global Planet encircling storm (MY25)

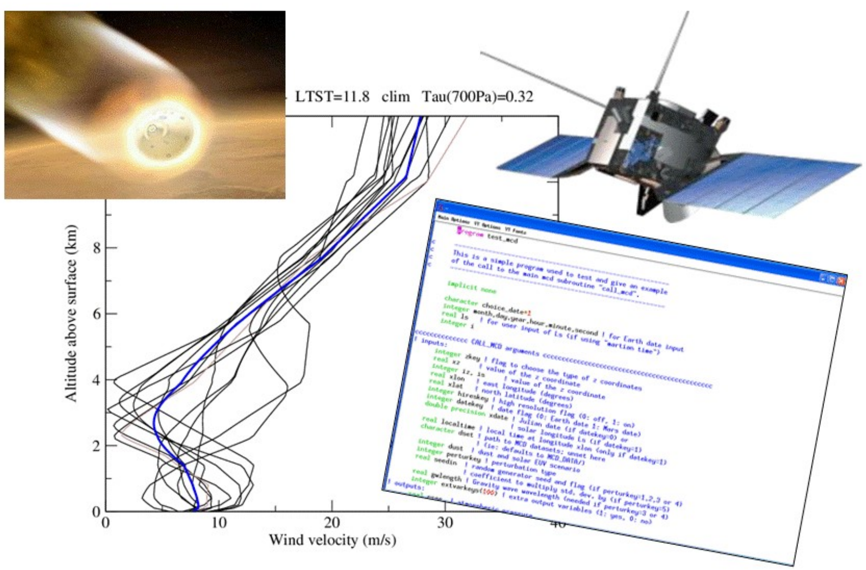




Obtaining/using the Mars Climate Database

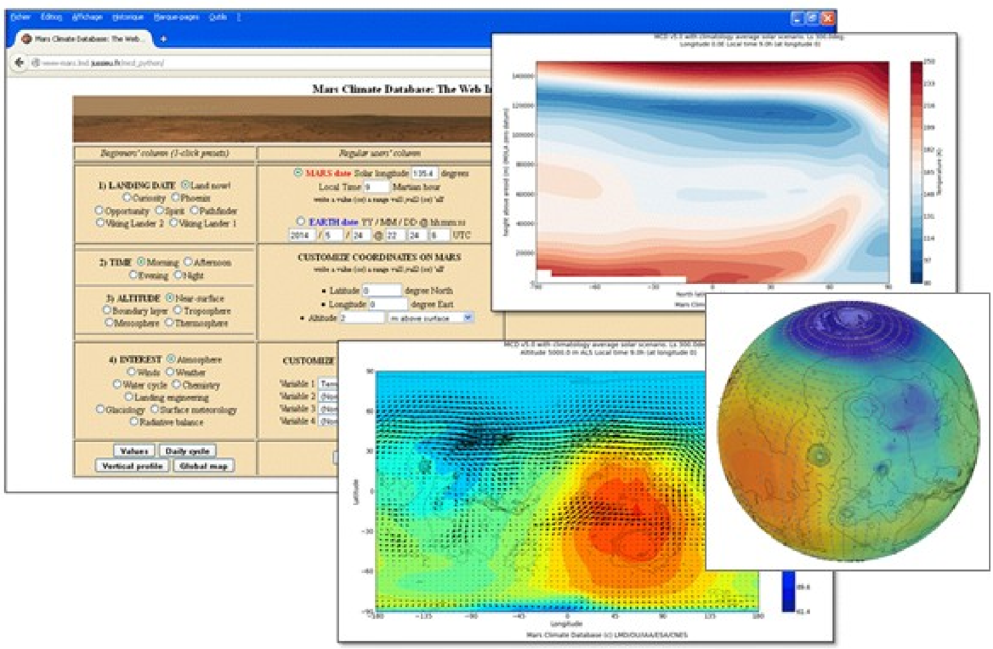
The full version: contact us!
millour@lmd.jussieu.fr,
forget@lmd.jussieu.fr

- Access software "call_mcd" (Fortran)
- With Matlab, C, C++, IDL, Python, and Scilab interfaces



The light "web" version:
http://www-mars.lmd.jussieu.fr

- For quick plots
- Very easy to use, all you need is a web browser.

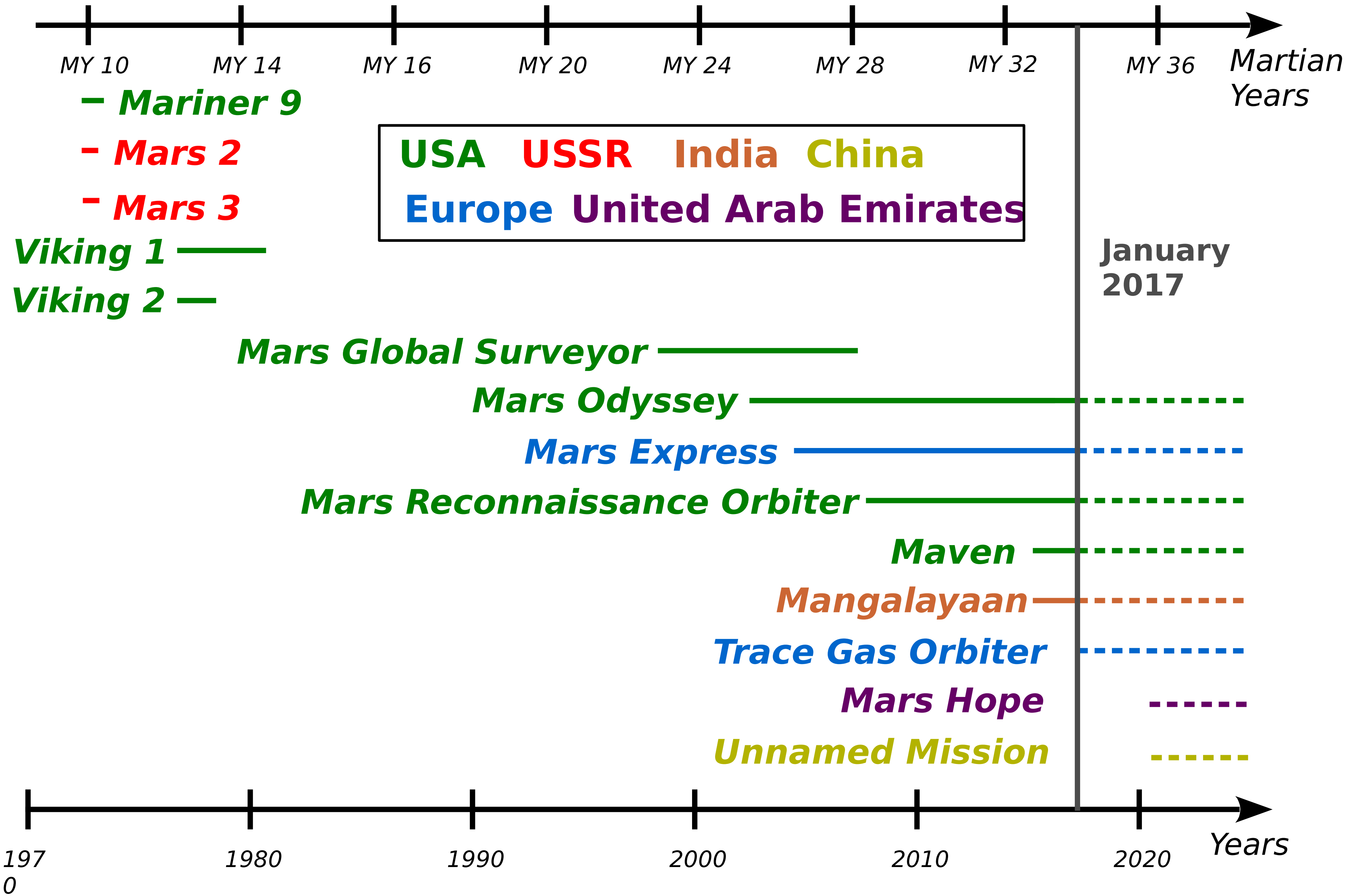


The challenge of atmospheric data assimilation

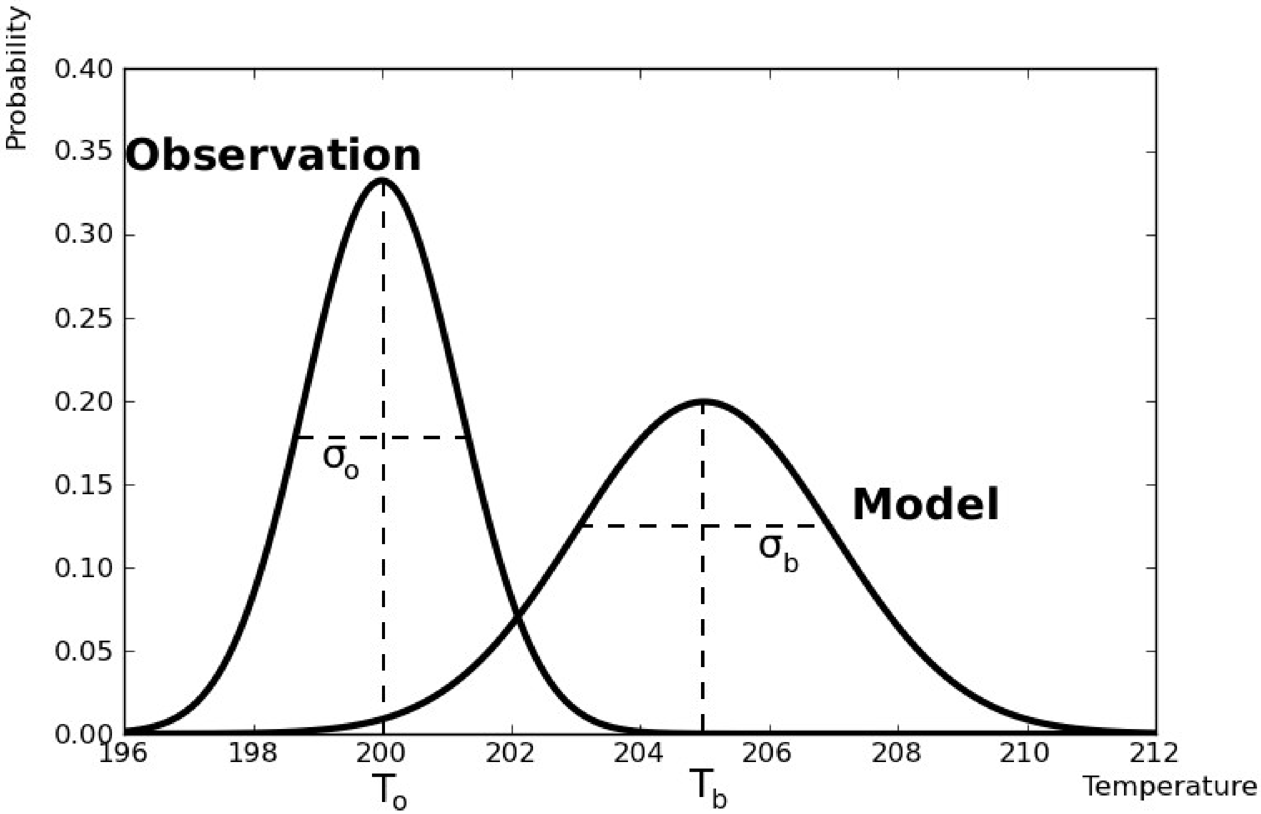
Illustration with the LMD GCM, MCS observations, and a Kalman Filter method

Thomas Navarro, Roland Young
François Forget
Ehouarn Millour

Observations from orbit

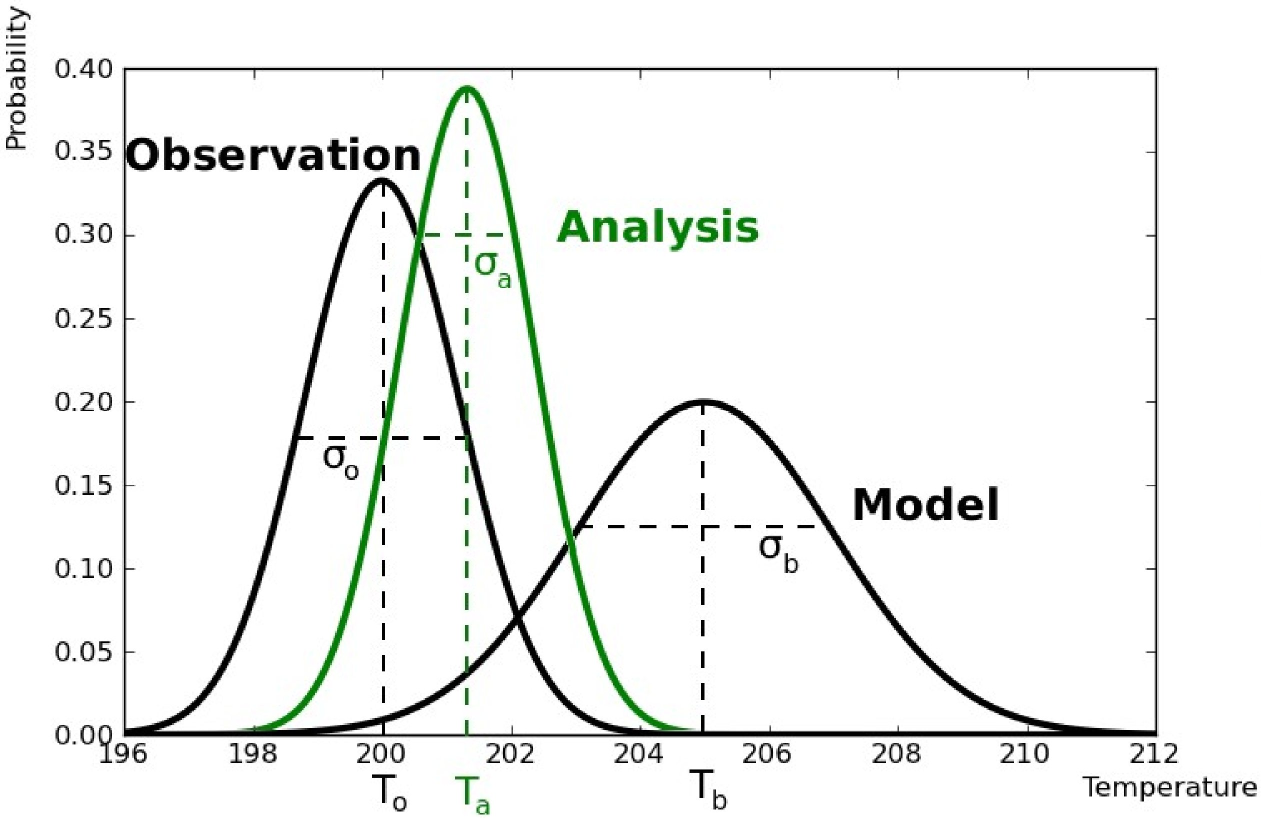


Data assimilation: Principle



« Using all the available information to determine as accurately as possible the state of the atmospheric flow »
(O.Talagrand)

Data assimilation: Principle

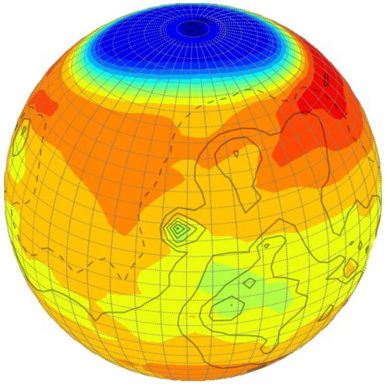


$$\frac{1}{\sigma_a^2} = \frac{1}{\sigma_b^2} + \frac{1}{\sigma_o^2}$$

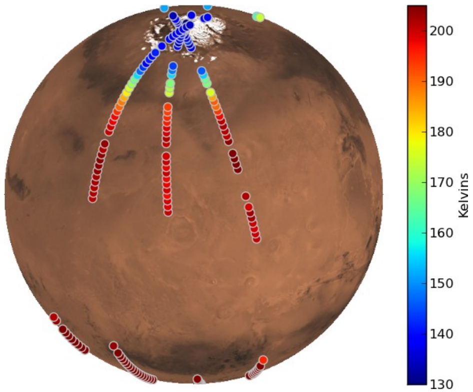
$$T_a = T_b + \frac{\sigma_b^2}{\sigma_b^2 + \sigma_o^2}(T_o - T_b)$$

1. The analysis value is surrounded by the model and the observation.
2. The analysis is closer to the observation, because the observation is more reliable.
3. The analysis uncertainty is smaller than both the model and the observation ones.

Data assimilation: Principle

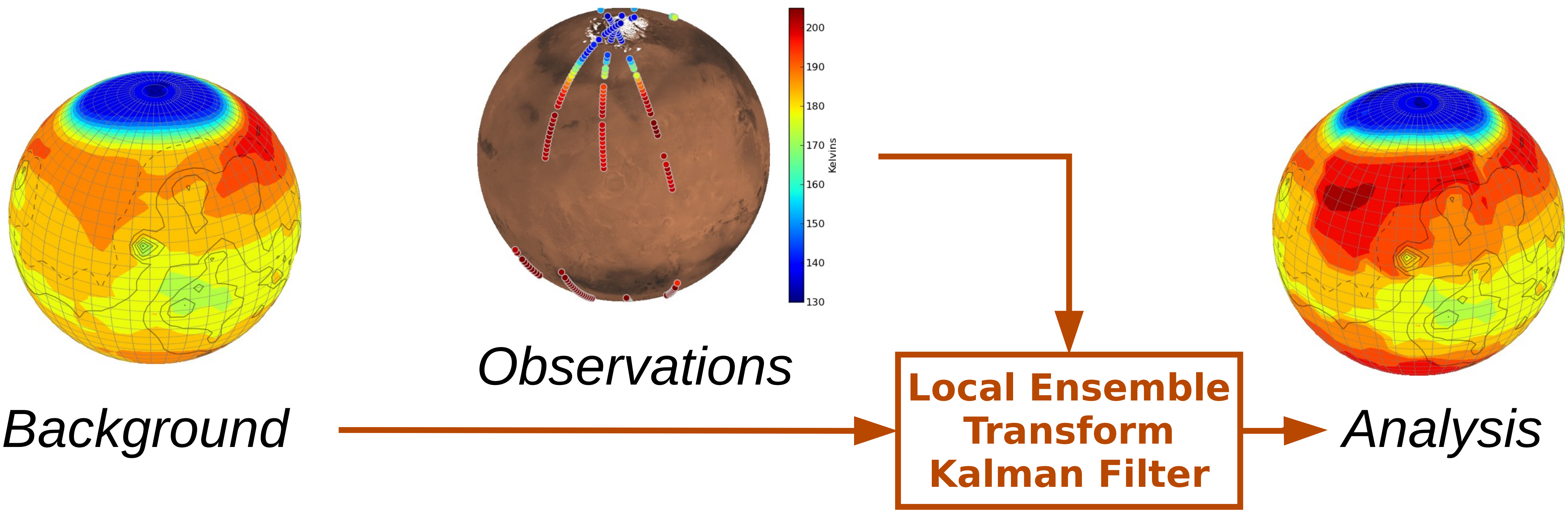


Background

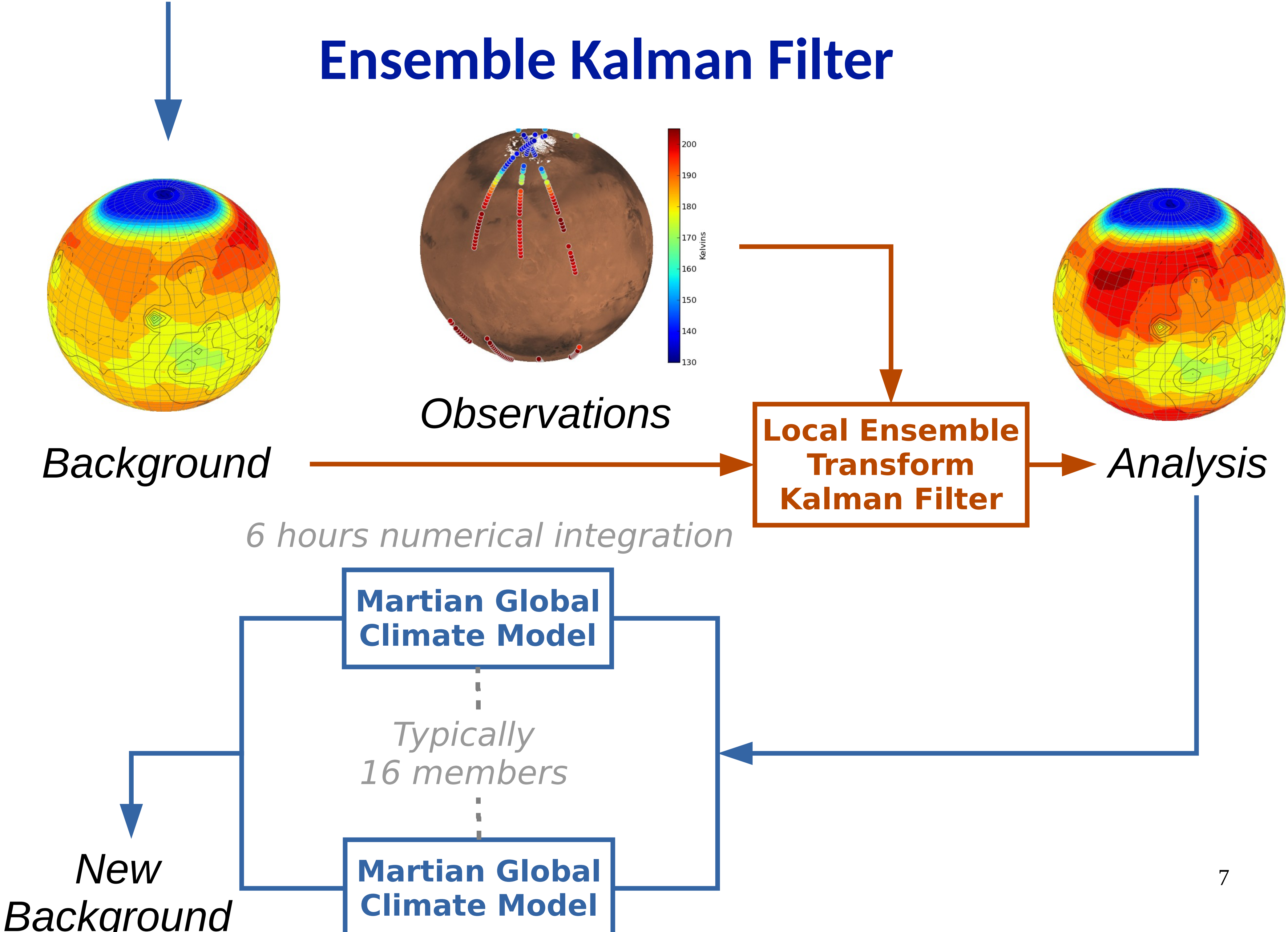


Observations

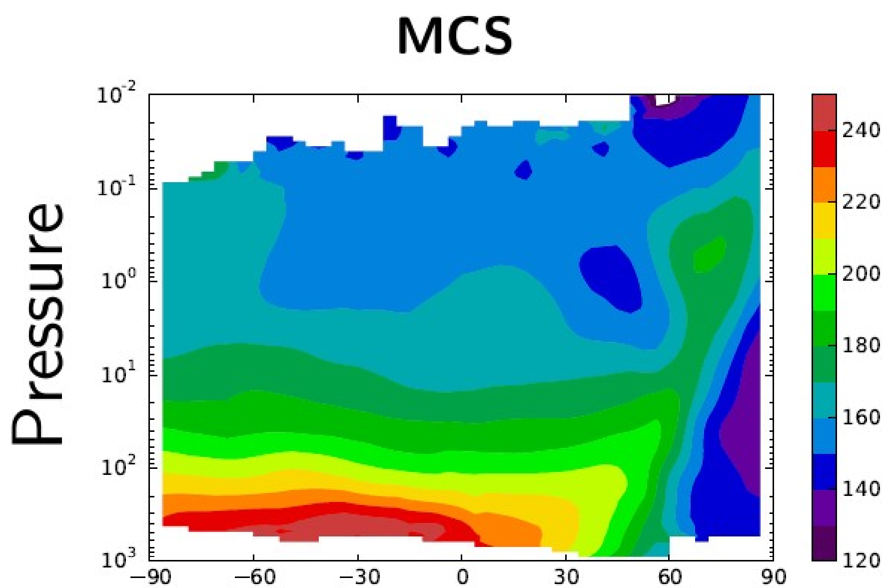
Ensemble Kalman Filter

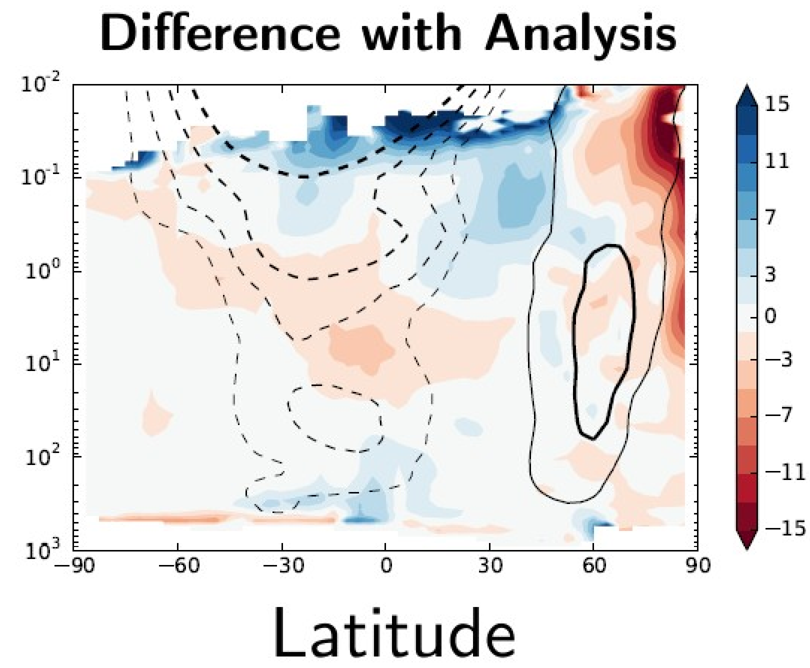


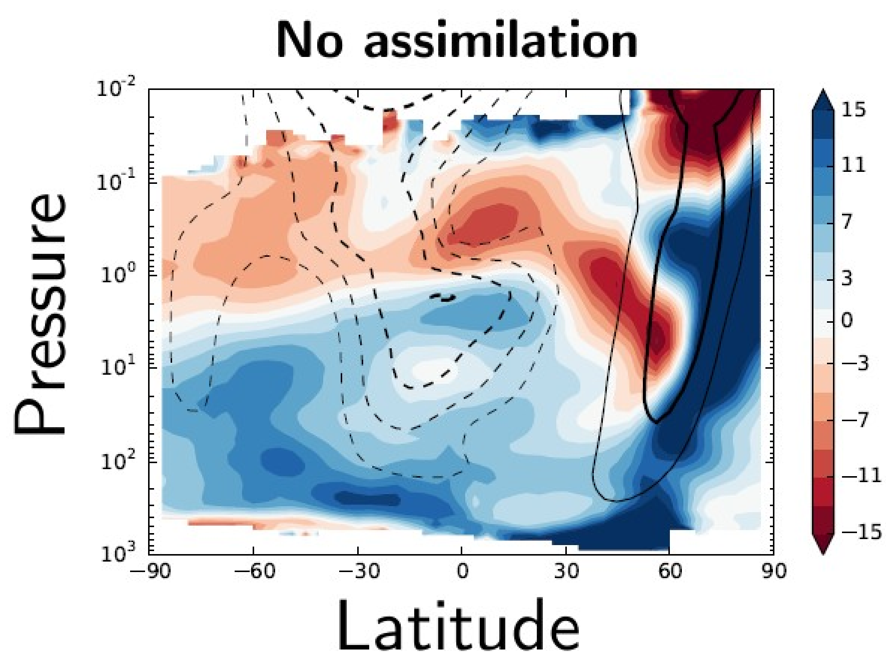
Ensemble Kalman Filter



MCS/MRO temperature assimilation

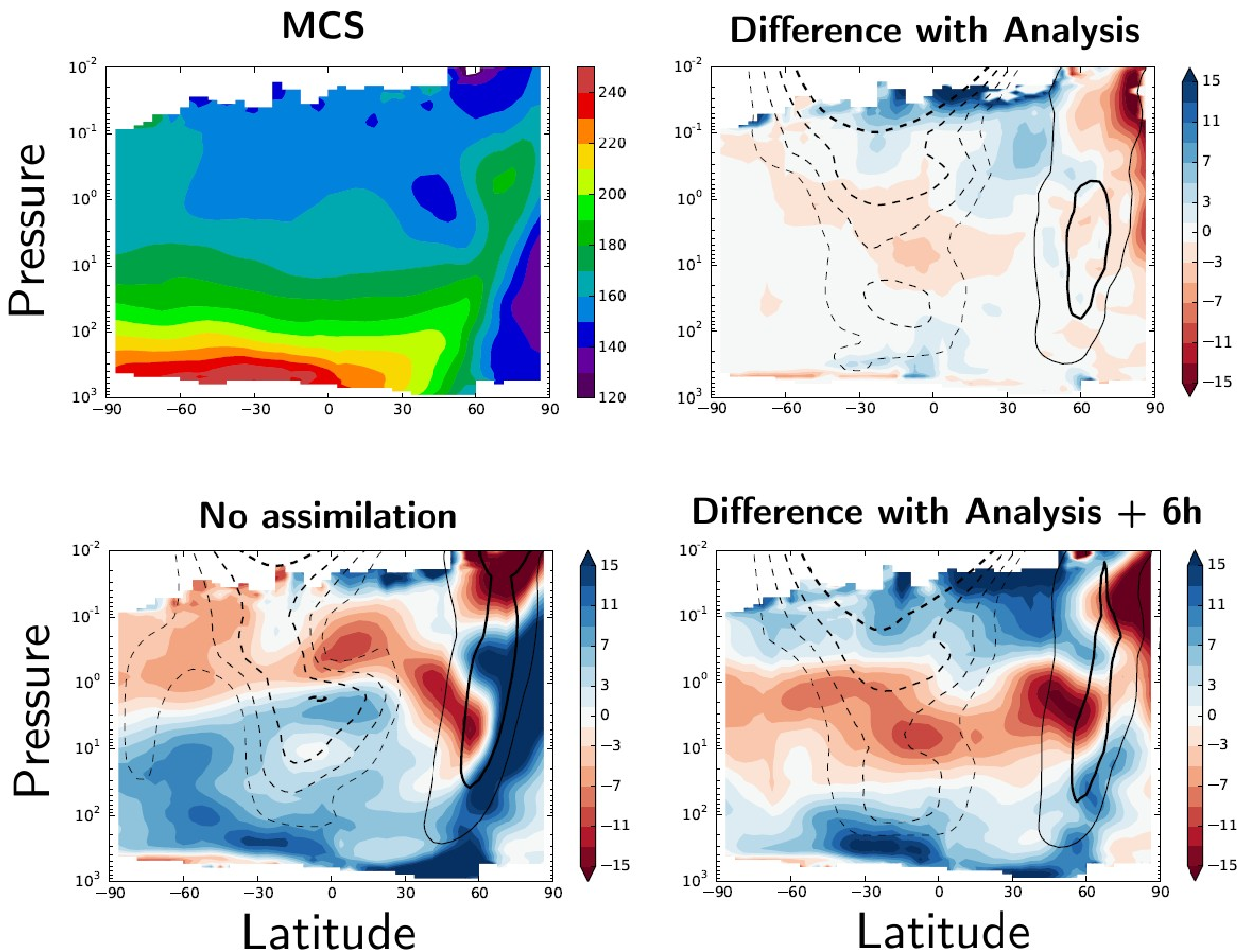






MY 29 Ls=300° - Dayside
Colors: Temperature
Contours: Zonal Wind

MCS/MRO temperature assimilation



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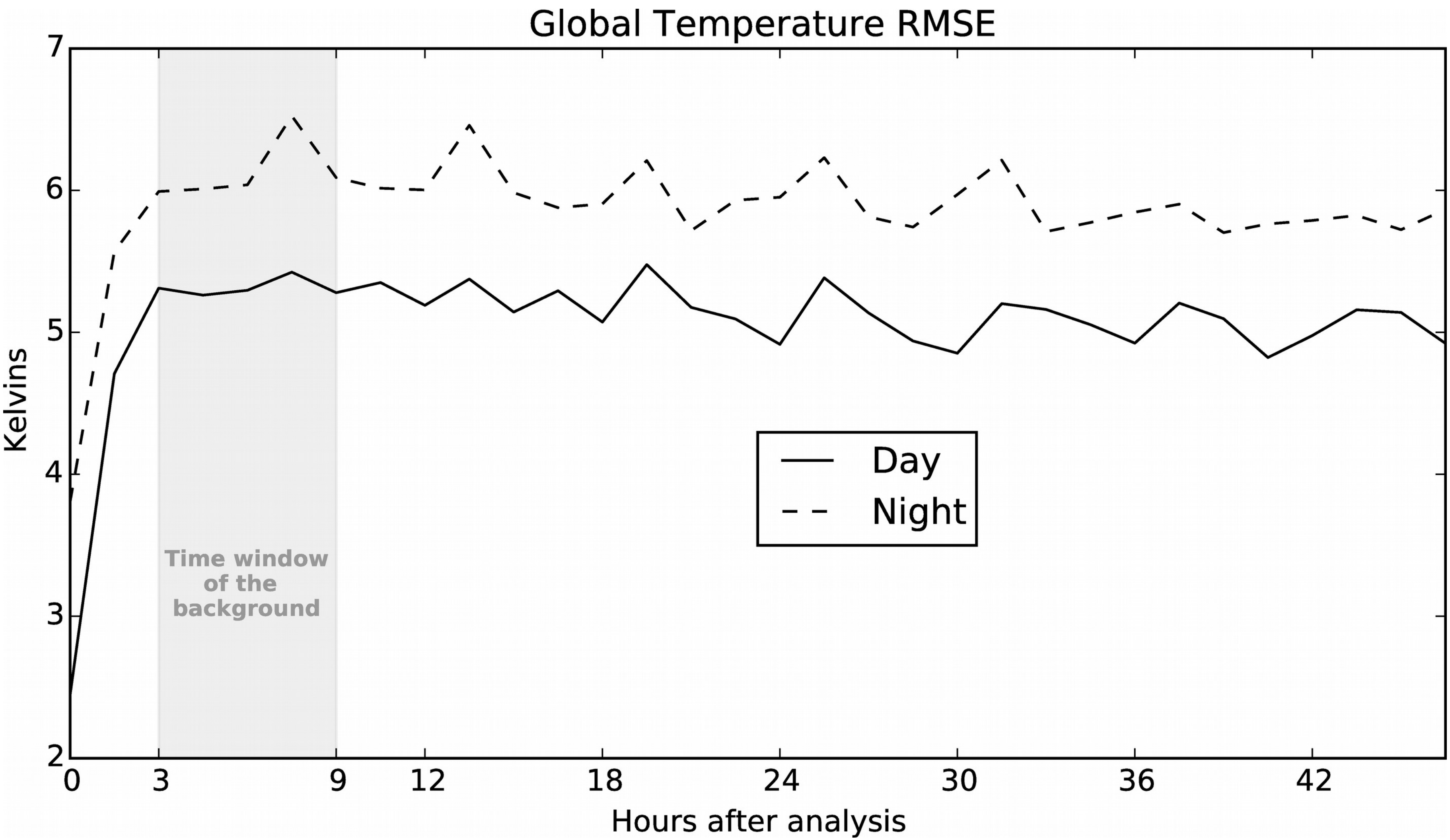

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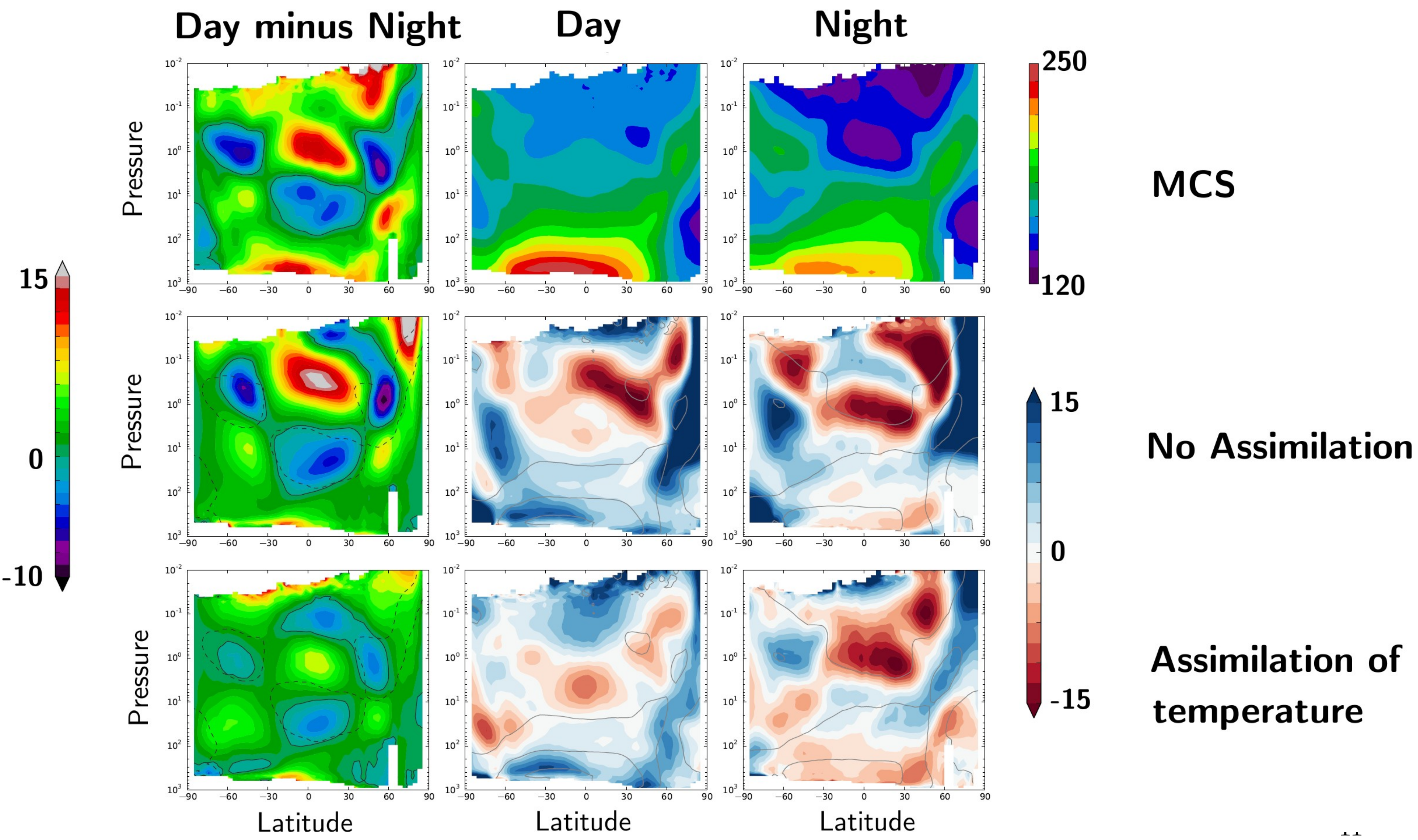

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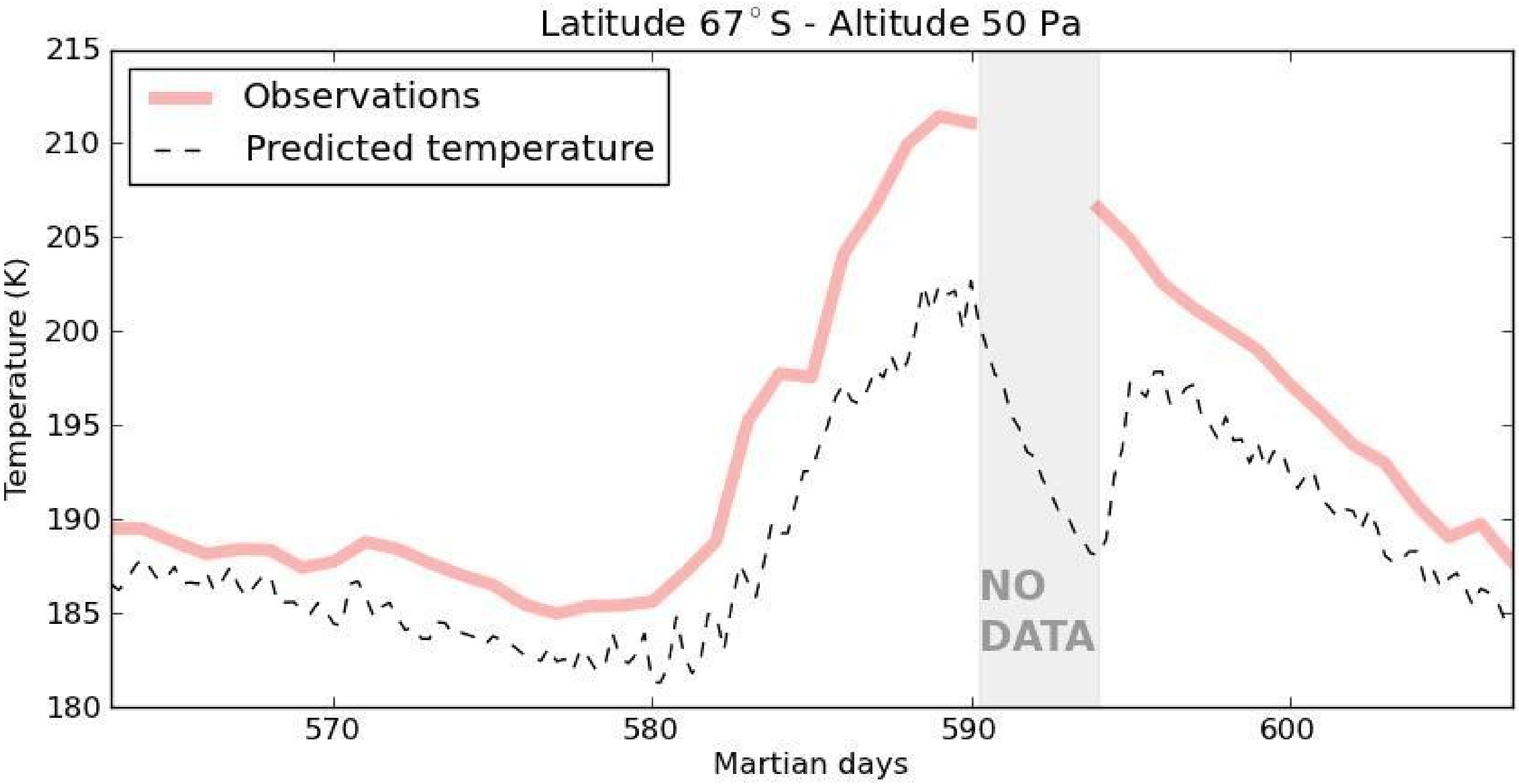
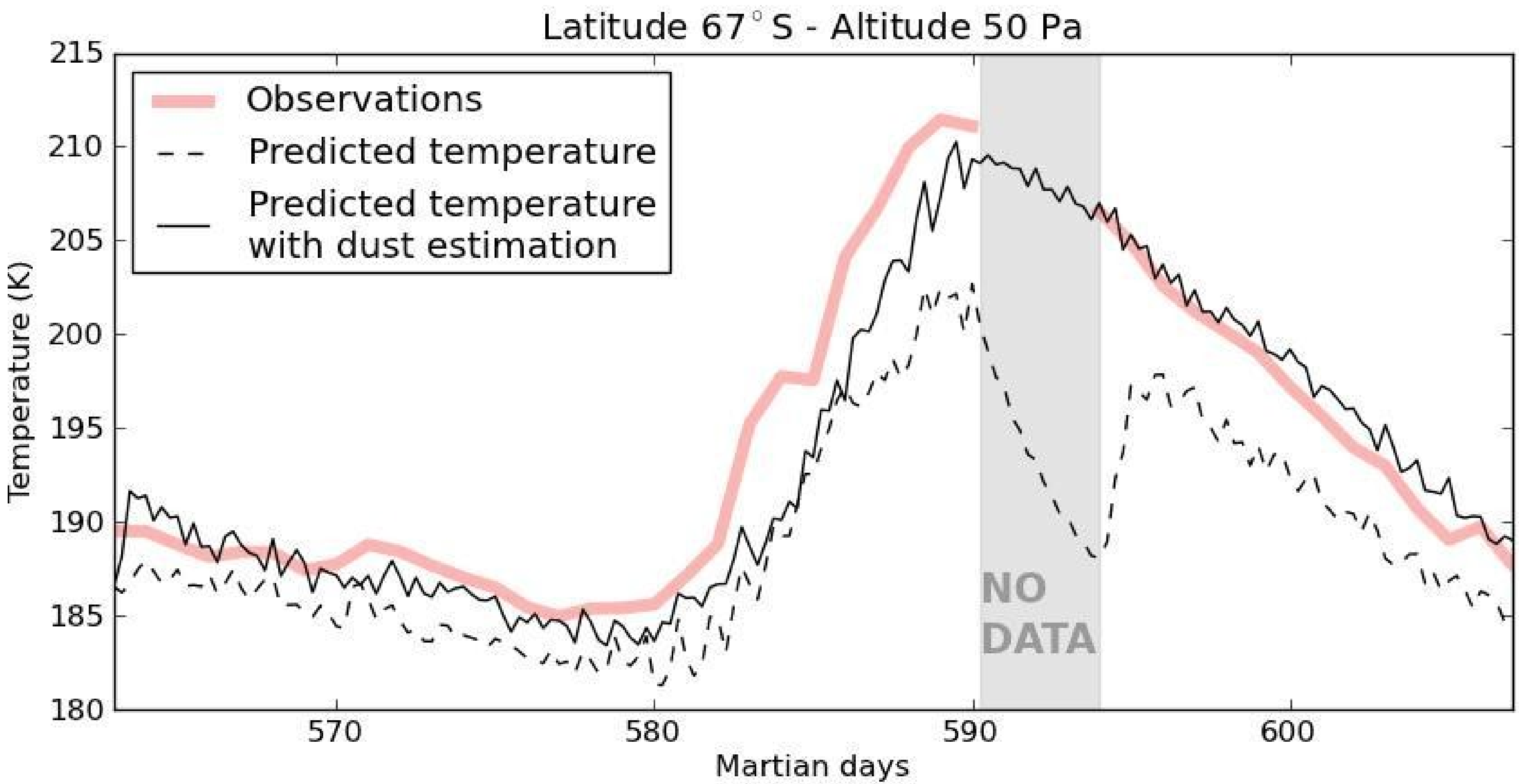


MCS/MRO temperature assimilation with estimation of dust (from ensemble correlations)



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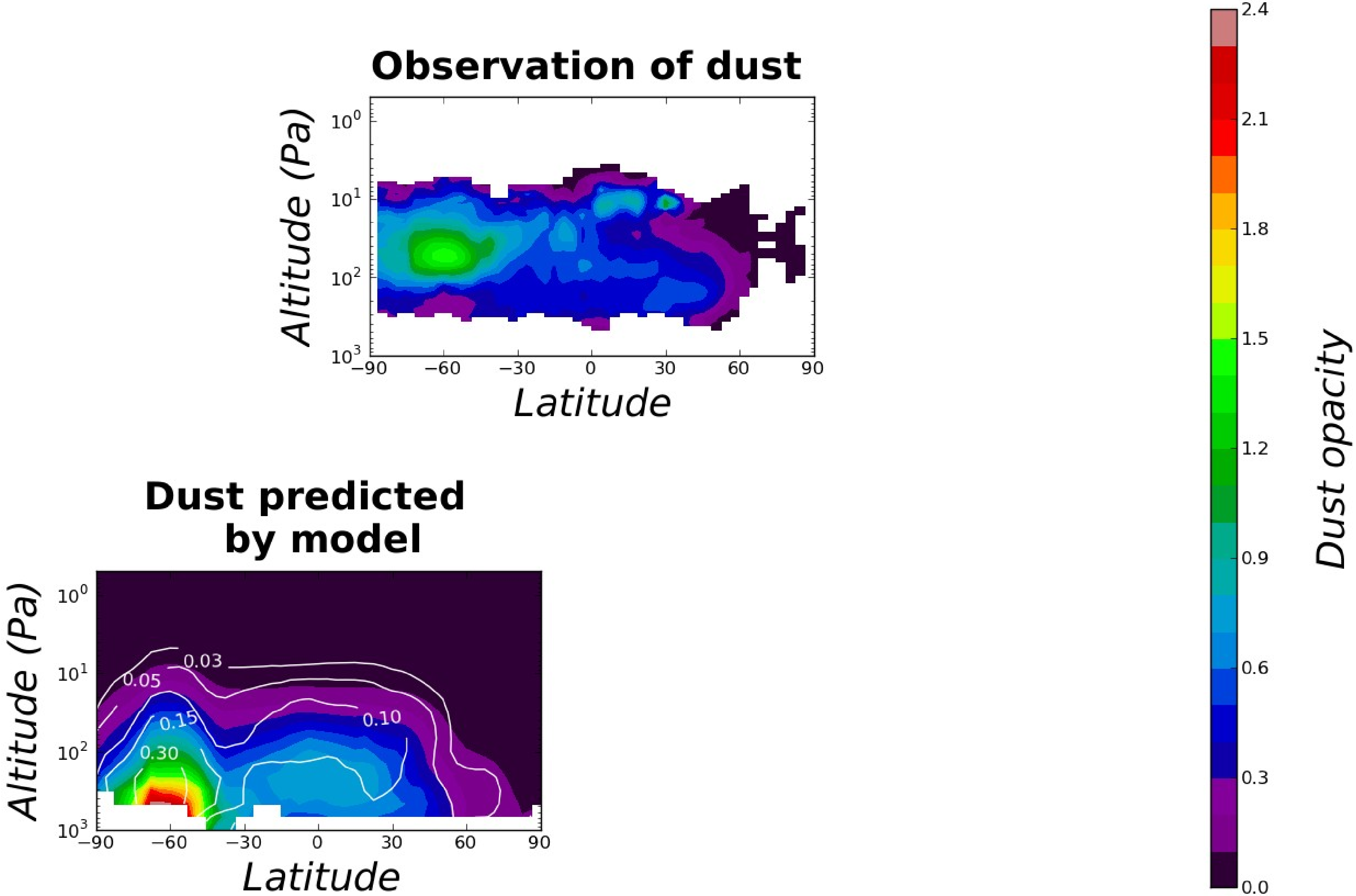
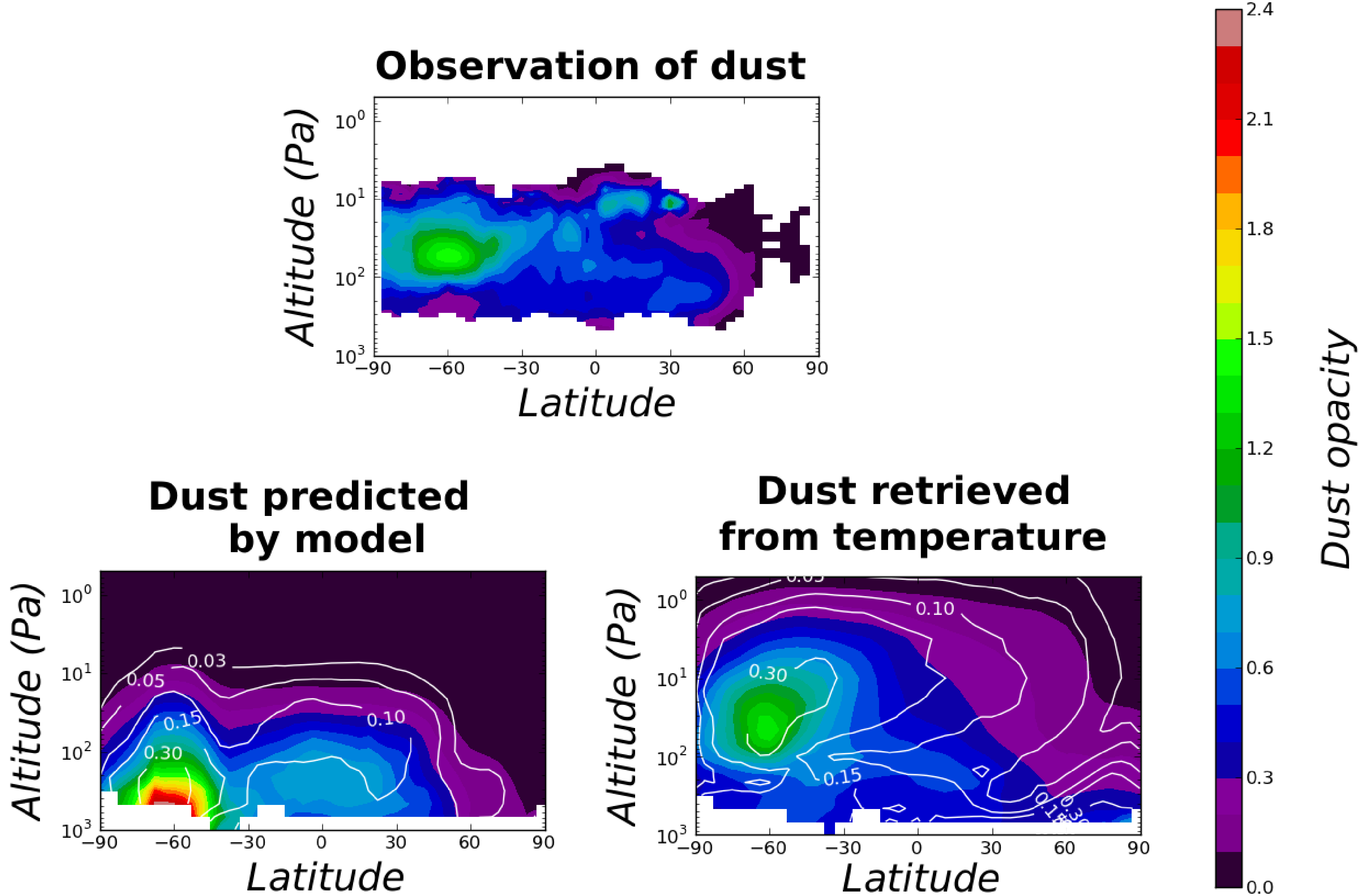


Navarro et al., 2014

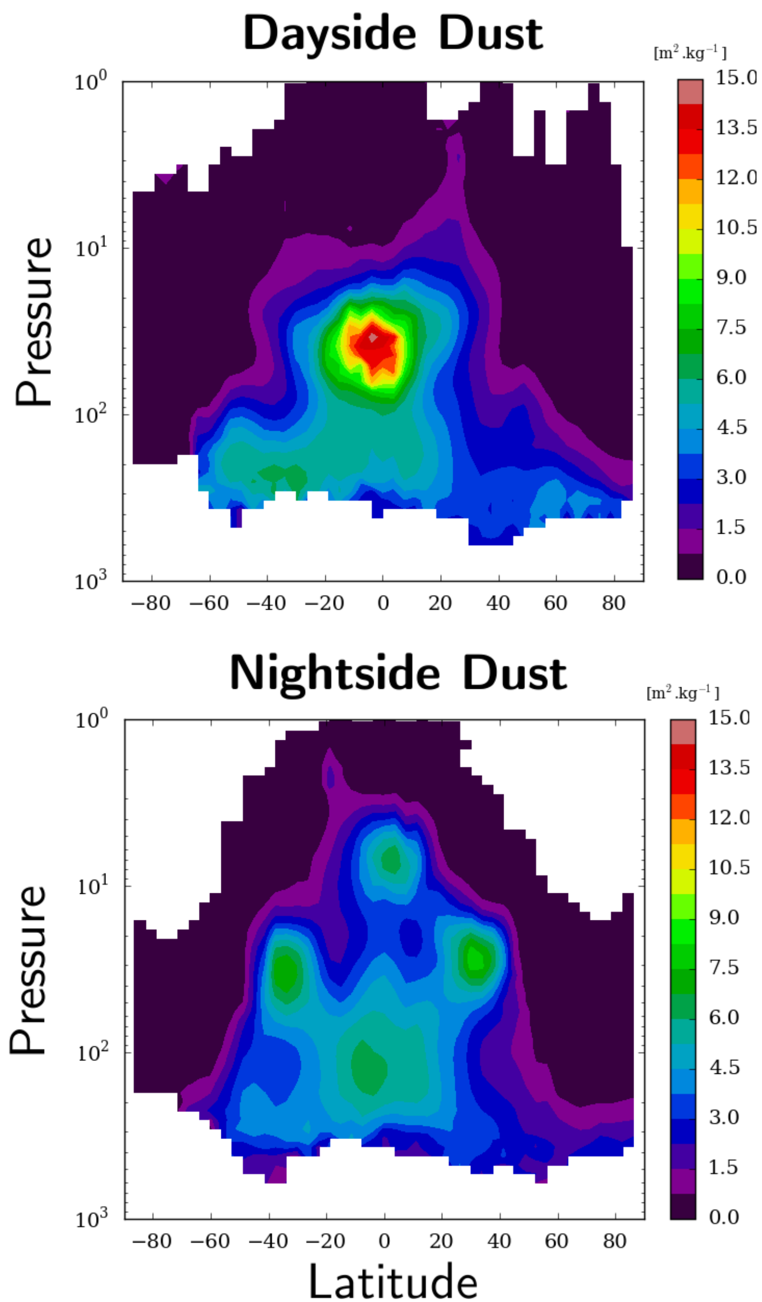
MCS/MRO temperature assimilation with estimation of dust (from ensemble correlations)



Navarro et al., 2014

Diurnal variations of dust seen by MCS are unexplained and a challenge for assimilation

Dust at Ls=150°



Strong diurnal variations of the altitude of dust between 3am and 3 pm.
(Heavens et al., 2014)

Origin unexplained.

Future efforts for assimilation

Trace Gas Orbiter

Nadir viewing instrument (Atmospheric Chemistry Suite)

High density of observations
+ Many different local times

= A call for assimilation

Assimilation of parameters

Parameters controlling the diurnal tides *(cf. Gilli's talk on Wednesday morning)* could be estimated with the assimilation of MCS temperature.

ACS observations to use

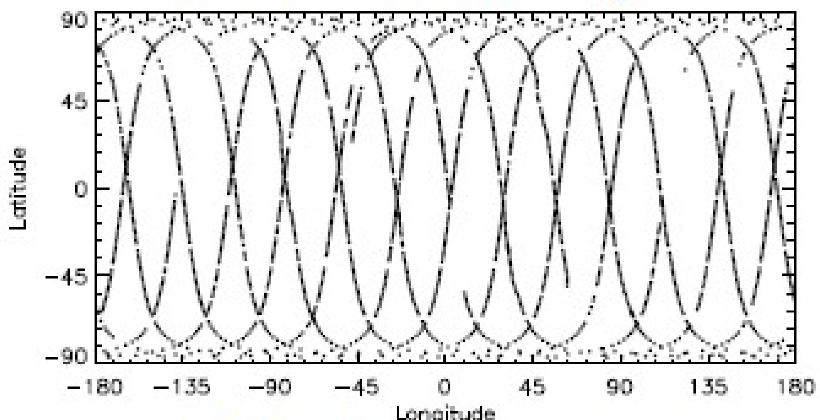
TIRVIM only. Profiles retrieved by Sandrine (?and Nikolay — for disucssion)

Initially: Atmospheric temperature profiles

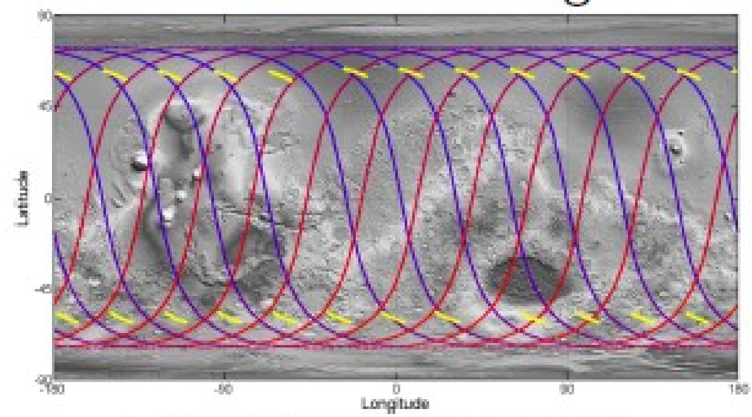
Potentially: Surface temperatures, column dust opacity, column ice opacity

Coverage vs MCS:

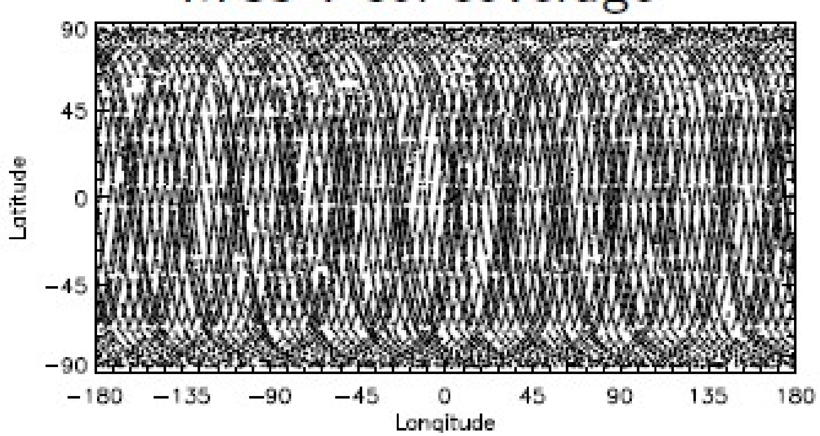
MCS 1-sol coverage



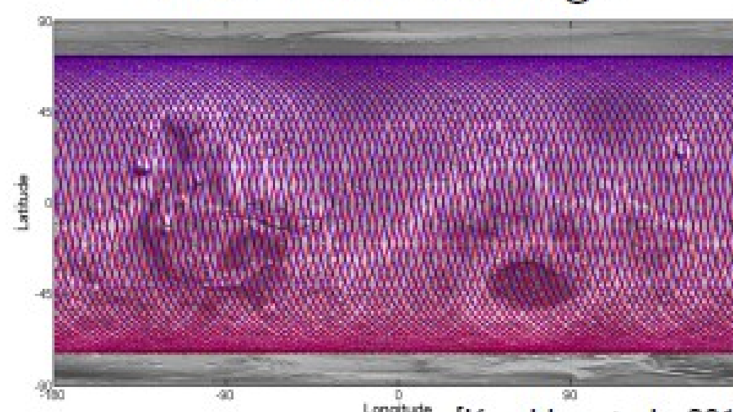
ACS 1-sol coverage



MCS 7-sol coverage



ACS 7-sol coverage



[Korablev et al., 2018]

A challenging assimilation

[…] numerical weather forecast for Mars [...] is **extremely demanding on the accuracy of the model**, despite the circulation of the Martian atmosphere being apparently somewhat **less complex and chaotic** than its terrestrial counterpart.

Rogberg et al., 2010
Assessing atmospheric predictability on Mars using numerical weather prediction and data assimilation

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