ENSEMBLE-BASED DATA ASSIMILATION WITH MAPPING DATASETS OF THE MARTIAN ATMOSPHERE

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"As it is in terrestrial atmospheric science, so it goes in planetary atmospheric science."

Gridded Climate Datasets

- great success in terrestrial atm. science
- have nearly replaced use of traditional data
- subsume data whence they came (to within the original data's uncertainty)
- the product of ***Data Assimilation***

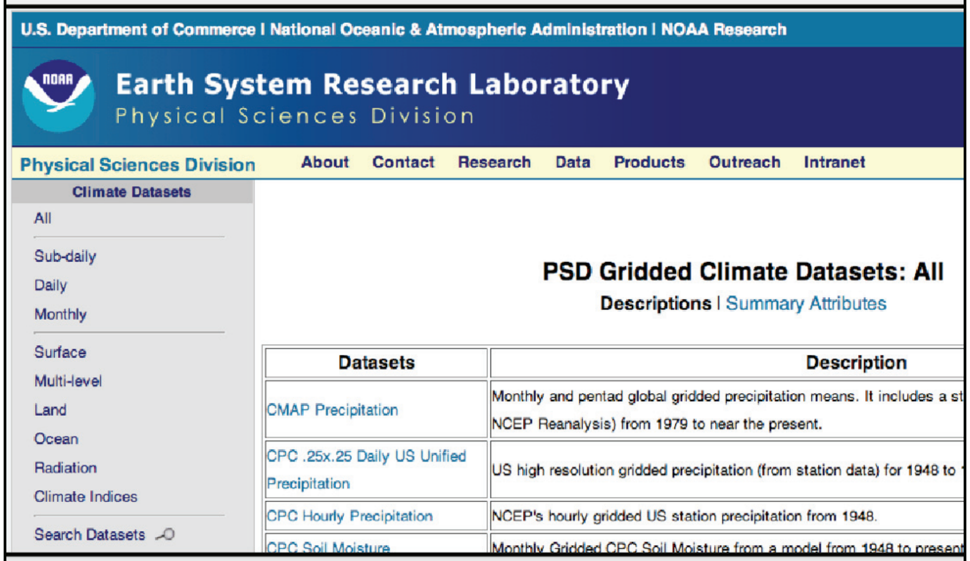
Data Assimilation is NOT just modeling arcana!

Tradition of "As it goes …" – we are leveraging their experimentation and adopting *successful* ideas.

Terrestrial data analysis often begins with downloading a GCD (even CO2 now)

DA is a COMPLETE and POWERFUL treatment of observations.

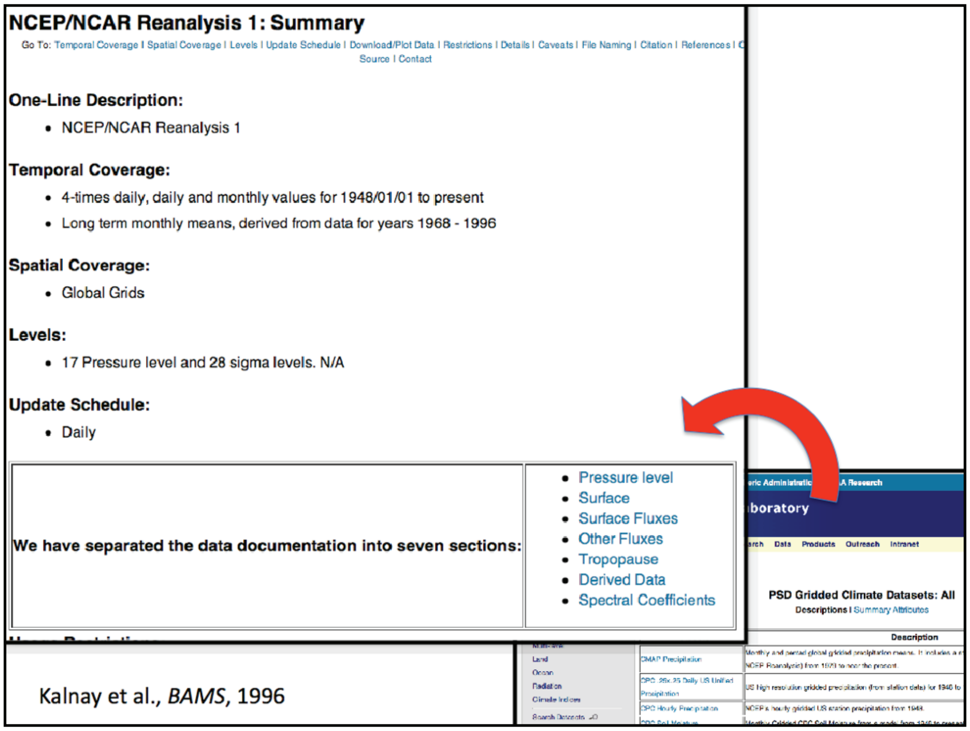
http://www.cdc.noaa.gov/PublicData/



[29 total datasets]

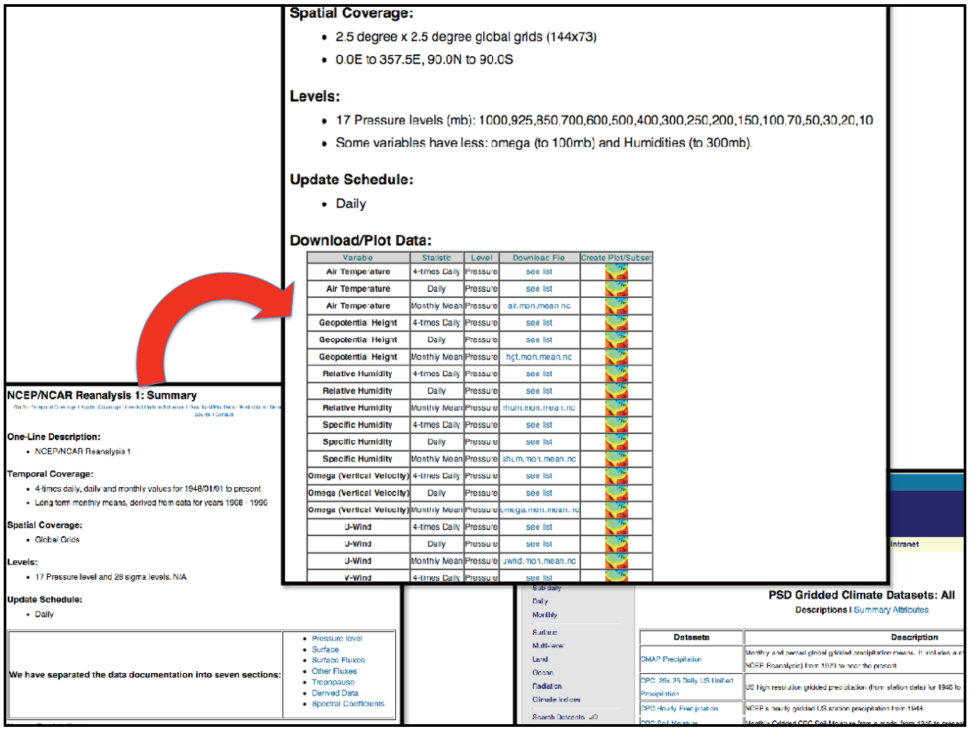
One of many different websites to find and download Gridded Climate Datasets

29 options here: Timescales go from monthly to sub-daily; Note options of dataset focus.



So-called Reanalysis is very popular

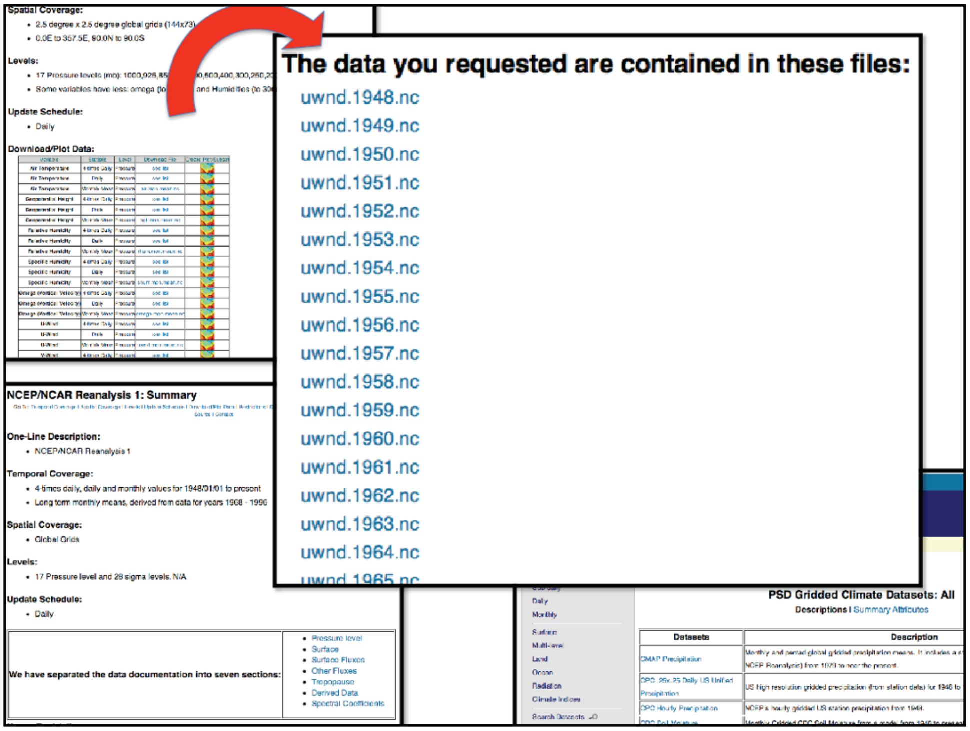
Several different options to choose from – Pressure level is very popular



Gridded analyses of T, Z, R, Q, W, U, V

Mandatory pressure levels

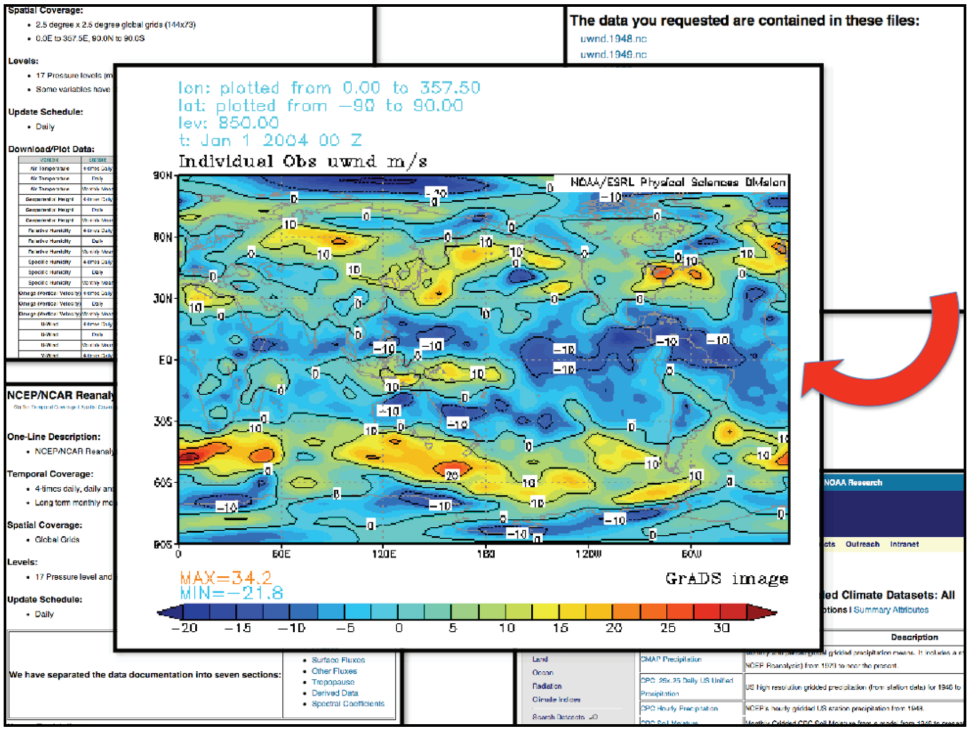
2.5 deg by 2.5 deg



4 times daily

netCDF files for each year from 1948 to present

Each file is about 500 MB



Zonal Wind (m/s) on 850 mbar level for 1 Jan 2004 with midnight on prime meridian

This is “data” – official record of U at this time in history.

Subsumes the wind obs whence this came.

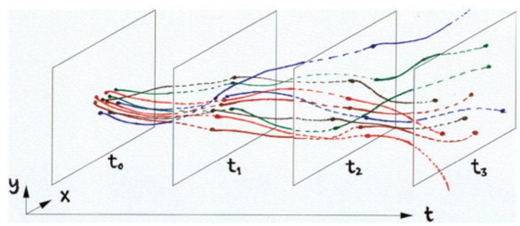
NOTE that this is very similar to the Mars Climate Database, except that instead of just being model output, this is the best estimate of what actually happened at this time on Earth!

More DA for the Mars atmosphere

*** Please see abstract ***

A little different than previous efforts:

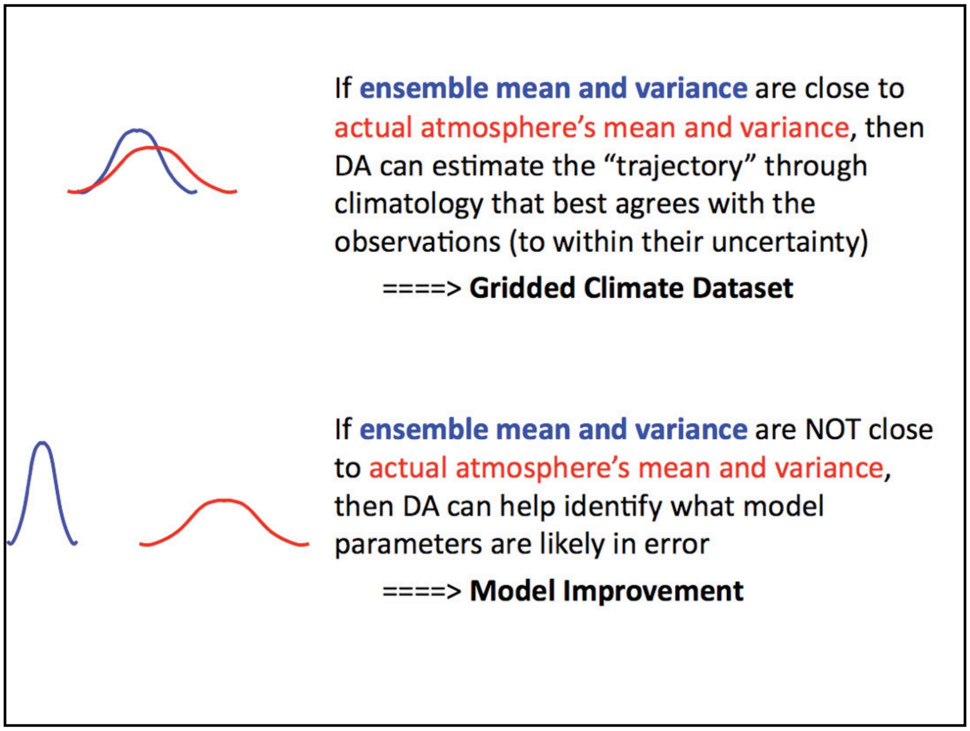
- We employ an **Ensemble** of GCM integrations -- Monte Carlo
- Ensemble approximates the real-time relationships -- covariances -- between observations and the GCM's variables
- Information is spread across space, time, and other variables according to physics encoded in covariances



Several groups have performed DA for MGS/TES nadir retrievals

PLEASE see my abstract – much more information there than I can present here in 10 minutes

Next two talks about science results from the Oxford effort.



Treating climate as PDF, DA's ability to generate Gridded Climate Dataset depends on model being skillful

If not skillful, DA can instead be used to improve model

Evidence that DA can do both simultaneously!

Some benefits of using an ensemble

1. Can easily assimilate any observations that can be ***Forward Modeled***, including Radiances:
   - this is what instruments like TES and MCS measure
   - terrestrial community found a clear benefit from assimilating radiances instead of retrievals

2. Ensemble DA automatically produces a compendium dataset of time-dependent, self-consistent error bars – ensemble spread

   … Could download U and δU

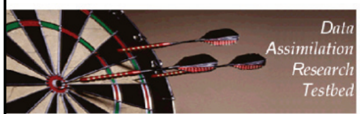
1. Retrievals inevitably have generally unknown correlated error structures

Really, DA and retrievals are one and the same -- not wise to assimilate an assimilation product

2. Treat sample standard deviation as uncertainty of state estimate

The pieces are in place (1)

*** Please see abstract ***



- **DART** is framework within which we are working
http://www.image.ucar.edu/DAReS/DART

planetWRF

- **MarsWRF** is GCM with which we are working (Richardson et al., *JGR*, 2007)
http://www.planetwrf.com

Framework is important; choice of GCM is not! Could use CAM or FMS or other.

Both DART and WRF are examples of planetary science leveraging successful ideas from terrestrial atmospheric science

Ensemble DA is explicitly modular

DART already includes hooks for the Earth versions of CAM and FMS

The pieces are in place (2)

*** Please see abstract ***

- We have received **TES nadir Forward Operator** from TES team (big thanks to M. Smith, M. Kaelberer, and B. Conrath)
- TES Forward Operator is now "DART compliant"

- We have received **MCS limb Forward Operator** from MCS team (big thanks to A. Kleinböhl, T. Schofield, D. Kass, W. Abdou, and D. McCleese)
- Still have work to do with MCS Forward Operator

Can add Forward Operators for other mapping datasets!

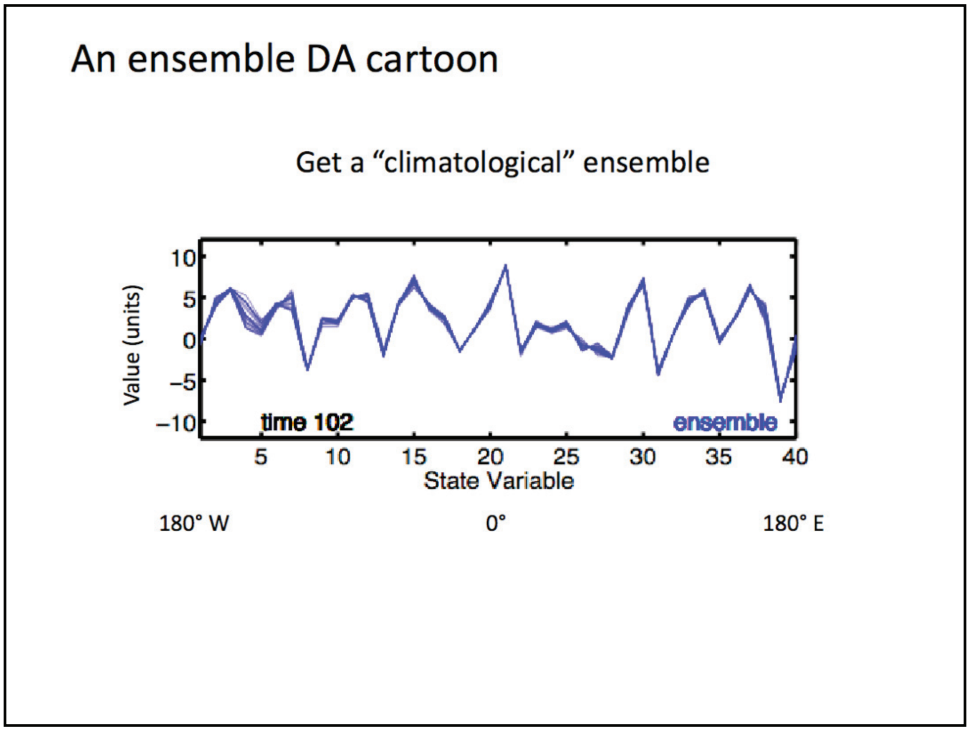
A demonstration of ensemble DA

1. A "Cartoon" of ensemble DA – pseudo-meteorological variable

2. Some glimpses of a DA experiment using MarsWRF and synthetic remote sensing observations from a TES nadir-like instrument in an MGS-like orbit

Necessary, but not sufficient, test to pass

Before delving into a Large, 3D, Multivariate example, we first consider a cartoon of how this works



Here we see output from an ensemble of model states for a pseudo-meteorological variable that will evolve under some specified dynamics.

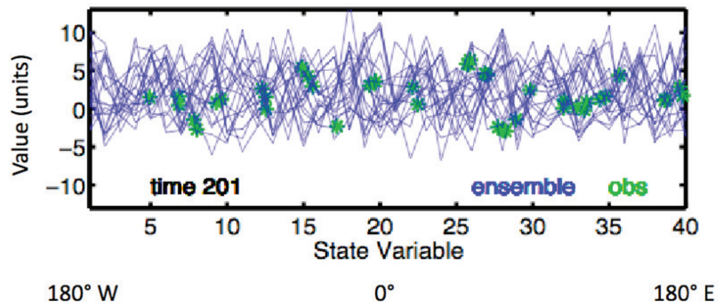
DON’T WORRY ABOUT DETAILS!!

Note periodic BCs and state is mainly comprised of waves

Here we allow our ensemble members to freely evolve into a climatological ensemble

An ensemble DA cartoon

Collapse ensemble to estimate of “truth”

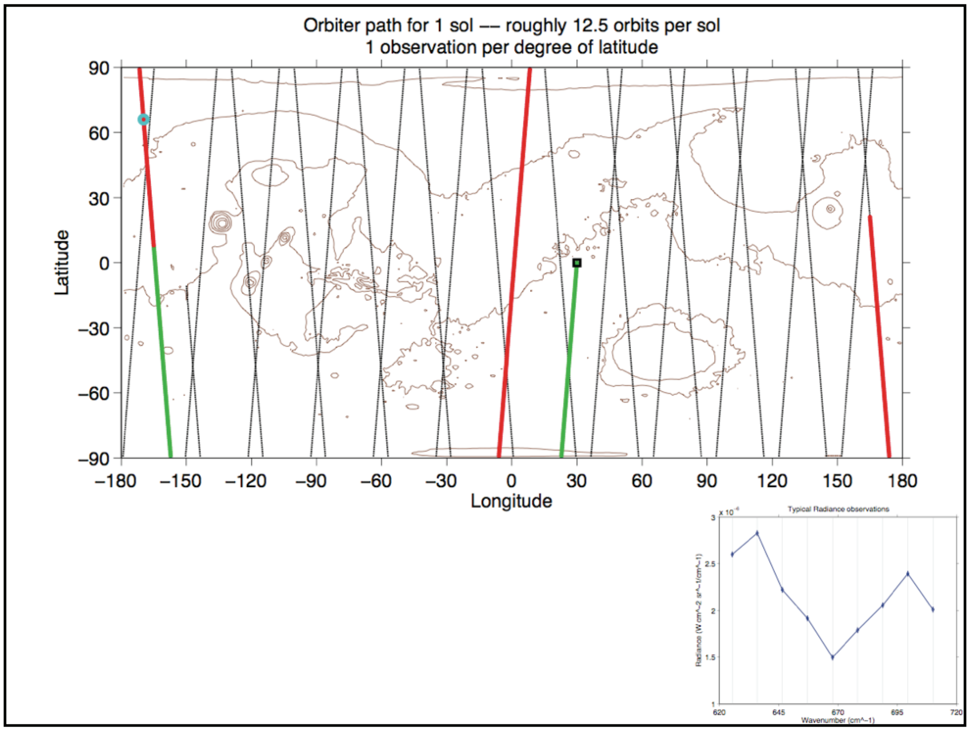


Now ensemble DA will collapse the climo ensemble to an estimate of Truth – only knowledge of truth is from observations (green *s)

Truth evolves under same dynamics as ensemble members, so model and truth have same mean and variance

Gridded Climate Dataset is time sequence of ensemble mean;
Self-Consistent Error Bars is time sequence of ensemble spread;

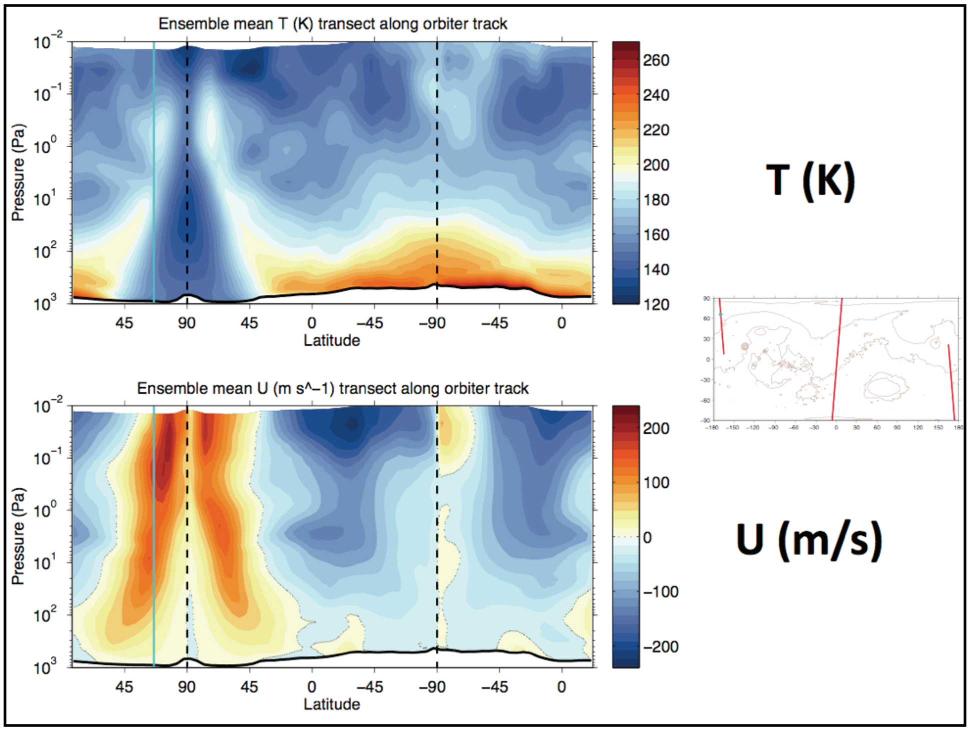
Note state estimate is more certain than observations are -- Consider usefulness of Gridded Climate Dataset vs. record of values of green *’s



For our MarsGCM DA experiment: MGS-like orbit (~12.5 orbits per sol)

Green segment goes over South Pole;
Red segment defines a transect of observations from about 1 complete orbit – I will be showing model output along this transect;
Cyan circle shows location whence I'll be showing individual vertical profiles

Observations are TES nadir-like – synthetic radiances over the 9 central wavenumbers of the 15 micron feature (low-res scan);
These 9 are the main observations used for T(p) retrievals.

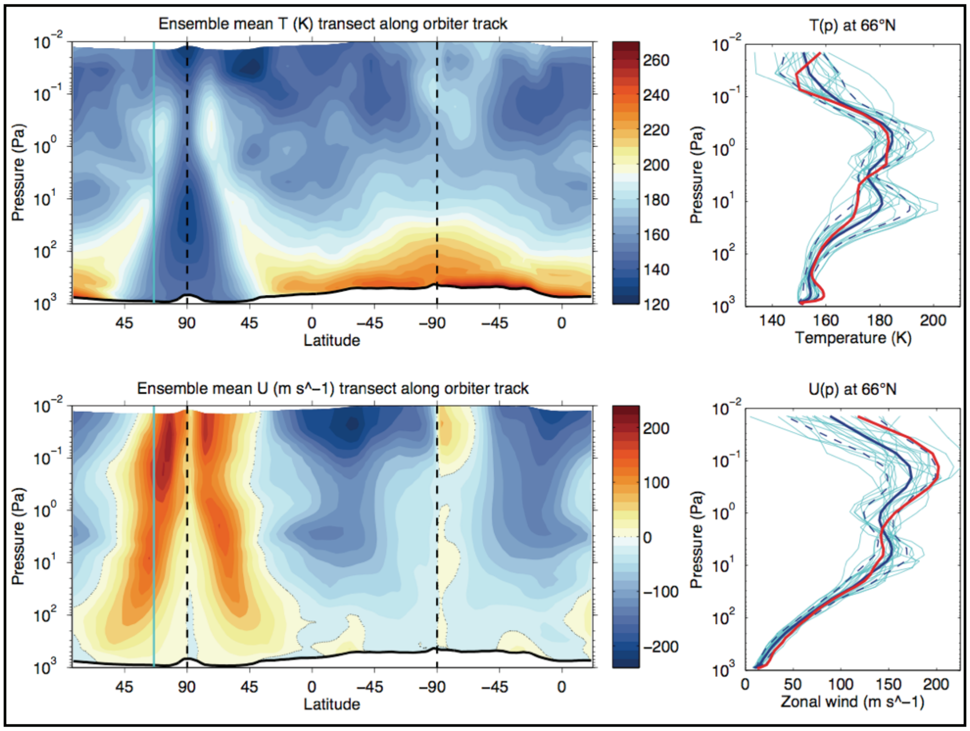


L_sub_s ~ 260; around sol 500 of Mars year;
specified Dust;
No H2O cycle or clouds
5 deg by 5 deg, 40 levels

Here is the ensemble mean along the red transect in the previous image: Latitude vs. Pressure (about 90 km)

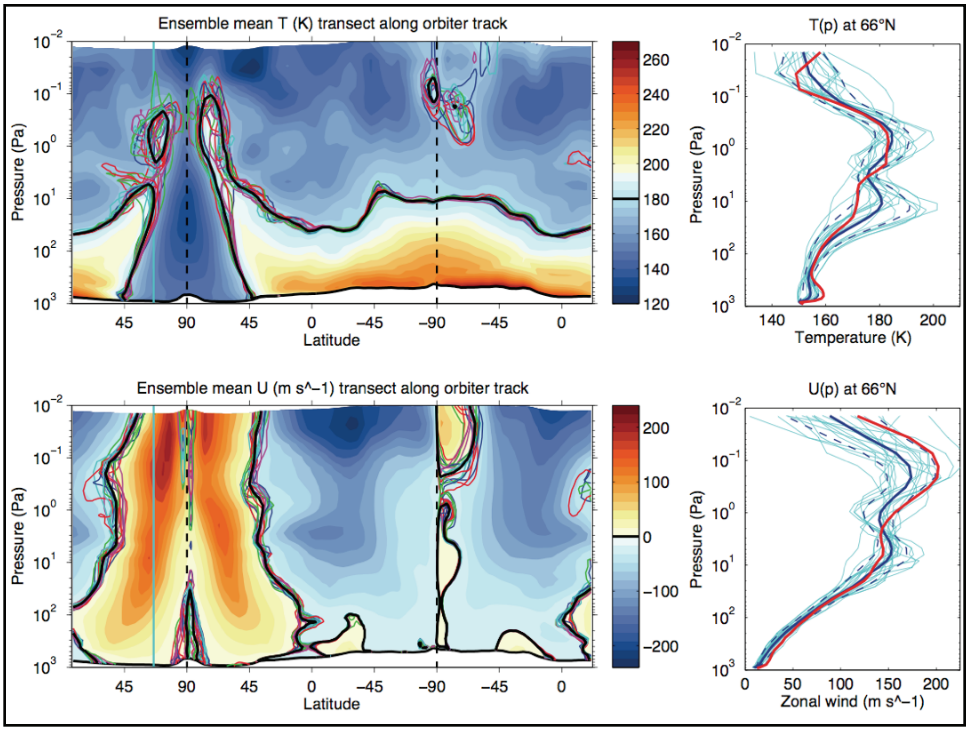
Ascending over the NP, Descending over the Equator and SP, and Ascending over the Equator

Note the northern Polar Vortex with temperatures high aloft and a strong jet stream



In effort to visualize climo spread, here are 20 individual T(p) and U(p) profiles at the cyan line

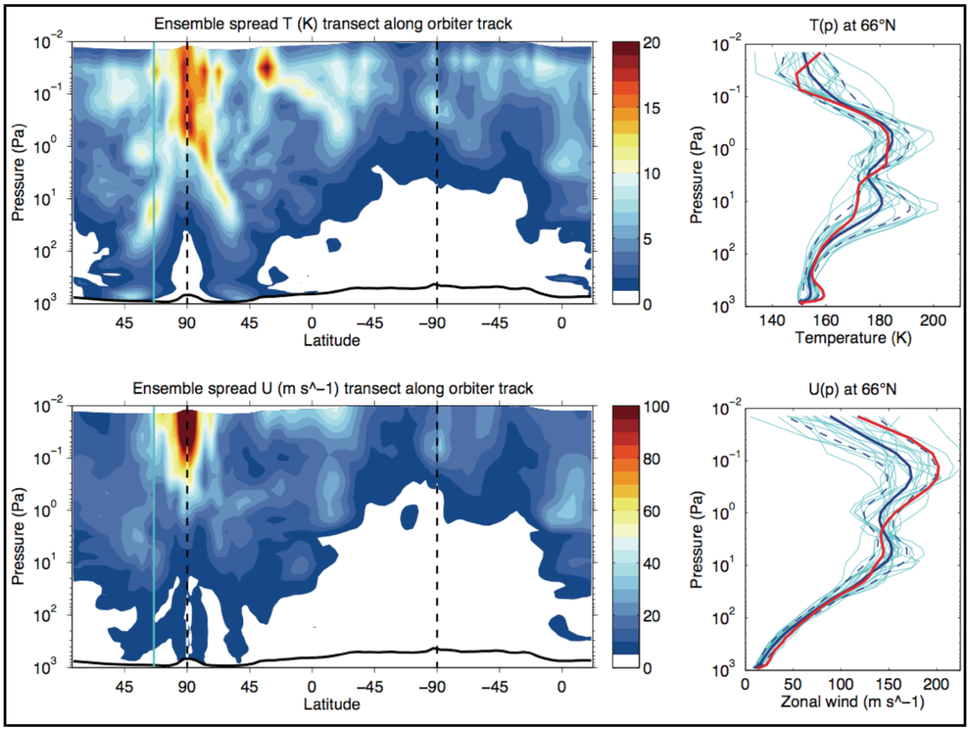
Cyan lines show members, Blue line show ensemble mean, Blue dashed lines show +/- 1-sigma ensemble spread, and Red line shows Truth



Another way to visualize climo spread – so-called Spaghetti Diagrams

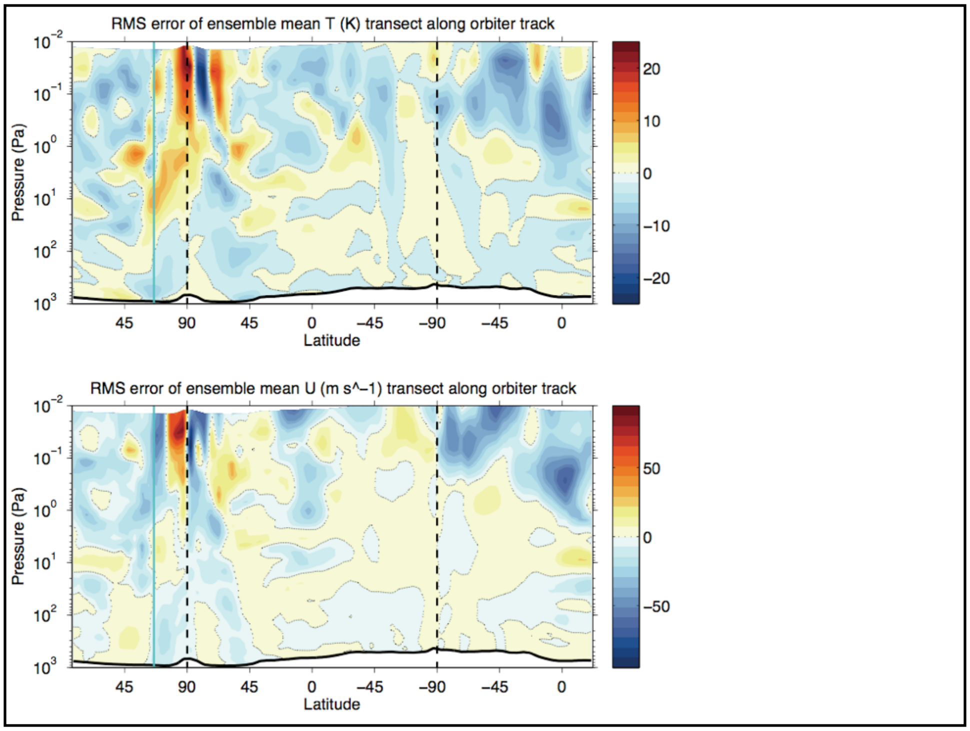
Ensemble mean 180 K contour is in thick black; all ensemble members' 180 K contour also plotted

Same with U 0 m/s contour



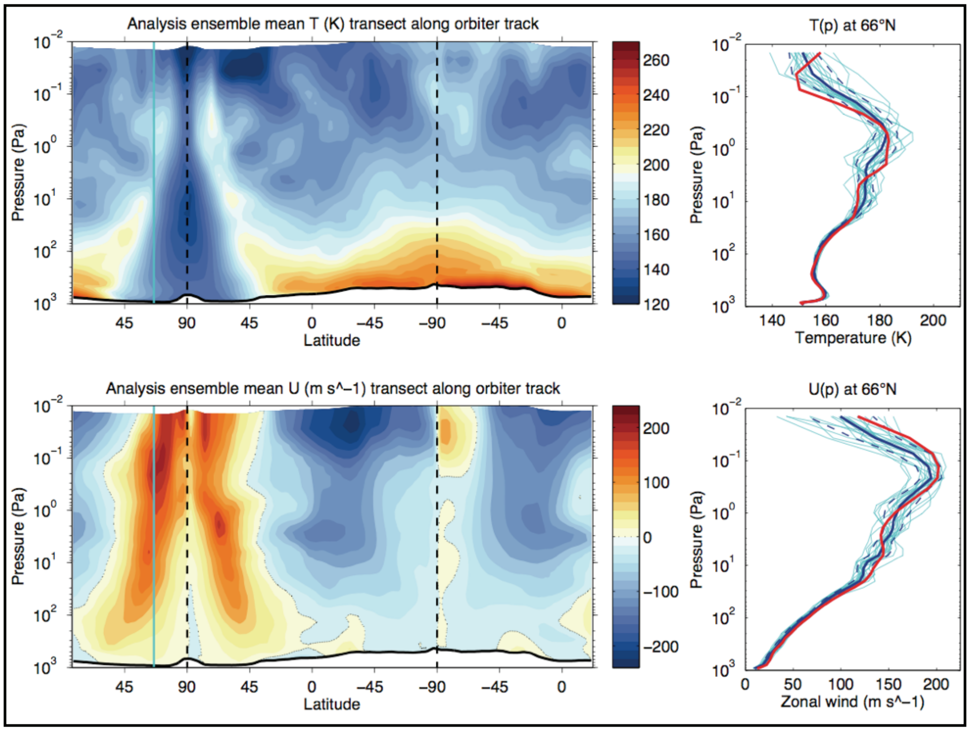
Yet another way to visualize climo spread – ensemble spread at all locations.

Greater than zero everywhere, but lowest values are plotted white: ensemble seems very certain of the S.H. lower atmosphere temperatures and that the air is condensing CO2 over the winter pole.



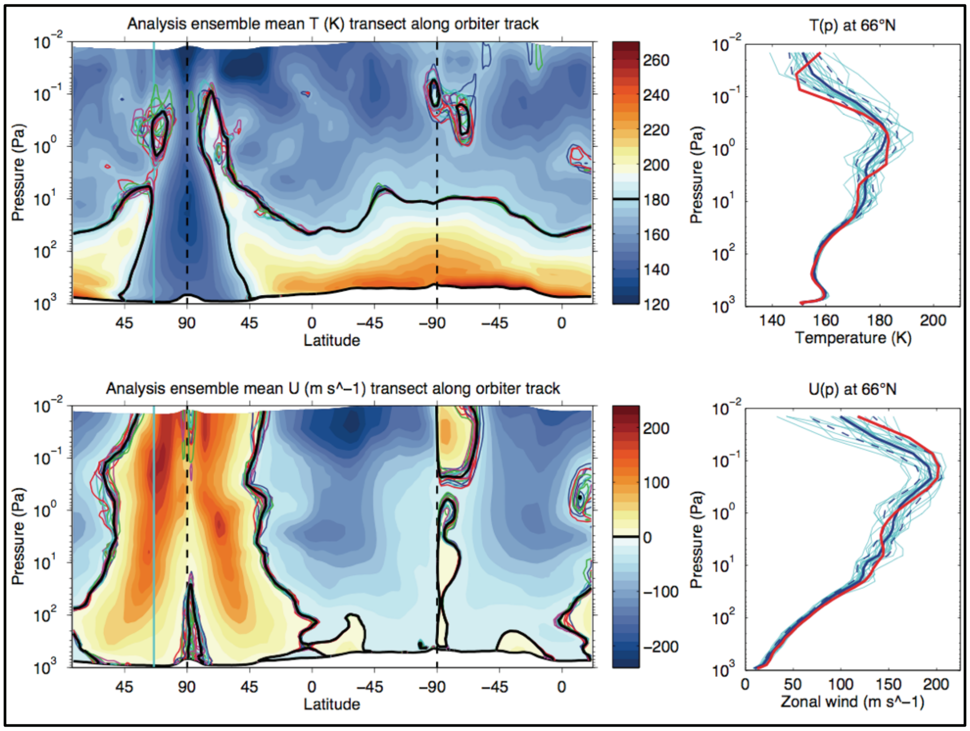
Since we have Truth available, we can actually find the RMS error value of the climo mean

Consistent with mispositioned polar vortex

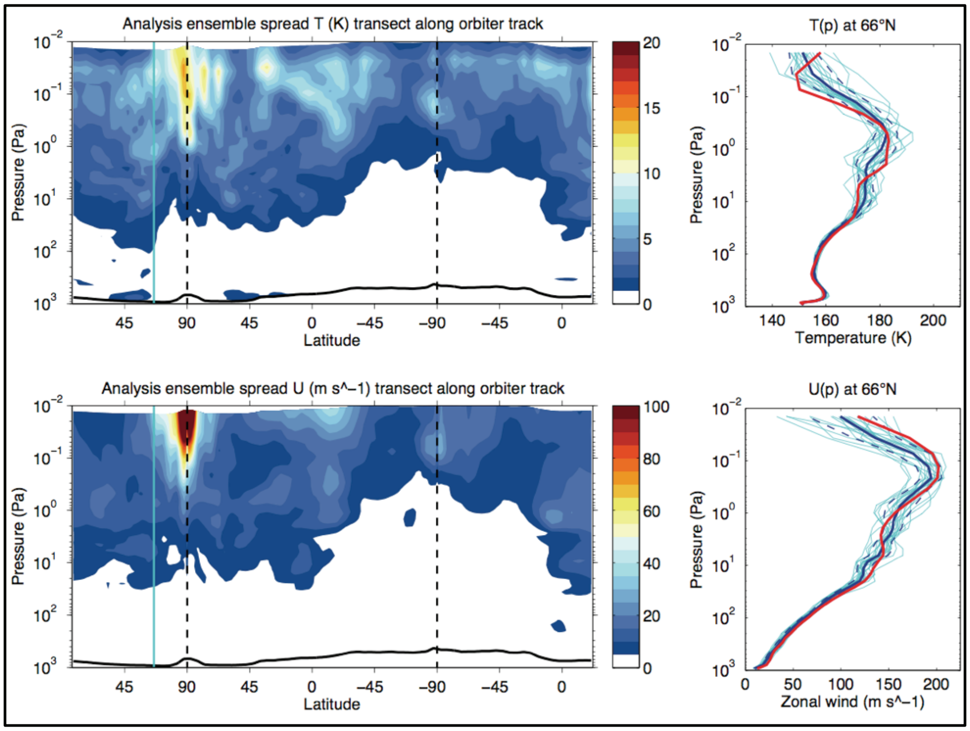


After we do the assimilation, all the ensemble members have been changed, hence so have the ensemble mean and spread.

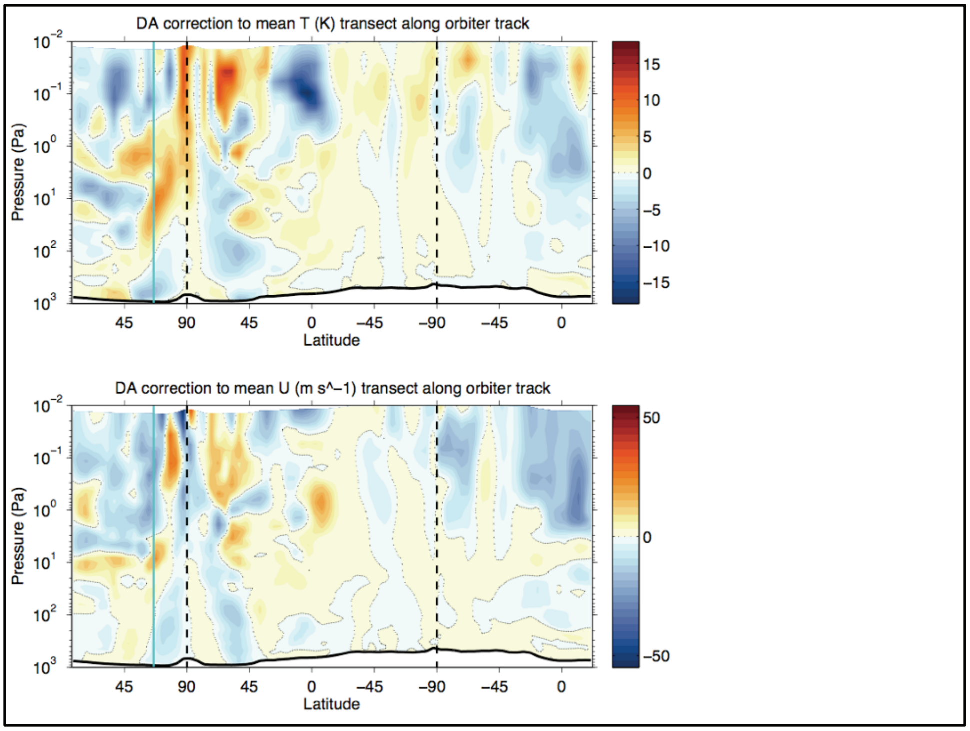
Much tighter spread in lower atmosphere, but also tightened aloft



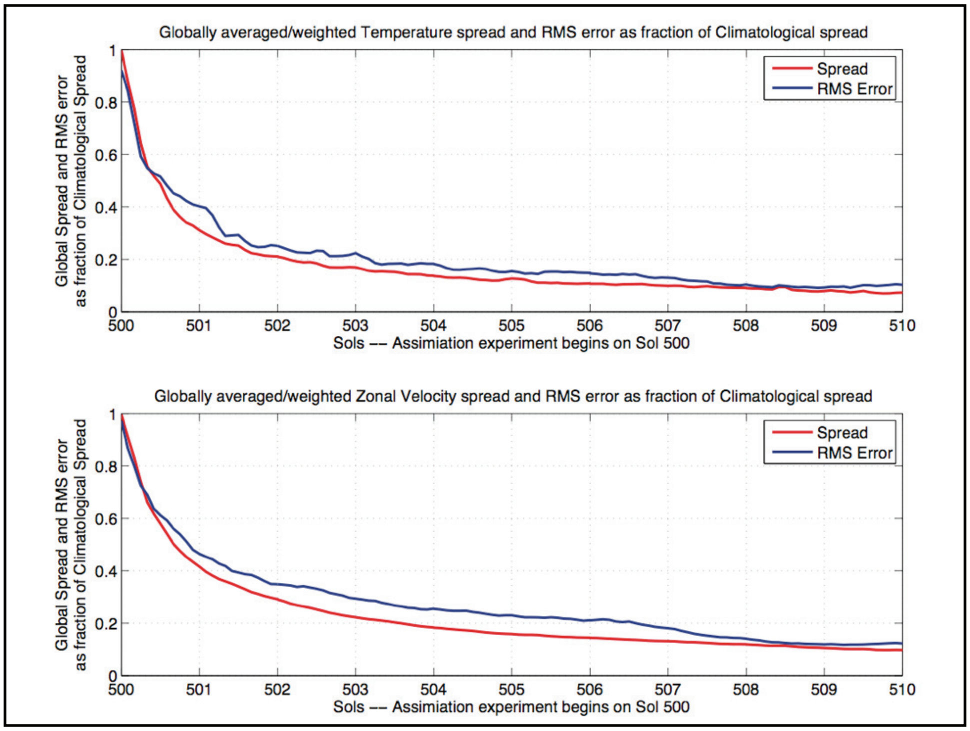
Analysis ensemble mean T (K) transect along orbiter track
Pressure (Pa)
Latitude
T(p) at 66°N
Temperature (K)
Analysis ensemble mean U (m s^−1) transect along orbiter track
U(p) at 66°N
Zonal wind (m s^−1)



Analysis ensemble spread T (K) transect along orbiter track
Pressure (Pa)
Latitude
T(p) at 66°N
Temperature (K)
Analysis ensemble spread U (m s^−1) transect along orbiter track
U(p) at 66°N
Zonal wind (m s^−1)



DA correction to mean T (K) transect along orbiter track
Pressure (Pa)
Latitude
DA correction to mean U (m s^−1) transect along orbiter track
Pressure (Pa)
Latitude



Defining a globally averaged value for the ensemble spread and for the RMS error of the ensemble mean compared to truth, we can watch a 10-sol time series of our ensemble estimate converge toward truth as we continue to assimilate TES-like observations.

Normalized as fraction of climo spread.

It's working! And it is correcting both temperature and zonal wind – other variables too!

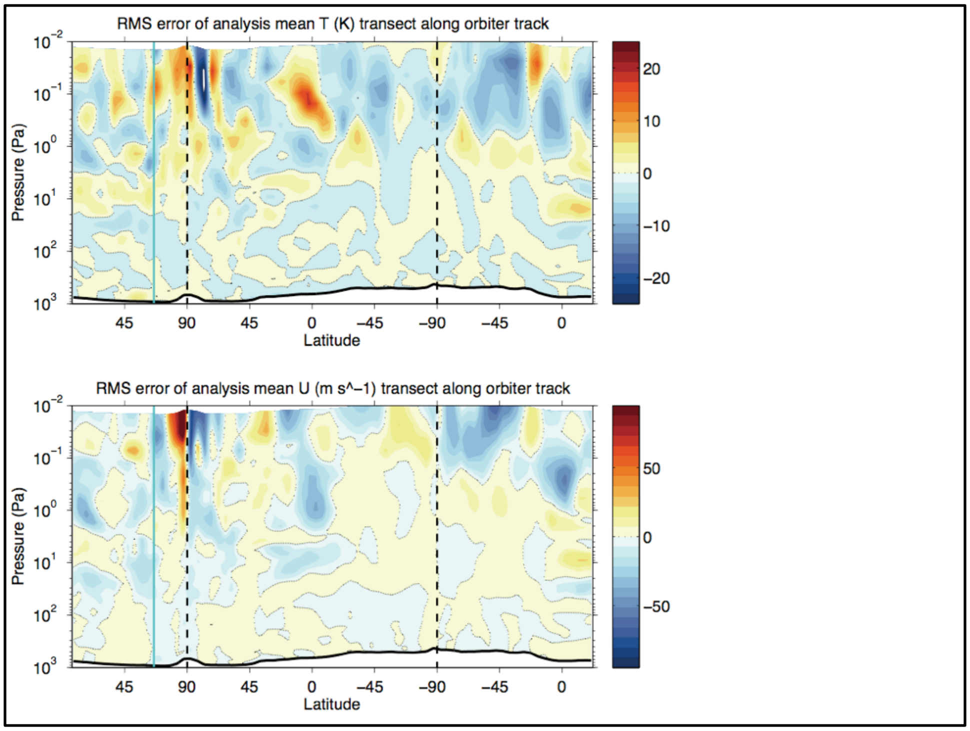
Last slide

*** Please see abstract ***

- We are getting close to using actual data
- Need to explore more synthetic observation experiments with radiatively active dust and a water cycle in the model

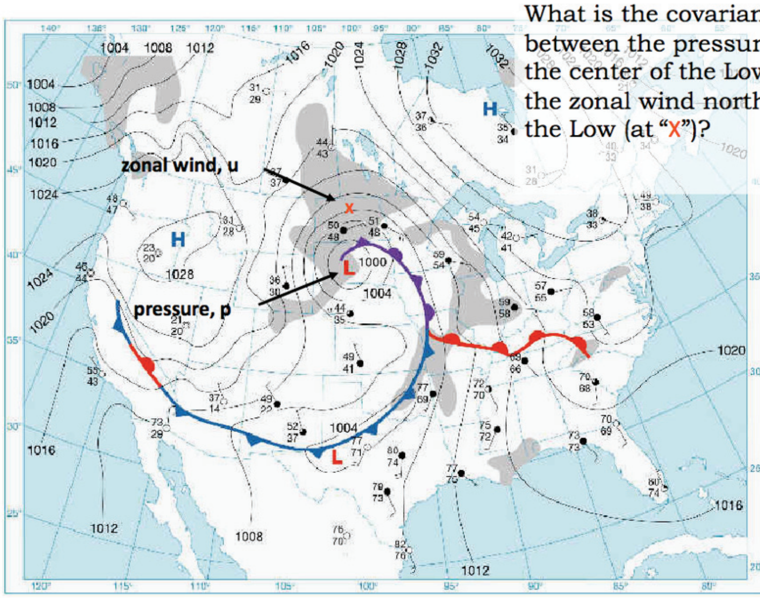
Again, big thanks to many who are helping us:

- **DART** :: J. Anderson, N. Collins, and T. Hoar
- **MarsWRF** :: A. Toigo, C. Newman, and C. Lee
- **TES** :: M. Smith, M. Kaelberer, B. Conrath, and J. Bandfield
- **MCS** :: A. Kleinböhl, T. Schofield, D. Kass, W. Abdou, D. McCleese, and N. Heavens



RMS error of analysis mean T (K) transect along orbiter track
Pressure (Pa)
Latitude
RMS error of analysis mean U (m s^−1) transect along orbiter track
Pressure (Pa)
Latitude

Dynamics imparts covariance



What is the covariance between the pressure at the center of the Low and the zonal wind north of the Low (at "X")?

Image from CUNY

Geostrophic balance

$$u_{\text{north}} \approx -\frac{1}{\rho f}\frac{\left(p_{\text{north}} - p_{\text{center}}\right)}{\Delta y}$$

$$u_{\text{north}} + \varepsilon_{\text{u}} \approx -\frac{1}{\rho f}\frac{\left(p_{\text{north}} - \left(p_{\text{center}} + \varepsilon_{\text{p}}\right)\right)}{\Delta y}$$

$$\boxed{\varepsilon_{\text{u}} = +\frac{1}{\rho f \Delta y}\varepsilon_{\text{p}}}$$

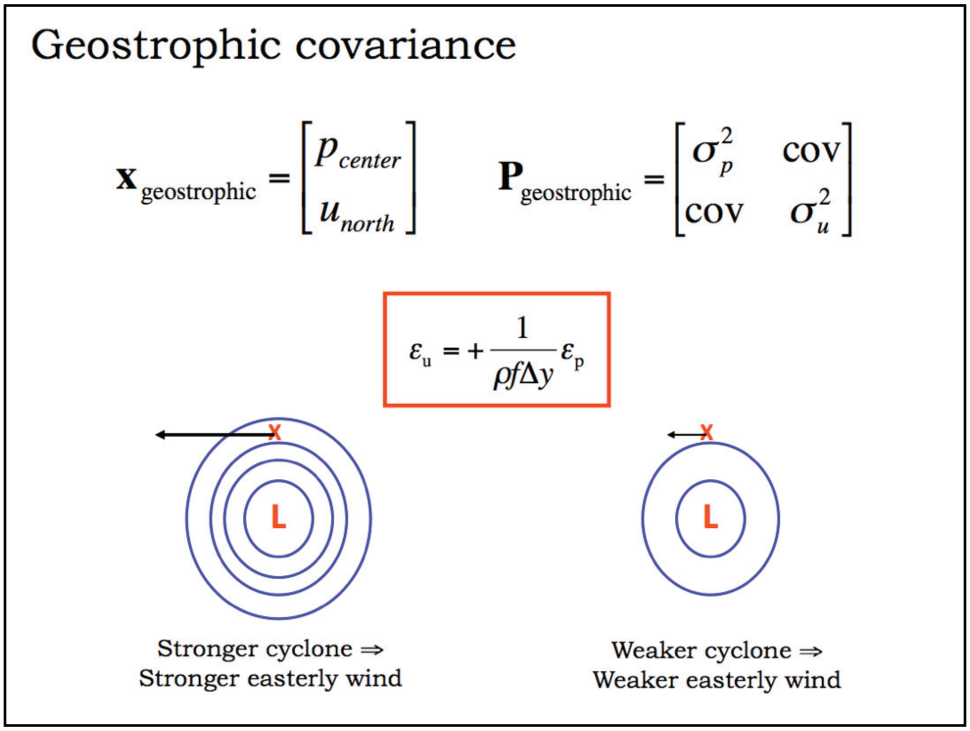
Error expectations:

$$\left\langle \varepsilon_p^2 \right\rangle = \sigma_p^2$$

$$\left\langle \varepsilon_u^2 \right\rangle = \sigma_u^2 = \left(\frac{1}{\rho f \Delta y}\right)^2 \sigma_p^2$$

$$\left\langle \varepsilon_p \varepsilon_u \right\rangle = \text{cov}\left(p_{\text{center}}, u_{\text{north}}\right) = +\frac{1}{\rho f \Delta y}\sigma_p^2$$

Don’t be scared by math!



Next slide is full multi-dimension extension, so lead into it with how covariance allows correction of u.