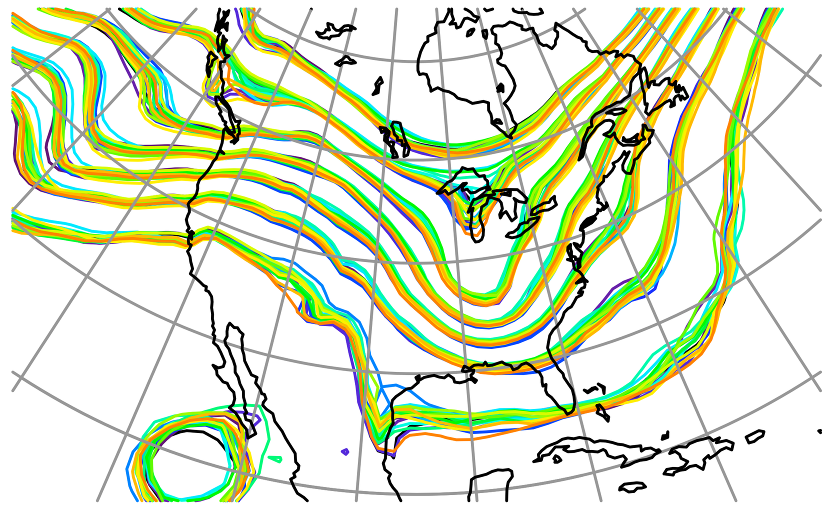

DART: Tools and Support for Ensemble Data Assimilation Research, Operations, and Education

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1. DART is ...

The Data Assimilation Research Testbed (DART) is an open source community software facility for ensemble data assimilation developed at the National Center for Atmospheric Research (NCAR). DART works with a wide variety of climate and weather models and observations. Building an interface between DART and a new model generally requires no modifications to the model code and no adjoints. DART works with dozens of models, including:

- weather models, e.g. WRF, COAMPS, NOAH, MPAS Ocean and MPAS Atmosphere,
- components of climate models, e.g. CAM, POP, CLM, WACCM, MITgcm-Ocean,
- ionosphere/thermosphere models, e.g. TIEGCM, GITM,
- low-order and simple models such as the Lorenz models for assimilation research and educational use.

DART assimilates dozens of observation types from a variety of sources, including:

- temperature, winds aloft, surface winds, moisture from NCEP, MADIS, and SSEC,
- total precipitable water, radar observations, radio occultation observations from GPS satellites,
- ocean temperature and salinity from the World Ocean Database,
- land observations such as snow cover fraction, ground water depth, tower fluxes, cosmic ray neutron intensity, and microwave brightness temperature observations.

DART provides both state-of-the-art ensemble data assimilation capabilities and an interactive educational platform to researchers and students. This poster highlights some recent DART developments and gives examples of research projects facilitated by DART.

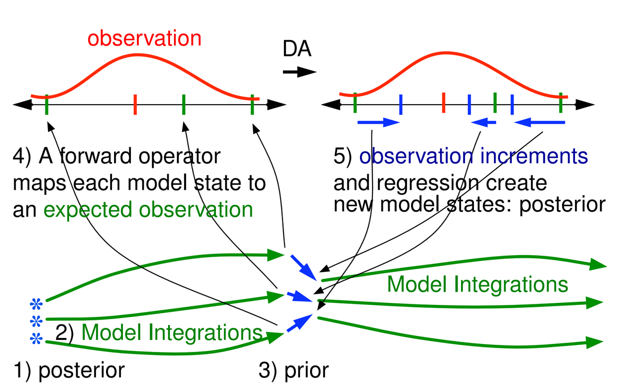


Figure 1: *Illustration for a toy ensemble size of 3.*

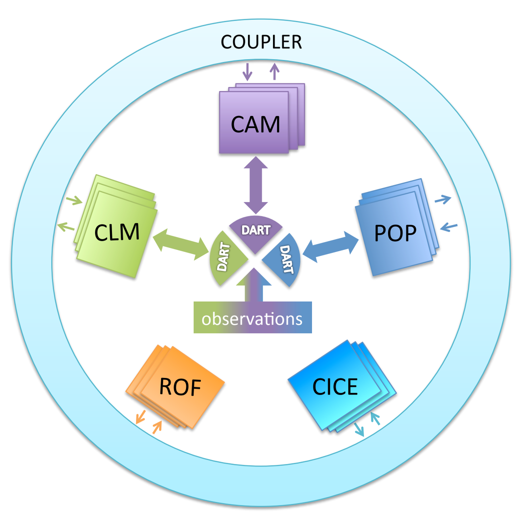


Figure 2: *CESM can advance multiple instances of one or more model components simultaneously, which facilitates assimilation with DART. Any of the models can be replaced with 'data' models that use archived model fields to enable different configurations.*

J. Anderson, T. Hoar, K. Raeder, H. Liu, N. Collins, R. Torn, and A. Arellano, 2009: *The Data Assimilation Research Testbed: A Community Data Assimilation Facility.* *BAMS* **90** No. 9 pp. 1283–1296

2. Assimilation with Earth System Models

2.1 Community Atmosphere Model – CAM

The impacts of observing only surface pressure on atmospheric uncertainty has been investigated in observing system simulation experiments (OSSE) using DART/CAM5. The ensemble Kalman filter is used to assimilate surface pressure observations with different temporal frequencies and spatial densities. The land surface and sea ice models are fully active and coupled to the atmosphere model but the ocean is specified.

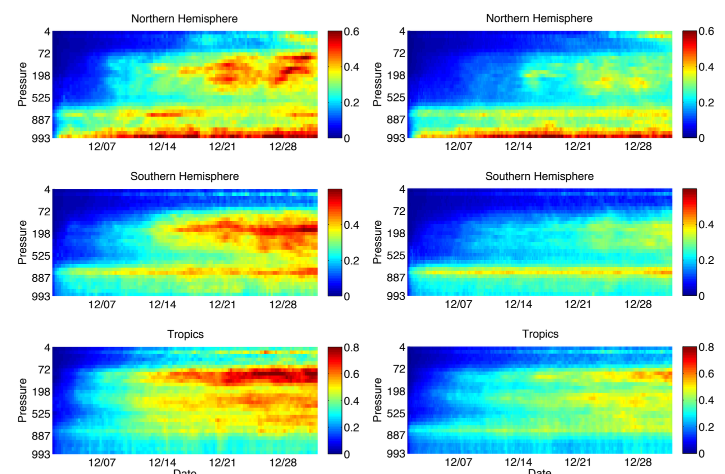


Figure 3: *Ensemble mean analysis temperature RMSE as a function of time and height averaged over the Northern Hemisphere, Southern Hemisphere, and Tropics from an OSSE assimilating 7200 surface pressure observations every 6 hours (left) and 1 hour (right).*

The time series of temperature RMSE at each vertical level (Figure 3) indicates that surface pressure observations can constrain uncertainty throughout the entire depth of the troposphere. The temperature RMSE generally decreases at every vertical level when observation frequency increases from 6 hour to 1 hour (left-to-right in Figure 3). Similar results are obtained with increased observation spatial density. In general, the error of the entire depth of troposphere can be better constrained with increased observation density and frequency.

2.2 Land Surface Assimilation – CLM

One of the more recent developments in DART/CLM is the ability to assimilate brightness temperatures. Ally Toure (NASA Goddard) and the DART team incorporated a radiative transfer model to predict the brightness temperature given a model state. Shown below are some diagnostics of a 'perfect' model simulation in which synthetic brightness temperature observations are assimilated in an 80-member ensemble every 24 hours starting from 1 Jan 2001.

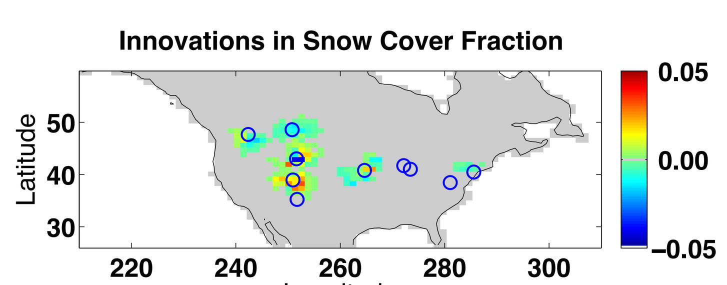


Figure 4: *Ensemble data assimilation allows brightness temperature observations to impact unobserved state variables. This figure shows the amount of change induced in the snow cover fraction state variable from assimilating synthetic brightness temperatures at 10 locations (shown as ◯) for 31 January 2001.*

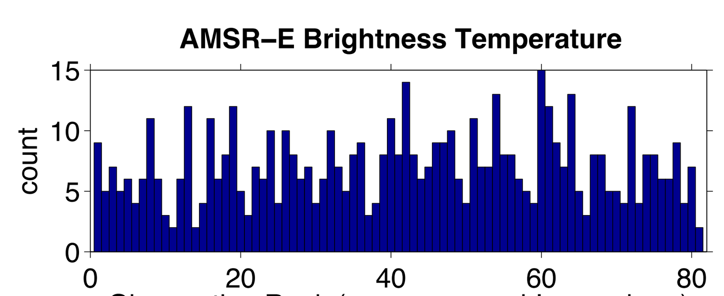
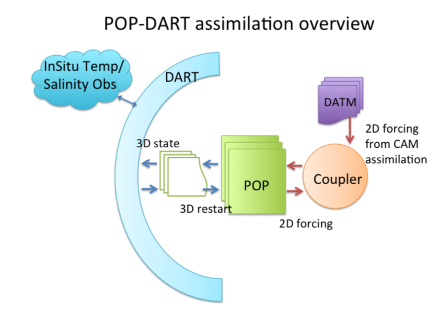


Figure 5: *This rank histogram demonstrates that the assimilation was effective in keeping the ensemble close to the true state (as represented by the synthetic observation).*

2.3 Global Ocean Assimilation – POP

The NCAR ocean assimilation system uses the DART Ensemble Adjustment Kalman Filter with the POP2 global ocean model. The assimilation state includes temperature, salinity, horizontal velocity components and sea level height on the POP2 nominal 1° grid with 60 vertical levels. Observations of temperature and salinity from the 2009 World Ocean Database are assimilated once per day.



POP/DART loosely coupled assimilation system. Each POP2 ocean ensemble member is forced by a unique ensemble member of a CAM4/DART atmospheric analysis.

In support of NCAR efforts to create a high-quality ocean reanalysis, recent work has focused on incremental improvements to the POP/DART system.

Examples of improvements

1. New filter initial conditions reduced strong, spurious, zonal mean meridional circulation in the deep equatorial Atlantic basin.
2. Spatially varying estimates of the representativeness errors for in-situ temperature and salinity are now in use.
3. Appropriate representativeness error estimates allow the use of adaptive covariance inflation.

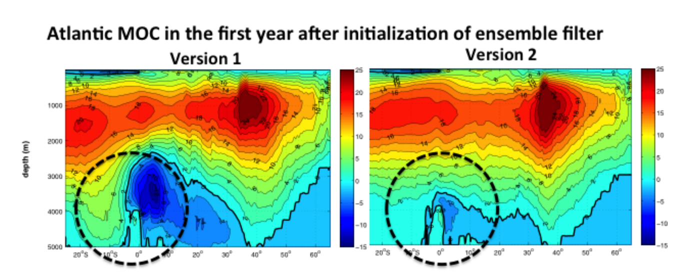


Figure 6: *Atlantic meridional overturning circulation in the old and new versions of POP/DART. New filter initial conditions eliminate spurious overturning circulation in the deep ocean.*

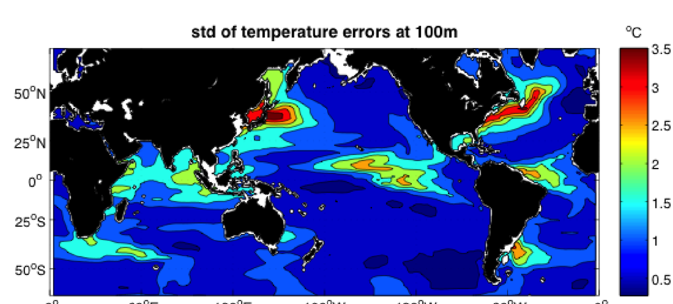


Figure 7: *Spatially inhomogeneous representativeness errors are more appropriate and enable the use of adaptive covariance inflation.*

	POP-DART v1	POP-DART v2
Filter initial conditions	Randomly drawn set of Jan 1 from forced ocean runs with varying salinity restoring	CCSM4 large ensemble experiment, re-centered to climatological T and S
Observational error estimates	Single value of obs/rep error for all T and S obs	Horizontally and vertically varying obs/rep error for T and S obs
Covariance inflation	None	Adaptive
Localization	Horizontal = 1200 km Vertical = none	Horizontal = 1200 km Vertical = currently being tested
Ensemble size	48	30
Ice model	Prescribed ice cover	Active ice model

2.4 Whole Atmosphere Chemistry Climate Model – WACCM

WACCM (Whole Atmosphere Community Climate Model) is identical to CAM, but with the model top extended to 5×10^{-6} hPa ($\approx$ 145 km) and with additional chemical, dynamical, and physical processes to model the upper stratosphere, mesosphere, and lower thermosphere. A new DART/WACCM interface facilitates studying of chemical and dynamical processes of specific events above the top of conventional atmospheric models and reanalysis products.

To illustrate the capabilities of WACCM+DART, a 40 member ensemble simulation was performed for January and February 2009 when a strong sudden stratosphere warming (SSW) occurred. Radiosonde and aircraft temperatures and winds, satellite drift winds, and COSMIC radio occultation observations are assimilated in the lower atmosphere. Middle and upper atmosphere temperature retrievals from TIMED/SABER and Aura MLS are also assimilated [Pedatella et al. 2013].

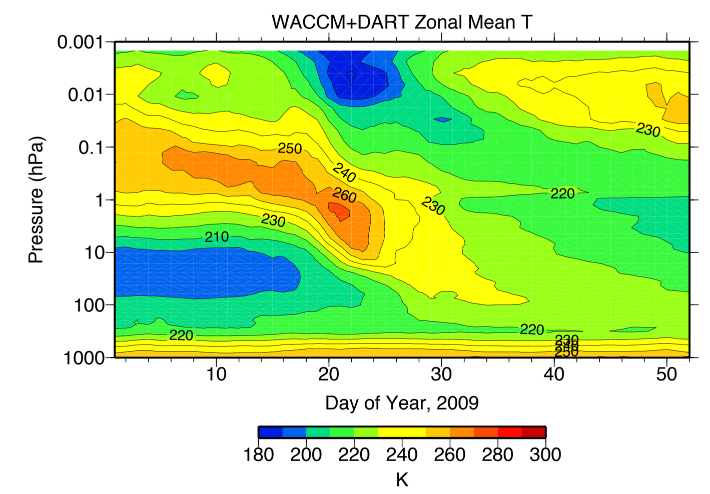


Figure 9: *WACCM+DART analyzed ensemble mean temperature during the 2009 SSW, averaged over longitude and from 70-80N. Around day 15 the stratopause (near 0.1 hPa) begins to descend, followed by a significant increase in stratospheric temperatures. This is accompanied by an approximately 40-50 K cooling of the mesosphere near 1×10^{-3} hPa ($\approx$ 95 km). Around day 35 the stratopause reforms at high altitudes.*

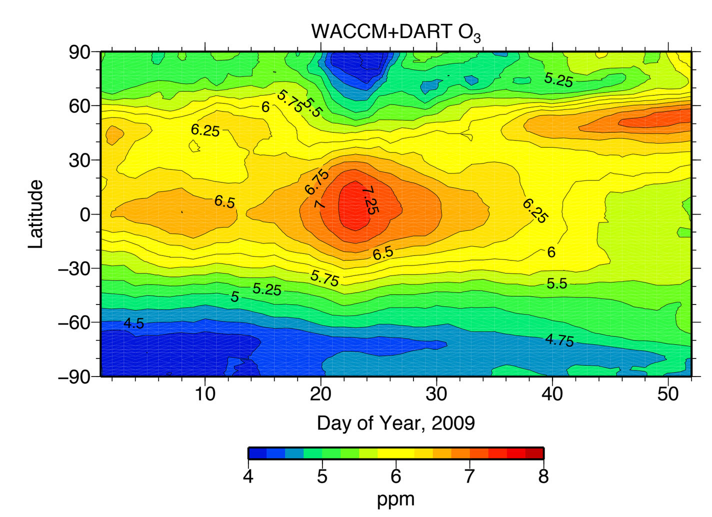


Figure 10: *WACCM+DART ensemble mean zonal mean ozone at 2 hPa during the 2009 SSW. A large increase in equatorial ozone occurs in late January and early February due to the SSW, accompanied by a decrease in ozone at mid-high latitudes in the Northern Hemisphere.*

The results in Figures 9 and 10 demonstrate the ability of WACCM+DART to simulate chemical and dynamical variability from the surface to the lower thermosphere during specific time intervals that are of scientific interest.

N. Pedatella et al., 2013: *Application of data assimilation in the Whole Atmosphere Community Climate Model to the study of day-to-day variability in the middle and upper atmosphere. GRL* **40** pp. 4469–4474

2.5 Multi-Component, Coupled Model Assimilation – CESM

Separate re-analyses for different model components (atmosphere, ocean, land) are useful but may be inconsistent. A DART interface with the fully-coupled CESM is now available and has been used for 'multi-component coupled data assimilation' where observations of each component model impact that model (e.g. atmosphere observations update the atmosphere state) and the fully-coupled model is used for the ensemble forecasts. This system makes better use of near surface observations and improves representation of coupled phenomena like processes that are linked by strong air-sea interaction. For example, there are significant differences in analyzed SSTs between an ocean only assimilation and a multi-component assimilation (see Figure 11). In the tropics, where coupling is strong, near-surface atmospheric observations influence the thermocline which in turn regulates SST. In mid-latitudes, assimilation of wind observations modifies the surface wind stress which regulates the sea surface height and the SST.

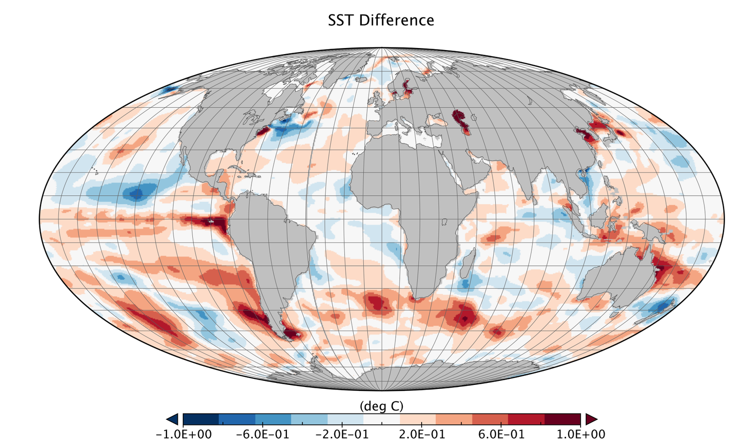


Figure 11: *Time-averaged mean difference in analyzed SST between a multi-component coupled data assimilation (atmosphere and ocean observations assimilated) and a single-component coupled data assimilation (only ocean observations assimilated). Note the large differences in the tropics, Gulf Stream and Southern Ocean.*

In the near future, DART will also support 'cross-component coupled data assimilation' for CESM where observations of any component can impact the state variables of all component models during the assimilation step.

3. WRF Real-time Convective Forecasts and Sensitivity Analysis

The Mesoscale Predictability Experiment (MPEX) was conducted from 15 May to 15 June 2013 over the central United States. MPEX sought to extend predictability of convective storms by reducing initial condition uncertainty with additional observations. The NCAR Gulfstream GV aircraft with the new dropsonde capability sampled during early morning hours upstream of anticipated convective events. Dropsonde locations were selected using ensemble sensitivity with a 30-member realtime ensemble forecast with WRF/DART initial conditions.

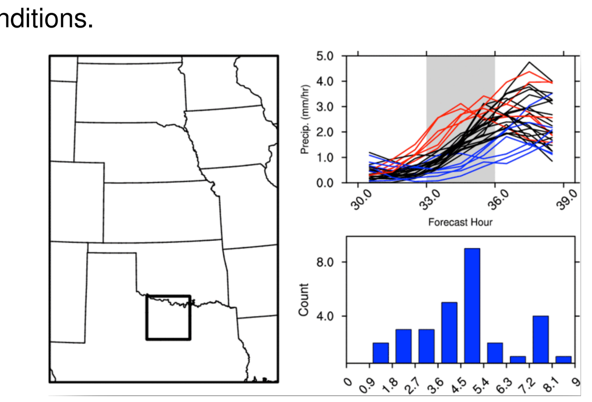


Figure 12: *A box over North Texas indicates an area with considerable precipitation forecast uncertainty. The upper right shows the hourly precipitation rate for each member within the boxed region. Gray shading indicates the time period of interest for the sensitivity calculation, with binned counts of total accumulated precipitation over this window shown below.*

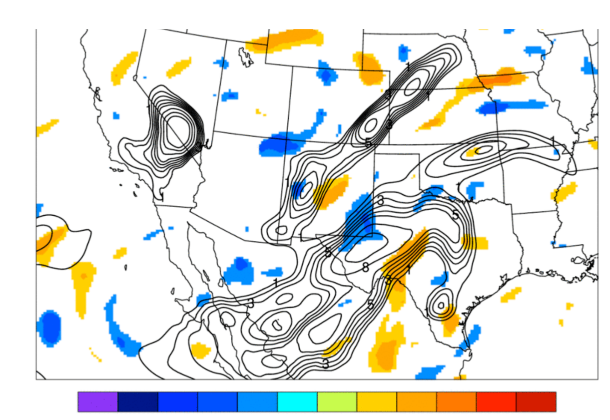


Figure 13: *A linear regression fit of the covariance of the precipitation in the box of Figure 12 and the ensemble forecast state during the sampling time highlights regions where additional observations could reduce uncertainty in the precipitation forecast in the box. Warm (cool) colors indicate where larger (smaller) 500 mb vorticity led to increased (decreased) precipitation.*

In Figure 13 a series of mid-tropospheric disturbances in the 24-hour forecast extend from Central Mexico into Oklahoma. More precipitation is expected in the box if the shortwave in West Texas is further east.

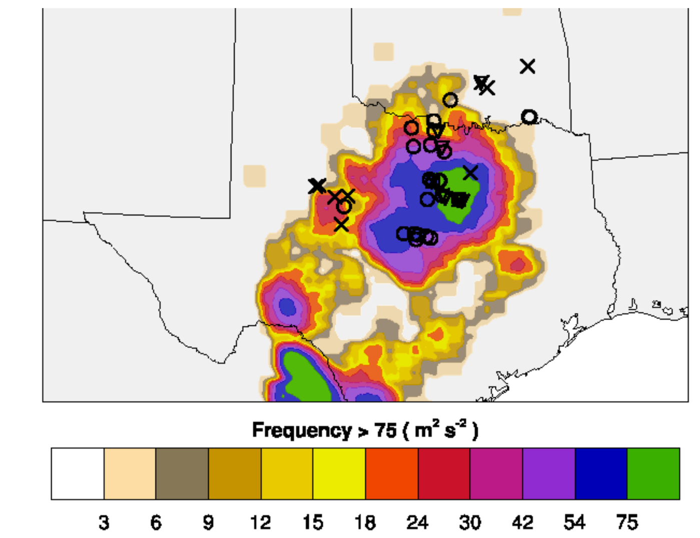


Figure 14: *A realtime ensemble forecast from the morning of the event. The colors shows the forecast probability of a severe storm and symbols show locations of reported severe weather: X - wind, ◯ - hail, ▽ - tornado*

The forecast in Figure 14 was skillful in highlighting regions of significant risk for severe storms, yet includes local errors in the timing and location of storms. Retrospective experiments will test the impact of assimilating the MPEX dropsondes to improve the forecasts.

4. Education

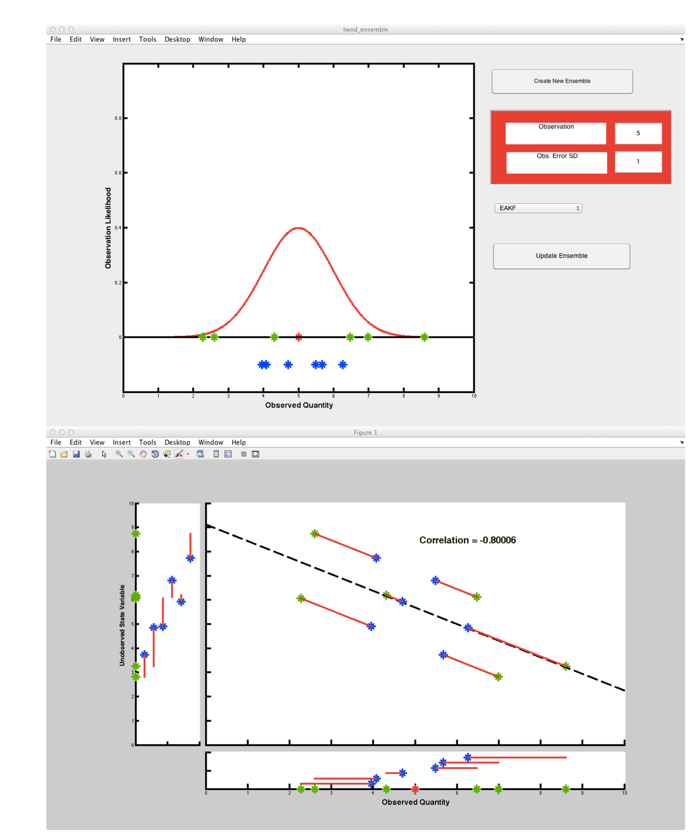
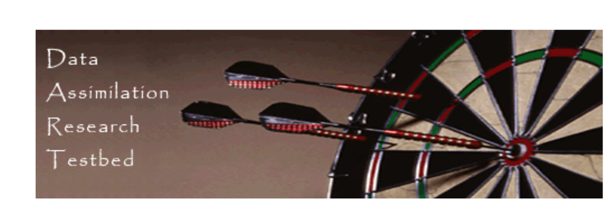


Figure 15: *DART contains a variety of instructional materials including slides and an interactive MATLAB tutorial with point-and-click GUI examples illustrating the ensemble data assimilation algorithms.*

5. Further Information

http://www.image.ucar.edu/DAReS/DART has information about how to download DART from our subversion server, a full DART tutorial (included with the distribution), and how to contact us.



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