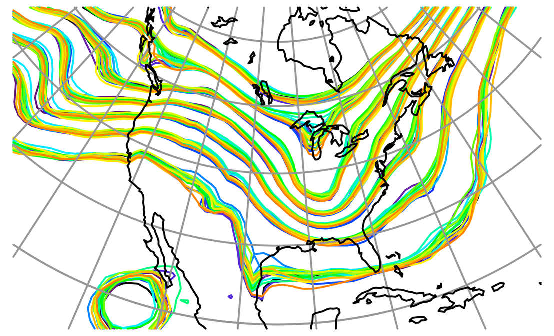

DART/WRF: A Community Mesoscale Ensemble Data Assimilation Facility

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1. Abstract

The Data Assimilation Research Testbed (DART) provides open-source, state-of-the-art software tools for ensemble data assimilation. DART includes interfaces that allow it to be used with regional, global, nested, and single-column domains with the latest releases of NCAR's Weather and Research Forecasting (WRF) model. DART can assimilate in-situ observations as well as radar reflectivity, radar radial velocity, GPS radio occultation, tropical storm position and intensity, and QuikSCAT winds. DART includes adaptive inflation, localization, and observation thinning tools that can produce high-quality, computationally efficient ensemble assimilations on a variety of parallel computing platforms. DART comes with an assortment of analysis tools that facilitate evaluating forecast quality, model systematic error, and the sensitivity of forecasts to initial conditions. Sample results are shown for ensemble analysis and prediction of convection over the United States and tropical storms in the Pacific and Atlantic.

2. David Dowell : Severe Thunderstorm Electrification and Precipitation Study

This supercell thunderstorm occurred in southwest Nebraska on 5 July 2000. This storm was observed by the Severe Thunderstorm Electrification and Precipitation Study (STEPS). We are assimilating data from the SPOL radar.

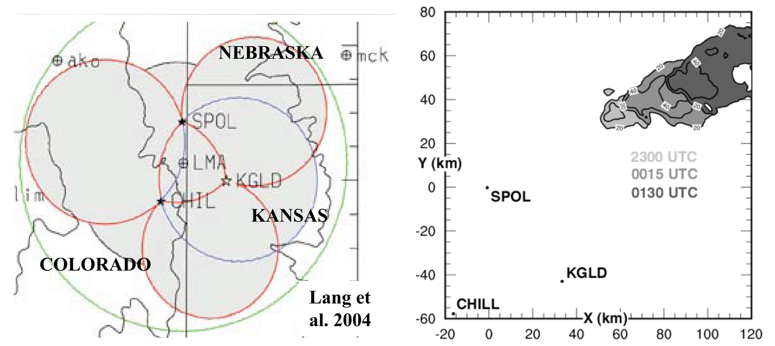


Figure 1: Left: *Multiple Doppler radar coverage for the STEPS study area.* **Right**: *The location of the supercell relative to the SPOL radar (providing the observations).*

2.1 WRF Model Characteristics

- WRF-ARW 2.2.1 run as a "cloud model" : Open lateral boundaries, no surface fluxes, no PBL, no radiation, Lin et al. (1983) microphysics.
- Horizontally homogeneous environment initialized with "environmental sounding": simple implementation and interpretation . . .
- Grid 120 km x 100 km, 20 km tall; dx = 1 km; dz = 100-500 m

2.2 Ensemble Kalman Filter (EnKF) Radar Data Assimilation

- Differences among $\approx$ 50 ensemble members are from: wind-profile perturbations, and local perturbations added to temperature, velocity, and water vapor in and near observed precipitation (Dowell and Wicker 2009).
- Background-error covariances estimated from ensemble statistics.
- DART was used to assimilate radar observations into the WRF model.
- Available radar observations assimilated every 2 min;
  doppler velocity only *(Reflectivity and other observations used for verification)*,
  6 km localization radius, all model fields updated.

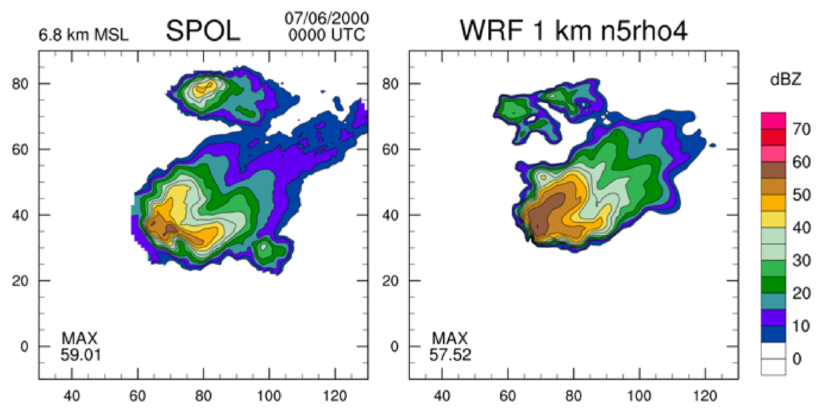


Figure 2: Left: *The observed Reflectivity of the 5 July 2000 supercell. The domain is 100km on each side.* **Right**: *The Ensemble Mean Reflectivity after 80min of Doppler velocity assimilation.*

2.3 Verification with Independent Observations

- Updraft volume derived from dual-doppler analysis where $w > 5$ m/s
- Total graupel mass
  1. Particle ID (PID) algorithm (Vivekanandan et al. 1999) with polarimetric radar data.
  2. Mass estimated at grid points where PID indicates graupel Z - M (reflectivity - mass) relationship.
  3. Graupel mass summed over the whole storm.

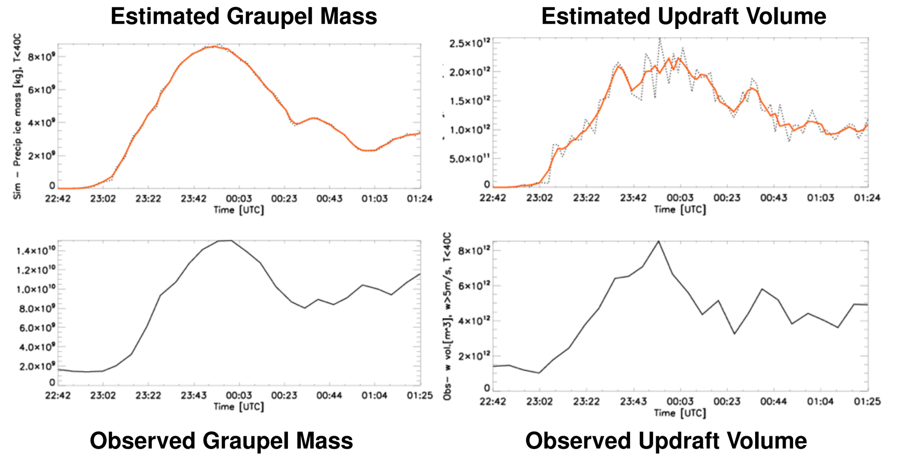


Figure 3: Left: *The top figure is the temporal evolution of the graupel mass [in kg] estimated by WRF-DART. The solid red line is a 6 minute running average. The black dotted line is the 2 minute WRF output. The bottom figure is the observed graupel mass. The correlation between the running average and the observed is 0.87.* **Right**: *The top figure is the temporal evolution of the updraft volume [m^3] estimated by WRF-DART. The bottom figure is the observed updraft volume. The correlation between the running average and the observed is 0.89. [Dowell 09]*

3. Ryan Torn : Storm Analysis and Forecasting

This work focuses on applying ensemble-based data assimilation to understand the predictability and dynamics of mesoscale weather systems. Ensemble-based techniques use a collection of short-term forecasts to compute flow-dependent background error statistics, which determine the weight given to observations and how to spread observation information to different locations and variables. Additionally, these ensembles are a set of equally-likely analyses that can be used for forecast initialization.

In addition to the storms presented here, there are track and intensity forecasts for ten more storms at: **http://www.atmos.albany.edu/facstaff/torn/hfip/results.html**. Those figures depict the ensemble members, the Official NHC forecast (human), the GFS forecast, the WRF forecast initialized from the GFS analysis, and the verification. There are also summary statistics over 69 different forecast initialization times.

3.1 Exploration of Atlantic Storms from 2008

These simulations use a standard set of WRF parameterizations and settings:

- WRF 5-class microphysics;
- 36 km grid spacing, 36 vertical levels up to 20 hPa;
- domain is as shown in Figure 7;
- assimilate conventional obs (surface pressure, rawinsondes, aircraft, satellite winds, TC position and minimum SLP) each six hours;
- uses spatially-adaptive inflation;
- 96 ensemble members, initialized 3 days prior to Fay being declared a TD, 32 total days of cycling (12 August - 14 Sept. 2008);
- initial ensemble generated by random draws from NCEP covariances;
- lateral boundaries are generated the same way as the initial ensemble.

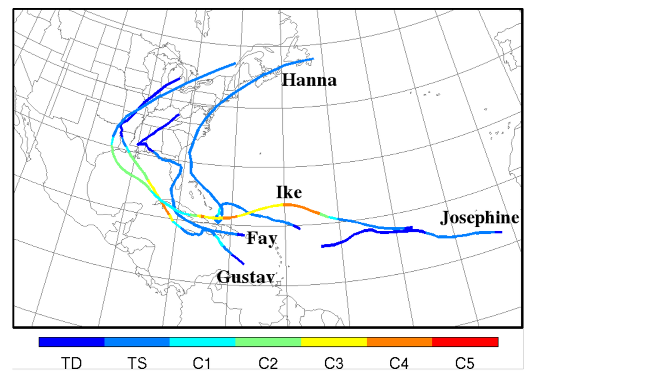


Figure 4: *Best track data from the National Hurricane Center. The colors depict the storm intensity.*

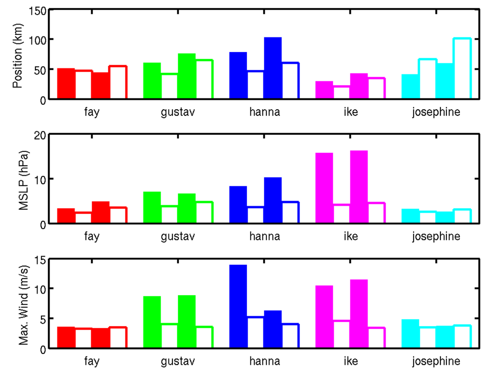


Figure 5: *RMS error and spread in TC position, minimum SLP and maximum wind for the posterior (left of TC name) and prior (right of TC name). The solid bars are the RMS error, the hollow bars are the total spread.*

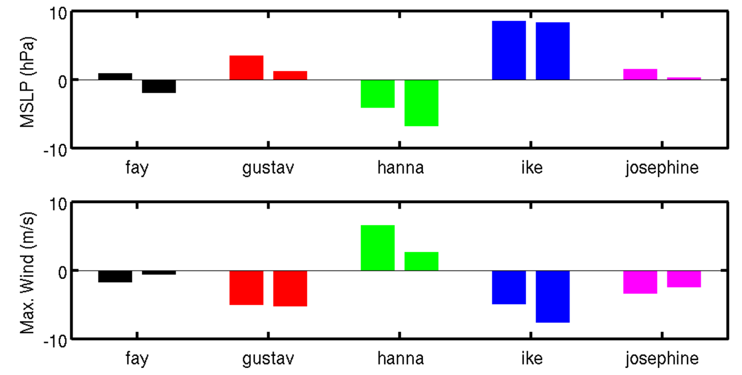


Figure 6: *Bias in TC minimum SLP and maximum wind for the posterior (left of TC name) and prior (right of TC name).*

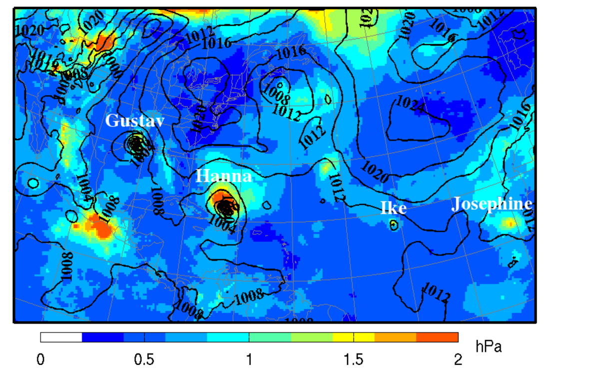


Figure 7: *Ensemble-mean (solid) SLP analysis valid 00 UTC 2 September 2008. The shading is the ensemble spread. This is a time when four Tropical Cyclones exist in the Atlantic basin.*

3.2 Hurricane Katrina Sensitivity Study

This figure depicts the sensitivity of a 48 hour forecast of Hurricane Katrina's longitude to the analysis of the deep-layer mean zonal component of the wind at each analysis grid point (colors). This forecast was initialized 00 UTC 25 August 2005. The figure shows that if the jet is shifted further south, the TC ends up further east.

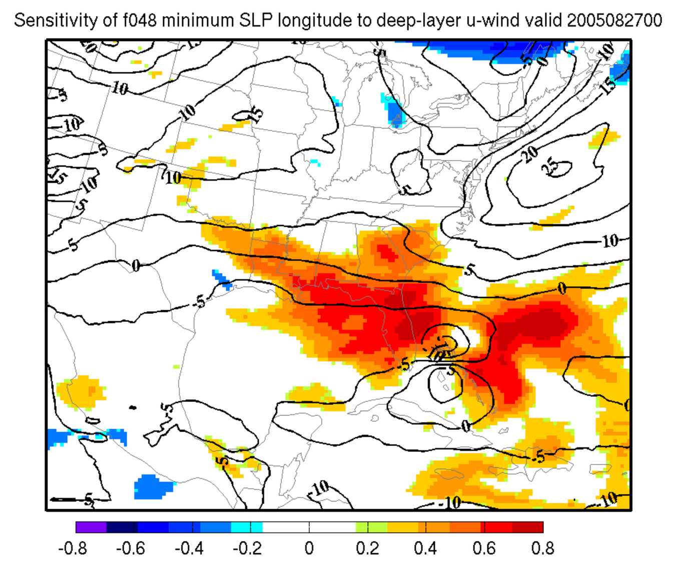


Figure 8: *The units of the colorbar are degrees longitude, such that the colors show how a one standard deviation change in the zonal wind will change the TC longitude. The contours are the ensemble-mean analysis of the deep-layer mean wind.*

4. Josh Hacker : Exploring the Boundary Layer

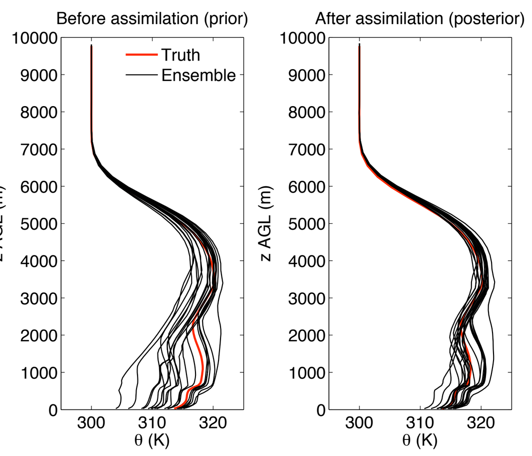


Figure 9: *Ensemble and truth (red curve) prior and posterior to assimilating synthetic surface observations with DART and WRF-ARW version 3.1 run as a single-column model (SCM). This OSSE case is valid 0300 10 June 2001 (8 PM LST) over Oklahoma. Synthetic observations of 2-m T, 2-m Q_v, and 10-m wind components were assimilated. The surface observations shift the distribution toward the truth and contract the ensemble.*

5. Hui Liu : COSMIC data impact on Typhoon analysis/forecasting.

Typhoon Shanshan formed as a tropical depression on 9 September 2006 near 14N, 139E. It went through rapid intensification becoming a Category 4 storm by 12 September. Shanshan then moved northwestward and skirted to the east of Taiwan on 15 and 16 September. The typhoon brought heavy rainfall over Taiwan and Eastern China.

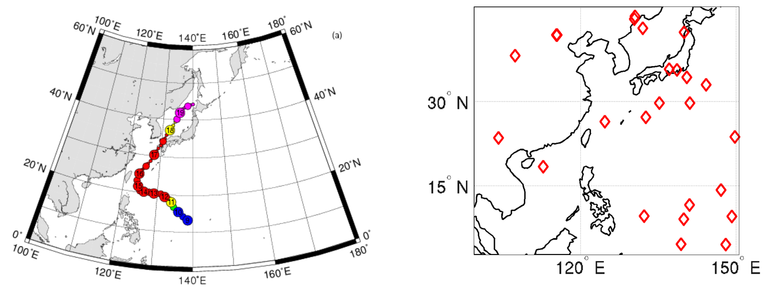


Figure 10: Left: *Observed best track from JMA and intensity of Typhoon Shanshan.* **Right**: *Locations of 24 COSMIC GPS RO profiles in the domain for 13 September 2006.*

DART/WRF was used to assimilate the observations and then WRF was run in forecast mode. DART is particularly good for mesoscale analysis because weather-dependent forecast error covariances are used in the generation of the analyses.

5.1 GPS Radio Occultation (RO) Refractivity observations

RO refractivity provides large-scale estimates of water vapor and can be collected under all weather conditions. Low-Earth-orbiting (LEO) satellites detect GPS signals just above the horizon and observe atmospheric refractivity as a function of height. RO refractivity is the only source of high vertical resolution ($\approx$ 200m near the surface) observations of water vapor for the middle and lower troposphere.

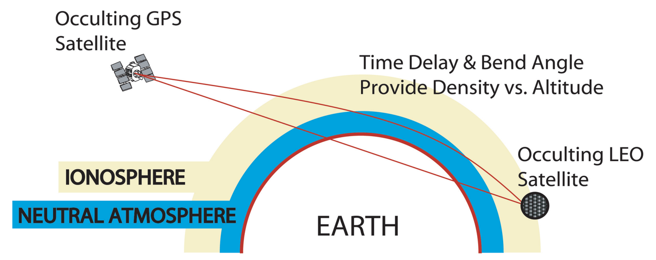


Figure 11: *Illustration of Radio Occultation.*

5.2 Experiment Overview

Two sets of nearly identical observations were used to determine the impact of the RO refractivity observations. WRF was configured to run with 35 vertical levels at 45km horizontal resolution with a 120 second timestep. Assimilations using 32 ensemble members were done every 6 hours starting from 00Z 8 September 2006 and resulted in a final analysis at 00Z 14 September 2006. Each ensemble member was then run forward to produce a 72-hour forecast.

5.3 Experiment 'NoGPS'

The following observations were assimilated:

- Radiosonde temperature, moisture, and winds (T,Q,U,V),
- Satellite cloud drift winds (U,V),
- SATEM thickness,
- standard surface observations (PS,T,U,V), and
- QuikSCAT ocean surface winds (U,V).

5.4 Experiment 'GPS'

This experiment used the RO refractivity observations from the COSMIC satellite network as well as the observations used in the NoGPS experiment.

5.5 Impact on the Forecast of Minimum Sea Level Pressure

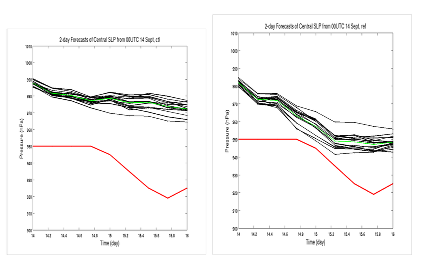


Figure 12: *48-hour forecasts of the typhoon's minimum central sea level pressure with the standard observations (**left**) and with the additional COSMIC observations (**right**). The intensity of the typhoon is increased and is closer to the observed (shown in red) when the assimilation used the COSMIC data.*

5.6 Impact on Forecast of Maximum Surface Wind

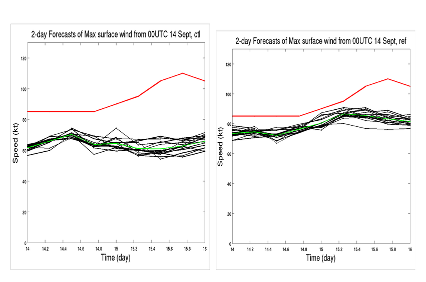


Figure 13: *48-hour forecasts of the typhoon's maximum surface wind with the standard observations (**left**) and with the additional COSMIC observations (**right**). The maximum surface winds are greater and are closer to the observed (shown in red) when the assimilation used the COSMIC data.*

5.7 Impact on precipitation forecast

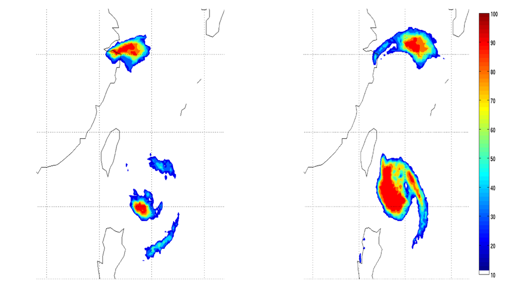


Figure 14: *The two panels show the probability forecast of 24-hour accumulated rainfall $>$ 60mm/day during the 24-hour period starting 12Z 14 Aug 2006. The forecasts from the 'NoGPS' experiment are on the* **left**, *the forecasts from the 'GPS' experiment are on the* **right**. *The 'GPS' experiment results in a higher probability of heavy rainfall.*

6. Ensemble Data Assimilation from the DART perspective.

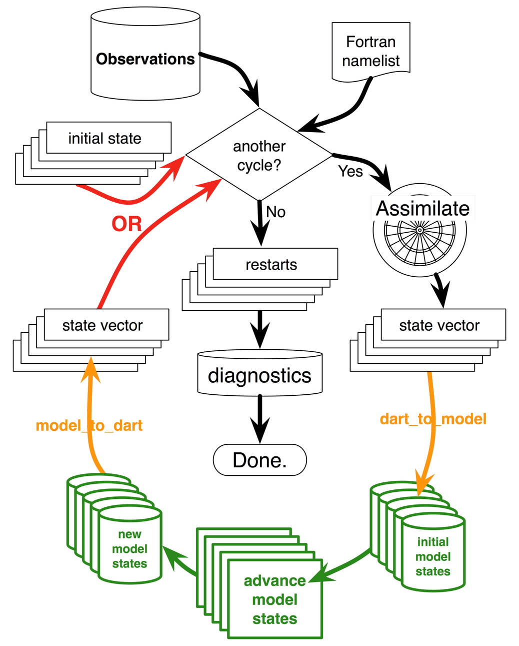
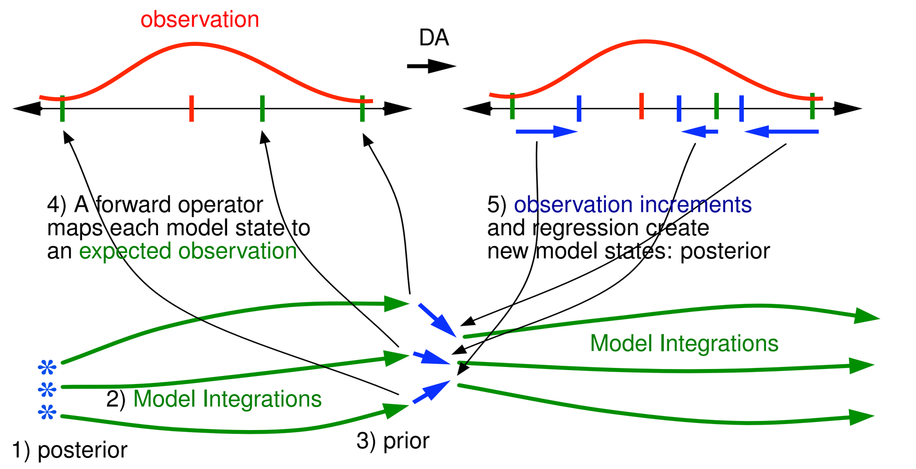


Figure 15: *The DART schematic.*

DART is a community software facility that allows users to easily try ensemble filter techniques. The distributed code includes many models with various levels of complexity, various sets of observations, and skeleton code to guide users in adding their own models or new observation types. DART is designed so that incorporating new models and new observation types requires minimal coding of a small set of interface routines, and does not require modification of the existing model code. The expected scaling of the DART parallel algorithm is independent of the forecast model. The main DART routine, called **filter**, is responsible for ingesting the initial ensemble and the observations and determining when to assimilate and when to request a model advance. Routines are required to convert the model output to a simple DART format and vice versa. The model instances (the ensemble members) may advance in turn or all-at-once.

7. Sequential Ensemble Filtering



8. Observations routinely used with DART.

DART supports a wide variety of observations; from the standard radiosonde to GPS radio occultations. The design paradigm for DART means that once an observation type is supported, all models that work with DART can assimilate those same observations.

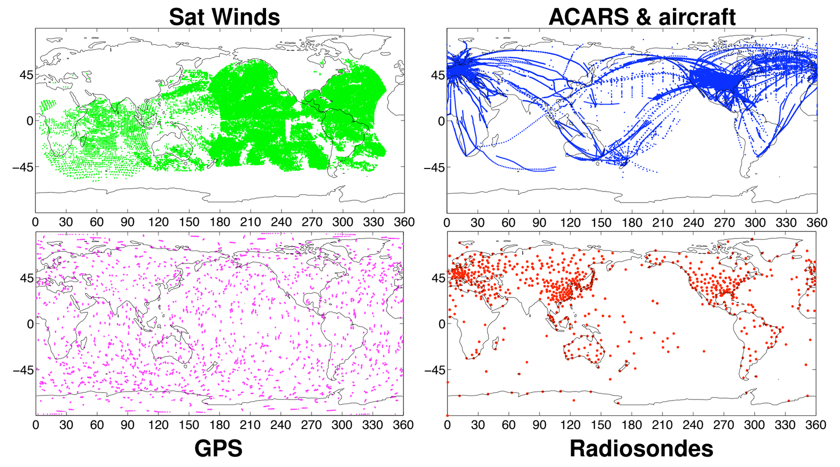
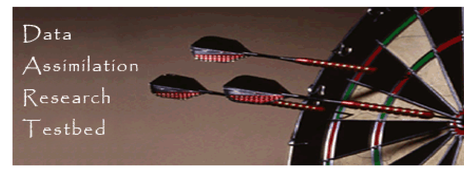


Figure 16: *Typical observation density routinely assimilated by DART. Observation locations for 1 Dec 2006.*

9. For further information

Our DART web site is: **http://www.image.ucar.edu/DAReS/DART**
There you will find information about how to download the latest revision of DART from our subversion server, information on a full DART tutorial (included with the distribution), and contact information for the DART development group.



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