A CESM+DART Atmospheric Reanalysis for Forcing Ocean, Land, and Other Surface Models

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NCAR
DART Is:

A flexible suite of software tools to accelerate Earth system research using ensemble Kalman filters.

Focused on:
- Open Source; community members develop:
  - model interfaces
  - observation forward operators
  - assimilation algorithms

Educational Resource

Used at:
- 50+ Universities
- 100+ other sites
- 1500+ registered users

Contributions are reviewed, streamlined, and tested before merging into the public DART.

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Geophysical Models Interfaced to DART

- WACCM-X
- WACCM
- GITM
- TIEGCM
- ROSE
- LMDZ
- AM2
- NCOMMAS
- PBL_1d
- SQG
- BGRID
- PE2LYR
- CAM
- CAM-SE
- CAM-Chem
- MPAS_ATM
- WRF
- WRF-Chem
- WRF-Hydro (NOAA)
- NOAH-MP
- CLM
- CICE
- POP
- COAMPS_nest
- MITgcm_ocean
- MPAS_OCN
- ROMS
- FESOM
- GCOM
- COAMPS
- NAAPS
- CABLE

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Earth System Observations (others available)
Expanding Earth System Observations

Remote Sensing Satellites

ISS observations offer insights into plant function

Ground Based Networks:
NEON, Ameriflux

Metzger et al., (2019)
Motivation for DA in Earth System Models

Sources of uncertainty

- Initial condition
  - Initialization
  - Climate feedbacks
  - Internal variability
  - Earth system model

- Model uncertainty
  - Ecosystem impacts

Scenario uncertainty

Scenarios

Initial value problem
Subseasonal to seasonal forecast (2 weeks – 12 months)

Decadal prediction (1 – 30 years)

Earth system projection (30 – 100+ years)

Boundary value problem

Simulated Biomass in Western US
Duarte et al., (in revision)

AGB (Pg C)

Boundary Condition Uncertainty

Model Uncertainty

Bonan & Doney 2018
Atmospheric forcing of surface components

Surface models in CESM2 (CLM, POP, CICE, ...) are forced by CAM6. DA using any of these can use an existing CAM6 reanalysis instead of re-running a CAM6 ensemble for each new case. Reanalysis $\approx$ actual atmosphere.

- Cpl history files:
  - frequencies ranging from 1-6 hours
  - ready to use in CESM in DATM mode
  - 1 year, 1 member per file
  - 2011-2020

These models have DART interfaces for assimilation.
DA with surface models, such as CESM’s Community Land Model (CLM5), requires not only a good model, but good forcing from the atmosphere, both in the mean and ensemble spread.
CLM5-DART Overview

CAM4 DART Reanalysis
(80 member ensemble)

Ds199.1 | DOI: 10.5065/38ED-R208

Grid Cell
(~1°x1°)

CLM Subgrid Processes

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Ensemble of Atmospheric Forcing

80-Member ensemble of forcing files for other CESM components (20 shown).

Black is ensemble mean.
2. Provide forcing for offline chemistry transport models or in a “nudging” framework.

3. Evaluate weather prediction capabilities of CAM.
   • Confront climate model with observations.
   • Identify systematic short-term forecast errors.
   • Compare to earlier CAM reanalysis.

4. Very large, labeled data set of atmospheric observations + ensemble estimates; useful for machine learning.

5. Ensemble of plant growth variable time series from CLM.
Reanalysis Quick Facts: Model

- CESM 2.1 release, also used for CMIP 6.
- Atmosphere: CAM6 0.9 degree latitude by 1.2 degree longitude, 32 levels.
- Land: CLM 5.0 BGC-CROP version, same grid as CAM.
- SST and Sea Ice *Coverage*: Specified daily 0.25 degree from AVHRR.
- Sea Ice *Thickness* from CICE model.
- Aerosols, greenhouse gases, volcanic forcing: from CESM when available.
Reanalysis Quick Facts: Assimilation

- DART Manhattan
- Ensemble Adjustment Kalman Filter (EAKF)
- 80 members with Sampling Error Correction
- 6-hour window
- Inverse $\Gamma$ adaptive inflation
- Tuned parameters for localization, inflation, etc.
- Land state well spun up; in balance with atmosphere(s).
Reanalysis Quick Facts: Observations

Observations assimilated:
• Temperatures and winds from radiosondes, ACARS and aircraft
• Cloud motion vector winds
• GPS radio occultation refractivity
• AIRS temperature retrievals

Observations evaluated ("withheld"):  
• Radiosonde specific humidity
• AIRS specific humidity retrievals
• Radiosonde, land and marine altimeter
Reanalysis Quick Facts: Observations

Example of observations used in 1 cycle; > 450,000 in this window.
Assimilation status evaluated monthly relative to all obs types; RMSE, bias, totalspread, numbers of obs available (o) and used (*), time series, profiles, 3 regions. All archived.
Research Data Archive: Contents

- [https://rda.ucar.edu/datasets/ds345.0](https://rda.ucar.edu/datasets/ds345.0)
- O(120 Tbytes) of data
- Organized by CESM component (cpl, atm, esp, ...)
- Useful units of compressed data for easy download
- CESM gridded data
- “Observation space” data; ensemble *model estimates* of the observations at the obs locations
Carbon Monitoring Across Western US

Contributed by Brett Raczka

- Vulnerable carbon stocks create drastic change to landscape and ecosystem functioning
- Complex terrain challenges traditional carbon monitoring, flux towers, atmospheric inversions

**Top-Down Modeling**
- Atmospheric CO₂
  - Atm. Transport Model
  - Land carbon exchange

**Bottom-Up Modeling**
- Weather/Climate
  - Land Surface Model (CLM)
  - Land carbon exchange

US Drought Monitor, June 10, 2021

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Leaf Area (Monthly)

The mean annual LAI in the assimilation run decreased by 63.7% compared with the free run.
More Projects Using the Reanalysis

- “Exploring Bounded Non-Parametric Filter Impacts on Sea Ice Data Assimilation” (Riedel AMS2023)
- “Evaluating Ocean Data Assimilation Procedures for Initialized Predictability in Coupled CESM2 Using Dart” (Amrhein AMS2023)
- “Leveraging DART Increments to Address Model Biase in the Community Atmosphere Model” (Chapman AMS2023)
- “Improving the Representation of Land Surface Processes using the Data Assimilation Research Testbed (DART)” (Raczka AMS2023)
- Enhancing Earth System Predictability by Diagnosing Model Error in Mode Water Regions (Johnson, Gharamti, Deppenmeier, Grooms)
- The kiloCAM experiments at KAUST (Gharamti & Johnson)
- Plant growth variable time series exported to AWS; [https://registry.opendata.aws/ncar-dart-cam6/](https://registry.opendata.aws/ncar-dart-cam6/)
+ DART is a flexible, research focused, community, ensemble DA system.
+ It’s used for a broad variety of Earth system research projects.
+ The CAM6+DART Reanalysis can accelerate research using non-atmospheric Earth system models at lower cost.
+ It provides objectively-derived, realistically variable forcing to surface models, with uncertainty estimates.

https://dart.ucar.edu
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Reanalysis description in Scientific Reports:
https://rdcu.be/ctUVQ

We would like to acknowledge high-performance computing support on NCAR’s Cheyenne computer (doi:10.5065/D6RX99HX) provided by the Computational and Information Systems Laboratory, sponsored by the National Science Foundation.
DART’s Algorithms (a sampling)

- Assimilation Flavors (9+):
  - Deterministic and stochastic ensemble Kalman Filters
  - Non-Gaussian rank histogram filters
  - Localized Particle Filter (Poterjoy)
  - Gamma/Inverse Gamma, Inverse Gamma/Gamma filters (Bishop)
  - Higher moment filters (Hodyss)
  - Quantile Conserving Ensemble Filter (Anderson)

- Ensemble Inflation; state-space, prior and posterior, adaptive, inverse $\Gamma$, damping
- “Localization”; spatial and by variable (esp. for chemistry)
- Sampling Error Correction, Spread Restoration, Sort Obs. Increments, Rank Regression
- Output 6 stages of assimilation in state space, plus observation space
- Quality Control; detailed reporting
- Compact enough for laptops, scales to thousands of processors (one-sided MPI, distributed states and mean)

Designed for flexible research and development, including computationally intensive ideas.
MPD Water Vapor Profile DA for Convective Weather Forecasts

Lead; Tammy Weckwerth

MicroPulse Differential absorption lidar (MPD) developed by Montana State University and EOL measures continuous relative backscatter and water vapor profiles.

Observing System Simulation Experiment (OSSE)

WRF/DART DA of MPD improves short-term forecasts of convection initiation and evolution compared to assimilating conventional observations (in the OSSE) and no DA (in the OSE).
Flood Prediction: WRF-Hydro/DART for Hurricane Florence 2018

High-resolution stream network with USGS streamflow gauges.

DA greatly improves analysis and forecasts of streamflow.

Novel Data Assimilation Science
1. Prior and Posterior Adaptive Covariance Inflation
2. Along-The-Stream (topology-based) Localization

Lead; Moha el Gharamti

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DA for Space Weather and Earth’s Upper Atmosphere

Lead; Nick Pedatella

- WACCMX+DART is first whole atmosphere DA system that can assimilate observations from the surface to ~500 km.

- Used to assess impact of new satellite missions (COSMIC2, NASA GOLD and ICON) on specifying and forecasting the space environment.

- Scientific applications:
  - Study middle-upper atmosphere variability forced by solar storms and lower atmosphere,
  - Predictability of the near-Earth space environment.

Assimilating COSMIC-2 observations during April 25-30, 2020 reduces forecast RMSE and bias by 6.4% and 28.1% at 300 km.
Field Campaign and Satellite Data: Pollution Emission Estimation

Lead; Benjamin Gaubert

Aircraft measurements from KORUS-AQ field study in Korea 2016
Satellite retrievals of CO from Terra/MOPITT
Chemistry modeling with CAM-Chem DART
Ensemble Kalman Filter with:
- Optimized CO initial conditions
- Optimized CO emissions

Inversion of MOPITT data updated emissions estimates, improved model performance
- Against the KORUS-AQ aircraft observations of CO (shown) and O₃, OH, HO₂
- Suggests underestimates of CO/VOCs in China

DA improves fit to NASA DC-8 aircraft CO measurements for all synoptic conditions:
DA closer to obs than no DA.

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Toward Global Convection-Permitting Data Assimilation

Leads; Craig Schwartz and Glen Romine

**Regional 3-km WRF/DART**

- Precipitation forecast skill for top 1% of events east of the Rockies

- 3-km analyses

- 15-km analyses

**Global 15-km MPAS/DART**

Outgoing longwave radiation standard deviation (W/m²)

0000 UTC 25 May 2019

**Gradual approach toward global convection-permitting ensemble-based DA**

Variable-resolution meshes → "Dual-resolution" DA → Global convection-permitting