Data Assimilation in WACCMX

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Data assimilation constrains the model directly based on observations providing a more realistic representation of the true state of the atmosphere at a specific time.

We use the DART ensemble Kalman filter to implement data assimilation in WACCM.

The ensemble approach eliminates the need to specify background covariance, since it is obtained directly from the ensemble of model simulations.

**DART** – Data Assimilation Research Testbed  
**WACCM** – Whole Atmosphere Community Climate Model
WACCM+DART provides an atmospheric reanalysis from the surface to the lower thermosphere (~145 km).

Lower Atmosphere Observations:
- Aircraft temperature and wind
- Radiosonde temperature and wind
- Satellite drift winds
- COSMIC GPS refractivity

Middle Atmosphere Observations:
- TIMED/SABER Temperature
- Aura MLS Temperature

Typically use a 40-member ensemble, which is a tradeoff between computational expense and having a sufficiently large ensemble to capture a variety of atmospheric states.

WACCM+DART is useful for correcting model biases, studying dynamical variability due to sudden stratosphere warmings, and short-term tidal variability.

Framework for WACCMX+DART is identical to WACCM+DART.

Same observations are assimilated in the troposphere, stratosphere, and mesosphere.

Main change between WACCMX+DART and WACCM+DART is increased damping in WACCMX which is necessary for model stability.

Changes made for model stability do have a slight negative impact on performance of the data assimilation in the troposphere-stratosphere.

We have performed initial WACCMX+DART simulations for the 2009 SSW time period.
Middle Atmosphere Variability in WACCMX+DART and SD-WACCMX

NO [mol/mol], ion average, lat 71.052632

WACCMX+DART

SD-WACCM
Figure 5. Total electron content at 1000 local time simulated by the (a) GAIA, (b) WACCMX+TIMEGCM, and (c) WAM+GIP models, and (d) observed by ground-based GPS receivers. The dashed vertical black line indicates the timing of the polar vortex weakening. and only apparent in WAM+GIP in the Southern Hemisphere. The inability of the GAIA and WAM+GIP simulations to adequately reproduce the variability in the morning may be related to the extended periods of enhanced morning upward vertical drift perturbations (Figures 1 and 2) that are seen in these simulations.

Comparisons of the model simulations of TEC with the ground-based GPS observations at 75°W at 1000 and 1800 LT are presented in Figures 5 and 6, respectively. Note that the TEC observations poleward of 35°S are not shown due to poor data quality resulting from the sparse observation coverage at these latitudes. Similar to the vertical plasma drift perturbations, a 3 day smoothing has been applied to the simulated and PEDATELLA ET AL. 2009 SSW MODEL COMPARISON.
Figure 6. Total electron content at 1800 local time simulated by the (a) GAIA, (b) WACCMX+TIMEGCM, and (c) WAM+GIP models, and (d) observed by ground-based GPS receivers. The dashed vertical black line indicates the timing of the polar vortex weakening.

Observed TEC. We reiterate that the TEC comparison should be considered in a qualitative sense since the model upper boundaries inhibit a direct, quantitative, comparison. The TEC at 75°W displays largely similar features to the zonal mean \(N_m F_2\). The similarities and differences between the different model simulations and the GPS TEC observations are also similar to the comparison of \(N_m F_2\). In particular, it is again evident that the GAIA and WAM+GIP simulations show extended periods of enhanced TEC at 1000 LT. This is in contrast to the WACCMX+TIMEGCM simulation and ground-based GPS TEC observations which indicate that the enhancement occurring after the SSW onset only occurs between days 25 and 30, and is followed by a short-term decrease in TEC between days 30 and 5. These differences are again attributed to the extended...
Perturbations in the vertical plasma drift velocity at Jicamarca, Peru (75°W, 12°S) simulated by the (a) GAIA, (b) WACCMX+TIMEGCM, and (c) WAM+GIP models. (d) The observed vertical plasma drift perturbations from the Jicamarca incoherent scatter radar. The gray areas in Figure 1d indicate periods when observations are unavailable. The solid vertical black line indicates the timing of the polar vortex weakening. Contours are every 6 m s\(^{-1}\).

The results in Figure 2 reveal similar features as those seen in Figure 1. The observations again indicate a morning enhancement and afternoon decrease following the SSW onset. Similar to the American longitude sector, this feature progresses toward later local times in the ∼5–10 days following the SSW. The GAIA and WAM+GIP models simulate a strong morning increase and afternoon decrease in the equatorial vertical plasma drifts, but do not indicate a shift of this feature toward later local times until around day 40, which is later than seen in the observations. The WACCMX+TIMEGCM simulation again appears to be the only simulation that well reproduces the shift of the vertical plasma drift perturbations toward later local times, providing further evidence that inclusion of the lunar tide may be critical for capturing this feature of the ionosphere variability during SSWs. We note that the shift of the plasma drift perturbations toward later local times could be related to a phase shift in the $\text{SW}_2$. However, as shown in Pedatella et al. [2014b], GAIA, WAM, and WACCMX have similar phase shifts in the $\text{SW}_2$ during the 2009 SSW time period. Furthermore, when the $M_2$ is not included in the WACCMX+TIMEGCM simulation, the movement of the vertical plasma drift...
Figure 2. Perturbations in the vertical plasma drift velocity at Tirunelveli, India (77°E, 8°N) simulated by the (a) GAIA, (b) WACCMX+TIMEGCM, and (c) WAM+GIP models. (d) Observed equatorial electrojet perturbations (ΔH) from differencing magnetometer observations at Tirunelveli and Alibaug. The gray areas in Figure 2d indicate periods when observations are unavailable. The solid vertical black line indicates the timing of the polar vortex weakening. Contours are every 6 m s⁻¹ perturbations toward later local times is no longer in good agreement with the observations (see Figures 7 and 8, which will be discussed later). We can therefore conclude that the inclusion of the lunar tide is crucial for capturing the local time variability of the vertical plasma drift perturbations. It is, however, important to recognize that the differences among the simulations are not solely due to inclusion of the lunar tide but are also related to differences in the neutral atmospheres and treatment of ionospheric processes.

Figures 3 and 4 present the zonal mean \( N_m F_2 \) from the GAIA, WACCMX+TIMEGCM, and WAM+GIP simulations along with the COSMIC observations at 1000 and 1800 local time (LT), respectively. A 5 day running mean has been applied to the simulations to be consistent with the observations. The results in Figures 3 and 4 are presented on different color scales to highlight the variability in the models, which is the focus of the present paper. There are, however, notable biases among the model simulations and observations that are also important to take into consideration. For example, a notable shortcoming of the WACCMX+TIMEGCM simulation is that the \( N_m F_2 \) is significantly smaller than the observations, and the latitudinal width of the equatorial...
Recent developments in WACCMX support whole atmosphere data assimilation, providing a global view of the troposphere, stratosphere, mesosphere, thermosphere, and ionosphere state.

Currently WACCMX+DART can assimilate lower and middle atmosphere observations.

We are planning to implement assimilation of ionosphere-thermosphere observations (COSMIC electron density, ground-based GPS TEC, ICON, GOLD, …) in the near future.

Assimilation of upper atmosphere observations into WACCMX+DART has the potential to provide new insights into the ionosphere-thermosphere system:
- Self consistently combines different observations that are spatially and temporally distributed.
- Can provide information about fields that are not directly observed.
- Provides global view of the ionosphere-thermosphere driven by both lower atmosphere forcing and solar/geomagnetic variability.

WACCMX+DART requires code modifications to the standard CESM2.0 release. These are available from nickp@ucar.edu