Analysis and hindcast experiments of the 2009 sudden stratosphere warming in WACCMX+DART

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Motivation: Sudden stratosphere warming events drive large disturbances in the middle and upper atmosphere.

Change in F-region Vertical Plasma Drift Velocity
Jicamarca, Peru (75W, 12S)

To study the middle-upper atmosphere variability during specific events it is necessary to constrain the model meteorology.
Motivation: “Nudging” towards reanalysis can lead to large differences at higher altitudes due to the sensitivity of the mesosphere to GW drag

Table 1.

<table>
<thead>
<tr>
<th>Model</th>
<th>Method of Constraint</th>
<th>Range</th>
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</thead>
<tbody>
<tr>
<td>GAIA</td>
<td>Nudge to JRA-25 Reanalysis</td>
<td>Surface to 12 hPa</td>
</tr>
<tr>
<td>HAMMONIA</td>
<td>Nudge to ECMWF Reanalysis</td>
<td>850 to 1 hPa</td>
</tr>
<tr>
<td>WACCM-X</td>
<td>Nudge to NOGAPS-ALPHA/MERRA Reanalysis</td>
<td>Surface to 0.002 hPa</td>
</tr>
<tr>
<td>WAM</td>
<td>NOAA Grid point Statistical Interpolation</td>
<td>Surface to 0.1 hPa</td>
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WAM only assimilates standard lower atmosphere observations, and the data assimilation thus only directly influences the model up to ∼0.1 hPa.
Differences in modeled MLT dynamics influence nitric oxide descent.

Direct assimilation of lower, middle, and upper atmosphere observations is one approach to improving simulations of MLT dynamics.

(Siskind et al., 2015)
Framework for WACCMX+DART is identical to WACCM+DART (next slide)

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

Main change between WACCMX+DART and WACCM+DART is increased damping in WACCMX. This was necessary for model stability, and to ensure that mixing from small scale waves introduced by the data assimilation do not excessively reduce thermosphere O/N₂ and electron density.

Changes made for model stability tend to damp tidal amplitudes, and have a slight negative impact on performance of the data assimilation in the troposphere-stratosphere.

Troposphere humidity is biased by ~20-30% due to model physics issue when using a 5 min time-step.

We have performed initial WACCMX+DART analysis and hindcast simulations for the 2009 SSW time period.
WACCM+DART provides an atmospheric reanalysis from the surface to the lower thermosphere (~145 km).

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

Sparse Middle/Upper Atmosphere Observations:
- TIMED/SABER Temperature (100 - 5x10^{-4} hPa)
- Aura MLS Temperature (260 - 1x10^{-3} hPa)

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.

Middle Atmosphere Variability in WACCMX+DART and SD-WACCMX

SD-WACCMX: Specified Dynamics WACCMX constrained to MERRA meteorology up to 50km
NO descent following the SSW

Figure 1. Upper panel: daily averaged NO\textsubscript{X} mixing ratios from satellite observations (open squares) at 0.022 hPa within 60–90\degree N (black is MIPAS-NOM, blue is MIPAS-UA, red is SMR/Odin, green is ACE-FTS) and those of the upper boundary condition (filled diamonds) sampled at the respective observations’ time and location. Lower panel: mean latitude averaged over all observations of the individual instruments within 60–90\degree N. All averages are area-weighted.

Figure 2. Observed and modelled NO\textsubscript{X} VMRs of MIPAS and ACE (upper two rows) and NO of SMR (lower row) in NH polar MLT region during November 2008–March 2009. Model output of the “high-top” models 3dCTM, HAMMONIA, and WACCM has been sampled at the locations and times of the observations (MPAS-UA, ACE-FTS, and SMR) for comparison. Pink lines indicate the observed VMR levels of 0.1, 1, and 10 ppmv. White regions reflect missing or not meaningful data.


(Funke et al., 2017)
Semidiurnal Migrating Tide (10^{-4} hPa)

Figure 10. SW$_2$ amplitude of temperature at 1 × 10^{-4} hPa (∼110 km) for (a) GAIA, (b) HAMMONIA, (c) WAM, and (d) WACCM-X. (e–h) Same as Figures 10a–10d except for the SW$_2$ phase.

4. Summary and Conclusions

Recent developments in whole atmosphere modeling have enabled realistic simulations of the atmospheric response to SSWs from the surface to the upper thermosphere. Model simulations of SSWs not only are important for understanding the variability throughout the atmosphere during SSWs but also are potentially useful for predicting upper atmosphere variability by running in a forecast mode. Verifying the simulation results in the middle and upper atmosphere has, however, remained difficult owing to the lack of global-scale observations with sufficient temporal resolution. The accuracy of the simulations in the middle and upper atmosphere is thus largely unknown, and this is especially true for the short-term variability.

(Pedatella et al., 2014)
GPS TEC Variability in WACCMX+DART and SD-WACCMX

a. SD-WACCMX TEC, 75°W, 1800 LT

b. WACCMX+DART TEC, 75°W, 1800 LT

c. GNSS TEC, 75°W, 1800 LT
2009 SSW Hindcast Experiments

- Initialize 40-member ensemble forecasts (hindcasts) of the 2009 SSW on January 5, 10, 15, 20, and 25.

- Ocean SSTs are specified as the true values (i.e., not forecasted)

- Solar activity is specified by using 27-days prior solar activity
2009 SSW Hindcasts: 70-90° N Temperature

a. Jan. 5, T 70-90°N

b. Jan. 10, T 70-90°N
c. Jan. 15, T 70-90°N

d. Jan. 20, T 70-90°N
e. Jan. 25, T 70-90°N
f. Analysis T 70-90°N

Pressure (hPa)

Day of Year, 2009
2009 SSW Forecasts: TEC at 75W

a. Jan. 5, TEC, 75°W, 1800 LT

b. Jan. 10, TEC, 75°W, 1800 LT

c. Jan. 15, TEC, 75°W, 1800 LT

d. Jan. 20, TEC, 75°W, 1800 LT

e. Jan. 25, TEC, 75°W, 1800 LT

f. Analysis TEC, 75°W, 1800 LT
Recent developments in WACCMX support whole atmosphere data assimilation, providing a global view of the troposphere, stratosphere, mesosphere, thermosphere, and ionosphere state.

Middle atmosphere chemical and dynamical variability are generally well reproduced in WACCMX+DART.

Tidal amplitudes are generally too weak in WACCMX+DART, indicating the need to determine a better method for filtering small-scale waves introduced by DA.

Ionosphere variability during the 2009 SSW is reproduced in WACCMX+DART.

Forecast experiments for 2009 SSW show that middle-upper atmosphere variability can be qualitatively predicted ~5-10 days in advance of the SSW.

Work is ongoing to improve ionosphere-thermosphere analysis fields through assimilation of ionospheric observations.
TEC hindcasts with fixed solar forcing
Diurnal Migrating Tide

Figure 9. \(DW_1\) amplitude of temperature at 0.01 hPa (\(\sim 80\) km) for (a) GAIA, (b) HAMMONIA, (c) WAM, and (d) WACCM-X. (e–h) Same as Figures 9a–9d except for the \(DW_1\) phase.

At altitudes (Figures 7 and 8), it is not surprising that there is little agreement for the \(SW_1\). Since \(SW_1\) is a non-migrating tide, and therefore is longitudinally dependent at a fixed local time, the considerable differences in the simulated \(SW_1\) may have consequences for the simulated local time variability at specific longitudes.

Results for the \(SW_1\) demonstrate that there are aspects of the modeled tidal response to the 2009 SSW that are significantly different among the models, and that portions of the middle and upper atmosphere response to SSWs are highly uncertain in the model simulations.

(Pedatella et al., 2014)
2009 SSW Forecasts: Solar+Lunar Semidiurnal Migrating Tide
Impact of DA ‘noise’ on the ionosphere electron density