MODERN ERA REANALYSIS FOR RESEARCH AND APPLICATIONS VERSION-2 (MERRA-2)

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Global Modeling and Assimilation Office
Overview

- Project Summary and Motivation
- Water Cycle and UTH
- Energy Budget and Temperature
- Weather
- Plans
Modern-Era Retrospective analysis for Research and Applications (MERRA)

- 1979-Present (will not continue, depending on radiance observations availability)
- $\frac{1}{2}^\circ$ lat x $\frac{2}{3}^\circ$ lon, 42 pressure levels (derived from 72 terrain following model levels)
- 1 hourly Surface/2D fields, 3 and 6 hourly 3D fields; over 300 variables
- NCEP GSI analysis (~2008)
- GEOS5 GCM (~2008)
- Offline land (MERRA-Land) and ocean reprocessing products
- Gridded Innovations and Observations (GIO)
MERRA-2 Motivation and Objectives

Produce an ongoing, intermediate reanalysis for the satellite era using a recent version of GEOS-5 to

1. address known limitations of MERRA (c. 2008), and

2. provide a stepping stone to a future coupled Earth system reanalysis.

Specifics:

• Incorporate modern satellite observation types not available to MERRA
• Reduce spurious trends and jumps related to changes in the observing system
• Reduce biases and imbalances in the water and energy cycles
• Test coupling GOES-5 meteorology with other Earth system components
• Data counts increase as more hyperspectral sensors become active
• No microwave radiance data after NOAA-18 in MERRA
• Data counts for MERRA could decrease rapidly, especially if AIRS data were no longer available
• In MERRA-2, current, AMSUA, IASI, and AIRS provide most global impact from radiances
The MERRA-2 data assimilation system

**GEOS-5.12.4 AGCM/GSI 3D-Var**
0.5° x 0.625° x 72 hybrid-eta levels to 0.01 hPa

**MERRA ➔ MERRA-2 Evolution**

- Updates to the AGCM and GSI
  - **AGCM**
    - *Cubed-sphere dynamics*
    - *Updated physics: limited deep convection, re-evap of rain, snow sublimation*
    - *Improved glacier model and cryosphere albedos*
  - **GSI**
    - *Modern observations: GPSRO, NOAA-19, MetOp-A/B, S-NPP, SEVIRI, Aura OMI and MLS, capable for JPSS, MetOp-C*
    - *Updated moisture control variable and background errors*
    - *Bias correction for aircraft temperature observations*
    - *Balance constraint for noise*
    - *TC Relocation*

- Aerosol assimilation with radiative coupling to AGCM (direct effects)
- Constraints on dry mass and globally integrated water
- Corrected precipitation for land surface forcing and aerosol deposition
Surface boundary conditions and emissions

**SST and Sea Ice Concentration**

- **HadISST1**
- **Reynolds OI.v2** (weekly 1°)
- **CMIP**
- **Reynolds** (daily 0.25°) **OSTIA** (daily 0.25°)

**Jan 1982** **Apr 2006**

**Aerosols and Trace Gasses**

- CO fossil fuel emissions *(EDGAR inventory)*
- Biomass burning *(QFED after 2010, RETRO before)*
- Volcanic SO$_2$ *(AEROCOM emissions and injection heights)*
Aerosols and Trace Gases in MERRA-2

MERRA-2 Aerosol Analysis 10 July 2013 1200UTC

- Black and organic carbon, dust, sea salt, sulfates
- GOCART – mixing, chemistry and deposition
- Radiatively coupled with the dynamics
- Global 2-D AOD analysis with 3-D increments via local displacement ensembles
- Data: AVHRR 1979–2002; MODIS 2000–present; MISR; AERONET

North America/Adjacent Atlantic AOD

East Asia/Adjacent Pacific AOD

Mt. Pinatubo

Lake Baikal Fires
MERRA-2 captures the Mt. Pinatubo eruption in June 1991
The eruption sent a thick sulfate plume rapidly upwards into the stratosphere, which fanned out westward on the prevailing easterly winds aloft (left). By July 1991, the sulfate plume encompassed the tropics globally (right).
Water Cycle
MW data sources with large impact on MERRA have somewhat less impact on MERRA-2 Precipitation
MW data sources with large impact on MERRA have much less impact on MERRA-2 Global TPW.
In MERRA, imbalances of P and E result from analysis adjustments, sensitive to changes in the observing system. Globally, precipitation, evaporation and analysis forcing are penalized for global imbalances (Takacs et al., NASA GMAO Tech Memo, 2015).

In MERRA-2, unphysical changes in total mass are ameliorated and global balance between P, E is maintained.
Land/Ocean Water Mass Budgets

- Ocean Precipitation and evaporation track each other's variability, than the analysis increment.
- Land evap follows the bias corrected precip. Land model precip follows the analysis increment trend.
- Increment jump in 2003 due to AIRS?
Aside: AIRS Withholding Experiment
AIRS Withholding Experiment

- 2003-2005 MERRA-2 without AIRS
- Land/Ocean offset in Latent Heat and Analysis Increment ($\sim 0.1 \text{ mm day}^{-1} \text{ Pr}$)

<table>
<thead>
<tr>
<th>W m$^{-2}$</th>
<th>Global</th>
<th>Land</th>
<th>Ocean</th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td>86.7 (0.5)</td>
<td>44.4 (0.0)</td>
<td>106.3 (0.8)</td>
</tr>
<tr>
<td>LPr</td>
<td>87.6 (0.5)</td>
<td>82.6 (-2.9)</td>
<td>89.9 (2.1)</td>
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<tr>
<td>HANA</td>
<td>-2.9 (-0.9)</td>
<td>-1.9 (2.4)</td>
<td>-3.4 (-2.4)</td>
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<tr>
<td>TOA(Net)</td>
<td>-4.5 (0.1)</td>
<td>-16.4 (0.4)</td>
<td>1.0 (-0.1)</td>
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<tr>
<td>Sfc(Lwnet)</td>
<td>-61.7 (-0.4)</td>
<td>-69.3 (-0.6)</td>
<td>-58.2 (-0.3)</td>
</tr>
<tr>
<td>Sfc(Swnet)</td>
<td>162.6 (0.4)</td>
<td>148.4 (0.9)</td>
<td>169.1 (0.2)</td>
</tr>
</tbody>
</table>
MERRA-2 Precipitation comparison with MERRA, GPCP

Blue shades imply MERRA-2 closer to GPCP than MERRA

MERRA-2 improves over oceans, but rains excessively over tropical high terrain
Corrected precipitation forcing of the land surface

The **land surface** in MERRA-2 sees precipitation that is a mix of observations and model-generated precipitation. (Reichle and Liu, *NASA GMAO Tech Memo, 2014*)

- Daily gauge-based **CPCU** data used over midlatitudes and tropics, except Africa
- Pentad gauge- and satellite-based **CMAP** data used over Africa
- Precipitation generated by **MERRA-2** itself used over high latitudes

- **MERRA-2 root zone soil wetness** differs from that of MERRA due to differences in precipitation forcing and, to a lesser extent, differences in catchment model parameters.
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Upper Tropospheric Humidity

- MERRA lacking some data used in M2 and ERA after 2002
- MERRA-2 increase in qv model not observing system, primarily in the tropics
Energy Budget and Temperature
Precipitation comparison with Padang, Sumatra station data

4400 mm average annual rainfall at 7-m elevation
(1) Both MERRA-1 and -2 are very realistic, showing tropical convection, mid-/high-latitude cloud, and subtropical subsidence zones (cloud minima); (2) MERRA-2 does better over continents and in subsidence zones; (3) MERRA-2 has excessive Western Pacific convection.
(1) MERRA-1 & -2 are both realistic, showing tropical convection, high-latitude stratus, and subtropical subsidence zones (cloud minima); (2) MERRA-2 does better than MERRA-1 over continents and in subsidence zones; (3) MERRA-2 has excessive Western Pacific & Southern Ocean cloud cooling (albedo).
Global OLR
Global TOA Absorbed SW
Global TOA Net

Global Monthly (12mo) TOA Net Flux (W m⁻²)
Global Surface Downward LW
Widespread negative shows net cooling due to clouds

(1) Both MERRA-1 & -2 show general net negative cloud forcing, especially in stratus regions; (2) MERRA-2 does better over Eurasia and North America; (3) MERRA-2 has excessive Western Pacific and Southern Ocean cloud cooling.

NCF relative to EBAF

Courtesy Peter Norris
MSU Temperature

- Mean from 1981-2010
- MERRA-2 leans warm in early 2000s, following SST
- MERRA-2 Lower Trop trend trend improved from MERRA

<table>
<thead>
<tr>
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<th>TLT</th>
<th>TLS</th>
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<tbody>
<tr>
<td>Mean (K)</td>
<td>Trend (K/10yr)</td>
<td>Mean(K)</td>
</tr>
<tr>
<td>UAH</td>
<td>268.7</td>
<td>0.14</td>
</tr>
<tr>
<td>MERRA-2</td>
<td>270.1</td>
<td>0.17</td>
</tr>
<tr>
<td>MERRA</td>
<td>270.1</td>
<td>0.19</td>
</tr>
<tr>
<td>ERA-I</td>
<td>267.3</td>
<td>0.13</td>
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</table>

Trend computed over 1980-2014
MERRA-2 Surface air temperature comparison with MERRA, HadCRU

MERRA-2 $T_{2m}$ minus HadCRU July (34yrs)

ABS(MERRA-2, MERRA) $T_{2m}$ vs. HadCRU July (34yrs)

Blue shades show MERRA-2 closer to HadCRU data than MERRA

Results for January show smaller overall improvement
Land 2m T Time Series

Land(60) Monthly (12mo) 2m Temp (K)

- MERRA-2
- MERRA
- ERA-I
- JRA-55
- CFSR
- 20CR
- CRU
• Temperature over sea ice is significantly affected by **surface albedo**. Other processes can be important (clouds!).
• In MERRA, ice albedo was fixed constant (0.6).
• In MERRA-2, Arctic ice albedo is seasonally prescribed (monthly).
• MERRA: ~10°C May bias., MERRA-2: reduced Bias, differences remain.

Courtesy Richard Cullather
- ~2ft snow depth over large portion of the East
- Vertical cross section shows a textbook depiction of the tropopause fold (in blue), jet stream (black contour and temperature gradients (red dash))
Plans
MERRA-2 12km Dynamical Downscaling: Hurricane Sandy 2012

12-km “Replay”
- Replay to 50-km MERRA2 Increments
- 12-km Horizontal Resolution
- 72 Vertical levels
- Non-Hydrostatic FV3 Dynamics
- Full Aerosol Reanalysis (MERRA2-aero)
- Including CO₂
- Initially Two Streams
  - Dec-1999 – May-2005
  - May-2005 – Nov-2010
- Eventually 30+ years 1979-present
MERRA-2 Products and Ancillary Applications

Completed 1980-present, now running as a continuing climate analysis with 2-3 week latency

Data release expected to begin in July 2015 via the NASA Goddard Earth Sciences (GES) Data Information Services Center (DISC)

- 1-hourly surface/2D fields, 3- and 6-hourly 3D fields
- Daily Products ~25 GB/day (9.1 TB/yr)
- Monthly Products ~34 GB/mo (408 GB/yr)

Ensemble of (initially) 10 AMIP integrations using the MERRA-2 model configuration

MERRA-2-driven analyses of ocean state (physics and biogeochemistry), atmospheric chemistry (EOS period), and carbon cycle.
Toward an Integrated Earth System Analysis
## Reanalysis Progression

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<thead>
<tr>
<th></th>
<th>MERRA</th>
<th>MERRA-2</th>
<th>Next Target</th>
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<tbody>
<tr>
<td><strong>System vintage</strong></td>
<td>2008</td>
<td>2014</td>
<td>2017</td>
</tr>
<tr>
<td><strong>Release</strong></td>
<td>2009</td>
<td>mid 2015</td>
<td>late 2018</td>
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<tr>
<td><strong>Scope</strong></td>
<td>Atmosphere</td>
<td>Atmosphere, including aerosols and land correction</td>
<td>Atmosphere-ocean-ice-land</td>
</tr>
<tr>
<td><strong>Resolution</strong></td>
<td>$0.5^\circ \times 0.66^\circ$ L72</td>
<td>$0.5^\circ \times 0.625^\circ$ L72 (C180 cubed sphere)</td>
<td>$0.25^\circ \times 0.3125^\circ$ L137 (C360 cubed sphere) + 25-km ocean</td>
</tr>
<tr>
<td><strong>Analysis</strong></td>
<td>3D-Var atmos</td>
<td>3D-Var atmos</td>
<td>4D EnsVar atmos</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>+ EnKF land</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>+ EnOI ocean</td>
</tr>
</tbody>
</table>
Thanks!