Efforts to Assimilate the AFWA Snow Depth Product into NCEP Operational CFS/GFS System

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ISWG Workshop in Monterey, CA • 19-20 July 2017
Outline

• NCEP Land Data Assimilation Systems
• NASA Land Information System Applications
• Land Data Assimilation Experiments
• Summary
Uncoupled “NLDAS” (drought)

Climate
- CFS
- MOM3

Global Data Assimilation

Regional Data Assimilation

Global Forecast System

Oceans
- HYCOM
- WaveWatch III

Hydrology

Short-Range
Ensemble Forecast
- WRF: ARW, NMM, ETA, RSM

Regional NAM
- WRF NMM (including NARR)

Air Quality
- NAM/CMAQ

Dispersion
- ARL/HYSPLIT

Severe Weather
- WRF NMM/ARW
- Workstation WRF

Rapid Update for Aviation (ARW-based)

Noah Land Model Connections in NOAA’s NWS Model Production Suite
Unified NCEP-NCAR Noah Land Model

- Four soil layers (shallower near-surface).
- Numerically efficient surface energy budget.
- Jarvis-Stewart “big-leaf” canopy conductance with associated veg parameters.
- Canopy interception.
- Direct soil evaporation.
- Soil hydraulics and soil parameters.
- Vegetation-reduced soil thermal conductivity.
- Patchy/fractional snow cover effect on sfc fluxes.
- Snowpack density and snow water equivalent.
- Freeze/thaw soil physics.

- Noah coupled with NCEP model systems: short-range NAM, medium-range GFS, seasonal CFS, HWRF, uncoupled NLDAS, GLDAS.
Noah Multi-Physics (Noah-MP)

Noah-MP is an extended version of the Noah LSM with enhanced multi-physics options to address shortcomings in Noah.

- Canopy radiative transfer with shading geometry.
- Separate vegetation canopy layer.
- Dynamic vegetation.
- Ball-Berry canopy resistance.
- Multi-layer snowpack.
- Snow albedo treatment.
- New snow cover.
- Snowpack liquid water retention.
- New frozen soil scheme.
- Interaction with groundwater/aquifer.

Main contributors: Zong-Liang Yang (UT-Austin); Guo-Yue-Niu (U. Arizona); Fei Chen, Mukul Tewari, Mike Barlage, Kevin Manning (NCAR); Mike Ek (NCEP); Dev Niyogi (Purdue U.); Xubin Zeng (U. Arizona)

Noah-MP references: Niu et al., 2011, Yang et al., 2011. JGR
Global Land Data Assimilation System (GLDAS)

- **Noah land model** running under NASA Land Information System forced with **Climate Forecast System** (CFS) atmos. data assimil. cycle output, & “blended” precipitation (gauge, satellite & model), “semi-coupled” –daily updated land states.

- **Snow** cycled if snow from Noah land model within a 0.5x/2.0x envelope of observed value (IMS snow cover, AFWA depth).

- **GDIS**: GLDAS soil moisture climatology from 30-year runs provides **anomalies for drought monitoring**.

- GLDAS land “re-runs”, with updated forcing, physics, etc.

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![Images](GDAS-CMAP precip, Gauge locations, IMS snow cover, AFWA snow depth)
North American Land Data Assimilation System (NLDAS)

- NLDAS: 4 land models run uncoupled, driven by CPC observed precipitation & NCEP R-CDAS atmospheric forcing.
- Output: 1/8-deg. land & soil states, surface fluxes, runoff & streamflow; anomalies from 30-yr climatology for drought.
- Future: higher res. (~3-4km), extend to N.A./global domains, improved land data sets/data assimil. (soil moisture, snow), land model physics upgrades inc. hydro., initial land states for weather & seasonal climate models; global drought information.

www.emc.ncep.noaa.gov/mmb/nldas
**Satellite-based Land Data Assimilation in NWS GFS/CFS Operational Systems**

- Use NASA Land Information System (LIS) to serve as a global Land Data Assimilation System (LDAS) for both GFS and CFS.
- LIS EnKF-based Land Data Assimilation tool used to assimilate soil moisture from the NESDIS global Soil Moisture Operational Product System (SMOPS), snow cover area (SCA) from operational NESDIS Interactive Multisensor Snow and Ice Mapping System (IMS) and AFWA snow depth (SNODEP) products.

**NGGPS Project: Land Data Assimilation**

Michael Ek, Jiarui Dong, Weizhong Zheng (NCEP/EMC)
Christa Peters-Lidard, Grey Nearing (NASA/GSFC)

1. Build NCEP’s GFS/CFS-LDAS by incorporating the NASA Land Information System (LIS) into NCEP’s GFS/CFS (left figure)
2. Offline tests of the existing EnKF-based land data assimilation capabilities in LIS driven by the operational GFS/CFS.
3. Coupled land data assimilation tests and evaluation against the operational system.
NASA Land Information System (LIS)

- LIS is a flexible land-surface modeling and data assimilation framework developed with the goal of integrating satellite- and ground-based observed data products with land-surface models.

Data Assimilation of: Soil Moisture, SWE, SCF, TWS
<table>
<thead>
<tr>
<th></th>
<th>GFS/CFS/GLDAS</th>
<th>Meso. NAM</th>
<th>NLDAS</th>
<th>LIS</th>
</tr>
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<tbody>
<tr>
<td><strong>Noah Version</strong></td>
<td>2.7.1</td>
<td>3.0</td>
<td>2.8</td>
<td>2.7.1 to 3.6 Noah-MP</td>
</tr>
<tr>
<td><strong>Resolution</strong></td>
<td>T1534</td>
<td>12km</td>
<td>1/8th degree</td>
<td>Multiple</td>
</tr>
<tr>
<td><strong>Grid</strong></td>
<td>Gaussian</td>
<td>B-grid</td>
<td>Lat/Lon</td>
<td>Multiple</td>
</tr>
<tr>
<td><strong>Forcing</strong></td>
<td>Coupled</td>
<td>Coupled</td>
<td>Offline</td>
<td>Offline</td>
</tr>
<tr>
<td><strong>Atmos. DA</strong></td>
<td>GSI/GSI/NA</td>
<td>GSI</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td><strong>Land DA</strong></td>
<td>DI/DI/DI</td>
<td>DI</td>
<td>NA</td>
<td>DI, EnKF</td>
</tr>
</tbody>
</table>
NCEP/EMC Land Team and DA Partners

NCEP/EMC Land Team: Michael Ek, Jiarui Dong, Weizhong Zheng, Helin Wei, Jesse Meng, Youlong Xia, Rongqian Yang, Yihua Wu, Caterina Tassone, Roshan Shresth, working with:

Land Data Assimilation Algorithm:
• NASA/GSFC: Christa Peters-Lidard, Sujay Kumar et al. (LIS)
• NASA/GMAO: Rolf Rechelie et al. (EnKF)
• University of Maryland: Ning Zeng, Steve Penny (LETKF)
• NESDIS/STAR: Xiwu Zhan et al. (EnKF)
• Monash University, Australia: Jeffrey Walker (EKF)

Remotely-sensed Land Data Sets:
• NESDIS/STAR land group: Ivan Csizs, Xiwu Zhan (soil moisture), Bob Yu (Tskin), Marco Vargas (vegetation) et al.
• NESDIS/OSPO: Sean Helfrich (IMS snow cover)
• AFWA: Jeffrey Cetola (snow depth)
• NASA/GSFC: Dorothy Hall (MODIS snow cover), James Foster (SWE)

Verification:
• GEWEX/GLASS, GASS projects: Land model benchmarking, land-atmosphere interaction exp. with international partners.
The **Air Force Weather Agency (AFWA)** snow depth is estimated daily by merging satellite-derived snow cover data with daily snow depth reports from ground stations.

Snow depth reports are updated by additional snowfall data or decreased by calculated snowmelt.

The **Interactive Multisensor Snow and Ice Mapping System (IMS)** snow cover product is a snow cover analysis at 4-km resolution manually created by looking at all available satellite imagery, several automated snow mapping algorithms, and other ancillary data.

Regions covered by cloud during the 24-hour analysis period take lower resolution passive microwave data and surface observations into account where possible. There are no missing values over the mapped region.
10,179 stations with at least one-year data records from year 2012 are selected

Global Historical Climate Network
Total Station Number: 50,020
Comparison of daily snow depth

AFWA SNODEP and GFS snow depth versus OBS

AFWA – OBS  (1.2 mm)
GFS – OBS  (-5 mm)
**Method**

POD$_S$ measures the fraction of observed snow cover presence that were correctly detected in AFWA/IMS/GFS

POD$_N$ measures the fraction of observed snow-free land that were correctly detected in AFWA/IMS/GFS

FAR measures the fraction of observed snow-free land that were incorrectly detected as snow cover in AFWA/IMS/GFS

\[ \text{POD}_S = \frac{SS}{NS + SS} \]

\[ \text{POD}_N = \frac{NN}{NN + NS} \]

\[ \text{FAR} = \frac{SN}{SN + NN} \]

POD: Probability of Detection

FAR: False Alarm Ratio
**Statistics**

**POD and FAR statistics of IMS SCA, AFWA snow depth and GFS snow depth**

\[ POD_s = \frac{SS}{NS + SS} \quad \text{FAR} = \frac{SN}{SN + NN} \]
Comparison of POD between AFWA SNODEP and IMS Snow Cover
1. Forcing:

- **Parallel GFS/GDAS**
  - 2012010100
  - 2013053123

- **Operational GFS/GDAS**
  - 20130601100
  - 2015011400

- **T574**
- **T1534**

2. Initial conditions:

   Spinup run three times over GFS forcing from 01/01/2009 to 12/31/2011

   **Control Run**: Starting at 00Z 01/01/2012 with initial condition from spinup run
   **Direct Replacement**: Starting at 01/01/2014 with the initial condition from the Control Run.
   **EnKF**: With 20 ensemble members starting at 01/01/2014 with the initial condition from the Control Run.

3. Model configuration:

   Model is configured at T1534 (3072 by 1536) globally
**Data Assimilation Formulation**

**Forecast**

\[
X_{i,k}^f = M_{k-1}[X_{i,k-1}^a] + \varepsilon_{i,k-1}
\]

**Update**

\[
X_{i,k}^a = X_{i,k}^f + K_k(y_k - H_k X_{i,k}^f + r_{i,k})
\]

**Kalman Gain:**

\[
K_k = \frac{P_k^f H_k^T}{H_k P_k^f H_k^T + R_k}
\]

**Forecast Covariance:**

\[
P_{k}^f = M_{k-1} P_{k-1}^a M_{k-1}^T + Q_{k-1}
\]

**Analysis Covariance:**

\[
P_{k}^a = (I - K_k H_k) P_k^f (I - K_k H_k)^T + K_k R_k K_k^T
\]
# Specifying Perturbations

<table>
<thead>
<tr>
<th>#ptype</th>
<th>std</th>
<th>std_max</th>
<th>zeromean</th>
<th>tcorr</th>
<th>xcorr</th>
<th>ycorr</th>
<th>ccorr</th>
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</thead>
<tbody>
<tr>
<td>Incident Shortwave Radiation</td>
<td>1</td>
<td>0.20</td>
<td>2.5</td>
<td>1</td>
<td>86400</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Incident Longwave Radiation</td>
<td>0</td>
<td>30.0</td>
<td>2.5</td>
<td>1</td>
<td>86400</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Rainfall Rate</td>
<td>1</td>
<td>0.50</td>
<td>2.5</td>
<td>1</td>
<td>86400</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Near Surface Air Temperature</td>
<td>0</td>
<td>0.50</td>
<td>2.5</td>
<td>1</td>
<td>86400</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

- **SNODEP obs**
  - 1    | 0.01 | 2.5    | 1    | 10800 | 0     | 0     | 1

- **Perturbation type:** additive (0) or multiplicative (1)
- **Std:** standard deviation of perturbations
- **Zero mean:** enforce zero mean across the ensemble
- **Std_max:** maximum allowed normalized perturbation (relative to $N(0,1)$)
- **Tcorr:** temporal correlation scale (in seconds) used in the AR(1) model
- **Xcorr, Y-corr:** Spatial correlation scale (deg)
- **Ccorr:** cross correlations between variables
Demonstration of LIS land data assimilation of AFWA Snow Depth

EnKF

01/01/2014 00Z
04/01/2014 00Z
07/01/2014 00Z
10/01/2014 00Z

Direct Insertion

Control Run

GFS/GDAS

Legend:
Land
0.1 0.2 0.3 0.4 0.5 0.6 0.8 0.9 1.0 1.1 1.2 1.3 m
GFS demonstrates a strong ability to simulate the presence of snow cover (98%) comparing to IMS (94%) and AFWA SNODEP (87%).

However, GFS show larger false snow cover detection (14%) than IMS (8%) and AFWA (9%).

LIS/Noah offline run with GFS forcing shows even higher POD in snow detection (99%), but false alarm ratio is as higher as 32%.

LIS/Noah-MP offline run with GFS forcing shows higher POD in snow detection (97%), and false alarm ratio is 12%.

\[ POD_S = \frac{SS}{NS + SS} \]
\[ POD_N = \frac{NN}{NN + NS} \]
\[ FAR = \frac{SN}{SN + NN} \]
Statistics of the offline LIS/Noah, LIS/Noah-MP, operational GFS/GDAS, IMS snow cover, and AFWA snowdepth with the in-situ observations

<table>
<thead>
<tr>
<th>Model</th>
<th>$POD_S$</th>
<th>FAR</th>
<th>Accuracy $POD_{S+N}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>IMS</td>
<td>93.85</td>
<td>8.29</td>
<td>91.91</td>
</tr>
<tr>
<td>AFWA</td>
<td>87.46</td>
<td>8.80</td>
<td>90.85</td>
</tr>
<tr>
<td>GFS/GDAS</td>
<td>98.35</td>
<td>14.47</td>
<td>86.69</td>
</tr>
<tr>
<td>LIS/Noah.3.3</td>
<td>99.50</td>
<td>32.10</td>
<td>71.01</td>
</tr>
<tr>
<td>LIS/Noah-MP3.6</td>
<td>96.57</td>
<td>12.73</td>
<td>88.19</td>
</tr>
</tbody>
</table>

POD$_S$ = \[
\frac{SS}{NS + SS}
\]  

FAR = \[
\frac{SN}{SN + NN}
\]  

POD$_{S+N}$ = \[
\frac{SS + NN}{NS + SS + SN + NN}
\]
Statistics over January 2014 to December 2016
EnKF VS Others

Statistics over January 2014 to December 2016
Challenges in land data assimilation

- 2100 (53.42N; 109.02E)
  - RMS_enkf = 0.0490
  - RMS_gfs = 0.1323
  - RMS_lis = 0.3432
  - RMS_ofwa = 0.0861

- 2113 (52.65N; 115.17E)
  - RMS_enkf = 0.2480
  - RMS_gfs = 0.2391
  - RMS_lis = 0.0365
  - RMS_ofwa = 0.3146

- 2120 (51.10N; 106.65E)
  - RMS_enkf = 0.1342
  - RMS_gfs = 0.0283
  - RMS_lis = 0.0185
  - RMS_ofwa = 0.1528

Model - OBS

Precip (mm/day)

Delta Precip (mm/day)
Challenges in land data assimilation

2109 (52.98N; 108.28E)
RMS_enkf = 0.0674
RMS_Jis = 0.0955

2118 (51.72N; 105.85E)
RMS_enkf = 0.0517
RMS_Jis = 0.4351

2101 (53.62N; 109.63E)
RMS_enkf = 0.0683
RMS_gfs = 0.4636
RMS_Jis = 0.1118
RMS_afwa = 0.1176
EnKF (12, 20 VS 40 members)

12 members

40 CPU hours/year

20 members

62 CPU hours/year

40 members

70 CPU hours/year
Challenges in land data assimilation

1) Differences between satellite retrievals and model simulations are due to errors in, and inconsistencies between:
   -- satellite retrieval algorithm,
   -- model physics and parameterization,
   -- representation of spatial heterogeneity,
   -- vertical resolution, ...

2) Validation is hampered by lack of ground truth data. In any case, station data are point observations, satellite data are area averages.

3) Assimilation of satellite retrievals must consider differences between satellite and model climatologies. Otherwise, excessive and unrealistic sensible and latent heat fluxes are generated, which matter in coupled assimilation.

4) Strategies to avoid such negative effects include:
   -- Scaling of satellite retrievals into the model climatology prior to assimilation
   -- Dynamic bias estimation
   -- Dynamic tuning of model parameters
Summary

• For NWP and seasonal forecasting, assimilation of AFWA SNODEP snowdepth demonstrated the improved estimates of surface states.

• Improve land data assimilation systems (LDAS) and land-surface model physics will require further verified in the fully coupled NWP systems (e.g., GFS/CFS, and future in NEMS).

• Future assimilation will include IMS snow cover, soil moisture, GVF, LAI, Carbon, etc.
THANK YOU!