Reducing Model Bias in a High Altitude Forecast System

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Thanks to: Karl Hoppel\textsuperscript{2}, Steve Eckermann\textsuperscript{1}, Nancy Baker\textsuperscript{3}, Ben Ruston\textsuperscript{3}, Steve Swadley\textsuperscript{3}

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Outline

• Motivation & Background
• Overview of Navy NWP/DA Tools
• High-altitude NWP/DA research
• Future Challenges
• Motivation & Background
  – Why is stratospheric DA important?
• Overview of Navy NWP/DA Tools
• New high-altitude NWP/DA research
• Future Challenges
## Vertical Coupling

<table>
<thead>
<tr>
<th>Upper Atmosphere 100-500 km</th>
<th>Ion/Neutral Interactions, Geomagnetic Storms, Short Radiative Time Scale, Short Memory (“Space Weather”)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Middle Atmosphere = stratosphere + mesosphere + lower thermosphere</td>
<td></td>
</tr>
<tr>
<td>15-100 km</td>
<td>Large Angular Momentum and Drag, Long Radiative/Dynamical Time Scale, Long Memory (NAM/AO/QBO)</td>
</tr>
<tr>
<td>Troposphere 0-15 km</td>
<td>Short Time Scales, Short Memory</td>
</tr>
<tr>
<td>Ocean</td>
<td>Large Heat Reservoir, Long Memory (ENSO/PDO)</td>
</tr>
</tbody>
</table>
Seasonal Time Scales: January 2009 SSW

From Coy et al., JAMES 2011
Weather Forecasts

Improved Tropospheric Forecast Skill

(Gerber et al. BAMS 2012)
Why is Stratospheric DA Important?

Ocean/Ice

NWP

Seasonal Prediction

Space Weather

Climate

ESMF

ESPC

Earth System Prediction Capability
Outline

• Motivation & Background
• Overview of current Navy NWP/DA Tools
• High-altitude NWP/DA research
• Future Challenges
High Altitude NWP/DA Research at NRL

- Initially based on high-altitude version of the Navy Operational Global Atmospheric Prediction System (NOGAPS)
- NOGAPS-ALPHA: Combined NAVDAS 3DVAR assimilation with global spectral NWP model (T79, T239, T479) from 0 - 95 km (L68, L74, L139).
- AR: Advanced Representer
- NAVGEM: Navy Global Environmental Model

**Operational NOGAPS T239L30**

- **NOGAPS-ALPHA with NAVDAS**
  - 3DVAR
  - New GWD
  - New SW/LW htg
  - H2O & O3 photochemistry

- **NOGAPS-ALPHA with AR**
  - New 4DVAR with adjoint
  - Ensemble approach

- **NAVGEM with AR**
  - New semi-Lagrangian dynamical core
  - New upper-level radiance channels
### Forecast Model
- Semi-Lagrangian/Semi-Implicit scheme
- T359L50 ($\Delta x = 37\text{km}$, top at 0.04 hPa or $\sim 70\text{ km}$ *for now*)
- Time step = 360 sec
  (Hogan et al., 2014)

### Data Assimilation
- NAVDAS-AR 4D-Var with Variational bias correction
  (Rosmond and Xu, 2006)

### New Physics
- Simplified Arakawa-Schubert scheme
- Shallow convection
- Prognostic cloud scheme with two species
- RRTMG 4-stream radiation
- Modified cloud fraction scheme
- Modified turbulent mixing scheme

**NAVGEM replaced NOGAPS in February 2013**
**Conventional Data Types**

- Radiosondes and Pibals
- Dropsondes
- Driftsonde (Concordiasi)
- Land and Ship Surface Obs
- Fixed and Drifting Buoys
- Aircraft Obs
  - AIREPS
  - AMDAR, MDCRS
  - UAS
- Synthetic Obs (TC Bogus)

**Satellite Data Types**

- **Surface Winds**
  - Scatterometer, ASCAT
  - SSMIS (3)
  - WindSat
- **Feature Tracked Winds**
  - Geostationary (5 satellites)
  - Polar - AVHRR, MODIS, (VIIRS)
  - Combined polar/geo winds (CIMSS)
- **Total Water Vapor**
  - SSMI/SSMIS (3)
  - WindSat
- **GPS Bending Angle** (9)
- **IR Sounding Radiances**
  - IASI and AIRS (NPP CrIS)
- **MW Sounding Radiances**
  - AMSU-A (Ch 4-14) (6)
  - SSMIS (Ch 2-7, 22-24) (3)
  - SSMIS/MHS 183 GHz (4)
  - NPP ATMS (1)

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**Sources**

- NOAA-15,16,18,19, NPP
- METOP-A, METOP-B
- AQUA, TERRA, (VIIRS), (MISR)
- GOES, MTSAT, METEOSAT
- DMSP F16,17,18, (19)
- WindSat
- COSMIC 1,2,4-6, GRAS from MetOp A/B, GRACE-A, (CORIS-C/NOFS), Terra SAR-X
Current Operational Assimilation:
MW Sounders - Temperature Jacobians

AMSU-A

SSMIS

ATMS
In current operational NAVGEM v1.2.1, MW sounders provide information up to about 65 km.
SSMIS UAS Assimilation

NAVGEM T359L50 Current Operational Navy Global NWP Model
Current operational MW data is capable of providing temperature information into the mesosphere (e.g. Bell et al., 2008; Swadley et al., 2008; Hoppel et al. 2013)
### NPP OMPS Assimilation

#### OMPS Nadir-Profiler

<table>
<thead>
<tr>
<th>Property</th>
<th>Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal cell size</td>
<td>250km</td>
</tr>
<tr>
<td>Vertical cell size</td>
<td>3km</td>
</tr>
<tr>
<td>Vertical coverage</td>
<td>Tropopause to 60km</td>
</tr>
<tr>
<td>Range</td>
<td>0.1 to 15 ppmv</td>
</tr>
<tr>
<td>Accuracy</td>
<td>0.1ppmv or 20% h&lt;15km; 10% h&gt;15km</td>
</tr>
<tr>
<td>Precision</td>
<td>10% or 0.1ppmv; except between 15-50km 3% or 0.05ppmv</td>
</tr>
</tbody>
</table>

NAVGEM Ozone Assimilation

Differences ~30 hPa (near Ozone maximum) after 1 month of Ozone assimilation

OMPS is capable of providing operational stratospheric ozone for NAVGEM
• Motivation & Background
• Overview of Navy NWP/DA Tools
  – NOGAPS \(\rightarrow\) NAVGEM
  – NAVDAS 3DVAR \(\rightarrow\) NAVDAS AR 4DVAR
• High-altitude NWP/DA research
• Future Challenges
• Motivation & Background
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  – NOGAPS-ALPHA
  – NAVGEM
• Future Challenges
High-Altitude Research with NOGAPS-ALPHA

NAVADAS: NRL Atmospheric Variational Data Assimilation System (3DVAR)

Top Data Insertion Operationally

\( p_{\text{TOP}} = 0.0005 \text{ hPa} \)

\( T79L68 \)

Combined Data Assimilation & Modeling of Upper Atmosphere

**WACCM**
Whole Atmosphere Community Climate Model
0–500 km

*Full spectrum variability in solar irradiance*
*Auroral effects, ion drag, Joule heating*
*Fully interactive photochemistry, radiation, dynamics*
*Ocean/atmosphere interactions*

“Specified Dynamics” (SD)

WACCM model simulations of Jan.-Feb. 2009 driven with NOGAPS-ALPHA winds and temperatures show anti-correlation between circulation anomalies in the equatorial stratosphere (black curve) and amplitudes of diurnal (blue) and semi-diurnal (red) tides at 100 km (Sassi et al., JASTP, 2014).
Combined Data Assimilation & Modeling of Upper Atmosphere

**TIEGCM**
Thermosphere-Ionosphere
Electrodynamics General Circulation Model

Neutral Dynamics & Chemistry
Joule heating, ion drag
Electrodynamics

**NOGAPS-ALPHA**
Met. obs. + NASA satellite data
Global 6-hourly output (winds, T, O3, H2O)

Tidal amplitudes as a function of wave number for March at the equator at ~115 km from (left) TIEGCM with forcing from NOGAPS-ALPHA and (right) standard NCAR/GSWM forcing (Siskind et al., JGR, 2014).
Stratospheric QBO and its Effect on Troposphere

Generation of an internal QBO in a high-vertical resolution version of the NOGAPS-ALPHA forecast model (L139) with stochastic GWD and reduced horizontal/vertical diffusion (red curve) removes persistent easterly flow in model equatorial lower stratosphere (blue curve).

Westerly QBO phase produces lower temps. & stronger zonal flow in polar stratosphere. Resulting changes in ensemble monthly mean March sea-level pressure resemble NAM+ pattern (lower polar pressures, stronger jet stream).

High-Altitude Research with NAVGEM

Navy Global Environmental Model

**NAVDAS-AR:** Advanced Representer (4DVAR)

**Zonal mean temperature**

On 14 July 2010 at 1200 UTC

SSMIS – an operational sensor – can constrain the atmosphere nearly as well as research sensors MLS and SABER

From Hoppel et al. (2013)
As we move from NOGAPS to NAVGEM, changes to the forecast model are needed for assimilation of upper level radiances

- Extension of the model vertical domain, first to L60 (hybrid $\sigma$-p) up to 0.04 hPa (~65 km), then to L74 up to $6 \times 10^{-5}$ hPa (~116 km)
- New stratospheric-mesospheric ozone photochemistry with diurnal variability in the upper stratosphere and mesosphere
- New parameterized stratospheric-mesospheric water vapor photochemistry and quality control
- New stochastic gravity-wave drag parameterization (Eckermann, JAS, 2011)

**Important:** Reduce upper-level temperature biases (i.e., improve modeled “climate”)

Influence of vertical coordinate on forecast skill

L60 hybrid $\sigma$-$p$ coordinate (green) produces smaller forecast temperature errors than pure $\sigma$ (blue) in tests with fully coupled forecast/assimilation system

(Eckermann et al., *Mon. Wea. Rev.*, 2014)
Extending Model Top Past 100 km

Extension of NAVGEM model vertical domain past 100 km (left, blue curve) fully resolves atmospheric region sampled by SSMIS UAS channels on operational DMSP platforms (right).
UAS assimilation needs Community Radiative Transfer Model (CRTM) containing Zeeman Splitting corrections \cite{Han2010}
Parameterized Ozone Photochemistry

NAVGEM currently uses a linearized ozone photochemistry parameterization based on diurnally averaged odd-oxygen (O₃+O) production and loss rates in the stratosphere. It does not account for diurnal cycle in ozone present above 1 hPa.

A new generalized ozone photochemistry parameterization has been tested in NOGAPS-ALPHA (above), and is slated for testing in L74 NAVGEM.

This will facilitate assimilation of both daytime & nighttime O₃ in upper stratosphere
Parameterized $\text{H}_2\text{O}$ Photochemistry

Spec. Humidity Analysis 15 Nov 2011

No H2O photochemistry

Spec. Humidity Analysis 15 Nov 2011

with H2O photochemistry

Nov Climatology

% Difference (H2O chem. – no H2O chem)
Parameterized H$_2$O Photochemistry: Reducing Forecast Temperature Bias

288-Hour Forecast Temperature Difference: (H$_2$O chem) – (no H$_2$O chem)

- Negative (colder)
  - More water, more IR cooling

- Positive (warmer)
  - Less water, less IR cooling
Improved background humidity enables IR (IASI) water vapor radianc assimilation

**IASI assimilation reduces humidity bias w.r.t. radiosondes**

**Reduced MW radianc bias in water vapor channels (blue lines)**

**Adding IR water vapor radiances improves fit to both radiosonde and MW radiances**

*Figures show plots of bias against pressure, illustrating the improvement with the addition of IR WV radiances and the reduction in humidity bias compared to radiosondes. The plots also demonstrate a reduction in MW radiance bias in water vapor channels.*
GWD Impacts During 2012 SSW

NAVGEM T425L60
No GWD

* NAVGEM
Aura MLS
NOGAPS-ALPHA
GWD Impacts During 2012 SSW

**NAVGEM T425L60**

**GWD on**

◊ * NAVGEM

- Aura MLS

- NOGAPS-ALPHA

![Graph showing temperature changes over time for 2012 SSW with NAVGEM, Aura MLS, and NOGAPS-ALPHA lines.](image-url)
Temperatures at top of NAVGEM model are too cold. Radiative heating (SW and LW) needs improvement.

Heating in upper mesosphere & lower thermosphere due to exothermic chemical recombination is also important.

We are currently testing various approaches to parameterize this process using output from Whole Atmosphere Community Climate Model (e.g., Garcia et al., JGR, 2007).
• Motivation & Background
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### Satellite Assimilation: Satellite Observation Types

#### Polar Orbiting Radiances
- DMSP F16 SSMIS LAS, UAS, Imager
- DMSP F17 SSMIS LAS, UAS, Imager
- DMSP F18 SSMIS LAS, UAS, Imager
- METOP-A AMSU-A, IASI, MHS
- METOP-B AMSU-A, IASI, MHS
- NASA EOS Aqua AIRS, AMSU-A
- NOAA 15 AMSU-A
- NOAA 16 AMSU-A
- NOAA 18 AMSU-A, MHS
- NOAA 19 AMSU-A, MHS
- NOAA NPP ATMS, CriS, VIIRS
- GCOM-W1 AMSR-2
- Megha-Tropiques MADRAS, SAPHIR
- OceanSat-2
- MSG Severi
- MSG-II HIR
- Jason-1 (SSH, SWH)
- Jason-2 (SSH, SWH)
- Cryosat2 (SSH, SWH)
- Aquarius (Salinity)

#### Satellite Derived Polar and Geostationary Winds
- Coriolis WindSat Ocean Wind Vector
- DMSP F16 SSMIS Ocean Wind speed
- DMSP F17 SSMIS Ocean Wind speed
- DMSP F18 SSMIS Ocean Wind speed
- METOP-A AVHRR, ASCAT
- METOP-B AVHRR, ASCAT
- NASA EOS Aqua MODIS
- NASA EOS Terra MODIS, MISR
- NOAA NPP VIIRS
- Meteosat 9
- Meteosat 10
- MTSAT
- NOAA GOES E
- NOAA GOES W
- NOAA GOES-R
- KMA COMS

#### GPS Radio Occultation
- C/NOFS CORISS
- COSMIC FM1-6
- GRACE-A
- MetOp-A GRAS
- MetOp-B GRAS
- SAC-C
- TerraSAR-X
- TanDEM-X
- COMS

#### Other Satellite Products
- NASA EOS Aura MLS, HRDLs, OMI
- NASA TIMED SABER
- NOAA SBUV
- JPSS NPP OMPS
- SMOS
- SMAP
- Coriolis WindSat TPW
- DMSP F16 SSMIS TPW
- DMSP F17 SSMIS TPW
- DMSP F18 SSMIS TPW

#### Operational

#### Research Only

#### Planned
There is currently no planned follow-on SSMIS instrument with UAS channels after DMSP.
Current Operational Microwave Nadir Sounders

AMSU-A
NOAA

SSMIS
DMSP

ATMS
JPSS
Current Operational Microwave Nadir Sounders

AMSU-A
NOAA

SSMIS
DMSP

ATMS
JPSS

“Operational Gap” in the 50-100 km altitude range
Current Middle Atmosphere Research Satellites

NOGAPS-ALPHA (T79L68)

Pressure altitude (km)

Pressure (hPa)

\( p_{\text{TOP}} = 0.0005 \text{ hPa} \)

MLS Temperature
MLS Water Vapor
MLS Ozone
SABER Temperature

180W  90W  0E  90E  180E
Aura MLS (O3, T, H2O)
- Launched July 2004
- “Nominal mission lifetime of 5 years, with a goal of 6 years of operation”
Current Middle Atmosphere Research Satellites

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TIMED SABER (O3, T)
- Launched December 2001
- "Original mission lifetime of 2 years extended to 5 years"
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The future of middle atmospheric temperature, constituent observations for stratospheric DA research is uncertain
Summary

• Good news
  – A great deal of progress has been made in improving the stratosphere/mesosphere in NWP/DA systems, with anticipated payoffs for both operational and research communities

• Bad news
  – As we reach the point where we can begin to realize the full benefit of this progress, we may be losing critical observational capabilities at higher altitudes
• This work was supported by the Chief of Naval Research and by the DoD High Performance Computing Modernization Program through a grant of computer time at the Navy Distributed Supercomputing Resource Center.
Related Publications

- Chua, B. et al., 2012: Recent Applications in Representer-Based Variational Data Assimilation, in Data Assimilation for Atmospheric, Oceanic and Hydrologic Applications, Springer-Verlag.
**NAVDAS Accelerated Representer (AR)**

\[ x_a = x_b + K[y - Hx_b] \]

- H transforms from x-space to y-space
- \( K = BH^T[R + HBH^T]^{-1} \)
- \( B = MB^0M^T \)

**Data Assimilation (DA) System 4D-Var**

- **Background** \((x_b)\)
- **Observations** \((y)\)
- **Observation Error** \((R)\)
- **Initial Background Error** \((B^0)\)

**TLM Model** \((M)\)

**Analysis** \((x_a)\)

**Forecast Model NAVGEM**

- **Short forecast: 9 hours**
- **Long forecast: 10 days**

[see, e.g. Rosmond and Xu, Tellus, 2005; Xu et al., Tellus, 2005; Langland and Baker, Tellus, 2008]
Excellent spatial coverage of SSMIS compared to MLS, SABER

From Hoppel et al. (2013)