MULTISCALE DATA ASSIMILATION: THE LOCAL ANALYSIS & PREDICTION SYSTEM (LAPS)

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Acknowledgements:
Forecast Applications Branch

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OUTLINE / SUMMARY

• **Multi-scale** behavior in nature
  – Factor of 1000 from convective to synoptic scales
  – Observations affected by all scales of motion

• **Challenge** for data assimilation
  – How to extract information on multiple scales?
  – Traditional approach handles only one scale

• **Multi-scale** data assimilation approach
  – Addition of successively finer scale information

• **Local Analysis and Prediction System (LAPS)**
  – Accurate, fast, portable multi-scale analysis system
  – Wide user base, community development
MULTISCALE BEHAVIOR IN NATURE
MULTISCALE BEHAVIOR IN THE ATMOSPHERE x3
MULTISCALE BEHAVIOR IN THE ATMOSPHERE x9
MULTISCALE BEHAVIOR IN THE ATMOSPHERE
GLOBAL DATA ASSIMILATION

• **Scales of phenomena to capture**
  – Planetary, synoptic, sub-synoptic, meso, convective
    • Factor of ~1000

• **Localized observations**
  – Reflect motions on all (multiple) scales

• **DA challenge**
  – How to extract observational info on multiple scales?
    • How to spatially spread observational info?
BACKGROUND ERROR COVARIANCES

• Definition
  – Relationships among atmospheric variables in nature
    • Correlation of each variable with others across space/time

• Estimation of covariances
  – Observations – too sparse
  – Analyses – too noisy
  – Forecasts – affected by model errors

• Use
  – Spread observation increment (obs - background) in space / time
    • To reduce error in background field

• Metric
  – How well covariances capture error in background field?

• Traditional applications
  – *Single realization of covariance matrix* used
  – *Due to very high degrees of freedom, in multi-scale environment*
    • Cannot capture observational impact well
OSSE EXPERIMENTS
DENSE OBSERVATIONAL NETWORK

Truth
OSSE EXPERIMENTS
DENSE OBSERVATIONAL NETWORK

3DVAR with short-scale correlations

Truth
OSSE EXPERIMENTS
DENSE OBSERVATIONAL NETWORK

3DVAR with short-scale correlations

3DVAR with medium-scale correlations

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3DVAR with short-scale correlations

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3DVAR with long-scale correlations

Truth
OSSE EXPERIMENTS
DENSE OBSERVATIONAL NETWORK

3DVAR with short-scale correlations

3DVAR with medium-scale correlations

3DVAR with long-scale correlations

Truth

Choice for global DA – works for synoptic but not for fine scales
OSSE EXPERIMENTS
DENSE OBSERVATIONAL NETWORK

3DVAR with short-scale correlations

3DVAR with medium-scale correlations

3DVAR with long-scale correlations

Multiscale approach - Both large & fine scales captured
LITERATURE

• Theoretical foundation

• Recent dual-scale studies
  – Zhijin Li- JPL
  – Keiichi Kondo, Tsukuba University, Tsukuba, Ibaraki, Japan; and T. Miyoshi at AMS annual meeting 2014
Solve a sequence of 3-4DVARs with proper balance constraints

\[
\begin{align*}
\min J &= \frac{1}{2} (X - X^b)^T B^{-1} (X - X^b) + \\
&\quad \frac{1}{2} (H(X) - Y^o)^T O^{-1} (H(X) - Y^o)
\end{align*}
\]

Hayden, and Purser, 1995: *J. Appl. Meteor.* also shows a 3DVAR is equivalent to one LAPS pass.

**MULTIGRID APPROACH**

Long waves

\[\text{\ldots} \]

Short waves

Background

Multi-scale approach:

- **More accurate** estimate of minimum
- **Order(s) of magnitudes faster**

Minimum with single scale approach – Not well posed problem

Minimum after LONG
+ MEDIUM
+ SHORT scale iteration
LOCAL ANALYSIS & PREDICTION SYSTEM (LAPS)

• **Purpose** – NWP system for
  – Situational awareness – Nowcasting
  – Warn-On-Forecasting

• **Unique / critical qualities**
  – Consistent with observations - **Quality**
  – Fine scale (1km)
  – Efficient (5-15 mins update frequency)
  – Easy to use
  – Portable

• **Users** – 150+
  – NWS Weather Forecast Offices – AWIPS2
  – Other US agencies, private sector, academia
  – International applications – numerous countries / weather services
LAPS USER BASE

- **NOAA**
  - ~120 WFOs (via AWIPS), ARL, NESDIS
- **Other US Agencies**
  - DHS, DoD, FAA, CA DWR, GA Air Qual.
- **Academia**
  - Univ of HI, Athens, Arizona, CIRA, UND, McGill
- **Private Sector**
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  - Precision Wind, Vaisala, Telvent
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  - BoM (Australia), Canary Islands, HKO
  - Greece, Serbia, Nanjing Inst. of Met.

*Courtesy Steve Albers*
APPLICATION AREAS

• Situational awareness / Nowcasting
  – NWS WFOs

• Warn-On-Forecasting (WOF)
  – HWT

• Aviation weather – Convective Initiation
  – “STMAS is a key component of the 0-2 hr forecast” – MIT/LL
  – Terminal-scale forecasting (ITWS)

• Hydro-meteorological Forecasting
  – Heavy precipitation – HMT

• Decision support for weather dependent operations
  – AFTAC, RSA

• Fire Weather
  – Downscaling wind and other variables

• Renewable Energy
  – Boundary layer winds & solar radiation

• Dispersion modeling
  – GTAS (DHS)

• Tropical cyclone forecasting
  – Taiwan Central Weather Bureau
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ADVANCED 3D VARIATIONAL TECHNIQUE

• Multiscale in space, multi-level in time
  – Convergence / accuracy of minimization increased
    • VERY fast – 18 times faster than GSI (T. Schlatter Report)
  – Extracts & spreads observational info on multiple scales
    • Captures fine scale variations in space / time

• Novel use of background forecast
  – In presence of observations, background values not used
    • Analysis draws close to observations
    • Influence of systematic background errors minimized
  – Background’s role
    • Provides gradient information
    • Fills data gaps
    • Imparts flow dependent covariances

• Flow & terrain dependent features
  – Handles topographic & coastal variations well
  – Increments follow synoptic pattern
LAPS DIVERGENCE ANALYSIS

Continental US

24-hr Loop for Mar. 23, 2011
LAPS vs PERSISTENCE & HR

Quality of very short range forecast is indicator of analysis quality
Unique feature of LAPS, critical for WOF, Nextgen, etc

Clouds as seen from top of DSRC building in Boulder by LAPS ANALYSIS

19:30-21:15 UTC Oct 31, 2013, 15-min frequency
7-DAY MEAN RADAR COMPOSITE REFLECTIVITY SCORES

**BIAS**

Composite Reflectivity 20dBZ 7-day Bias (vlaps hwt domain)

Composite Reflectivity 30dBZ 7-day Bias (vlaps hwt domain)

Composite Reflectivity 40dBZ 7-day Bias (vlaps hwt domain)

**EQUITABLE THREAT SCORE**

Composite Reflectivity 20dBZ 7-day ETS (vlaps hwt domain)

Composite Reflectivity 30dBZ 7-day ETS (vlaps hwt domain)

Composite Reflectivity 40dBZ 7-day ETS (vlaps hwt domain)
WINDSOR, CO TORNADO SIMULATION

Cylindrical all-sky forecast image loop initialized at 1700 UTC 2008 05 22
1.7 km resolution LAPS, 1-min output frequency, out to 15 minutes

Loop starts ~45 mins before tornadic winds reached ground.
Supercell approaching from South
• **Multi-scale** behavior in nature
  – Factor of 1000 from convective to synoptic scales
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• **Local Analysis and Prediction System (LAPS)**
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OPPORTUNITIES FOR LAPS COLLABORATION?
REDRAW MAP OVER INDIA?

- **NOAA**
  - ~120 WFOs (via AWIPS), ARL, NESDIS

- **Other US Agencies**
  - DHS, DoD, FAA, CA DWR, GA Air Qual.

- **Academia**
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Courtesy Steve Albers
BACKGROUND
• **Publications**
  


  – Zoltan Toth, Mark Tew, Daniel Birkenheuer, Steve Albers, Yuanfu Xie, and Brian Motta. 2013: Multi-scale data assimilation and forecasting. BAMS, in press.


• **Point of contact:** Zoltan Toth
HISTORY OF LAPS

• Wind analysis & radar remapping (V, Z) 1989
• Cloud analysis / Hotstart 1991
  – Major innovation – 150+ citations
• T-LAPS - Terminal-LAPS at 40 ITWS/FAA sites 1992
  – Major advancement
  – 5-min update at 2km, 20+ years ahead of national guidance
• O-LAPS – System adapted at OU / CAPS 1990s
• K-LAPS - Technology transfer to KMA 1990s
• Cloud analysis / hot start elements in other systems 1995-2005
  – ADAS, RUC, etc
• LAPS operationally used at NWS WFOs (AWIPS) ~1998
• New 2DVar surface analysis – STMAS 2004
• NOAA Tech Transfer Awards 2005, 2008
• 3D-Var STMAS 2009
• STMAS transitioned to FAA operations 2012 - 2015
INNOVATIONS – (TRANSITION TO GSI)

- Downscaling first guess (easy)
- Enhanced STMAS surface analysis (easy)
- Enhanced use of observations (easy)
- Improved background error covariance (easy)
- Variational hot-start (moderate)
- More sophisticated optimization technique (moderate)
- Improved physical balance constraints (moderate)
- Multigrid technique (difficult)
- New control variables (difficult)
- Non-linear variational approach inside GSI inner loop (difficult)
- Preconditioning of the minimization (difficult)
GSI COMPONENTS TO BE USED

• Satellite data ingest modules

• Satellite bias correction

• Domain decomposition for parallelization

• Some forward operators handling remotely sensed data
INNOVATIONS – (TRANSITION TO GSI)

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LAPS CONFIGURATION

• **Domain, resolution**
  – CONUS - 2.5 km
  – Subregions – 1km

• **Observing systems / formats used**
  – 2D version: 1-min ASOS, METARs, mesonet, marine, all MADIS surface
  – 3D version: all conventional & retrieved obs, radar wind & reflectivity, satellite data

• **NDFD elements**
  – T, Td, u, v, p; visibility
  – Also available
    • Cloud ceiling, mslp, skin temp, wind gust
    • Precipitation amount & type, sky condition, visibility
LOCAL ANALYSIS & PREDICTION SYSTEM (LAPS)

- **Purpose** – NWP system for
  - Situational awareness - Nowcasting
    - Verification
  - Warn-On-Forecasting
    - For severe weather, convective initiation, aviation, fire weather, hydrometeorology, etc

- **Unique / critical qualities**
  - Consistency with observations - **Quality**
  - Fine scales to resolve severe weather related processes (1-3 km)
  - Efficiency for reduced latency and v. frequent updates (5-15 mins)
  - Ease of use
  - Portability

- **Users** – **150+ users**
  - NWS WFOs – AWIPS2
    - Critical for local control of analysis (incl. QC) & WOF process
  - Other US agencies, private sector, academia
  - International applications – numerous countries / weather services
SUMMARY

• **Quality**
  – Fine scale variations, no model bias, terrain/flow following
  – Excellent fit to withheld observations
    • 2m temp – 0.56 C MAE
  – Very short range forecast superior to other guidance
  – Positive user feedback from HWT, FDSE, CWB, MIT, KMA, CMA, etc

• **Speed**
  – 18 times faster than GSI
    • Due to multigrid technique (Schlatter report, 2013)

• **Community development**
  – Major national / international contributions / leveraging

• **Operational at WFOs**
  – Forecaster familiarity with 3D version on AWIPS2

• **Expansion to 3D**
  – Ready for use for national scale RUA applications
    • Run operationally by several agencies

• **Ease of implementation**
  – Many installations worldwide
SINGLE VS MULTISCALE MINIMIZATION

Cost function curve at coarser grid
Cost function curve at finer grid
Cost function curve at finest grid

- Initial guess of the variational analysis
- A local minimizer
- Minimizer at a coarser grid
- Minimizer at a finer grid
- The global minimizer of the variational analysis
MULTIGRID APPROACH

Solve a sequence of 3-4DVARs with proper balance constraints

Variational analysis simulating LAPS objective analysis

A Space–Time Multiscale Analysis System: A Sequential Variational Analysis Approach
Xie, et al., 2011 Monthly Weather Review.

Hayden, and Purser, 1995: J. Appl. Meteor. also shows a 3DVAR is equivalent to one LAPS pass.

Standard 3-4DVAR With a band covariance
Possible ensemble Filter application
1. Scale title
2. Outline
3. Multi-scale example - zoom in
4. Large scale DA - do a graphic scale challenge to spread stats
5. Convince not well known
   - No truth known estimates in dark?
6. Multi-scale approach - speed - not just possible
7. Scale - multi-scale
   - LAPS example
   - EP & fast border in multi-scale
8. LAPS features
9. LAPS history - multi-scale
   - 2012
10. Use LAPS features
11. May be collaboration
12. EDAR
13. Verification example 5

end - open for collaboration?

LAPS user map again

Appendix: Derivation of the Analysis Precision Equation
LAPS STATUS

• **Versions** available
  – 2D Faster
  – 3D More accurate

• **Operations**
  – Operationally used by 20+ agencies nationally and internationally
    • 3D operational on AWIPS at NWS, KMA, CWB, CMA, FMI, etc
    • 2D operational at CWB, CMA, being ported to FAA operations
  – Wide & diverse national and international user base

• **Archive**
  – Reanalysis available for China, Korea, Taiwan
    • KMA, CMA, CWB uses as proxy for truth / analysis of record
  – US real-time analysis or reanalysis can be saved / created
OSSE EXPERIMENT
DENSE OBSERVATIONAL NETWORK

3DVAR with small-scale covariance

Medium-scale

3DVAR with large-scale covariance

Truth

LAPS

STMAS
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*Courtesy Steve Albers*
• Review
  – LAPS responses to questionnaire

• Demonstrate
  – Perceived strengths/weaknesses
  – Methods to assess analysis accuracy

• Discuss
  – Lessons learned
  – Way forward

• Pose question of
  – Operational implementation requirements
LAPS INFORMATION TECHNOLOGY

• **Software design**
  – Fortran language
  – Object oriented architectural design
    • To support testing across multiple development efforts
    • Modularity

• **Code management**
  – Central code repository hosted by GSD
  – GIT revision control system
    • To support distributed development model

• **Community development**
  – Multiple partners at national & international levels
  – Major contributors led by GSD
    • KMA, FMI, CMA, CWB, Vaisala
ADVANCED 2/3D VARIATIONAL TECHNIQUE

• **Multiscale** in space, multi-level in time
  – Convergence / accuracy of minimization increased
    • **VERY fast** – 18 times faster than GSI (T. Schlatter Report)
  – Extracts & spreads observational info on multiple scales
    • Captures fine scale variations in space / time

• **Novel use of background forecast**
  – In presence of observations, background values not used
    • Analysis draws close to observations
    • Influence of systematic background errors minimized
  – Background’s role
    • Fills data gaps
    • Imparts flow dependent covariances

• **Flow & terrain dependent features**
  – Handles topographic & coastal variations well
  – Increments follow synoptic pattern
QUALITY OF LAPS SURFACE ANALYSIS

• **KMA data denial study:** Jan-Dec 2009, hrly analysis
  – 230 of 600 surface obs sites withheld
    • Measure fit to independent observations
    • Challenging terrain – 0-2000 m
  – Surface RH - 4% Mean Absolute Error (MAE)
  – 2m temperature - 0.56 °C (1.01 °F) MAE, 0.11 °C bias
  – Wind Speed – 0.2 m/s bias

• **KMA precipitation type analysis**
  – Based on wet bulb temp & thicknesses
  – Relationship tuned
  – Analyzed precipitation type (rain, snow, mixed)
    • Matches independent observations 90% of time at 76 sites
FIT TO INDEPENDENT OBSERVATIONS - KMA

2009.1.1 ~ 12.3
HOURLY ANALYSIS – 2 Million + INDEPENDENT OBSERVATIONS

2m RH

BIAS (%)

1.7%

MAE (%)

4.4%

10m Wind Speed

BIAS (m/s)

0.2 m/s

2m Temp

BIAS (°C)

-0.11 C

MAE (°C)

0.56 C

Courtesy YongHee Lee
Based on wet bulb temp & thicknesses
- Relationship tuned
Analyzed precip type at 76 sites with independent obs
  - Matches independent observations 90% of time
“LAPS again. Higher CAPE, bow echo. Lower CAPE, bye bye bow echo.”

“In my opinion, the LAPS surface-based CAPE product was one of the stars of the day.

Consistently, storms lived and died based on entering and exiting the tongue of higher CAPE values which extended north and northeast from the Big Bend area for most of the day. This first image shows the LAPS surface-based CAPE at 00Z, and the radar at the same time. Shouldn’t be hard to pick out the storm of interest. Note that the storm is still in the tongue of 1000+ J/kg of CAPE as noted on LAPS. One hour later, the storm is exiting and entering a less favorable instability regime. And predictably, it starts to weaken.

Any questions?

LAPS nailed it.”

CL

LAPS Observations and Determining Future Storm Development...

“Just a quick post about observations of the LAPS theta-e field this afternoon. It was interesting to see the near stationary aspect of the theta-e boundary in assoc/w the dryline to our south across portions of north Texas this afternoon. This suggests that continued development is possible late this afternoon especially across northern Texas, where the gradients have been sustained and have even increased lately. However, notice that the gradients have decreased generally across much of Oklahoma where convection and related effects (rain cooled air, cloud shield) have helped to stabilize the environment.”

“The 15-minute temporal resolution of the product can be very useful for diagnosing locations of continued convection especially in rapidly developing convective situations.”

Surface Theta-e (K, shades) and wind vectors (blue arrows)
3D 1 km CLOUD ANALYSIS LOOP

Unique feature of LAPS, critical for WOF, Nextgen, etc

Clouds as seen from top of DSRC building in Boulder by LAPS ANALYSIS

19:30-21:15 UTC Oct 31, 2013, 15-min frequency
Quality of very short range forecast is indicator of analysis quality

Composite Reflectivity 20dBZ 30-day ETS (vlaps hwt domain)
OUTLOOK – IT & COMMUNITY OUTREACH

- **IT environment** – facilitate outreach
  - Community Data Assimilation Repository (CDAR)
    - Design general object oriented DA architecture
    - Make LAPS modules compatible with CDAR

- **Community outreach** – accelerate development
  - Harness LAPS community improvements to enhance NOAA capabilities
  - Compare LAPS modules with alternatives from community
OUTLOOK – SCIENCE & APPLICATIONS

- **Scientific technology**
  - 3DVAR
    - Merge 2 & 3D version (with terrain following coordinates)
    - Further improve covariances in analysis via
      - Additional dynamical & physical constraints
      - Flow dependent cross-variable covariances from ensemble
    - Variational cloud analysis
  - Adjoint-based 4DVAR

- **Applications**
  - Exploit flexibilities offered by multiscale approach
    - Urban scales – sub-km (disaster & incident meteorology)
    - National scale central guidance
    - Global 4DVAR for NIM & MPAS convective scale initialization
LAPS PROS - SUMMARY

• Quality
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  – Positive user feedback from HWT, FDSE, CWB, MIT, KMA, CMA, etc

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• Expansion to 3D
  – Ready for use for national scale RUA applications
    • Run operationally by several agencies

• Ease of implementation
  – Many installations worldwide
LAPS IN KMA CENTRAL OPERATIONS

- **LAPS analysis** operational at KMA since 2006
  - 5km resolution, regional domain
  - 6-min data cutoff, 4 mins execution time
  - Analysis available 10 mins after nominal time

- **12-hr WRF forecast initialized with LAPS** in operations since 2010
  - Available 21 mins after nominal time

- **LAPS reanalysis**
  - 2005-2012 with radar observations
  - With ECMWF background field
  - Used as analysis of record, verification, etc
REQUIREMENTS FOR NCEP IMPLEMENTATION?

• Is there a list of specific requirements?
  – Quality, efficiency, science, software?

• LAPS group will
  – Make necessary changes
  – Provide implementation & maintenance support
HOW TO IMPOSE DESIRED COVARIANCES?

• **Statistical background error covariance matrix**
  – Statistical limitations
    • Crutches – use only if you have to
  – Climatologically fixed
    • Forces solution into Procrustean bed”
  – Ensemble-based flow dependent
    • Noise from spurious correlations, localization

• **Dynamical and physical constraints**
  – Ideal solution
    • Flow dependent, variational
  – Approaches
    • Weak & strong constraints in 3DVAR
    • Adjoint-based 4DVAR
APPROACHES TO IMPOSING COVARIANCES

• **Standard 3DVAR**
  – Typically inadequate constraints
  – Single scale, inaccurate / noisy covariance

• **LAPS**
  – Spatiotemporal correlations
    • Smoothing constraints on analysis increments in space & time
      – Multiscale approach fits observations on all (incl fine) scales
  – Cross-variable correlations
    • Constraints being developed
    • **Use of derivatives (not values) from background**
      – Retains more dynamical consistency from background
  – Results
    • **Eat & have your cake – Analysis**
      – Draws close to observations WHILE
      – Retains dynamical balances from first guess
GSI 3DVAR Cost Function

\[(X \ X^b)^T B^1 (X \ X^b) + (HX \ Y)^T O^1 (HX \ Y)\]

VLAPS 3DVAR Cost Function

\[(X \ X^b)^2_{xx} + (X \ X^b)^2_{yy} + (HX \ Y)^T O^1 (HX \ Y)\]
Colliding outflow boundary case: Comparison of divergence analyses at 22 on 4 August 2010.

LAPS and STMAS both have a max in convergence in eastern Weld County (white oval), but LAPS has a sharper pattern around the bigger outflow. RTMA has a broad zone of convergence from eastern Denver northward. Could argue that all of these show some type of max in convergence southeast of Denver (yellow circle).
Transition of STMAS/LAPS to FAA Operation

• STMAS has been used by MIT/LL for two main applications, storm boundary detection and short-term forecast improvements since 2004;

• For CoSPA, “STMAS is a key component of the 0-to-2 hour forecast” quoted from MIT/LL;
  – A new MOU under review between NOAA and FAA;
  – Plan is system will be installed at FAA operations center (late 2012 or early 2013) by (probably) FAA contractor
  – We are excited and work on making sure upgrades to LAPS/STMAS will be incorporated after installation

• New improvement will be added to the annual upgrades.