Convective-Scale Data Assimilation

Dale Barker
WMO DA Symposium, 8 October 2013
Acknowledge: B. Macpherson, S. Ballard, G. Dow, R. Marriott, etc.
Why Convective-Scale Data Assimilation?

- Flexibility/need to introduce observations more frequently (e.g. sub-hourly).
- Simple downscaling -> spin-up problems
- Improved fit to observations through more accurate background forecast.
- Reduced obs representivity error.
- Additional, high-res ‘novel’ observations available (e.g. radar reflectivity)
Challenges For Convective-Scale DA

- Fast processes (e.g. convection) require rapid DA updates and quick turnaround.
- Limited predictability -> probabilistic NWP/DA.
- Imperfect high-res NWP models – model error.
- Highly nonlinear (non-Gaussian fcst errors).
- Need to add value to global DA/NWP.
- Many novel observation types, complex errors.
- Careful treatment of LBCs/large-scales.
- Coupling with land, hydrological, ocean DA.
Convective-Scale Predictability

- Are we able to predict convection?
- Crook (1996) found strong sensitivity to surface conditions.
- Perturbations $\leq$ ob/model error can make difference between convection and blue skies.

Solutions:
- Better/more observations.
- Improve models/DA.
- Probabilistic forecasting.
Ensemble Mean Visibility

Ensemble Probability (vis<1km)

(currently downscales global perturbations - no interaction with high-res DA yet)
Error Correlations With Single Reflectivity Ob

Shading: Full Fields  Line Contours: Error Correlations

Tong and Xue, 2005
Partition of Error Covariance Between Different Regimes

Brousseau (2009)
Adaptive Mesh Transform

- Motivation: Introduce flow-dependence analysis response near strong temperature inversions in presence of stratocumulus clouds (no UKV ensemble so can’t use hybrid method yet).

- Static adaptive mesh methods concentrate grid points where there is a rapid variation of the atmospheric field.

- Transformation from the physical grid to the computational grid is guided by a monitor function:

\[
\sqrt{\text{Monitor Function}}
\]

- Grid transformation introduced within VAR control variable transform:

\[
\delta x = U v = U p U a U v U h v
\]
Iterative Calculation of Monitor Function

M (background-state - 3h forecast)

M (After 10 iteration 3D-Var)

M (After 2\textsuperscript{nd} converged 3D-Var)

Adaptive vertical grid provides a small positive impact to the UK index:

<table>
<thead>
<tr>
<th>Period</th>
<th>Vis</th>
<th>Precip</th>
<th>Cloud amount</th>
<th>Cloud base</th>
<th>Temp</th>
<th>Wind</th>
<th>Overall</th>
</tr>
</thead>
<tbody>
<tr>
<td>23 Dec 2010 – 3 Jan 2011</td>
<td>-2.56%</td>
<td>5.48%</td>
<td>-1.05%</td>
<td>3.03%</td>
<td>0.22%</td>
<td>-0.04%</td>
<td>+0.25%</td>
</tr>
<tr>
<td>10 Aug 2010 - 20 Aug 2010</td>
<td>12.20%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>4.17%</td>
<td>0.23%</td>
<td>0.10%</td>
<td>+0.55%</td>
</tr>
</tbody>
</table>

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Met Office Main NWP Models (2014)

**UKV and MOGREPS-UK**
- 1.5km 70L (40km model top)
- 3DVAR (3 hourly) (→ hourly 4DVAR?)
- 36hr forecast
- 8 times per day
- 12-member EPS - 2.2km 4x/day 36h

**Global and MOGREPS-G**
- 17km 70L (80km model top) (17km from PS34)
- Hybrid 4DVAR – 60km
- 66hr forecast twice/day
- 144hr forecast twice/day
- 12-member EPS - 33km 4x/day 72h

• Before 2011, cost of global NWP >> convective-scale NWP.
• In 2013, costs are similar.
• Next HPC (2015-16) – cost of high-res NWP > global NWP.
• Similar situation for people costs.
Convective-Scale NWP – Why Bother?

* UK Index = Forecast skill for surface weather: surface u/T, cloud fraction/amount, precip, visibility

- Global NWP improvements included in baseline above (~1-2%/yr).
- So 10% benefit of UKV represents > 5-10 yrs lead over global model.
UKV Benefit Over Global Model: Broken Down by Weather Variable

- OK, great – but what’s this got to do with data assimilation?
# UK Data Assimilation Impact Studies (3hourly 3DVAR)

Forecasts to $T+24$ at 00Z, 06Z, 12Z & 18Z

<table>
<thead>
<tr>
<th>Period</th>
<th>Dates</th>
<th>No. of Forecasts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer</td>
<td>Jul 1$^{st}$ → Aug 10$^{th}$</td>
<td>4x40=160</td>
</tr>
<tr>
<td>Autumn</td>
<td>Nov 1$^{st}$ → Dec 14$^{th}$</td>
<td>4x44=176</td>
</tr>
<tr>
<td>Winter</td>
<td>Jan 3$^{rd}$ → Feb 10$^{th}$</td>
<td>4x38=152</td>
</tr>
<tr>
<td>Spring</td>
<td>Mar 10$^{th}$ → Mar 31$^{st}$</td>
<td>4x21=84</td>
</tr>
</tbody>
</table>

Period picked at Random
Period picked due to specific (SCu) event

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Observations Assimilated Into UKV Model (updated September 2013)

<table>
<thead>
<tr>
<th>Observation group</th>
<th>Observation Sub-group</th>
<th>Items used</th>
<th>Daily extracted</th>
<th>% used in assimilation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground-based vertical profiles</td>
<td>TEMP</td>
<td>T, V, RH processed to model layer average As TEMP, but V only</td>
<td>23</td>
<td>95, 95, 92</td>
</tr>
<tr>
<td></td>
<td>PROFILER</td>
<td></td>
<td>2500</td>
<td>20</td>
</tr>
<tr>
<td>Satellite radiances</td>
<td>METOP-A/B</td>
<td>Radiances directly assimilated with channel selection dependent on</td>
<td>MHS/AMSU-B: 20,000</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>NOAA-16/18/19</td>
<td>surface type and cloudiness</td>
<td>MSG Ch5: 2,500,000</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>Met-10 MSGRADUK</td>
<td></td>
<td>MSG Ch9: 2,500,000</td>
<td>0.1</td>
</tr>
<tr>
<td>Satellite-derived cloud</td>
<td>MSGRADUK / GeoCloud</td>
<td>Cloud-top pressure</td>
<td>2,500,000</td>
<td>11</td>
</tr>
<tr>
<td>Aircraft</td>
<td>Manual AIREPS (incl. ADS)</td>
<td>T, V as reported, with duplicate checking and reject lists</td>
<td>130</td>
<td>85, 70</td>
</tr>
<tr>
<td></td>
<td>Automated AMDARS</td>
<td></td>
<td>9,000</td>
<td>68, 68</td>
</tr>
<tr>
<td></td>
<td>TAMDAR</td>
<td></td>
<td>800</td>
<td>0, 0</td>
</tr>
<tr>
<td>Satellite atmospheric motion vectors</td>
<td>Meteosat 10 BUFR</td>
<td>IR, WV</td>
<td>40,000</td>
<td>5</td>
</tr>
<tr>
<td>Satellite-based surface winds</td>
<td>METOP-A/B</td>
<td>KNMI retrievals</td>
<td>40,000</td>
<td>5</td>
</tr>
<tr>
<td>Ground-based surface</td>
<td>Land Synop</td>
<td>P (processed to model sfc), V, T, RH, Vis, Cloud</td>
<td>6,800</td>
<td>99, 97, 98, 92, 90, 100</td>
</tr>
<tr>
<td></td>
<td>Ship</td>
<td></td>
<td>100</td>
<td>80, 40, 75, 60</td>
</tr>
<tr>
<td></td>
<td>Fixed Buoy + Rigs</td>
<td></td>
<td>1,800</td>
<td>99, 99, 50</td>
</tr>
<tr>
<td></td>
<td>Drifting Buoy</td>
<td></td>
<td>200</td>
<td>99</td>
</tr>
<tr>
<td></td>
<td>METAR</td>
<td></td>
<td>6,000</td>
<td>17, 16, 16, 2</td>
</tr>
<tr>
<td></td>
<td>CDL</td>
<td></td>
<td>3,600</td>
<td>97, 98, 92</td>
</tr>
<tr>
<td></td>
<td>OPENROAD (H.A.)</td>
<td></td>
<td>8,000</td>
<td>17, 17</td>
</tr>
<tr>
<td>Ground-based radar</td>
<td>RADRATE</td>
<td>Rain rate</td>
<td>400,000</td>
<td>0-5?</td>
</tr>
<tr>
<td></td>
<td>RADAR WINDS</td>
<td>Doppler radial winds</td>
<td>Depends on ppm</td>
<td>...</td>
</tr>
<tr>
<td>Ground-based satellite</td>
<td>GPSIWV</td>
<td>ZTD</td>
<td>50,000</td>
<td>0.3</td>
</tr>
</tbody>
</table>

* Subset of data assimilated only in UK model
Verification by Element

<table>
<thead>
<tr>
<th>Period</th>
<th>Vis</th>
<th>Precip</th>
<th>Cloud Amount</th>
<th>Cloud Base Height</th>
<th>Temp</th>
<th>Wind</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jul 2011</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nov 2011</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jan 2012</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mar 2012</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Colours indicate best setup for element/period

- Full DA(9)
- Partial DA(11)
- DownScaler(4)

Note: Some boxes are more significant than others.
## Impact of Global/CS-Scale DA

NWP Range (UK Index): T+6 to T+36

<table>
<thead>
<tr>
<th>Trial</th>
<th>Model</th>
<th>Vis</th>
<th>Precip</th>
<th>Cloud Cover</th>
<th>Cloud Base Height</th>
<th>Temp</th>
<th>Wind</th>
<th>Overall</th>
</tr>
</thead>
<tbody>
<tr>
<td>UK Index Benefit</td>
<td>UKV DA (vs DS)</td>
<td>+1.270</td>
<td>+0.193</td>
<td>-0.001</td>
<td>+0.090</td>
<td>+0.038</td>
<td>-0.013</td>
<td>+4.26%</td>
</tr>
<tr>
<td></td>
<td>UKV DA (vs No DA)</td>
<td>+1.168</td>
<td>+0.269</td>
<td>+0.098</td>
<td>+0.160</td>
<td>+0.210</td>
<td>+0.060</td>
<td>+5.31%</td>
</tr>
<tr>
<td></td>
<td>UKV DS (vs No DA)</td>
<td>-0.101</td>
<td>+0.076</td>
<td>+0.099</td>
<td>+0.067</td>
<td>+0.169</td>
<td>+0.072</td>
<td>+1.08%</td>
</tr>
<tr>
<td>DS Benefit / DA Benefit</td>
<td></td>
<td>-9%</td>
<td>28%</td>
<td>101%</td>
<td>42%</td>
<td>80%</td>
<td>120%</td>
<td>20%</td>
</tr>
</tbody>
</table>

DA = Cycling Convective-Scale DA, DS = Downscaler (Global DA)
NoDA = No DA (forcing through LBCs)

- Most benefit through CS-scale DA (DA vs DA).
- High-res DA benefit is ~half of total benefit of high-res NWP (~10%)
### Impact of Global/CS-Scale DA

Nowcasting Range: T+6 to T+12

<table>
<thead>
<tr>
<th>Trial</th>
<th>Model</th>
<th>Vis</th>
<th>Precip</th>
<th>Cloud Cover</th>
<th>Cloud Base Height</th>
<th>Temp</th>
<th>Wind</th>
<th>Overall</th>
</tr>
</thead>
<tbody>
<tr>
<td>UK Index Benefit</td>
<td>UKV DA (vs DS)</td>
<td>+1.867</td>
<td>+0.632</td>
<td>+0.069</td>
<td>+0.261</td>
<td>+0.141</td>
<td>-0.030</td>
<td>+5.62%</td>
</tr>
<tr>
<td>UK Index Benefit</td>
<td>UKV DA (vs No DA)</td>
<td>+1.747</td>
<td>+0.890</td>
<td>+0.320</td>
<td>+0.449</td>
<td>+0.562</td>
<td>+0.181</td>
<td>+7.93%</td>
</tr>
<tr>
<td>UK Index Benefit</td>
<td>UKV DS (vs No DA)</td>
<td>-0.111</td>
<td>+0.259</td>
<td>+0.253</td>
<td>+0.187</td>
<td>+0.415</td>
<td>+0.210</td>
<td>+2.46%</td>
</tr>
<tr>
<td>DS Benefit / DA</td>
<td>DS Benefit / DA Benefit</td>
<td>-6%</td>
<td>29%</td>
<td>79%</td>
<td>42%</td>
<td>74%</td>
<td>116%</td>
<td>31%</td>
</tr>
</tbody>
</table>

DA = Cycling Convective-Scale DA, DS = Downscaler (Global DA)
NoDA = No DA (forcing through LBCs)

- Increased benefit of DA for very-short range (LBC impact less)
Stratocumulus Period
Mar 10\textsuperscript{th} - 15\textsuperscript{th} 2012

- Blocked episode
- Cloud not breaking soon enough
- Significant $T_{2m}$ errors
- Suspect analysed cloud depth too large

Full DA
Partial DA

DownScaler
Cloud Cover March 2012

10-15\textsuperscript{th} (SCu)  

\begin{itemize}
  \item Similar Bias at T+0
  \item Large Bias in Control at T+12
\end{itemize}

16-31\textsuperscript{st} (post-SCu)  

\begin{itemize}
  \item Partial DA $\sim$ Control – MOPS Cloud
\end{itemize}

Full DA  Partial DA  DownScaler  Full DA – MOPS Cloud
**UK4 Observation Network denial experiments**
*(Autumn period)*

<table>
<thead>
<tr>
<th>Observation Type</th>
<th>Benefit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface</td>
<td>+2.9%</td>
</tr>
<tr>
<td>Upper Air (excluding aircraft)</td>
<td>+2.1%</td>
</tr>
<tr>
<td>Aircraft</td>
<td>+2.0%</td>
</tr>
<tr>
<td>Radar</td>
<td>+2.0%</td>
</tr>
<tr>
<td>Satellite</td>
<td>+1.7%</td>
</tr>
<tr>
<td>“Extra” (all obs networks not in global model)</td>
<td>+0.5%</td>
</tr>
</tbody>
</table>

• Conclude: All ob types adding benefit, mainly from ‘standard obs’ in high-res DA.
Nowcasting Demonstration Project (NDP)

Met Office

- 1.5 km NWP-based nowcasting system
- Southern UK only (May 2012 – April 2013)
- Hourly cycling 4DVAR (UKV=3hourly 3DVAR)
NWP-Nowcasting: Precipitation Skill

Verification of hourly precipitation forecasts against **radar**
Same validity time, Available at same time to forecasters

**NDP** better than older **UKV** forecast at all ranges
**NDP** better than **STEPS** extrapolation/merged nowcast from T+2

**Sue Ballard**

Aggregated Fraction Skill Score
From 2012/07/01 @ 00:00Z To 2012/07/31 @ 23:00Z

Aggregated Fraction Skill Score
From 2012/08/01 @ 00:00Z To 2012/08/31 @ 23:00Z

July 2012

August 2012

Fraction Skill Score (Roberts and Lean) for 1.0mm/h/40km square Against Forecast Range

**Next stage**: UK-wide implementation of hourly 4DVAR in 2015-2016.
Forecast Sensitivity to Observations (FSO)

Energy-weighted forecast error norms

Assimilation of observations moves the model state from the background to the new analysis trajectory

Observation impact is quantified as the difference in forecast error norm

$$\delta e = e_a^f - e_b^f$$

Adjoint of NWP model/DA system used to derive analysis/observation sensitivity.

- FSO technique can estimate individual contribution of every observation.
- Reduces need for expensive data denial experiments.
- Assists optimal design of observation networks.
Convective-Scale FSO?

Test accuracy of linear model: 3.0km UM linearisation Tests

T+3 (10\textsuperscript{th} Mar 2012 – 06Z)  

- Accuracy of convective-scale linear model VERY situation dependent.
- Hourly 4DVAR less susceptible than adjoint-bases FSO tool.
T+6 FSO result dependence on LBC

Same LBCs (00, 06, 12, 18Z)  Diff LBCs (03, 09, 15, 21Z)

• 6/3-hourly global/UKV DA cycle means LBCs for background/forecast inconsistent.
• Very different FSO result depending on LBC origin.
• Other issues with FSO: adjoint accuracy, analysis/forecast correlation.
Conclusions

1. Predictability is limited to a few hours (at most) at convective-scale.

2. Despite this, convective-scale NWP has shown great promise in recent years with significant human/HPC resource being devoted to it.

3. Convective-Scale Variational Data Assimilation is the workhorse for current operational schemes, and contributes significantly to benefit of CS-scale NWP, BUT…

4. Convective-Scale Ensemble(-Variational?) Data Assimilation likely to become more common in future - needs a (very expensive) convective-scale ensemble….
Thank You!
Tuesday AM – Global/Regional DA

- Miyoshi – first of a number of presentations describing multiscale localization, also vision of DA in next decades.

- ECMWF (Isaksen, Tremolet, Fisher earlier) clearly planning to stay with global ['hybrid', long-window WC] 4DVAR/EDA – scalability issues solved?

- Buehner: Canada retiring global 4DVAR – there appears no going back now! 4DEnsVar working well for global/regional. Different approach (EnKF) at convective-scale scientifically sensible – general trend for the future?

- Lei – first of many talks describing US ensemble-variational efforts.

- Apparent (real or effect of shutdown on talks?) trend from last WMO DA:
  a. Less EnKF vs. 4DVAR, more which flavour of ensemble-variational DA?
  b. Global/regional less an emphasis compared to high-res, Earth System.
Tuesday AM – Reanalysis

- **Compo**: Impressive plans for 20CR V3 global ensemble reanalysis (1850-2013).

- **Pauli**: similarly impressive plans for ERA-CLIM (also Dee talk) using ensemble of 4DVARs (more emphasis on careful tuning of B, even more than NWP).

- **Kobayashi**: JRA-55 (Go! Go!) just about complete – congratulations to JMA team. Showed another example of relative contribution of Obs/model/DA over past decades – contributes to cost/benefit analysis.

- General Comment – reanalysis:
  a. Moving more to global reanalysis for climate services (**at expense of NWP benefit?**).
  a. No talks on regional reanalysis (but many discussions over coffee!).

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