Adjoint-based impact studies of surface-based observation types at the UK Met Office

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Specific questions addressed

• **S3AMDAR**: Coverage of AMDAR - What is the impact of current AMDAR observations? What are the priorities for expansion of the network?

• **S4ASAP**: Coverage of ASAP - What is the impact of current coverage of profiles from the Automated Shipboard Aerological Programme (ASAP)? How might coverage be optimised for a given level of resources?
Contents:

- Overview of the UKMO FSO system
- The observation impact of conventional, surface-based observation types
- E-ASAP case-study
- S4ASAP – Current ASAP impact
  - Ideas for optimisation of coverage
- UK AMDAR case-study
- S3AMDAR – Impact of AMDAR observations
  - Priorities for expansion of the network?
The Met Office FSO system

• The forecast impact, $\Delta J$, is given by:

$$\Delta J = (\delta x^a)^T C (\delta x^a) - (\delta x^b)^T C (\delta x^b) = (\Delta x^f)^T C (\delta x^a + \delta x^b)$$

• We are finding the impact of finite increments and so, rather than differentiating the norm, we instead take the "finite gradient" across the impact:

$$\frac{\Delta J}{\Delta x^f} = C (\delta x^a + \delta x^b)$$

• Doing so avoids linearisation errors.
The Adjoint Forecast Model

- Averaging the forecast error gradients at T+24 also means we only need perform a single integration of the adjoint forecast model.

- Our observation sensitivities are calculated using the following:

\[
\frac{\Delta J}{\Delta y^o} = K^T \left( \frac{\Delta x^f}{\Delta x_0} \right)^T \left( \frac{\Delta J}{\Delta x^f} \right) = K^T M_{PF}^T C (\delta x^{fb} + \delta x^{fa})
\]

(I have expressed $M_{PF}^T$ using finite notation to emphasize that our PF model is designed to approximate the growth of finite perturbations in a nonlinear model.)
Overview of the UKMO FSO system

- Implemented in **global** model
- Impact on **24-hour** forecasts measured
- Moist energy-norm \( (u, v, \theta, p, q) \) up to **150hPa** using latent heat of condensation
- Penalty calculations and adjoint steps performed at Var-resolution on **simplified forecast states**
- **Finite forecast sensitivity** calculated
- **Single adjoint model integration** (linearised about averaged trajectory) with moist physics enabled
- **\( K^T \) linearised about analysis** – no outer-loop but nonlinear inner-loop
- **\( K^T \) evaluated by minimisation of FSO cost-function.**
  I.e. not line-by-line adjoint or Lanczos vectors.
  **~55 iterations** performed to get close to full convergence.

\[
J(\hat{a}) = \frac{1}{2}(\hat{a} - \hat{v})^T(\hat{a} - \hat{v}) + \frac{1}{2}\hat{a}^T U^T G^T R^{-1} GU \hat{a}
\]
Results

Most results shown here come from the trial detailed below. (Exceptions will be mentioned explicitly.)

**Period**: 22nd Aug to 19th Sept 2010

**System**: Operational copy from March-July 2011

**Forecast model res.**: N320L70 (~40km)

**Var res.**: N108/N216L70 (~60km)

**VarAdjoint res.**: N216L70 (~60km)
Forecast impacts

- 24.8% error reduction during period from an average of 12.0 to 9.0 J/kg.
- Observation impacts calculated to an accuracy of 97.2%.
- (Dry: 26.2% from 7.8 → 5.7 J/kg. Moist aspect contributes ~33%)
Observation impacts per day

Impact per day (J/kg)
• These results for a 3-day period only.
Surface-based observation impacts in context

- Surface-based ob-types account for 36% of the total 24-hour forecast impact.
Surface-based observation impacts in context (Satellite impact)

- Consistently good impact over ocean
- Small but beneficial over land
Surface-based observation impacts in context
(Surface-based impact)

- Impacts larger but fewer than for satellite.
- (Red square is NOAA wind profiler 70197)
The observation impact of conventional, surface-based observation types

- Of the 36%, impacts are distributed as above.
- SYNOP impact possibly an overestimate.
Impacts per observation

- Large impact per ob from drifters but remember there are many more observations per “station” for other ob-types (aircraft, profilers and sonde).
- Globally, TEMPSHIP is the weakest-impacting sonde type. However, there are no TEMPSHIPs in the southern hemisphere.
- TEMPSHIP impact per ob larger than for PILOT and TEMP in the NH.
ASAPs
E-ASAP case-study

- Three similarly located groups of ~20 sondes assessed: ASAP sondes, “remote” island-based sondes and continental “inland” sondes.
- (Notice the ship in Libya.)
• Some detrimental impacts but the sample at any one location is small for this period.
• Average ASAP impacts not as high as remote sondes.
• However, 8/18 remote sondes are in the SH and we have already seen that impacts there are larger.

• (Error bars denote the standard error in the mean, i.e. $\sigma/\sqrt{n}$
  Is this valid...?)
A quick note on confidence intervals

- Black dots represent the stdev of the mean of many random samples of obs from the full set (500 samples of N impacts from 119,670).
- Blue dots represent $\sigma/\sqrt{n}$ for a single sample of N impacts.
- The red line is the absolute value of the mean for the 119,670 impacts.
- Quite large errors in $\sigma/\sqrt{n}$ until larger sample sizes are reached.
- You can only have confidence in your confidence intervals after about 1500 to 2000 obs.
• Problem with ASAP RH?
• ASAP profiles have similar features to remote island sondes.
• Possible model boundary layer RH problem over oceans?
- Evidence of bias in O-Bs.
- Model boundary layer problem?
- Radiative-drying effects up to tropopause (~200 hPa)? (No RH bias correction is performed at UKMO.)
TEMP impacts

- TEMP impact per observation is generally largest over the Atlantic.
- Impact per observation likely to be larger still over tropical and SH ocean.

- No ASAPs for the Spain → South America route. (At least not in 2010.)
- Make use of Pacific/Indian Ocean ships?

VOS shipping routes (Apr/May 2012)
• In 4D-Var systems observations towards the end of the assimilation time-window have a larger impact.

• This is because the error-modes which are corrected are those which have grown and will ultimately affect the forecast.
• ASAP launch procedure (which apparently takes 20 mins) is usually started 60-90 mins before the main synoptic hour, presumably because the ascent can last up to ~2 hours.

• Impacts in 4D-Var systems could be greatly improved by releasing later (although probably to the detriment of 3D-Var systems).

• Improvements might also be gained by assimilating sonde obs using the actual observation time rather than the time of release.
AMDAR observation times

![Bar chart showing AMDAR observation times](image-url)
Ideas for ASAP network improvements

• Encourage the initiation of Pacific/Indian Ocean programs. (ASAP sondes are far more beneficial than inland sondes, at least in Europe.)

• Try to make more use of shipping routes which pass into the tropics and SH.

• Instruct observers to always use default (GPS-based) locations.

• Use the reported time at each observed level in 4D-Var to gain advantage of the larger impacts to be had later in the assimilation time-window.
• Additional AMDARs received from easyJet flights throughout the UK on a trial basis from Nov 2010 – May 2011.

• Extending the supply period would mean committing to a three-year contract at a cost of roughly US $15,000 per month.

• AMDAR data from regional UK airports seen as one of the solutions for meeting convective-scale NWP requirements for higher temporal and spatial resolution data.

• Only global FSO results available for Sept - Dec 2010 and for 12 UTC runs only.
UK AMDARs

- Results suggest that we may be paying for AMDARs over London airports which are having no measurable impact.
- Remember though that the high-density data could be having a beneficial impact in regional models.
UK AMDARs

- All statistically significant impacts are beneficial.
- There is correlation between impact per AMDAR observation and the total number of observations in the region.
- **Lesson** – we need obs in data-sparse areas!
Global AMDAR network considerations

• Number of vertical profiles from each airport.
• Ascent/descent sample rates.
• Locations for flight-level sampling.
• Flight-level sample rates.
• Data targeting strategies. (Which airports/airlines to collaborate with.)
• Cost.
• NWP data-thinning strategies.
AMDAR and Sonde profile coverage

Airports shown in red

- Together with sondes there is a good land coverage of vertical temperature and wind profiles - except for over Africa.

- There looks to be an untapped crop of airports spread over Africa and also in Colombia/Venezuela.

- (African coverage currently provided by EUMETNET and South Africa.)

- (South American coverage currently provided by USA and EUMETNET.)

- What is the status of the EUMETNET ASECNA collaboration project in Africa?
Global AMDAR impact

- Obs beneficial at all levels.
- Slightly more impact from flight-level obs in total (>400 hPa).
- Twice as much impact from wind observations.
Global AMDAR impact
Flight-level (400-0 hPa)

- Fairly uniform total impact globally despite concentrated regions of observations over Europe and USA.
- Impact per ob. large over southern Indian Ocean, South Atlantic and Pacific but total impact is small.
  - Increase flight-level sampling rate in those locations?
**AMDAR flight-level sampling rates**

- Current UKMO AMDAR thinning: 80km, 120mins, 50hPa.
  - At a speed of 900 km/h, 1 ob every 80km requires a sample interval of 5.3mins.
- N216 Var (~60km) should be able to cope with one ob. every 4.0mins.
- N320 Var (~40km): 2.7mins
- Default flight-level AMDAR sampling interval of 7mins.

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Global AMDAR impact
Ascent/Descent (Surface-400 hPa)

- Very non-uniform coverage at lower levels.
- Impacts mixed but detrimental impacts tend to be small – could be sampling errors.
- Impacts per ob. very small over Europe and USA.
  - Could decrease sample rates although obs are cheaper over land anyway.
Global AMDAR impact
Sensitivity to temperature observations

- Little sensitivity to flight-level temperature obs in the NH.
- Fairly uniform sensitivity at lower levels (except over Europe and USA). This implies that we can probably still benefit from more (good quality) profiles in the NH.
Global AMDAR impact

Sensitivity to wind observations

- Similar result for sensitivity to wind observations.
Ideas for AMDAR network improvements

- Increase number of vertical profiles outside USA and Europe.
  - Ensure any collaboration projects with South America and Africa (ASECNA) come to fruition.
- Increase flight-level sample rates over southern Indian Ocean, South Atlantic and Pacific.
- Potential cost-savings over USA and Europe. Convective-scale results would be interesting.
Summary

- Conventional data more important than satellite data in the NH.
- TEMP and AMDAR most important conventional ob-types (followed by SYNOP).
- ASAP impact per ob is high but there are few of them. (Four times per day? TR/SH Atlantic shipping routes + Pacific/Indian Oceans?)
- Use true sonde observation times in 4D-Var assimilations.
- UK AMDAR study showed information saturation in the global model and correlation between large impacts and few other observations.
- Scope for more AMDAR profiles in Africa and northern South America.
- Low AMDAR saturation over southern Indian Ocean, South Atlantic and Pacific. - Room for increased sample rates in modern DA systems.

Questions...