Can we improve substantially weather forecasts using future observations without **cheating**?

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Classic Data Assimilation:
To improve Numerical Weather Prediction (NWP) we need to improve observations, analysis scheme and model.
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CLASSIC DA:

Every 6 hours we make a new forecast, get new observations, and combine them to get the new analysis, which is the new initial condition for the model forecast.
A pioneer of long-range forecasting, Kiku Miyakoda, said “if you use future data in your tests, you are cheating”

- We found a way to find whether each observation is beneficial or detrimental for the forecast using the observations 6 hour later observations.

- This improves the forecasts substantially.

- Are we cheating? Can this be implemented operationally, when we don’t know the future?
NEW applications of modern Data Assimilation:
We can also use DA to improve both observations and model
We will show how to identify and delete detrimental observations to improve the analysis and the forecasts. The idea is to use future observations to QC the current observations.

Many observations are beneficial: they improve the 6 hr forecast:
But some observations are detrimental! They make the forecast worse!

How to identify and delete detrimental observations?

OBSERVATIONS

at t=0 hr

ANALYSIS

6 hr forecast

MODEL

Forecasts
We use the observations 6 hours later, and consider the new analysis as truth for \( t=6 \) hr. This allows to use EFSO to determine whether each observation at \( t=0 \) made the 6hr forecast better or worse.
We check each observation at t=0, and (using EFSO) find whether it improved the forecast (beneficial) or made it worse (detrimental). We delete all the detrimental observations, and repeat the analysis at t=0 assimilating only beneficial observations.
The Final Analysis is cycled, accumulating the improvements obtained every 6 hours by deleting the detrimental observations and assimilating only the beneficial observations (Proactive QC).

As a result, both the Analysis and the Model Forecasts improve substantially. See the example of 10-day forecasts using the GFS-LETKF system.
An example of EFSO estimation of beneficial and detrimental obs
Experimental setup for **GFS-LETKF** (Lien, 2015, Chen, 2018)

<table>
<thead>
<tr>
<th>Period (~1 month)</th>
<th>Jan/01/2008 00Z – Feb/06/2008 06Z (5 days for DA spinup)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>GFS T62 L64 (lower resolution)</td>
</tr>
<tr>
<td>DA</td>
<td>LETKF with 32 members ensemble size</td>
</tr>
<tr>
<td>Observations</td>
<td>prepBUFR data from NCEP (all obs except radiances)</td>
</tr>
<tr>
<td>Localization</td>
<td>Horizontal: 500 km</td>
</tr>
<tr>
<td></td>
<td>Vertical: 0.4 scale height</td>
</tr>
<tr>
<td>Inflation</td>
<td>RTPP (Zhang 2004) + adaptive inflation (Miyoshi 2011)</td>
</tr>
<tr>
<td>Verifying truth</td>
<td>NCEP Climate Forecast System Reanalysis (CFSR)</td>
</tr>
</tbody>
</table>

**Efficient but realistic GFS system**
Cycling PQC in DA accumulates the reduction of the analysis error.

- Cycling PQC reduces analysis RMSE (blue).
- U and T improve globally, especially over the southern ocean.
- Q improves over the tropics and the subtropical region.

Analysis is improved globally for every variable!
Most (~90%) benefit comes from the accumulated correction. So, the accumulated (cycled) PQC is feasible in operations!

• We separate total correction of cycling PQC into immediate and accumulated correction over 10 days.

• Most of the total correction are provided by the cycled PQC (accumulated from previous corrections.)

• This indicates that PQC is feasible for operations even if we don’t have time for an immediate correction in operational tight schedule (correct only GDAS, the final analysis).

Relative Forecast Error Reduction [%] (only 10% rejection)
The results with and without the last immediate correction are almost identical.

We don’t use the last correction, so we don’t use future observations: no cheating.
Immediate and Accumulated impact of cycling PQC

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- This indicates that PQC is feasible for operations even if we don’t have time for an immediate correction in operational tight schedule (correct only GDAS, the final analysis).

Most (~90%) benefit comes from the accumulated correction.
So, the accumulated (cycled) PQC is feasible in operations!
Rejecting more detrimental obs (up to 50%) improves the forecasts

- More improvement when rejecting more (10%, 30%, 50%) detrimental observations.
- Rejecting all detrimental (~50%) observations gives good results.
- About 20% improvement in short-term forecast.
- The improvement remains at about 5% after 6 days.
- In the NH 30% is better than 50%.

 rejecting 50% detrimental observations improves 10 day forecasts only in the tropics, in the NH 30% is best.
We now briefly explain EFSO and show how useful it is in monitoring the quality of the observations at the analysis time $t=0$. 
Ensemble Forecast Sensitivity to Observations (EFSO)

\[ \Delta e^2 = e_t^T C e_t - e_{t-6}^T C e_{t-6} \approx \frac{1}{K-1} \delta y_0^T R^{-1} Y_0^a X_{t|0}^f C (e_{t|0} + e_{t|6}) \]

Kalnay et al. 2012,
inspired by Langland and Baker (2004),
Liu and Kalnay (2008)

- EFSO is a linear mapping from each observation to the 6 hour forecast error.
- **Negative EFSO shows the observation reduced the forecast error (beneficial).**
- **Positive EFSO shows the observation increased the forecast error (detrimental).**
- EFSO is efficient: the matrices above are already computed by the EnKF.
- **There is no need to repeat the reanalysis without the detrimental observations.**
- Simply apply the EFSO corrections (Ota et al., 2013, Chen and Kalnay, 2018).
**Experimental Setup: semi-operational (all observations)**

<table>
<thead>
<tr>
<th></th>
<th>Exp. 2012</th>
<th>Exp. 2017</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Period (~1 month)</strong></td>
<td>Jan/10/2012 00Z – Feb/09/2012 18Z (Winter, 2012)</td>
<td>Jun/01/2017 00Z – Jun/27/2017 00Z (Summer, 2017)</td>
</tr>
<tr>
<td><strong>Model</strong></td>
<td>GFS T254 / T126 L64</td>
<td>GFS T670 / T254 L64</td>
</tr>
<tr>
<td><strong>DA</strong></td>
<td>LETKF / 3D-Var Hybrid GSI v2012</td>
<td>EnSRF / 3D-Var Hybrid GSI v2016</td>
</tr>
<tr>
<td><strong>Localization cut-off length</strong></td>
<td>Horizontal: 2000 km Vertical: 2 scale heights</td>
<td></td>
</tr>
<tr>
<td><strong>Error norm</strong></td>
<td>$MTE = \frac{1}{2} \frac{1}{</td>
<td>S</td>
</tr>
</tbody>
</table>
Powerful QC monitoring for every system every 6hr!

Users can see which instruments have detrimental episodes.
• Innovation bias of MODIS winds depends on wind direction
• Data selection can be designed from these long-term EFSO statistics
GOES Winds: O-B and Wind Direction

- No such bias for any geostationary satellite winds
Two RAOB stations (JDP and PTL) in India was found very detrimental in the 1-month period.
Check Radiance Channel Selection: HIRS

Channel 13 of HIRS has always provided detrimental impacts.

Detrimental channel 13 in HIRS is easily identified using EFSO.
Multi-channel instruments: **GOES sounder, HIRS**

- **GOES15**
  - Detrimental
  - Beneficial

- **GOES13**
  - Detrimental

- **HIRS**
  - Detrimental

- **Channel 8 (11.03 um), 13 (4.57 um):** sensitive to surface and low-level temperature.

- **Map shows the 2 channels are detrimental in tropical Pacific and Atlantic.**
Even Hyperspectral Instruments: IASI, AIRS

- Efficient channel-wise impact evaluation even for hyperspectral instruments.
- Detrimental impact from Australia and tropical oceans.
Comparing EFSO from 2012 and 2017

2012

2017

• Detrimental channels are mostly the same.
• Some of the new IASI channels are beneficial and a few detrimental.
Hyperspectral instruments: CrIS

- All channels from 9-12 um (surface sensitive) are detrimental.
- The detrimental impact is from southern tropical oceans.
Choose location, time, instrument, and instantly get EFSO
Experiments with the Lorenz (1996) model

| Model                  | Lorenz 1996:  \\
|-----------------------|----------------|
|                       | \[
| dx_i \over dt  = -x_{i-2}x_{i-1} + x_{i-1}x_{i+1} - x_i + F \\
|                       | 40 variables \|
|                       | F = 8, dt = 0.05, \|
|                       | Integration scheme: RK4 \|
| Period                | 5000 cycles \|
|                       | (plus 500 cycles of spin up) \|
| Data Assimilation     | ETKF-40 members \|
|                       | No localization or inflation \|
| Observations          | 40 variables from a nature run \|
|                       | Obs. error: N(0, 0.1) \|
Even non-cycling PQC improves the forecast!

Non-cycling PQC with **flawless obs.** (Lorenz, 1996)

- Rejected observations from most *detrimental* to most *beneficial* EFSO impact.
- Rejecting *worst few detrimental observations* provides most of the improvement.
- The *improvement grows* as the forecast advances in time (log-scale!)

**Colored**: forecast error trajectory  
**Black**: forecast error at different forecast lengths.
PQC analysis update methods: EFSO is optimal!

<table>
<thead>
<tr>
<th>Methods</th>
<th>Mechanism</th>
<th>Change in $K$</th>
<th>Change in Spread</th>
<th>Repeat analysis</th>
<th>Computational cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>PQC_H</td>
<td>Recompute $K$ without observation</td>
<td>Large</td>
<td>Increased</td>
<td>Yes</td>
<td>High</td>
</tr>
<tr>
<td>PQC_R</td>
<td>Recompute $K$ with up-weighted $R$</td>
<td>Large</td>
<td>Increased</td>
<td>Yes</td>
<td>High</td>
</tr>
<tr>
<td>PQC_K</td>
<td>Reuse the original EFSO $K$</td>
<td>None</td>
<td>None</td>
<td>No</td>
<td>Low</td>
</tr>
<tr>
<td>PQC_BmO</td>
<td>Assimilate background minus observation</td>
<td>Low</td>
<td>Reduced</td>
<td>(Serial update)</td>
<td>Medium</td>
</tr>
<tr>
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PQC_K is both beneficial and robust (most consistent with EFSO)
Concluding remarks for Lorenz96 system

- **PQC-K**, reusing the original Kalman gain, is most efficient in computation and most accurate in the correction!
- PQC improves even the **flawless** observing system. (Harvest additional information from the observations)
- Rejecting around **10%** of the most detrimental observations provides most of the improvement (it is less sensitive to additional rejections).
Summary: Using future observations to do PQC without cheating

- Advanced DA can be used to improve both the model and the observations.
- At t=0 we use future (6 hour) observations to create a 6hr analysis that we use as the best estimate of the truth.
- We have two 6 hour forecasts from t=0 to t=6hrs, one with and one without assimilating the current (t=0) observations.
- Identify the observations at t=0 that make the 6hr forecasts worse using EFSO. (Kalnay et al., 2012).
- The results with real atmospheric observations, and a realistic but inexpensive atmospheric model show large forecast improvements that last over 8 days.
- EFSO is almost cost free, and since it accumulates the improvements, it does not need to use “future observations” in operational NWP.
- It only requires an EnKF data assimilation (or a hybrid).
- Reanalysis and other DA applications should use future observations!
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