Adjoint Sensitivities for Impact Assessment of Future Observing Systems

Application to spaceborne Doppler wind lidar

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Context: ADM-Aeolus

- ESA Earth Core Explorer Mission
- Doppler wind lidar to measure wind profiles
- Scheduled launch: October 2007
- Main characteristics:
  - polar orbit, dawn-dusk
  - 400 km altitude
  - 355 nm laser
  - Single line of sight (LOS)
  - 35° looking angle
  - Sampling scheme: 50 km on a 200 km track
  - Range from surface to 26 km

First observing system to provide a global coverage of 3-D wind
Study objective

- Assess the added value of a space-borne DWL in numerical weather prediction (NWP) systems to enhance the predictive skill of high-impact weather systems
- Requirements for wind quality and coverage for ADM-Aeolus follow-on missions
- ADM-Aeolus design
  - Focus on quality rather than quantity
  - OSSE
    - Positive impact on average
    - No extreme weather events

What DWL coverage and quality is sufficient to capture rapidly-evolving sensitive structures?

OSSE analysis wind error reduction
Aeolus sampling of sensitive structures

ADM samples sensitive structures in otherwise data sparse regions
• OSSE, OSRE (DWD), assimilation ensemble method (ECMWF)

1. Realistic
2. Provides a good short-term (2-day) forecast
3. Not in conflict with existing observations

SIMULATED “TRUE” ATMOSPHERE

- Simulation of the new observing system
- Combined assimilation of synthetic and existing observations in operational NWP environment
- Impact on 2-day forecast

Requires simulation of only the new observing system
Standard adjoint sensitivity computation

Diagnostic tool to evaluate forecast failures; back-trajectories are used to determine the analysis perturbation, $\delta x_0$, needed to prevent the failure

- Diagnostic function: 2-day forecast error aspect
- Norm at final time: total energy (TE)
- Norm at initial time; TE or $B$-matrix

$$J(x_0) = \frac{1}{2} \left< M \left[ F(x_0 + \delta x_0) - x_{t+48} \right] M \left[ F(x_0 + \delta x_0) - x_{t+48} \right] \right>$$

$$\langle x, x \rangle = \frac{1}{2} \int \int \left[ u^2 + v^2 + R_u T_r (\ln p_s)^2 + \left( \frac{c_p}{T_r} \right)^2 + w \frac{L^2_{\text{cond}}}{c_p T_r} q^2 \right] d\Sigma dp$$

$$\| \delta x_0 \|_C = N$$

TE norm wind perturbation

$B$-matrix norm wind perturbation

$B$-matrix norm wind structures are broader and have larger amplitude
Sensitivity impact on analysis/forecast

Sensitivities do reduce the 2-day forecast error; different norms give equal reduction.

Sensitivities do **NOT** reduce the analysis error.

*Synthetic observations might conflict with existing observations*

- Standard sensitivity computations do not include the data assimilation system.
- The diagnostic function has no constraint on the analysis error.

*Standard sensitivity computation not good enough for simulating a true atmosphere*
New approach: **first-guess sensitivity assimilation**

Motivation: assimilation pushes the sensitivity structures to the truth in data dense areas while they are maintained in data sparse areas

Method

1) First-guess forecast + sensitivity computation $\Rightarrow$ first-guess (FG) perturbation
2) Assimilation cycle initiated with perturbed FG $\Rightarrow$ AN perturbation $\Rightarrow$ “true” atmosphere

Assimilation corrects sensitivity structures above data dense continents

Sensitivity structures are maintained above data sparse oceans
Sensitivity assimilation

- 500 hPa, Pacific
- Overall structure maintained
Observation conflict; $|an\text{-}truth| - |an+pert\text{-}truth|$

- **Temperature**
  - Standard sensitivity: conflict
  - Assimilated sensitivity: no conflict

- **Wind**
  - Standard sensitivity: no conflict
  - Assimilated sensitivity: conflict
Assimilated sensitivity impact on forecast

- Analysis perturbations from assimilated adjoint FG sensitivities
  - reduce the 2-day forecast error significantly
  - Give small/no increase of the analysis error for TE/ $B$-matrix perturbations

Assimilated perturbations match with existing observations and maintain (part of) the forecast error reduction capability

The First THORPEX International Science Symposium; Montreal; 6-10 December 2004
**Outlook**

- Simulation and assimilation of Aeolus and follow-on candidates
- Focus on extreme events that were badly forecasted

**Aeolus tandem**

Information content single LOS vs. dual perspective

“alternative” dual perspective
Summary and conclusions

- **Objective**
  - Impact assessment of Aeolus and future spaceborne DWL systems in extreme weather events

- **FOSE (Future Observing System Experiment)**
  - Simulated true atmosphere based on adjoint sensitivities
  - Combined assimilation of existing observations and synthetic observations from the new observing system in operational NWP system
  - Added value of new observing systems in real forecast failure cases

- **Application to various DWL sampling scenarios**

_requirements for wind quality and coverage for ADM-Aeolus follow-on missions_
END
Assimilation corrects sensitivity structures, in particular over data dense continents.
Sensitivity observability

- Correlation of adjoint sensitivities with clouds
  (A.P. McNally, QJRMS, 2002)

\[ S^* = S \cdot F(C_c, \tau_c) \]

\[ F(C_c, \tau_c) = (1 - C_c) + C_c \cdot \tau_c \]

- Sensitivity observability = \[ \frac{S^*}{S} \cdot 100\% \]

<table>
<thead>
<tr>
<th></th>
<th>surface</th>
<th>700 hPa</th>
<th>500 hPa</th>
<th>200 hPa</th>
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<tbody>
<tr>
<td></td>
<td>40%</td>
<td>65%</td>
<td>75%</td>
<td>96%</td>
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Clouds are no fundamental limitation for sampling sensitive structures by spaceborne DWL
Adjoint sensitivity method (ctd.)

- New approach: *first-guess sensitivity assimilation*
- Motivation: assimilation pushes the sensitivity structures to the truth in data dense areas while they are maintained in data sparse areas
  1) First-guess forecast; sensitivity computation $\Rightarrow$ first-guess perturbation, $\delta x_b$
  2) Assimilation cycle initiated with perturbed first-guess $\Rightarrow$ true atmosphere $\tilde{x}_a$

\[
\tilde{x}_{b} = x_{b} + \delta x_{b}
\]
Impact of future observing systems in NWP

TRUE ATMOSPHERIC STATE ???

• OSSE (Observing System Simulation Experiment)
  – True atmospheric state: Nature run (model simulation)
  – Limitations: Requires huge resources (For the wealthy), outcome critically depends on proper specification of observation error statistics (You get out what you put in), Sometimes too optimistic (Models are more similar to each other than any of the models to reality), Requires careful calibration

• OSRE (Observing System Replacement Experiment)
  – True atmospheric state: Model analysis
  – Limitations: Applicable only in data dense areas, No clear assessment of impact in data sparse regions

• Assimilation ensemble method; ECMWF (D. Tan, E. Andersson)
  – True atmospheric state: Model analysis of other weather centre

• FOSE (Future Observing System Experiment)
Adjoint sensitivity method

- Impact of future observing systems in NWP
  - OSSE, OSRE (DWD), assimilation ensemble method (ECMWF)
- Find an atmospheric state at forecast initial time that
  1. is realistic
  2. provides a good short-term (2-day) forecast
  3. is not in conflict with operational observations
- True atmospheric state = (incorrect) analysis + perturbation
- Perturbation candidate: adjoint sensitivity structures
- Issues
  - Two flavours available for the sensitivity computation, based on
    1. Total Energy (TE) norm
    2. Background error covariance matrix ($\mathcal{B}$-matrix) norm
  - Relevant to verify sensitivity structure realism