Some challenges in assimilation of stratosphere/tropopause satellite data

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Thanks to: ASSET partners, ESA®
Importance of stratosphere/tropopause

- radiative-dynamics-chemistry feedbacks associated with strat $O_3$ & relevant to studies of climate change & attribution (WMO 1999)

- quantitative evidence knowledge of the strat state may help predict the tropospheric state at time-scales of 10-45 days (Charlton et al. 2003)

- important role UTLS water vapour plays in atmos radiative budget (SPARC 2000)

- need realistic representation of the STE & transport between tropics & extra-tropics in strat -> key role in the distribution of strat $O_3$ (WMO 1999)
Importance of stratosphere/tropopause

Recognition of key role of stratospheric O$_3$ in determining temperature distribution & circulation of atmosphere ->

Incorporation of photochemical schemes of varying complexities into climate models:

- Coupled climate/chemistry models (e.g. Austin 2002)
- CTMs for study of ozone loss (e.g. Khattatov et al. 2003)
- Cariolle scheme in NWP systems (ECMWF; Struthers et al. 2002)
Recent developments

- Satellite data (Research)
  - NASA: EOS-Terra, EOS-Aqua, EOS-Aura
  - ESA: ERS-2, Envisat, ESA’s Living Planet Programme
  - NASDA: ADEOS-1,-2, GOSAT
  - ESA/CSA: ODIN

- Future satellite data (Operational): e.g. METOP, MSG

- Synergy between research & operational satellite data (make research satellite data operational?)
Recent developments

- Atmospheric models (increases in computing power)
  - Increases in horizontal resolution (T511 at ECMWF)
  - Increased vertical resolution in UTLS
  - Top of atmospheric models extended upwards

 -> Together with DA: Improve forecasting & long-term capability
  - Extend range of validity of forecasts; novel geophysical parameters
  - More consistent & realistic climate models
  - Confront & evaluate forecast & climate models
Recent developments

- Data assimilation
  - Increasing use outside NWP agencies (CTMs, NWP models)

- Use of DA by ESA
  - Envisat cal-val
  - OSSEs (e.g. SWIFT)
Recent developments

- Computers
  - More power -> more sophisticated models

- GRID technology
  - Efficient use of data & models
  - Increased collaboration
  - Web-based training

- Many obstacles to be removed (e.g. access to large EO archives & metadata, common formats)
Wealth of Envisat data: ESA©

GOMOS: limb
- Ozone
- Water vapour
- Temperature
- + more

MIPAS: limb
- Ozone, water vapour, methane
- Nitrous oxide, nitrogen dioxide, nitric acid, temperature
- + more

SCIAMACHY:
- Limb + nadir
- Total column ozone
- Total column nitrogen dioxide
- Height resolved ozone
- + more
Synergy of Envisat data

Chemistry:
Nitrogen species
Chlorine species
+ more

Transport:
Water vapour
Nitrous oxide
Methane

Ozone distribution in space + time (+more species)

Limb geometry: Height resolved information

Atmosphere

Parton information between troposphere and stratosphere

Nadir geometry: Constraint on total information

$\text{Envisat}$

Represent influence from chemistry and transport
Wealth of observations (Envisat, EOS, ODIN, ADEOS-II)

Sophisticated models (NWP - dynamics, CTM - photochemistry)

Powerful tools: Data Assimilation 3d-, 4d-var, KF

Increasingly powerful computers

E-Science concepts

High resolution
Dynamics/chemistry coupling
Tropospheric chemistry

Improved forecasts & analyses: E.g. Ozone hole split Sep 2002

Increasingly powerful computers
Challenges in data assimilation (1)

- Assimilation of water vapour in stratosphere/tropopause region
  (challenge in assimilation: estimation of error statistics)

- Assimilation of novel geophysical parameters (e.g. ozone, stratospheric winds) into NWP systems

- Synergy from measurement geometries

- Coupled dynamics/chemistry in data assimilation

- Limb radiance assimilation
Challenges in data assimilation (2)

- Assimilation of novel photochemical species (e.g. CFC-11, CFC-12, ClONO$_2$)
- Aerosol assimilation (stratosphere & troposphere)
- Tropospheric chemistry
- Novel retrieval methods (e.g. tomography)
- Data management
The ASSET (ASSimilation of Envisat daTa) consortium

Challenges listed addressed by ASSET partners (examples):

- **UREADMY/MO**: stratospheric water vapour assimilation (*)
- **MF/CERFACS**: Coupled dynamics/chemistry assimilation (*)
- **ECMWF**: Limb radiances (*)
- **KNMI**: Synergy from measurement geometries
- **UPMC**: Assimilation of novel photochemical species
- **BIRA-IASB**: stratospheric aerosol
- **U. Koeln/U. Karlsruhe**: Tropospheric chemistry/novel retrievals
- **CNR.IFAC**: Tomographic retrievals
- **NILU**: Data management

ASSET is a FP5 project: [http://darc.nerc.ac.uk/asset](http://darc.nerc.ac.uk/asset)
Assimilation of water vapour in stratosphere/tropopause
Water vapour:

Radiation: Dominant GHG in atmosphere

Dynamics: Diagnostic of atmospheric circulation

Chemistry: Source of OH; PSCs
- **Troposphere:** hydrological cycle *(climate change; precipitation)*
- **UTLS:** radiative forcing from $\text{H}_2\text{O}$ *(climate change; monitoring environment)*
- **Troposphere/Stratosphere:** transport studies *(climate change; ozone loss via PSCs; testing climate models)*
Recommendations from SPARC assessment on UT/S water vapour (1):

- **Quantify & understand** differences between sensors (importance of high resolution in situ data for trop/strat transport)

- **Strong validation** programmes (previous lack in UT)

- **Continuity of measurements** to determine long-term changes (especially stratospheric $H_2O$)
Recommendations from SPARC assessment on UT/S water vapour (2):

- **Monitor UTH** to determine long-term variations. Complementary observations

- **Process studies of UTH & convection.** Joint measurements of H$_2$O, cloud microphysical properties & tracers with signature of “age of air”

- **More observations in tropical tropopause region** (15–20 km) (*in situ* & remote sensing) needed to improve understanding of STE

- **Monitor stratospheric H$_2$O** (*CH$_4$* measurements desirable). Overlap of future satellites with current instruments

- **Theoretical work** to understand observations
Assimilation of UT/S data from Envisat (H$_2$O, as well as CH$_4$) will help address many of the recommendations in the SPARC assessment.
Stratospheric Humidity Assimilation
(MO & UREADMY)

$H_2O$ data assimilated:

- **Troposphere:**
  - ATOVS:
    - HIRS: ch 10-12 (900, 700 & 500 hPa)
    - AMSU-A: ch 18-20 (500, 750 & 900 hPa)
    - Radiosondes (up to 20 km)

- **Stratosphere:**
  - MIPAS (available 100 - 1 hPa; assimilated 100 - 40 hPa)
Old dynamics

- RH is control variable (-> New dynamics, ND)
  Problems with RH: low values in stratosphere; dependence on temperature. Other options, q?

- B calculated using NMC method (turned off for levels above ~40 hPa; turned on in ND)

- No flow dependence (use Riishojgaard ideas?)

- No CH$_4$ oxidation (yes in ND)
Problems with existing stratospheric assimilation (found in old dynamics, reasons to believe are present in new dynamics)

- Ill-conditioned vertical transform of $B$ matrix (currently weighted by mass and standard deviation - max in boundary layer).
- Excessive increments in lower stratosphere (e.g. 50 hPa), suspect due to spurious correlations with lower levels.

Also:

- To date, no assimilation of water vapour over the whole stratosphere (only MIPAS $H_2O$ up to $\sim 40$ hPa - very preliminary results being evaluated).
- Desirable to assimilate $CH_4$ and $N_2O$ (tracer advection scheme)
MIPAS H₂O data
ESA © 2002

ECMWF H₂O data
850 K

~10km

No B info

TROPOSPHERE
(ATOVS)

12UTC 2002/9/26

ECMWF/SPARC Workshop - Shinfield, ECMWF 23-26 June 2003
Humidity assimilation - possible solutions  
(MO/UREADMY)

Need to revisit calculation of \( \mathbf{B} \) matrix
- vertical weighting
- rotation of vertical modes
- treatment of tropopause?

Also for the future
- flow dependence
- advection scheme

MO investigating performance of stratospheric \( \text{H}_2\text{O} \) in ND
B: STD RH (%)
December
New Dynamics
50 levels
0-63 km
NMC Method
B: RH correlations, December.

New Dynamics: NMC Method
B: RH correlations, December.

New Dynamics: NMC Method
Coupled dynamics/chemistry in assimilation schemes
Approaches to assimilation:

- **GCM**: dynamics with “simple” chemistry (Cariolle)
  - 3d-, 4d-var; Feedback between dynamics, chemistry & radiation; operational obs (UREADMY/MO, ECMWF)

- **CTM**: sophisticated photochemistry driven by off-line winds/temperature; KF, 4d-var
  - No feedbacks (KNMI, UPMC, BIRA-IASB, UKOELN)

- Coupled GCM/CTM (time-step?): Idea is to get the best from above approaches (MF/CERFACS)

- **ASSET**: assess strategies to assimilate data into NWP systems
Recent developments in assimilation:

- **GCM:**
  1. incorporation of novel atmospheric species (ozone)
  2. extensions of simple photochemical parametrizations (Cariolle)
  3. incorporation of novel observation geometries (limb)
  4. improvements in error characterization of model
  5. radiance assimilation
Recent developments in assimilation:

- **CTM:**
  1. extension of models to include novel species (e.g. CFCs)
  2. improvements in heterogeneous chemistry
  3. incorporation of aerosols (troposphere & stratosphere)
  4. improvements in error characterization of model
  5. radiance assimilation
Recent developments in assimilation for GCMs & CTMs feed into coupled dynamics / chemistry assimilation
ARPEGE

Conventional data
Ozone ENVISAT data

Met. analyses
U,V,T,q,surface

Chemical analyses
3D ozone

MOCAGE

 ENVISAT data
GOME data…

Palm

Chemical data: L2, then L1
Advantages:

- Improve assimilated winds & forecasts in NWP model
- Realistic $O_3$ (later aerosol) fields for NWP radiative transfer scheme
- CTM: improved distribution of photochemical species (observed & unobserved) & improved fluxes in the UV

Disadvantages: Complexity & cost
Limb radiance assimilation
Why assimilate radiances?

Better to assimilate information nearer in form to data received by instrument (i.e. radiances instead of retrievals)

Overcomes shortcomings associated with retrievals:

1) need to include *a priori* information to make problem well-posed & fill in data gaps – “contamination” of solution

2) common assumption that measurement errors uncorrelated (expediency) not strictly true for retrievals.
Why assimilate radiances?

- Radiance assimilation overcomes (to a large extent) these shortcomings
  
  (Note it has been argued that correlations between radiances can be important: T. von Clarmann & MIPAS)

- Estimation of observation errors & bias characteristics is generally easier for radiances than for retrievals
  
  (It is argued that shortcomings of standard retrievals can be overcome to a large extent by performing a SVD of retrievals; Rodgers and Connor (2003).)
Assimilation of MIPAS infrared limb radiances

Idea:

1. Use radiances as observations, rather than retrieved profiles of temperature, humidity, ozone, ...

2. Observation operator includes (fast) radiative transfer calculations

Why?

1. Very successful at ECMWF for nadir sounders; flexibility

2. Estimation of observation error and bias characteristics easier for radiances than for retrievals

3. Avoids having to account for the use of a priori information in the retrievals
Some challenges:

- **Limb geometry:**
  - Assimilation of IR limb radiances has not been done before.

- **Computationally feasible forward model for IR limb radiances:**
  - Current fast radiative transfer schemes have to be extended.
  - “Fast” means: Ideally similar to about 3.4s for the simulation of 8,461 IASI channels on IBM rs6000 workstation.

- **Data volumes:**
  - MIPAS provides measurements of ~60,000 spectral points/“channels”.
  - Need to select channels for simultaneous assimilation of p, T, H₂O, O₃ information, with selection optimised within resource limitations.

- **Error characteristics:**
  - Observations: Inter-channel correlations for high-spectral sounders?
  - Background: Improved characterisation in stratosphere and for ozone may be necessary.
Normalised weighting functions for 9 km tangent height (along path)

<table>
<thead>
<tr>
<th>Path distance [km]</th>
<th>Corresponding pressure [hPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tangent height</td>
<td></td>
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<tr>
<td>Ozone 9.6 µm</td>
<td></td>
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</tbody>
</table>

Choice of “microwindows”
Future directions
Operational use of research satellite data by NWP centres: ozone (already assimilated at ECMWF), stratospheric H₂O. Estimation of B: challenge throughout DA

- Assimilation of limb radiances by research/operational groups. Development of fast & accurate RT models & interface between models & assimilation. Progress more advanced for IR radiances than UV/Vis

- Chemical forecasting & tropospheric pollution forecasting

- Coupled dynamics/chemistry DA systems (e.g. GCM/CTM)

- Earth System approach to environmental & socio-economic issues