Prognostic aerosols in the Ensemble Prediction System and impacts at the monthly/sub-seasonal scales

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With contributions from:
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OUTLINE

• General context: the Copernicus Atmosphere Monitoring System (CAMS)

• Scientific motivation

• Overview of modelling efforts with focus on aerosols

• Impact of aerosols on NWP (medium-range and sub-seasonal range)

• Summary and future perspectives
THE COPERNICUS ATMOSPHERE MONITORING SYSTEM (CAMS)
Atmospheric composition is a pivotal element between human activities and the Earth Environment. Atmospheric composition and its changes affect our health and well-being, with impacts on air quality, climate change, ozone hole, numerical weather prediction, emissions, mitigation, ozone, PM, NOx, greenhouse gases, exposure, adaptation, and numerical weather prediction.
CAMS: A Significant Heritage

• A decade-long series of R&D projects and an internationally respected European achievement (GEMS, MACC, -II, -III)
• An equally long experience in engaging with users and potential users in Europe and across the world (PROMOTE, MACC, -II, -III)
From Earth Observation to policy-quality products

Over 70 EO instruments are assimilated in the global system.

Boundary conditions feed an ensemble of high-resolution European AQ systems (in order to assess uncertainties).

More data are assimilated (in particular in situ) and used for extensive validation.

Policy-relevant (here health indicator for ozone) products are delivered. They are “maps with no gaps”, which observations alone don’t provide and are essential to assess impacts.
CAMS Portfolio

AIR QUALITY AND ATMOSPHERIC COMPOSITION
European air quality analyses, forecasts and assessments in support of reporting and policy making, pollen forecasts, global transport of constituents/pollutants.

CLIMATE FORCING
Distributions of aerosol components and their radiative impacts, other radiative forcings.

OZONE LAYER AND UV
Monitoring and forecasting of the ozone layer / hole, UV index, UV radiation (crops, ecosystems).

SOLAR RADIATION
Estimates of solar irradiance at surface, improved potential yield assessments for solar plants.

EMISSIONS AND SURFACE FLUXES
Estimates of human emissions globally and in Europe (high-resolution), emissions by wildfires, surface fluxes of CO₂, CH₄ and N₂O.

http://www.copernicus-atmosphere.eu
CAMS online catalogue search
(open data policy)

Search criteria based on service themes, species, geographic area, etc.

Products found

Pop-up window with product description and links to plots, data, and validation

http://www.copernicus-atmosphere.eu
NO2, Europe-wide, ~15 km, hourly +96h

Global and European maps of major pollutants

NRT / on-line evaluation

Multi-model spread as a measure of forecast uncertainty
GROWING CAMS AUDIENCES (3000+ USERS)

Daily time-critical users of Global Services

Daily time-critical users of Regional Services

Users of the global re-analysis

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<table>
<thead>
<tr>
<th>Service</th>
<th>Number of Users/Requests for data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global NRT Analyses &amp; Forecasts</td>
<td>~225 users</td>
</tr>
<tr>
<td>Regional NRT Analyses &amp; Forecasts</td>
<td>155 users</td>
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<tr>
<td>Global Reanalysis</td>
<td>1600 users</td>
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<tr>
<td>GHG flux inversions</td>
<td>40 users</td>
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<tr>
<td>Solar Radiation</td>
<td>~1000 requests/year</td>
</tr>
<tr>
<td>Global ftp</td>
<td>~40 users</td>
</tr>
<tr>
<td>Emissions, fire</td>
<td>1773 users (716 institutes)</td>
</tr>
</tbody>
</table>

atmosphere.copernicus.eu web

Islandic volcano event
Fire Radiative Power (W/m²) accumulated over Indonesia during the 2015 fire season (Aug-Oct). Credits: Francesca Di Giuseppe
INDONESIAN FIRES (AUG-OCT 2015)

O3 anomaly: 30-40%

Biomass burning AOD anomaly: up to 2000%

CO anomaly: up to 500%

Benedetti et al, 2016, in “State of Climate 2015”, BAMS.
Credits: Antje Inness, Mark Parrington (ECMWF), Gerry Ziemke (NASA)
EXTREME EVENTS: CHILEAN FIRES (JAN 2017)

Chile battles devastating wildfires: 'We have never seen anything on this scale'

The world’s largest firefighting aircraft has flown in from the US, alongside help from France, Peru and Mexico, as fires continue to rage Chilean lands.

Credit: Mark Parrington (ECMWF)
AEROSOL MODELLING
CAMS aerosol forecasts

- Built on the ECMWF NWP system with additional prognostic aerosol variables (sea salt, desert dust, organic matter, black carbon, sulphates)
- Aerosol data used as input in the aerosol analysis:
  - NASA/MODIS Terra and Aqua Aerosol Optical Depth at 550 nm
  - NASA/CALIOP CALIPSO Aerosol Backscatter (experimental)
  - AATSR, PMAP, SEVIRI, VIIRS (experimental)
- Verification based on AERONET Aerosol Optical Depth (and now also Angstrom exponent)
- Part of multi-model ensemble efforts such as the International Cooperative for Aerosol Prediction (ICAP) and the WMO Sand and Dust Storm Warning and Assessment System (SDS-WAS) North-African-Middle-East-Europe and Asian nodes.

Source: http://sds-was.aemet.es
Aerosols in the ECMWF IFS (C-IFS)

12 aerosol-related prognostic variables:

* 3 bins of sea-salt (0.03 – 0.5 – 0.9 – 20 µm)
* 3 bins of dust (0.03 – 0.55 – 0.9 – 20 µm)
* Black carbon (hydrophilic and –phobic)
* Organic carbon (hydrophilic and –phobic)
* SO$_2$ -> SO$_4$

Physical processes include:

• emission sources (some of which updated in NRT, i.e. fires),
• horizontal and vertical advection by dynamics
• vertical advection by vertical diffusion and convection
• aerosol specific parameterizations for dry deposition, sedimentation, wet deposition by large-scale and convective precipitation, and hygroscopicity (SS, OM, BC, SU)
Recent developments: Use of a mass fixer for aerosol species in CIFS

- For aerosol species as for chemical species, the Semi Lagrangian Advection (SLA) scheme is not mass conservative.
- With the hybrid sigma-pressure system, the vertical discretization changes with surface pressure and orography.
- The GRG project already studied the impact of this phenomenon (Flemming and Huijnen, 2013, Diamantakis and Flemming, 2014) on chemical species.
- Tests with the same mass fixer as used by GRG: additive mass fixer
- Impact important on OM and BC (-10% AOD), significant on Sulfates (+3% AOD), small on total AOD (-1%)
- It was the missing term to balance aerosol species' budgets!

Mean global AOD for May 2014 for BC (top) and sea-salt (bottom), reference in red, with mass fixer in blue

Credits: Samuel Rémy (LMD), Johannes Flemming (ECMWF)
Recent developments: Dust emissions

- Overestimation of dust AOD: the aerocom average is 0.023
- Compared to the literature and other models, the amount of larger particles in dust emissions is too low.
- => decrease of the amount of small particles in the emissions, increase the amount of larger particles

Global dust AOD for May 2014 as a function of lead time, with (red) and without (blue) data assimilation

- Better balance between the model and observations after the introduction of new emissions

AOD at the AERONET station of Tamanrasset (Algeria), from 15/4/2014 to 1/8/2014. Observations (blue), old emissions (red) and new emissions (black)

Credits: Samuel Rémy
Future: GLOMAP aerosol in C-IFS

Aerosol mass as “components” in internally mixed modes

**Sulphate, sodium, black carbon, organic carbon, dust**

**Ammonium, nitrate, chloride**

*Also emit sea-spray as sodium chloride & sodium sulphate.*

*Account for sea-salt-SO4 as well as usual nss-SO4.*

Credits: Graham Mann (University of Leeds)
Evaluation suite for assessing IFS- GLOMAP (also in UM, TOMCAT)

GLOMAP evaluation strategy involves assessing a range of aerosol metric against observations. As well as aerosol optical depth speciated mass, size-resolved number concentrations are used.

Sulphate mass evaluation against EMEP, IMPROVE, U. Miami obs datasets for reference IFS-GLOMAP run

Credits: Graham Mann, Sandip Dhomse (Uni Leeds)
CAMS REANALYSIS RUNS

- “Interim” reanalysis from 2003-2016 has been produced (Flemming et al 2017, ACP)
- Limited number of archived fields & reduced number of meteorological datasets
- Overall good performance
- Used for contribution to the State of Climate (BAMS) publication (2015 and 2016 contributions)
- New CAMS reanalysis in preparation

In collaboration with: Johannes Flemming and Antje Inness
CAMS VS MACC REANALYSIS RUNS

- Main differences in AOD are down to model changes since the CAMS “Interim” reanalysis uses MODIS Dark Target as the MACC reanalysis
- Increase in dust (particularly close to the source areas)
- Perhaps now too much dust but this is being corrected for the next reanalysis

- Striking differences in sea salt are attributable to model changes (big impact)
- Bias correction for MODIS data includes also surface wind speed as predictor (smaller impact)

In collaboration with: Johannes Flemming and Antje Inness
REANALYSIS RUNS: BAMS STATE OF CLIMATE 2015

TOTAL AOD TREND
2003-2014

2016 contribution is in preparation!
• CAMS offers many services related to atmospheric composition from daily forecasts to reanalysis runs both at the global and at the regional (European) level

• Model developments related to aerosols have been carried out for the past 12 years during precursors projects. These are now part of the ECMWF’s Integrated Forecast System (IFS)

• Several datasets related to atmospheric composition are routinely assimilated and more are in the pipeline (Copernicus Sentinel satellites)
AEROSOL IMPACTS ON NUMERICAL WEATHER PREDICTION
This inter-comparison aims to evaluate the impact of aerosols on Numerical Weather Prediction.

Three situations were proposed:

- Dust storm over Egypt on 18th of April 2012
- Extreme pollution over Beijing, 12-16th of January 2013
- Extreme biomass burning over Brazil in September 2012 during the SAMBBA field campaign

Participants: Météo-France, Met-Office, JMA, ECMWF, NOAA, NASA, CPTEC (Brazil)
Dust case of April 2012 – AOD forecasts

- Cycling forecast with the MACC global system, with aerosol direct effect from climatology or prognostic aerosols at T511, L60
- Dust bins: 0.03 – 0.55 – 0.9 – 20 µm
- AOD peak of 18th of April well timed but underestimated
- End of the event forecast too soon

Dust case of April 2012 – Impact on temperature, winds and dust production

Difference between run with interactive aerosols (TOTAL_ASSIM) and reference run (REF_ASSIM) 36 hour forecast (valid on April 18th at 12UTC)

- Reduced 2m temperature
- Increased surface winds
- Increased dust production

Climatological AOD 550nm distribution
MACC vs Tegen et al 1997 (OPER)

• MACC run (2003-2012): sources of biomass burning from GFAS, sulphate aerosol precursor from EDGAR 4.1, prognostic for sea salt and dust, revised dust model

• Optical properties recomputed for RRTM spectral bands and for each aerosol type/size bin. Mass mixing ratio as input to radiation

• Vertical distribution following an exponential decay with scale height derived from the MACC model for each aerosol type. Monthly varying for dust.

Credits: Alessio Bozzo
Impacts on forecast errors

- Change in mass distribution and optical properties -> reduction in SW absorption -> reduction in temperature (positive)

- This is of the order of 0.1K for a bias of the order of 0.3K – it explains at least ~30% of the temperature error.

- Similar for winds at upper levels

Credits: Alessio Bozzo
Impacts on FC errors

June-July

U 925 hPa – model bias at D+5

20 year run

OLD climatology

NEW climatology

GPCP (obs)

Credits: Alessio Bozzo, Linus Magnusson
Impacts on FC errors

(c) Day 5
- Unit: 0.1K Mean: -0.49 RMS: 4.26 Sig: 36%
-34 -10 -6 -2 2 6 10 62
3 ms⁻¹

(c) Day 5
- Unit: 0.1m/s Mean: 1.07 RMS: 6.95 Sig: 25%
-26 -10 -6 -2 2 6 10 30
3 ms⁻¹

(c) Day 5
- Unit: 0.01K Mean: -1.76 RMS: 11.8 Sig: 17%
-81 -15 -9 -3 3 9 15 69
0.8 ms⁻¹

(c) Day 5
- Unit: 0.01m/s Mean: 0.01 RMS: 2.11 Sig: 10%
-11 -5 -3 -1 1 3 5 29
0.8 ms⁻¹

T@850 hPa – FC errors
U@850 hPa – FC errors
T@850 hPa – changes in FC errors
U@850 hPa – changes in FC errors
Impacts on precipitation patterns - JJA

Model error against GPCP2.2
Monthly EPS coupled runs with interactive aerosols

- Control run for the period 2003-2015 uses standard Tegen et al 1997 climatology
- Interactive aerosol run covers the same period and uses fully prognostic aerosols in the radiation scheme – only aerosol direct effect
- Free-running aerosols with updated emission for biomass burnin
- Ensemble size is 11 members, T255 resolution, 91 levels
- 5 different start dates around May 1 (55 cases in total) – summer runs (focus of this talk)
- 3 different start dates around November 1 (33 cases in total) - winter runs
Aerosol impacts on monthly forecasts (summer)

- Preliminary results show a positive impact (reduction in bias) of the interactive aerosols on meteorological fields (winds and precipitation) as observed in studies using a more up-to-date aerosol climatology.
- More prominent (positive) impact over the Indian Ocean and to a lesser extent in other areas which is also consistent with new climatology results for the same model release.
Aerosol impacts on monthly forecasts (summer)

CONTROL RUN – 850 hPa U WIND BIAS WEEK 4

INTERACTIVE AEROSOL RUN – U WIND BIAS WEEK 4

Scorecards measures

- Performance of interactive aerosol experiment with respect to a control run for several parameters.
- Blue circles indicate positive impact
- Dark blue circles indicate significant impact

(Scores are applied to bias corrected fields)

- Similar impacts are observed with the new ECMWF/CAMS climatology
- Need to understand the relative importance of the meteorological feedback on the daily variability of aerosols
Improvements to sub-seasonal skill scores

Active aerosols

Coupled vs pers SST

May start dates only (summer runs)
2003-2015 period
Observed (prescribed) Fire emission
Biomass burning AOD anomaly: up to 2000%

Benedetti et al, to appear in State of Climate 2016, BAMS.
Credits: Antje Inness, Mark Parrington (ECMWF), Gerry Ziemke (NASA)

Prediction of fire emissions is needed (under development)
By-product: monthly dust forecast (May 2015)

DUST AEROSOL OPTICAL DEPTH @ 550nm

CAMS ANALYSIS – 30 May 2015 @ 1200UTC

MONTHLY FORECAST valid for 30 May 2015 @ 1200UTC
Summary and Future Perspectives

• Using prognostic aerosols interactively in the radiation seems to be beneficial to model skill at the sub-seasonal range

• Similar positive results were obtained with an improved aerosol climatology

• More investigation is needed to understand if positive impact comes from resolved time and spatial variability or from a better representation of the aerosol fields which could be also delivered by an up-to-date accurate climatology

• Extreme events like the Indonesian fires of 2015 could only be captured with prognostic aerosols (and prognostic fire emissions) – these events are connected to El Nino and have a high degree of predictability at the seasonal scale

• By-products of using interactive aerosols is the sub-seasonal aerosol prediction per se

• More systematic experimentation is needed to understand benefits vs costs. In the current configuration the additional cost in the monthly EPS is 40-50%. HIGH RES runs are possibly prohibitive and perhaps benefits in the medium-range are smaller – an aerosol climatology would remain the most viable option.

• Experiments planned with the latest model release: control run with Tegen et al (1997) climatology, run with new ECMWF/CAMS climatology, runs with fully interactive prognostic aerosols

Thank you!