A European Global-to-Regional that Combines Modeling

A novel forecasting system for atmospheric composition operates daily to forecast global air pollution.

by Johannes Flemming, Vincent-Henri Peuch, Richard Engelen, and Johannes W. Kaiser

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Atmospheric trace gases and aerosols have been observed from satellites for more than two decades, but only recently have these observations been exploited for air pollution applications. The European Copernicus program (formerly known as GMES—Global Monitoring for Environment and Security)[1] supports the development of operational monitoring capabilities of the environment, which rely strongly on remote-sensing from satellites, as well as in situ observations. A novel forecasting system for atmospheric composition has been developed for the Copernicus atmosphere service in a series of research projects (GEMS, MACC, and MACC-II)[2] funded by the European Commission since 2005. The system is now operated daily to forecast global air pollution, as well as air quality over Europe. The forecasts are an important input to air quality warning systems for protecting human health. Besides air quality, the global forecasts are used to predict ultraviolet exposure, available solar energy, and hazards caused by dust storms.

The Copernicus prototype forecasting system consists of a single global model and an ensemble of regional air quality models for the European domain, which use the predictions of the global model as boundary conditions to allow for long-range

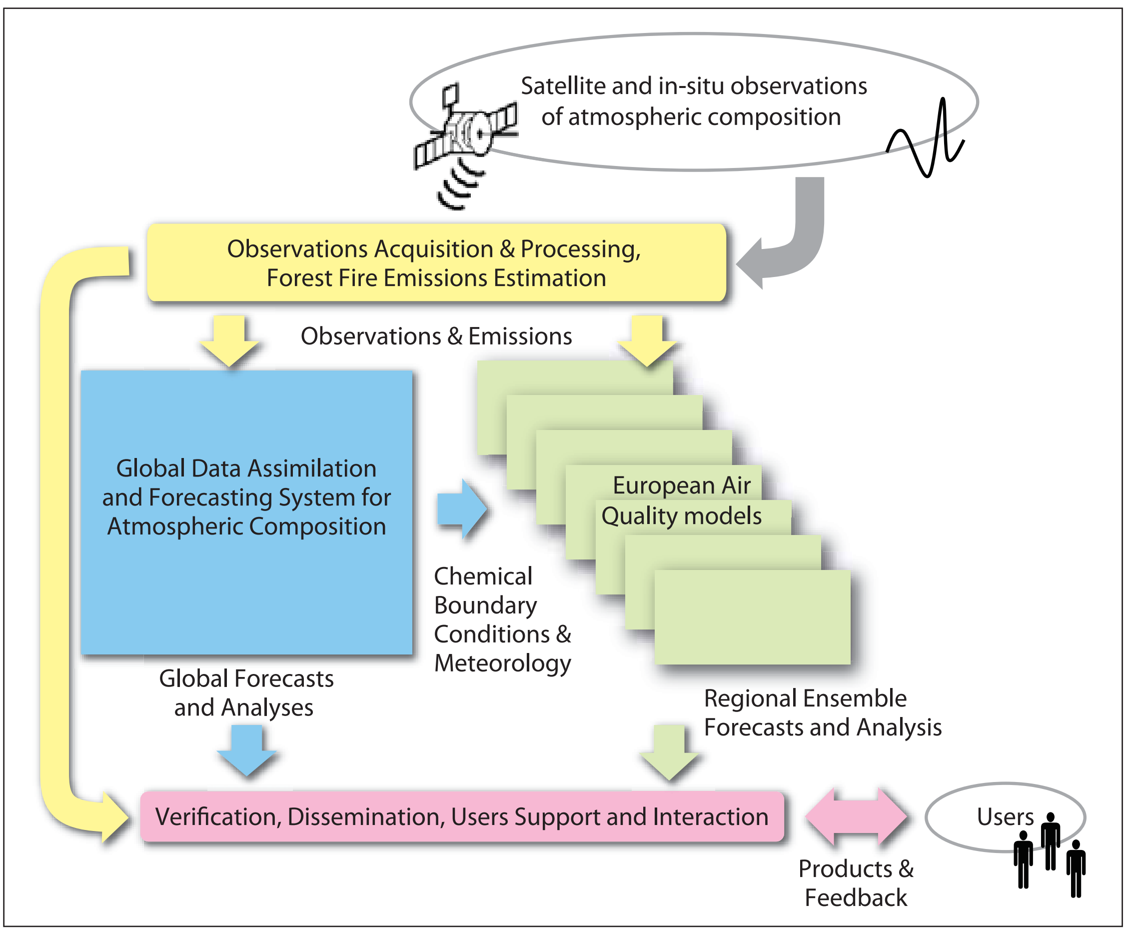

Figure 1. Building blocks of the Copernicus forecasting and data assimilation system for atmospheric composition. Observations are fed into the global and regional forecasting systems. An ensemble of seven regional air quality models uses the global forecast as boundary conditions for air quality forecast for the European domain. The global and regional forecast are validated and presented at www.copernicus-atmosphere.eu

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Air Pollution Forecasting System with Satellite Observations

transport of pollutants. Satellite observations are fed into the global model to improve the initial conditions of the forecasts, and also to infer the latest distribution of forest fire emissions. The regional models use surface observations, as well as some satellite data, to correct their initial conditions. Each of the regional models has a different formulation of the chemical processes. The spread of forecasts of the individual regional models is used as an indication of the uncertainty of the predictions, and the ensemble median has a better overall forecast skill than any of the individual models.

A Global Model and Data Assimilation System

The global component of the system has been developed at the European Centre for Medium-Range Weather Forecasts (ECMWF) by extending ECMWF's weather forecasting model to predict the fate of trace gases[3] and aerosols.[4,5] The atmospheric composition forecasts are currently run over five days at a horizontal resolution of 80 km, which is about five times coarser than the resolution of ECMWF's operational weather forecasts because of the extra computational cost of the representation of chemical processes. Figure 1 shows a schematic of the building blocks and the data flow within the global and regional forecasting systems.

Significant progress[6] in numerical weather prediction in recent decades can be attributed to the improved exploitation of observations, in particular from satellite instruments. The satellite observations, together with in-situ observations, are blended with the model results using a technique called data assimilation. Data assimilation is used in numerical weather prediction to produce a realistic starting point for the model forecast, which is essential for the forecast quality. For the Copernicus atmosphere service, ECMWF's meteorological data assimilation system has been adapted for the assimilation of satellite observations of atmospheric composition.

Observations of atmospheric gases and aerosols by satellites instruments have limitations. The vertical resolution is low and the signal from the boundary layer is often weak. Nevertheless, the assimilation of satellite observations by the Copernicus system is successful in reducing large-scale model biases and introducing the effects of emissions that are not

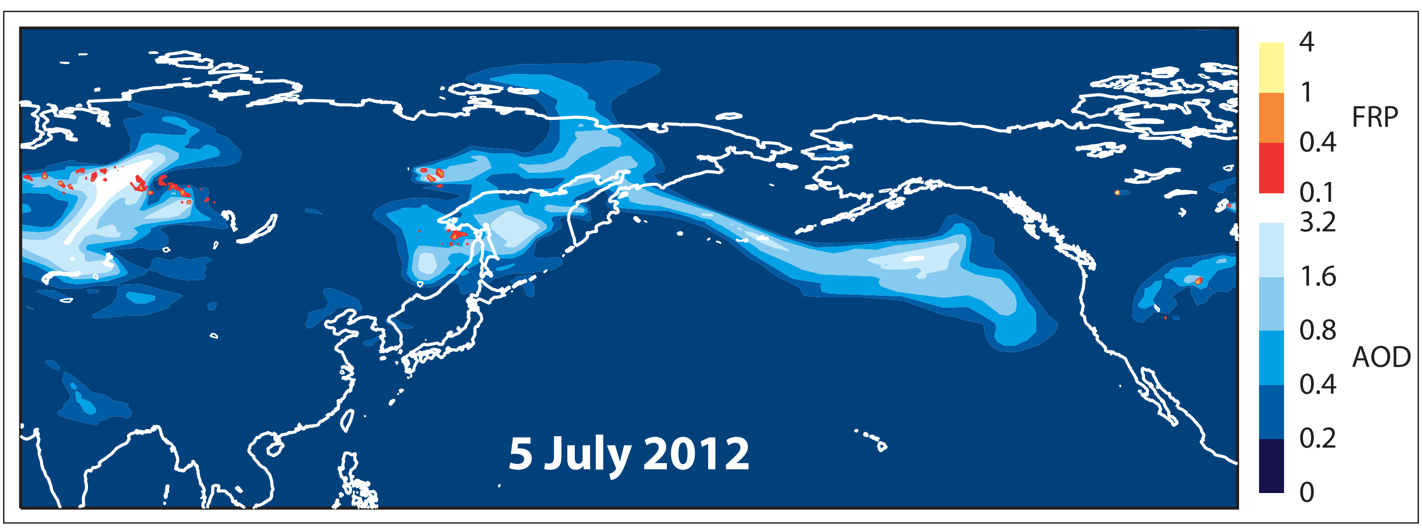

Figure 2. Forecast of a smoke plume traveling from Asia to North America on July 5, 2012. The plume came from intensive forest fires in Eastern Siberia, which were observed by the MODIS satellite instrument in near-real-time. The corresponding emissions were used in the forecast. The observed fire radiative power (FRP) is shown in a red color scale, aerosol optical depth (AOD) of the forecast plume is shown in a blue color scale. An animated version of the plume is available online at www.copernicus-atmosphere.eu/news/seattle_haze/seattle_haze_details/.

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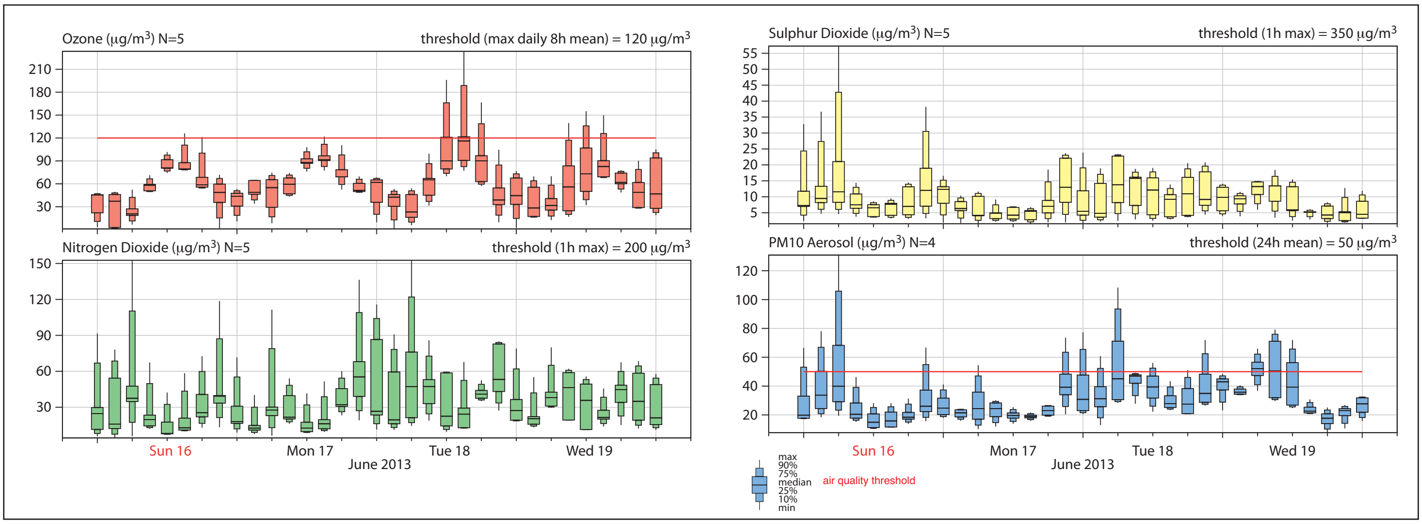

Figure 3. Presentation of a four-day forecast (June 16–19, 2013) for Paris, including an ensemble of seven regional air quality models for ozone, nitrogen dioxide, sulfur dioxide, and PM_{10}. The size of the boxes represents the range of the predicted values. The median of the ensemble is represented by the line in the middle of the box. The red line indicates the air quality threshold according to European legislation. The latest ensemble forecasts are available online at http://macc-raq.gmes-atmosphere.eu/som_eps.php.

accurately accounted for. It can also help to correct the strength of specific events like dust storms or forest fire plumes.[7] Assimilation of surface observations is a successful approach to correct the initial surface concentration in the regional models, but may have limited impact on the forecasts if the emissions remain uncorrected. Therefore, the correct knowledge of the emissions, the manifold chemical conversions, and the removal processes, together with a good representation of the transport, remains decisive for air pollution forecasting at the global and regional scale.

Emissions from Inventories and Observed Forest Fires

Specific inventories of anthropogenic and biogenic emissions at the global[8] and the European scale[9] have been compiled for the Copernicus atmosphere service. Besides using the inventories, the Copernicus atmosphere service also pursues efforts to capture the day-to-day variability of the emissions in near-real-time. The thermal radiation from large forest fires, which can have a strong effect on air pollution locally or by long-range transport, can be observed from space. The observations are converted to emissions[10] of 40 smoke constituents, including black carbon and carbon monoxide, which are then used by the global and regional models.

As an example, Figure 2 shows space-borne observations of forest fires in Siberia and the resulting simulated smoke plume. The plume traveled over the Pacific and had a profound impact on the aerosol burden at the West Coast of the United States in July 2012. Wind-blown dust is another type of an emission event that can impact air quality, but is not described in inventories. Dust and sea salt emissions are derived based on wind forecasts. Transport events of Sahara dust to Europe and the Middle-East, as well as dust storms in China and Australia, have been correctly predicted by the global forecasts.

A Regional Forecast Ensemble for Europe

Seven state-of the-art regional air quality models (CHIMERE, EMEP, EURAD, LOTOS, MATCH, MOCAGE, and SILAM)[11] are run daily for the European region, as part of the Copernicus atmosphere service. The models have a horizontal resolution of 10–20 km, which is well suited to capture the characteristics of air pollution events such as increased ozone levels in summer.[12] The forecasts are provided to a wide range of users, who use the regional results to make air quality forecasts at the urban- or even the street-level scales. The simulated chemistry of the regional models is more comprehensive than that in the global system, in particular for the secondary aerosol formation, which is an important contribution to fine particulate matter ($PM_{2.5}$). The feasibility to forecast sources and transport of birch pollen over Europe, for example, was demonstrated in spring 2013.

The regional models use the same emissions, boundary conditions, and meteorological input from the operational ECMWF forecast, but still the results differ owing to different formulations of chemical and physical processes, which is an indication of the uncertainty[13] in the forecasts. Following the example in weather prediction, where the spread of an ensemble forecast is used to illustrate forecast uncertainty, the forecasts of the regional models are presented in a common framework.

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As an example, Figure 3 shows the air quality ensemble forecast for Paris during a period with increased ozone concentrations in June 2013. The regional models predict a similar variability, but the individual differences can be large. In contrast to an ensemble of weather forecasts, in which the ensemble spread tends to increase for longer forecast times, the spread of the "chemical ensemble" does not steadily increase with forecast lead time, but often shows a diurnal variability.

Running, Evaluating, and Presenting Operational Air Pollution Forecasts

The routine operation of the air pollution forecast benefits greatly from the operational infrastructure offered by ECMWF. All meteorological data, as well

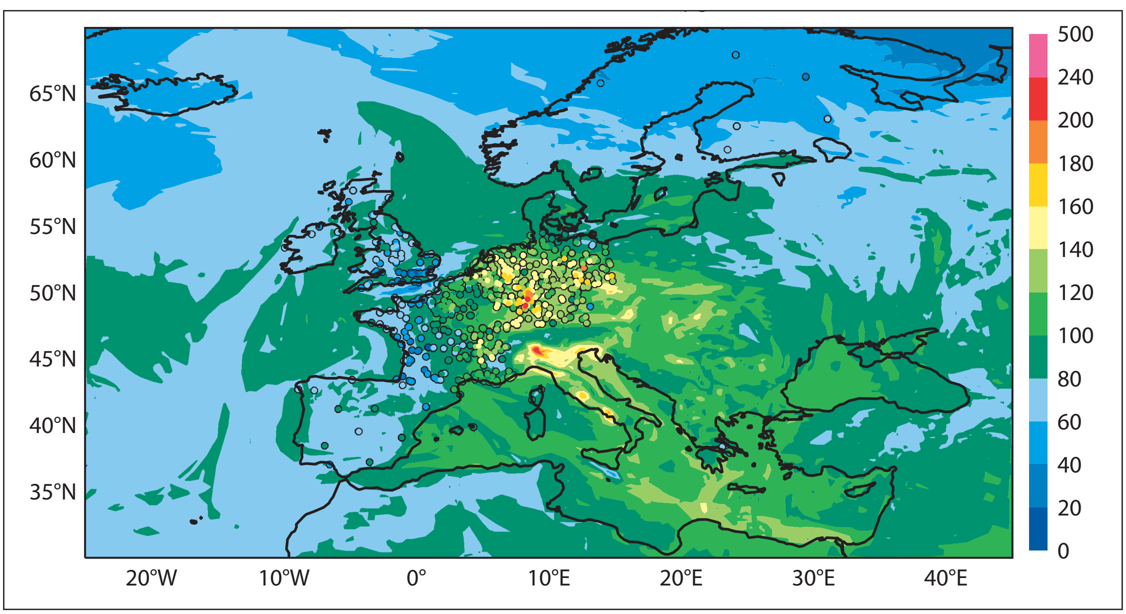

Figure 4. Forecast of ozone over Europe for June 18, 2013, by the median of an ensemble of seven regional air quality models and near-real-time evaluation (circles) with air quality observations from several European networks. The latest verification plots are available online at http://macc-raq.gmes-atmosphere.eu/som_OF.php/.

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Transport events of Sahara dust to Europe and the Middle-East, as well as dust storms in China and Australia, have been correctly predicted by the global forecasts.

as satellite observations of forest fires (MODIS), aerosol optical depth (MODIS), carbon monoxide (MOPITT and IASI), nitrogen dioxide (OMI), and ozone (MLS, SBUV-2, IASI), are received, processed, and fed into the global system. The regional models are run by their owners once the global forecast is completed.

The evaluation of the global and regional forecasts is at the heart of the Copernicus atmospheric service. In-situ observations available shortly after the forecast are used for the evaluation of the latest forecast. These observations come from the operational air quality networks in the European countries collated by the European Environment Agency (see Figure 4), the AERONET network for aerosol optical depth, the IAGOS program of carbon monoxide and ozone air craft observations, the global ozone sonde network, and the Global Atmospheric Watch network. The forecast accuracy is documented by quarterly reports, which rely on an even wider set of in-situ and remote-sensing observations. Updates of the global forecast model, or changes in the assimilated satellite retrievals and emissions, are carried out according to a specific protocol, which makes sure that the update does not cause a degradation of the forecast skill.

Conclusion

The European Copernicus prototype forecasting system for atmospheric composition and regional air quality is constantly being developed, especially the methods to infer emissions and surface concentrations from satellite observations. The Copernicus system also forecasts and monitors greenhouse gases and performs retrospective analyses of atmospheric composition.[14] The near-real-time forecasts and the retrospective data are freely available. The data and their evaluation are presented in a large catalog of images on the Copernicus Web site at www.copernicus-atmosphere.eu. **em**

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