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Smoke in the air

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Smoke in the air

Johannes W. Kaiser, Olivier Boucher, Marie Doutriaux-Boucher, Johannes Flemming, Yves M. Govaerts, John Gulliver, Angelika Heil, Luke Jones, Alessio Lattanzio, Jean-Jacques Morcrette, Maria R. Perrone, Miha Razinger, Gareth Roberts, Martin G. Schultz, Adrian J. Simmons, Martin Suttie, Martin J. Wooster

Smoke from forest fires can greatly impact regional air quality and thus human health. The degree of human exposure depends on the fire location, amount of fuel burned, type of fire, and the atmospheric transport of and chemistry in the plume. We have started developing a global fire assimilation system that produces emission estimates for the monitoring and forecasting of fire plumes in the GMES Atmospheric Core Service (GACS), which is developed in the GEMS and MACC projects under the leadership of ECMWF. Note that projects and satellite instruments referred to in this article are briefly described in Box A.

The system currently delivers global fields of observed fire intensity. Figure 1 provides an example that illustrates the huge range of the global fire intensities. Note that the fire season in Sub-Saharan Africa dominates the global picture. Large fire intensity is also evident in South America, Cambodia and Vietnam. Also note the localized spot of extreme fire intensity in Victoria, in the southeast of Australia, which is associated with the worst bush fires in Australian history in terms of death toll.

Due to the high variability of fires on all time scales from hours to decades, the smoke emissions have to be derived from fire observations. Open fires can be observed from space. The EUMETSAT Land Satellite Application Facility (SAF) in Lisbon, Portugal, has recently started the production of a quantitative fire product from the observations of SEVIRI onboard the geostationary satellite Meteosat-9. It features an unprecedented combination of quantitative accuracy and temporal resolution.

The Greek fires of August 2007 were well observed by SEVIRI because of cloud-free conditions over the whole period. We have used the SEVIRI data to estimate the fire emissions and to simulate the resulting smoke plumes with the GEMS global aerosol model. We found good agreement with independent aerosol observations and widespread population exposure to fine mode particulate matter in excess of a World Health Organization (WHO) guideline.

Satellite-based fire observations

Satellite instruments can either detect the thermal emission during a fire or the burnt area after. The former products are referred to as ‘hot spots’, ‘active fires’, ‘fire pixels’ or ‘fire counts’, while the latter are known as ‘burnt area’, ‘burnt scar’, ‘burnt pixel’ or ‘fire affected area’. Only the hot spot products can be delivered in real time, which is required by the GACS. One example is ESA’s ATSR World Fire Atlas (dup.esrin.esa.int/ionia/wfa/).

Hot spot products are typically derived from satellite observations of the thermal emission in a mid-infrared atmospheric window channel near 4 μm wavelength, where fires produce a strong signal with radiance increases of several orders of magnitude. The intensity of fires varies greatly, which is partly due to fires being a sub-pixel size process. Traditional hot spot products from polar orbiting imagers can estimate the likelihood of a fire being present in each pixel, but they are unable to quantify the fire intensity. A quantitative fire product, WF_ABBA, has been available since the 1990s from the GOES satellites; it estimates fire temperature and burning sub-pixel area with a resolution of about 4 km at the sub-satellite point.

AFFILIATIONS
Johannes W. Kaiser, Johannes Flemming, Luke Jones, Jean-Jacques Morcrette, Miha Razinger, Adrian Simmons, Martin Suttie: ECMWF, Reading, UK.
Olivier Boucher, Marie Doutriaux-Boucher: Met Office Hadley Centre, Exeter, UK.
Yves Govaerts: EUMETSAT, Darmstadt, Germany.
John Gulliver: University of the West of Scotland, Paisley, Scotland, UK.
Angelika Heil, Martin G. Schultz: Forschungszentrum Jülich, Jülich, Germany.
Alessio Lattanzio: Makalumedia GmbH, Darmstadt, Germany.
Maria R. Perrone: Università del Salento, Dipartimento di Fisica, Lecce, Italy.
Gareth Roberts, Martin Wooster: King’s College London, Department of Geography, London, UK.

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Another quantitative hot spot product is available from the two MODIS instruments aboard the Terra and Aqua satellites, the design of which has taken requirements for quantitative fire observations into account. The fire products generated by NASA and NOAA contain a Fire Radiative Power (FRP) estimate that quantifies the thermal radiation emitted by the fires in units of megawatts (MW) with a resolution of about 1 km at the sub-satellite point. FRP is roughly proportional to the chemical energy released by the fires, and thus also to the biomass combustion and pollutant emission rates. Therefore, FRP is considered the most appropriate fire observation product for emission estimation.

The main shortcoming of the MODIS observations is that the polar orbits of the satellites limit the sampling frequency. The potential for fire observations is also reduced by the presence of clouds. Figure 2a illustrates the observation return periods of potential fire observations that have actually been achieved during a given 24-hour period. Water, ice, cloud and snow pixels are not processed. The satellite orbits induce stripey patterns (e.g. over the Sub-Saharan region) and persistent cloud cover inhibits observations in several regions. Otherwise there is coverage with indicative return periods typically between 4 and 12 hours.

In March 2008 the EUMETSAT Land SAF started real-time production of a newly developed FRP product generated from SEVIRI observations. This product maintains SEVIRI's return (sampling) period of 15 minutes. It is therefore capable of resolving the diurnal cycle of open fires in Africa and Southern Europe with unprecedented accuracy. The high sampling frequency also helps to take advantage of brief cloud-free spells for fire observations in mostly cloudy regions.

Figure 2b illustrates the return periods of potential observations of fires for SEVIRI. The FRP product is limited to the geographical disk visible from Meteosat-9. But, within this disk, it covers higher latitudes than the MODIS fire products since snow/ice pixels are being processed. It is apparent, however, that the observational capabilities of SEVIRI are affected by the same cloud pattern as in the MODIS data. For example, the ITCZ over Central Africa is particularly persistent in this respect. Nevertheless return periods of around 30 minutes in the SEVIRI disk constitute a major improvement over those of the MODIS instruments.

Programmes and satellite instruments

A

Programmes

FREEVAL. The Fire Radiative Energy Evaluation (FREEVAL) project was funded by EUMETSAT to validate the FRPPIXEL data product from METEOSAT's SEVIRI sensor and explore its potential use in operational systems.

GACS. The GMES Atmospheric Core Service (GACS) will provide coherent information on the atmospheric composition at European and global scale in support of European policies and for the benefit of European citizens.

GEMS. An EU-funded project to develop comprehensive data analysis and modelling systems for monitoring the global distributions of atmospheric constituents important for climate, air quality and UV radiation, as a baseline for the GACS.

GMES. Global Monitoring for Environment and Security (GMES) is a European initiative for the implementation of information services dealing with environment and security.

MACC. The EU-funded project Monitoring Atmospheric Composition and Climate (MACC) is the successor to GEMS and the ESA-funded GMES Service Element project PROMOTE.

Satellite instruments

MODIS. This is a key instrument aboard the Terra and Aqua satellites. These instruments view the entire Earth's surface every 1 to 2 days, acquiring data in 36 spectral bands.

SEVIRI. This instrument on the Meteosat Second Generation (MSG) satellites delivers daylight images of the weather patterns, plus atmospheric pseudo-soundings and thermal information. It provides image data in visible, near-infrared and infrared channels. The image sampling distance is 3 km at the sub-satellite point for the standard channels and down to 1 km for the so-called High Resolution Visible channel.

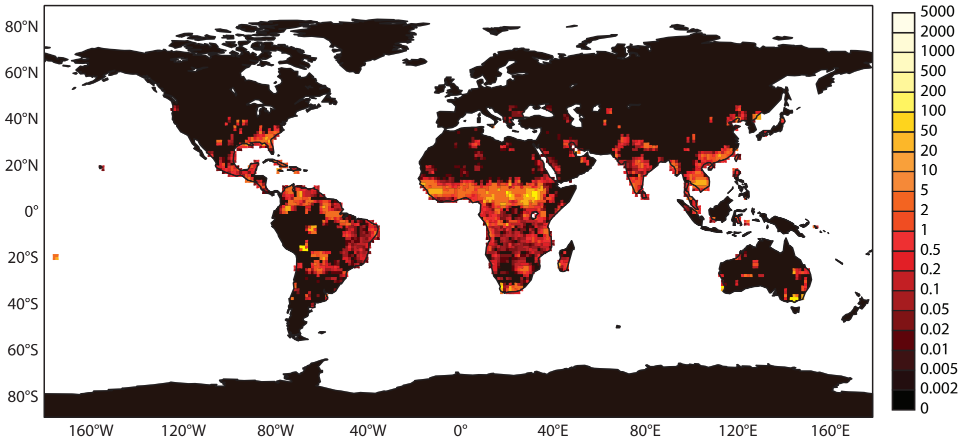

Figure 1 Daily averaged fire intensity (mW m^{-2}, with ~125 km resolution) observed by the two MODIS instruments and SEVIRI on 7 February 2009. Coverage subject to observational limitations illustrated in Figure 2 (http://gems.ecmwf.int/d/products/aer/fire).

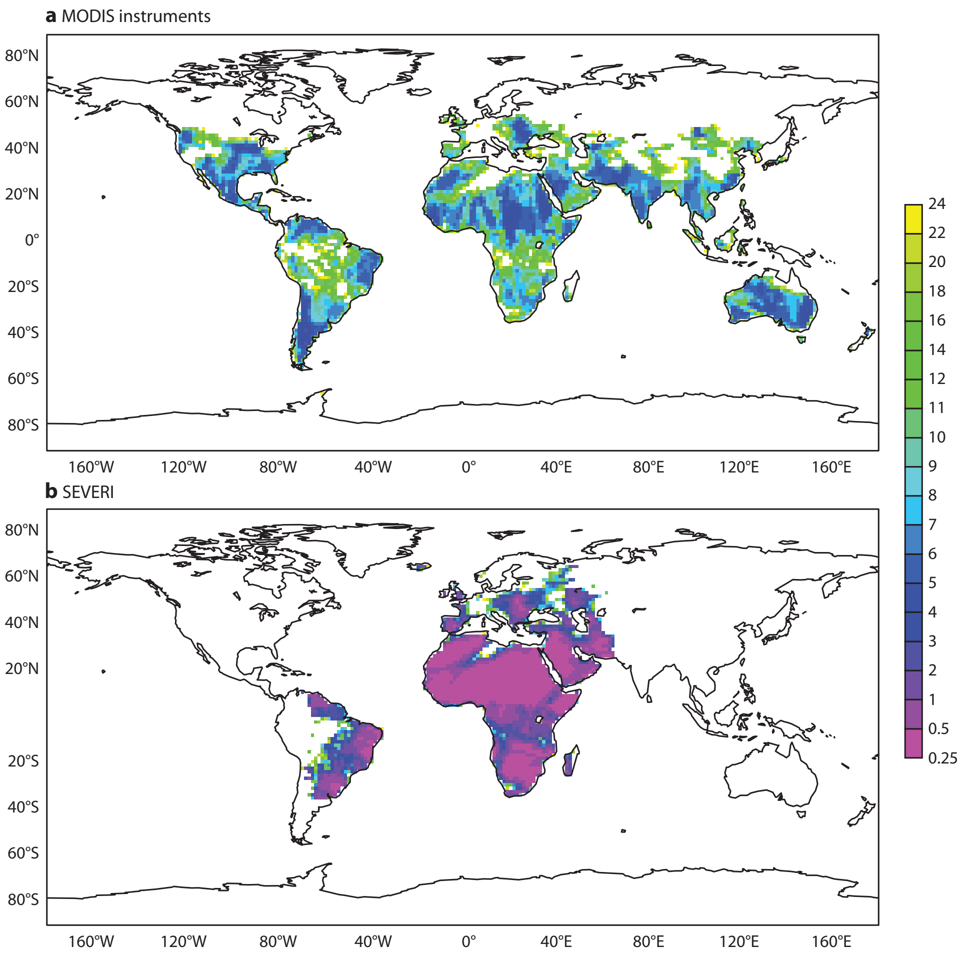

Figure 2 Indicative return periods (hours) for observations with the potential to detect a fire by (a) the two MODIS instruments and (b) SEVIRI on 7 February 2009.

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Smoke from the Greek fires in August 2007

The EUMETSAT project FREEVAL and GEMS have combined SEVIRI FRP data with the global atmospheric aerosol model developed by GEMS to test how accurately the combined system can simulate smoke plumes. The catastrophic Greek fires in August 2007 were selected as a test case.

The total FRP observed over Greece during the huge fire event in August 2007 is shown in Figure 3. It exhibits strong diurnal and day-to-day variations with the maximum fire intensity occurring on the afternoon of 25 August around 15:45 local time. The fire behaviour of burning continuously through the night is typical for large fire events in middle and high latitudes, while tropical fires mostly extinguish during night-time. The plot highlights the high temporal resolution of the SEVIRI data.

Smoke aerosols are represented as black carbon and organic matter in the GEMS model. The emission coefficient relating FRP (W m^{-2}) to the total aerosol emission rate (kg s^{-1} m^{-2}) has been taken from a previous study of FRP and aerosol optical depth (AOD) observed by MODIS. The partitioning of the aerosol species is prescribed according to the Global Fire Emissions Database (GFED). Thus the smoke aerosol fluxes for the entire fire episode have been calculated from the SEVIRI data with a spatial resolution of ~25 km (T799) and a temporal resolution of 1 hour.

The global GEMS products are generally produced at 125-km (T159) resolution. For this study we have operated the model with the higher resolution of T799 because it is more typical for present-day regional air quality models, which are the primary tool for forecasting European population health impacts. The atmospheric simulation was set up in a 'cycling' mode, in which the meteorological fields are calculated in a series of consecutive 12-hour forecasts that are initialised from the operational analysis. In contrast the aerosol fields are solely governed by the model parametrization and the surface flux input. The SEVIRI-derived fluxes were injected into the lowest model level.

Figure 4a shows the observed FRP at 25-km resolution and the AOD of the modelled smoke aerosols at 12 UTC on 25 August. For comparison, Figure 4b shows a visible composite of concurrent MODIS observations that is overlaid with red markers for MODIS hot spot fire detections. SEVIRI and MODIS agree well on the locations of the fires.

Figure 4b shows that the smoke is blown in a south-westerly direction over the Mediterranean Sea to Northern Africa. The modelled smoke plumes in Figure 4a reproduce the main observed features. In particular, the observations show that the plume is structured in a series of 'pulses' originating from the daily fire intensity maxima. Clearly visible just off the Peloponnesian coast is the pulse emitted by the fire earlier in the day. The pulse emitted the day before just reaches Libya; the landfall is well reproduced while the timing is slightly shifted. Also it is apparent that the widening of the plume over the central Mediterranean Sea is well represented.

SEVIRI also detected strong fires in Algeria on 28–30 August 2007. We have simulated the transport of the emitted smoke plumes, mixed with a larger desert dust plume, northwards over the Mediterranean. Ground-based AOD observations in Lecce, Southern Italy, confirm the plume simulation quantitatively.

Simulating the separation of the plume into pulses from the Greek fires obviously depends on the high temporal resolution and quantitative nature of the SEVIRI FRP product. Also the good representation of the plume transport is a testament to the accuracy of tropospheric winds produced by ECMWF's Integrated Forecast System (IFS). The remaining discrepancies are primarily attributed to shortcomings of our approach in the very active research fields dealing with plume rise and emission factors that scale FRP to the individual species fluxes, depending on fuel type and meteorological conditions.

In order to relate the plume simulations directly to regional air quality and its impact on human health, we have calculated the respirable fine mode (i.e. PM2.5) concentration in the smoke by assuming that two thirds of the smoke is of type PM2.5, which is a conservative estimate. An example of the resulting surface concentrations is plotted in Figure 5.

The World Health Organization (WHO) has determined an air quality guideline of the PM2.5 concentration not exceeding 25 µg m^{-3} for any 24-hour average. A comparison of our simulation with a population density map indicates that more than 40 million people were exposed to smoke PM2.5 concentrations exceeding the WHO guideline due to the large fires in Greece and Algeria and smaller fires in neighboring countries. It is recognized, however, that the injection of all fire emissions into the lowest model level may introduce some overestimation. On the other hand, the exposure to PM2.5 from other sources, such as traffic, also needs to be taken into account. While this case study highlights the potential of ingesting SEVIRI FRP products into regional air quality models, extensive validation is needed before such a system is used for epidemiological studies. Such studies are use to quantify the toxic potentials of the different chemical component of air pollution.

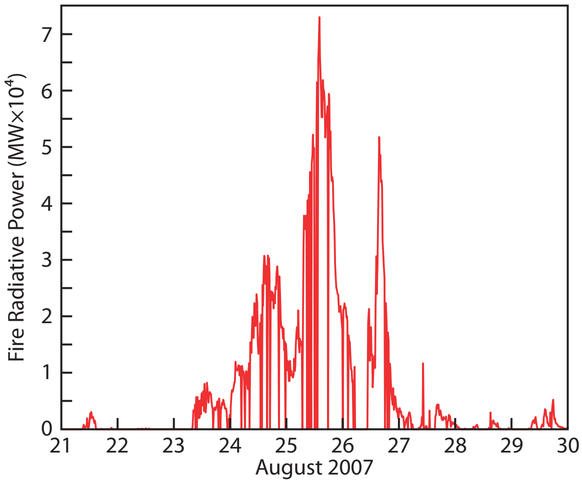

Figure 3 Total Fire Radiative Power (FRP) observed over Greece by SEVIRI. Date ticks at 00 UTC, 2 a.m. local time. The results are derived from a test version of the operational Land SAF product.

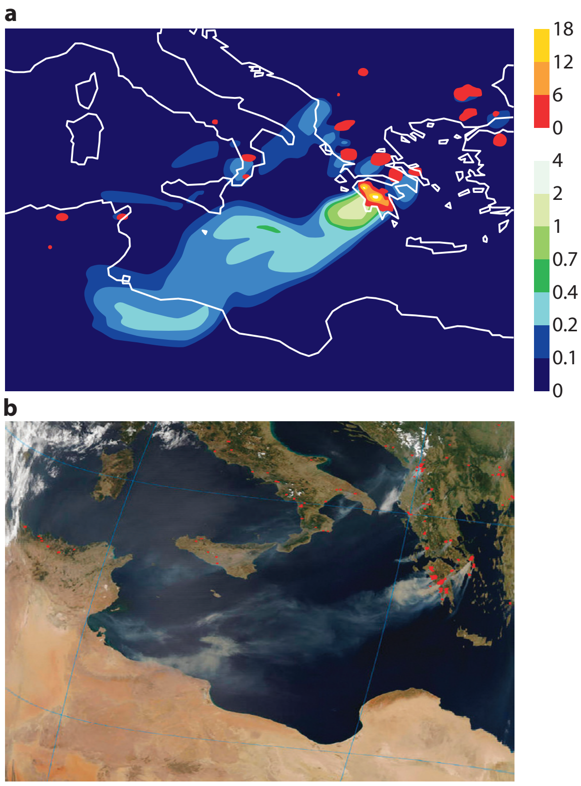

Figure 4 (a) FRP observed by SEVIRI (reddish, W m^{-2}, with ~25 km resolution) and modelled smoke column optical depth (blueish) compared to (b) observed hot spots (red) and true colour image by MODIS aboard Aqua at 1205 UTC on 25 August 2007 (http://rapidfire.sci.gsfc.nasa.gov).

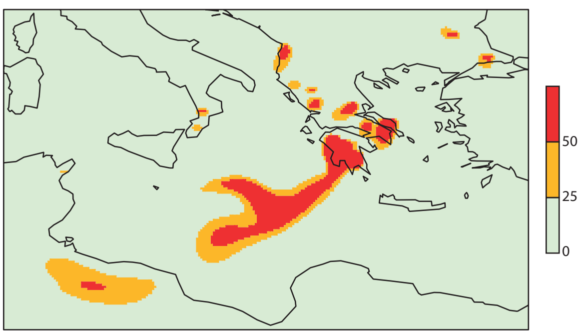

Figure 5 Simulated surface-level concentration of fine mode aerosol (μg m^{-3}) at 12 UTC on 25 August 2007.

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Development of a Global Fire Assimilation System

Based on the success of the case study concerning the Greek fires, GEMS has started to implement a fire assimilation system at ECMWF that merges FRP observations from SEVIRI and other instruments to achieve global coverage. It provides real-time estimates of pollutant fluxes from fires that are ultimately intended for use in all global atmospheric composition and regional air quality systems in the GACS.

While SEVIRI was able to observe the diurnal variability of the Greek fires directly, cloud cover may generally get in the way. Outside the SEVIRI disk, the MODIS instruments provide global coverage, albeit with large data gaps (see Figure 2). Since the operation of the GACS will require continuous global flux input that resolves diurnal variations, complementary observations from several satellite instruments must be merged. Also the remaining observational gaps must be filled by data assimilation with a numerical model of the fire intensity.

As a first development step, the FRP products of SEVIRI and MODIS are acquired and pre-processed for use in a dedicated fire assimilation system. We obtain the SEVIRI FRP pixel product with a time lag of 30 minutes via EUMETCast and the MODIS fire products with a time lag of 3–4 hours by ftp from NOAA. The way in which the Fire Radiative Power (FRP) products are merged to derive the distribution of the fire intensity on a global grid for a given time period is described in Box B.

The observations are currently merged to generate daily observed FRP maps with T159 resolution that are published on the GEMS web site, see Figure 1 for an example. The daily observed FRP maps are already used to calculate carbon monoxide emission fluxes. Based on these fluxes, the GEMS global reactive gas system has forecast fire plumes in support of the POLARCAT campaign that was part of the International Polar Year.

Converting FRP satellite products to global gridded fields — B

We merge Fire Radiative Power (FRP) products from several satellite-based instruments to derive the distribution of the fire intensity on a global grid for a given time period (e.g. for one day).

A gridded field of FRP is generated from each individual observation product by averaging the observed FRP values [W m^{-2}] of all cloud-free land pixels in each grid cell. Additionally, the observed pixel sizes are summed in another field. This field of 'observed area' provides quantitative information on the accuracy of the corresponding FRP field. Several FRP fields can subsequently be merged consistently in space and time by interpreting the observed area as inverse variance of the FRP error. Quasi-global coverage can be achieved by merging observation fields from sufficiently many complementary instruments and a sufficiently long period of time.

The observed area fields are also calculated for the merged FRP fields. The ratio of a grid cell size to its merged observation area indicates the observation return period. An example is shown in Figure 2. Note that the so-called butterfly effect of the MODIS observation geometry leads to duplicate observations along the edges of its swath and an arguably spurious decrease in the calculated return periods.

Our approach is unique in so far as it avoids ad-hoc assumptions on the diurnal cycle or on the burning duration of the fires by also processing no-fire (FRP = 0) observations. Their inclusion will also enable an assimilation system to remove a fire once its extinction is observed. It requires the processing of large volumes of satellite products, though currently about 12 Gigabyte per day.

Outlook

In the future, the global fire assimilation system will be implemented to provide hourly fire emission estimates of the various smoke constituents, based on the observations by an increasing number of satellite instruments. A spatial resolution of 10 km is planned to meet the requirements of regional air quality modelling. To achieve this, the work on fires will be intensified in a dedicated subproject in the GEMS follow-up project MACC.

Our study of population exposure to fine mode particulate matter from smoke demonstrates the potential for retrospective assessments, including epidemiological studies. In view of the established accuracy of atmospheric wind forecasts, we conclude that the new SEVIRI FRP product can, and will, be used for air quality forecasts, too. It will thus contribute to emergency preparedness in relation to hospital admissions and preventive medication in Europe and Africa.

In addition to its local and regional effects on human health, biomass burning is a significant source for the global distributions of atmospheric black carbon, organic matter, sulphate aerosols, carbon monoxide and dioxide, nitrogen oxides and other species. Therefore biomass burning needs to be accurately observed and modelled for the quantitative mapping of long-range transport of air pollutants and the carbon cycle.

Finally, the interactions of fires with weather are manifold: Weather influences fires with wind and precipitation being major factors in the development and propagation of wildfires. Vice versa, fires influence the weather as the smoke aerosol particles efficiently absorb solar radiation and act as cloud condensation nuclei. In extreme cases, fires have been observed to generate so-called pyroconvection that may even penetrate the tropopause. Proper description of these effects has a potential for improving future numerical weather predictions and, with the help of the new global fire products, MACC will be able to quantify all these effects more accurately.

Further Reading

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