aeromap

# Bulletin 3

Final report

# 1 Publishable summary

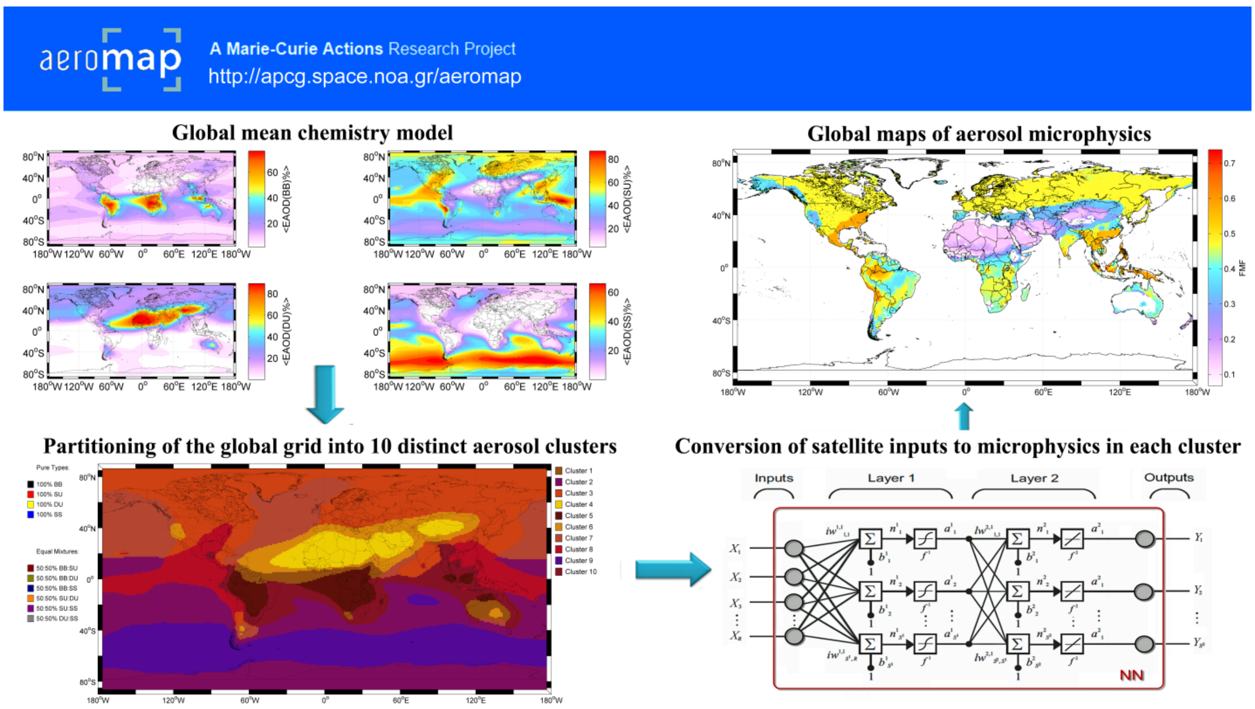
The largest uncertainty in current estimates of the planetary radiation budget is due to atmospheric aerosols and has caused the International Panel on Climate Change (IPCC) to call for an urgent expansion of global studies to help monitor and characterise aerosols. Aerosol properties are most routinely monitored by the ground-based aerosol robotic network (AERONET). However, while there is a high density of AERONET instruments in populated areas and megacities, the most dominant sources of aerosol originate from often uninhabited regions like the planet's deserts, oceans and ice-caps where few instruments exist. There is therefore a lack of knowledge of the overall global spatial and temporal variation of aerosols and their composition. The AEROMAP project was designed to provide a solution to overcome this lack of information without the need to invest in hundreds of new AERONET sites. To achieve this, AEROMAP capitalizes on full-Earth measurements provided daily by satellite remote sensing instruments to produce global maps of aerosol microphysics including the distribution of particle sizes in the atmosphere. In this regard, AEROMAP has developed and validated new data mining tools based on cluster analysis and neural networks to convert satellite measurements into aerosol microphysical properties for different globally-distributed aerosol types – something which has, until now, not been possible from space. The near-daily global maps produced allow for monitoring and classification of aerosols as they move across the Earth's surface.

The main goals of AEROMAP have been to find a way to partition the globe into distinct aerosol type/mixture and then to code neural network models to convert satellite measurements in each pixel of the global grid to estimates of aerosol microphsics. In addition, AEROMAP aimed to test the feasibility of performing global near real-time monitoring of aerosols and to construct an air quality index from microphysics data to assess climatological risks for issuing early-warning alerts of aerosol impact. It was found that the average global distribution of aerosols can be separated into 10 distinct regions, each having a distinguiable aerosol composition. Neural model models were then successfully trained on over 8 years of daily data in each region and validated for their ability to accurately retrieve aerosol microphysics. As a result, global maps of the size distribution of atmospheric aerosol in each 1x1 degree pixel were produced and used to monitor the evolution of events including volcanic eruptions, urban smog clouds and desert dust storms. AEROMAP's "virtual observatories" provided access for the first time to the detailed microphysics of aerosol originating from vast and previsouly invisible natural sources over the oceans, deserts and ice caps. AEROMAP has also produced the first near-daily global air quality index maps deduced from aerosol microphysics rather than chemistry. Two indices have been produced to measure the potential impact on health and also visibility.

The project has brought together the skills of the fellow Dr Michael Taylor as an experienced researcher in the fields of applied mathematics and computational physics with the expertise of the scientist in charge Dr Stelios Kazadzis in the fields of atmospheric physics, remote sensing and aerosol science at the National Observatory of Athens - a world leading centre for aerosol monitoring. The highly multidisciplinary nature of AEROMAP has meant that it has been able to successfully capitalize on the synthesis and exchange of knowledge, 4 peer-reviewed publications in top journals in the fields of atmospheric physics, chemistry and measurement techniques, as well as 2 conference papers. The aticles published have already accrued a total of 658 PDF downloads and 937 HTML views.

AEROMAP is actively contributing to the provision of new information on one of the most important climate change parameters - the global distribution of aerosol. Until now, it has not been possible to exploit the full-Earth coverage provided by satellite remote sensing in order to globally-characterise aerosols via their microphysical properties. The AEROMAP project demonstrated that this is now possible on a timescale of the order of a couple of days thanks to neural network models. Considering the cost of satellite data acquisition, and especially the large data quantities involved with

global modelling, AEROMAP has placed great emphasis on efficient data exploitation so that these new modelling techniques can be readily incorporated into existing operational algorithms. The interest that the published results of the project are generating as indicated by a large number of downloads and online views is helping to raise the profile of the host institute as a centre of excellence in the field and the European Research Area as a pole of attraction for researchers. AEROMAP's global classification of aerosol types and composition, together with near-daily maps of aerosol microphysics can help funding agencies at the national or regional level better determine where to locate new aerosol monitoring stations. In addition, AEROMAP's near-realtime global maps of air quality indices that measure the impact of aerosols on health and visibility from space can help to ensure that environmental policy-making decisions will have positive rather than negative repercussions.

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**Project Website**

http://apcg.space.noa.gr/aeromap

## Overview of the project objectives

An initial objective of AEROMAP was to obtain the complete record of relevant satellite and ground-based remote sensing data and to extract co-located and synchronous data. With this data, AEROMAP then had as its goal the development and validation of neural network models for converting global satellite inputs to microphysical parameter outputs and for assessing their capability to extrapolate spatially and temporally. The next main aim was to use cluster analysis to partition the globe by aerosol type/mixture region, and to then code neural networks to learn the relation between daily-averaged satellite inputs and aerosol microphysical parameters as outputs for each region. A further objective was to generate daily or near-daily global maps of microphysical parameters and to track the spatio-temporal evolution of important events such as desert dust storms, forest fire outbreaks, urban brown cloud pollution episodes, and volcanic eruptions. A goal, related to this, was for AEROMAP to develop and assess an algorithm for global near real-time monitoring of aerosol microphysics, and to construct an air quality index based on microphysical parameter values and corresponding alerts for levels of hazard. A final objective was to disseminate the results of the project widely so as to showcase it as an important product from the European Research Area to attract future collaboration.

## Overview of the progress of the work and training activities/transfer of knowledge

During the first 12 months of the project satellite inputs comprising over eight years of daily measurements (2004-2013) of the AOD at 470, 550, 660nm and the columnar H2O from the MODIS Aqua Level 3 Collection 5.1 together with the absorption AOD at 500nm from the Ozone Measuring Instrument (OMI) Level 3 OMAERUV algorithm were derived at a spatial resolution of 1×1 degree (latitude x longitude). In conjunction with this, co-located (in the same pixel) and synchronous daily-averaged ground-based AERONET Level 2.0 Version 2 Inversions Product parameters spanning the years 1993-2013 and including the AVSD retrieved in 22 logarithmically-equidistant radial bins spanning the range of particle radii from 0.05 to 15μm, the real and imaginary parts of the CRI(λ), the SSA(λ) and the asymmetry parameter ASYM(λ) centred at λ = 440, 675, 870 and 1020nm were downloaded and pre-processed to filter for complete records (**Task A1**). The functional relation between the AOD measured by satellite and ground-based remote sensors was found by linearly-regressing derived MODIS AODs on co-located and synchronous AERONET direct-sun AOD values and validated for AERONET sites having long data records (GSFC-Washington and MSUMO-Moscow). A poster to engage the public on the general approach being adopted was then presented at the European Science Open Forum 2012 in Dublin, Ireland. (**Tasks: A2 & E3, Objective: 9, Deliverable: 3**). Following this, the functional relation between AERONET direct-sun AODs and AERONET Level 2.0 Version 2 inversion products (the AVSD, CRI, ASYM and SSA) was deduced by training and validating neural networks (NNs) with data from the following AERONET individual sites known to be dominated by dust, biomass burning and urban sulphate ($SO_2$) aerosol: Banizoumbou (Niger), Alta Floresta (Brazil) and GSFC-Washington (USA) respectively. AEROMAP developed a new methodology for optimizing neural network architectures and for identifying optimal network configurations. The ability of the optimal NN architecture in each case to extrapolate to another qualitatively-similar but distant site was tested by presenting them with unseen data at the following dust, biomass-burning and urban $SO_2$ sites: Solar Village (Saudi Arabia), Mongu (Zambia) and MSU-MO-Moscow respectively (**Task: A3, Objectives: 1 & 2, Deliverable: 1**). Importantly, the functional relation between satellite-derived AOD and AERONET Level 2.0 Version 2 inversion products (the AVSD, CRI, ASYM and SSA), was deduced by training and validating a new NN with complete records of co-located and synchronous data at GSFC-Washington and then testing its ability to extrapolate to data in the pixel containing MSUMO-Washington. The results were presented at the

European Aerosol Conference 2012 in Granada, Spain (**Tasks: A3 & E3, Objectives: 4 & 9, Deliverable: 2**). The ability of satellite-input NNs to extrapolate using capped data was investigated by training NNs with co-located and synchronous data from a cluster of pixels of similar aerosol composition (as per the chemical composition provided by the GOCART model) for the cases: dust, biomass burning and urban $SO_2$. In each case half of the data was used for NN training and validation and half was used for testing. The NNs were validated also at the weekly, monthly and seasonal timescales (**Task: B1**), and the ability of satellite-input NNs to extrapolate to regions where no sites exist, was investigated by feeding the Northern Africa dust-trained NN with satellite inputs at the distant dust locations Solar Village (Arabian desert) and Dalanzadgad (Gobi desert),  and the Amazonian biomass burning cluster-trained NN with satellite inputs at Mongu (Zambia) – all well outside the geographical domain of the datasets used to train, validate and test the NNs in (5): (**Task: B2, Objective: 4**). During this period, the project website was designed and created (http://apcg.space.noa.gr/aeromap) to help inform the general public and the environmental research community about the project and its scope. In addition, educational resources were uploaded on the website as a gateway to engage the public about the important role of aerosols on climate change and the contribution of the project to this issue (**Tasks: E1 & E4, Objective: 9, Deliverable: 9**).

During the second 12 months of the project, the complete global data record of 3-hourly measurements of AOD per aerosol type at 1×1 degree (latitude x longitude) spanning the years 2000-2006 (inclusive) from the global ozone chemistry aerosol radiation and transport (GOCART) model was downloaded and converted into daily-averages. Cluster analysis was then performed on the mean global values and used to partition the global 1x1 degree grid into 10 distinct aerosol type/mixture regions (**Task: C1, Objective 5: Deliverable 5**). The temporal variation of NN-derived AMPs in the dust cluster was monitored at the monthly, weekly and daily timescale and validated (**Task: C2, Objective: 6, Deliverable 7**), and two pilot studies were performed to help calibrate Saharan dust LIDAR AOD retrievals for CALIPSO and to compare AERONET-retrieved microphysical parameters obtained at Athens with higher temporal frequency values provided by the precision filter radiometer instrument (**Task: C2, Objective: 6: Deliverable: 7**). Global NN-derived AMP maps were then rendered using the aerosol typing provided by the cluster analysis of Task C1 (**Task: C3, Objective: 7, Deliverable 6**) and high accuracy daily global NN-derived AMP maps were rendered at 1x1 degree spatial resolution (**Task: C3, Objective: 7, Deliverable 8**). The feasibility of performing near-real time monitoring was then assessed by modelling the spatio-temporal evolution of sulphate emission from the Karthala volcanic eruption in Madagascar (**Task: D1, Objective: 8, Deliverable: 9**), and 2 air quality indices to measure the impact of aerosol on health and visibility were constructed and mapped globally at 1x1 spatial resolution. In addition, the indices were normalized to a the European standard categorical scale and alert advice was produced for each category (**Task: D2, Objective: 8, Deliverable: 9**). On the public engagement front, a large volume of new content was added to the project website to raise public awareness about the project, its aims and expected results, and the role of Marie-Curie Actions in supporting research in the ERA aerosols (**Task E2: Objective: 9, Deliverable 10**), large-scale dissemination of results was accomplished via publication of 6 peer-reviewed research articles (**Task: E3, Objective: 9, Deliverable 10**), and a public talk on the role of aerosols, their impact on climate change and the way AEROMAP's global outputs contribute to advancing our understanding of their global distribution and characterization (**Task: E4: Objective: 9, Deliverable 10**).

### Training activities and Transfer of Knowledge

One of the main training objectives of the project was to aid the transition of the fellow as an applied mathematics to principal investigator level in the field of environmental modeling so that he could have acquired the competences to ensure tenure in this area. The fellow has designed, managed and performed the research competently and productively. The results have led to satisfaction of the project objectives for these phases and have produced several important and high-impact bi-products. The fellow has been exposed to a broad array of contemporary methods, techniques and analyses in the field of aerosol science while at the host institute including: i) adaptation to the technical basics of ground-based aerosol instrumentation, measurement, retrieval and databases, ii) adaptation to satellite remote sensing retrieval techniques and databases, and iii) the development of algorithms for advanced analysis. This experience has substantially increased the fellow's knowledge of aerosol science, remote sensing, atmospheric physics and the impact of aerosols on climate. New collaborations in the field of environmental modeling have been established and have led to co-authorship on two important published articles led by international teams in the journals of *Atmospheric Measurement Techniques* and *Atmospheric Chemistry and Physics*. Through presentation of his results in 3 first-author publications and 2 conference papers, the fellow has helped to introduce neural networks models and other applied mathematics techniques to a community with limited experience of these approaches. Furthermore, the fellow has given talks in bi-monthly meetings of the APC Group at IERSD-NOA. In particular, he has given two Power-point presentations providing report-backs on the progression of the project, the new methods developed and the main results of the work performed in each Phase. These report-backs marked important points in the progression of the project and have helped ensure its smooth running. The high international standing of members of the APC Group has provided the fellow with the opportunity to attain a high technical level of scientific communication skills via co-authorship and lead-authorship of several peer-reviewed research articles. These opportunities arose as a direct consequence of the great deal of in-house expertise of the APC Group members who are internationally recognized through their editorships on scientific journals, their invited talks at international conferences, invited review papers in top journals, high citation rates, and through their coordination of EU-funded research projects. The fellow, by working at the host institute, has been in contact with broad scientific expertise in the fields of aerosol science, climate change, satellite remote sensing and ground-based instrumentation, measurement and data analysis and atmospheric chemistry. This has enabled collaboration and interaction with other principal investigators in the field at both the national and international level.

The SIC has included the methods introduced in the project in grant funding proposals with a view to hopefully creating a post-project job opening for the fellow at the host institute. The host institute's success in obtaining state funding for a large national project meant that the fellow was able to secure a research contract at the host institute following on directly the completion of AEROMAP in March 2014. In addition, the AEROMAP project was included in the research portfolio of the host institute during a recent national assessment of research centers. Techniques developed during the course of the project meant that the fellow could contribute to 2 important articles as co-author. In the first article, published in the *Journal of Atmospheric Chemistry and Physics,* which presented a methodology for optimising dust retrievals with improvements to the CALIPSO LIDAR algorithm, the fellow played a key role in the writing/editing of the manuscript as co-author in a large international consortium. In a second article, published in the *Journal of Atmospheric Measurement Techniques Discussions*, which compared aerosol microphysical retrievals from the World Meteorological Organisation's precision filter radiometer with those of AERONET's inversion algorithm, the fellow acquired and processed data to make it synchronous and produced contour plots and time series of key microphysical parameters. The article was the result of international collaboration with colleagues from the Physics Instrumentation Centre in Moscow and the World Radiation Centre at Davos among others.

Collaboration with the Director of the APC Group Dr. Evangelos Gerasopoulos who is expert in atmospheric chemistry led to the development of an important new technique for improving the fitting and interpretation of AERONET-retrieved aerosol size distributions. This collaboration created new synergies between the fields of remote sensing and atmospheric chemistry leading to 4 peer-reviewed articles reports with the fellow as first author.

## Dissemination activities

During the first 12 months of the project, the fellow participated in the European Open Science Forum 2012 in Dublin, Ireland to engage the general public via a digital poster presentation on AEROMAP's methodology and on the importance of global monitoring of aerosols. Public engagement with the scientific community was initiated with presentation of a technical poster session presenting initial results from Tasks A1-A3 at the 500+ participant European Aerosol Conference 2012 in Granada, Spain. A graphical abstract was displayed as part of the activities of the host institute at the FP7-funded Researcher's Night 2012 at the National Hellenic Research Foundation, and the fellow has given 2 seminars reporting back on the progress of the project and its results. The fellow has an active profile page on the ACP Group website (http://apcg.space.noa.gr) where copies of his talks and conference posters are exhibited. In addition, the fellow created a Twitter account (handle: _AEROMAP) for tweeting updates and news about the project, and has designed a website/portal for the project (http://apcg.space.noa.gr/aeromap) that has prominent hyperlinks to the personal webpages of the fellow, the scientist in charge, and the host institute, and describing the important role played by Marie-Curie actions in facilitating European research and mobility in an abstract describing the project, its objectives and a timeline for monitoring progress.  The fellow developed a Researchers' Gateway and Education Gateway at the project website to engage scientists and the non-technical reader on the role and impact of aerosols on climate, he participated in the CERN OA18 Workshop on Innovations in Scientific Communication to learn how researchers can use new web-based technologies to improve the dissemination of their results, he started using Twitter to find, follow and engage with interested readers in the fields of aerosol science, environmental research and science communication (https://twitter.com/_AEROMAP). The fellow has established international collaborations leading to co-authorship and publication of 4 peer-reviewed articles in leading journals in the field, and has submitted conference papers for publication in the proceedings of the *prestigious International Conference on Meteorology, Climatology and Atmospheric Physics* (COMECAP) to be hosted by Greece this May – further disseminating the results of the project post-completion. At the end of the project, the fellow will write and issue a press release announcing in the national and academic press, and on social media, the completion of the project and its main findings. The outreach activities above, led by the fellow, have helped and will continue to help increase the national, European and international impact of AEROMAP. In all, AEROMAP has produced 7 peer-reviewed publications (including papers under peer-review or at submission stage):

1. Taylor, M., Kazadzis, S., Tsekeri, A., Gkikas, A., Amiridis, V. (2013). Satellite retrieval of aerosol microphysical and optical parameters using neural networks: a new methodology applied to the Sahara desert dust peak. *Atmospheric Measurement Techniques Discussions* 6, 10955-11010, 2013.
2. Taylor, M.**,** Kazadzis, S., Gerosopoulos, E. (2013). Multi-modal analysis of aerosol robotic network size distributions for remote sensing applications: dominant aerosol type cases. *Atmospheric Measurement Techniques Discussions* 6, 10571–10615, 2013 (accepted and in press at AMT)
3. Amiridis, V., Wandinger, U., Marinou, E., Giannakaki, E., Tsekeri, A., Basart, S., Kazadzis, S., Gkikas, A., Taylor, M.**,** Baldasano, J., & Ansmann, A. (2013). Optimizing Saharan dust CALIPSO retrievals. *Atmospheric Chemistry and Physics* 13, 12089-12106.

4. Kazadzis, S., Veselovskii, I., Amiridis, V., Gröbner, J., Suvorina, A., Nyeki, S., Gerasopoulos, E., Kouremeti, N., Taylor, M.**,** Tsekeri, A., Wehrli, C. (2014). Aerosol microphysical retrievals from Precision Filter Radiometer direct solar radiation measurements and comparison with AERONET. *Atmospheric Measurement Techniques Discussions* 7, 99-130, 2014.
5. Taylor, M.**,** Kazadzis, S., Tsekeri, A., Gkikas, A., Amiridis, V. (2014). AEROMAP: Satellite retrieval of dust aerosol microphysical and optical parameters using neural networks. *Proc. 12$^{th}$ Int. Conf. on Meterology, Climatology and Atmos. Phys. (COMECAP), 28-31/05/2014, Heraklion, Crete, Greece.* (under review).
6. Taylor, M.**,** Kazadzis, S., Gerosopoulos, E. (2014). Multi-modal fitting of AERONET size distributions during atypical aerosol conditions. *Proc. 12$^{th}$ Int. Conf. on Meterology, Climatology and Atmos. Phys. (COMECAP), 28-31/05/2014, Heraklion, Crete, Greece.* (under review).
7. Taylor, M., Kazadzis, S., Gerosopoulos, E. (2014). Multi-modal analysis of aerosol robotic network size distributions for remote sensing applications II: temporal evolution of high load events. *Atmospheric Chemistry and Physics Discussions* (manuscript ready for submission).

## Management activities

The host institute and in particular the SIC, has successfully provided research supervision, expertise and has facilitated collaborations essential for the advanced training needs of the fellow. Following provision of a comfortable workspace in the ACP Group at IERSD-NOA and incorporation of the fellow into the group and its website, the SIC helped the fellow smoothly through the process of registering with the Greek tax office, obtaining health insurance, arranging payment and generally settling in to his new environment. Necessary technical equipment (namely the purchase of a state-of-the-art desktop PC for the project) and software (namely MATLAB) was made an immediate priority and quickly acquired. On the technical side, the SIC assisted the fellow in accessing and obtaining satellite remote sensing and ground-based datasets and showed his great experience in this regard – allowing the fellow to get up to speed rapidly. As a result, the first neural networks were trained within the first 4 months of the start date and gave the fellow the opportunity to meet the call for abstracts at the European Aerosol Conference 2012 where the first results of the project were presented. In addition, the SIC early on capitalised on his collaboration network and opened up a collaboration with the University of Ioannina where Dr Antonios Gkikas had recently developed a more precise technique for sampling MODIS pixel data. Furthermore, the SIC placed the fellow in contact with an expert on airborne aerosol measurement and retrieval, Dr Alexandra Tsekeri, who has recently completed her doctorate at the City University of New York. In particular, Dr Tsekeri's experience of handling measurement errors has helped arm the fellow with the knowledge base needed for developing precise neural network results from satellite data whose uncertainties can be quantified. The SIC has also taken steps to ensure that the algorithms, computational tools and data to be developed and acquired during this project will be made available at the project website/portal and incorporated into the Greek GEO Office data center. Technologies developed by AEROMAP will also be included in the National Bank of Environmental Observation which is coordinated by NOA. In particular, the Greek GEO Office which since 2008, has initiated an inventory of meteorological and atmospheric data coming from the Public Sector, Research Institutes and Universities, ensures that its national portal harmonizes and shares data among producers, providers and policy-makers in the field of environmental observation. This database will be enhanced with the climatological data collected during the operation of AEROMAP which is expected to assist the identification of gaps between available and required Earth observations. AEROMAP's databases will be linked to existing Earth Observation portals and online resources and the portal will enable users to access and download data, products, algorithms and tools. The invitation of the fellow to be part of NOA and to lead the project is bringing international expertise and interdisciplinary research to the host institute and helped raise the profile of the fellow. Finally, the host institute's ground-based Atmospheric Remote Sensing Station (ARSS) is the federated site of AERONET that monitors aerosol pollution over the city of Athens. As a result, the fellow as a member of the ACP Group is in direct contact with scientists that are expert in aerosol measurement, online data provision and database management. This skill base has proved invaluable as the project progressed into Phase D and the development of the algorithm for global real-time monitoring. The fellow has also been provided with access to UV radiative-transfer codes and to the European UV database should the need arise and time permit the assessment of atmospheric radiative-budgets. In summary, the general scientific arrangements required for the success of this project have been comprehensively provided to the fellow including: a) access to satellite aerosol databases, b) access to ground-based aerosol retrievals and techniques, c) access to a high-tech AERONET station, d) access to PCs, computing power, resources and software for the coding and running of neural networks, and image processing and web development software, and importantly, e) access to expertise in the field via direct interaction with or via the collaborative networks connected with APC group members. The wealth of experience that the host institute has in accommodating visiting scientists and implementing projects of this scale, has meant that AEROMAP has progressed smoothly and could deal with new challenges smoothly. The regular personal mentoring by the SIC and regular group meetings have enabled the fellow to flourish.

**Supporting the acquisition of competencies of the fellow in the field of environmental modeling**

The expert training provided to the fellow by the SIC during frequent (weekly) project meetings has meant that a steep learning curve was achieved quickly in this rapidly developing research area. The fellow now has a high level of technical background knowledge in the field of global aerosol characterization and measurement. This is evidenced by the publication of 4 peer-reviewed publications in top atmospheric physics journals and acceptance of 2 conference papers in the proceedings of the prestigious International Conference on Meteorology, Climatology and Atmospheric Physics. Furthermore, an additional 3 manuscripts are at submission stage – strongly enhancing the fellow's publication record and contributing to increased visibility and impact of his research. The very positive climate of collaboration engendered at the host institute has allowed the fellow to be well integrated in the ACP Group. An early outcome of this has been the introduction of the fellow to the wider environmental research, remote sensing and atmospheric chemistry and physics community. The fellow is acquiring strong competencies that are establishing him as an independent scientist in the field of satellite retrievals and aerosol modelling. These achievements of the project are testament to the successful collaboration between the fellow and the SIC and the transfer of knowledge of between their corresponding fields of expertise: applied mathematics and environmental research. The high volume of traffic that the pages of the project website are attracting, combined with a growing social media presence on Twitter are giving added weight to the national and European presence of the fellow in a rapidly evolving field, and are helping in the formation of new collaborations between the fellow, the host institute and other foreign research groups in the field of environmental research. Finally, the scientific experience of the SIC and the host institute have ensured the effective exploitation of the results of the project.

**Contribution to career development and re-establishment of the fellow**

One of the principal goals of the fellowship in terms of the medium to long-term development of the fellow's career is to enable the fellow to achieve the level of principal investigator as a medium term goal, and to help him secure a permanent research or academic position in the field of environmental modelling in atmospheric physics as a long-term goal. The project funding from a Marie Curie IEF has provided the mobility that enabled the fellow to relocate at an expert host institute where he has been able to interact and collaborate with world-leading researchers in the field. As a result, he has obtained competence in the fields of aerosol science, remote sensing, measurement techniques, atmospheric physics and chemistry modeling. As such, the fellowship has supported his transition from an applied mathematician applying advanced methods in several academic disciplines, to an experienced scientist in the field of environmental research. The fellowship, in addition to helping focus the fellow's skills in one field, is also supporting the fellow's transition to research independence. The fellow has already taken a leading role in terms of the implementation of project work plan and the development of the AEROMAP website. The close collaboration between the fellow and the SIC has led to significant new results and numerous peer-reviewed research publications that have strengthened the fellow's CV. Furthermore, the fellow has developed the skills required to manage a project of this scale and importance - which will be a valuable asset in the future when he applies for more senior scientific positions. Working at the host institute has exposed the fellow to the operational algorithms of satellite-based instruments, to global monitoring and mapping techniques and to ground-based atmospheric information analysis. His involvement with the latest methodologies used to obtain aerosol retrievals from the satellites MODIS and OMI, the global chemical model GOCART, and the ground-based AERONET stations has provided him with in-depth knowledge of contemporary measurement techniques, retrieval methodologies, uncertainties and limitations associated with remote sensing of aerosols from space and ground. Furthermore, the techniques he has developed and has applied are supporting the call of the IPCC to greatly expand efforts to monitor and globally-characterize aerosols. The successful completion of the project has substantially enriched the fellow's research profile and is helping him establish a professional career in the field.

**Contribution to European excellence and competitiveness**

AEROMAP is contributing to one of the most important climate change parameters – the global distribution and composition of atmospheric aerosol. As such, the project is helping to raise the profile of the ERA for researchers in this field. The large number of published results has contributed to European excellence and competitiveness by demonstrating that European centers like the host institute NOA are pioneering new methods to exploit satellite remote sensing and are making a major contribution to efforts to globally-monitor and characterize aerosols. Furthermore, the use of cutting edge mathematical/computational methods like neural networks, cluster analysis, Gaussian mixture models and state-of-the-art mapping techniques, implemented in AEROMAP contribute to the creation of a pole of attraction for scientists from outside the ERA who will be interested in learning such techniques, applying them in their own fields of research, or incorporating them in existing operational aerosol retrieval algorithms. The cross-fertilization of knowledge that this engenders is helping raise the status of European science as originator of such methodologies and will hopefully attract more talent to the ERA. The project website has matured into a showcase for the project, the fellow, the host institute and Marie Curie actions in general. It now houses global maps of aerosol microphysical properties and characteristics not provided anywhere else. The real-time monitoring algorithm, aerosol impact index and aerosol hazard alerts developed are highly innovative products and will hopefully attract a wide audience. The research findings produced by AEROMAP have the potential to help reduce the uncertainty associated with the impact of aerosols on the planetary radiation budget, and this in turn is expected to have a positive impact on environmental policy-making decisions worldwide – further drawing attention to the ERA as instigator. Until now, it has not been possible to exploit the full-Earth coverage provided by satellite remote sensing in order to globally-characterize aerosols via their microphysical properties. As a result Europe has followed the example of other continents in building instruments and investing in ground stations federated to AERONET. The methodology developed by AEROMAP for extrapolating AERONET retrievals from stations to off-site locations via the use of satellite inputs fed to neural networks, has been validated and is moderately accurate for deducing key aerosol parameters on the daily timescale. Small scale but high impact projects like AEROMAP are helping to ensure that Europe can meet the challenges of the 21st century where the quality of the environment affects everyday life and the impact of aerosols on climate change, air quality and business (e.g. aviation) is high in the public conscience. Europe is strongly affected by inflows of dust from the Sahara and the Arabian Peninsula, biomass burning from wildfires like those in Moldova, Northern Greece, Spain and the coastline region of Portugal. One direct and long-term structuring effect of AEROMAP is that its products will allow for determination of the best sites to locate new AERONET stations to monitor such phenomena more accurately. This motivated choice of pilot studies performed by the fellow in his paper on multiple-mode aerosol identification via the size distribution.

**Problems that have occurred and how they were solved or solutions envisioned**

This ambitious project has encountered a couple of theoretical obstacles which have all been overcome. Early results at the end of Phase A revealed that the proposed use of only 3 MODIS satellite AOD measurements as inputs to the NNs was capable only of retrieving mean values of optical and microphysical parameters and not the daily trends in these parameters needed to attain the goal of real-time monitoring. This problem was solved by expanding the set of satellite inputs to include other parameters and then identifying which combination of available inputs is required for retrieving the daily variation of aerosol parameters. In particular, in the context of desert dust over an extensive region (Northern Africa), it was found that the columnar measurement of water vapour content from MODIS was required to supplement the 3 MODIS satellite AOD measurements as inputs in order to successfully retrieve the AVSD. This study was carefully focused, well founded and brought dividends including a publication in the *Journal of Atmospheric Measurement Techniques Discussions* describing this new approach. In order to check that this success was not confined to the case of dust, NNs using satellite inputs were also trained and tested during Phase B on co-located and synchronous satellite and AERONET data for biomass burning aerosol over an extensive region of the Amazon, and for urban sulphate aerosol in 2 northern hemisphere cities having a long data record (Washington-GSFC and Moscow-MSUMU). As described in detail in the mid-term report for reporting period 1, the NNs were shown to be able to retrieve the required aerosol parameters to a satisfactory level of accuracy at the daily timescale required for the development of a real-time monitoring algorithm.

During Task C1, a serious technical constraint inherent to AERONET inversion products presented itself (see Section 2.1 for details). This meant that the proposed approach of applying cluster analysis to AERONET inversion products for distinguishing sites by aerosol type/mixture in Gobbi coordinates could not be adopted. To mitigate this, with the approval of the SIC, the fellow investigated other potential approaches for performing global aerosol typing and after some initial tests a methodology was developed based on downscaling mean global data from the GOCART chemical model to a 1x1 degree (latitude x longitude) grid (the same spatial resolution as the satellite products used as NN inputs) and then applying cluster analysis to the aerosol components (see Section 2.1 for details). This new methodology was able to achieve the required partitioning of the globe into distinct aerosol types/mixture regions. A secondary effect of this was that Deliverable 5 was modified slightly (see Section 2.1 for details). In parallel with this, during Phase C (months 9-15) the fellow was heavily involved in the co-authoring of 4 peer-reviewed articles which meant that, while Tasks C1 and C2 were completed successfully and bore additional fruit in the form of publications, an unforeseen delay of 3 months of research time was created. Task C3 was completed without a problem and Phase C of the project concluded in month 18 rather than month 15.

In Phase D, the fellow coded, trained and validated 10 NNs, one for each distinct aerosol type/mixture identified with the results of the cluster analysis developed in Task C1. This was an enormous challenge and involved isolating and data-processing co-located and synchronous satellite inputs and AERONET outputs in the 64800 pixels (360 longitude x 180 latitude) of the global grid. The first global maps of aerosol microphysical parameters were successfully produced in month 21 and a positive assessment was made regarding the potential of the NN-based algorithm to perform near real-time monitoring. This was verified also by a study of the 3D spatio-temporal dispersion of sulphate over Madagascar resulting from eruption of the Karthala volcano. However, the study showed that, while the AEROMAP algorithm successfully produces maps of AMPs, patchiness in the availability of satellite inputs on the daily timescale limited their applicability on this temporal scale. Averaging over a 4-day timescale solved this problem and led to successful completion of Task D1. At this stage, it was realized that fully real-time monitoring will require the installation of a MODIS antenna at the host institute NOA to directly obtain data from the satellite instrument as it passes overhead. While this prevented immediate implementation of a real-time monitor, it is soon to be acquired and the AEROMAP algorithm will then, post-project, be able to start producing daily outputs in real-time. In preparation for this, the project also constructed multi-parametric indices of aerosol impact together with alerts (see Section 2.1 for details). The fellow has been contracted for 12 months by the host institute to continue evolving the AQIs and to validate them against those being produced from ground-based chemical measures.

The technical and theoretical problems described above and the mitigating actions taken to overcome them had a small negative effect on the projected work plan timeline – causing a delay of just over 3 months. On the one hand, the actions implemented led to a large number of (7) peer-reviewed publications which are greatly increasing the visibility of the project in the fields of aerosol science, remote sensing, atmospheric physics and measurement techniques. However, on the other hand, the need to focus more attention on the scientific component of the project was at the partial expense of some of the public engagement initiatives. In a project meeting between the fellow and SIC, a decision was made to mitigate this by engaging the public via exploitation of the project's growing online presence and the development of the Education Gateway at the AEROMAP website. Having presented an overview of the project at the European Science Open Forum in Dublin, Ireland in 2012 in the form of a manned digital poster session, and also at public seminars at the host institute, it was decided that the proposed public talk on Marie-Curie Actions and atmospheric chemistry (Task E2) could achieve the same goal by efficiently engaging the community via an Education Gateway where background information on climate change could also be housed. This decision helped raise the footfall at the project website and freed to the fellow to focus his efforts on the production of the algorithm and related tools needed for achieving real-time maps of aerosol parameters, and to focus on the preparation and revision of the large number of peer-reviewed publications produced during the second reporting period. The public talk of Task E4 (scheduled for month 23) will now take place post-project on the 9$^{th}$ of April at the Host Institute.

**Project planning and status**

A project meeting has been held on a weekly basis between the research fellow and the scientist in charge. These meetings have proven invaluable in that:

1. they allowed communication to the SIC from the fellow of the progress of the work
2. they allowed the fellow to learn from the expertise of SIC
3. they functioned as efficient brainstorming sessions for new ideas to advance the work
4. they allowed solutions to be found to mitigate unforeseen problems as they arose
5. they allowed the SIC to help the fellow in managing the workload efficiently

6. they allowed the SIC to assist the fellow with administrative paperwork related to routine administrative matters.

The project progressed smoothly and, in addition to achieving the stated project deliverables, these meeting enabled the efficient production and exploitation of additional bi-products.

**Impact of possible deviations from the planned milestones and deliverables**

As described in Section 2.3.2, Deliverable 5 was slightly modified (global maps in Gobbi coordinates were found to be both unsuitable and not necessary). Deliverable 9 was partially-achieved in that an algorithm capable of producing global maps of AMPs from daily satellite inputs was developed and tested, fully real-time monitoring was not able to be implemented due to the absence of a MODIS antenna. All other stated project deliverables have been fully met including the development of new AQIs and associated health and visibility alerts. Technical obstacles encountered during the course of the project were overcome and solutions were found to mitigate problems that arose in all cases. All 4 of the stated milestones were also achieved. Indeed, as this report hopes to show, many additional bi-products have been created as a result of novel problem-solving strategies introduced, and from the new collaborations the fellow is building with the worldwide environmental modeling community facilitated by the host institute. Finally, while the additional time involved in co-authoring the large number of peer-reviewed publications produced by the project was not factored into the proposed project timeline, this investment brought dividends in terms of engaging and generating interest within the scientific community. While this was at the expense of time originally allocated to engaging also the public, it is hoped that the science communication elements incorporated into the Education Gateway, the press release to be published on project completion, and the public talk next month – will help to mitigate this. The contracting of the fellow at the host institute to fully implement the real-time monitor and to evolve and validate the AQIs will mean that the project will have continued impact post-completion. It is envisaged that the real-time monitoring algorithm produced, the AQIs and alerts and the novel global maps of aerosol microphysics will have a substantial impact on policy-making decisions and the public understanding of the impact of aerosols worldwide.

**Development of the Project website**

As a result of completing Task E1, an extensive project website was designed and produced, housed at the host institute's website: http://apcg.space.noa.gr/aeromap. The website was further developed during tasks E2 and E3. The website is structured around 5 core pages: 1) an *About* page contains the project abstract and highlights the important role of Marie-Curie Actions in facilitating the mobility of researchers in the ERA, presents the project's objectives and phases and has check-lists showing the progress to completion of the project with regard to expected results and milestones, 2) a *News* page presents a chronological list of events including conference attendances of the fellow, participation in outreach activities, and highlights important landmarks such as the publication of project results in peer-reviewed journals. Readers can be kept up to date of changes by following https://twitter.com/_AEROMAP, 3) a *Research* page lists the lines of investigation being undertaken and the research methods being implemented by AEROMAP, 4) a *Publications* page contains: a) all open-access peer-review publications resulting from the project, b) materials resulting from conference participation including: posters, abstracts and proceedings, c) project reports including i) the mid-term report, ii) the second periodic report and iii) the final report (note that links to the reports will become publicly-available as soon as the research results they contain are published), and d) a link to co-authors, and 5) a *Media* page (example screenshot shown below) houses multimedia including an image gallery of graphical abstracts and published images. In addition, 3 gateways have been developed to provide "click-through" routes for users of differing levels of experience and interest: A) a New Visitors Gateway links to the About and Media pages and includes a pictorial guide to the project produced with Prezit to help first-time users quickly understand what the project is about, B) a Researchers' Gateway links to the About, Research and Publications pages for those with technical understanding of atmospheric aerosols to quickly find up-to-date results and open-source ware produced by the project. In order to provide a vehicle for attracting new researchers in the field to AEROMAP, the gateway also houses a carefully-chosen and comprehensive list of links to data portals for the aerosol community. This "portal of portals" is helping increase the traffic of researchers to the project website. The gateway also houses links to key publications in aerosol science and the empirical techniques used by AEROMAP. Finally, MATLAB code produced by the fellow to assist researchers to load and parse large data files, is made available at this gateway as open source, and C) an Education Gateway presents links to beautiful animated videos of monthly global maps of aerosol optical depth, size and the distribution of fires, chlorophyll, clouds and carbon monoxide. The gateway also links to important reports like those of the International Panel on Climate Change and open-access, online feature articles in magazines like Science and Nature so that readers can get an approachable but accurate overview of the subject. Finally, the gateway links to Open Course Ware online lecture courses on Earth, atmospheric and planetary science and series of graduate lectures on remote sensing, clouds, aerosols and climate.

The Researchers' Gateway provides, in one place, links to online data centres used by the remote sensing and aerosol science community to facilitate "click-throughs" by users who are using this page as of the AEROMAP website as a portal. The page also links to specialized aerosol science tools and makes available MATLAB scripted utilities produced by AEROMAP to help researchers load data for their own studies. On this page, datasets to be produced by AEROMAP and referred to in future publications, will be permanently housed so as to provide persistence of the project's end-products. The Education Gateway is dedicated to outreach activities of the project and is designed to help inform interested readers about aerosol science and the global impact of aerosols with videos and other online electronic resources. On this page, open-access popular science articles about the impact of aerosols on climate are also linked to and, for students thinking of pursuing a career in environmental research, hyperlinks to relevant Open Course Ware lecture notes have been selected and provided. The content and volume of traffic associated with the project website are helping to raise awareness of the project, the fellow, the scientist in charge, the host institute, co-authors, and the impact on society of scientific research on the global aerosol system being funded and undertaken in the ERA.