SPECIAL PROJECT PROGRESS REPORT

Progress Reports should be 2 to 10 pages in length, depending on importance of the project. All the following mandatory information needs to be provided.

Reporting year …… July 2015 to June 2016……..……

Project Title: …… Development and testing of a microphysical aerosol scheme in the IFS ……..……

Computer Project Account: SPGBWOOD ……..……

Principal Investigator(s): Dr Graham Mann…...……..……

……..……

Affiliation: NCAS-Climate, University of Leeds……

Name of ECMWF scientist(s) collaborating to the project (if applicable) Richard Engelen, Johannes Flemming, Angela Benedetti……..

……..……

Start date of the project: Jan 2015 (previous project ran Jan 2012 to Dec 2014)...…

Expected end date: Dec 2017 ……..……

Computer resources allocated/used for the current year and the previous one

(if applicable)

Please answer for all project resources

		Previous year		Current year	
		Allocated	Used	Allocated	Used
High Performance Computing Facility	(units)	3,000,000	942,452 (to Jun15) 1,602,949 (to Dec15)	3,000,000	109,585 (to Jun16)
Data storage capacity	(Gb)	15,000	????	30,000	????

Summary of project objectives

(10 lines max)

A new aerosol module "GLOMAP-mode" has been implemented into the IFS to upgrade on the mass-based scheme developed initially and referred to here as IFS-LMD (Morcrette et al., 2009). The GLOMAP-mode aerosol microphysics scheme (e.g. Mann et al., 2010; Mann et al., 2012) simulates the evolution of the particle size distribution, with explicit sources and sinks of particle number (e.g. via nucleation and coagulation) as well as mass. The scheme tracks the same component masses as the IFS-LMD scheme (sulphate, sea-salt, mineral dust and black and organic carbon) but calculates their composition across the size range resolving internal mixtures and gas to particle transfer. Resolving these aerosol microphysical processes has been shown to improve the fidelity of simulated aerosol radiative forcings (Bellouin et al., 2013) and provides improved aerosol boundary conditions to regional air quality models, many of which include similar aerosol microphysics schemes. In this 2nd phase of the IFS-GLOMAP special project (SPGBWOOD) the focus is on coupling the model to other aspects such as the sulphur cycle from the TM5 tropospheric chemistry scheme in C-IFS for a sulphate-coupled chemistry-aerosol-microphysics capability. This sulphate-coupled C-IFS-GLOMAP system will also be extended to also link up with the ammonia and nitric acid species already simulated in TM5, with the two semi-volatile gases then partitioning into each size mode using a new "dissolution module" for GLOMAP (Benduhn et al., 2016).……

Summary of problems encountered (if any)

(20 lines max)

The resource request for the spgbwood special project was written in mid-2014 with the expectation that through MACC-III and into the CAMS period (which was intended to immediately follow on from MACC-III), there would be an ongoing PDRA at Leeds working alongside the PI (Mann) and the NCEO PhD student (Tim Keslake), with also the possibility of an additional post (either PDRA or PhD student) to take forward developments to enable an interactive stratospheric aerosol capability.

These considerations explain why we requested 3,000,000 SBU's per year when formulating the project – we had the expectation that there would be 2 active users each running C-IFS-GLOMAP experiments which are inherently computationally expensive since they are running atmospheric chemistry (TM5 or othere MACC scheme) and aerosol microphysics (GLOMAP) interactively.

Over the 1st half of MACC-III (to June 2015), the MACC-III PDRA (Sandip Dhomse) and PhD student Tim Keslake were active users of the spgbwood special project account and also PI Graham Mann and the previous MACC-II PDRA (Will Hewson, now at Leicester University) as occasional users (mainly for referring to their account and assisting with developments & evaluation).

However, despite the CAMS43 (Development of Global Aerosol Aspects) proposal initially costing one PDRA (Dhomse), 20% time for PI (Mann) and 50% contribution to PhD studentship, in the end Leeds received just 15% time for PI (Mann) and the 50% contribution to the PhD studentship. The Leeds PDRA position that had continued through MACC-1, MACC-II and MACC-III was cut.

As a consequence, the usage of the spgbwood account over July 2015 to June 2016 has decreased considerably compared to the equivalent period last year (July 2014 to June 2015).

Leeds no longer has a PDRA post on aerosol developments (CAMS43) and we now only have the one active user of the spgbwood (Keslake) who is running short integrations through the SAMBBA field campaign period. Our longer integrations were being carried out by the PDRA and these have had to cease (for the timebeing) with the PDRA position no longer funded.

Summary of results of the current year (from July2015 to June 2016)

This section should comprise 1 to 8 pages and can be replaced by a short summary plus an existing scientific report on the project

Despite the issues described above (related to the reduction on Leeds staff working on CAMS43), there has been considerable progress made this year, in particular work to assess the influence of AOD data assimilation on speciated aerosol mass (e.g. black carbon [BC], particulate organic matter [POM]) in C-IFS, improvements to the optimisation of C-IFS-GLOMAP, the submission of benchmark C-IFS-GLOMAP simulations to AeroCom, the coupled-chemistry configurations of C-IFS-GLOMAP becoming further tested and ported to the latest cycle, a new PhD studentship at Leeds on volcanic forcings and the publication with GMDD of the nitrate-extended GLOMAP aerosol model (Benduhn et al., 2016), as implemented into C-IFS-GLOMAP during MACC-III.

1) Influence of AOD assimilation in improving C-IFS simulation of BC and POM
   An NCEO-funded PhD studentship at Leeds (Tim Keslake) co-supervised by Prof. Martyn Chipperfield and the PI for SPGBWOOD (Mann, NCAS-Climate) has involved analysing a range of model experiments with C-IFS and C-IFS-GLOMAP. A particular analysis carried out during the project has been to assess the improvement in the skill of the C-IFS model that AOD data assimilation brings when comparing to (independent) aerosol measurements of speciated mass (black carbon, organic matter) from surface sites and aircraft measurements during the SAMBBA field campaign in 2012. Limitations of the existing operational mass-based aerosol scheme are also assessed comparing free-running C-IFS simulations with parallel C-IFS-GLOMAP simulations which use the microphysical aerosol scheme.

2) Optimisation of C-IFS-GLOMAP
   The Leeds PI (Graham Mann) and MACC-III PDRA (Sandip Dhomse) have worked with former ECMWF scientist Samuel Remy (now at CNRS, Paris), who is testing ways that the existing C-IFS-GLOMAP system can be made to run more quickly. Dr. Remy has achieved major reductions in run-times in CY40R3 simulations by reducing the amount of sub-stepping in the model, reaching an acceptable compromise between the benefits from faster run-times and the cost in terms of the fidelity of simulated variations in aerosol particle size distribution.

3) Submission of benchmark C-IFS-GLOMAP simulations to AeroCom
   Four benchmark 1-year C-IFS-GLOMAP simulations at cycle 40R3 have been submitted to the AeroCom database at Met Norway, adding to the existing two C-IFS-GLOMAP simulations previously submitted at cycle 38R1. Results from the simulations were presented as part of an EGU poster describing and evaluating the C-IFS-GLOMAP chemistry-aerosol microphysics capability. An electronic version of the poster is appended to this report for information.
   The first two 40R3 simulations were updated versions of the two 38R1 simulations previously submitted, a pair of year 2003 runs with and without a source of marine DMS -- demonstrating the global effects of DMS on marine tropospheric aerosol (sulphate and CCN concentrations).
   The 2nd two 40R3 simulations were year-2008 simulations, one using the "stand-alone" IFS-GLOMAP configuration (where SO2 oxidation proceeds according to a constant timescale, matching the approach implemented in the operational C-IFS aerosol scheme) and a 2nd run where the sulphate production proceeds as simulated by the TM5 tropospheric chemistry scheme within C-IFS (known as the coupled-chemistry configuration of C-IFS-GLOMAP).

4) Coupled-chemistry configurations of C-IFS-GLOMAP further tested and port to latest cycle
   The coupled-chemistry configuration of C-IFS-GLOMAP has been compared to surface observations of sulphate mass from the EMEP network, and against observations from the CASTNET and IMPROVE monitoring sites in North America. In particular, a persistent wintertime low bias in sulphate over Northern Europe is shown to be much improved when the sulphate production accounts for variations in oxidants, as simulated interactively within the

TM5 chemistry scheme (compared to the simpler constant timescale approach, see EGU poster). Code-changes to enable the C-IFS-GLOMAP to run in either stand-alone or coupled-chemistry configuration have been consolidated at 40R3 and are currently being ported to the latest cycle.

5) New PhD studentship at Leeds co-funded by CAMS43 on volcanic forcings
A PhD studentship at Leeds (Sarah Shallcross) began April 2016 and is 50% funded by CAMS43 (Development of global aerosol aspects). The studentship will lead to improved understanding on the influence of volcanic eruptions on climate, in particular to better quantify how the major eruptions of Pinatubo (1991), El Chichon (1982) and Agung (1963) perturbed the stratospheric aerosol layer. In particular, the project will use measurements of stratospheric aerosol from those periods in combination with an interactive stratospheric aerosol (UM-UKCA, which includes GLOMAP) to provide improved estimates of the volcanic radiative forcing, and improved aerosol forcing and surface area density datasets for global composition-climate models. The activity aligns closely with CAMS43 aerosol development activities that will update the GLOMAP codebase to match that used in the interactive strat-trop simulations in UM-UKCA, alongside planned further development of the coupled-chemistry configuration of C-IFS-GLOMAP to optionally couple to the combined C-IFS-CB05-BASCOE troposphere-stratosphere atmospheric chemistry capability developed by researchers in the Reactive Gases grouping within CAMS (see Huijnen et al., 2016)

   The PhD studentship will build on an existing collaboration with CSIRO, Aspendale (Australia) by applying a new "lidar emulator" for GLOMAP developed by Dr. Stuart Young and Dr. Martin Cope (CSIRO) in collaboration also with Nicolas Bellouin (Univ. Reading) to enable simulations to diagnose attenuated backscatter profiles consistently with the size-resolved aerosol composition simulated within the model. The approach will be applied to enable improved interpretation of comparisons to ground-based lidar measurements during the Pinatubo-perturbed period, but also provide a potentially powerful future technique by which C-IFS-GLOMAP could provide an accurate observational operator for satellite-borne lidar measurements such as CALIPSO.

6) New paper describing nitrate-extended GLOMAP scheme for C-IFS published in GMDD
Aligned with activities during MACC-III to extend the coupled aerosol-chemistry configuration of C-IFS-GLOMAP to simulate the size-resolved inorganic aerosol composition (sulphate-nitrate-ammonium-water aerosol system), a major milestone achieved this year has been the publication in the Discussions forum of Geoscientific Model Development of the documentation and evaluation paper for the nitrate-extended version of GLOMAP. The paper comprehensively describes the hybrid dissolution solver (HyDiS), which constitutes the major component of nitrate-extended GLOMAP, together with results from box model and global model simulations which carefully assess the operation of the scheme and illustrate the importance of resolving the timescales for gas-to-particle transfer in terms of simulated size-resolved aerosol composition.

Note: the Dhomse et al. EGU poster on C-IFS-GLOMAP and the Young et al. extended abstract to the International Laser-Radar Conference are appended to this report for info.

List of publications/reports from the project with complete references

Benduhn, F., Mann, G. W., Pringle, K. J., Topping, D. O., McFiggans, G. and Carslaw, K. S. "Size-resolved simulations of the aerosol inorganic composition with the new hybrid dissolution solver HyDiS-1.0 – Description, evaluation and first global modelling results", *Geosci. Mod. Dev. Discuss.*, doi:10.5194/gmd-2015-264, 2016

Dhomse, S. S., Mann, G. W., Carslaw, K. S., Flemming, J., Morcrette, J.-J., Engelen, R., Remy, S., Boucher, O., Benduhn, F., Hewson, W. and Woodhouse, M. T. "Evaluation of global aerosol properties simulated by the high resolution coupled chemistry-aerosol-microphysics model C-IFS-GLOMAP", *poster presentation to European Geosciences Union General Assembly*, April 2016.

Huijnen, V., Flemming, J., Chabrillat, S., Errera, Q., Christophe, Y., Blechchmidt, A.-M., Richter, A. and Eskes, H., "C-IFS-CB05-BASCOE: Stratospheric Chemistry in the Integrated Forecasting System of ECMWF", *Geosci. Model Dev. Discuss.*, doi:10.5194/gmd-2016-40, 2016.

Young, S., Cope, M., Lee, S., Emmerson, K., Woodhouse, M. and Bellouin, N., "Simulation of CALIOP attenuated backscatter profiles using the GLOMAP aerosol model", *Extended abstract to the 27th International Laser Radar Conference in New York, USA* (July 2015)

Summary of plans for the continuation of the project

(10 lines max)

Despite the loss of the PDRA position at Leeds, work will continue with active users Tim Keslake and Dr. Sandip Dhomse, with also contributions from the SPGBWOOD PI Graham Mann.

Tim Keslake (PhD student, Leeds) will continue his research to understand the impacts of biomass burning on atmospheric composition, including further analysis on the impacts of data assimilation, and how the microphysical representation of biomass smoke affects its simulated optical properties.

Dr. Dhomse and Dr. Mann will assist in the implementation of the coupled stratosphere-troposphere chemistry-aerosol system, coupling the GLOMAP aerosol microphysical scheme to the CB05-BASCOE tropospheric-stratospheric chemistry scheme within C-IFS, in collaboration with colleagues at ECMWF (Johannes Flemming), CNRS-Paris (Samuel Remy), KNMI (Vincent Huijnen) and the Belgian Institute for Space Aeronomy in Brussels (Simon Chabrillat). In particular, as part of the CAMS43 activity, several benchmark interactive stratospheric aerosol simulations in C-IFS-GLOMAP are planned over the coming 12-24 months.

Further activity from the SPGBWOOD PI (Graham Mann) to advise and contribute to activities with C-IFS-GLOMAP at CNRS (Samuel Remy) and with two new aerosol-facing posts at ECMWF (one on general aerosol modelling and one on aerosol data assimilation) is anticipated this year.

Evaluation of global aerosol properties simulated by the high resolution coupled chemistry-aerosol-microphysics model C-IFS-GLOMAP

Sandip Dhomse, Graham Mann, Ken Carslaw (University of Leeds, Leeds, U.K.) Johannes Flemming, Jean-Jacques Morcrette, Richard Engelen (ECMWF, Reading, U.K.) Samuel Remy, Olivier Boucher (LMD, Paris, France), Francois Benduhn (IASS, Potsdam, Germany) Will Hewson (University of Leicester, U.K.) Matt Woodhouse (CSIRO, Aspendale, Australia)

1. Introduction

The EU Framework Programme GEMS and MACC consortium projects co-ordinated by the European Centre for Medium-range Weather Forecasts (ECMWF) have developed an operational global forecasting and reanalysis system (Composition-IFS) for atmospheric composition including greenhouse gases, reactive gases and aerosol.
The current operational C-IFS system uses a mass-based aerosol model coupled to data assimilation of Aerosol Optical Depth measured by satellite (MODIS) to predict global aerosol properties.

During MACC, the GLOMAP-mode aerosol microphysics scheme was added to the system, providing information on aerosol size and number for improved representation of aerosol-radiation and aerosol-cloud interactions, accounting also for simulated global variations in size distribution and internally-mixed particle composition.

The IFS-GLOMAP system has 2 alternative configurations, a "stand-alone" version (which runs without chemistry) and a coupled configuration where the SO_4 production comes from the online TM5 tropospheric chemistry.

In MACC-III he C-IFS-GLOMAP system was extended to also use the "HyDis" extension to GLOMAP (Benduhn et al., 2016) to realistically treat the size-resolved gas-particle partitioning of the semi volatiles NH_3 & HNO_3.

2. GLOMAP in multiple model frameworks

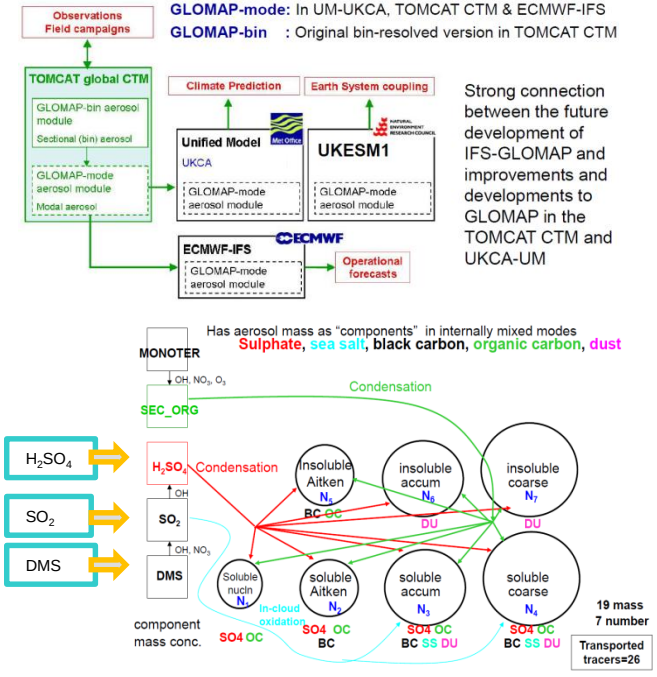

Figure 1: - Representation of GLOMAP aerosol scheme in "IFS-GLOMAP" and "coupled-chemistry mode (C-IFS-GLOMAP)"

3. Climatological aerosol loading

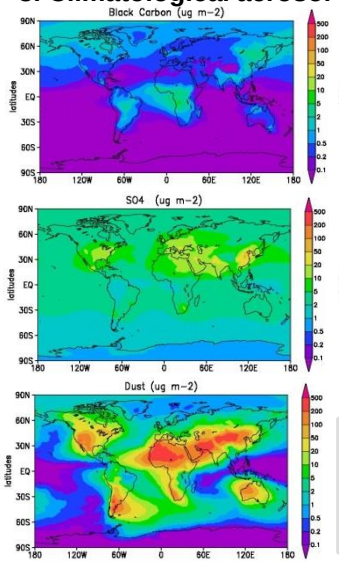

Figure 2: – Annual mean (year 2003) aerosol loading (in μg/m²) from a benchmark control simulation (Woodhouse et al., 2016, *in prep.*). submitted to the AeroCom database

4. DMS influence on Feb03 simulated aerosol properties

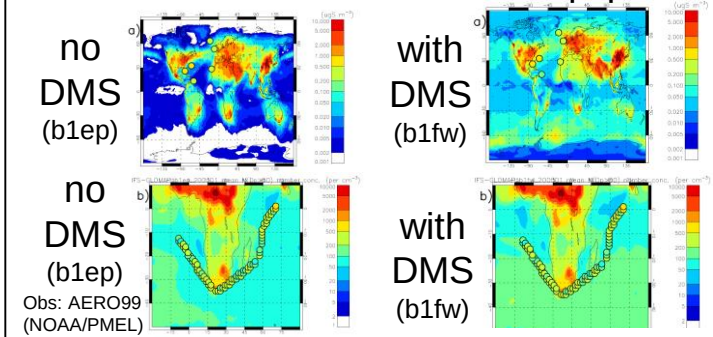

Figure 3: DMS is major source of marine sulphur and plays an important role in CCN changes. Top: surface sulphate concentrations from the simulations with and without DMS emissions. Bottom panel compares N50 illustrate its importance for simulated aerosol-cloud interactions.

6. Global aerosol burdens from benchmark integrations

Experiment	SO4 (Tg S)	BC (Tg C)	POM (Tg C)	NaCl (Tg)	Dust (Tg)
Reference (2003)	0.58	0.15	1.41	5.97	11.7
No-DMS (2003)	0.54	0.21	2.65	6.05	13.5
Reference (2008)	0.70	0.13	1.47	5.92	13.7
C-IFS (2008)	0.11	0.11	1.80	5.93	22.76

5. Improved wintertime sulphate in C-IFS-GLOMAP

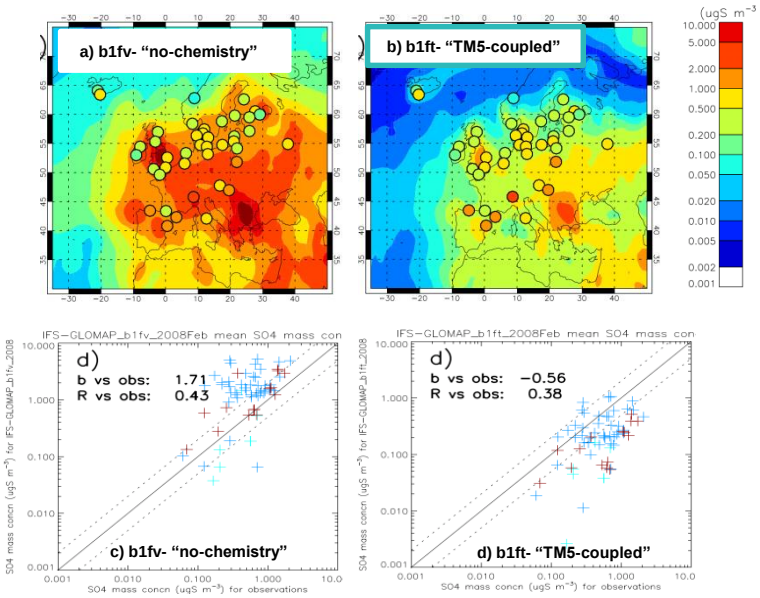

Figure 4: (a) and (b) shows "no-chemistry" and "TM5-coupled" simulations of C-IFS-GLOMAP comparing February simulated monthly-mean surface sulphate concentrations over Europe against observations from EMEP sites during the year 2000.

With sulphate-production provided by the TM5 chemistry ("TM5-coupled") configuration, winter-time sulphate is considerably improved compared to the EMEP observations.

Summary

- GLOMAP aerosol microphysics module successfully implemented into IFS.
- Simulated global burdens are consistent with other GLOMAP host frameworks (e.g. chemistry transport model TOMCAT, and UK Met Office UM-UKCA)
- IFS-GLOMAP at ECMWF cycle 40R3 also simulates dust in modal scheme.
- An improvement over the MACC re-analysis (e.g. Innes et al., 2013) has been the inclusion of DMS-derived aerosol and this is now added to IFS-GLOMAP.
- The IFS-GLOMAP now also couples to the TM5 tropospheric chemistry scheme included in C-IFS, which improves a known limitation of the simpler mass-based scheme in simulated wintertime sulphate over Europe
- This C-IFS-GLOMAP coupled chemistry-aerosol-microphysics capability is being extended to handle size-resolved partitioning of TM5 NH_3 and HNO_3 to GLOMAP.

References
- Benduhn et al, (2016), Geosci. Model Dev. Discuss., doi:10.5194/gmd-2015-264
- Dhomse et al., *in prep*
- Innes et al. (2013), ACP
- Mann et al. (2010), GMD
- Mann et al. (2012) ACP
- Morcrette et al, (2008), GRL
- Morcrette et al., (2009), JGR
- Woohouse et al. (2010), ACP
- Woodhouse et al., *in prep*

SIMULATION OF CLOUD-AEROSOL LIDAR WITH ORTHOGONAL POLARIZATION (CALIOP) ATTENUATED BACKSCATTER PROFILES USING THE GLOBAL MODEL OF AEROSOL PROCESSES (GLOMAP)

Stuart Young[1]*, Martin Cope[1], Sunhee Lee[1], Kathryn Emmerson[1], Matthew Woodhouse[1], Nicolas Bellouin[2]

[1]*CSIRO Oceans & Atmosphere, Aspendale, VIC 3195, Australia, *Email: stuart.young@csiro.au*

[2]*Department of Meteorology, University of Reading, Reading, RG6 6BB, UK*

ABSTRACT

To permit the calculation of the radiative effects of atmospheric aerosols, we have linked our aerosol-chemical transport model (CTM-GLOMAP) to a new radiation module (UKCA-RADAER). In order to help assess and improve the accuracy of the radiation code, in particular the height dependence of the predicted scattering, we have developed a module that simulates attenuated backscatter (ABS) profiles that would be measured by the satellite-borne Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) if it were to sample an atmosphere with the same aerosol loading as predicted by the CTM. Initial results of our comparisons of the predicted ABS profiles with actual CALIOP data are encouraging but some differences are noted, particularly in marine boundary layers where the scattering is currently under-predicted and in dust layers where it is often over-predicted. The sources of these differences are being investigated.

1. INTRODUCTION

Atmospheric aerosol is well known to lead to perturbations in the radiation balance, via direct, and indirect (i.e. changes to cloud properties) effects. Accurate representation of the aerosol size distribution and characteristics such as solubility are essential if models are to simulate correctly the coupling between aerosol loading and radiative forcing.

Because the vertical distribution of aerosol layers in the atmosphere, in addition to their optical properties, can have a significant effect on their radiative impact, we consider it necessary to assess the accuracy of our model's predictions of those vertical profiles. As we apply our model over scales ranging from continental to global, we need to compare with vertically resolved measurements made on such scales. An ideal source of such data is the CALIOP lidar on board the CALIPSO satellite [1]. While it is common to compare model predictions with measurements of such quantities as aerosol optical depth or particulate extinction coefficient, it should be remembered that CALIOP is an elastic-backscatter lidar and does not measure either of these quantities directly. Rather it retrieves these quantities from its primary measurement, the attenuated backscatter coefficient, via a combination of analysis algorithms [1,2] and an optical model of the scattering properties of the aerosol (or cloud) particles. The optical model can only describe the average properties of an identified aerosol type. A misidentification of the aerosol type, or natural variation of the optical properties from the average values, will lead to errors, of various magnitudes, in the retrieved extinction and optical depths [3]. As a result, a difference between simulated and measured profiles of a certain optical quantity could be the consequence of an incorrect prediction of aerosol concentrations, location or type, or of optical properties on the side of the chemical transport model (CTM-GLOMAP), or of errors in the optical properties used to retrieve the profiles from the measurements. In some cases, this is effectively comparing one model with another, which is neither what is intended nor is it very informative. To overcome these problems, we choose instead to compare the fundamental lidar measured quantity, the attenuated backscatter profile, with simulated profiles derived from the radiation module (UKCA-RADAER) that is used by our CTM. Attenuated backscatter is the product of the sum of the molecular and particulate backscatter coefficients at any height and the molecular and particulate two-way transmittances between that height and the lidar. It is simply the calibrated backscattered power

measured by the lidar corrected for the range-squared decrease in signal with distance from the lidar. In this way all of the uncertainties are on one side of the comparison thus permitting unambiguous assessment of the model.

2. METHODOLOGY

(a) The Models

In our modeling system, continental-scale atmospheric transport is modeled using a coupled system that comprises (1) the CSIRO Conformal-Cubic Atmospheric Model [4,5] for simulating weather, (2) a population-based anthropogenic emission inventory with natural primary emission sources such as sea salt, wind-blown dust, plus biogenic and fire emissions, and (3) a chemical transport model (CTM,[6]) for simulating the atmospheric chemical transport and subsequent fate, via wet and dry deposition, of gaseous and particulate species. It has a comprehensive chemistry incorporating the Carbon Bond 5 mechanism [7], the Volatility Basis Set approach [8] for secondary organic aerosols, and the ISORROPIA-II model [9] for secondary inorganic aerosol modeling.

The CTM is coupled with the GLObal Model of Aerosol Processes (GLOMAP, [10]), which is a comprehensive, size-resolving global aerosol model. In this work CTM-GLOMAP employs 7 modes and 5 components. Its boundary and initial conditions for aerosol components and modes are obtained from an instance of GLOMAP running in a nudged global general circulation model. The CTM-GLOMAP domain for the Australia continent has a resolution of 0.5^{o}.

The optical properties such as aerosol optical depth (AOD), and aerosol backscatter and extinction coefficients are calculated at each model grid by the RADAER module via a Mie look-up table for the appropriate sizes and refractive indices. The lidar signals are then simulated, as described below, at each of the 19 model levels, which extend from 0.02 km to 8 km above the surface, with a vertical resolution that varies from 0.02 km near the surface to 2 km at the top of the simulation. The comparison with the measurements is then currently done off line, by extracting simulated profiles from the model output file at each model grid point along the CALIPSO ground track of interest.

(b) The Simulator

In each model grid cell, the model system predicts the aerosol components and their size modes. For each of these aerosol components, the particulate backscatter, β_P, and extinction coefficients, σ_P, are then obtained at the CALIOP wavelengths (532 nm and 1064 nm) via a pre-calculated Mie look-up table. In addition, the atmospheric temperature and pressure profiles, available from the modeled meteorology, can be used to calculate the molecular number density profile and, hence, the backscatter, β_M, and extinction coefficient, σ_M, profiles at the lidar wavelengths. The ozone number density is also available from the model allowing the ozone absorption profile, $\alpha_{O3}(z)$, to be calculated. (Ozone absorption is only significant at the shorter wavelength.) It is then a simple matter to calculate profiles of attenuated (total) backscatter:

$$\beta'_T(z) = [\beta_M(z) + \beta_P(z)]T_M^2(z_s, z)T_P^2(z_s, z),$$

where

$$T_M^2(z_s, z) = \exp\left\{-2\int_{z_s}^{z}[\sigma_M(r) + \alpha_{O_3}(r)]dr\right\},$$

and

$$T_P^2(z_s, z) = \exp\left\{-2\int_{z_s}^{z}\sigma_P(r)dr\right\}$$

are, respectively, the molecular and particulate two-way transmittance profiles. The profile of attenuated scattering ratio, $R'(z)$, is obtained from the attenuated total backscatter coefficient profile by dividing by the profile of attenuated molecular backscatter,

$$\beta'_M(z) = \beta_M(z)T_M^2(z_s, z),$$

to give

$$R'(z) = [1 + \beta_P(z)/\beta_M(z)]T_P^2(z_s, z).$$

To simulate the satellite-borne CALIOP profiles, the calculation is started at the top of the atmosphere (or the satellite altitude z_S), and proceeds down towards the surface in order to account correctly for the increasing signal attenuation with range from the satellite (decreasing height).

(c) CALIOP Attenuated Backscatter Profiles

The CALIOP data used in the comparisons here are the "Total_Attenuated_Backscatter_532" from the CALIPSO, level-1, version 3 files and the "Feature_Classification_Flags" in the corresponding, level-2, vertical feature mask (VFM) files.

Although the aim of this exercise is to compare measured and modeled profiles in an atmosphere containing air molecules and aerosol particles, in practice, the measured atmosphere often also contains clouds, which can complicate the comparison somewhat. To facilitate the comparisons, the measured data were filtered to exclude from the calculated average profiles all points in any single profile below the top of cloud layers that were identified in the corresponding VFM profiles. The filtered profiles were then averaged to produce a horizontal resolution comparable to that of the model in the domain of interest (10°S - 45°S, 110°E to 165°E). The vertical resolution of the measured data was, however, not degraded to that of the model but kept at 30 m over the complete height range.

3. RESULTS

In Figure 1 we present an example of our comparisons. The 532-nm attenuated total backscatter measured as CALIPSO passed over Australia on 7 October 2006 at approximately 1621 UTC is shown as a function of height and latitude in (a) with the simulation in (b). The aerosol subtype as identified by CALIPSO's algorithms is shown in (c). Notable features are a strongly scattering marine boundary layer extending to an altitude of 1 km to the North and 2 km to the South of the continent, and a deep moderately strongly scattering aerosol layer that extends to nearly 4 km altitude at latitudes of 20° and 30° S. Between these latitudes, the strength of the signal decreases markedly to the extent that it cannot be detected by the algorithms and does not appear in the VFM. CALIPSO's algorithms identify these aerosols as being predominantly "polluted dust" (a mixture of dust and smoke) with an indication that the weaker signal recorded between these latitudes is from pure dust.

The model generally correctly reproduces the location and heights of the marine layers, although the southern layer is slightly too low in places. The height of the continental layers is also fairly well reproduced as is the extension of the dust layer above the southern marine layer.

Although the horizontal and vertical locations of the various layers are correctly reproduced in the simulation shown, the magnitudes of the simulated signals are, in some places, rather different from what are observed.

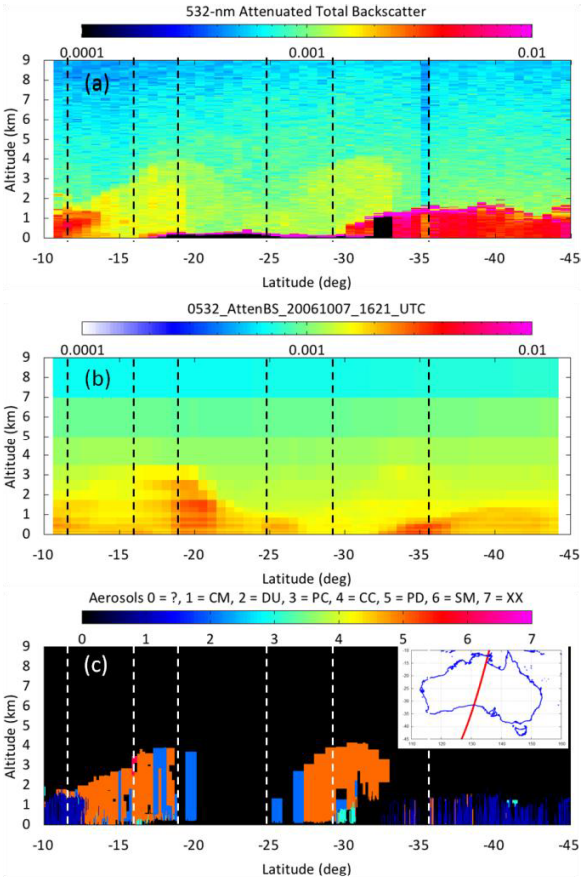

Figure 1. 532-nm Attenuated Total Backscatter (a) CALIOP, (b) Simulation. (c) Aerosol sub-type Vertical Feature Mask. CM = Clean Marine, DU = Dust, PC = Polluted Continental, CC = Clean Continental, PD = Polluted Dust, SM = Smoke, XX = not defined. Vertical, dashed lines indicate locations of profiles in Fig. 2. Inset shows CALIPSO ground track over Australia on 7 October 2006 at ~1621 UTC.

In order to study these differences in more detail, in Figure 2 we compare measured and modeled profiles of attenuated backscatter. The profiles correspond to the locations of the dashed vertical lines in Figure 1. Note that the magnitudes of the simulated profiles are larger than those of the

measured profiles in the free troposphere. This is a result of the additional atmospheric attenuation that was measured between the lidar (at 705 km) and the top of the simulation (at ~ 9km) that has not been corrected for in these figures as it helps separate the profiles horizontally and, thereby, improve legibility. In the first profile, at 11.51 ° S, this difference is increased by the attenuation caused by a layer of high cloud above 9 km and not shown here. The comparison of profiles shows the marked under-prediction of scattering in the marine layers in (a) and (f), reasonable agreement in the polluted dust in (b), but less so at (e), and a significant over-estimation of the signal from dust at (c) and (d). The extent to which these differences are attributable to incorrectly predicted number densities, hydration (for the marine layers) or optical properties (e.g. the use of Mie-scattering code for dust) is being investigated and will provide useful information for the development and improvement of our model and radiation code.

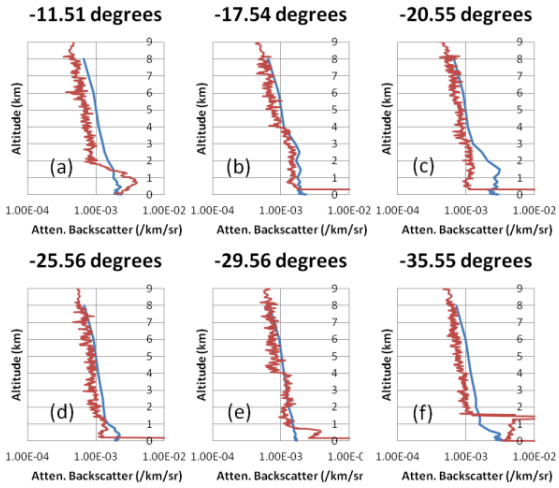

Figure 2. Profiles of 532-nm Attenuated Total Backscatter at the locations indicated by the dashed lines in Fig. 1. The red, noisy profiles are CALIOP data while the blue, smooth profiles are the simulations.

ACKNOWLEDGEMENT

The CALIPSO data were obtained from the NASA Langley Research Center Atmospheric Science Data Center.

REFERENCES

[1] Winker, D. M., et al., 2009: Overview of the CALIPSO Mission and CALIOP Data Processing Algorithms, *J. Atmos. Oceanic Technol.*, **26**, 2310–2323.

[2] Young, S. A., and M. A. Vaughan, 2009: The Retrieval of Profiles of Particulate Extinction from Cloud-Aerosol Lidar Infrared Pathfinder Satellite Observations (CALIPSO) Data: Algorithm Description, *J. Atmos. Oceanic Technol.*, **26**, 1105–1119.

[3] Young, S. A. et al., 2013: The Retrieval of Profiles of Particulate Extinction from Cloud-Aerosol Lidar Infrared Pathfinder Satellite Observations (CALIPSO) Data: Uncertainty and Error Sensitivity Analyses, *J. Atmos. Oceanic Technol.*, **30**, 395–428.

[4] McGregor, J. L., and M. R. Dix, 2001: The CSIRO conformal-cubic atmospheric GCM. In: UTAM Symposium on Advances in Mathematical Modelling of Atmosphere and Ocean Dynamics, P. F. Hodnett (Ed.), Kluwer, Dordrecht, 197-202.

[5] McGregor, J. L., and M. R. Dix, 2008: An updated description of the Conformal-Cubic Atmospheric Model, In: Hamilton K. and W. Ohfuchi (Eds.), *High Resolution Simulation of the Atmosphere and Ocean* Springer, 51–76.

[6] Cope, M. E., et al., 2009: Chemical Transport Model - Technical Description: Centre for Australian Weather and Climate Research, Technical Report 15, Melbourne, Australia.

[7] Sarwar, G., et al., 2008: Impact of an updated carbon bond mechanism on predictions from the CMAQ modeling system: Preliminary assessment, *J. Appl. Meteorol. Clim.*, **47,** 3–14.

[8] Donahue, N. M., et al., 2006: Coupled partitioning, dilution, and chemical aging of semivolatile organics, *Environ. Sci. Technol.*, **40,** 2635–2643.

[9] Fountoukis, C., and A. Nenes, 2007.: ISORROPIA II: a computationally efficient thermodynamic equilibrium model for K^+-Ca^{2+}-Mg^{2+}-NH_4^+-Na^+-SO_4^{2-}-NO_3^--Cl^--H_2O aerosols, *Atmos. Chem. Phys*, **7,** 4639–4659.

[10] Mann, G. W., et al., 2010: Description and evaluation of GLOMAP-mode: a modal global aerosol microphysics model for the UKCA composition-climate model, *Geosci. Model Dev.*, **3,** 519–551.