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Norsk institutt for luftforskning
Norwegian Institute for Air Research

Roadmap towards EarthCARE and Sentinel-5 precursor

A strategy preparing for operational application of planned European atmospheric chemistry and cloud/aerosol missions in Norway

Aasmund Fahre Vik, Cathrine Lund Myhre, Kerstin Stebel, Ann Mari Fjæraa, Tove Svendby, Harald Schyberg, Michael Gauss, Svetlana Tsyro, Michael Schulz, Alvaro Valdebenito, Alf Kirkevåg, Øyvind Seland, Jan Griesfeller

Scientific report

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Scientific report

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1 Introduction

The current report is a main deliverable of the project “Roadmap towards EarthCARE and Sentinel-5 precursor” which is funded by the Norwegian Space Centre through their “Følgemiddel” program. The project is developing a strategy for how applied Norwegian research communities should prepare for planned European atmospheric satellite missions and the current report is the first draft of this strategy. The project started in February 2010 and was scheduled to last for one year, but the duration has been extended up to October 2011. This was due to delays with certain aspects of the project, but also due to delayed planning and launch dates of both EarthCARE and Sentinel-5 precursor. The project has four work packages:

1. Example for utilization of novel satellite products: Assessment of usability of GOSAT CH_4 and CO_2 data for Scandinavia/Arctic climate gas monitoring
2. Stakeholder requirements
3. Strategy for exploitation of EarthCARE and Sentinel-5 precursor
4. Strategy for national satellite related operational support to aviation for volcanic ash avoidance

Only WPs 2 and 3 are relevant for the current report while WPs 1 and 4 have been reported on separately (WP1 reported on in the project final report and in the Klif annual monitoring report, while the final report from WP4 was delivered to the space centre October 10th (Tørseth and Hov, 2011)). The current report was delivered to the space centre on October 3rd 2011.

1.1 About the project partners

NILU and met.no are both applied research organisations with national and international tasks and responsibilities for monitoring, modelling, assessing and reporting on the state of the atmospheric composition (Atmospheric composition includes chemical trace gases and aerosols in air). NILU is responsible for national monitoring programmes on climate gases, stratospheric ozone/UV, background monitoring of acidifying and eutrophying compounds and also maintain quality control of many of the urban/local scale monitoring networks in Norway. National monitoring is done on behalf of and funded by the Norwegian Climate and Pollution authority (Klif). NILU is furthermore coordinating the monitoring programme in EMEP under the Convention for Long Range Transport of Air Pollution (CLRTAP) and collects and reports on observational data from all EMEP member countries. Met.no is responsible for performing Meteorological and climatological observations in Norway, its adjacent seas and the polar areas, and is providing met service for public and private sectors. They furthermore host the EMEP meteorological synthesizing centre (west) and are responsible for modelling, assessing and reporting (together with NILU) on transboundary Air Quality issues to the EMEP steering body.

1.2 Motivation for using Earth Observation data

Common to both NILUs and met.no's tasks is that they are to a large extent based on routine use of ground based observations for determining levels and trends in atmospheric compositions and for validation of model simulated properties. For this use, the main benefits of ground based observations are:

- Data are commonly provided as time series and it is possible to study changes in concentration over decades
- Observations have high accuracy and are based on well tested instrumentation
- Measurements are undertaken at "well described" sites with known influence from local pollution sources – EMEP stations are commonly rural sites with little local influence and are representative for large areas
- Ground based in-situ measurements describe the boundary layer well and are useful for Air Quality studies and assessments – ground based remote sensing data cover well the whole atmosphere above the ground level
- Ground based in-situ observations have high temporal coverage and often high temporal resolution. Continuous sampling (i.e. the air is always measured) is normal and the sampling frequency varies from seconds (e.g. process oriented measurements such as aerosol size distribution) to days (e.g. effect oriented measurements of chemical composition in precipitation). Ground-based remote sensing instruments run continuously (e.g. mm-wave radiometer, spectrometer) or less frequent when operator control is needed (e.g. advanced LIDAR)

The main weaknesses with ground based data are:

- The lack of spatial coverage and resolution (measurements are only done at distinct points/stations)
- There are hardly any or no measurements in remote areas (e.g. African continent, S-America) and over water bodies/oceans
- There are often few measurements in regions with limited economical resources, which are often heavily polluted areas (like Eastern Europe, Caucasus and Central Asia)
- Data from two measurement stations are not always uniformly comparable since they are commonly undertaken by a multitude of organisations (at least on European and international scale) who follow more or less the same standard procedures (if such exists at all)
- For some variables there are different types of instruments and variations in methodological approaches and protocols between continents, and also on regional level. In some cases this results in non-comparable measurements across regions and continents.

Due to the very different nature of satellite observations and ground based data, the two observational approaches generally have opposite strengths and weaknesses. This is the main motivation for using Earth Observation data. It must, however, be emphasized that ground based in-situ, ground based remote sensing and satellites are complementary platforms – none of them are able to describe all aspects of the atmosphere sufficiently well and combined use is therefore beneficial. It is essential to initiate more activities bridging the gap between ground based and satellite observations to improve the knowledge of atmospheric composition and change.

2 Upcoming European Earth Observation missions

Monitoring of atmospheric composition from space has been available since the seventies (weather satellites were available even since late fifties/early sixties) and missions like the NASA-TOMS satellites were important for the study of polar ozone loss in the eighties and nineties. Mapping spectrometers on board ERS2 (GOME) and Envisat (SCIAMACHY) in the decades to follow paved the way for monitoring of more chemical species, and advanced studies of aerosols became possible with sensors such as MODIS (Aqua, Terra), MERIS (Envisat), AATSR (Envisat), MISR (Terra), AIRS (Aqua), etc. In recent years, the CALIPSO satellite, with its onboard CALIOP LIDAR, has enabled information on aerosol and cloud distribution also in the vertical direction.

Currently available satellite sensors are commonly focusing on research applications and the concept of the sensors themselves are often tested out in space for the first time. Most of the instruments are not designed for routine monitoring of atmospheric composition and e.g. assessment of Air Quality for regulatory purposes is difficult due to poor data coverage, insufficient sensitivity towards surface, etc. New European sensors with interesting potential both for routine monitoring and research are, however, being developed and will be launched within the next few years. Some of these are discussed in the following. EarthCARE and the Sentinel-5 precursor missions are especially central and are given special attention.

2.1 EarthCARE

According to Wehr et al, 2010, the overarching EarthCARE mission objective is to improve the understanding of cloud-aerosol-radiation interactions that play an important role in climate regulation. The aim is to include them correctly and reliably in climate and NWP (Numerical Weather Prediction) models. EarthCARE is an ESA Earth Explorer mission which is jointly implemented by ESA and the japanese space agency JAXA. The instrument package consists of a high spectral resolution polarized 355nm aerosol LIDAR called ATLID, a Doppler cloud radar, a multi-spectral imager and a broadband radiometer. The Japanese contribution is the Doppler Cloud Profiling Radar, CPR, while the other three instruments are from ESA.

The idea is that the simultaneous measurements of these sensors give complementary information, following the idea from the A-train constellation of CloudSat-CALIPSO-Aqua, providing simultaneous insight into clouds, cloud properties and interaction with aerosol and radiation. A potential bridge between CALIPSO and EarthCARE can be partly covered by the Earth Explorer Atmospheric Dynamics Mission (ADM-Aeolus), which will mainly provide global observations of wind profiles from space, but as by-products information on cloud top heights, vertical distribution of cloud and aerosol properties (although with crude vertical resolution) are expected.

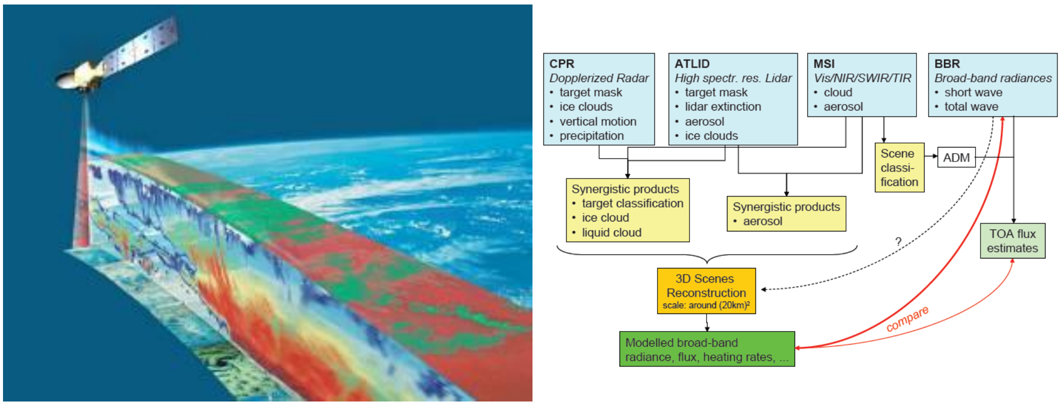

Figure 1: EarthCARE consist of four instruments that is jointly able to provide vertically and spatially resolved information on aerosol and cloud properties and also provide total radiance measurements suitable for comparison against radiances calculated by aerosol and cloud models. Graphics are from ESA.

A main capability of EarthCARE is vertically resolved measurement of cloud cover. The mission is also expected to have some capability on cloud microphysics information such as water vs. ice phase, “effective” droplet/particle size, water content profile and cloud Doppler velocities. As for aerosol, expected capabilities are the detection of occurrence of aerosols layers, their profile of extinction coefficients and boundary layer height, and the presence of absorbing and non-absorbing aerosols from anthropogenic and natural sources.

The mission is delayed from the original plans, and a possible launch date is 2015.

Level 2 products are basically being developed in three main projects (Wehr, pers. comm.):

1. ATLAS: Cloud and aerosols products retrieved from LIDAR. KNMI, NL
2. IRMA: Imager cloud and aerosol products and synergistic imager-LIDAR products, IfT, Univ. Bremen, DWD (all Germany)
3. RATEC: Synergistic cloud and aerosol products (variational schemes; Univ. Reading, UK) and radiative products derived from retrieved clouds and aerosols (heating rates, fluxes; Environment Canada)

These development activities are ongoing, together with several other supporting studies.

Results from the EarthCARE are expected to improve our understanding of the Earth's radiative balance, which will have high relevance for Numerical Weather

Prediction (e.g. validation of modelled clouds), for air quality assessments and forecasting (e.g. validation using aerosol products) and for process studies, also in connection with Earth System Modelling activities.

2.2 Sentinel-5 precursor

The main objective of Sentinel-5 precursor is atmospheric composition monitoring (gases and aerosols), as a precursor for the future operational GMES Sentinel-5 instrument (expected around 2020). Sentinel-5 precursor (expected launch in 2014) will fill the gap between the current atmospheric monitoring instruments - SCIAMACHY (ESA's Envisat) and OMI (NASA's Aura) and Sentinel-5. It will also complement the GOME2 payload onboard the operational EUMETSAT mission MetOp.

The main payload is the UV-Vis-NIR-SWIR spectrometer named TROPOMI. This is a Dutch developed instrument and can be seen as the next generation in the GOME, SCIAMACHY, GOME2, OMI family. Compared to these previous and existing nadir looking mapping spectrometers, TROPOMI will have an improved spatial resolution (7x7 km^2), improved signal to noise ratio, better spectral resolution (at least in some bands) and daily global coverage (with a 114° swath). TROPOMI covers the OMI wavelengths to measure O_3, NO_2, HCHO, SO_2 and aerosols and adds a NIR channel and a SWIR module for improved cloud detection, aerosol height distribution and CO and CH_4 measurements.

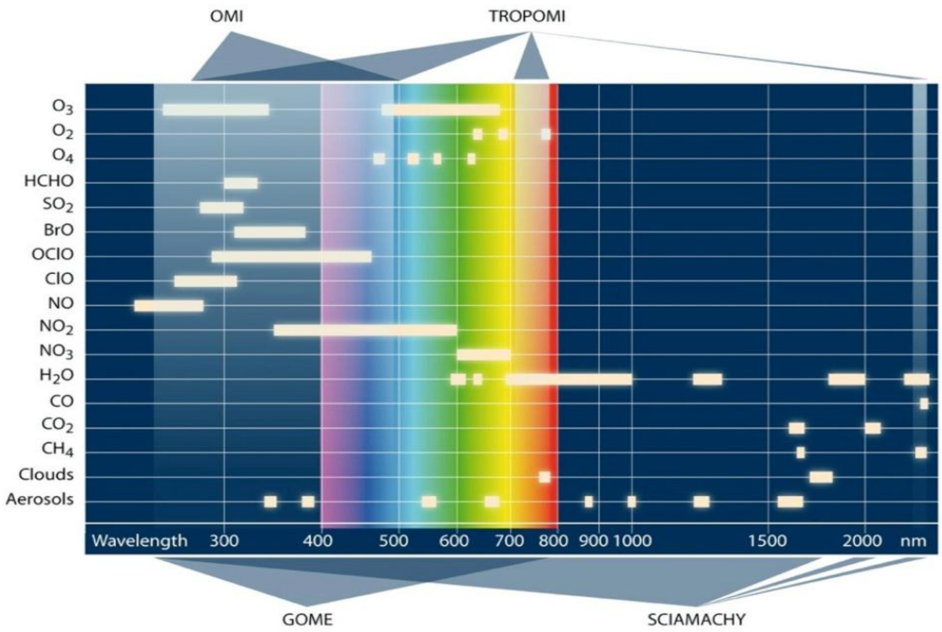

Figure 2: Comparison of capability of TROPOMI with OMI, GOME and SCIAMACHY. The white bands indicate at which wavelengths the different species may be detected.
(Figure taken from Veefkind P., & the TROPOMI team, TROPOMI status, presentation:
www.knmi.nl/research/climate_observations/meetings/presentations/Veefkind_20110211.pdf*).*

TROPOMI will deliver the following (Level-2) data products:

- O_3 total column and Profile (6 km vertical resolution)
- NO_2 total and tropospheric column
- CO total column
- CH_4
- SO_2 volcanic plume, tropospheric column
- Aerosol (Absorbing Index, Layer Height, Optical Thickness, Single Scattering Albedo)
- Cloud height, radiation fraction
- Surface UVB flux (derived from O_3, aerosol and cloud product)
- HCHO and CHOCHO total column
- H_2O total column
- BrO and OClO (polar vortex only) total column Surface reflectance – monthly climatology

Due to the improved capabilities compared to previous/existing missions, the Sentinel 5 precursor satellite will be very useful for operational monitoring tasks. Global coverage, in the Arctic probably several overpasses, combined with improved spatial resolution and cloud detection facilities will increase significantly the number of useful observations per day.

2.3 Other European satellites

Beside EarthCARE and the Sentinel-5 precursor satellites, there are other important satellite missions (or mission concepts) under development that will be important for NILU and met.no.

The Sentinel-3 satellites, also part of the GMES family of operational environmental satellites, will be a mission to measure sea-surface topography, sea- and land-surface temperature and ocean- and land-surface colour with high-end accuracy and reliability in support of ocean forecasting systems, and for environmental and climate monitoring. The platform will carry instruments that are further developments of the currently flying AATSR and MERIS (both Envisat) sensors, and both of these are useful for aerosol monitoring (a third instrument, a Synthetic Aperture Radar Altimeter, is also onboard, but this is less interesting for atmospheric composition monitoring). Sentinel-3 will fly as a pair of two satellites and will be an important source to operational aerosol products when it is launched in 2013 (currently planned launch data for the first of the satellites).

Sentinel-4 and Sentinel-5 are planned for launch towards the end of the current decade and will provide essential information on atmospheric composition from geostationary and polar orbiting orbits respectively. Sentinel-4 will enable frequent mapping of Air Quality properties over Europe (and Africa) while Sentinel-5 will be a further refinement of the currently planned precursor. The two missions are still in an early planning phase and are not discussed further in the current document.

MetOp A is Europe's first polar-orbiting satellite dedicated to operational meteorology and it also carries instruments suitable for atmospheric chemistry and aerosol monitoring (most notably IASI, GOME-2 and AVHRR). The satellite is the first in the series of three identical satellites that will be launched by EUMETSAT in order to secure long-term measurement capabilities (last launch planned 2020) from space. The instruments provide operational measurements, but with a lower quality, coverage and resolutions compared to other planned missions, but they are important for the long-term perspective and for preparing for the other missions (such as EarthCARE and Sentinel-5 precursor).

ESA’s Earth Explorer programme includes current missions such as SMOS (Soil Moisture and Ocean Salinity) and Cryosat-2 (to measure floating sea ice thickness and surface of ice sheets) and planned missions such as the ADM-Aeolus and EarthCARE. Six Earth Explorers missions are all in all selected and two more are currently in the process of being selected. These will be Earth Explorer 7 and 8 (EE7 and EE8) and there are interesting atmospheric candidates for both missions. PREMIER (PRocess Exploration through Measurements of Infrared and millimetre-wave Emitted Radiation) is a candidate for EE7 to study processes that link trace gases, radiation, chemistry and climate in the atmosphere. CarbonSat is a candidate for EE8 and will measure globally the atmospheric concentrations ("dry-air column-averaged mixing ratios") of CO_2 and CH_4 with high spatial resolution (2 x 2 km^2) and very good spatial coverage (500 km swath width). Both PREMIER and Carbonsat will be important missions for met.no and NILU if they are selected.

3 Stakeholder requirements

A main aspect of the Roadmap project and the resulting strategy was to initiate a dialogue with important national Earth Observation stakeholders. A stakeholder, in this context, could be any party with an interest in satellite data, either as an end user, a funding agency, a data owner, etc. Besides The Norwegian Space centre (NRS), two main stakeholders were identified; the National Climate and Pollution (Klif) authority and the Norwegian Research Council (NFR). Two meetings were therefore scheduled as part of the project to focus on operational use of satellite data for monitoring purposes and on research needs related to such use. The purpose of both meetings was to discuss use of satellite data and to get a better understanding of needs and wishes for such observations.

The meeting focusing on operational use of satellite data was organised at Klif on September 9th 2010 while the meeting focusing on research needs was organised at NILU on March 28th 2011. NRS, Klif, met.no and NILU were present at both meetings while NFR were only present at the last meeting. The importance, benefits and challenges of using satellite observations were discussed on both occasions. The meetings did not provide any further conclusions on which satellite data or products that were most important. In brief:

- Klif were interested in any information source that could improve the monitoring programme, but use of satellite data would probably have to happen within the existing programmes and their budgets. Monitoring of black carbon (BC) in Arctic areas would be of special interest. Despite ongoing efforts (e.g. Solber, R. et al, PRODEX Black Carbon pilot project), the expected albedo reduction of snow by a few procent due to BC is below the accuracy of satellites and the meeting concluded that this property cannot (yet) be monitored sufficiently well with satellites.

- NFR was represented by a contact person of the Space Research (Romforskning) programme and it was stated that this programme mainly looked for scientific excellence and did not distinguish one atmospheric topic from another. Other NFR programs, such as the Norklima programme, would naturally prioritise research application related to climate, but no one from this programme was able to attend the meeting at NILU due to other conflicting meetings.
- NRS is through its mandate focusing on application and use of satellite data and not on research tasks. They are thereby promoting wider use of Earth Observation data in operational context such as the NILU and met.no tasks described under section 1.1.

A main outcome of the meetings was the realisation that NILU and met.no have to identify for themselves what are the most important satellite related tasks for their National monitoring and research needs. The stakeholder consultations did not result in a specific preference to e.g. “use of satellite retrieved NO_2 data for data assimilation and chemical weather forecasting” instead of support to “application of satellite measurements of stratospheric Ozone to better understand spatial trends and variability in the Arctic”. Instead, it became necessary to analyse our current and expected future “official” national and international tasks and find out where satellite data would be most beneficial for the final results. With a special focus on the future EarthCARE and Sentinel 5 precursor satellites, the following chapter shows the result of how NILU and met.no foresee to work with Earth Observation data in the coming years in order to fully exploit the new sensors operationally once they are in orbit.

4 Towards EarthCARE and Sentinel-5 precursor

NILU and met.no have identified a number of applications and themes that would be beneficial to exploit once the satellites are in orbit. In order to prepare for such use, it is necessary to investigate further the feasibility of the products before launch. Suggested activities are presented in the following sections under chapter 4.

We have, as far as possible, tried to be concrete in our descriptions on what exactly we want to do in order to prepare for the two missions. For some cases, we see an immediate need and a possibility to proceed with preparations right away (i.e. to start work already next year in 2012), while more time is needed is other cases. The latter is especially the case for Earth Observation applications that are not sufficiently mature to be implemented for operational use. A summary of all the proposed activities is provided in table-form in chapter 6 and we have here also indicated which tasks which are most relevant to initiate soon.

4.1 Climate gases, stratospheric ozone and UV

4.1.1 Background; the national monitoring of climate drivers, UV and ozone for KLIF

National monitoring of climate gases and selected aerosol properties

In 1999 The Climate and Pollution Agency (Klif, the former SFT) and NILU signed a contract commissioning NILU to run a programme for monitoring greenhouse gases at the Zeppelin station, close to Ny-Ålesund at Svalbard. This collaborative Klif/NILU programme currently includes monitoring of 23 greenhouse gases at the Zeppelin observatory in the Arctic. In 2009 NILU upgraded and extended the observational activity at the Birkenes Observatory in Aust-Agder and in 2010 the monitoring programme was extended to also include the new observations from Birkenes of the greenhouse gases CO_2 and CH_4 and selected aerosol observations relevant for the understanding of climate change. The purpose of the programme is to:

- Provide continuous measurements of greenhouse gases in the Arctic region and at Birkenes (only CO_2 and CH_4 at Birkenes) resulting in high quality data that can be used in trend analysis
- Provide trend analysis and interpretations of the observations from Zeppelin to assess the influence regional anthropogenic emissions of greenhouse gases has on the radiative balance
- Provide information on the status and the development of the greenhouse gases with a particular focus on the gases included in the international conventions (the Montreal and Kyoto protocols)
- Provide results of aerosol observations of relevance to the understanding of climate change
- Indicate source regions with high influence on the measurements.

National monitoring of Ozone and UV

It is important to follow the development of the ozone layer in order to verify that the Montreal Protocol and its amendments work as expected and detect other possible changes in the ozone layer.
Klif (as former SFT) established the programme “Monitoring of the atmospheric ozone layer” in 1990 and NILU has been responsible for the operation and maintenance of the monitoring programme since the start. Currently the program includes measurement of total ozone (the ozone layer) and UV at three locations (Oslo, Andøya and Ny-Ålesund). The purpose of the programme is to:

- Provide continuous measurements of total ozone and natural ultraviolet radiation that reach the earth surface
- Provide data that can be used for trend analysis of both total ozone and natural ultraviolet radiation.
- Provide information on the status and the development of the ozone layer and natural ultraviolet radiation
- Notify the Climate and Pollution Agency when low ozone/high UV episodes occur.

National monitoring in Antarctica
Within the Norwegian Antarctic Research program, NILU is responsible for atmospheric monitoring at the Norwegian Antarctic station Troll (72°0S, 2°3E), which was upgraded in 2005 from a summer station to a year-round station. The goal was to operate a comprehensive and continuous monitoring programme of important atmospheric parameters in this transition and mixing zone between air from the sub-polar ocean and central polar ice sheet air masses (see Hansen et al, 2009 for early results). Measurements comprise e.g. surface ozone, aerosols, inorganic and organic pollution, UV radiation, total ozone, and mercury chemistry.

4.1.2 Preparing for operational application of planned European missions

Both monitoring programs presented above will benefit from wider and more integrated use of satellite observations. Such work was already initiated in the SatLuft project ("Use of satellite observations in the national and regional assessment of air quality, the atmospheric ozone layer, ultraviolet radiation, and greenhouse gases – SATLUFT", ESA PRODEX contract nr. C90283), and the section below presents suggested new supplements for the national monitoring programs utilizing satellite products and preparation for future use.

Preparation for use of CH_4 from the Sentinel-5 precursor
The Sentinel-5 Precursor mission is optimised to provide good measurements of ozone, NO_2, SO_2, CO and aerosols, but will also provide results for CH_4. While ground based in-situ observations of CH_4 will still form the backbone of the monitoring programme, improved identification of emission hot spots and source regions of CH_4 will be possible through the use of satellite based observations. This is of high interest for the national authorities to distinguish natural and human sources and in the development of abatement strategies.

To prepare for such operational use, a main activity could be to (further) investigate feasibility and quality of methane products from currently available satellite (SCIAMACHY and GOSAT) as already initiated in WP1 of the current project. A starting point is a comparison with ground based observations, both absolute values and variations and relative changes throughout the year. Based on the previous SatLuft project we know that the quality of SCIAMACHY products for CH_4 is not satisfactory in the Arctic region. There is, however, a need to explore this further for other sites and regions, such as the southern part of Norway, and to validate against ground based observations from the Birkenes observatory. Both direct overpass data from SCIAMACHY and GOSAT and monthly, seasonal and annual mean products are valuable and could be assessed. Also observations from other sites available from international databases could be utilised to explore latitudinal variations and discrepancies between ground based and satellite based data which are assumed to be relevant. Also ground based total column data from the TCCON network exists. TCCON is a network of ground-based spectrometers in the near-infrared spectral region, and accurate and precise column-averaged abundance of CO_2, CH_4, N_2O, HF, CO, H_2O, and HDO may be retrieved. TCCON data are used in the validation of the SCIAMACHY, and GOSAT by other European institutes. A new activity can be to also include the validation of IASA CH_4 products.

Aerosols – climate effects in Scandinavia and Polar Regions

Atmospheric aerosols have masked the temperature rise at the surface caused by the increase of greenhouse gases, maybe with as much as 1/3rd since pre-industrial times. Understanding of all aspects of aerosols; their sources, amount, chemical, optical and physical properties, geographical distribution and deposition, is of crucial importance.

An important application of satellite data is to assess the geographical extent of high aerosol episodes detected at the ground at Birkenes (Sothern-Norway) and Zeppelin (in the Arctic), as well as aerosol transport to Troll (Antarctica). Currently there are various aerosol observations at the Scandinavian sites and high episodes of aerosols and CO due to long range transport of pollution are occurring frequently. A better description of the spatial and horizontal distribution and load of aerosols would be important for the national monitoring and reporting to the authorities. Examples of such recent events include the transported ash and CO from the eruptions at Iceland in 2010 and 2011 and the smoke plumes from Russian wild fires in summer 2010. Biomass burning aerosols from South America have also been identified at the Troll station (Fiebig, 2009). For this activity, the following TROPOMI (Level-2) data products: Aerosol (all products), SO_2 and CO and the vertically resolved aerosol products from EarthCARE are relevant.

In order to prepare for such use, it is therefore suggested to assess the suitability and fitness for purpose of similar products from current satellite instruments such as MODIS (spatial aerosol distribution), CALIOP (aerosol profiles), OMI (SO_2) and SCIAMACHY (CO). Some work towards such a better understanding of satellite data capabilities is already being done through the reporting efforts to Klif/EMEP and the previous SatLuft project but a more detailed and systematic study is needed. Concretely, it is suggested to investigate recent years episodes with high aerosol loads and examine what additional information that can be retrieved from the currently available sensors. Through participation in the validation team of ESA's AEROSOL-CCI project, direct contact to EO aerosol data providers are given. This will enable us to exploit recent aerosol retrievals from e.g. POLDER (Tanré, et al, 2011.), ATSR or AATSR (Istomania et al., 2010 and Istomania et al., 2011), as well as IR data retrievals from SEVIRI/IASI. This will prepare us for operational use of sentinel 5 precursor and EarthCARE once they are in orbit.

Also an automatic warning system for high episodes would be very valuable both for health/security reasons and to provide an alert initiating intensive measurement periods with higher frequency of observations at the ground. At NILU, satellite column measurements have been used for inverse transport modeling (e.g. Eckhardt et al., 2008; Stohl et al., 2011). NILU operates a EumetCast system for real-time collection of SEVIRI/IASI and AVHRR data and has direct access to 3-hr AIRS data (near real-time). While geostationary / weather satellites will allow for a service on a 24 hr basis (data updates every 15–30 minutes are most suitable for an alerting system), products from EarthCARE and TROPOMI will be very valuable for validation of plume location, extend and characterization. Future developments will benefit from the experience made within the on-going downstream-service "Dust load monitoring of natural courses of exceedance subservice” within PASODOBLE, a collaborative project under Theme FP7-SPACE-2009-1 of the EC’s Seventh Framework Programme. A possible aerosol alert system should be developed in parallel or jointly together with a volcanic ash alert system.

The vertical distribution of aerosols and in particular absorbing aerosols located above clouds which have high impact on the atmospheric radiative balance on local and regional scale is another important satellite product to assess.

Lofted aerosol layer can be observed by ground based LIDAR, e.g. the tropospheric aerosol LIDAR at ALOMAR. This is true for clear-sky conditions and optical thin clouds, but during overcast conditions these layers are not visible in observations from ground, and the space borne LIDAR on EarthCARE is expected to be very useful to asses such aerosol loading. Figure 3 is showing an example of this. Recently, Devasthale and Thomas (2011), perform a global survey of aerosol-liquid water cloud overlap based on four years of CALIPSO-CALIOP data, concluding that the frequency of occurrence of aerosol-water cloud overlaps is far from negligible. Nevertheless, the sparse spatial coverage of CALIOP data decreases their feasibility. Alternatively, the aerosol absorbing index (OMI) has been used as indicator for absorbing aerosol presence (e.g. Peters, et al., 2011). For the preparatory pre-launch phase of ADM Aeolus, the PRODEX project proposal from met.no and NILU suggest to characterize lofted layers at and around ALOMAR. A more general study utilizing passive satellite sensors including Northern latitudes is lacking and needed in order to understand the contribution of lofted layers to climate.

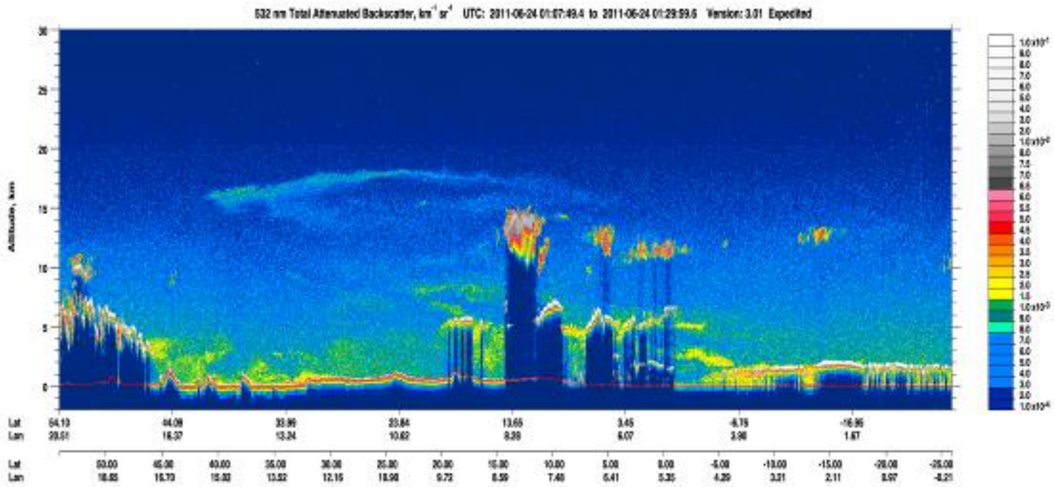

Figure 3: Example of faint aerosol layers above clear sky-conditions as well as clouds, seen by CALIOP on 24 June 2011.

Stratospheric O_3 and related species

Total ozone is a core product from the Sentinel-5 Precursor, and is specifically useful for following the total ozone distribution above Scandinavia, Antarctic and Arctic regions in the future. There are indications that the Arctic stratosphere is becoming colder and this is favourable for Arctic spring time ozone depletion. See figure below from WMO.

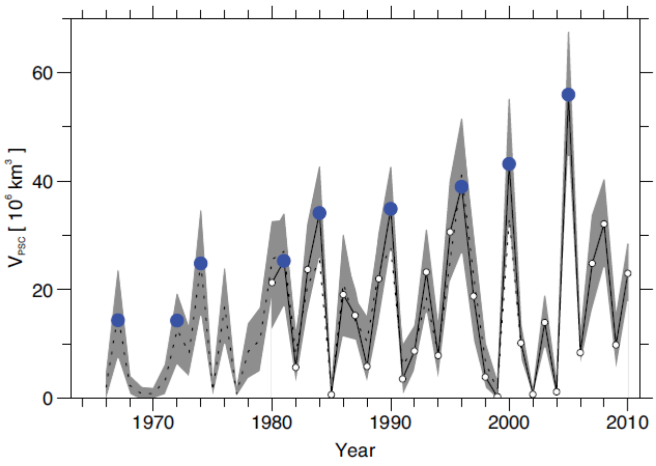

Figure 4: Evolution of VPSC (km³) (volume of air experiences PSC formation conditions) for the Arctic over the past four decades obtained from WMO, (2010).The blue dots represent the maximum values of VPSC during five-year intervals. The dotted line is based on radiosonde analyses, and the solid line is ECMWF ERA-15 data. Note that 2011 was new record year, not included in the figure.

This year, 2010/2011, was a record year with respect to high Arctic ozone depletion and NILUs measurements at Ny-Ålesund show almost 40% loss in the total ozone. It is of high relevance both for science community and authorities to follow the situation carefully. Exploration of available satellite products to describe the extent and development of the ozone layer in the Arctic is very valuable in the reporting to the national authorities to follow up on the Montreal protocol.

Ground based observations are only made at few locations and do not cover the full region. Thus an important activity to prepare for Sentinel-5 Precursor is to assess available satellite products to bridge the gap between time series from ground and satellites and eventually include new products and versions of old data when available. Various satellite products (OMI, SCIAMACHY etc) are not in agreement (as demonstrated in the previous NRS Satluft project), particularly in Polar Regions, and the link to ground based observations are crucial for the integration. It is therefore suggested to continue the work from SatLuft and assess how well the different satellite time series fit with each other and with ground based observations. It is suggested to expand the study to include all Norwegian sites with ground based observations (Troll, Oslo, Andøya, Ny-Ålesund). It is also suggested to compare the spatial variability of the different satellite sensors – i.e. quantify how well their mapping capabilities compare.

Since 30 years, satellite observations of stratospheric aerosols were made, starting with SAM II / SAGE and SAGE II instruments. Sensors revealing the altitude resolution have recently become available with the launch of CALIPSO, and

ALADIN and ATLID will continue the space borne LIDAR observations and create a unique opportunity for long term monitoring of stratospheric aerosol loading as well as polar stratospheric clouds (PSCs, see Figure 5 as an example). While the CALIOP is not able to measure aerosol extinction (it is retrieved from back-scatter by using an estimated LIDAR-ratio), extinction will be a directly measured product of the EarthCARE mission. Alternative stratospheric aerosol products can come from MIPAS or SCIAMACHY. Within the ESA AEROSOL-CCI, NILU is responsible for the validation of the GOMOS stratospheric aerosol products (BIRA) using CALIOP. The global test dataset covers the year 2008, where the Mount Okmok and Kasatochi volcano eruptions in July – August led to an increased stratospheric aerosol load for a period of a few months.

It is suggested to include the stratospheric aerosol and PSC products from satellites into the reporting to Klif, to better understand the development of the total ozone distribution above Scandinavia, Antarctic and Arctic regions.

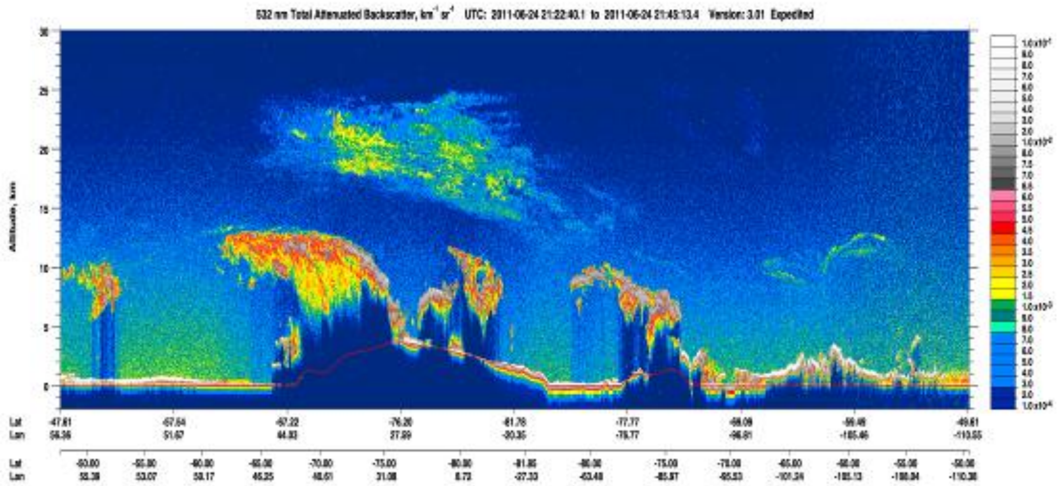

Figure 5: Example of Antarctic Polar Stratospheric Clouds, seen by CALIOP on 24 June 2011.

Satellite validation needs in the Arctic are investigated in ‘’The Svalbard Integrated Arctic Earth Observing System’’ (SIOS) project.

UV-warning system and validation of forecasts

Warning systems for high UV days and periods is important for the public health, and identification of low ozone values like the one we observed summer 2009 is crucial. The days with lowest ozone values during that period was 27th of June and 3rd of July (see Figure 6). Also included are the assimilated ozone fields from SCIAMACHY showing the regional area experiencing low ozone (Figure 7).

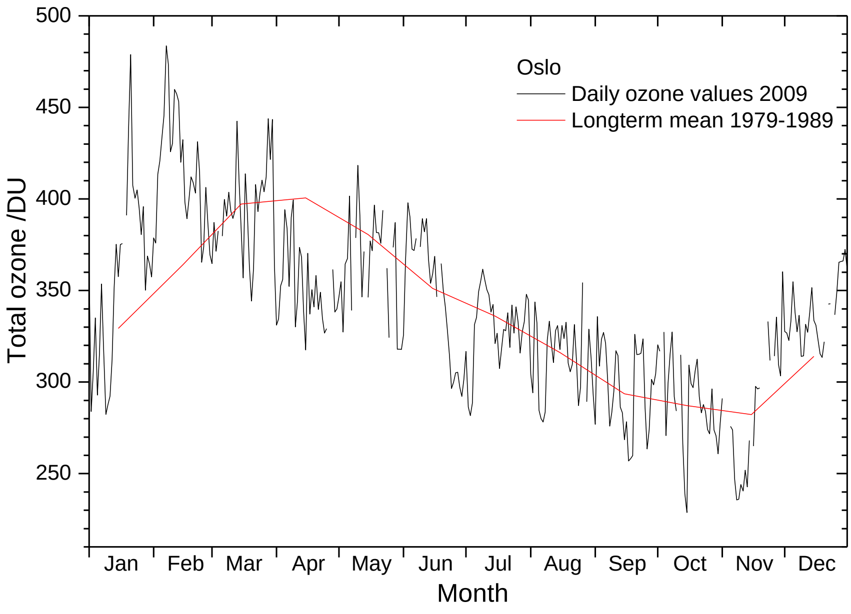

Figure 6: Daily total ozone values measured at the University of Oslo in 2009. The red curve shows the long-term monthly mean values from 1979-1989. Note the low ozone values late June, beginning of May.

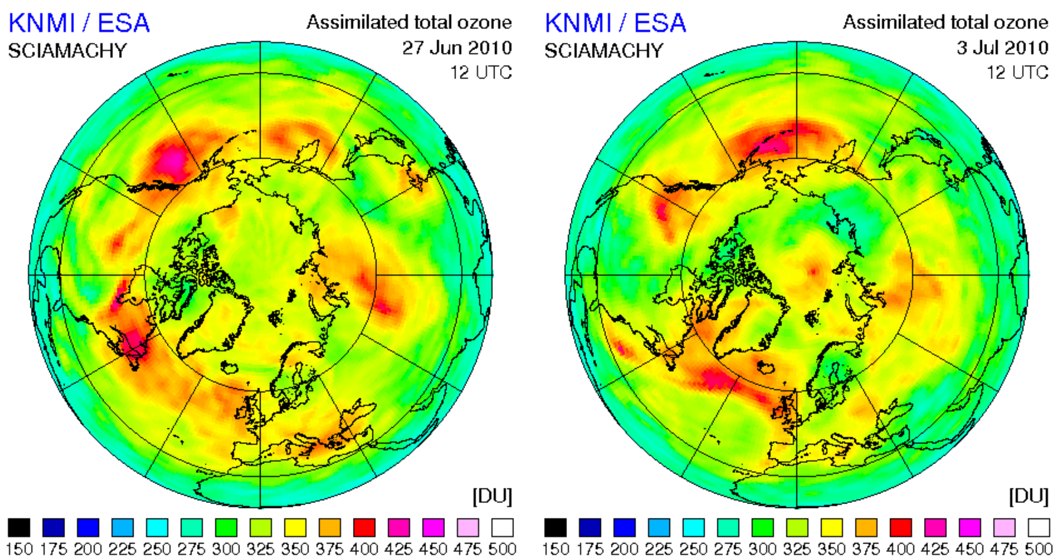

Figure 7: Daily assimilated total ozone fields from SCIAMACHY for the days with lowest ozone.

A suggested activity to prepare for the Sentinel-5 precursor is to set up of automatic alerting routines for low ozone values in order to issue public warning trough media. Also validation of UV-forecasts would be very valuable including both ozone and aerosol as variables. Both total atmospheric aerosol load and ozone is central for the surface UV level, and episodes with high aerosol load reduce the UV at ground significantly (a reduction in UV as high as 20-30% is observed during episodes with high aerosol content). Thus it might be relevant to couple an aerosol warning and a UV alert system together.

4.2 EMEP reporting on aerosol and acidification/eutrophication

4.2.1 Regional scale EMEP monitoring

For EMEP regions with sparsely located monitoring sites, the Sentinel-5 precursor can prove to be specifically useful for filling gaps and cover areas with no groundbased monitoring facilities. This is the case particularly in Eastern Europe, Caucasus and Central Asia (EECCA region, see figure 8). Of special interest are tropospheric columns of NO_2, SO_2 and possibly CO. As an alternative to no observations at all, the main idea is to use Earth Observation data to establish trends in Air Quality levels and to assess the spatial distribution of pollutants across these vast areas. In the future the TROPOMI (Level-2) data products; aerosol, NO_2 (total and tropospheric column), CO, and SO_2 are assumed to of particular relevance and it is a goal to include these data in the annual reporting to EMEP if the mission becomes successful. The ongoing measurements from OMI, SCIAMACHY and GOME2 are also valuable even though they have a lower expected quality than the Sentinel-5 precursor. It is therefore suggested to use products from these missions in order to prepare for Sentinel-5. This will be a natural continuation of work undertaken in previous projects such as ESA-GSE PROMOTE (I & II) and SatLuft.

Figure 8: EECCA region: Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Moldova, Republic of, Russian Federation, Tajikistan, Turkmenistan, Ukraine, Uzbekistan.

As an example from NILUs SatLuft PRODEX project, SO_2 maps are shown in Figure 9. Emissions of SO_2 are largest over Eastern Europe and in particular over industrial parts of Poland, Romania and Bulgaria, and a region in Eastern Europe (Romania) was therefore selected for a closer study. In the frame of potential future collaboration programs between Romania and Norway, utilization of EO data for regional air quality monitoring seems valuable to exploit in more depths.

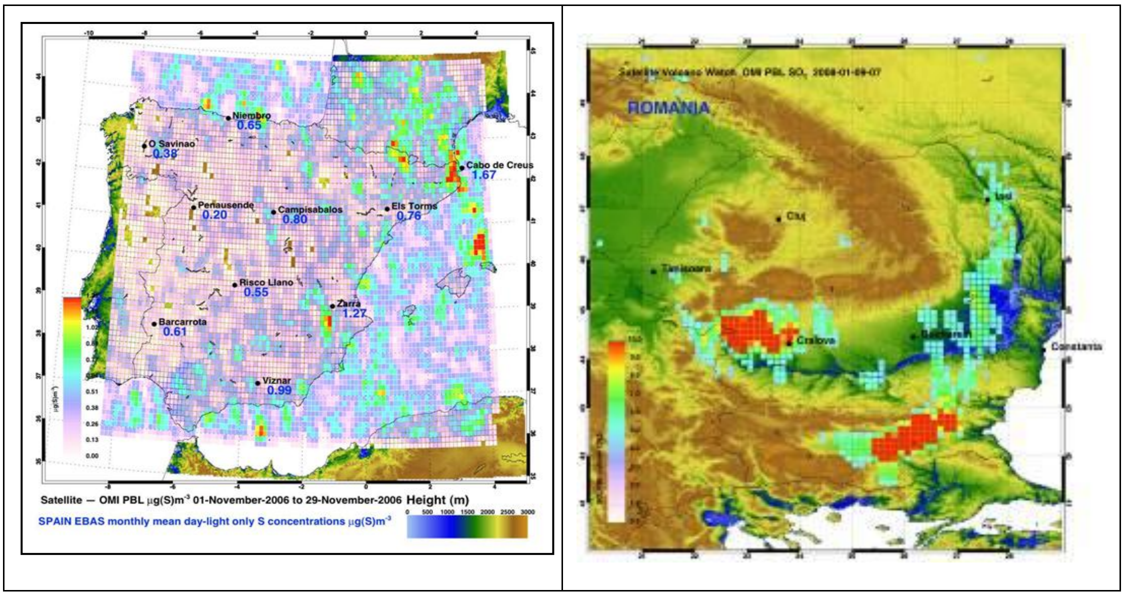

Figure 9: Left panel: SO_2 measurements over Spania, overlayed on top of EMEP-measurements (in blue) Right panel: OMI Planetary Boundary Layer SO_2 for Romania and Bulgaria on 1–7 September 2008. Units are Dobson units (DU) and each 0.25 x 0.25 degree box contains SO_2 amounts accumulated over the period of 7 days, i.e. the first week of September 2008 in this case.

EMEP-CCC and MSC-W (i.e. NILU and met.no) have the intention to continue to incorporate space borne Earth Observation data in operational routines for assessment of air quality levels in Europe. NILU studied satellite based particulate matter measurements in the SatLuft PRODEX project where an evaluation of the SYNAER method (from DLR) showed good potential, but also weaknesses in terms of e.g. data-coverage. An example comparison is shown in Figure 10.

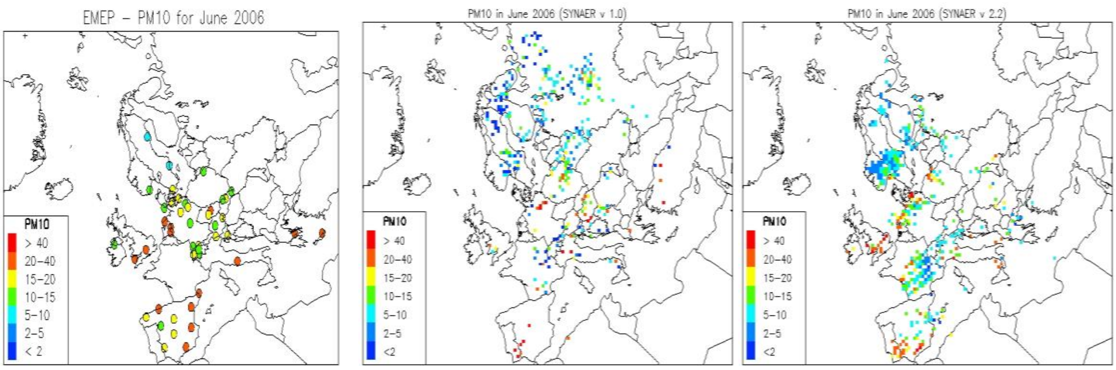

Figure 10: Monthly averaged PM_{10} values from EMEP (left panel), SYNAER PM_{10} version 1.0 (middle panel) and SYNAER version 2.2 (right panel) for June 2006 [in µg m^{-3}). SYNAER data are shown as averages when more than five centers of SYNAER pixels were found within a 50 x50 km ^{2} EMEP grid-cell.

It seems worthwhile to continue towards the goal of utilization of EO particulate matter data, but for proper validation one would have to further develop methods to compare the dry in-situ aerosol measurements (in-situ measurements) with those performed in ambient humidity (remote sensing measurements). Thus, information on e.g. hygroscopic growths factors for particle diameter and particle scattering coefficients and knowledge about the vertical aerosol distribution are needed.

Within the AEROSOL-CCI optional package, a few GAW sites, representing the aerosol in the dry state, are suggested to be adjusted to ambient humidity, as seen by the satellite. Applying this to additional data sets in the World-Data-Center-for-Aerosols (WDCA) in the future, could provide a very valuable validation data set for aerosol-parameter, beyond AOD

Another important aspect for EMEP is early identification of hot spots and warning of transport of desert dust and other aerosols and trace gases from fires or other large emission sources/special conditions.

As a concrete preparation for the Sentinel 5 precursor instrument, it is suggested to establish multi-sensor, multi-parameter trends on key parameters such as CO, SO_2 and NO_2 for the EECCA countries and some eastern European countries with sparse ground based monitoring facilities. Such time series would provide a unique and essential source of information for the EMEP assessments and they could readily be extended further once Sentinel 5 precursor becomes available.

4.2.2 Regional scale EMEP/MSC-W model evaluation

Within the EMEP Programme, monitoring of air pollution for air quality assessment and model evaluation have traditionally been carried out at ground-based measurements stations. As already discussed, monitoring of air pollution from satellites has several advantages compared to in-situ surface measurements and especially larger spatial coverage is useful for model validation. The satellite is furthermore a powerful instrument in detecting pollution episodes, caused for example by volcano eruptions, desert storm outbreaks and forest fires.

First endeavours to make use of MODIS AOD for comparison with the EMEP model were carried out within the framework of the AeroKval project, 2007-09 phase (which was undertaken by met.no). Among others, AOD at 550 nm wavelength from model and MODIS were jointly used in case studies of smoke transport from forest fires in 2003 and 2006, and to compare with data from AERONET sun photometers. As a continuation of the work in AeroKval-2011, model calculated AOD is further being evaluated with AERONET sun-photometer data. For this evaluation, quality controlled AOD data at six wavelengths (as well as 440-870nm Ångstrøm coefficient and Fine Mode Fraction at 500nm) have been provided to met.no by the University of Valladolid, Spain. The data is available for 58 AERONET stations for June-July 2009. The aim of the work is an extended test of EMEP-MSC-W model’s skills with respect to aerosol properties calculations, and it is considered to be an important step in model preparation for comparison with new data from EarthCARE and Sentinel-5.

Aerosol retrievals from EarthCARE and Sentinel-5 precursor will provide very useful data for further evaluation of the EMEP model's ability to calculate the pollution transport, which is particularly valuable in the regions with a lack of surface monitoring. One of the main merits of EarthCARE mission will be application of multisensor remote sensing techniques. Compared to the quality of existing retrievals, application of novel synergetic retrieval approaches among the instruments on board EarthCARE, is expected to provide improved datasets and thus facilitate a more sound model evaluation.

Measurements from the ATLID LIDAR on the EarthCARE platform would additionally provide the possibility to evaluate model calculated vertical profiles of aerosols. This is particularly valuable as modelling of pollutants' vertical distribution is associated with uncertainties in emission's vertical distribution and meteorology (turbulent mixing). Further, it is expected that the aerosol vertical profiles from EarthCARE will distinguish between anthropogenic and natural aerosols. Comparison of such data with model calculations is very relevant with respect to identifying the sources of air pollution episodes (and exceedances of Air Quality standards). As a preparatory step, the EMEP/MSC-W model has been extended to calculate 3-dimentional aerosol extinction coefficients. Model calculated vertical profiles of aerosol extinction will be compared with measurements from CALIOP using the AEROCOM tool (see also section 4.3 under aerosols). Further work towards establishing modelling capability for making use of ATLID LIDAR data will involve model development to implement aerosol back-scattering calculation and testing modelled back-scattering coefficients against surface-based LIDARs from EARLINET network.

Furthermore, there have been several attempts to estimate surface concentrations of PM_{10} and $PM_{2.5}$ from satellite AOD data (Schaap et al., 2009; Glantz et al., 2008 etc). Some of the proposed approaches could be evaluated for use in future. If successful, this additional data could contribute to a more comprehensive evaluation and improvement of the EMEP model for PM_{10} and $PM_{2.5}$, which are presently the metrics for air quality assessment. First attempts to compare PM_{10} and $PM_{2.5}$, from the EMEP model with DLR SYNAER (SYNargetic Aerosol Retrieval) data showed reasonably good agreement, but it was noted that further algorithm development was expected to improve the accuracy of the product (EMEP, 2008; Stebel et al., 2008).

AOD data from EarthCARE and Sentinel-5 can also be used for re-analyses of air quality maps and potentially for reducing the uncertainties in emission data (in particular emissions' spatial and temporal variation) by constraining the inventories prepared by the emission experts. Met.no's work on development and testing of data assimilation techniques within the GEMS and MACC projects would make a solid basis for this study.

An important application of satellite NO_2, SO_2 and aerosol observations could be assessment of trends in pollutants burden and potentially emissions. Use of long-term satellite data together with surface monitoring and model calculations could contribute to the assessment of air quality improvement resulting from emission regulation measures. With the EU project CityZen, which met.no is coordinating, a consistent 10-yr data set based on retrievals from GOME and SCIAMACHY has been created, against which the EMEP model can be compared.

The way towards EarthCARE and Sentinel-5 precursor

As mentioned in the previous section, large data sets from satellites are now available, especially from the European FP7 project CityZen (greenhouse gases, air pollutants, and aerosols), which was coordinated by met.no, but also from other projects such as MACC. While the EMEP model has been traditionally evaluated against ground-based measurement data, mainly from the EMEP monitoring network, the evaluation against satellite observations is of increasing value as such measurements become more accurate in low altitudes. Efforts have been made, but there is still a long way to go until systematic and continuous evaluation can be done. The tools for this should be developed well in time before the launch of the new satellites. The already available data sets from past and ongoing mission constitute an excellent test bed for this. Due to the good spatial coverage and (it is hoped) continuous nature of satellite measurements the EMEP model would benefit greatly from such evaluation tools, both with regard to its mandate under the LRTAP convention and its operational tasks within GMES, especially as the EMEP domain extends to regions with limited coverage of ground-based data.

4.3 Chemical weather forecasting

The MACC project (Monitoring Atmospheric Composition and Climate), funded through EU FP7 Space, is part of a pilot GMES Atmospheric Core Service and provides daily global forecasts of atmospheric composition, detailed air-quality forecasts and assessments for Europe, and key information on long range transport of atmospheric pollutants. Both NILU and met.no are lead partners within the MACC consortium. At met.no, MACC is now the most important project making use of satellite products to improve air quality modelling. MACC II, the follow-up project of MACC, will continue the operation and development of the GMES service lines established by MACC and prepare for its transition in 2014 to become the atmospheric monitoring component of GMES Operations. MACC II will maintain and further develop the efficiency of its end-to-end processing system and refine the quality of its products. It will adapt the system to make use of observations from new satellites, in particular the first of the atmospheric Sentinels. Met.no will have two scientists working for MACC II, the focus being on aerosol products, the improvement of global emission data and air quality forecasts. For the latter product, further development of data assimilation for the Unified EMEP model is of particular importance.

Trace gases

Under the AeroKval (2008, 2009, 2011), GEMS (2008-2009) and MACC (2009-2011) projects, a 3-dimensional variational (3D-Var) data assimilation (DA) system has been developed by met.no around the Unified EMEP model (Simpson et al., 2003; Valdebenito et al., 2010). Extensive work has been dedicated to the characterization of the model bias against satellites products from MODIS, GOME, GOME2 and OMI (e.g. Huijnen et al., 2010; Heiberg et al., 2010; Tsyro, 2009; Valdebenito and Fjæraa, 2009; Valdebenito and Heiberg, 2009). NO_2 tropospheric column satellite products have been part of the DA system test bed since the early model development. Current work focuses into the assimilation of Near-Real Time (NRT) NO_2 tropospheric column satellite products into the daily forecasts and reanalysis produced semi-operationally under the MACC umbrella. The transition to an operational status will be achieved during the MACC II project (2012---2014). Also under MACC II, the DA system will be extended to assimilate Aerosol Optical Depth (AOD) from MODIS.

Sentinel-5 precursor products are the natural continuation for this work. In addition to NO_2 tropospheric column, Sentinel-5 precursor potential products include total column measurements of O_3, SO_2, formaldehyde and methane. The inclusion of these satellite products to the assimilation system, to be used either as control (assimilated) or diagnostic (evaluation) variables, holds a great potential for improvement of the system. For example, SO_2 column products can be used as an aid to determine the intensity of volcanic eruptions.

For the Unified EMEP model, satellite products will also be used increasingly, both in MACC and other projects, for model evaluation purposes. Another opportunity connected to NRT satellite data is to help refining the temporal variation of emissions in the model, which are key input to air quality modelling. Officially reported emission data to EMEP are still given as annual means.

As preparation to Sentinel-5 the data assimilation tools will be further developed, including new species. However, before data assimilation of new observations can be achieved, a deep understanding of the retrieval algorithms involved and a detailed characterization of the model bias towards observations are needed. At the moment neither retrieval algorithms nor observations are available. However, it is possible to assess the potential gains from assimilating Sentinel-5 precursor products by following the DA experiment set-up described in Kahnert, M. (2009). Such a study has the additional benefit of helping to identify potential pitfalls in the system before dealing with the actual observations.

Once descriptions of the Sentinel-5 precursor retrieval algorithms are made available by product providers, a thorough algorithm review is envisioned, as was the case for NO_2 tropospheric column and AOD in Heiberg et al. (2010). As the satellite products become available, making use of the tools for analysis of NRT satellite data (developed under MACC & MACC-II) the model bias against these new observations (e.g. SO_2 column) will be characterized as a step previous to its full incorporation into the DA system.

The funding allocated from MACC-II to further development of DA tools in the EMEP model is rather limited, but it is hoped that this work can continue at met.no because the assimilation of satellite data is very promising, especially in view of the better accuracy and the inclusion of new chemical components in future missions.

Aerosols

Met.no is also responsible within the MACC-II project (2012-2014) for implementing an aerosol alert system based on the ECMWF IFS global aerosol model, in close coordination with EMEP regional model forecasts of aerosol. Met.no further chairs the regional steering group for the North African and European node of the WMO sand and dust storm forecast and advisory system (http://sds-was.aemet.es/). The new challenges of aerosol forecasting require additional efforts both for using and preparing satellite data. Aerosol pollution events can have multiple economic and health effects, but warnings need to be prepared with special expertise and communicated well to be understood to the benefit of the end-user. Fire plumes, dust storms, air pollution events and volcanic ash appear on short notice and require an operational near-real-time evaluation. Several of the problems mentioned here under the header of chemical weather forecasting apply also to general model evaluation tasks, e.g. would be of benefit to the EMEP model and NORESM model in general. Several aspects are to be developed for an optimal use of new satellite products:

A near real time evaluation of the initial conditions used in model derived forecasts can be strongly underpinned by satellite products due to their spatial coverage. Operational satellite products need to have known quality for this purpose, something which is not known sufficiently. NRT satellite products require special quality check procedures so that they can be used for operational advisory work.

The data quality of EarthCARE and Sentinel-5 aerosol products has to be compared to those products from NASA and ESA currently in use. It is foreseeable that MODIS and CALIOP sensors will stop functioning near the time frame when EarthCARE and Sentinel-5 will become available. Continuity across different satellite generations requires overlapping quality checks, which could be done with ground based networks. Such continuation efforts will also largely help to establish trends for climate applications.

Assimilation can guide the initial conditions of models and thus improve the model forecast products. Such usage is currently tested by several models including MACC-ECMWF, using MODIS Terra and Aqua aerosol optical depth. Research is needed to ensure that EarthCARE and Sentinel-3 satellite data provide sufficient information content to be a backup of the aging MODIS sensors.

Of great potential is the NRT vertical aerosol profile information (as foreseen by EarthCARE), since such data would allow to allocate the aerosol column loading info from passive sensors to surface level PM concentration or flight level aerosol concentrations. Aerosol optical depth, as retrieved from passive sensors, contains no information about where the aerosol is located. Further exploitation of the EarthCARE LIDAR capabilities could benefit from current work at Met.no to exploit the CALIOP LIDAR retrieved extinction in cooperation with the ICARE centre in Lille (Koffi et al., 2011 in preparation).

The understanding and scientific use of EARTHCARE lidar data use can be tested already now very realistically with the current CALIOP data. Integration of these into the AeroCom database and tools, hosted by Met.no, requires considerable effort to digest this new type of vertical data along transects. Calibration against other satellite and Aeronet data is needed. Separation of cloudy and clear sky scenes requires special filter mechanisms. Preparing such data work-up algorithms will enable MetNo to make best use of EARTHCARE data when they become available.

The merging of satellite information and model derived aerosol forecasts into advisory material for the expert user has not been done to a large extent so far. Users require new scientific visualization and documentation efforts. Inclusion of climatological background info on aerosol levels and error estimates can enhance the usability of the satellite products greatly.

4.4 Numerical weather forecasting

As explained in section 2.1, the EarthCARE payload will provide unique and highly interesting information on cloud and cloud processes. Better analysis and forecasting of cloud and precipitation is an area with a significant improvement potential. Numerical Weather Prediction (NWP) models are main ingredients of modern weather forecasting, but cloud microphysical processes are represented with different assumptions and approaches in these models. Improvements in NWP models would translate directly into improved accuracy of weather forecasts (and might also be applicable to climate and earth system models).

Some areas seen as important to attack in improving the cloud and precipitation modelling capabilities are:

- Better horizontal resolution in NWP models
- Better parameterisation of cloud microphysical processes and dynamics connected to clouds
- Better utilization of the satellite based cloud and precipitation observing system

The EarthCARE instrument suite is well suited to contributing to validation and tuning when schemes for cloud parameterisations are being developed and also to study the impacts on cloud modelling capability of the other model improvements.

Even if EarthCARE is a contributor to the cloud observing system in itself, other available instruments are also providing information on water vapour and cloud. This includes profiling information from IASI and AIRS, microwave sounders such as MHS and satellite imagery from AVHRR, VIIRS and SEVIRI. These sensors will provide better spatial coverage than EarthCARE, even if they do not have comparable vertical resolution capability, and can be seen as the “backbone” of the moisture observing system.

However, EarthCARE has a large potential as a *validator*, and can play a major role in providing reference data for validating efforts towards applying data from other satellite systems in NWP or improvements connected to other NWP model developments. In parallel with preparations for EarthCARE it is important that operational forecasting systems are developed to take advantage of the most important components of the moisture observing system, such as IASI.

Several level 2 products from EarthCARE are planned which could be useful for these purposes. A preliminary list has been given of so called level *2a* products (Wehr et al, pers. comm.), which are single instrument products. From the Cloud Profiling Radar it is foreseen to derive ice water content and effective radius, liquid water content and effective radius, precipitation and vertical motion in clouds. From the ATLID LIDAR it is planned to derive ice water content. A set of level *2b* products, which are synergetic multi-sensor products based on retrieval by including all the different sensor measurements in a variational optimization scheme, are planned as well. The list of planned level 2b products includes synergistic ice water content and efficient radius, the same for liquid water, as well as rain water content and rain rate.

The algorithms for these level 2 products are still under development. Several research group have been involved in the developments of the above mentioned products (KNMI, Univ. Bremen, DWD, Univ. Reading, McGill Univ.), and it is unclear how the integration of this work for the final products will be done (the Invitation To Tender for part of that work was released in the spring of 2011). At this stage few algorithm details are ready or known to us. Even if all these products are expected to contain valuable information, it is likely that the application and interpretation of these level 2 products for validation of NWP models will not be straightforward, since different products with different underlying assumptions and techniques will be available. Direct comparison with NWP data will display both the error properties of the NWP model and the observation/algorithm error properties of the level 2 products. These two will be difficult to distinguish, so it is crucial to know which assumptions are done when deriving the various level 2 products and how they affect the products.

Given this situation, one should prepare for applying the data in NWP cloud validation efforts by analysing the properties and capabilities of the available NWP models in describing the cloud parameters to be observed by EarthCARE. This could be done by preparing relevant output from the different available models and do a comparison analysis of the modelled cloud parameters. This would give an advance assessment of which cloud properties are expected to be more uncertain than others and where EarthCARE data will be expected to contribute most in settling issues of discrepancies.

It will also be crucial to acquire as much information as possible on the level 2 algorithms relevant for the interpretation of the level 2 products when this becomes available from the developers. When applying the data for comparison with NWP models we could make an additional independent assessment of the various products, how they compare, and their usefulness ourselves. At met.no several different NWP models will be available for comparison. The application of more than just one NWP model could give more confidence and aid the interpretation of the validation efforts. New cloud resolving high-resolution NWP models systems will be tested and gradually taken into use at met.no, and such models will contain more details on cloud microphysics (distinguishing between more cloud particle species) than present lower-resolution models, and will be highly valuable in this context.

Good preparation and comparison analysing both several of the level 2 products and several NWP model products will thus be crucial before applying the data for NWP validation. Such preparation would ensure EarthCARE data will serve as a unique cloud profile dataset to aid and guide NWP model development.

4.5 Research on Cloud-Aerosol-Radiation interaction

Being able to validate model results are invaluable for the research toward an improved understanding of aerosol and aerosol-cloud interaction processes in the climate system. Validation of aerosol and cloud droplet (or ice crystal) properties in climate models has historically been hampered by poor horizontal and vertical coverage in the observational data. For comparison with results from a typical climate model without the capability of “nudging” or assimilation of meteorological parameters, also temporal coverage is of importance: Time series should ideally be long enough to be representative of a climatological average, either directly or from model data that has been filtered and processed by a “satellite simulator” algorithm in the climate model code. Development of good simulators which are representative with regard to the obtained parameter, are important for the usefulness of the product both with respect to validation and possibly development of the model parameterisations. Similarly the need for long time series, including long term trends also point to the fact that advanced and quality-checked retrieval algorithms are more important for Earth System Modelling (e.g. with NorESM) than to get near real-time values.

Excepting the need for near real-time values and high temporal resolution needed for forecasts, many of the conclusions in section 4.3 on chemical weather forecasting are valid also for cloud-aerosol interaction, in particular on homogenized long term time-series of aerosol optical depth and vertical profiles of aerosol extinction and/or concentrations. A combination of products from EarthCARE together with ground based measurements, including measurements of optical depths, LIDARs and ground concentration measurement together with older instruments such as the MODIS sensors, should give a good overview over the aerosol distribution, both in time and space. In addition to the aerosols themselves, also aerosol pre-cursor information, e.g. SO_2 is useful in order to understand the processes both in nature and in the model.

To obtain as much information as possible about aerosol cloud interactions from the satellite product, one would ideally need data that allow estimates of the aerosol size distribution, or at least estimates (from satellite retrievals) of the number concentrations of aerosol particles large enough to become activated and grow to cloud droplets, in addition to droplet number concentrations and effective droplet sizes. Aerosol large enough to grow to cloud-droplets have radii that typically range from 0.05 – 0.2 µm (prior to hygroscopic growth) and upwards. The activation size is, among other parameters, dependent on the hygroscopicity of the particles and the realized super-saturation of ambient air. Light extinction retrievals for two or more wavelengths comparable in magnitude to the aerosol radii in question (i.e. NIR, visible and down into the UV spectrum if possible) can provide important size information. Near or inside clouds these particles are humidified, and information about relative humidity and updraft velocities (for estimates of realized super-saturation with respect to water vapour) would also be very useful. Additional information about aerosol absorption is important for validation of the modelled aerosol optical properties, but may also indirectly give clues about the hygroscopic properties, since absorbing aerosols, such as soot and mineral dust, are generally less soluble than non-absorbing constituents, such as sulphate and nitrate aerosols.

Modelling of ice-clouds and ice particles in Earth System Models is still in an early phase, although it is expected that the number of models which include explicit ice-cloud parameterisation will increase during the coming years. The thin ice-clouds (cirrus) cover about 30% of the globe and have a major impact on climate. The climatic effects depend on the scattering and absorption properties of the ice crystals, which are related to the shape and size distribution of the crystals. Unfortunately, cirrus clouds are often entirely removed (screened) from satellite retrievals. EarthCare will include retrievals important for modelling ice-clouds and provide some information on ice particle size and number, even if details on the algorithms and the product error properties are not known to us yet. However, information on the vertical distribution of effective ice crystal sizes, water and ice water content within clouds, coupled with temperature distribution, would also be very valuable. In addition to validation of the model parameterisation, the temperature distribution, in particular in newly formed ice-clouds, gives information on the chemical composition of the ice-particle. Similarly, in ambient air geometric information may give a constraint on the amount of available ice nucleation particles.

4.6 Other themes/application

Besides the already mentioned applications, met.no and NILU have been discussing additional tasks that could be undertaken as a preparation for EarthCARE and Sentinel-5 precursor. These ideas are, however, not fully developed and only an overview of different possibilities is therefore presented here. Possible additional future tasks include:

- Trend analysis on aerosol and clouds from present satellites using the A-Train to prepare for EarthCARE
- Further develop AeroCom tools (at met.no, and as a continuation of the ESA Aerosol-CCI project) to investigate further which algorithms are most efficiently retrieving aerosol information from current and future satellite sensors.
- Further develop dust aerosols products as a continuation of the NILU efforts within PASODOBLE
- Study emission inventories in relation to current satellite measurements from e.g. OMI and SCIAMACHY as a preparation for the Sentinel-5 precursor
- Build on the ESA Aerosol CCI project and study further aerosols over sea ice/Antarctica, high latitude issues in retrieving aerosol in general and aerosols above clouds (detection of absorbing aerosols above clouds are of particular importance and not available from ground based observations)

These ideas need to be further developed before any concrete tasks can be suggested.

5 Funding opportunities

Both met.no and NILU has long term and sustainable funding for the activities related to monitoring, assessment, forecasting, etc., but funding is only to a certain level available for developing the services to utilise Earth Observation data more operationally. External funding for developing such capabilities is therefore needed.

Both institutes, and now referring only to the parts of the institutes that are of relevance to the current document/project, are routinely participating in projects funded by ESA and the EU and are able to pursue some of the activities listed in chapter 4 through such collaborative efforts. ESA and EU are, however, not interested in developing purely national (or EMEP) monitoring or assessment activities through their open calls and there is therefore a clear need for additional national funding to reach our goals. For such activities the "Følgemiddel" programme from NRS is probably most suitable, but the ESA PRODEX (or even STRIN) program could also be suitable if the task fits well with the overall ESA strategy. PRODEX funding will in many ways be preferable due to the possibility of coordinating the work with ESA centrally, but the "Følgemiddel" would allow for more nationally focused tasks.

The research oriented task described under section 4.5 is probably mostly suitable for funding through the Norwegian Research Council – either the "Romforskning" or the "NorKlima" programmes.

6 Conclusions

The current document presents a range of ideas and suggestions for how NILU and met.no foresee to exploit the the EarthCARE and Sentinel-5 precursor satellites and how we want to prepare for such usage while waiting for their launch. The two missions are expected to provide improved atmospheric monitoring capabilities and will be important for the official national and international activities the two institutes are involved in. The current report is submitted to the Norwegian Space Centre in order to stimulate the discussion on where we should focus efforts and resources in the coming years. It is expected that several of the suggested activities will be brought forward in a proposal for the NRS "følgemiddel" program already this year, while others will be postponed until we are somewhat closer to the launch dates of the two missions. Below is a table where we summarise all the concrete activities that has been suggested in chapter 4 with description of what we want to pursue soon/later and why. An indication on who will do the work is also provided.

Table 1: Summary of activities that are proposed by met.no and NILU in order to prepare for the Sentinel 5 precursor and the EarthCARE satellites.

Proposed activity	**Described in section:**	**Could be started in 2012**	**To be undertaken by:**
Preparation for use of CH_4 from the Sentinel-5 precursor: Intercomparison between different current satellite missions and groundbased in-situ and remote sensing measurements	4.1.2	Probably not. The currently available satellite products are not yet sufficiently mature. It is suggested to postpone the activity at least until GOSAT provides reliable observations comparable to surface data	NILU
Aerosols – climate effects: Investigate recent years episodes with high aerosol loads in Scandinavia/Arctic/Antarctica and examine what additional information that can be retrieved from the currently available sensors for aerosols spatial (MODIS, POLDER, IR sensors etc.) and vertical distribution (CALIOP), OMI (SO_2) and SCIAMACHY (CO)	4.1.2	Yes	NILU
Aerosols – climate effects: Development of an automatic warning system for high aerosol episodes.	4.1.2	Probably not. Such a service must be seen together with the needs and the plans for development of a volcanic ash alert system and also the aerosol alert system being developed through MACC II (met.no is involved). The activity should therefore be postponed until later	NILU
Aerosol and – climate effects: Evaluation of tropospheric aerosol profile data with a focus on lofted layers	4.1.2	Yes, a localized study is addressed in the proposed and accepted ESA PRODEX proposal to prepare for ADM-AEOLUS. Might require research; is time-demanding, should also be proposed to NFR	NILU
Stratospheric O3 and related species: Assess how well the different satellite time series fit with each other and with groundbased observations at Troll, Oslo, Andøya and Ny-Ålesund. Furthermore compare the spatial variability/mapping capability of the different satellite sensors.	4.1.2	Yes	NILU
Stratospheric O3 and related species: Assess and potentially incorporate stratospheric aerosol and PSC products into the annual O3/UV assessment report to Klif	4.1.2	Yes	NILU
UV-warning system and validation of forecasts: Set up of automatic alerting routines for low ozone values in order to issue public warning trough media. System would be prepared for Sentinel 5 precursor data	4.1.2	Could be done now, but should probably be done together with an aerosol alert system and is not recommended for 2012	NILU
Regional scale EMEP monitoring: Establish multi-sensor, multi-parameter trends of key parameters such as CO, SO_2 and NO_2 for the EECCA countries and some eastern European countries with sparse ground based monitoring facilities	4.2.1	Yes. Similar proposed activities for aerosols should wait at least one year until the validation results of the ESA Aerosol CCI project is evident	NILU
Regional scale EMEP Model evaluation: Development of tools for systematic model evaluation against satellites	4.2.2	Yes	met.no
Chemical weather forecasting - trace gases: Assimilation of more gases	4.3	Yes, in coordination with MACC-II	met.no

Proposed activity	Described in section:	Could be started in 2012	To be undertaken by:
Chemical weather forecasting – aerosols: Integration of CALIOP data into AeroCom tools (as preparation for EarthCare)	4.3	Yes	met.no
Numerical Weather forecasting: Comparison analysis of cloud parameters from different NWP models to assess model error properties and identify focus areas for validation with EarthCARE..	4.4	Possibly. Should be started well before launch, but probably not a pressing item yet. (Could possibly be integrated in a IASI moisture assimilation project application.)	met.no
Numerical Weather forecasting: Prepare software tools for EarthCARE-NWP model comparison analysis after launch.	4.4	No. Should be prepared some time before launch.	met.no
Research on Cloud-Aerosol-Radiation interaction	4.5	No. This is foreseen to be a research project that is foreseen to use actual EarthCARE data and the activities must be postponed until about one year ahead of launch.	met.no, NILU and other relevant Norwegian geophysics/climate communities

7 References

Devasthale, A., Thomas, M. A. (2011) A global survey of aerosol-liquid water cloud overlap based on four years of CALIPSO-CALIOP data. *Atmos. Chem. Phys.*, *11*, 1143-1154. doi:10.5194/acp-11-1143-2011

Eckhardt, S., Prata, A.J., Seibert, P., Stebel, K., Stohl, A. (2008) Estimation of the vertical profile of sulfur dioxide injection into the atmosphere by a volcanic eruption using satellite column measurements and inverse transport modeling, *Atmos. Chem. Phys.*, *8*, 3881-3897.

EMEP (2008) Transboundary particulate matter in Europe. Kjeller, Norwegian Institute for Air Research (EMEP/CCC& MSC-W & CEIP Status Report 4/2008).

Fiebig, M., Lunder, C.R., Stohl, A. (2009) Tracing biomass burning aerosol from South America to Troll Research Station, Antarctica. *Geophys. Res. Lett.*, *36*, L14815. doi:10.1029/2009GL038531

Glantz, P., Kokhlanovsky, A., von Hoyningen-Huene, W., Johansson, C. (2009) Estimating $PM_{2.5}$ over Southern Sweden using space-borne optical measurements. *Atmos. Environ.*, *43*, 5838-5846.

Hansen, G., Aspmo, K., Berg, T., Edvardsen, K., Fiebig, M., Kallenborn, R., Lunder, C.R., Stebel, K., Schmidbauer, N., Solberg, S., Wasseng, J.H., Yttri, K.E. (2009) Atmospheric monitoring at the Norwegian Antarctic station Troll: Measurement programme and first results. *Polar Research*, *28*, 353-363.

Heiberg, H., Tsyro, S., Valdebenito, A., Schyberg, H. (2010) Strategic review of satellite products and recommendations for future comparison with model results and data assimilation. Oslo, Norwegian Meteorological Institute (Met.no Note 5/2010).

Huijnen, V., Eskes, H.J., Poupkou, A., Elbern, H., Boersma, K.F., Foret, G., Sofiev, M., Valdebenito, A., Flemming, J., Stein, O., Gross, A., Robertson, L., D'Isidoro, M., Kioutsioukis, I., Friese, E., Amstrup, B., Bergstrom, R., Strunk, A., Vira, J., Zyryanov, D., Maurizi, A., Melas, D., Peuch, V.-H., Zerefos, C. (2010) Comparison of OMI NO2 tropospheric columns with an ensemble of global and European regional air quality models. *Atmos. Chem. Phys., 10*, 3273–3296.

Istomina, L. G., von Hoyningen-Huene, W., Kokhanovsky, A. A., Burrows, J. P. (2010) Retrieval of aerosol optical thickness in Arctic region using dual-view AATSR observations. In: *Proceedings of ESA Atmospheric Science Conference, Barcelona, Spain, 07–11 Sept. 2009. ESA SP-676.*

Istomina, L.G., von Hoyningen-Huene, W., Kokhanovsky, A.A., Schultz, E., Burrows, J.P. (2011) Remote sensing of aerosols over snow using infrared AATSR observations. *Atmos. Meas. Tech., 4*, 1133–1145.

Kahnert, M. (2009) On the observability of chemical and physical aerosol properties by optical observations: Inverse modelling with variational data assimilation. *Tellus B*, *61*, 747-755.

Peters, K., Quaas, J., Bellouin, N. (2011) Effects of absorbing aerosols in cloudy skies: A satellite study over the Atlantic Ocean. *Atmos. Chem. Phys., 11*, 1393-1404. doi:10.5194/acp-11-1393-2011

Read, K.A., Lewis, A.C., Bauguitte, S., Rankin, A.M., Salmon, R.A., Wolff, E.W., Saiz-Lopez, A., Bloss, W.J., Heard, D.E., Lee, J.D., Plane, J.M.C. (2008) DMS and MSA measurements in the Antarctic Boundary Layer: Impact of BrO on MSA production. *Atmos. Chem. Phys., 8*, 2985-2997. doi:10.5194/acp-8-2985-2008

Schaap, M., Apituley, A., Timmernams, R.M.A., Koelemeijer, R.B.A., de Leeuw, G. (2009) Exploring the relation between aerosol optical depth and $PM_{2.5}$ at Cabauw, the Netherlands. *Atmos. Chem. Phys.*, *9*, 909-925.

Simpson, D., Fagerli, H., Jonson, J.E., Tsyro, S., Wind, P., Tuovinen, J.-P. (2003) The EMEP unified eulerian model. Model description. Oslo, Norwegian Meteorological Institute (MSC-W EMEP Status Report 1/2003).

Solberg, R., Bøggild, C.E., Aamaas, B., Trier, Ø.D., Koren, H., Wangensteen, B., Larsen, S.Ø. (2010) Measuring and modelling black carbon in Svalbard - Final results from the PRODEX Black Carbon pilot project. Oslo, Norwegian Computing Center (SAMBA/16/10).

Stebel, K., Fjæraa, A., Johnsrud, M., Vik, A.F., Holzer-Popp, T., Schroedter-Homscheidt, M. (2008) Use of SYNAER data for regional scale air quality assessments in Europe through EMEP. Powerpoint presentation. European Aerosol Conference (EAC2008), 24-29 August 2008, Thessaloniki, Greece. Kjeller, NILU (NILU F, 74/2008).

Stohl, A., Prata, A.J., Eckhardt, S., Clarisse, L., Durant, A., Henne, S., Kristiansen, N.I., Minikin, A., Schumann, U., Seibert, P., Stebel, K., Thomas, H.E., Thorsteinsson, T., Tørseth, K., Weinzierl, B. (2011) Determination of time- and height-resolved volcanic ash emissions and their use for quantitative ash dispersion modeling: The 2010 Eyjafjallajökull eruption, *Atmos. Chem. Phys., 11*, 4333-4351. doi:10.5194/acp-11-4333-2011

Tanré, D., Bréon, F. M., Deuzé, J. L., Dubovik, O., Ducos, F., François, P., Goloub, P., Herman, M., Lifermann, A., Waquet, F. (2011) Remote sensing of aerosols by using polarized, directional and spectral measurements within the A-Train: The PARASOL mission. *Atmos. Meas. Tech.*, *4*, 1383-1395. doi:10.5194/amt-4-1383-2011

Theys, N., Van Roozendael, M., Hendrick, F., Yang, X., De Smedt, I., Richter, A., Begoin, M., Errera, Q., Johnston, P. V., Kreher, K., De Mazière, M. (2011) Global observations of tropospheric BrO columns using GOME-2 satellite data. *Atmos. Chem. Phys*., *11*, 1791-1811. doi:10.5194/acp-11-1791-2011

Tsyro, S. (2009) Further development of AOD observation operator and testing with MODIS data. Oslo, Norwegian Meteorological Institute (Met.no Report 6/2009).

Tsyro, S., Heiberg, H., Klein, H., Schyberg, H., Tarrasón, L., Jonson, J. E. (2007) First results from comparison of model calculated AOD with MODIS data. Oslo, Norwegian Meteorological Institute (Met.no Report 11/2007).

Tørseth, K., Hov, Ø. (2011) Strategy for national satellite related operational support to aviation for volcanic ash avoidance. Kjeller, Norwegian Institute for Air Research (NILU OR 59/2011) (in Norwegian).

Valdebenito B., Á.M., Heiberg, H. (2009) First results from comparison of model calculated tropospheric NO2 column with GOME data. Oslo, Norwegian Meteorological Institute (Met.no Note 12/2009).

Valdebenito B., Á.M., Tsyro, S., Kahnert, M., Heiberg, H. (2010) The EMEP data assimilation system: Technical description and first results. Oslo, Norwegian Meteorological Institute (Met.no Note 4/2010).

Valdebenito B., A.M., Fjæraa, A.M. (2009) Modelled and observed NO_2 tropospheric column and surface concentrations. In: *Transboundary Acidification, Eutrophication and Ground Level Ozone in Europe in 2007*. Oslo, Norwegian Meteorological Institute (EMEP MSC-W 1/2009). pp. 107-109.

Wehr, T., Ingmann, P., Eisinger, M., Lajas, D., Lefebvre, A. (2010) EarthCare: The ESA-JAXA cloud, aerosol and radiation mission. In: *Proceedings of the ESA Living Planet Symposium, 28 June –2 July 2010, Bergen, Norway*. *ESA SP-686.* In press.

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ABSTRACT
A strategy for how Norwegian applied organizations should prepare for the upcoming EarthCARE and Sentinel 5 precursor satellite missions is discussed, and long- and short-term plans are provided. The satellites and their potential products are discussed in terms of possible applications by NILU and met.no and data are considered for operational use in (a) reporting of climate gases, aerosols, ozone and UV to Klif, (b) EMEP reporting on aerosol and acidification/eutrophication, (c) chemical weather forecasting, (d) numerical weather forecasting and (e) research on Cloud-Aerosol-Radiation interaction.

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