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JAXA Japan Aerospace Exploration Agency

7th International EarthCARE Science Workshop - Report -

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Acknowledgment

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Welcome and Introduction

Mr. H.-P. Lüttenberg welcomed the participants as representative of the management of DLR. Mr. M. Borgeaud addressed the workshop on behalf of the ESA Earth Observation Directorate management. Mr. T. Nakajima addressed the workshop on behalf of the JAXA Earth Observation Research Center management.

The EarthCARE satellite was introduced and presented by the ESA EarthCARE Project Manager, Mr. A. Lefebvre, who provided the project overview and programmatic status. The Cloud Profiling Radar (CPR) onboard EarthCARE was introduced and its status presented by the JAXA CPR Project Manager, Mr. E. Tomita. The EarthCARE satellite is the largest and most complex satellite in the ESA Earth Explorer Programme and implemented in cooperation with JAXA, that contributed on of the four scientific instruments, the CPR. The other instrument are the Atmospheric Lidar (ATLID), the Multi-Spectral Imager (MSI) and the Broad-Band Radiometer (BBR). The satellite project was presently in Phase D.

Mr. A.J. Illingworth, University of Reading, and Mr. H. Okamoto, Kyushu University, presented an overview of the science background and expected contribution of the EarthCARE mission. The geophysical data products that will be derived from the mission were presented by Mr. D. Donovan, KNMI, and Ms. R. Oki, JAXA. The EarthCARE satellite will address how clouds and aerosols influence the incoming solar and reflected/emitted terrestrial radiation. For this purpose, vertical profiles of ice and liquid water in clouds are being retrieved from the backscattered radar and lidar signals and vertical aerosol profiles are determined from the lidar. Additional information is derived from the collocated imager channels. These synergistically derived products, collocated with the nadir-pointing geometry of the active instruments, are expanded into the across-track dimension using the swath information of the imager. Radiative transfer calculations are used to determine the radiative properties – heating rates, radiances and radiative fluxes – and assessed against the observations of the Broad-Band-Radiometer. A complex advanced data retrieval system exploiting the synergy of the four satellite instruments is being developed in Europe, Canada and Japan, so that the scientific satellite data exploitation can commence soon after the satellite has been launched.

The introductory session was followed by four dedicated sessions plus a Panel Discussion to solicit the community feedback and recommendations.

Session 1: Process Studies

Chairs: R. Hogan, T. Nakajima

This session consisted of six talks that explored how the new observational capabilities of EarthCARE will offer new insights into cloud, precipitation and aerosol processes. They all highlighted the value of careful analysis of existing ground-based, airborne and satellite data to better understand relevant meteorological and particle-scattering processes, which will feed into a better interpretation of the new EarthCARE measurements when available. The talks were followed by a discussion that covered a wider array of processes for which EarthCARE will provide valuable data, such as convection, and ways in which EarthCARE could be used to evaluate these processes in models.

- *Warm clouds and rain formation*: Keynote speaker T. Y. Nakajima described how the combination of radar reflectivity from CloudSat and optical depth from MODIS elucidated details of the formation of drizzle and rain from shallow clouds, and how "CFODD" diagrams could be used to evaluate models over land and ocean. Further information was available from the effective-radius estimates by different near-infrared wavelengths that are sensitive to different depths into the cloud. EarthCARE's Doppler capability, combined with geostationary imagery to provide context, will add crucial extra information on updrafts and rain rates to better understand cloud life cycles. J. Bühl described how cloud-top temperature provided insights into the mechanisms of rain formation in different parts of the globe, and how such analysis would be improved by the use of EarthCARE's Doppler radar.

- *Mixed-phase clouds and snow*: There is an urgent need to be able to make quantitative estimates of snowfall from space, but current algorithms, even those using radar, are subject to large errors. Retrievals are made more complicated by the fact that snow typically falls from mixed-phase clouds, and the growth of snowflakes may be by aggregation, deposition or riming. S. Mason and D. Moisseev showed how the process of riming changes the radar reflectivity and Doppler velocity of snow, and how riming was linked to the amount of supercooled water in the cloud. We should therefore expect EarthCARE's Doppler radar to significantly improve our understanding of mixed-phase cloud and precipitation processes, as well as enabling more accurate retrievals of snowfall rate.

- *Particle scattering properties*: A key strength of EarthCARE will be the synergy of instruments with different wavelengths on the same platform, but correct interpretation of these measurements will require consistent and realistic particle scattering models, particularly for ice and snow particles. L. Bugliaro reported reasonable agreement between airborne radar-lidar retrievals of ice effective radius and optical depth with solar-radiance retrievals, but larger differences compared to in-situ estimates. D. Moisseev highlighted the difference between radar backscattering using different assumptions about snowflake morphology, also emphasizing the need to improve our understanding of scattering processes if retrievals are to be reliable.

- *Aerosols*: A. Devasthale described the use of CALIPSO to understand the different transport pathways of aerosol pollution into the Arctic. The HSRL capability of ATLID will provide crucial new information on aerosol type and extinction coefficient, and therefore be of interest for work, such as this, that is concerned with the interplay of aerosols with weather and climate processes. Aerosol typing gives us a much better handle on solar heating of the atmosphere, which is known to impact the evolution of monsoon and other weather systems, but could also be used to evaluate chemical transport models. As mentioned by T. Y. Nakajima and J. Bühl, EarthCARE's aerosol measurements could also help us to better understand aerosol-cloud-precipitation interactions.

The following oral presentation were given:

T. Nakajima, Key Note: Observing the cloud evolution process by using passive and active spaceborne sensors such as EarthCARE, A-Train, and Himawari-8

L. Bugliaro, Interpretation of passive geostationary microphysical properties of ice clouds using synergistic lidar-radar observations

S. Mason, The diagnosis of mixed phase cloud and estimates of aggregation and riming rates from Doppler radar

D. Moisseev, Parametrization of falling snow microphysical and scattering properties for W-band radar retrievals

J. Bühl, Combined lidar and radar observations of the relationship between cloud-top temperature, in-cloud dynamics and rain rate

A. Devasthale, How do temperature inversions control aerosol vertical distribution in the Arctic during polar winter?

Session 2: Observational Techniques

Chairs: T. Nishizawa, U. Wandinger

The session on observational techniques dealt with a variety of synergistic instrumental approaches and retrieval algorithms focusing on the exploitation of EarthCARE-like observations of clouds, aerosol and radiation. Two keynote speeches demonstrated the high potential of active remote sensing from space for Earth system and climate research. Based on CALIPSO/CloudSat results, D. Winker emphasized the importance of long-term synergistic observations to identify, understand, and characterize cloud-climate feedbacks and to characterize key modes of climate variability. Only the combination of active sensors allows us to observe vertical cloud structures, to characterize cloud-aerosol-precipitation processes and to reveal the linkages between clouds and circulation. EarthCARE is critical in extending and improving the long-term data records that have been started with CALIPSO and CloudSat. In her keynote presentation, H. Chepfer discussed in particular the importance of long-term lidar observations of cloud top heights to constrain uncertainties on cloud feedbacks, since the sign and amplitude of cloud feedbacks is a major source of uncertainty for future climate prediction.

From the various contributions to this session and dedicated discussions thereafter, a number of challenges and needs for further development and validation activities have been identified.

- *Instrument continuation*: EarthCARE provides the opportunity to continue long-term measurements as started with CALIPSO/CloudSat, which are strongly needed to observe trends in a changing climate (Winker et al., Chepfer et al.). A long-term parameter continuity is required, and therefore we should already now plan beyond EarthCARE. Observational gaps of more than 2 years without intercalibration between missions must be avoided. Passive instruments may help to cover gaps. Polarimetry has a high potential to improve the synergy of active and passive instruments in future.
- *Shallow clouds*: Changing atmospheric circulation patterns might become visible not only in increasing top heights of deep convection, but also in changing shallow tropical cumulus and stratocumulus clouds. Shallow cloud feedbacks depend on the balance of a competition between weakening turbulent mixing and strengthening convective mixing. Lidar monitoring of trends in the vertical structure of shallow clouds can constrain model estimates of cloud changes starting after about 20 years of observation (Winker et al., Chepfer et al.).
- *Ice clouds*: The radiative impact of ice clouds as well as the retrieval of ice cloud properties strongly depend on the ice-crystal microphysics. Therefore, realistic microphysical models and synergistic retrieval techniques, also considering more than the four EarthCARE instruments, are required. Active sensors can help in developing better imager algorithms, while geostationary imager data provide better global and temporal context for the polar-orbiting instruments (Strandgren et al.). Radiative closure studies using imager measurements of solar radiation can help constrain combined lidar-radar retrievals of ice cloud properties (Ewald et al., Bozzo et al.). Retrieval schemes that include lidar measurements also need to consider multiple-scattering effects properly (Okamoto et al.). New synergies by using radar and sub-millimeter Ice Cloud Imager (ICI) are being exploited (Duncan et al.).
- *Best-estimate retrievals and validation efforts*: Synergistic approaches often rely on best-estimate retrievals (Bozzo et al., Ewald et al.). Such challenging methods require an in-depth validation. Ground-based and airborne campaigns can help in acquiring datasets for algorithm evaluation and prepare for EarthCARE calibration and validation activities (Cazenave et al., Ewald et al., Groß et al.). The agencies should use opportunities resulting from big field campaigns.
- *Exploitation of the CPR Doppler capability*: The Doppler capability of the EarthCARE CPR will provide new insight into deep convection. However, space-borne Doppler radar observations are challenging and require adequate consideration of the impact of aliasing and non-uniform beam filling in the retrieval algorithms. An accuracy of better than 1–2 m/s can be reached above the freezing level, if the pulse repetition frequency is > 7000–7200 Hz (Kollias et al.).
- *Aerosol retrievals*: Aerosol radiative properties are type-dependent. Thus, proper aerosol classification is required in order to calculate aerosol radiative effects. Lidar measurements of particle depolarization ratio, lidar ratio and spectral

extinction/backscatter coefficients, as well as synergistic lidar/imager retrievals of spectral AOD, can be used for aerosol typing (Kudo et al.). Since the optical aerosol properties strongly depend on wavelength, a harmonization between CALIPSO observations at 532/1064 nm and EarthCARE observations at 355 nm is required for long-term atmospheric studies.

- *Small-scale problems*: Uncertainties in both cloud feedbacks and indirect aerosol forcing involve processes acting on broken clouds at small spatial scales. Retrievals at best possible horizontal and vertical resolution are needed to minimize sampling uncertainties (Winker et al., Tornow et al.).

The following oral presentation were given:

D. Winker, Key Note: Lidar Observations as Climate Data Records

J. Strandgren, From collocated spaceborne lidar-imager observations to the geostationary remote sensing of thin cirrus clouds and the anvil cirrus life cycle

Q. Cazenave, Comparison of airborne configurations in a radar-lidar retrieval technique as a preparation for EarthCARE

F. Eward, How Solar Reflectance can be used to improve a Variational Radar-Lidar Retrieval for Ice Clouds

A. Bozzo, A synergistic "best estimate" retrieval of clouds, precipitation and aerosol for EarthCARE, and its planned use in evaluating the ECMWF forecast model

H. Okamoto, Observations of cloud- and precipitation-microphysics and vertical motion

P. Kollias, The EarthCARE CPR Doppler measurements in Deep Convection: Challenges, Post-Processing and Science Applications

D. Duncan, Radar Sub-Millimeter Synergy

F. Tornow, EarthCARE’s Broadband Radiometer: Unforeseen Sampling Uncertainties Associated with Cloudy Atmospheres

H. Chepfer, Key Note: The potential of a multi-decades space-borne lidar record to constrain cloud feedbacks

S. Groß, EarthCARE-like measurements on the research aircraft HALO for preparation and validation studies

R. Kudo, Global 3D distributions of aerosol components retrieved by synergy of CALIOP and MODIS

Session 3: Modelling

Chairs: J. Cole, K. Suzuki

Within this session presentations were given that touched on three aspects linking models to space-based Earth observations in an effort of constraining cloud-relevant uncertainties in global models. Cloud properties from CALIPSO are the basis of one such analysis which partitioned contributions to longwave cloud feedback and evaluate this feedback in a single global climate model (GCM). Contrary to previous studies, and the GCM, longwave cloud feedback is found to be mainly due to changes in opaque cloud fraction changes rather than changes in cloud top height [Guelis et al., 2018].

Two presentations illustrated the utility of active and passive cloud observations for evaluation of simulated cloud microphysics. One presentation illustrated a methodology in which a combination of radar and imager observations was used to diagnose warm cloud processes which were used to constrain their representations in a particular climate model. Such process-oriented constraints, however, turned out to produce unrealistically large aerosol indirect forcing, exposing compensating errors in the model that is amplified through aerosol-cloud interplay [Jing and Suzuki, 2018]. The second presentation used active and passive observations to evaluate mixed-phase clouds in their phase partitioning simulated over the Southern Ocean in NICAM as a method to guide model development. The single- and double-moment microphysics schemes in NICAM are evaluated against satellite measurements to seek a way for improving the single-moment approach based on more realistic double-moment results.

The final two presentations of the session summarized research results from ECMWF to assimilate space-based radar and lidar data into their forecast model in preparation for the launch of EarthCARE [Janisková and Fielding, 2018]. In order to incorporate the data into the assimilation system several technical issues needed to be overcome. This included developing a sufficiently fast and accurate operators, accounting for subgrid-scale cloud variabililty and associating observation errors to the data. A side benefit of incorporating the radar and lidar data into the assimilation system is that it is included in the automatic data monitoring system, which can provide information about changes to the quality of the data. With the data being assimilated into the ECMWF global weather prediction, model tests were performed to assess the impact of the new observations. A positive impact was found on short-term forecasts in the period August 2007 with a notable improvement in tropical rainfall rates. These initial results of better forecasts suggest that future studies may further improve and optimize the assimilation of EarthCARE cloud radar and lidar data at ECMWF.

Reference:

Guelis, T. V., H. Chapfer, R. Guzman, M. Bonazzola, D. M. Winker, and V. Noel, 2018: Space lidar observations constrain longwave cloud feedback. *Sci. Rep.*, **8:16570**, doi:10.1038/s41598-34943-1.

Janisková, M. and M. Fielding, 2018: Operational Assimilation of Space-borne Radar and Lidar Cloud Profile Observations for Numerical Weather Prediction (Report no. WP-6000:

Conclusions and recommendations). Retrieved 23 December 2018 from https://www.ecmwf.int/en/elibrary/18500-operational-assimilation-space-borne-radar-and-lidar-cloud-profile-observations.

Jing, X., and K. Suzuki, 2018: The impact of process-based warm rain constraints on the aerosol indirect effect. *Geophys. Res. Lett.*, **45**, 10729-10737, doi:10.1029/2018GL079956.

The following oral presentation were given:

H. Chepfer, Space Lidar observations constrain longwave cloud feedback

W. Roh, Evaluation of microphysics in mixed-phase clouds over the Southern Ocean in NICAM using Joint simulator

K. Suzuki, Exploring a dichotomy between process-based constraint and energy-balance requirement on aerosol-cloud interaction in climate modeling

M. Fielding, The ECMWF observation operator for direct 4D-Var assimilation of cloud radar reflectivity and lidar backscatter: developments and its use for monitoring

M. Janiskova, Experimental 4D-Var assimilation of space-borne cloud radar and lidar observations in advance of EarthCARE

Session 4: Radiation

Chairs: K. Suzuki, N. Clerbaux

The "Radiation" session was introduced with a key note presentation about radiative heating rate in the atmosphere by Dr. S. Kato from the CERES team (NASA Langley Research Center). The session then pursued with 5 presentations encompassing a large panel of studies combining passive and active instruments. All those contributions confirmed the interest of the EarthCARE's payload to address several key scientific challenges linked to the effect of radiation, either shortwave or longwave, in the climate system.

Atmospheric heating rate is a key element in the climate system. However, it is not directly measured by satellite. Satellite broadband observations provide Top Of Atmosphere (TOA) measurements acting as boundary conditions when retrieving the atmospheric heating rate and/or the surface radiative budget. The retrieval involves necessarily a radiative transfer modeling step over the (reconstructed) scene as observed from passive and active instruments.

For a long time, atmospheric heating rates have been estimated from passive instruments only. During the key note presentation, Dr. Kato, showed some limitations of the heating rate climatology when obtained with only passive instruments (in the study MODIS cloud properties). An advantage of using active instrument observations, from CloudSat and CALIPSO, is the suppression of the heating and cooling peak "artifacts" that are modeled at the altitudes of the cloud base and top that serve to define the cloud type. Another big advantage of active instrument's observations is the possibility to investigate radiative effect of multi-layers cloudiness which is usually not possible with passive instrument technologies. In a contribution, Dr. Devasthale (SMHI, Sweden) used 4 years of CALIPSO and CloudSat data to quantify the radiative effects of two-layer cloud systems. In general, high level thin clouds, like cirrus, are known to present a radiative heating effect due to the strong longwave absorption and the limited shortwave effect. The study presented by Dr. Devasthale showed that, in case of underlying optically thick cloud, the heating rate of this type of cloud can be completely suppressed. The separation in altitude between the cloud layers seems to play a major role: when this distance is less than 4 kilometers, the radiative effect of cirrus turns from warming to cooling.

Radiation is also known to have some effect on the available eddy potential energy. Dr. Kato showed that the longwave cooling at the top of the stratocumulus clouds contributes to the generation of eddy available potential energy. Similarly, the West-East contrast in temperature between land and ocean is a factor contributing to the generation of potential energy through the longwave heating rate. Many contributions recognize the importance of aerosol in atmospheric heating rate, and the high variability of this key element of the climate system.

The active instruments pairs like the CALIPSO+CloudSat (and the future EarthCARE CPR+ATLID) provide however a limited spatial coverage and synergetic use of passive instrument data is still highly profitable. Dr Feofilov (UPMC/LMD, France) showed how the active instrument data can be combined with hyperspectral radiometers like IASI and AIRS. The synergetic approach has been used to estimate IWC(z), the profile of the Ice Water Content and the effect on the radiation budget at the TOA and the surface, as well as the atmospheric heating rate. Furthermore, it is stressed that the synergy with passive instruments (in this case IASI in a morning orbit and AIRS in the afternoon) could be useful to resolve the diurnal cycle of many important atmospheric processes.

For EarthCARE, the radiation profiles will be validated by comparison with the BBR TOA radiances and fluxes products. Additional validations are also foreseen at the surface, by comparison with pyranometer stations. An interesting contribution about the spatiotemporal variability of the surface solar irradiance is presented by Dr. Deneke (Tropos, Germany). A network of 99 pyranometers has been deployed to cover an area similar to the future EarthCARE's standard footprint (10km x 10km). Several months of data have been acquired and provide several implications for closure assessment and also for EarthCARE radiative profile validation.

Finally, the estimation of the reflected solar and emitted thermal fluxes from the 3-views EarthCARE BBR radiometer is summarized by Dr. Domenech. Validation of the part of the EarthCARE ground segment (namely the BMA-FLX processor) is presented and discussed.

The following oral presentation were given:

S. Kato, Key Note: Radiative heating rate computed with clouds derived from satellite based active and passive sensors and their effects on generation of eddy available potential energy.

A. Devasthale, The radiative impact of double layered cloud systems in the tropical upper troposphere and lower stratosphere.

A. Feofilov, Radiative effects of clouds from the synergy of active and passive satellite instruments: missing elements of puzzle.

F. Szczap, The McRALI Monte Carlo simulator to evaluate (HSR) lidar and (Doppler) radar observables in 3D cloudy atmospheres: Application to EarthCARE mission.

H. Deneke, Spatiotemporal variability of solar irradiance at the surface: Implications for radiative closure at the surface.

C. Domenech, Solar and thermal radiative flux estimation for the EarthCARE BBR instrument: Analysis of results.

Posters

The oral introductory session on the satellite and data products was supported by 30 poster presentations. The posters provided details on the instruments and their level 1 data products, the Ground Segment, the ESA end-to-end EarthCARE Simulator and the Japanese Joint-Simulator, and in particular on the numerous geophysical data products and their retrieval techniques.

The science sessions 1 to 4 were supported by 18 poster presentations, addressing additional science preparatory activities, science activities in the EarthCARE context and expected EarthCARE contributions.

Special Contributions

F. Seidel, NASA, presented the outcome of the NASA 2017 Decadal Survey with regards to the recommendations on aerosol, cloud, convection and precipitation observables.

T. Tremas, CNES, discussed the support CNES is providing to the French research community for science activities related to EarthCARE.

D. Lajas, ESA, introduced the EarthCARE Simulator, a tool developed by ESA for end-to-end simulation of the EarthCARE performance, from the definition of an atmospheric scene, through radiative transfer modelling and Satellite instrument data processing to the retrieval of geophysical data products. The geophysical retrieval processors, developed by the European and Canadian science groups are used by the simulator and are fully compatible with both the simulator and the actual ESA Payload Data Ground Segment. The EarthCARE Simulator is available to algorithm developers and will become available for scientific mission users.

Panel Discussion and Recommendations

Chairs: A.J. Illingworth, H. Okamoto

The importance to visualize temporal evolution of clouds was discussed. The participants agreed that simultaneous observations of the Himawari-8 and EarthCARE are expected to reveal the evolution of cumulus clouds as demonstrated by Dr. Takashi Nakajima. Remaining open question whether we can expect this analysis to convective clouds was also identified. Applicability of closure study of cloud microphysics using radar/lidar and imager was revisited and there exists a difficult case when ice cloud on top with water cloud below, as demonstrated by Dr. Luca Bugliaro.

Importance of Doppler capability from EarthCARE on snow microphysics was discussed and it is conclude that it will provide significant insights into snow and heavy snow with riming and also will retrieve snow fall much better than previous space-borne sensors, as demonstrated by Dr. Shannon Mason and Dr. Dmitri Moisseev.

Possibility to study interaction of aerosols and cloud/precipitation by EarthCARE for future climate prediction was discussed. As Dr. Johannes Buehl suggested, EarthCARE Doppler information can disentangle the global picture of role of aerosols and in cloud vertical air motion for rain formation. Dr. Manu Anna Thomas (presented by Dr. Abhay Devasthale) successfully showed that temperature inversion controls aerosol vertical structure in Arctic winter. Since aerosol layers are predominant below 1 km in Arctic, we concluded that vertical resolution of 100 m of EarthCARE will play a critical role.

Constraints on climate models that will be achieved by EarthCARE was discussed. Dr. David Winker emphasized a strong need to have a continuous long-term data records of global cloud vertical structure for contribution to a grand challenge: how fast will the Earth warm, what will be the regional impacts and what is the coupling of clouds to atmospheric circulation such as cloud-response to ENSO. Since cloud top heights from active and passive sensors are different and also the NUBF effect should be corrected for the interpretation of active sensors signals, we need further studies. Combination of Geo-stationary satellite and EarthCARE was further discussed for evolution of anvils as presented by Dr. Johanne Strandgen. In 2021, 1km resolution by MTG will be available in time for EarthCARE launch so that there is a great chance to achieve same horizontal resolution of 1km between EarthCARE and Geostationary satellite.

It was also discussed about the possible additional information when the two air-borne HSRLs at 355nm and 532nm are available. To conclude the information content for the case needs to more flights with HSRLs and in situ and ground-based HSRL studies, as suggested by Dr. Quitterie Cazenave.

Difficulties in retrieval of LWC in mixed phased clouds were discussed as presented by Dr. Floran Ewald and was identified to be difficult and uncertainties leaded to 1.5W/m2 and to be an observational gap. The topics needs more intensive studies.

Evaluation of ECMWF by EarthCARE data was discussed as demonstrated by Dr. Alessio Bozzo. Accurate retrievals need to have a good knowledge to PIA of the bright band as also for GPM. We concluded observations are needed.

Multiple scattering in space-borne lidar was discussed. As demonstrated by Dr. Hajime Okamoto, the multiple-field of view multiple scattering lidar can penetrate optically thicker clouds and to infer droplet size, to have such functions for future spaceborne lidar seems to be a good idea.

Correction of satellite vertical motion, NUBF, Aliasing, Multiple scattering in CPR was discussed. PRF of 7500Hz could correct all of the issues as Dr. Pavlos Kollias showed. Synergy of sub-millimetre radiometer ICI onboard MetOp Second Generation that is scheduled to be launched in 2022, and EarthCARE was discussed. Ice water path from submm radiometer will be an additional constrain for EarthCARE retrievals as suggested by Dr. Dave Duncan.

We also discussed about the beam filling problem for the BBR in relation chopper speed. Verification was required whether MSI can identify NUBF in BBR and correct.

Recommendations

1. *HSRL-Doppler radar synergy*. More simultaneous observations with high spectral resolution lidar (HSRL) and Doppler radar from aircraft and ground based platforms are needed to establish the accuracy and reliability of the retrieved products, in particular the retrievals of optical depth from the HSRL.
2. *Optical depth from the integrated ATLID backscatter from the ocean*. Should this be a new EarthCARE level 2 product to provide an additional constraint to the HSRL optical depth? It should be fairly easy to retrieve.
3. *Optimum Doppler pulse repetition frequency*. Examine the trade-off between operating the Doppler radar at 7.2 -7.5 kHz for more accurate Doppler velocities or at lower frequencies with less accuracy but increased maximum altitude
4. *Doppler and microphysical retrievals*. What Doppler accuracy and with what spatial resolution is needed to improve the retrievals of snowfall, riming, drizzle rainfall and ice cloud properties?
5. *Radar attenuation by the (melting layer) bright band*. 94GHz observations at the ground could quantify this parameter. Currently, model values are used.
6. *Aerosol extinction*. A study is recommended for the components of the aerosol extinction retrieval and how they depend on aerosol model assumptions.
7. *Data assimilation (DA) studies*. DA studies at ECMWF have shown positive impact of CloudSat/Calipso data on forecasts (e.g. of tropical rainfall). Need to continue such work to enable DA of EarthCARE data with latest model versions.
8. *How is radiative heating linked to dynamics?* Can only answer with a model because latent heat is important. The SW aerosol heating profile depends on (uncertain) SSA. Can we estimate SSA from lidar aerosol classification schemes? How do aerosol extinction retrievals depend on aerosol model assumptions? The extra 7dB radar sensitivity should lead to more accurate heating profiles of tropical high cirrus – but by how much? How much ground clutter from the radar? Observations of cloud base at

lower altitudes would improve accuracy of down-welling LW radiation estimates. Radar observations closer to the ground would improve rainfall and snowfall estimates (see pt. 4).

9. *Radiative impact of thin (<300m) layers of super-cooled water at the top of stratiform ice clouds.* The global impact is significant, but observations are difficult; they attenuate the lidar and do not fill the depth of the radar pulse.
10. *Synergy with Himawari 8*. Can we study the evolution of convective clouds?
11. *LEVEL 3 products*. Need to define these. Are they intended to inform NWP parameterisation schemes and/or to adjust retrieval algorithms?
12. *Continuation of CloudSat/Calipso data sets*. To achieve continuity we need to consider how to account for the different sampling of EarthCARE. Do we have the ability with Atlid to detect climatological shifts of cloud top height to within a few metres per decade?