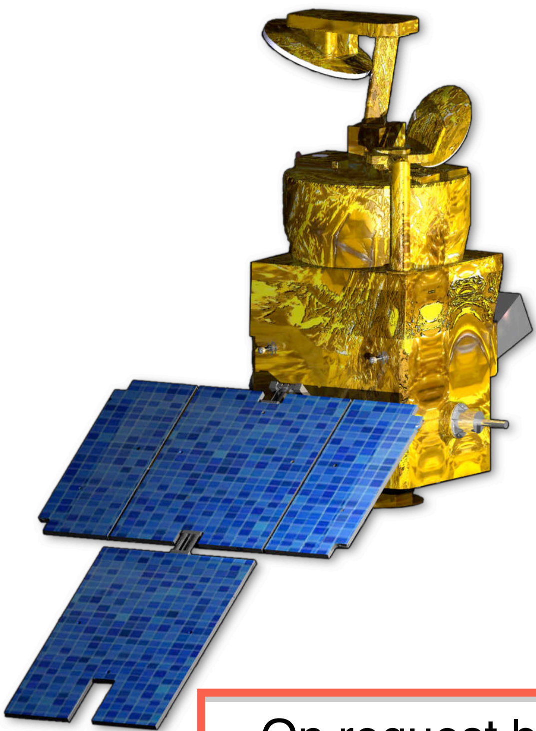
CloudIce

A Proposal for Earth Explorer Opportunity Mission EE-8

June 1, 2010

Stefan Buehler and the CloudIce Mission Community



On request by Astrium-SAS, this public copy of the proposal is lacking the technical and programmatic sections 5 and 6.

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2 Executive Summary

2.1 Scientific Objectives

The CloudIce mission will deliver urgently needed global data on ice clouds, particularly on the so far poorly characterized 'essential climate variable' ice water path (IWP) and on the characteristic cloud ice particle size.

It will deliver data with near global spatial coverage every 24 hours, and on a spatial scale consistent with future global climate models, to both evaluate and improve the models.

It will also demonstrate the benefit of submillimeter observations for precipitation retrieval, an important step towards a possible future deployment of submillimeter radiometers in a geostationary precipitation mission.

2.2 Mission Requirements

Besides the calibrated radiances themselves, the core data products of CloudIce will be cloud ice water path (IWP), particle size (Dme), and cloud altitude (Zme). See Table 2.1 for brief definitions and accuracy requirements for these products. It also lists mission requirements for spatial and temporal resolution and coverage.

Besides the core products, which are used for mission sizing, a larger range of products will be produced on a best-effort basis. These include vertical profiles of humidity and vertical profiles of five different hydrometeor species (cloud ice, graupel, snow, rain, cloud liquid), as well as the non-profile quantities precipitation rate and total column water vapor.

Table 2.1: Scientific mission requirements for a passive submillimeter-wave cloud ice mission from *Buehler et al.* [2007]. The accuracy requirement for IWP is the maximum of relative accuracy and threshold for each IWP value. The horizontal resolution requirement assumes continuous coverage, which requires an appropriate footprint overlap.

Parameter	Requirement [target-threshold]	Remark
IWP accuracy	10-50% relative with 1-10 g/m^2 threshold	The total vertical column of cloud ice.
Zme accuracy	100-500 m	The median IWP altitude, representative for the altitude where most of the cloud mass is located.
Dme accuracy	10-50 μm	The median mass equivalent sphere diameter, a size parameter related to the particle mass, not the cross-section.
Spatial coverage	Global/near global	For global climate model evaluation.
Horizontal resolution	5-20 km	Assuming continuous coverage.
Diurnal sampling	Fixed local time (± 0.5 h)	To avoid aliasing of the diurnal cycle.
Observation cycle	6-24 h	At least one measurement per day, in order to derive monthly climatologies.
Delay	1-4 h	For NWP.
Observation time period	7-1 years	Goal is one ENSO cycle.

Table 2.2: **CloudIce channel specifications and radiometric requirements.**

#	Center freq. GHz	Freq. offset GHz	Bandwidth MHz	Pol.	NeΔT K
1	183.31	0.20	200	V	2
2		1.00	500	V	1.5
3		3.00	1000	V	1
4		5.00	1500	V	1
5		7.00	2000	V	1
6		11.00	3000	V	1
7	243.20	2.50	3000	V	1.5
8				H	
9	325.15	1.50	1600	V	1.5
10		3.50	2400	V	1
11		9.50	3000	V	1
12	448.00	1.40	1200	V	2
13		3.00	2000	V	1.5
14		7.20	3000	V	1.5
15	664.00	4.20	5000	V	1.5
16				H	

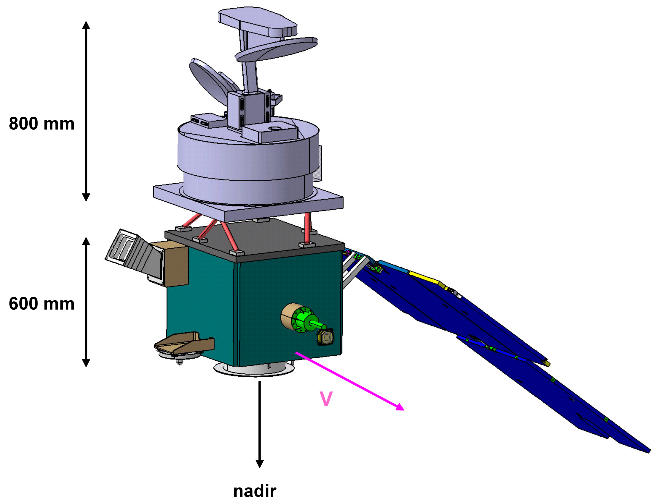


Figure 2.1: **A picture of the CloudIce satellite.**

2.3 Observation Technique

The CloudIce mission has only one scientific instrument, a conically scanning submillimeter radiometer, with channels as summarized in Table 2.2. Submillimeter-wave observations at different wavelengths are necessary to obtain information about ice particle size, which is implicitly needed for the ice water path retrieval, but also interesting in its own right. The instrument has several channels around each observed water vapor line. These channels, sounding different altitudes in the atmosphere, are used to obtain vertical information. Simultaneous infrared data has a large benefit for the data analysis and interpretation. CloudIce will therefore fly in formation with an operational meteorological satellite, Metop-C.

2.4 Instrument Concept

The company Astrium SAS has derived a strawman instrument and mission concept, and has confirmed its feasibility within the required budget envelope with the required technology readiness level. The instrument is a rotating 16-channel radiometer, placed on the zenith floor of a standard microsatellite platform of the 200 kg class (Myriade type). The main reflector size is 32 cm, channels are separated by a quasi-optical network, and detected with heterodyne receivers. A picture of the instrument, together with the satellite is shown in Figure 2.1.

2.5 Mission Elements

The CloudIce mission consists of a single satellite, carrying the CloudIce radiometer. It is flying in formation with Metop-C, roughly 2.5 minutes behind the Metop satellite, leaving the place in front of Metop to the PREMIER mission. Launch can be with a range of launchers, due to the relatively small satellite size. The ground segment is simple and standard.

About this document:

- **Sectioning** follows the instructions in the ESA call (Sections 1-6).
- The **technical sections** 5 and 6 were provided by Astrium SAS.
- **References** are given in Annex 7.1.
- **Acronyms** are not always properly defined (to keep the text compact). Instead, we give a comprehensive list of acronym definitions in Annex 7.2.
- **Contributing authors** are listed in Annex 7.3.
- Two **data user statements** are included in Annex 7.4, as supplementary material to the use cases described in Section 3.6.
- Some **support letters** are included in Annex 7.5.

3 Scientific Objectives, Requirements and Justification

3.1 Mission Objectives

3.1.1 Importance of Cloud Ice Measurements

Clouds play a crucial role for the climate on planet Earth. They are also a major source of uncertainty in climate predictions, as affirmed by the most recent fourth assessment report by the Intergovernmental Panel on Climate Change [*IPCC*, 2007]. The report states that:

> 'In many climate models, details in the representation of clouds can substantially affect the model estimates of cloud feedback and climate sensitivity [...]. Moreover, the spread of climate sensitivity estimates among current models arises primarily from inter-model differences in cloud feedbacks [...]. Therefore, cloud feedbacks remain the largest source of uncertainty in climate sensitivity estimates.'

Particularly large uncertainties are associated with those clouds that consist partly or entirely of ice particles [e.g., *Stephens et al.*, 1990; *Wendisch et al.*, 2005; *Penner*, 2004]. The microphysical formation mechanisms of cloud ice particles are less well understood than those of liquid droplets. Also, ice particle shapes and physical properties vary widely, complicating their interaction with radiation.

At the same time, there is a lack of reliable global measurements of cloud ice for climate model evaluation. As a consequence, different climate models exhibit large discrepancies in their cloud ice water content fields [*Waliser et al.*, 2009]. For example, as shown by Figure 3.1, which is from a recent study by *Eliasson et al.* [2010], the annual zonal mean ice water column at 60° North ranges from approximately 15 to approximately 400 g/m^2 for the climate models that participated in the fourth assessment of the IPCC [*IPCC*, 2007].

The existing space-based measurement capabilities, mostly by infrared and visible instruments, provide important information on the radiation effect of ice clouds. However, with the exception of radar measurements, which are discussed below, it is inherently difficult to relate these measurements to the bulk mass of ice, which is a basic climate model parameter, the parameter that can be linked to other stages of the water cycle by the requirement of total water mass continuity. We therefore argue that there is a particular need for cloud ice mass measurements.

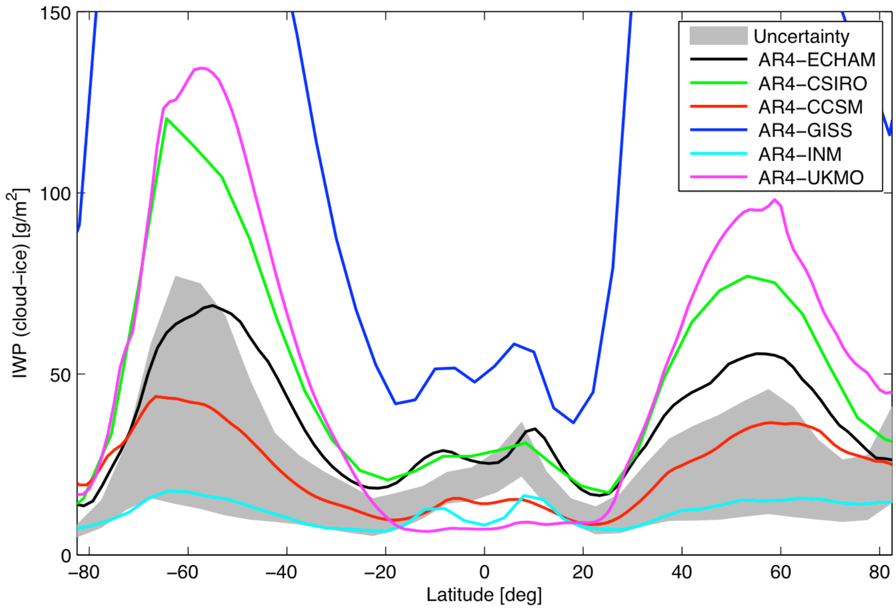


Figure 3.1: Zonal averages of IWP for climate models from 100 years of monthly mean data. The upper and lower limits of the uncertainty range (grey shaded region) are based on a combination of CloudSat measurement uncertainties and the fraction of cloud-only ice mass to total column ice mass of two models presented in Waliser et al. (2009). A factor of 0.5 has been applied to AR4-GISS, in order to make it visible in the domain of this figure. Figure from *Eliasson et al.* [2010].

The need for ice mass measurements is demonstrated for example by a recent study by *Mitchell et al.* [2008], who find that

> '[...] the direct effect of ice particle size on cirrus radiative properties may be secondary to its effect on ice fall speed and subsequent impacts on the global radiation budget. Since fall velocities depend on an ice particle's mass and area cross-section, these properties need to be well characterized in cirrus clouds. Currently ice particle mass is poorly characterized.'

This has also been recognized by the World Meteorological Organization (WMO), which classifies the total column of cloud ice (also called ice water path, IWP) as one of the essential climate variables (ECV) in the framework of the Global Climate Observing System (GCOS) [*WMO*, 2006].

Infrared measurements can provide IWP data and particle size information for relatively thin cirrus clouds [*Stubenrauch et al.*, 2004], but not for IWP exceeding approximately 100 g/m^2.

3.1.2 Advantages of Submillimeter Sensors

Active radar systems and passive millimeter/submillimeter instruments provide data that are directly related to the bulk mass of ice in an ice cloud. The two techniques are highly complementary. Radars, such as the CPR instruments of CloudSat and EarthCARE, provide high vertical resolution at the cost of poor horizontal coverage. Their main measurement uncertainties for ice mass are connected to unavoidable assumptions on the particle size distribution, and to assumptions on the radar signal attenuation in thicker clouds.

Figure 3.2 illustrates the horizontal coverage for radar data. It shows CloudSat IWP climatologies for different time periods and grid resolutions. Quite long time periods and quite coarse grid resolutions are necessary to bring down the sampling error (the 'noise' in the images) to an acceptable level. The reason for this is that the radar samples only directly below the satellite and does not do any horizontal scanning. Another way to express this is to note that CloudSat measurements cover an area of roughly 12 km^2/s, whereas CloudIce measurements will cover an area of roughly 10,000 km^2/s.

Passive millimeter/submillimeter sensors can provide continuous near-global coverage on a daily basis, at the cost of a poor vertical resolution. If suitable frequencies are chosen, these measurements sample different parts of the ice particle size spectrum. The reason for this is that high frequencies interact more strongly with small particles, whereas low frequencies interact more strongly with large particles (see Figure 4.3). A combination of channels at different frequencies therefore allows an estimation of the particle size, and thus also a more accurate estimation of the total ice mass.

3.1.3 Summary of Mission Objectives

The CloudIce mission will deliver urgently needed global data on ice clouds,

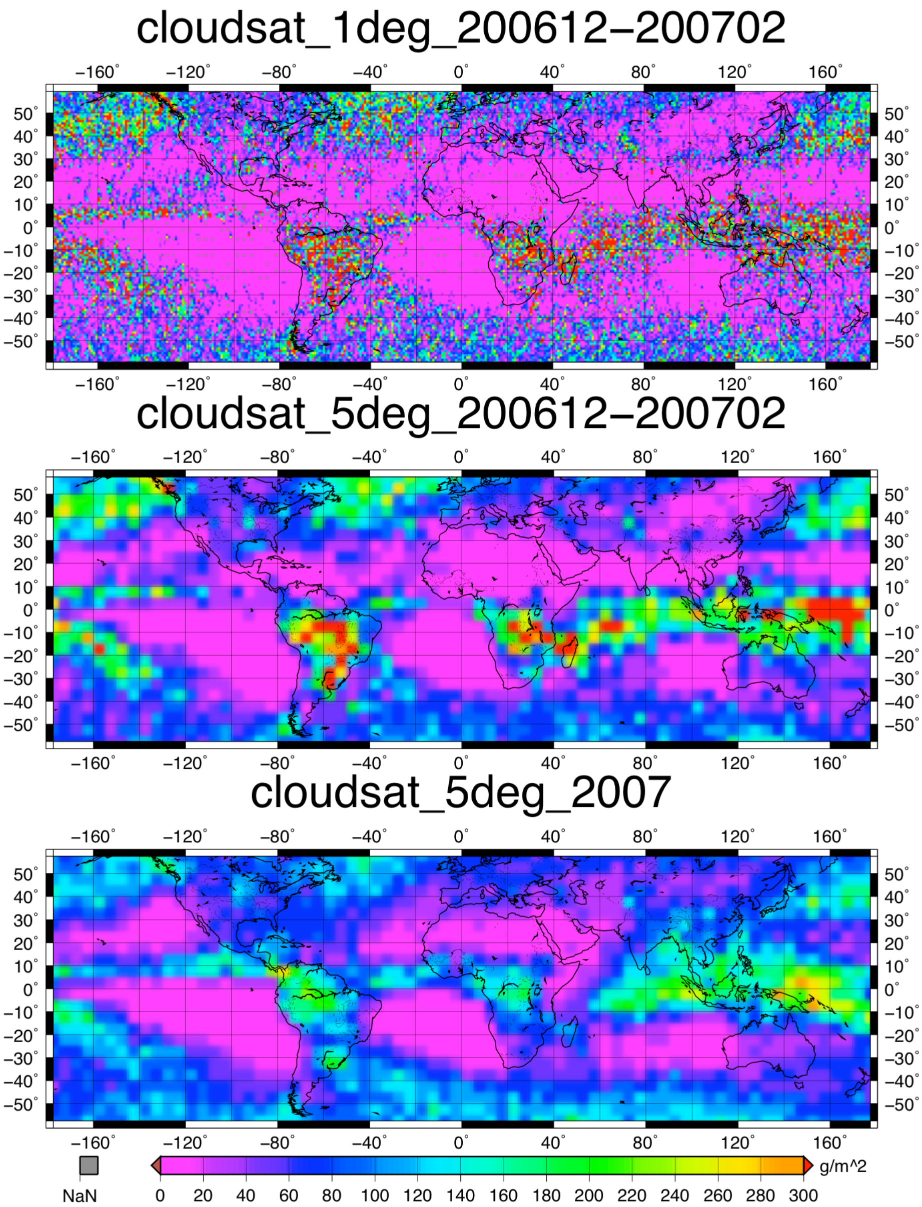


Figure 3.2: An IWP climatology from CloudSat data. Top: seasonal climatology (winter 2006/2007) at 1° spatial resolution. Middle: Same seasonal climatology at 5° resolution. Bottom: Yearly climatology (2007) at 5° resolution.

particularly on the so far poorly characterized 'essential climate variable' ice water path (IWP) and on the characteristic cloud ice particle size.

It will deliver data with near global spatial coverage every 24 hours, and on a spatial scale consistent with future global climate models, to both evaluate and improve the models.

It will also demonstrate the benefit of submillimeter observations for precipitation retrieval, an important step towards a possible future deployment of submillimeter radiometers in a geostationary precipitation mission.

3.2 Relevance to ESA Living Planet Program

The ESA Living Planet program document [*Herland et al.*, 2006] defines five challenges for atmospheric science. The first of these challenges is:

> 'Challenge 1: Understand and quantify the natural variability and the human-induced changes in the Earth's climate system.'

In this context, the document explicitly recognizes the pressing need for better satellite measurements of clouds, by stating that:

> 'There are still large uncertainties in climate predictions because of our lack of understanding of the coupling processes within the atmosphere, and the interactions between the different components of the Earth System. Clouds and their radiative feedbacks are a key issue in this context.'

Herland et al. [2006] then go on citing the second [*IPCC*, 1995] and third [*IPCC*, 2001] assessment reports by the IPCC:

> 'In the IPCC Second Assessment report it is stated that: "The single largest uncertainty in determining the climate's sensitivity to either natural or anthropogenic changes are clouds and their effects on radiation and their role in the hydrological cycle." This is further discussed in the IPCC Third Assessment Report, where it is concluded that increased availability of satellite measurements is needed to constrain the model-based estimates of climate sensitivity.'

As shown in Section 3.1, even the fourth IPCC report [*IPCC*, 2007] stresses the crucial importance of understanding cloud feedbacks. Ice clouds, the main target of the proposed mission, are both poorly understood and highly relevant for the climate system. The CloudIce mission thus directly addresses one of the major issues raised in *Herland et al.* [2006], and by the last three IPCC reports.

3.3 Scientific Requirements

Scientific requirements for submillimeter-wave satellite observations of cloud ice were examined in the context of four recent ESA studies [*Charlton et al.*, 2002; *Golding and Atkinson*, 2002; *Sreerekha et al.,* 2006; *Jarret et al.*, 2007]. The last of these studies attempted a synthesis of all available earlier results. It is summarized in an article by *Buehler et al.* [2007]. Here we just briefly summarize this last assessment, and refer to the article for details.

The process of deriving scientific mission requirements involved several steps. As a first step, a table of pure scientific requirements for cloud ice observations was compiled. Sources for this table were the CEOS/WMO requirement database [*Hinsman*, 2003], the earlier ESA studies, and an independent new requirement analysis structured by parameter and application. Since cloud ice is currently not well covered by the global observing system, the range between threshold and target in the pure scientific requirement table is large for most parameters. The pure scientific requirement table is therefore not suitable for mission sizing.

In a second step, the concept of breakthrough ranges was used to narrow down the requirements from the pure science table. The breakthrough range is the sub-range between threshold and target in the pure scientific requirements where there is a particularly steep increase of benefit with increasing cost. It is therefore very suitable for mission sizing. The result of this analysis is summarized in Table 3.1.

Buehler et al. [2007] contains detailed justifications for the numbers in Table 3.1, which we do not want to repeat here. Instead we broadly outline below what considerations influence the different requirements.

The accuracy requirements for IWP, Zme, and Dme are influenced by the need for model evaluation, but also by comparison to existing sensors. The requirement for near global coverage comes from the need to evaluate and improve global circulation models. The horizontal resolution requirement comes from the typical resolution of mesoscale circulation models, an appropriate scale to represent clouds globally by the time of the mission launch. The observation cycle requirement (once to several times per day) comes from the need to derive monthly or seasonal climatologies with reasonable temporal sampling (the monthly mean value should be an average of individual measurements on many different days). The delay requirement comes from operational weather forecasting. Lastly, the observation time (mission lifetime) requirement comes from the need to observe several different annual cycles (preferably one entire ENSO cycle) in order to capture at least some of the natural variability of the atmosphere.

Besides the scientific requirements for the CloudIce mission itself, there is a more general scientific requirement for an airborne companion instrument. In the mission preparation phase this will be used for algorithm development and test/validation. During the flight of CloudIce it will be used for validation. The airborne instrument should participate in campaigns where synergistic measurements with other cloud sensors can be made. A good example for the

Table 3.1: Scientific mission requirements for a passive submillimeter-wave cloud ice mission, derived from breakthrough ranges in the pure scientific requirements for cloud ice observation. See Table 3.3 for parameter definitions. Delay requirements refer to NWP applications, since for climate and GCM validation/development applications the delay is not critical. The accuracy requirement for IWP is the maximum of relative accuracy and threshold for each IWP value. The horizontal resolution requirement assumes continuous coverage, which requires an appropriate footprint overlap. Table from *Buehler et al.* [2007].

Parameter	Requirement [target-threshold]	Remark
IWP accuracy	10-50% relative with 1-10 g/m^2 threshold	The total vertical column of cloud ice.
Zme accuracy	100-500 m	The median IWP altitude, representative for the altitude where most of the cloud mass is located.
Dme accuracy	10-50 μm	The median mass equivalent sphere diameter, a size parameter related to the particle mass, not the cross-section.
Spatial coverage	Global/near global	For global climate model evaluation.
Horizontal resolution	5-20 km	Assuming continuous coverage.
Diurnal sampling	Fixed local time (± 0.5 h)	To avoid aliasing of the diurnal cycle.
Observation cycle	6-24 h	At least one measurement per day, in order to derive monthly climatologies.
Delay	1-4 h	For NWP.
Observation time period	7-1 years	Goal is one ENSO cycle.

Table 3.2: Timing of CloudIce and important other missions. The column 'type' states the type of the instrument that is of main interest to CloudIce. Note that missions usually will have also other instruments. In the case of ACE-2, we list it in both the mm/submm and the radar category, since the submm instrument is less certain to be implemented than the radar instrument. Source: *CEOS EO Handbook* [2009].

Type	Mission	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Passive IR	Metop A	■	■													
	Metop B			■	■	■	■	■								
	Metop C								■	■	■	■	■			
mm / submm	CloudIce									■	■	■	■	■		
	Post-EPS											■	■	■	■	■
	GPM				■	■	■	■	■	■	■					
	ACE-2 submm											■	■	■		
	PREMIER								■	■	■	■	■			
Radar	CloudSat	■	■													
	EarthCARE				■	■	■	■								
	ACE-2 radar											■	■	■		

usefulness of an airborne instrument in both mission phases is MIPAS and its aircraft and balloon companion instruments. (See also Section 3.8 with example aircraft data and Section 4.4 on available aircraft instruments.)

3.4 Relation to Other Missions

Table 3.2 gives an overview of the planned timing of CloudIce and important other missions, with information mostly taken from the *CEOS EO Handbook* [2009]. We have grouped the missions loosely by the type of instrument that is of main interest for CloudIce. This grouping is subjective, but hopefully will become clear to the reader in subsequent sections, where we discuss the different instrument types separately.

3.4.1 Passive IR Measurements

Retrieval simulations show that simultaneous infrared data can improve the CloudIce retrieval accuracy, particularly for thin cirrus types and small ice particles [*Jiménez et al.*, 2007]. Although this is not the place for technical requirements, we can already reveal here that this results in a strong requirement for simultaneous IR data, which we propose to meet by flying in tandem with an operational meteorological mission. Metop C has perfect timing to be our tandem partner. Collocation is expected to be easy, thanks to the high spatial resolution of AVHRR, the IR imager on Metop, and thanks to the continuous coverage of both Metop and CloudIce data.

3.4.2 Millimeter / Submillimeter Measurements

CloudIce is not the only initiative for a submillimeter instrument to measure cloud ice. The CPL mission of Post-EPS includes channels at similar frequencies. It is not currently clear whether these channels will actually be implemented. If they are, then Post-EPS will continue the data record started by CloudIce, which would be scientifically very desirable (a longer data set for climate model evaluation). CloudIce algorithms could also be applied rather straightforwardly to Post-EPS data, which would mean that advanced Post-EPS science data products could be derived more or less from day one. If the missions overlap in time there would be additional science benefits, such as cross-validation, coverage of different local times, and global coverage in shorter time.

The US instrument SIRICE also is similar in science and technical requirements to CloudIce. There are strong ties between the science teams of SIRICE and CloudIce, as demonstrated by the participation of key US scientists in this proposal. SIRICE is currently under consideration as part of the ACE-2 mission, which includes a large suite of active and passive cloud observation instruments. As in the case of Post-EPS, SIRICE could potentially continue the CloudIce data series. The science benefits that were identified for time overlap with Post-EPS also apply to SIRICE (cross-validation, coverage of different local times, global coverage in shorter time).

PREMIER is a passive infrared and submillimeter limb sounder mission considered for Earth Explorer 7. As PREMIER is also planned to fly tandem with Metop (PREMIER will fly in front of Metop, CloudIce behind Metop) there is a very strong scientific synergy between the two missions. The PREMIER science objective — to understand atmospheric processes linking trace gases, radiation, chemistry and climate — will clearly benefit from simultaneous measurements of cloud ice. Likewise, the CloudIce mission will benefit from the simultaneous PREMIER data, particular of upper tropospheric humidity, but also of thin clouds. The viewing geometries of PREMIER and CloudIce are complementary, the limb sounders on PREMIER deliver high vertical resolution with relatively poor horizontal resolution (compared to downlooking sensors), the downlooking sensor on CloudIce delivers poor vertical resolution, but high horizontal resolution.

GPM is a precipitation mission with a constellation of passive microwave radiometers united by a core observatory carrying a Ka/Ku-band radar and a conically-scanning radiometer with 10-183 GHz channels. CloudIce will complement and extend GPM measurement capabilities.

3.4.3 Radar Measurements

With a launch date in 2018, the proposed CloudIce mission will provide important cloud ice data in the time period between two active cloud missions, EarthCARE (launch 2013) and ACE-2 (launch possibly 2020, but still uncertain). It is possible that we will have a time overlap with ACE-2, which would be scientifically very desirable. Maximizing the chance to get an overlap is an independent reason to aim for a long mission lifetime of CloudIce (besides the pure scientific reasons stated in Section 3.3).

3.4.4 General Comment on Satellite Trains

Quite generally, 'trains' of several satellites (like the US A-train) have enormous advantages. The 'mini train' PREMIER/Metop-C/CloudIce could serve as the core of a new larger atmospheric mission train. We therefore propose that ESA invite NASA and other agencies to join the train with further missions, for example carrying active sensors.

This is not required for CloudIce to achieve its objectives, but would significantly increase the benefit of all involved missions.

3.5 Geophysical Variables and Data Products

Figure 3.3 gives an overview of data levels and dependencies, Table 3.3 gives brief data product definitions. Submillimeter radiances contain information on the cloud ice water content, the ice particle size, their vertical distribution, and, with polarized measurements, their aspect ratio. As with any remote measurement, the information is indirect, and the retrieval underconstrained to different degrees, depending on product. To account for this, we define a hierarchy of retrieval products, ordered by the amount of a priori information that is needed for the retrieval. Table 3.4 gives an overview of the different classes of data products. Note, that the concept of retrieval product classes is different from the concept of data levels: L3 data are normally derived from L2 data, but class 3 products are not derived from class 2 products. Table 3.4 lists also the associated data levels for each product class.

Class 1 products are simply calibrated radiances (data level L1b), in units of Planck brightness temperatures. They require no a priori information. These data are valuable for the interpretation of the radiometric signal relative to the sampled atmosphere (in the presence of cloud and precipitation), for assimilation into circulation models, and for cloud/radiative transfer model evaluation. Recent examples for the direct use of radiances for scientific studies are *Nesbitt and Zipser* [2003] and *Prigent et al.* [2005]. The CloudIce science team will provide a forward operator (a radiative transfer model), which is essential for the use of these data.

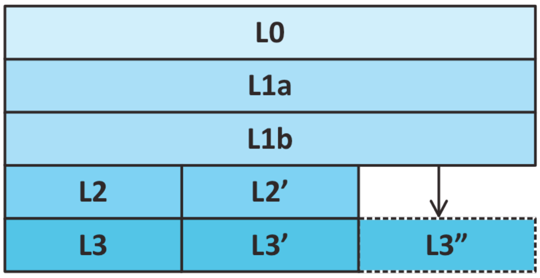


Figure 3.3: Data levels. L0 are raw data. L1a are raw data with calibration coefficients, L1b are calibrated radiances in units of Planck brightness temperatures. L2 and L2´ are retrieved parameters for each instrument field of view. L3, L3´, and L3´´ are retrieved parameters on standard grids. The processing chain progresses from the top down, so L3´ depends on L2´, and so on. L3´´is special, because it depends directly on L1b.

Table 3.3: Data product definitions.

Name	Description
Tb:	Radiances in units of Planck brightness temperatures
IWP:	Ice water path in g/m^2, the total column value of the mass of ice particles in the atmosphere.
Dme:	Median mass equivalent sphere diameter in µm. A measure for the characteristic size of the particle population.
Zme:	Median mass cloud altitude in m. The altitude where the partial IWP above and below are equal. A measure for cloud altitude, related to the ice mass (in contrast to the cloud top altitude).
CIWC:	Cloud ice water content in g/m^3. The mass of ice (per cubic meter) that is identified as cloud particles. Model dependent.
CLWC:	Cloud liquid water content in g/m^3. The mass of liquid water (per cubic meter) that is identified as cloud droplets. Model dependent.
GWC:	Graupel water content in g/m^3. The mass of ice (per cubic meter) that is identified as graupel. Model dependent.
SWC:	Snow water content in g/m^3. The mass of ice (per cubic meter) that is identified as snow. Model dependent.
RWC:	Rain water content in g/m^3. The mass of liquid water (per cubic meter) that is identified as rain. Model dependent.
RH:	Relative humidity in percent.
TWV:	Total water vapor in g/m^2. The total column mass of water vapor.
PR:	Precipitation rate in mm/h. The rate of precipitation (liquid and frozen) at the ground.

Table 3.4: Retrieval product classes. Classes 1 and 2 are the primary ones, for which the mission is sized. Classes 3 and 4 will be provided on a best-effort basis.

Name, Description	Data Level	Products
Class 1 No a priori 'Radiances'	L1b	Calibrated radiances
Class 2 Weak a priori 'Physics based'	L2, L3	IWP, Dme, Zme
Class 3 More a priori (particularly correlations between retrieved species) 'Model based'	L2´, L3´	TWV, PR, profiles of CIWC, CLWC, GWC, SWC, RWC, and RH
Class 4 Explicit a priori from model forecast 'Assimilation'	L3´´	Same as class 3

Class 2 products are the relatively simple parameters IWP, Dme, and Zme (see Table 3.3 for definitions and units). The data level of these products is L2 (for instrument fields of view) and L3 (gridded). These products are still 'close' to the measurement in the sense that they require only weak a priori information, in the form of assumptions on the statistics of cloud vertical structure and microphysics. Products will be obtained by a retrieval scheme, based on standard methods such as neural networks or Bayesian Monte Carlo integration. Class 2 products are the core parameters of the CloudIce mission.

Class 3 provides a richer set of hydrological parameters, namely profiles of five different hydrometeor types: Cloud ice water content (CIWC), cloud liquid water content (CLWC), graupel (GWC), snow (SWC), rain (RWC), and relative humidity (RH). Additionally, class 3 provides total column water vapor (TWV) and the precipitation rate at the surface (PR). See Table 3.3 for definitions and units of the different parameters. As for class 2, these products are derived from the L1b data, so we call the data levels for class 3 L2´, and for gridded data L3´.

Whereas class 2 data are relatively 'close' to the measurement, class 3 data are 'close' to atmospheric models. A mesoscale circulation model is used to generate the training data, and the retrieved parameters are those that represent humidity, clouds, and precipitation in the model. The training data thus contain implicit information on the correlation of the different hydrometeor species according to the model. This allows the retrieval of parameters that are not directly measured, such as the precipitation rate. This works well, since the physical mechanism for generating many types of precipitation is through the ice phase, and hence the precipitation rate is strongly correlated with the amount of cloud ice. The retrieval algorithm itself is similar to class 2 (a neural network).

In contrast to class 2, class 3 data depend on the cloud model that is used for training the algorithm. They are thus not the best suited data class to evaluate other models (there class 1 is best). But class 3 provides a complete picture of the hydrological state and will be very useful for case studies.

Class 3 products will be derived on a best effort basis, but will not be used for mission sizing.

Class 4 products result from assimilating L1b radiances into an atmospheric circulation model. We assign data level L3´´ to them. There is no data level L2´´, since L3´´ is generated directly from L1b. For class 4, a mesoscale circulation model is used not only for training data generation, as for class 3, but explicitly in the assimilation process. The a priori information for the derived products is the model forecast. The variables considered are the same as for class 3. Class 4 would give the best estimate of the true state, but would be furthest from the 'pure' measurements. Assimilation of cloudy radiances into circulation models is still experimental. We expect significant progress in this area by the time of the CloudIce launch. For the moment this class is speculative. This class will not be provided by the CloudIce science team itself, but will be provided on a best-effort basis by weather centers such as ECMWF and Met Office (UK) that assimilate the L1b data.

3.6 Use Cases

Table 3.5 lists some examples how CloudIce data might be used in practice. These are intended as illustrative examples, not as an exhaustive list. Due to lack of space, we cannot describe the individual examples in more detail. However, as supplementary material, Annex 7.4 contains statements from two data users (from the climate modeling and NWP communities) in their own words.

3.7 Retrieval Algorithm Status

In this section we briefly describe the retrieval approach for the different product classes and note their algorithm development status.

3.7.1 Class 1 'Radiances'

Approach: Instrument counts have to be properly calibrated to radiances in units of Planck brightness temperature, using the cold-space and internal hot load calibration measurements that are performed in each scan cycle (L0 to L1b processing). The procedure will be similar to the one for existing operational instruments of the AMSU-B/MHS family, as described for example in *Lambrigtsen* [2003]. Data quality control will also be an important activity for this class. Beyond that, class 1 does not require a retrieval algorithm, but it requires that data users be provided with a forward operator in the form of a fast radiative transfer (RT) computer program. The program should allow modelers an easy adaptation to the cloud microphysical assumptions of their specific model. This also requires an accurate reference RT program, for development and validation of the fast program.

Status: The L0 to L1b data processing and quality control are straightforward, using established procedures. Concerning the forward operator, the public domain RT code ARTS [*Buehler et al.*, 2005] is available as reference RT code for CloudIce. It was developed to handle all aspects of submillimeter cloud ice observations. The development was partially funded by ESA in a study reported by *Sreerekha et al.* [2006]. ARTS simulates the full Stokes vector, so it is applicable for polarized measurements. Also, it includes two different algorithms to simulate scattering by cloud particles [*Emde et al.*, 2004; *Davis et al.*, 2005].

There is not yet a fast RT model for CloudIce. The best option would be to implement this as part of the RTTOV [*Saunders et al.*, 1999] model, which provides fast forward operators for all operational meteorological missions. Since the current version of RTTOV already includes scattering, the implementation of the CloudIce channels is expected to be fairly straightforward, since the reference model is readily available.

Table 3.5: Example use cases for CloudIce data.

Topic	Where	Data
Convection Scheme Development Needs statistics of occurrence, extent, and IWP of convective clouds.	Met. Agency	IWP (L2), hydrometeor profiles (L2´)
Microphysics Scheme Development Scheme uses a mix of physical approximations and statistical assumptions. Needs statistics on Dme and IWP.	Met. Agency / University / Research Institute	IWP, Dme (L2,L3)
Climate Model Evaluation Evaluate climate model with new cloud physics, requires global data for several years. Compare model and data mean state and variability in IWP. Can alternatively be done in radiance space, using forward operator.	Climate modeling center	Entire L3 dataset (or entire L1B dataset)
Case Studies on Frontal Precipitation Compare CloudIce data to mesoscale model simulations.	University / Research Institute	Hydrometeor profiles (L3´)
Role of Convective Ice Clouds in Moistening the UT Correlate cloud ice and humidity data to assess the relevance of cloud ice particles in moistening the upper troposphere.	University / Research Institute	Hydrometeor profiles (L3´) plus humidity (L3´)
Precipitation Statistics Calculate regional statistics of precipitation over land in areas without weather radar network.	University / Research Institute	Precipitation rate (L3)
Weather Forecasting Use IWP maps as a support tool to interpret the model analysis/forecast.	Met. Agency	L2 (realtime)
Operational NWP Assimilate CloudIce radiances.	Met. Agency	Radiances (L1b, realtime)
Radiative Transfer Scheme Development Develop fast scheme for radiation flux, taking into account particle asphericity. Needs CloudIce data for assumptions on size and asphericity.	University / Research Institute	L2, L1b (polarized)
Volcano Ash Mass Ejection Estimate Estimate ash particle single scattering properties from assumed refractive index. Retrieve ash total column in intense plume near the source. Estimate total mass by assuming continuity between daily observations.	University / Research Institute	Radiances (L1b)

3.7.2 Class 2 'Physics based'

Approach: The retrieval approach for class 2 products consists of two distinct steps. Firstly, creating an atmospheric profile database with realistic statistics of temperature, water vapor, cloud profiles, and cloud microphysics (size, shape, and orientation distributions), based on in-situ and remote measurements. Secondly, using this database to approximate the a posteriori distribution of the atmospheric state, given the observation. The retrieved state is then selected from the a posteriori distribution by some appropriate criterion (e.g., the mean value). Different standard methods to numerically estimate the retrieved state are readily available, notably Bayesian Monte Carlo integration and Neural Networks. The former is conceptually simpler and automatically provides an estimate of the retrieval error. The latter is computationally more efficient, but the derivation of retrieval errors is less straightforward. These two methods are described well in *Rydberg et al.* [2009].

Status: Extensive retrieval simulations with different submillimeter channel combinations and different training databases have been carried out in the ESA study reported by *Jarret et al.* [2007]. These results have also been published in

Jiménez et al. [2007], which deals with the retrieval simulations themselves, and in *Buehler et al.* [2007], which deals with the overall instrument and mission concept. Some results of these activities are shown in Section 3.8.

3.7.3 Class 3 'Model based'

Approach: The approach for class 3 data is similar to class 2, but the source of the training data is a mesoscale circulation model, instead of measured data. The retrieved parameters are the different microphysics species and state parameters of the model. The approach is therefore model dependent, but the validity of the model can be checked by comparing its outputs to concurrent ground-based and space-based observations.

Status: Retrieval simulations for class 3 products have been carried out and are described in Section 3.8.

3.7.4 Class 4 'Assimilated'

Approach: The approach for class 4 data is direct assimilation of the CloudIce L1b radiances into a mesoscale circulation model.

Status: Already today, weather centers such as ECMWF operationally assimilate cloud and precipitation-affected radiances from microwave imagers [*Bauer at al.*, 2006a; *Bauer at al.*, 2006b]. There has been rapid development in this area in recent years, and it is reasonable to assume that by the time of the CloudIce launch also high frequency imager data can be treated in the same way.

3.7.5 Retrieval Algorithm Summary

Overall, the retrieval algorithms for CloudIce rest on a firm scientific basis, with the exception of the speculative class 4 products. The algorithms have been successfully tested in several case studies, some of which are highlighted in the next section. On the other hand, coding the algorithms for operational processing, as well as doing thorough validation of the products, will still be considerable work. For this work aircraft data is very useful. Fortunately, we will have an ESA co-funded submillimeter-wave aircraft radiometer soon. Together with the two already available US instruments this creates excellent opportunities for scientific studies with campaign data, and for further algorithm validation and fine-tuning. For a summary of the available airborne instruments, see Section 4.4.

3.8 Retrieval Demonstrations

3.8.1 Class 2 Products Retrieval Simulation Study

Detailed retrieval simulations of the class 2 products IWP, Dme, and Zme were carried out in a recent ESA study [*Jarret et al.,* 2007]. Different channel combinations were investigated, in order to determine an optimum instrument configuration. The retrieval algorithm was as outlined in Section 3.7. The setup is described in detail in a scientific article about the simulations [*Jiménez et al.*, 2007].

As explained in Section 3.7, the retrieval algorithm needs training data, consisting of simulated radiances for a diverse atmospheric state dataset. Two different diverse datasets have been developed. D1, developed by Frank Evans, uses randomly generated profiles and microphysics. Statistics for the vertical structure are taken from radiosondes and statistics for the microphysics are taken from aircraft campaigns. D2, developed by Bengt Rydberg and Patrick Eriksson, uses cloud radar data for the vertical structure, and combines them with randomly generated microphysics. As for D1, microphysics statistics are taken from aircraft campaigns. Different databases are useful to test the dependence of the retrieved products on the a priori assumptions. Results in *Jimenez et al.*, [2007], where inversions using D1 and D2 were compared, showed consistency between both derived IWPs.

Figure 3.4 is from *Buehler et al.* [2007]. It shows the expected retrieval performance for IWP, Dme, and Zme, based on dataset D1. These simulations confirm that the mission can meet its scientific requirements.

3.8.2 Class 3 Products Retrieval Simulation Study

Radiative transfer simulations have been performed with the help of an RT model

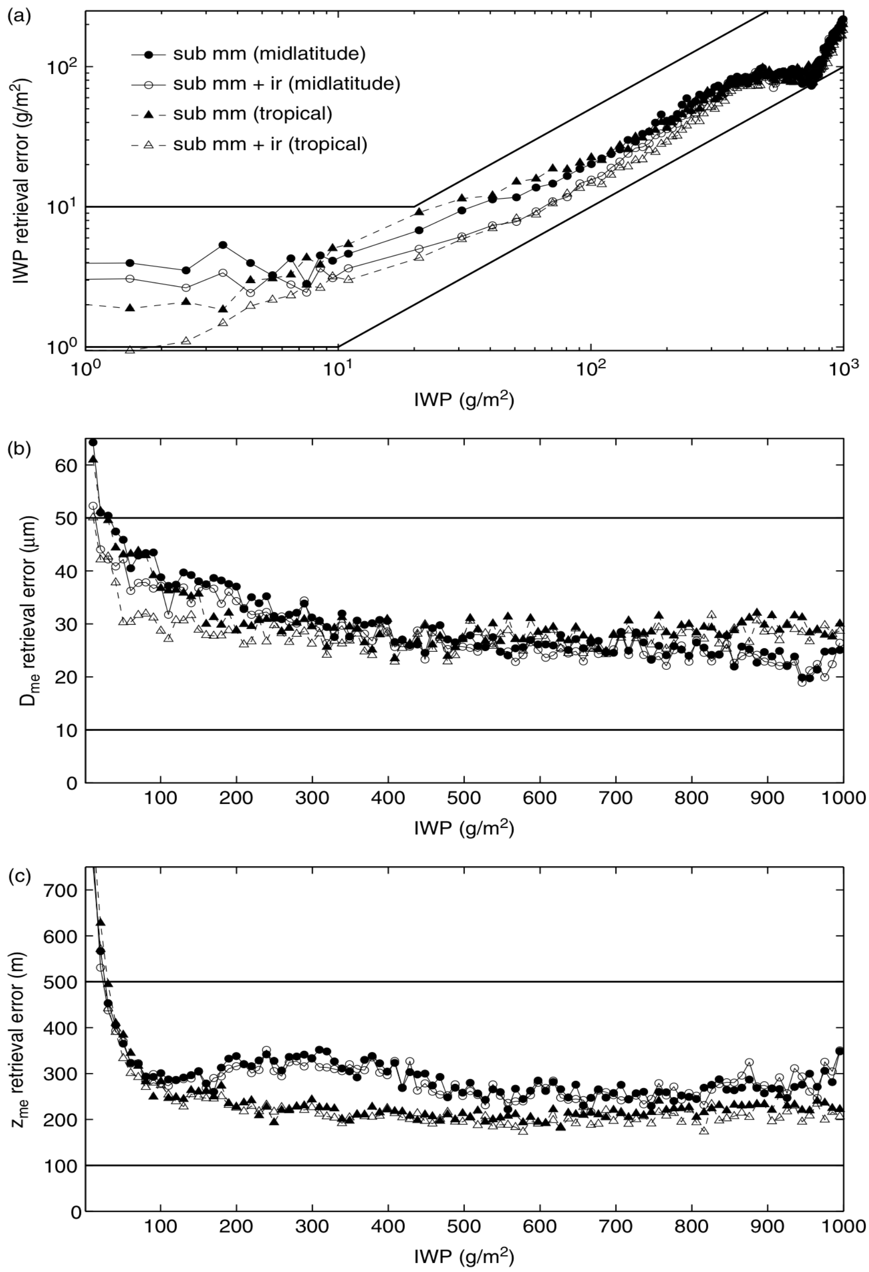
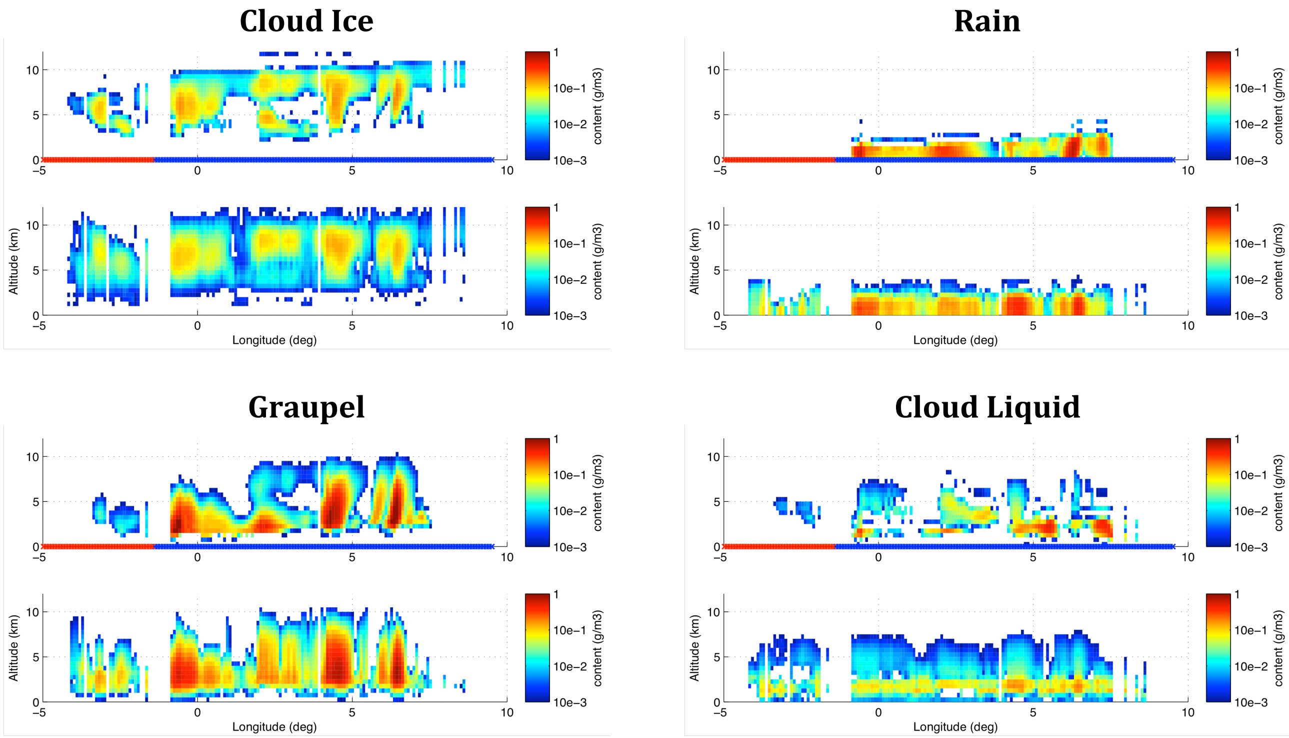


Figure 3.4: Retrieval performance for (a) ice water path, (b) particle size, and (c) cloud altitude, all as a function of the true IWP. Retrieval results are shown with and without additional infrared channels, as available from Metop. Also shown are results for two different atmospheric scenarios (midlatitude and tropical). Solid black lines indicate the scientific mission requirement ranges. (Figure from *Buehler et al.* [2007].)

based on realistic atmospheric/microphysics profiles derived from the MESO-NH cloud-resolving model in an ESA study [*Zanifé et al.*, 2007]. The RT simulations are in good agreement with coincident AMSU and SSM/I observations [*Chaboureau et al.*, 2008; *Meirold-Mautner et al.*, 2007]. The neural-network retrieval scheme is built from a synthetic database composed of realistic atmospheric/microphysics profiles derived from the cloud-resolving model and concurrent simulated brightness temperatures for sea and land separately [*Defer et al.*, 2008] and for different atmospheres [*Charlton et al.*, 2010].

The database was used to explore the information contents that can be derived from submillimeter observations [*Zanifé et al.*, 2007; *Mech et al.*, 2007] and to confirm the pertinence of submillimeter radiometry in quantifying precipitation [*Zanifé et al.*, 2007; *Defer et al.*, 2008]. The same method was recently applied in an ESA study to assess the performance of an airborne demonstrator at mid-latitude and tropical atmospheres [*Charlton et al.*, 2010].

Figure 3.5 demonstrates the capability of CloudIce to retrieve hydrometeor vertical profiles. The hydrometeor species retrieved are the five species of MESO-NH: cloud ice, graupel, snow, rain, and cloud liquid. (In Table 3.3 these products are labeled CIWC, GWC, SWC, RWC, and CLWC, respectively.) The microphysical properties of the different species are summarized in Table 3 of *Chaboureau et al.*



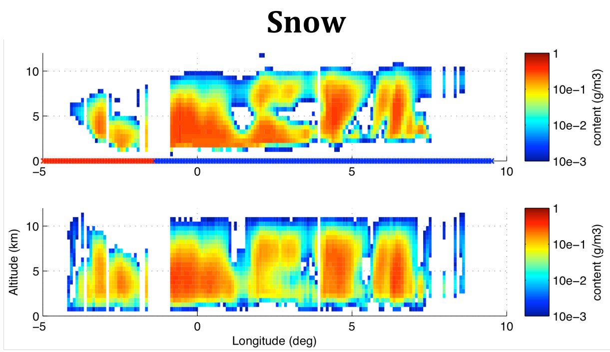


Figure 3.5: Hydrometeor content profile retrieval for the MESO-NH microphysics species cloud ice, graupel, snow, rain, and cloud liquid. For each species, original (top) and retrieved (bottom) profiles are shown along a longitudinal transect for a simulated case over the Mediterranean Sea (the Algier case of the SIMGEO database [*Chaboureau et al.*, 2008].) Sea and land surface cases are indicated in blue and red in each top panel.

[2008].

Preliminary retrieval schemes, over sea and land separately, have been applied to derive hydrometeor profiles from simulated noisy brightness temperatures. The retrieved hydrometeor profiles are then compared to the original profiles. As shown in the figure, cloud regions with significant ice content are well-captured and similar vertical cloud structures can be found in the retrieved transect relative to the original one.

One of the mission objectives of CloudIce is to validate the capability of submillimeter radiometry for precipitation retrieval. Radiometry at these wavelengths is predominantly sensitive to cloud ice particles, and precipitation detection and quantification mainly relies on the correlation of precipitation with the ice particles above. The retrieval error for the precipitation rate has been evaluated with the use of the microphysics/brightness temperature database. Table 3.6 shows that the CloudIce radiometer could provide precipitation rate above 10 mm/h with an error range of 30 to 60%. Comparing this to the EUMETSAT Position Paper [*Rizzi et al.*, 2006] reveals that the performance is near the breakthrough level for global and regional NWP applications, but poorer than the threshold level for hydrology applications.

3.8.3 Aircraft Data

The European submillimeter-wave aircraft radiometer, ISMAR, is still in development, but we already have data from US instruments (see Section 4.4 for a summary of ISMAR and other available instruments). The Compact Scanning Submillimeter-wave Imaging Radiometer (CoSSIR) is an aircraft based instrument built at the NASA Goddard Spaceflight Center. During the Tropical Composition, Cloud, and Climate Coupling (TC4) field campaign in July and August 2007 CoSSIR flew on the NASA ER-2. For that deployment CoSSIR had 11 channels with receivers at 183, 220, 380, 640, and 874 GHz, and dual polarization at 640 GHz, all with 4° beamwidths. CoSSIR performed forward and aft conical scans at 53° plus two quick scans through nadir in each 10 second scan cycle.

Figure 3.6 (a) shows the forward conical scan brightness temperatures from part of one flight during TC4. The higher frequencies (640 and 874 GHz) are seen to be more sensitive than the lower frequencies (183 and 220 GHz) to the smaller ice particles in the anvil (e.g., at 16.6 UTC) adjacent to the convective core. The multiple channels around the 183.3 and 380.2 GHz water vapor lines are seen to have vertical profile information with only the highest altitude ice cloud features appearing in the channels with the highest altitude weighting functions. Small differences between the 640H and 640V channels are apparent.

Table 3.6: Estimated RMS error (in %) of precipitation rate for 3 different ranges. The last three columns show the corresponding threshold accuracies (and breakthrough accuracies in parentheses) for different applications. Applications considered are numerical weather prediction (NWP) and hydrology, with requirements taken from the EUMETSAT Position paper [*Rizzi et al.*, 2006].

Precipitation rate range	CloudIce RMS retrieval error (%)	NWP global (%)	NWP regional (%)	Hydrology (%)
< 1 mm/h	Not retrievable	100 (50)	100 (50)	80 (40)
1-10 mm/h	50-70	100 (50)	100 (50)	40 (20)
> 10 mm/h	30-60	100 (50)	100 (50)	20 (10)

Submillimeter-wave brightness temperature polarization differences are indicative of higher aspect ratio ice particles (e.g., columns or plates) being horizontally aligned [e.g., *Evans et al.* 1998]. Figure 3.6 (b) shows a retrieved polarization index, which is defined as the difference between V and H polarization, normalized by the cloud signal. In anvil regions, this index has values

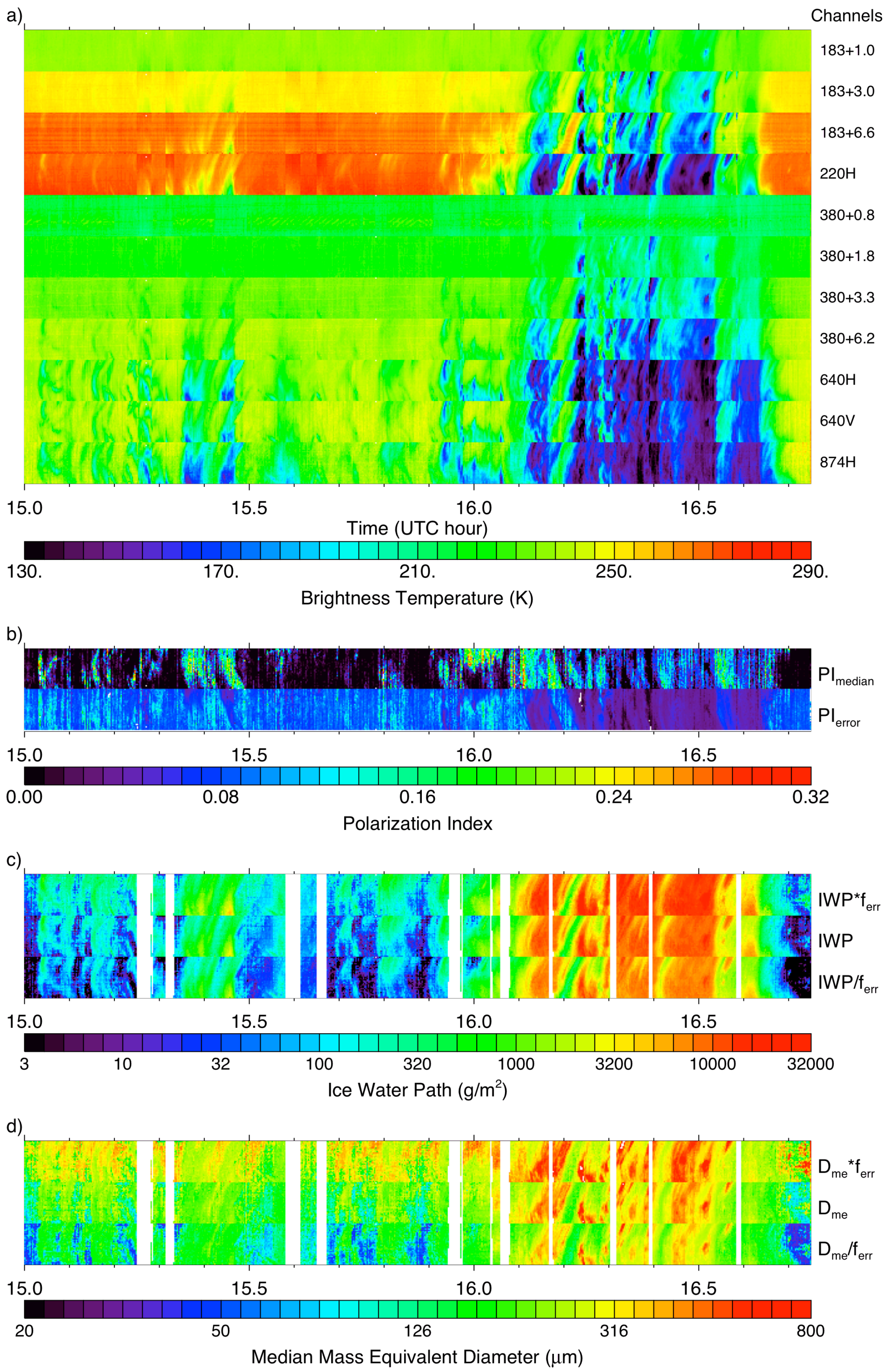


Figure 3.6: CoSSIR forward conical scan swath images from 2007-07-17 showing (a) brightness temperatures for the 11 channels, (b) retrieved 640 GHz polarization index (median and RMS error), (c) retrieved ice water path, and (d) retrieved median mass diameter. The retrieved error range for IWP and Dme are shown using the error factor, f_{err}, which is the exponential of the RMS error of ln(IWP) or ln(Dme). Retrievals are not performed during turns of the ER-2 aircraft, leaving the white vertical bars.

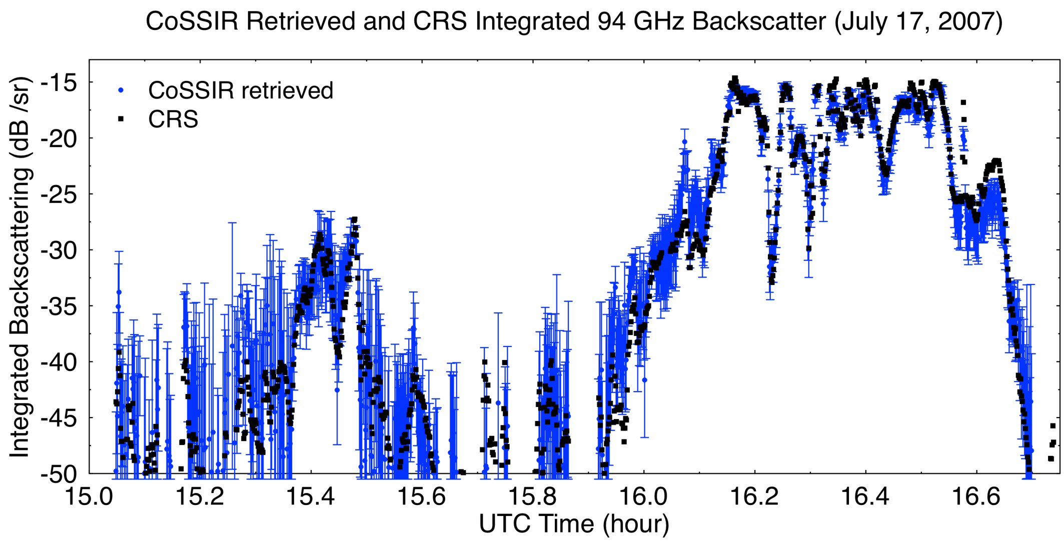


Figure 3.7: CoSSIR retrieved nadir viewing vertically integrated 94 GHz backscattering with error bars and integrated backscattering from the 94 GHz Cloud Radar System.

from 0.15 to 0.25, indicating oriented ice crystals. The convective core, on the other hand, has low polarization index, presumably indicating quasi-spherical tumbling ice particles, such as graupel.

Retrievals of IWP and Dme were performed with a Bayesian Monte Carlo integration algorithm described in *Evans et al.* [2005]. A priori information is represented by 10^6 profiles of atmospheric and ice cloud properties generated from statistics relating temperature, IWC, and Dme (from in situ microphysical probes), and statistics of temperature and relative humidity (from TC4 radiosondes). One difference of these retrievals from *Evans et al.* [2005] is that the Bayesian integration is done with ln(IWP) and ln(Dme). Figure 3.6 (c) and (d) shows the retrieved IWP and Dme with the uncertainty range. There was no way to directly validate IWP during TC4, but an indirect validation was made by comparison to the nadir viewing 94 GHz Cloud Radar System. CoSSIR nadir viewing brightness temperatures are used to retrieve vertically integrated 94 GHz backscattering, which is compared to the integral of the measured radar reflectivity profile. Figure 3.7 shows good agreement, usually comparable to the retrieved error bars, in integrated radar backscatter over a large range. This good agreement lends confidence to the submillimeter-wave retrievals of IWP and Dme.

CoSSIR has recently been upgraded to more closely match the frequency configuration for the proposed submillimeter-wave radiometer on the planned NASA ACE-2 mission. This brings it also closer to the CloudIce configuration. There are now three channels each around the 183.3, 325.1, and 448.0 GHz water vapor absorption lines, dual polarization at 640 GHz, and a channel at 874 GHz. Test flights of the new CoSSIR configuration over clear skies in August 2009 were successful, with good noise performance for the new 325 and 448 GHz receivers.

3.8.4 Operational Millimeter-Wave Data

There is no operational down-looking submillimeter satellite instrument, but the AMSU-B/MHS instrument family provides at least measurements around the 183.31 GHz water vapor line, which will also be observed by CloudIce. Together with collocated CloudSat data, these data can therefore be used to demonstrate the

CloudIce retrieval, although with much poorer performance than CloudIce would have. *Holl et al.* [2010] describe this in a recent article.

Figure 3.8, taken from that article, shows the measured and simulated cloud ice signal as a function of IWP. IWP is here taken from the CloudSat data. The figure demonstrates that radiative transfer model, CloudSat radar measurement, and MHS brightness temperature signal are all consistent, within the expected

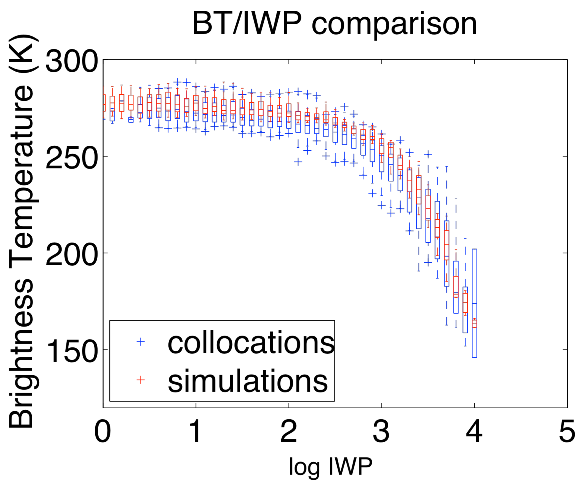


Figure 3.8: Brightness temperature versus IWP for measured MHS data (183.31±7 GHz) and simulations, based on collocated CloudSat data. Boxes show medians with 1st and 3rd quartile. This figure is from *Holl et al.* [2010], where further details are explained. The good agreement between measured and simulated cloud signal demonstrates our adequate understanding of the radiative effect of cloud ice.

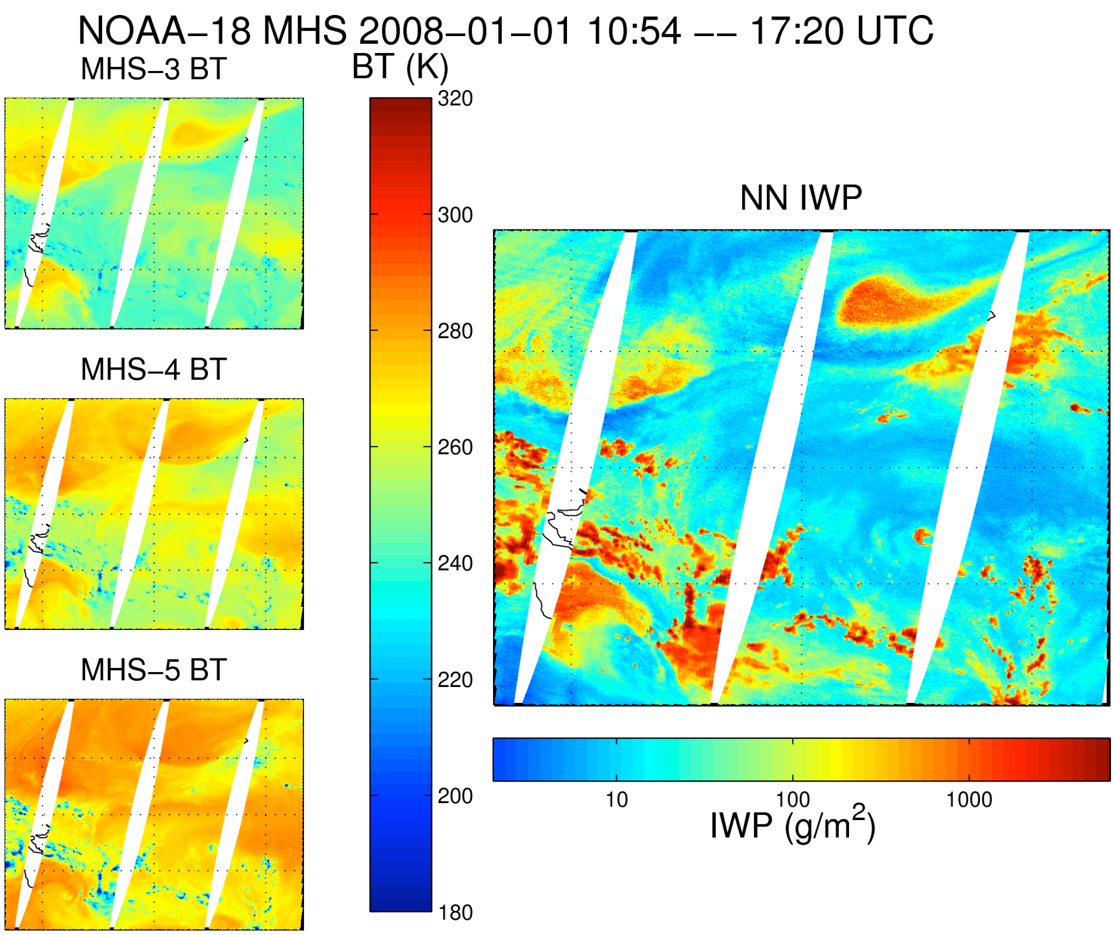


Figure 3.9: IWP retrieval from MHS data. Left: MHS brightness temperatures for 183.31± 1, 3, and 7 GHz. Right: Retrieved IWP. The retrieval used a neural net, as described in Section 3.7, but trained with CloudSat IWP data. The data is from the NOAA-18 satellite on January 1, 2008 between 10:54 and 17:20 UTC. Cold areas in the left panel correspond to high IWP areas in the right panel. Figure from *Holl et al.* [2010].

uncertainty. This signal can then be used to implement an IWP retrieval from the MHS data, which is shown in Figure 3.9. In this case the CloudSat IWP measurement is assumed as truth. An error analysis (not shown, but discussed in *Holl et al.* [2010]) reveals that the retrieval performance is consistent with the CloudIce simulations as described in *Jiménez et al.* [2007], when they are restricted to use only the MHS channels.

3.8.5 Odin IWP Retrieval

No down-looking submillimeter satellite instrument has yet been launched, as mentioned, but there are three operational submillimeter limb sounders (Odin-SMR, Aura MLS and SMILES). All three instruments scan down below the point where the transmission through the troposphere approaches zero. This situation is encountered for tangent altitudes below approximately 10 km. For this tangent altitude range the basic properties of the observations are the same as for CloudIce, although the incidence angles are considerably higher. A consequence of the high incidence angle is that only relatively high clouds can be seen by these instruments.

Data from low tangent altitudes have been studied especially for Odin-SMR. The latest retrieval approach is described in *Rydberg et al.* [2009], which is based on *Evans et al.* [2005]. Special attention was given to generating the retrieval training database, where CloudSat observations were used to ensure that both vertical and (local) horizontal cloud structures are correctly represented (see left side of Figure 3.10). The right side of Figure 3.10 shows a climatology of retrieved IWC at different altitudes. IWC and (partial) IWP retrievals for MLS have also been done and are presented in *Wu et al.* [2008].

The limb sounder ice cloud data have been analyzed in detail (compared to climate model data and other measurements) and appear to have a high quality. Their usefulness is demonstrated for example in *Eriksson et al.* [2010], where the diurnal cycle of IWC in the tropical upper troposphere is analyzed by combining CloudSat and SMR retrievals, and where it is shown that climate models still fail to represent this cycle correctly.

3.8.6 Retrieval Demonstrations Summary

In summary, several approaches for CloudIce retrieval demonstration have been followed. Pure simulation studies have demonstrated the retrieval algorithm for class 2 and class 3 data products. Studies with aircraft data have shown that the class 2 product retrieval algorithm works also with real millimeter/submillimeter data, and that the result is consistent with airborne radar measurements. Studies of operational millimeter-wave data near 183.31 GHz, combined with collocated CloudSat data, have demonstrated that IWP retrieval works with these data. (Of course the performance without the higher frequency channels is much poorer than CloudIce, but it is consistent with expectations.) Retrievals from submillimeter data from the Odin and MLS missions (the latter not discussed here) further demonstrate our capability to handle also submillimeter data correctly.

When all these approaches are taken together, they demonstrate that we have a robust understanding of the radiative properties of cloud ice in the millimeter/submillimeter spectral range, and that we have a proven toolbox of retrieval algorithms to work with these data.

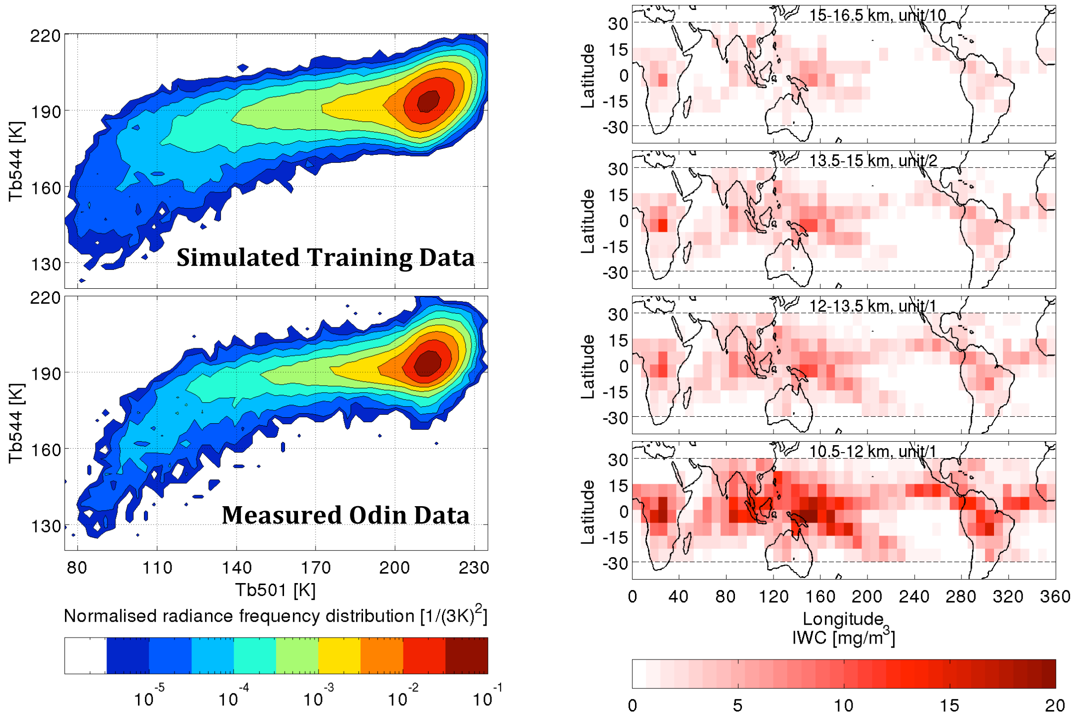


Figure 3.10: Left: The upper panel gives a representation of the retrieval database, as the occurrence frequency of different combinations of the brightness temperature of the two channels. The lower panel shows the real Odin SMR data in the same way. The high consistency between the panels shows that both atmospheric variability and radiative transfer are treated correctly when generating the database. Right: Averages of retrieved IWC data at different altitudes. A single retrieval database is used and all horizontal structures are pure measurement information. The fact that the structure of the IWC field at the different altitudes differs shows that vertical information has been retrieved.

4 Mission Assumption and Technical Requirements

4.1 Observation Technique

The use of passive submillimeter-wave measurements to retrieve cloud ice water content and ice particle size was first suggested by *Evans and Stephens* [1995], and refined in subsequent publications [e.g., *Evans et al.*, 1998]. A schematic picture of the observation geometry is shown in Figure 4.1.

Since water vapor absorption is strong in the submillimeter-wave spectral range, the lower atmosphere is in most cases opaque. This has the desired effect that the surface and low clouds do not contribute to the upwelling radiation. Furthermore, in this frequency range the interaction between cirrus clouds and radiation is mainly by scattering, so emission and therefore cloud temperature are not important. The situation can be described to a good approximation as that of a layer of cloud ice lying on top of a radiation source. Hence, the effect of the cloud is to reduce the brightness temperature compared to the clear-sky case. The brightness temperature depression is proportional to the IWP, except for saturation effects that occur for high IWP at high frequencies. This linearity has the advantage that radiation averages correspond to the radiation of an average atmospheric state, i.e., problems related to beam-filling in the presence of inhomogeneities are less significant than for optical and IR techniques.

Figure 4.2 gives an example how thick ice clouds are seen at microwave frequencies by the AMSU-B instrument. Figure 4.2 (a) and (b) show some AMSU data at 183±7 GHz, and a model IWP field for comparison. Figure 4.2 (c) and (d) show simulated radiances for the same AMSU channel and for a channel at 664 GHz. The figure demonstrates that radiative transfer simulations in the presence of ice clouds agree well with the available observations at AMSU frequencies and that the cloud signal is more pronounced at higher frequencies. (More details on the radiative signature of cloud ice can be found in *Rydberg et al.* [2007] and *Rydberg et al.* [2009]). At the high-frequency end, the usable frequency range is limited by the rising opacity due to water vapor absorption, which will hide the ice

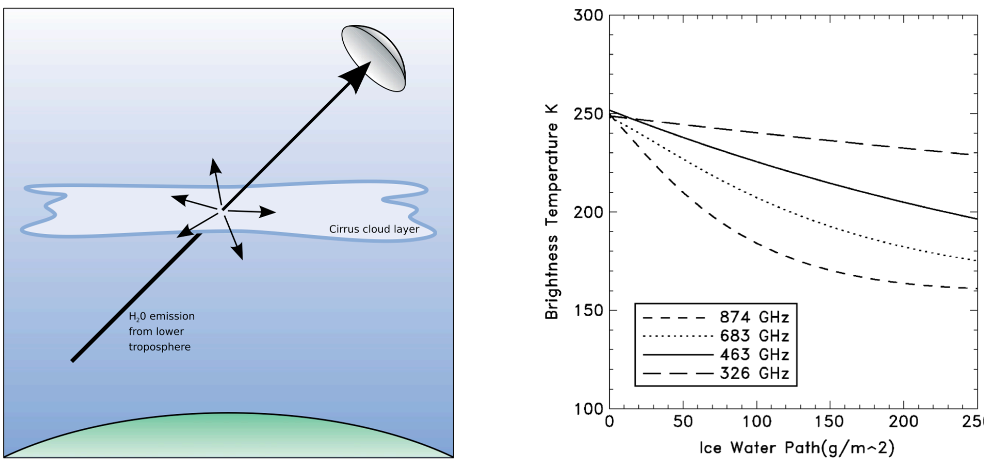


Figure 4.1: Left: The observation geometry. Some of the upwelling radiation is scattered away by the ice cloud. Right: Sensitivity of radiance to IWP for different frequencies in the submillimeter-wave spectral range. Conditions: midlatitude winter, nadir viewing direction, homogeneous cloud between 5 and 7 km altitude, spherical ice particles of 200 µm diameter. The simulation used the discrete ordinate iterative solution method [*Emde et al.*, 2004] that is part of the open source Atmospheric Radiative Transfer Simulator ARTS [*Buehler et al.*, 2005]. Figure from *Buehler et al.* [2007].

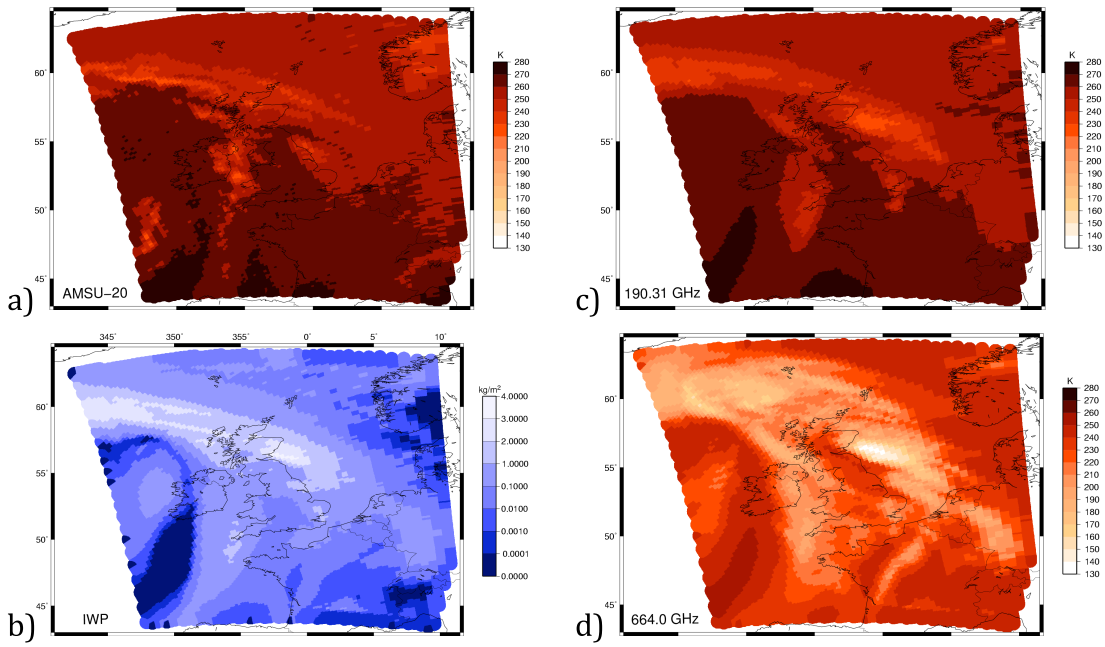


Figure 4.2: (a) AMSU Channel 20 measurements at 183.31 ± 7 GHz over the UK and northern parts of continental Europe, on 25 January 2002. The bright areas show the signature of the thick ice cloud associated with a frontal system passing over the UK. (b) Ice water path (IWP) from the Met Office (UK) mesoscale model. (c) Simulated AMSU measurement, based on the mesoscale model atmosphere. (d) Simulated measurement at 664 GHz. The simulations were done with the radiative transfer model ARTS, assuming a *McFarquhar and Heymsfield* [1997] size distribution for the ice particles. This parameterization was chosen for convenience, and because it is the parameterization used for operational EOS-MLS retrievals [*Wu et al.*, 2006]. The simulation for AMSU used the correct AMSU viewing angles, and the one for 664 GHz a fixed viewing angle of 45°. Note the much stronger sensitivity to ice for the higher frequency. Figure from *Buehler et al.* [2007].

clouds from the satellite sensor at frequencies above roughly 1 THz. The submillimeter frequency range thus presents a unique window for the observation of ice clouds.

The interaction of ice particles with radiation depends strongly on the ratio of particle size and wavelength. Figure 4.3 shows the sensitivity to particles of different sizes for selected submillimeter channels. For comparison, the sensitivities for IR measurements and for radar backscatter at 95 GHz (CloudSat and EarthCARE CPR) are also shown. As demonstrated by the figure, measurements at different frequencies can be used to sample the particle size distribution. To make accurate measurements of IWC or IWP, it is important that a significant part of the size distribution is detected, i.e., a part that contains a significant fraction of the total mass of ice. Parts of the size distribution that are not detected will lead to errors in IWC, because the mass of ice hidden in particles of that size must be estimated from assumptions on the size distribution. This is the reason why neither IR measurements (seeing only very small particles), nor radar measurements (seeing only very large particles) can provide very accurate estimates of IWC. Millimeter/submillimeter measurements, combined with IR measurements for the very small ice particles, can provide a reasonable coverage of the size distribution.

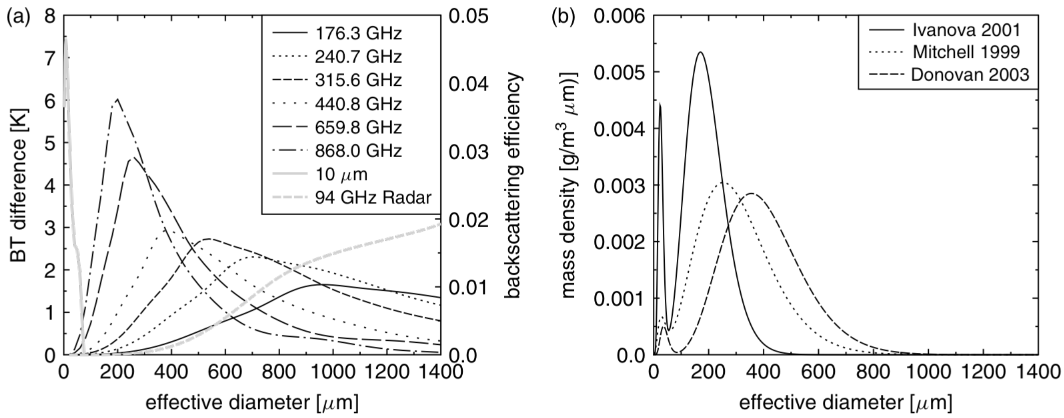
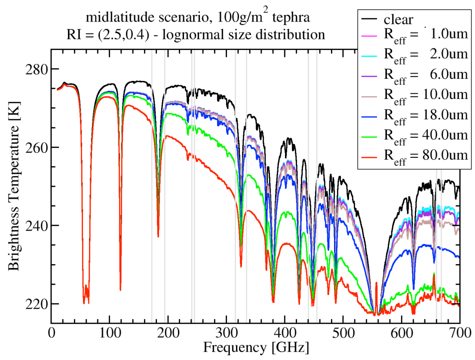


Figure 4.3: (a) The sensitivity of measurements at different frequencies to particle size. To generate this figure, a fixed amount of cloud ice (IWP = 2 g m^{-2}) was put into narrow size distributions with different Dme. For each Dme, the difference between clear-sky and cloudy radiance is displayed. For comparison, the two grey curves show the size sensitivity for IR radiances at 10 µm (solid), and for radar backscatter measurements at 94 GHz (dashed). The right axis is for the radar curve, the left axis for all other curves. (b) Three typical ice particle size distributions from the literature (mass per size bin), all normalized to a total IWC of 0.5 g m^{-3}. Figure from *Buehler et al.* [2007].

Volcanic Ash

In light of the recent eruption of volcano Eyjafjallajökull on Island, an interesting side issue is whether CloudIce will be sensitive to volcanic 'ash' particles. We did a very quick sensitivity study to assess this.

The main uncertainties here are what size distribution and refractive index to assume for the volcanic particles. The figure to the right shows the brightness temperature spectrum for a total column ash content of 100 g/m^2, an assumed refractive index of 2.5+0.4i, and different particle effective radius.



The study shows that, as expected, the submillimeter measurements will not be sensitive enough to detect the small ash concentrations far away from the source that still pose an air traffic risk (below 1 g/m^2). The strength of submillimeter measurements lies in the fact that they can penetrate the fresh ash plume close to the source (which will have comparatively large particles and a high mass content). This should allow an estimate of the amount of ash that is emitted. This idea has already been applied for SSM/I data by *Delene* [1996] and is expected to work with higher accuracy for CloudIce data.

4.2 Technical Instrument and Mission Requirements

Instrument requirements for CloudIce were derived in a series of simulation studies, most notably *Evans* [2004] and *Jarret et al.* [2007]. Details of the latter study have also been published in two scientific articles: *Jiménez et al.* [2007], which focuses on the describing the retrieval simulations, and *Buehler et al.* [2007], which focuses on the scientific and technical mission requirements.

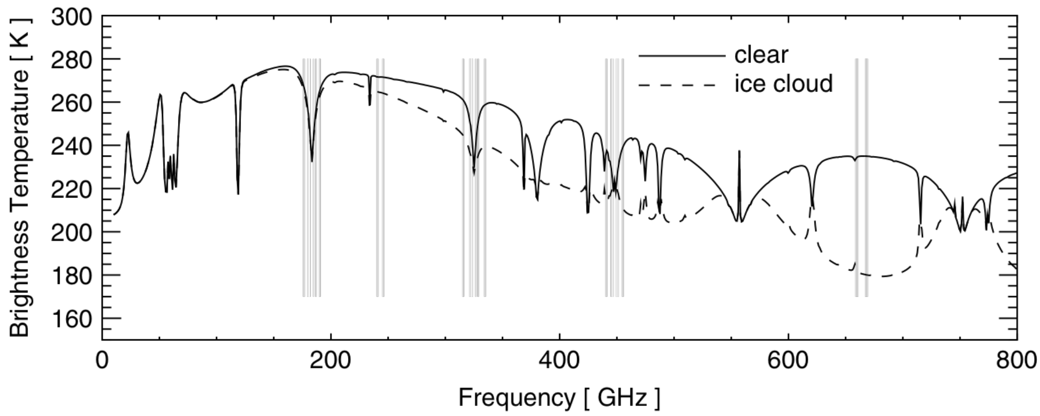


Figure 4.4: The submillimeter spectrum of a clear-sky and a cloudy midlatitude winter atmosphere, with bars indicating the positions of the prototype instrument channels. A homogeneous cloud was assumed from 8 to 10 km with an IWC of 0.04 g m^{-3}, consisting of spherical ice particles with 100 μm radius. The widths of the pass bands are drawn smaller than in reality (compare Table V), so that the individual channels can be distinguished. For details of the channel positions, see Table 4.1. Figure from *Buehler et al.* [2007].

4.2.1 Channel Positions and Radiometric Requirements

Figure 4.4 shows the proposed channel positions, relative to the atmospheric spectrum for clear and cloudy conditions. The exact positions are listed in Table 4.1. Receivers are spread out over a wide frequency range in order to sample frequencies with different cloud particle single scattering properties. Most receivers have multiple channels centered on a common water vapor absorption line. This is shown in more detail in Figure 4.5. Because of the varying distance from the line center, the different channels are associated with different atmospheric opacities and sample different altitudes in the atmosphere. A good way to visualize this is by calculating the clear-sky Jacobians, as shown in Figure 4.6. The peaks of the Jacobians indicate the sounding altitude for the different channels.

Compared to the CIWSIR mission proposal in 2005, the highest frequency channel was dropped, since retrieval simulations showed that its impact was not very strong. Furthermore, the 183 GHz H_2O line, which was sampled with three channels in the CIWSIR proposal, is now sampled with six channels in order to extend the altitude range of that receiver.

The receivers at 243 and 664 GHz are proposed to be polarized in order to gather information on cloud particle asphericity and orientation [*Prigent et al.*, 2001; 2005]. Should the instrument get too expensive, then the polarization option could be given up without jeopardizing the overall mission goals. But we propose it here, because the extra information would be very valuable.

The single-polarization channels should all measure in V polarization. There are two reasons for this. Firstly, and most importantly, simulations show that there is less uncertainty due to ice particle shape in the V signal, compared to the H signal. Secondly, since the incidence angle of CloudIce will be close to the Brewster angle for water, the V polarization will result in a ‘warm’ radiative background even under those conditions where some channels start to see the surface, and thus minimize surface effects.

Table 4.1: CloudIce channel specifications and radiometric requirements. NeΔT is the random error in the measurement, due to radiometric noise. Abs. ΔT is the absolute error in the measurement.

#	Center freq. GHz	Freq. offset GHz	Bandwidth MHz	Pol.	NeΔT K	Abs. ΔT K
1	183.31	0.20	200	V	2	1
2		1.00	500	V	1.5	1
3		3.00	1000	V	1	1
4		5.00	1500	V	1	1
5		7.00	2000	V	1	1
6		11.00	3000	V	1	1
7	243.20	2.50	3000	V	1.5	1
8				H		1
9	325.15	1.50	1600	V	1.5	1
10		3.50	2400	V	1	1
11		9.50	3000	V	1	1
12	448.00	1.40	1200	V	2	1
13		3.00	2000	V	1.5	1
14		7.20	3000	V	1.5	1
15	664.00	4.20	5000	V	1.5	1
16				H		1

The requirements for radiometric precision and absolute accuracy (in Table 4.1) reflect our expectation of what is technologically feasible. They have been used as input to retrieval simulations for the channel selection (see Figure 3.4). Radiometric noise is not very critical for CloudIce, since the cloud signal is strong. (This is in contrast to missions focused on measuring humidity, such as AMSU, where the signal variation due to humidity fluctuations is ten times weaker.)

4.2.2 Other Requirements

Other important requirements for CloudIce are summarized in Table 4.2. Below, we briefly comment on the most important requirements. See *Buehler et al.* [2007] and *Jarret et al.* [2007] for more detailed discussions.

Viewing Geometry

The requirement for conical scan geometry has two main reasons. Firstly, polarization is not consistent or very meaningful for a cross-track scan. Secondly, due to the three-dimensional structure of clouds, view angle biases for cloudy radiances are more difficult to correct than for clear-sky radiances. The conical scan ensures that all pixels are viewed with the same incidence angle, largely eliminating view angle biases. (There could be residual azimuthal view angle biases due to the typical orientation of frontal systems.)

The exact incidence angle is not very critical, 53.5° was chosen as a good compromise between maximum sounding altitude range and maximum horizontal swath range. See *Jarret et al.* [2007] for a more detailed discussion.

Azimuth Scan Angle

The azimuth scan angle requirement of ±65° ensures a broad swath in the forward direction. Side views are scientifically less useful and are therefore used for the radiometric calibration. Optionally one wants to have also an aft view, even if this is limited to a central part of the scan (±15°). This will allow innovative experimental retrievals, exploiting either the stereo effect due to the nearly opposite azimuth angle, or exploiting the short time difference (a few minutes) to study the temporal evolution of convective systems.

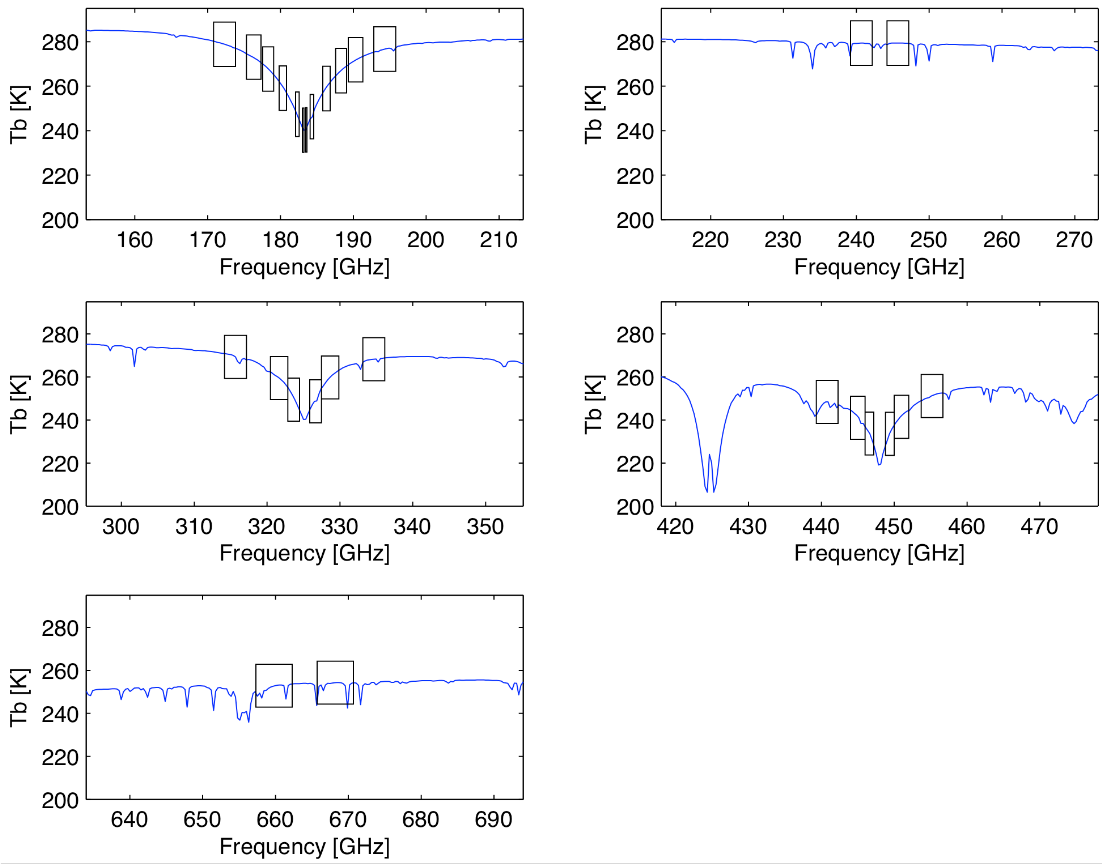


Figure 4.5: A detailed view of the CloudIce channel positions. The spectrum shown is the simulated clear-sky radiance (in Planck brightness temperature units) for a tropical model atmosphere. Each channel consists of two sidebands, located on either side of a central frequency. The heterodyne technique used implies that only a single measurement value is recorded for the integrated radiance in both sidebands.

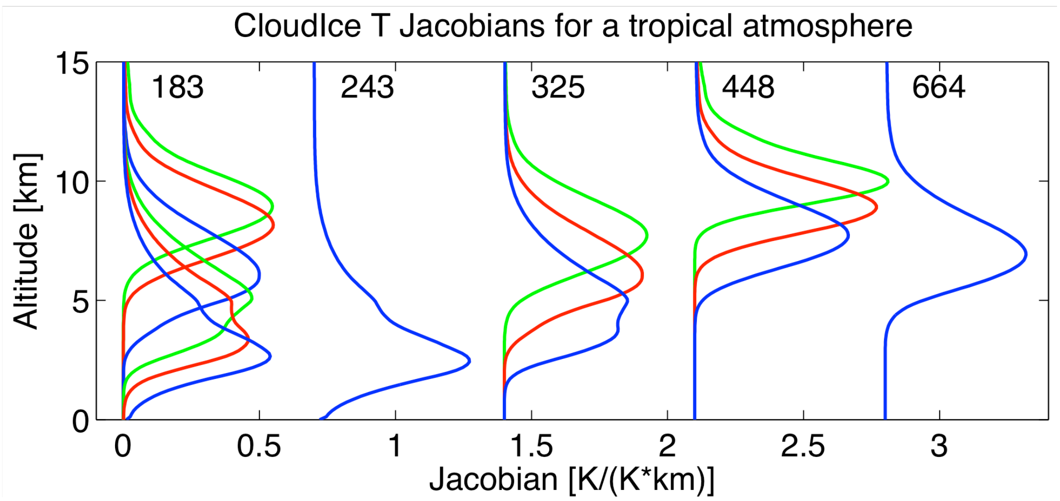


Figure 4.6: CloudIce Jacobians. These are the derivatives of the measurement with respect to changes in the atmospheric temperature at different altitudes. The Jacobians indicate the measurement altitude of the different channels. The figure is for a tropical clear-sky scenario. (Jacobians for different radiometers have been shifted to the right by different amounts, so that they all can be displayed in a single graph.)

Table 4.2: A summary of CloudIce system requirements. Goal, breakthrough, and threshold are given where relevant, otherwise only breakthrough.

Parameter	Goal	Breakthrough	Threshold	Comments
Viewing geometry	Conical scan with 53.5° ground incidence			~ - 45° on board elevation angle
Line of sight scan angle in azimuth On ward		± 65° in satellite reference frame		
Line of sight scan angle in azimuth back ward	± 65°	± 15°	0°	
Crosstrack pixels size	10 km	15 km	20 km	
Crosstrack pixels overlap		10%		
On track pixels size	10 km	15 km	20 km	
Ontrack pixel overlap		10%		
Collocation of pixels		Yes, ± 10% pixel size	No	
Antenna efficiency		>95%		
Science data dynamics		16 bits		
Geolocation	10% pixel size		30% pixel size	
Operations		Systematic acquisition		
Latency	4 hours		1 week	4 hours corresponds to GPM need
Orbit		MetOp orbit		800 km mean altitude, 9:30 equat. cross. time
Coregistration with MetOp (IASI)	1 min	5 min	10 min	
Lifetime	7 years	3 years	1 years	

Spatial Resolution

A spatial resolution of 10-15 km is consistent with the resolution of mesoscale circulation models and thus a good scale to study clouds. Even higher resolution would also give a clear science benefit, since clouds are a multi-scale phenomenon. See *Buehler et al.* [2007] for a more detailed discussion.

Orbit

As argued in detail in *Buehler et al.* [2007], the scientific requirement of near global coverage within 24h, together with the requirement of constant local time (to avoid aliasing due to the diurnal cycle), imply a sun-synchronous orbit near 800 km orbit altitude. However, there is another crucial issue here, namely the requirement for simultaneous infrared data. This requirement is addressed by flying in formation with MetOp, which fixes all orbit parameters (altitude and local time of ascending node). The time difference requirement of 1-10 minutes to MetOp comes from the need to observe the same atmospheric state, together with the typical time scale of cloud evolution.

The planned equator crossing times of MetOp-C (9:30 a.m. and p.m.) are suitable to observe cirrus clouds, including anvil cirrus generated by convection. Furthermore, the planned launch date of Metop is 2017, one year before the planned CloudIce launch, so we assume it will be available as tandem partner. In case Metop-C is not available, the fallback alternatives would be (a) to fly tandem with another operational meteorological satellite, or (b) to fly solo. Fallback option (a) is the preferred one, since it maximizes the science benefit. But option (b) is clearly also feasible, and would still make CloudIce scientifically worthwhile.

Latency

We propose that CloudIce should deliver data in near realtime (<4h latency) to satisfy the needs of numerical weather forecasting. This is not a strict requirement, since the mission is primarily a science mission. But the data would be very useful for NWP, so it should be provided on a best-effort basis.

Lifetime

The technical requirement on mission lifetime follows directly from the scientific lifetime requirement (compare Table 3.1).

4.3 Heritage

The instrument is an updated version of the CIWSIR instrument that was proposed in the previous two Earth Explorer calls by the same science team. Subsequent to the 2005 submission, ESA has funded several preparatory activities for this instrument, including the establishment of mission and instrument requirements [*Jarret et al.*, 2007; *Buehler et al.*, 2007] and the definition of an aircraft instrument with similar submillimeter channels [*Charlton et al.*, 2010]. Furthermore, the funding for the actual implementation of the aircraft instrument has now been approved. The instrument will be subsequently available for concept validation campaigns and postlaunch calibration and validation.

Similar submillimeter channels are also planned for an ice cloud instrument on the operational platform Post-EPS, but the inclusion of this mission is not yet confirmed. (See Section 3.4 for a discussion of the relationship and timing of Post-EPS relative to CloudIce.) Independent industry consortia (led by Astrium SAS and Thales Alenia Space Italy, respectively) have already developed conceptual designs for the Post-EPS instrument. The CloudIce mission can take advantage of these initial studies, which will allow a rapid start of the mission program, as necessary to achieve the planned launch in 2018. CloudIce would be an important precursor for a possible operational instrument on Post-EPS.

The strawman mission concept presented in the next section is based on an instrument concept by Astrium SAS. Other instrument concepts are available, for example by Sula Systems. The choice for the Astrium concept was made for practical reasons, since having a single provider for instrument, platform, and overall mission concept greatly simplified the proposal preparation. The choice does not imply a judgment on the relative merits of the different instrument concepts. A Sula Systems instrument concept is described in *Jarret et al.* [2007]. The final mission concept will be selected in Phase A.

4.4 Aircraft Instruments

As mentioned in Section 3.3 and demonstrated in Section 3.8.3, aircraft instruments play a key role for retrieval algorithm validation and fine-tuning. Furthermore, they allow exciting scientific studies in their own right. For both applications it is crucial that these instruments are deployed within coordinated campaigns, so that complementary data from other sensors are available. The CloudIce scientific community can use three such instruments, as summarized in

Table 4.3: A summary of airborne submillimeter-wave radiometers available to the CloudIce science community.

Instrument	CoSSIR	PSR-S	ISMAR
Agency	NASA	NOAA	Met Office/ESA
PI	F. Evans	A. Gasiewski	C. Lee
Aircraft	ER-2, WB-57	P-3, DC-8, ER-2, WB-57, Geophysica	FAAM (possibly HALO)
Reference	*Evans et al.* [2005]	*Piepmeier and Gasiewski* [1996]	*Charlton et al.* [2010]
Channels [GHz]	183.3 (3), 325.1 (3), 448.0 (3), 640 (V+H), 874	183, 340, 380, 424 (several channels per line)	118.75 (5), 243.3 (V+H), 325.25 (3), 424.7 (3), 664 (V+H) Also available from MARSS/Deimos: 23.8(V+H), 50.1(V+H), 89(V+H), 183.3 (3) Additionally planned: 448 (3), 874

Table 4.3. (The two US instruments are available already, the European one will be available in time for Phase A.)

Concerning the European instrument, the Met Office (UK) is developing a submillimeter airborne instrument ISMAR (International SubMillimeter Airborne Radiometer), to extend the current microwave capability of MARSS and Deimos (similar to AMSU B & A channels) on the FAAM (Facility for Airborne Atmospheric Measurements) BAe-146 aircraft (see Figure 4.7). ESA are planning to upgrade ISMAR to enable its use as an airborne companion for CloudIce and other submillimeter satellite missions. The anticipated timescale will provide results during Phase A of the CloudIce mission. ISMAR has been designed to allow the addition of further channels, as well as the ability to be flown on other platforms (e.g., HALO).

Figure 4.7: Left: The FAAM aircraft with the positions of ISMAR (submillimeter channels) and MARSS (183 GHz and below). Right: A cutaway view of ISMAR mirror, scan drum, and feedhorn cluster.

7 Annexes

7.1 References

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7.2 Table of Acronyms

8PSK	8 Phase Shift Keying
ACE	Aerosol-Cloud-Ecosystems
Ah	Ampère-hour
AIT	Assembly Integration and Tests
AMSR-E	Advanced Microwave Scanning Radiometer - Earth Observing System
AMSU	Advanced Microwave Sounding Unit
AOCS	Attitude and Orbit Control System
AR4	Assessment Report 4
ARTS	Atmospheric Radiative Transfer Simulator
ASAP	Ariane Structure for Auxilliary Payloads
ASAP-S	Arianespace System for Auxiliary Payloads- Soyuz
AVHRR	Advanced Very High Resolution Radiometer
BE	Back End
BOL	Beginning Of Life
BT	Brightness Temperature
CCSM	Community Climate System Model
CDR	Critical Design Review
CEOS	Capabilities of Earth Observation Satellites
CIWC	Cloud Ice Water Content
CIWSIR	Cloud Ice Water Submillimeter Imaging Radiometer
CLWC	Cloud Liquid Water Content
CNES	Centre National d'Études Spatiales
CoSSIR	Compact Scanning Submillimeter-wave Imaging Radiometer
CPL	Cloud, Precipitation and Large Scale Land Surface Imaging
CPR	Cloud Profiling Radar
CRS	Cloud Radar System
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CSW	Central SoftWare
DC	Down Converter
Dme	Median mass equivalent sphere diameter
DWD	Deutscher Wetterdienst
EarthCARE	Earth Clouds, Aerosols and Radiation Explorer
EC	Economic Conditions
ECHAM	European Centre HAmburg Model
ECMWF	European Centre for Medium-Range Weather Forecasts
ECV	Essential Climate Variables
EE	Earth Explorer

EGSO	Electrical Ground Support Equipment
ENSO	El Niño Southern Oscillation
EO	Earth Observation
EOS	Earth Observing System
EPS	EUMETSAT Polar System
ER	Earth Resources
ESA	European Space Agency
ESOC	European Space Operations Centre
ESRIN	European Space Research INstitute
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
FAAM	Facility for Airborne Atmospheric Measurements
FDIR	Failure Detection, Isolation and Recovery
FSS	Frequency Selective Surfaces
g	Gram
GaAs	Gallium arsenide
Gb	Gigabit
GCM	General Circulation Model
GCOS	Global Climate Observing System
GHz	GigaHertz
GISS	Goddard Institute for Space Studies
GPM	Global Precipitation Measurement
GSE	Ground Segment Equipment
GWC	Graupel Water Content
H	Horizontal
h	hour
HALO	High Altitude and Long Range Research Aircraft
HK	HouseKeeping
HKTM	HouseKeeping TeleMetry
IASI	Infrared Atmospheric Sounding Interferometer
ICU	Instrument Control Unit
IF	Intermediate Frequency
IPCC	Intergovernmental Panel on Climate Change
IR	InfraRed
ISRO	Indian Space Research Organisation
IWC	Ice Water Content
IWP	Ice Water Path
ITAR	International Traffic in Arms Regulations
ISMAR	International SubMillimeter Airborne Radiometer
JPL	Jet Propulsion Library
K	Kelvin
kbps	Kilobit per second
km	Kilometer
L0/L1/L2	Level-0, Level-1, Level-2
LEO	Low Earth Orbit
LNA	Low-Noise Amplifier
LO	Local Oscillator
LTDN	Local Time Descending Node
m	Meter
MADRAS	Microwave Analysis and Detection of Rain and Atmospheric Structures
MARSS	Microwave Airborne Radiometer Scanning System
Mb	Megabit
MESO-NH	MESOscale Non-Hydrostatic model
Metop	The current generation of European polar orbiting operational meteorological satellite
MGSE	Mechanical Ground Support Equipment
MHS	Microwave Humidity Sounder
MHz	MegaHertz
MIMR	Multi-Frequency Imaging Radiometer
MIPAS	Michelson Interferometer for Passive Atmospheric Sounding
MLS	Microwave Limb Sounder
mm	Millimeter
NASA	National Aeronautics and Space Administration
NeDT	Noise equivalent delta temperature

NOAA	National Oceanic and Atmospheric Administration
NWP	Numerical Weather Prediction
OBC	On-Board Computer
OGSE	Optical Ground Support Equipment
PA	Product Assurance
PDHT	Payload Data Handling and Transmission
PDR	Preliminary Design Review
PFM	Proto-flight model
PI	Principal Investigator
PR	Precipitation Rate
PREMIER	PRocess Exploration through Measurements of Infrared and millimetre-wave Emitted Radiation
PSR	Polarimetric Scanning Radiometer
QON	Quasi Optical Network
RAL	Rutherford Appleton Laboratories
RF	Radio Frequency
RH	Relative Humidity
RMS	Root-Mean-Square
RT	Radiative Transfer
RTTOV	Radiative Transfer for TOVS
RWC	Rain Water Content
SAPHIR	Sondeur Atmospherique du Profil d'Humidite Intertropicale par Radiometrie
SIMGEO	SIMulations GEOstationnaires database
SIRICE	Submillimeter and Infrared Ice Cloud Experiment
SS	Separation System
SSM/I	Special Sensor Microwave Imager
SSMI-S	Special Sensor Microwave Imager / Sounder
SWC	Snow Water Content
Tb	Brightness temperature
TBC	To Be Confirmed
TC	TeleCommand
TC4	Tropical Composition, Cloud and Climate Coupling
TIROS	Television InfraRed Observation Satellite
TM	TeleMetry
TM&C	TeleMetry and Control
TMI	TeleMmetry image
TOVS	TIROS Operational Vertical Sounder
TRL	Technology Readiness Level
TT&C	Telemetry, Tracking and Command
TWTA	Traveling-wave tube amplifier
TWV	Total Water Vapor
UK	United Kingdom
UKMO	United Kingdom Met Office
US	United States
UTC	Coordinated Universal Time
V	Vertical
VDI	Virginia Diodes, Inc
WMO	World Meteorological Organisation
Zme	Median IWP altitude
µm	Micrometer

7.3 Contributing Authors

Below is a list of persons that have in some way or other contributed to this proposal (in alphabetical order).

Peter Ade (Cardiff University, UK)
Stefan Buehler (Luleå University of Technology, SE)
Claude Camy-Peyret (Université Pierre et Marie Curie, FR)
Janet Charlton (Sula Systems, UK)
Susanne Crewell (University of Cologne, DE)

Eric Defer (Observat. de Paris, FR)
Abhay Devasthale (SMHI, SE)
Salomon Eliasson (Luleå University of Technology, SE)
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Steve English (Met Office, UK)
Patrick Eriksson (Chalmers, SE)
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Paul Field (Met Office, UK)
Al Gasiewski (NOAA, US)
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Viju John (Met Office, UK)
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7.4 Data User Statements

This section contains two statements from prospective data users (one from the climate research community, one from numerical weather prediction). They are intended as supplementary material to the short use cases summary in Section 3.6.

7.4.1 Climate Modeling

Within the climate modeling community, global datasets of key variables are of particular interest. Parameterizations of small-scale processes, such as clouds that are made up of cloud droplets and/or ice crystals, are usually constructed based on space and time limited detailed observations and process modeling. The next step is to evaluate how they are performing in the global model. For this it is essential to have high quality global datasets spanning several years to constrain the models. Before CloudSat, no global dataset of cloud ice content was available at all, thus a huge spread in the global models is seen. Ice clouds are playing an important role in the cloud forcing and thus for the earth's radiation balance. Improvement of modeling ice clouds are of high priority for increasing the reliability of climate models, which are the only tool available for predicting future climate change.

So, a climate modeler will use the entire CloudIce dataset as benchmark to test improved parameterizations of convection and cloud microphysics. She or he will run the global model for the same time period as the measurements, and compare mean state and variability of parameters such as IWP.

7.4.2 Numerical Weather Prediction

Global Numerical Weather Prediction models are used operationally to provide forecasts for a week or so ahead, but are increasingly also being used for longer range forecasting (monthly, seasonal, decadal and longer term climate prediction). Hence it is important for the model to have a 'climate' that is close to that observed. Global distributions of ice water path would therefore be used to assess a model's annual mean 'climate' as well as seasonal variations. Even one year of data can be informative and would provide an observational ice water path and particle size reference for validating the model in different geographical regions across the globe and assessing the impact of changes as model developments are implemented. Combined with other observational datasets, this would help to constrain the parametrization of cloud microphysical processes for the ice phase.

In addition to evaluating the data for the mean state, the near global coverage every 24 hours would allow a direct assessment of the skill of the ice cloud field from a NWP model, for example in terms of root mean square error or specific skill scores. A regime-dependent analysis of the skill of ice water path and mean ice particle size could be performed in order to determine when and where the deficiencies in the model ice field are occurring, for example in the tropics, where the ice water path associated with glaciation of large-scale organised deep convective activity is particularly uncertain.

7.5 Letters of Support

The following pages contain alphabetically sorted support letters by:

- The German Weather Service (DWD)
- Jet Propulsion Laboratory (JPL)
- Met Office (UK)
- Swedish Meteorological and Hydrological Institute (SMHI)

Deutscher Wetterdienst
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Deutscher Wetterdienst - Postfach 10 04 65 - 63004 Offenbach

Prof. Dr. Stefan Bühler

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Offenbach, 3. May 2010

Dear Dr Bühler,

We would like to express our strong support for the CloudIce Mission Proposal.

Considering the currently available observing systems and its use for numerical weather prediction (NWP) as well as climate monitoring the quantitative measurement of cloud ice water path (IWP) and related variables presents a gap in the present system. Although the active instruments of CLOUDSAT and Calipso provide very detailed measurements of ice cloud, their use in operational weather prediction, e.g. data assimilation, is limited. CloudIce is undoubtedly an important step to fill this gap and provide IWP data with continues near-global coverage on a daily basis.

The modelling department of DWD has recently extended their global model GME with a fully prognostic cloud microphysics scheme, and a major challenge is the initialization and validation of the cloud ice mass. Similar efforts are currently under way at ECMWF. CloudIce could play a key role in improving the representation of ice clouds in NWP and climate models.

Best regards,

Prof. Dr. Gerhard Adrian

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Der Deutsche Wetterdienst ist eine teilrechtsfähige Anstalt des öffentlichen Rechts im Geschäftsbereich
des Bundesministeriums für Verkehr, Bau und Stadtentwicklung.
Das Qualitätsmanagement des DWD ist zertifiziert nach DIN ISO 9001:2000 (Reg.-Nr. 616/2324 ZER-QMS)

Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, California 91109-8099

April 16, 2010

To:
Professor Stefan Buehler
Department of Space Science
Luleå university of technology
Box 812
981 28 KIRUNA, SWEDEN

Re: CloudIce Mission Proposal

Dear Prof. Buehler,

I am writing to express my strong support and interest in the proposal for CloudIce Mission.

Future climate and weather research depends critically on how well clouds are understood, and ice cloud is a critical link in the aerosol-cloud-precipitation processes in the Earth's atmosphere. As numerical prediction models continues to improve, there will be a sharp increasing need for global high-resolution cloud data to better understand, model, validate, and predict these processes. Therefore, the CloudIce Mission reflects a version to address such a critical need in the future Earth science research.

For the CloudIce Mission, NASA/JPL can play a significant role with experiences and new capabilities in science and technology. Several NASA/JPL instruments, including Microwave Limb Sounder (MLS) and CloudSat, have made a great initial step in providing and proving usefulness of global cloud ice observations. However, more coverage and sampling are needed for enabling process studies, and the CloudIce Mission is aimed to improve these capabilities. Therefore, we will be enthusiastic to collaborate with you on this proposal and make it as a successful mission.

Sincerely,

Dong L. Wu, Ph.D
Principal Research Scientist
Supervisor, Aerosol and Cloud Group
Jet Propulsion Laboratory

Met Office
Hadley Centre

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24 May 2010

Dear Professor Buehler

I am writing to offer the strong support of the Met Office for the CloudIce Mission proposed by the consortium and led by yourself.

Considering the global observing system as a whole, observations of cloud ice water is a major gap. This is recognised by WMO in the context of global and regional NWP, and an accurate description of clouds remains one of the key problems identified by IPCC. Current instruments such as the Microwave Humidity Sounder are insensitive to small ice hydrometeors and can not therefore give reliable information on the ice water path, which is poorly constrained in climate and NWP models. CloudIce would fill this gap and provide information of unprecedented quality on global distribution and variability of ice water path and particle size.

The Met Office, with additional funding support from ESA, are developing an international airborne submillimeter instrument, ISMAR, which can be used as a satellite concept demonstrator for CloudIce, as well as for scientific atmospheric research. The Met Office are funding some flights hours specifically for this instrument, to provide measurements of ice clouds and precipitation cases. The anticipated timescale of demonstrator case studies fits with the phase A of CloudIce. This will provide data to improve scattering and radiative transfer modelling, and for CloudIce algorithm development, test and validation. Once CloudIce is launched the airborne instrument would also be available for validation and calibration.

If the mission is approved the Met Office will initiate projects to use the CloudIce data. In particular the Met Office would:

- use the data to evaluate the ice water climatology of global and regional model systems
- use the data to study ice cloud processes and improve model parameterisations
- evaluate the feasibility of direct assimilation of such data into 4D-var
- use the distribution of IWP from CloudIce to challenge NWP convective schemes and large scale clouds
- use the data to challenge climate models and their sensitivities to the treatment of cirrus clouds.

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Met Office
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In recent years the Met Office and other climate and NWP centres have invested considerable resources into improving the capability to exploit satellite millimetre and submillimeter observations of ice clouds, and are now in a very strong position to exploit these wavelength radiances.

Yours sincerely

Dr Clare Lee
Manager of Observation Based Research Facilities, Met Office

SMHI

Prof. Dr. Stefan Buehler
Satellite Atmospheric Science Group
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Sweden

Date: 2010-05-31
Our ref: Dnr 2010/1161/142

Support letter CloudIce Mission

Dear Prof. Buehler,

I am writing to you to express our strong support for the proposed CloudIce mission. It is addressing several themes of importance to our meteorological service, and would allow for preparation of algorithms for sub-mm channels hopefully to be continued operationally on post-EPS. The CloudIce mission will greatly further our knowledge about ice clouds, and thus contribute to reducing current uncertainties of cloud impact in the climate system. Better knowledge of Ice Water Path will also impact on both global and regional NWP models and thus improve weather prediction, both by exploiting the information to better model and represent cloud processes, and by directly assimilating the information into the weather prediction models.

Also we are looking forward to be able to investigate and exploit precipitation retrievals from sub-millimeter wavelength, which should be specifically interesting at higher latitudes and to characterize snowfall and light precipitation, representing yet another gap in the current observation system.

Flying the CloudIce mission in train with METOP-C gives excellent opportunities to sample the atmosphere in a consistent way, and to fully exploit the additional information gathered by the CloudIce Mission for both research and operational purposes. We wish you good luck with your proposed mission.

Best regards

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