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TOWARDS AN UPDATED/UPGRADED GLOBAL OBSERVING SYSTEM

This paper is the opinion of an expert appointed by EUMETSAT. It is a follow-on of discussions in CGMS-XXVII (Beijing 13-18 October 1999) and CGMS-XXVIII (Woods Hole 16-20 October 2000) followed by a CGMS “Workshop on long-term future of the basic sounding and imagery missions” hosted by WMO in Geneva, 23-24 April 2001. Its scope is to suggest specific topics for the envisaged increased cooperation between operationally-oriented agencies as represented in CGMS and R&D space agencies, according to intentions expressed at the “First consultation meeting on high-level policy on satellite matters” (Geneva, 22-23 January 2001).

This paper addressed the main gap areas between user requirements and space capabilities and provides suggestions on how to proceed with developments in such a way as to minimise the gaps in the post-2015 timeframe. Specifically, the necessary developments will be identified and classified according to a possible implementation schedule also reflecting the respective responsibilities of CGMS members and R&D space agencies, as follows:

- developments of long-term operational interest, to be demonstrated by R&D space agencies in the decade 2006-2015, and thereafter taken over by CGMS member for long-term continuation;
- missions that, for one or another reason (affordability within CGMS, evolutionary nature of the requirements and/or the technology, existence of another user community driving the requirements and the programmatic framework, …), will continue to be of primary interest of R&D space agencies or commercial entities, but access by operational meteo-climate users is required.

The conclusion will be represented by two “manifests” possibly to be used as reference starting point to help focusing discussions in future “Consultation meetings on high-level policy on satellite matters”.

Note: this document has been prepared by Dr. Bizzarro Bizzarri on request of the EUMETSAT Director as an input for discussion at CGMS XXIX (Capri, 22-25 October 2001) following documents on the same topic presented at CGMS XXVII and CGMS XXVIII. This does not imply EUMETSAT endorsement of the content, which remains responsibility of the Author, though the document itself attempts to incorporate at best all suggestions put forward at the CGMS Workshop on 23-24 April 2001.

1. Introduction

References for this document are:

- the CGMS XXVII EUM/WP-06 paper "*Compliance of the post-2000 satellite-based component of GOS with requirements and possible approach to update/upgrade future systems*", prepared by B. Bizzarri;
- the CGMS XXVIII USA/WP-08 paper "*Requirements and possible approach to update/upgrade the satellite-based component of GOS*", also prepared by B. Bizzarri;
- the proceedings of the "*CGMS Workshop on long-term future of the basic sounding and imagery missions*" hosted by WMO in Geneva, 23-24 April 2001, reported to CGMS XXIX by P. Menzel.

The first two papers:

- identified the most serious gaps in the post-2000 GOS, and proposed missions to fill them, all based on small-medium size satellites, also preparing for the eventual replacement of current/developing large satellites by smaller elements within a spread mission context;
- identified those mission which, for one or another reason, should in the long-term future be run under the full responsibility of CGMS members, though to be prototyped/demonstrated by R&D space agencies in the medium term (a "manifest" of such mission was introduced);
- identified a number of WMO requirements which are unlikely to be met within the resources of CGMS members, but could be fulfilled by accessing data from scientific/technological/commercial programmes (a "manifest" listing such measurements was shown, for the attention of R&D space agencies and possible other space operators).

The idea of increased cooperation between CGMS and R&D space agencies to better address WMO requirements was preliminary discussed at CGMS XXVIII in a short joint meeting with representatives of R&D space agencies. This was formally followed by a "First consultation meeting on high-level policy on satellite matters" organised by WMO in Geneva, 22-23 January 2001.

Meanwhile, CGMS XXVIII also decided to hold the "*Workshop on long-term future of the basic sounding and imagery missions*" on 23-24 April 2001 in Geneva. There, in addition to the broad-scope discussion paper of B. Bizzarri, focused contributions were presented on several items. It should be noted that the Workshop results consist of a number of recommendations, generally on specific advanced methods to fulfil certain requirements, but discussion of an overall strategy to the future GOS was not in the purpose of the Workshop. This document captures the various proposals in the context of the implementation strategy previously developed, adapted/revised/corrected as necessary. The purpose of this document is still to provide CGMS with tools (the two "manifests") possibly to be used to focus the discussion with R&D space agencies in the context of the next "Consultation meetings on high-level policy on satellite matters" in order to avoid that the momentum acquired at the First meeting is lost because of persistent generic approach and lack of specific objectives.

To keep trace of the presentations at CGMS XXVII and XXVIII, ***Table 1*** reminds the *geophysical parameters* introduced by CEOS and adopted by WMO to formulate user requirements and evaluate space capabilities (Note: parameters that cannot be measured from space have not been reported). Starting from Table 1, key parameters or group of parameters will be discussed in respect of the potential compliance of performances with requirements; and parameters which have perspective of been available in an operational fashion will be screened from those more appropriate to be acquired by cooperation with other programmes outside the operational GOS. For the parameters candidate to be operationally available an implementation strategy will be recommended. To be noted that certain parameters will be found to belong to both categories (i.e., an operational "core" information complemented by specific supporting information available from non-GOS satellites).

Table 1 - List of geophysical parameters in the CEOS/WMO Database observable from space

Required geophysical parameters observable from space
Atmospheric thermodynamics
Atmospheric temperature profile; Specific humidity profile
Atmospheric stability index; Height and temperature of the tropopause; Height of the top of the Planetary Boundary Layer
Atmospheric dynamics
Wind profile
Atmospheric chemistry
Ozone profile; Trace gases other than ozone
Clouds and precipitation
Cloud imagery, cover, type, top temperature and height; Cloud base height
Precipitation rate at the ground**;** Precipitation index (daily cumulative)**;** Lightning detection
Clouds and radiation
Cloud water profile; Cloud ice profile; Aerosol profile; Aerosol size (average on total column); Volcanic ash
Cloud optical thickness; Cloud ice content and drop size (at cloud top); Short-wave cloud reflectance; Long-wave cloud emissivity
Downwelling solar radiation at TOA; Outgoing short-wave radiation at TOA; Outgoing long-wave radiation at TOA; Outgoing spectral radiance at TOA
Downwelling short-wave radiation at the Earth surface; Downwelling long-wave radiation at the Earth surface; Short-wave Earth surface bi-directional reflectance; Outgoing long-wave Earth surface radiation; Long-wave Earth surface emissivity
Ocean surface and sea-ice
Wind over sea surface; Sea surface temperature; Significant wave height; Dominant wave period and direction; Sea level; Ocean dynamic topography; Geoid
Water-leaving spectral radiance; Ocean chlorophyll, suspended sediment concentration, yellow substance absorbance; Ocean salinity
Sea surface imagery; Bathimetry
Sea-ice cover, type, thickness and surface temperature; Sea-ice elevation; Ice-sheet topography; Icebergs fractional cover and height
Land surface and vegetation
Snow cover, melting conditions and water equivalent; Glacier cover, motion, topography
Land surface temperature, Permafrost; Soil moisture; Fires area and temperature
Normalized Difference Vegetation Index (NDVI); Leaf Area Index (LAI); Photosynthetically Active Radiation (PAR), Fractional Photosynthetically Active Radiation (FPAR)
Land cover; Soil type; Vegetation type; Land surface imagery; Coastlines; Land surface topography

In the Table, parameters have been grouped under headlines representing the "themes" as will be discussed in the next Sections. In each Section, the importance of the theme/parameters is recalled, as well as the projection of future plans of observation. Then, the technical possibilities for improved quality are mentioned, and the implementation strategy for improvement outlined.

2. Atmospheric thermodynamics

Parameters: Atmospheric temperature profile; Specific humidity profile; Atmospheric stability index; Height and temperature of the tropopause; Height of the top of the Planetary Boundary Layer

Temperature and humidity soundings are basic satellite observations. They enter the motion primitive equations and control the mass field that thereafter forces the atmospheric circulation. Atmospheric temperature and humidity soundings enable retrieving the other parameters of this group, i.e. Atmospheric stability index, Height and temperature of the tropopause and Height of the top of the Planetary Boundary Layer.

In addition, other parameters benefit of the radiance measurements observed for the purpose of temperature/humidity sounding, specifically:

- *Cloud cover, type, top temperature and height, emissivity*, obtained as by-products during the retrieval process;
- *Sea surface temperature* and *Land surface temperature*, very accurate because of abundant information on atmospheric correction and differential effect of surface emissivity;

- *Downwelling long-wave radiation at the Earth surface*, a cascade product;
- *Cloud water (total column)* from the MW component of the sounding system;
- *Outgoing long-wave radiation at TOA* and *Outgoing spectral radiance at TOA*, for synergy.

Further applications of temperature/humidity sounding in support of other parameters stem from the suitability of these parameters to be submitted to 4-D assimilation. The most important are:

- *Wind profile* (see Section 3) and *Precipitation* (see Section 4).

The development of the temperature/humidity sounding mission for the polar orbit is well established. The MW component (AMSU-A [1] + AMSU-B [2] / MHS [3]) is currently operational and will continue to be used till about 2010 on NOAA satellites and 2015 on METOP/EPS. It will be replaced by ATMS [4] on NPOESS in 2009 (with a precursor flight on NPP [5] in 2006), but the performances will be only marginally improved (it should be noted that there is no chance to perform high-vertical-resolution sounding within clouds, as users would wish to do by MW). The IR component will move to spectroscopic instrumentation (for high-vertical-resolution) shortly by AIRS [6] on EOS/Aqua [7] and then by IASI [8] on METOP/EPS (2005) and CrIS [9] on NPP (2006) and NPOESS (2009). Here also, there is no way to further dramatic improvement of performances, thus we can draw the following conclusion:

- the long-term plan for the basic IR/MW temperature/sounding mission from polar orbit is rather consolidated: it will be progressively implemented during the next decade and will substantially continue with steady performances in post-2015, in the absence of better physical principles of remote sensing to be exploited for the bulk of the mission;
- the service from polar orbit, assuming a three-satellite coordinated system, will provide global coverage at 6-hour intervals (accounting for the non-horizon-to-horizon swath); the yield will be regular (from the MW component), but best quality (from the IR) will only be achieved in clear or near-clear air conditions; the product resolution will range from 50 km (for regular yield) to some 10-20 km (under favourable cloud conditions).

This situation does not fully meet user requirements. The following shortcomings exist:

- the frequency of observation is marginal for Regional NWP and totally insufficient for Nowcasting;
- vertical resolution and accuracy are not sufficient to capture atmospheric discontinuities (height of the tropopause and of the top of PBL);
- the error structure of the measurement is unfavourable for long-term averages intended to achieve the level of accuracy required for climate monitoring;
- the physical principle exploited to observe water vapour (passive radiometry) cannot provide vertical resolution commensurate to the variability of this compound;
- in the higher stratosphere, the accuracy of temperature profile is not sufficient for application to long-term NWP and climate modelling.

In the order, the necessary developments to overcome these problems are described as follows, ending with suitable recommendations (to be taken over again in next Sections).

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[1] AMSU-A = Advanced Microwave Sounding Unit A.
[2] AMSU-B = Advanced Microwave Sounding Unit B.
[3] MHS = Microwave Humidity Sounder.
[4] ATMS = Advanced Technology Microwave Sounder.
[5] NPP = NPOESS Preparatory Program.
[6] AIRS = Atmospheric Infra Red Sounder.
[7] Formerly EOS-PM/1.
[8] IASI = Infrared Atmospheric Sounding Interferometer.
[9] CrIS = Cross-track Infrared Sounder.

The only chance to provide an observing cycle sufficient for Regional NWP and Nowcasting is to extend the temperature/humidity sounding mission to the geostationary orbit. At present, only GOES carries out a sounding mission, but only with coarse vertical resolution (by an IR radiometer). It is necessary to move to spectroscopic means, and to extend the sounding mission to all the meteorological geostationary satellites in the equatorial belt. A first experiment is planned by NASA (GIFTS [10]) around 2005, to pave the way for an operational follow-on on GOES (ABS [11]) sometimes in 2009. In Europe, the nearest occasion to upgrade the Meteosat system will be in 2015 with a possible Meteosat Third Generation. From this discussion, we have the premises for our first recommendation:

- **Recommendation 1** - ***In the 2015 timeframe, all meteorological geostationary satellites in GOS should be equipped with spectrometers for frequent temperature/humidity sounding in IR***.

Extension of the temperature/humidity sounding mission to the geostationary orbit in the MW range is less straightforward to be recommended. The frequencies currently used are in the bands 57 GHz (temperature) and 183 GHz (humidity). Because of the diffraction law, the antenna size necessary to ensure a decent resolution (10-30 km) from geostationary orbit would be prohibitive. To stay within the limits of, say, 2-3 m antenna, frequencies in the Sub-mm range could be envisaged (425 GHz for temperature and 380 GHz for humidity; for temperature, there is also the 119 GHz band which implies larger antenna). The problem with these frequencies is that, because of the water vapour continuum, they are nearly blind to the lower troposphere, which is a handicap for a geostationary satellite generally assumed to contribute to Nowcasting. In addition, these frequencies are strongly affected by clouds, specifically ice clouds, to the extent that one new application has been thought for them, i.e. "cloud sounding" for the purpose of *Quantitative Precipitation Forecast* (QPF). In front of this exciting perspective, caution is needed because a technological gap still exists at these frequencies, which, e.g., precludes that a fully operational instrument (i.e. to systematically observe the full disk in 1 h) can be built in the near future. Also, the size of the antenna anyway needed (2-3 m) suggests that, as an alternative to embarking such a volumetrically embarrassing instrument on a multi-purpose satellites, a dedicated (small) satellite could be preferable. An appropriate recommendation could be:

- **Recommendation 2** - ***An early demonstration mission on the applicability of MW/Sub-mm radiometry for temperature/humidity and cloud sounding from geostationary orbit should be provided, in view of possible operational follow-on in the 2015 timeframe.***

For the problem of vertical resolution of cross-nadir temperature/humidity sounding, and also for acquiring "absolute" measurements suitable for long-term averaging, the solution of ***radio-occultation sounding*** has now being on the table since long. Several instruments have already been (GPS/MET) or are being (CHAMP [12]) flown, and others are planned, including GRAS [13] for METOP/EPS and GPSOS [14] on NPOESS, and some mini-constellation also is in view (COSMIC [15]). However, a true operational mission to provide sufficient density/frequency to organically support Global NWP requires several tens of satellites (nominally 24 for one measurement each 6 h in most 300-km cells) in a well coordinated system (i.e. a "constellation"). The key question is the affordability of such a system, which, obviously, makes sense only if it can be maintained for an indefinite time. The subject of affordability will be discussed in a next Section devoted to all systems requiring constellations. For the moment, we have:

- **Recommendation 3** - ***A large constellation of radio-occultation sounders should be implemented, designed to minimise running costs so as to make possible a long-term operational follow-on.***

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[10] GIFTS = Geostationary Imaging Fourier Transform Spectrometer.
[11] ABS = Advanced Baseline Sounder.
[12] CHAMP = Challenging Minisatellite Payload.
[13] GRAS = GNSS Receiver for Atmospheric Sounding.
[14] GPSOS = GPS Occultation Sensor.
[15] COSMIC = Constellation Observing System for Meteorology, Ionosphere and Climate.

The problem of vertical resolution of water vapour observation cannot be solved by cross-nadir passive sounding. In fact, the principle implies that the water vapour in one layer is determined as difference between the total columns from the top and the bottom of the layer to the satellite. If narrow layers are desired, the accuracy rapidly degrades. To overcome the problem, active measurements have been proposed, and tested by airborne instrumentation, based on the use of ***Differential Absorption Lidar (DIAL)***. This works by measuring the intensity of the signal backscattered in a water vapour absorption band (e.g., 940 nm) as compared to that one in a nearby window, and determining the height by ranging. The vertical resolution may be of 0.5 km in the lower troposphere and 1 km in the higher troposphere. Trade-off is necessary between accuracy and horizontal resolution, due to the need to collect many (decorrelated) samples to get sufficient signal-to-noise. For an accuracy of 10 % the resolution could be around 100 km along track (it is essentially a nadir-only instrument, though the pointing direction can be somewhat moved off-track). Although, from a strict viewpoint, an "uneducated" comparison with user requirements would show impossible compliance because of the poor observing cycle (about two weeks for a global coverage of one observation each 100-km cell at the equator), it should be noted that, anyway, the instrument generates about 6000 profiles/day which, if the quality is good, could provide a very sizeable impact on NWP after 4-D assimilation in the context of the sounding observations from the IR/MW cross-nadir instruments. Unfortunately, a DIAL cannot be an instrument as small as necessary to allow thinking to a constellation bringing the observing cycle to a few hours, as desirable (a telescope with a primary optics larger than 2 m is necessary). Therefore, the recommendation needs to be limited to research purposes (see also Section 6 on *Clouds and radiation*), with the requirement to have data available for operational use:

- **Recommendation 4** - ***Active sensing of water vapour by DIAL for high-vertical resolution profiling should be pursued, primarily for research purposes, procuring that data are accessible for operational use.***

As mentioned, the accuracy and vertical resolution of temperature profiles observed in cross-nadir mode are not sufficient for the purpose of long-term NWP and climate modelling in the higher stratosphere. However, a problem does not exist, since all atmospheric chemistry instruments operating in limb mode are capable to contextually measure the temperature of the observed layer. This information should therefore made available for operational use, thus we have the recommendation:

- **Recommendation 5** - ***Temperature profiles in the higher stratosphere from missions oriented to atmospheric chemistry exploiting limb sounders should be made available for operational use.***

3. Atmospheric dynamics

Parameter: wind profile.

With increasing interest in long-term NWP and Seasonal and interannual forecasts (which implies greater impact of general circulation in low latitudes) and, on the opposite side, with decreasing scales of motion described in Regional NWP models (perspective resolution in 2015: 3-5 km) the importance of wind observation is becoming a true emergency, also at high latitudes. It is reminded that the wind profile is by far the most active parameter in the motion primitive equations, and that, at high values of the Rossby parameter, i.e. either because of low latitude or small motion wavelength, the wind cannot be derived by balance equations from the mass field.

Unfortunately, wind is not an easy parameter to be measured by remote sensing, i.e. through radiation measurements. The available observing principles are:

- tracking atmospheric parcels as "signed" by some feature (cloud mesoscale patterns; water vapour patches; possibly ozone patches, …) so as to enable their recognition in successive images;
- passively measuring the Doppler shift of line radiation from molecules (only applicable to the upper atmosphere);

- actively measuring the Doppler shift (by lidar) of atmospheric eddies "signed" by aerosol and/or molecular scattering.

In addition, the wind field description can be improved by 4-D assimilation of any parameter of sufficient conservative properties (temperature profile, water vapour profile, ozone, …).

The first method is the only one currently used, exploiting image sequences from geostationary satellites. There are several limitations, such as;

- insignificant vertical resolution: one or two levels, generally in atmospheric layers where clouds are more frequent, or where the weighting functions of WV channels peak;
- irregular yield: more dense with cloud tracers (but limited to cloudy areas), more sparse (and less accurate) in cloud-free areas (from water vapour);
- unfavourable error structure, controlled by the suitability of the tracer, the accuracy of height assignment, the proximity of jet-streams, etc.;
- conflicting requirements of resolution and accuracy: if the air parcel is smaller to enhance resolution, its "conservative" properties (mesoscale structure) are less firm and the quality degrades.

These well known problems may be reduced by several improvements to be applied to the imagery mission from geostationary orbit: better resolution to increase the number of tracers; much faster observing cycle (e.g., 1 min) to increase yield and accuracy by tracking short-living targets also more representative of the wind field (being passive). The problem of height assignment is better solved by relying on a co-flying temperature/humidity sounder, rather than by increasing the number of channels of the imager (height assignment requires good spectral information rather than fast observing cycle and high resolution). Thus we have the recommendation:

- **Recommendation 6** - ***Imagers of future geostationary satellites should have improved spatial resolution and much improved observing cycle, at least for those channels relevant for wind information retrieval.***

As mentioned, with increasing interest of regional NWP models for small motion scales, wind information has become a necessity also at high latitudes. Imagers from polar orbiters provide large overlaps at high latitudes, thus the practise of wind determination from tracer displacements could be extended to polar orbiters. The tracking interval between two successive passes (about 100 min) is rather long, but still suitable to high-latitude clouds or water vapour patches, as demonstrated by experiments performed by the EOS/Terra [16] MODIS [17] (which implies that the NPOESS VIIRS [18] should also be able to do the job). Thus we have:

- **Recommendation 7** - ***Imagers of future polar satellites should be designed as to enable trace motion wind determination in overlapping areas at high latitudes, similarly to what is done from geostationary satellites.***

However, the greatest gap of wind profiling from image sequences is the vertical resolution. In cloud-free areas, where water vapour channels are used, there is the possibility to populate several atmospheric layers if the water vapour profile is available with reasonably high vertical resolution (i.e. by a spectrometer). To make this possible, however, the instrument resolution must be reasonably good (to enable identifying fine water vapour structures) and the sampling interval reasonably short (consistently with the short lifetime of fine structures): i.e., the sounder must possess most characteristics of an imager. This is the principle of the GIFTS experiment (2005), which provides 4 km resolution in the

[16] Formerly EOS-AM/1.
[17] MODIS = Moderate-resolution Imaging Spectroradiometer.
[18] VIIRS = Visible/Infrared Imager Radiometer Suite.

4.4-6.1 µm range which includes H_2O and CO_2 bands (about 10 km in the 15 µm CO_2 band), and observing cycle of 1 h when used for global sounding. Simulations and aircraft campaigns have shown that there is little doubt that the objectives can be achieved, thus the recommendation:

- **Recommendation 8** - ***Sounders from future geostationary satellites must be designed in such a way as to enable wind profiling by water vapour profiling with conveniently high resolution (horizontal, vertical and time).***

Coming to instantaneous measurements by exploiting the Doppler effect, so far passive methods only have been used (e.g., WINDII [19] on UARS [20], exploiting lines of neutral and ionised oxygen and of OH). Further proposals have been put forward, but the technique is only applicable in limb mode (by LEO) to the upper atmosphere. Nevertheless, it is still worth to have:

- **Recommendation 9** - ***Any wind profile data available from experimental satellites, e.g., by passive Doppler spectroscopy of the upper atmosphere, should be made available for operational use.***

All methods so far described have unsurpassable limits of vertical resolution and accuracy, in addition to the problem of yield regularity. The introduction of ***active sensing*** (Doppler lidar) could solve this problem. The (side looking) lidar measures the Doppler shift of the return pulse due to the relative velocity of the LEO satellite and the atmospheric eddy as "signed" by aerosol (Mie scattering) and/or molecules (Rayleigh scattering). The first demonstration mission (Aeolus [21]) is being developed by ESA for a launch in 2006. To spare resources, it makes use of an incoherent lidar at 355 nm and a single side look, with some sacrifice of performance in the lower troposphere, and coarse horizontal resolution (return echoes are averaged over 50 km and the 50-km measurement is taken at 200 km intervals along the satellite motion direction). The anticipated accuracy is about 0.5 m/s in the lowest 2 km and 1.2 m/s above; the vertical resolution is 0.5 km in the lowest 2 km, 1 km in the layer 2-16 km and 2 km above. Better performances could be achieved by using coherent lidar and longer wavelengths (e.g., 10.6 µm): however, a much bigger instrument would be necessary. The ALADIN [22] instrument on Aeolus also is rather large (300 kg / 300 W), to the extent that the mission is on the wedge of the "small" class (800 kg / 600 W, also thanks to the favourable dawn-dusk orbit selected for the demonstration).

The main problem with Aeolus is the observing cycle, requiring about 1 week to get one measurement in each 200-km cell at the equator. As an additional limitation, measurements are only radial, thus full assimilation is required to build the vector information (which, in a sense, biases the use of the data towards the specific model used for assimilation). Notwithstanding the limitations of the presently developing system, this is one way to go, since it is the only one potentially able to provide the required accuracy and vertical resolution. It is reminded that, when certain data have specific high quality characteristics, their impact on the assimilation model is sizeable even with a small number of measurement (Aeolus, will produce about 3000 soundings/day). Two recommendations stem from this discussion:

- **Recommendation 10** - ***A long-standing technological programme to follow Aeolus is solicited, to improve coverage characteristics and reduce instrument size to the extent that a sustainable Doppler wind lidar system may become operational in due time.***

- **Recommendation 11** - ***Wind profiles from Doppler lidar technology demonstration programmes must be made available for operational use.***

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[19] WINDII = Wind Doppler Imaging Interferometer.
[20] UARS = Upper Atmosphere Research Satellite.
[21] Formerly ADM = Atmospheric Dynamic Mission:
[22] ALADIN = Atmospheric Laser Doppler Instrument.

Finally, the role of 4-D assimilation to retrieve the wind field must be mentioned. Wind is the most active parameter in the motion equations, thus any adjustment of initial conditions to force convergence of predicted and observed values of any parameter sufficiently conservative, automatically leads to adjust the wind field. In this respect, the role of frequent temperature/humidity sounding from geostationary satellite must be re-emphasised. Particularly in areas distant from heat sources, the assimilation of frequent temperature/humidity sounding ("trend") is immediately reflected into dynamical information throughout the ω-equation. Thus the recommendation (overlapping with Recommendation 1):

- **Recommendation 12** - ***Frequent temperature/humidity sounding from geostationary satellites should be implemented also to circumvent (by 4-D assimilation) the difficulty of directly measuring the wind profile.***

4. Atmospheric chemistry

Parameters: Ozone profile; Trace gases other than ozone.

The situation of user requirements on atmospheric chemistry is rather evolutionary, and it is not easy to distinguish between requirements to be fulfilled in a fully operational fashion (i.e. by instrumentation reasonably conservative to be used for a long time extent) and other ones which could be met within a scattered and evolutionary context. In order to focus discussion, we assume that, within the CGMS membership, priority is given to ozone and to the total columns of the main "greenhouse" gases, whereas it is assumed that other trace gases and the profiles of any gas but ozone are of priority interest for user communities more research oriented.

As regards ozone, operational monitoring is already implemented (e.g., by NOAA SBUV [23] and ERS-2 GOME [24] in the UV range, and NOAA HIRS [25] in IR) and will be further improved in both ranges of UV (by METOP GOME-2 and NPOESS OMPS [26]) and IR (by METOP IASI and NPOESS CrIS). To be noted that both UV and IR are necessary, since the IR alone has degraded accuracy in the lower troposphere and higher stratosphere. What could be added is IR observation from geostationary orbit, both to capture possible diurnal variations and for use in 4-D assimilation (target: improved wind field). The associated recommendation is:

- **Recommendation 13** - ***IR sounding spectrometers from geostationary orbit should contribute to frequent ozone profiling to follow diurnal variations and as an input to 4-D assimilation models intended to improve determination of the wind field.***

The same spectrometers to work in IR primarily for temperature/humidity sounding and in UV/VIS/NIR primarily for ozone, can observe a number of other species, at least as regards their total columns. For instance, in the IR, greenhouse gases such as CO, CH_4, N_2O are detected, and in the UV/VIS/NIR several species impacting with the ozone cycle, such as HCHO, BrO, ClO, $ClONO_2$ and OClO. SO_2 can be detected in both ranges when large amounts are injected into the atmosphere by volcanic eruptions.

To go beyond what can be observed by moderate-spectral-resolution spectrometers such as IASI and CrIS in IR, and GOME-2 and OMPS in UV/VIS/NIR, would require large facilities, with very-high spectral resolution and very often, if good vertical resolution is required, limb sounding. Also, the spectral range could require extension to the Far IR and to the Sub-mm. It also should be noted that, for ozone, if the low troposphere is targeted for high vertical resolution and good accuracy, DIAL lidar becomes necessary. On the other hand, if a specific species is addressed, with favourable spectroscopic

[23] SBUV = Solar Backscatter Ultra Violet.
[24] GOME = Global Ozone Monitoring Experiment.
[25] HIRS = High-resolution Infrared Radiation Sounder.
[26] OMPS = Ozone Mapper/Profiler Suite.

condition (i.e., isolated lines in a clean window without a continuum background), a rather simple instrument could be designed for operational use (examples are: CO_2 around 1.6 μm and CH_4 around 3.4 or 8 μm). The recommendations stemming from this discussion are:

- Recommendation 14 - ***Operational observation of trace gases other than ozone should, in general, be limited to total columns of those species which can be observed by the spectrometers for temperature/humidity/ozone sounding in IR and ozone sounding in UV/VIS/NIR.***

- Recommendation 15 - ***Profiles of species other than ozone, and total columns of species requiring instrumentation exceeding the operational one, as well as high-vertical resolution ozone by DIAL lidar, should be made accessible from scientific programmes for operational use.***

- Recommendation 16 - ***Special effort on key species of particular value for climate monitoring is possible to be made at operational level by small dedicated instrumentation, provided that the spectroscopic conditions are favourable.***

5. Clouds and precipitation

Parameters: Cloud imagery, cover, type, top temperature and height; Cloud base height; Precipitation rate at the ground; Precipitation index (daily cumulative); Lightning detection.

Cloud imagery is the most traditional mission of meteorological satellites since TIROS-I in 1960. It has been upgraded at intervals on both LEO and GEO satellites. The present operational instrument (AVHRR [27]) is rather obsolete, waiting for a step improvement on NPOESS (VIIRS), with precursor NPP. Its main limitation is the lack of water vapour channels. On geostationary satellites, there is a large variability of performances, the highest being those of SEVIRI [28] on MSG. On future GOES, an ABI [29] imager is being thought of, with improved horizontal resolution, number of channels and observing cycle. Due to the dominantly "regional" purpose of cloud imagery from GEO, standardisation of performances is not mandatory, but some "minimum common target" to be accomplished in the 2015 timeframe should be established. The following is recommended:

- Recommendation 17 - ***Depending on the characteristics of the envisaged temperature/humidity sounder, the imagery mission from GEO can be based on different number of channels. The minimum should enable monitoring cloud development and water vapour growth at time intervals in the range of 1-2 min.***

Cloud images are processed to generate parameters such as cover, type, top temperature and derived height. However, for Cloud top height the accuracy achievable by IR measurement (i.e. through the brightness temperature and an estimate of the emissivity) is not sufficient for climatological purposes. More direct observation by backscatter lidar would do the job, but this is a too large facility to be sustainable in an operational framework (and fails to meet operational requirements because of the very long observing cycle due to the nadir-only viewing geometry). Spectroscopy of the oxygen A-band around 760 nm provides results of very variable quality depending on a variety of reasons. Cloud base height can only be estimated by cloud radar, again a too large facility to be sustainable in an operational framework, also failing to meet operational requirements because of lack of scanning capability. However, the observing cycle is sufficient for climatological purposes. Both backscatter lidar and cloud radar are going to be flown in scientific missions (lidar on ESSP-3 [30]; cloud radar on CloudSat) which are expected to have some sort of follow-on, for instance in the ESA framework. We put forward:

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[27] AVHRR = Advanced Very High Resolution Radiometer.
[28] SEVIRI = Spinning Enhanced Visible and Infra Red Imager.
[29] ABI = Advanced Baseline Imager.
[30] Formerly Picasso-Cena.

- **Recommendation 18** - ***Accurate measurements of cloud top height and observation of cloud base height performed by research satellites should be made available for operational use.***

As regards precipitation, user requirements have stepwise increased in the last few years. The reason is that, in addition to the traditional use of precipitation for climate modelling and characterisation, precipitation data in NWP were only used for verification of the model performances, with particular regard to the cloud/precipitation parameterisation scheme. In recent models, and more in future Regional NWP models with resolution at level of precipitation cell, precipitation data are going to be assimilated to improve initialisation. Obviously, this greatly forces to organise a *Global Precipitation Mission* and to maintain it in the long term in an operational fashion.

The principles available to measure precipitation are:

- active MW (rain radar), the only way to obtain precipitation profile
- passive MW using channels at several frequencies and polarisations
- passive radiometry at Sub-mm frequencies in absorption bands (through correlation with ice).

In addition, lightning can be used as proxy of convective precipitation. Furthermore, 4-D assimilation of frequent temperature/humidity sounding can provide precipitation fields of highly predictive value.

Rain radar has been demonstrated by TRMM [31] and further advanced designs (with two frequencies) are being pursued. It can provide images over a limited swath (a few hundred kilometres), which implies observing cycles of several days, totally inconsistent with the time-scale of precipitation. In addition, to get resolution consistent with precipitation cells at the operating frequency of, say, 14 GHz, the antenna size must be in the range of 2 m, with mass and power in the range of 500 kg and 500 W respectively. Therefore, it is not possible to think to a rain radar constellation for frequent global coverage. The Global Precipitation Mission (GPM) is conceived in terms of a large "core" satellite equipped with rain radar and other instruments, plus a number of "drones" equipped with *passive MW radiometers*.

MW radiometers measure precipitation by using several channels in the range 10 to 90 GHz, generally with dual polarisation, which implies conical scanning. The swath can be rather large (e.g., 1400 km from an orbital height of 840 km), to ensure global coverage in one day. The GPM envisages eight drone satellites in sunsynchronous orbits to provide global coverage each 3 hours. In the GPM concept, the core satellite equipped with rain radar moves in a drifting orbit to cross all other orbital planes at intervals, acting as a "calibrator" to improve quantitative precipitation estimates. GPM is planned to be implemented in 2007. The recommendation is:

- **Recommendation 19** - ***Data from the Global Precipitation Mission must be made available for operational use, and arrangements should be sought to ensure long-term continuity to the system.***

There is no prescription how "drone" satellites should be designed, except that they must include a large-swath MW radiometer. For the rest, certain drones may actually be implemented by hosting a MW radiometer on a large satellite, some other ones may be a MiniSat. In addition to the essential MW radiometer, other instruments relevant to precipitation may be hosted, such as lightning mappers. These instruments help characterising the precipitating (or close-to-precipitate) cloud by counting the number of lightnings over a certain area in a given time. They have been flown on several LEO satellites, and proposed for GEO as well.

It should be recognised that, even when the GPM is fully implemented, the observing cycle (3 hours) will be very far from meeting the requirement for Nowcasting (few minutes !). Only geostationary satellites can provide the required observing cycle, but, unfortunately, at the MW frequencies more

[31] TRMM = Tropical Rainfall Measuring Mission.

directly sensitive to precipitation (10 GHz, 19 GHz, 37 GHz, 90 GHz) the antenna size necessary to get a horizontal resolution consistent with the size of precipitating cells (say, 10 km) would be prohibitive. In the Sub-mm range it is possible to observe precipitating clouds in the absorption bands of water vapour (e.g., 380 GHz) and oxygen (e.g., 425 GHz). The resolution with a 3-m antenna would be about 10 km. Bands with coarser resolution (119 GHz for oxygen and 183 GHz for water vapour) would be supportive to observe the effect of different drop sizes, and channels of different absorption strength would sense cloud ice at different altitudes in convective system penetrating the higher troposphere. Simulations supported by aircraft experimentation have shown that this is feasible. Though recognising that much scientific, technological and experimental work needs to be done, the subject of frequent precipitation observation is so important that the following recommendation (similar to Recommendation 2) is worth being introduced:

- **Recommendation 20** - ***An early demonstration mission on the applicability of MW/Sub-mm radiometry for frequent precipitation observation from geostationary orbit should be provided, in view of possible operational follow-on in the 2015 timeframe.***

Finally, the possibility to infer precipitation fields by 4-D assimilation of frequent temperature/humidity profiles should not be forgotten. The product of assimilation cannot be considered as something directly comparable to actual precipitation, but its prognostic value could be higher than that one of actual measurements, since the field is obtained in balance with other parameters of high predictive value, whereas inputting actual observations, in this case of fractal field of little conservative nature, may have reduced impact. Therefore, Recommendation 1 and Recommendation 12 should be complemented by:

- **Recommendation 21** - ***Frequent temperature/humidity sounding from geostationary satellites should be implemented also to derive (by 4-D assimilation) precipitation fields to complement actual observations not easy to be performed from space.***

6. Clouds and radiation

Parameters: Cloud water profile; Cloud ice profile; Aerosol profile; Aerosol size (average on total column); Volcanic ash; Cloud optical thickness; Cloud ice content and drop size (at cloud top); Short-wave cloud reflectance; Long-wave cloud emissivity; Downwelling solar radiation at TOA; Outgoing short-wave radiation at TOA; Outgoing long-wave radiation at TOA; Outgoing spectral radiance at TOA; Downwelling short-wave radiation at the Earth surface; Downwelling long-wave radiation at the Earth surface; Short-wave Earth surface bi-directional reflectance; Outgoing long-wave Earth surface radiation; Long-wave Earth surface emissivity.

It is currently considered that the limits of predictability in NWP and the accuracy of General Circulation Models are largely controlled by the poor description of the interaction between clouds and radiation, with the associated fields of aerosol and precipitation. The parameters to be addressed in the context of this theme are:

- the ***cloud "classical" parameters*** mostly referring to the top surface, with emphasis on ice/liquid discrimination and drop size;
- the ***cloud interior***, specifically water phase (ice or liquid) and whether drop size is likely to produce precipitation;
- the ***outgoing radiation*** from the Top of Atmosphere to space;
- the main parameter impacting with both clouds and radiation in the 3-D atmosphere, i.e. ***aerosol***;
- the primary source of clouds, i.e. ***water vapour***, also primary factor of radiative processes in the 3-D atmosphere;
- the indicator of final removal of water from the atmosphere, i.e. ***precipitation***;
- contextually, the ***radiative parameters at the Earth surface***, interacting in both directions with atmospheric radiation.

The subject implies two aspects: physical processes have to be better understood, to improve modelling and parameterisation; and routine measurements are necessary, to feed initialisation of NWP models as they make progress in explicitly describing radiative processes, and to monitor climate evolution.

Several research missions are being run or have been approved or have been proposed in the area of process study. They generally single out one or very few aspects (e.g., cloud interior by cloud radar; aerosol and cloud top height by backscatter lidar; outgoing radiation at TOA by broad-band radiometry; precipitation by rain radar; Bi-directional Reflectance Distribution Functions by multi-angle and multi-polarisation radiometers; …). In several cases, the mission does not need to be carried out on a long-term basis, beyond what is needed to achieve the scientific objective. Also, often the instrumentation needed for process study is unsuitable for operational use (e.g., because of insufficient observing cycle) or not sustainable (e.g., because of size). One further main reason to make process study missions unsuitable for long-term continuity is that, as a rule, to allow studying so many processes, many satellites are needed, thus necessary "small", so that the addressed observation only constitutes a narrow window in the context of the full set of parameters which should be contextually measured to procure a sizeable impact on operational activities.

In order to prepare for a phase when atmospheric radiation parameters are used for operational application, a new mission should be studied, based on large-swath instruments (thus passive) capable of global coverage in 1-2 days, with moderate resolution as sufficient for this application, but providing a rather comprehensive set of measurements to be co-processed. It is reminded that radiative budgets are very tiny figures to be computed as differences of many large figures, which makes impossible to achieve significant results if the originating observations are taken from different instruments on different platforms under different viewing conditions at different times of the day. In order to acquire the required information without using active techniques, use should be made of the full e.m. spectrum, from UV to MW passing through VIS, NIR, SWIR, MWIR, TIR, FIR and Sub-mm [32], exploiting more polarisations and more viewing angles as needed. The EC-supported "CLOUDS" study has shown that such satellite could stay within the limit of the "SmallSat" class (< 1 ton) [33]. The recommendation is:

- **Recommendation 22** ***- A mission should be demonstrated, designed to meet operational requirements for atmospheric radiation observations as input to long-term NWP and GCM. Unlike process study missions, which single out a small number of parameters to enhance accuracy and vertical resolution aspects, this mission should provide frequent observation of a wide set of parameters which need to be measured in compliance with strict comprehensiveness and consistency criteria.***

It should be recognised that, even with the addition of a dedicated satellite to what is provided by NPOESS, METOP/EPS and other systems, certain radiative parameters need such frequent observation (because of dependence of solar illumination, on the diurnal cycle of cloud development, etc.) that only the geostationary orbit and/or a constellation of many satellites can help. A specific case is that one of broad-band radiometry for Earth Radiation Budget (typical instruments: CERES [34] and ScaRaB [35] from LEO and GERB [36] from MSG). ERB is not terribly important to initialise NWP, but it is essential to validate CGM's and monitor climate changes. Geostationary satellites can provide observations at changing solar illumination, but only from fixed viewing directions. A constellation of LEO would provide observations from different viewing directions at a number of nearly-fixed local solar hours. The recommendation is:

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[32] Definition: UV 0.01-0.38 µm; VIS 0.38-0.78 µm; NIR 0.78-1.3 µm; SWIR 1.3-3 µm; MWIR 3-6 µm; TIR 6-15 µm; FIR 15-1000 µm (= 300 GHz); Sub-mm (part of FIR) 3000-300 GHz; MW 300-0.3 GHz.

[33] Definition: NanoSat < 10 kg; MicroSat 10-100 kg; MiniSat 100-500 kg; SmallSat 500-1000 kg; MediumSat 1-2 tons.

[34] CERES = Clouds and Earth's Radiant Energy System.

[35] ScaRaB = Scanner for the Radiation Budget.

[36] GERB = Geostationary Earth Radiation Budget.

- <u>**Recommendation 23**</u> ***- In order to make ERB measurements effective for operational radiation climatology, broad-band radiometers should be introduced on each geostationary satellite and on a constellation of LEO.***

It is understood that these ERB radiometers represent a limited additional payload, important to be associated to cloud imagers to acquire synergistic information on the main effect affecting ERB.

One issue increasingly acknowledged on the theme of atmospheric radiation is the ***spectral composition*** of the outgoing radiation from TOA, specifically as concerns the wavelength ranges controlled by ***water vapour in the upper troposphere / lower stratosphere (UT/LS)***. This is the most effective layer to trap radiative energy in the Earth/Atmosphere system, and water vapour is by far the most abundant and effective greenhouse gas. At the UT/LS temperatures, a large fraction of radiation falls in the Far IR range, with H_2O specifically involved because of a large rotational band and a <u>continuum</u> stretching from the main IR window around 10-12 µm to the mm-wave region. Knowledge of the FIR region is essential for both quantitative reasons (the fraction of outgoing radiation from TOA to space in the FIR, which is not observed by any system, may reach and exceed 50 %), and because the evolution of the water vapour continuum could impact on the cleanness of the main IR window, moving the Earth's climate towards "Venusisation". Specific importance is placed on the water vapour profile in the UT/LS layer, which is best sensed in the FIR rotational band around 20 µm (to be noted that water vapour profiling necessitates support from temperature profile from the nearby 15 µm CO_2 band). The recommendation is:

- <u>**Recommendation 24**</u> ***- An exploratory mission should be implemented, to collect spectral information in the Far IR region, with specific emphasis on water vapour profiling significant of the UT/LS region, and on improved knowledge of the water vapour continuum.***

To be noted that water vapour profiling significant of the UT/LS layer also can be observed at Sub-mm frequencies such as 380 GHz (with support from the 425 GHz O_2 nearby band for temperature profile). The advantage over FIR is that imagery mode could be obtained (i.e., for frequent coverage), whereas in the FIR only measurements essentially nadir can be obtained. Another method has been proposed, based on LEO-to-LEO occultation of signals generated in the 23 or 183 GHz water vapour bands, but this requires a constellation of satellites to obtain a decent observing cycle.

Notwithstanding the difficulty of making operational use of incoherent data from different instruments on different satellites in different orbits at different time, there are so many interesting data available from R&D programmes that it is worth to collect them, either for model improvement/parameterisation or for initialisation when appropriate. Specifically, it is necessary to collect and evaluate data from clouds and radiation process study missions (e.g., ESSP-3, CloudSat and similar ESA future programmes), and from instruments flown on multi-purpose missions, addressing Earth's surface characterisation and, most important, <u>aerosol</u> (e.g., MERIS [37], MODIS, POLDER [38], MISR [39] and similar future instruments). With the advent of VIIRS on NPOESS several of these observations will become operational, but complementary information from R&D missions will continue to be valuable. We therefore have:

- <u>**Recommendation 25**</u> ***- Data from process study missions on clouds and radiation as well as from R&D multi-purpose satellites addressing Earth's surface characterisation and aerosol should be made available for operational use.***

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[37] MERIS = Medium Resolution Imaging Spectrometer.
[38] POLDER = Polarisation and Directionality of the Earth's Reflectance.
[39] MISR = Multi-angle Imaging Spectro-Radiometer.

7. Ocean surface and sea-ice

Parameters: Wind over sea surface; Sea surface temperature; Significant wave height; Dominant wave period and direction; Sea level; Ocean dynamic topography; Geoid; Water-leaving spectral radiance; Ocean chlorophyll, suspended sediment concentration, yellow substance absorbance; Ocean salinity; Sea surface imagery; Bathimetry; Sea-ice cover, type, thickness and surface temperature; Sea-ice elevation; Ice-sheet topography; Icebergs fractional cover and height.

This area has to be analysed taking into account that the number of involved user communities includes much more than meteorology and operational climatology (still to be considered as driving applications for CGMS partners). Therefore, a reasonable approach is to accept as much as possible from satellite programmes driven by other communities, and focus on those issues where meteo-climate requirements are not met by non-CGMS programmes.

Sea surface temperature and Wind over sea surface are, in this group of parameters, those where the meteo-climate community have dominant interest. Therefore, it is not surprising that CGMS members are and will continue to provide these data. Problem areas are in the mid-term future, till the advent of NPOESS. At that time (2009) VIIRS will improve the quality of IR-derived sea-surface temperature thanks to larger amount of information useful for atmospheric corrections as compared to AVHRR, and also will add all-weather measurements in the MW range (also somewhat significant of the bulk temperature) by CMIS [40]. Till then, it will be useful to acquire high-quality data, specifically needed for climate monitoring, from e.g., AATSR [41] and MODIS. We have:

- **Recommendation 26** - ***Till the advent of NPOESS, high-quality sea-surface temperature data from R&D satellites must be made available for operational use, specifically for climate monitoring.***

In coastal zones, the frequency required for capturing diurnal variations and increasing probability of cloud-free observation can only be provided by geostationary satellites. The required accuracy can either be achieved by IR sounders (provided they have good horizontal resolution) or improved IR imagers. We have:

- **Recommendation 27** - ***Future geostationary satellites must have improved capability of observing sea surface temperatures for use in coastal zones. This may be achieved either by IR sounders with good horizontal resolution or IR imagers with a convenient number of channels.***

Wind over sea surface, in future (i.e. with the two CMIS instruments on NPOESS and the METOP scatterometer) seems to be on the safe side, provided that the principle adopted by CMIS to evaluate the wind direction (by multi-polarisation passive measurements) proves to be sufficiently accurate. It is urgent to confirm that this alternative to scatterometry is practicable (something to be done by the incoming WindSat/Coriolis experiment). Of course, it is required that the post-METOP EPS programme continues to contribute by either passive or active MW observation. We have:

- **Recommendation 28** - ***In the 2010 timeframe, sea surface wind must be observed in a fully operational framework (i.e. by NPOESS and METOP/post-METOP). It is urgent to assess whether the multi-polarisation passive MW radiometry is competitive with scatterometry.***

It should be noted that, at present and till the advent of METOP (2005), Wind over sea surface is only available from R&D satellites. There are, however, several programmes that, with some coordination effort, could provide at least one-satellite coverage (possibly two) to fill the gap. We have:

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[40] CMIS = Conical-scanning Microwave Imager/Sounder.
[41] AATSR = Advanced Along-Track Scanning Radiometer.

- <u>**Recommendation 29**</u> ***- In the near and mid term future, sea-surface wind data from R&D satellites must be made available for operational use, and relevant satellites programmes should possibly be coordinated so that a two-satellite coverage is achieved.***

Global NWP models and General Circulation Models for long-range NWP and climate prediction have increasing need to describe the interaction between atmosphere and ocean circulations. <u>Sea level</u> and <u>Ocean dynamic topography</u> are the most significant active parameters from the ocean to the atmosphere. Their observation requires *radar altimeters* which therefore, in the long-term future, should be incorporated into the CGMS-supported satellite system. It should be noted that radar altimeters may have rather different complexity (and different optimal orbit characteristics) depending on the requirements they address. For meteo-climate operational applications, relatively simple instruments in relatively high orbits are suitable (e.g., Jason). For "geodetic" applications (Geoid, Sea-ice thickness, Sea-ice elevation, Ice-sheet topography, Icebergs height), more demanding instruments in relatively low orbits are necessary. They might use lidar instead of radar. We have two separate recommendations:

- <u>**Recommendation 30**</u> ***- Missions for ocean topography, implying a couple of SmallSat's in relatively high orbits, should gradually in the next decade become an integral part of the CGMS-supported operational system.***

- <u>**Recommendation 31**</u> ***- Data from geodetic-class radar or lidar altimeters from R&D satellites should be made available for operational use, specifically for the cryosphere.***

The primitive observation from radar altimeters is the <u>Significant wave height</u>, a very important meteo-climate parameter *per-se*. However, being the radar altimeter essentially a nadir-only viewing instrument, the observing cycle is totally insufficient for sea-state observation, specifically in coastal zones. Concepts to stretch the swath of altimeters have been proposed (multi-spot for gross sea-state evaluation; interferometry of signals from two side-by-side antennas). The swath would anyway be limited (< 100 km), but could be sufficient if joined to the concept of a constellation. Thus, we have:

- <u>**Recommendation 32**</u> ***- Large-swath radar altimeters for frequent sea-state observation should be demonstrated, with the eventual aim of an operational constellation.***

<u>Dominant wave period and direction</u> require spectral analysis of *SAR images*, which also provide Sea surface imagery, Bathimetry and a number of sea-ice parameters (Sea-ice cover and type; and, by interferometry, Sea-ice elevation, Ice-sheet topography, Icebergs fractional cover and height). SAR, however, is a large multi-purpose facility, whose use is driven by other user communities (including commercial ones). The recommendation is:

- <u>**Recommendation 33**</u> ***- Data from SAR for wave spectra and other observations of ocean and ice should be acquired from R&D and commercial satellite programmes for operational use.***

It should be noted that a number of observations on sea-ice (specifically cover, type and surface temperature) are available from the multi-purpose IR and passive MW radiometers of current and future meteorological satellites, though the horizontal resolution is much worse than with SAR (but the observing cycle much better).

<u>Ocean-colour</u> derived measurements (Water-leaving spectral radiance; Ocean chlorophyll, suspended sediment concentration, yellow substance absorbance) will in future be operationally provided by the VIIRS NPOESS, with sufficient quality and frequency for meteo-climate applications. Till then, and also afterward to improve certain characteristics (accuracy, frequency in coastal waters, …), data from a variety of R&D satellites (and possibly commercial satellites) can be used. We have:

- **<u>Recommendation 34</u>** ***- In the near and mid term future, ocean colour data from R&D satellites must be available for operational use. In the NPOESS era, continued access may be useful for specific purposes, particularly in coastal zones.***

<u>Ocean salinity</u> is one of the few conservative parameters enabling to infer vertical exchanges in the ocean (salinity controls density), in addition to horizontal inflow from rivers and polar ice. It is a difficult measurement, since it requires MW radiometry operating at very-low frequencies (typical, 1.4 GHz), implying very large antenna sizes to get good resolution. Good resolution as required in coastal zones can be achieved by interferometry of thin stick antennas, such as in the ESA SMOS [42] project, to the expenses of accuracy and absolute calibration. For meteo-climate, accuracy must be very good and calibration must be available, whereas the horizontal resolution may be relaxed to some 100 km. Good accuracy also implies that the instrument must include more than the essential channels, in order to enable applying all necessary corrections (for temperature, for roughness/wind, …). Thus we have two recommendations:

- **<u>Recommendation 35</u>** ***- A mission to observe ocean salinity for meteo-climate applications, based on a SmallSat to provide limited horizontal resolution and great accuracy should be demonstrated, for possible operational follow-on.***

- **<u>Recommendation 36</u>** ***- Observations of ocean salinity from R&D satellites with horizontal resolution suitable for applications in coastal zones should be made available for operational use.***

8. Land surface and vegetation

<u>Parameters</u>: Snow cover, melting conditions and water equivalent; Glacier cover, motion, topography; Land surface temperature, Permafrost; Soil moisture; Fires area and temperature; Normalized Difference Vegetation Index (NDVI); Leaf Area Index (LAI); Photosynthetically Active Radiation (PAR), Fractional Photosynthetically Active Radiation (FPAR); Land cover; Soil type; Vegetation type; Land surface imagery; Coastlines; Land surface topography.

As in the case of ocean and ice, this area also has to be analysed taking into account that the number of involved user communities includes much more than meteorology and operational climatology (the driving applications for CGMS partners). Also, several parameters of this list are measured by the multi-purpose imaging radiometers of meteorological satellites, therefore, a reasonable approach is to accept as much as possible what is provided by the multi-purpose imagers on meteorological satellites and relay on satellite programmes driven by other communities for more specific applications; and then focus on those issues where meteo-climate requirements are not met by any programme.

<u>Land snow/ice parameters</u> (Snow cover, melting conditions and water equivalent; Glacier cover, motion, topography) are observed to a certain extent by multi-purpose VIS/IR imagers (AVHRR and then VIIRS) and more will be with the advent of MW imagers (CMIS). However, the horizontal resolution will be a limitation for small-scale applications, particularly for hydrology. The optimal observing tool is SAR [43], particularly for Snow water equivalent and, by interferometry, Glacier motion and topography. The recommendation is:

- **<u>Recommendation 37</u>** ***- SAR observation data of land snow and ice from R&D and commercial satellites should be made available for operational use.***

<u>Land surface temperature</u> (including Permafrost), and <u>Fires area and temperature</u> are observed by multi-purpose IR imagers. The frequency required for capturing diurnal variations and increasing probability of cloud-free observation can only be provided by geostationary satellites. The required accuracy can

[42] SMOS = Soil Moisture and Ocean Salinity.
[43] SAR = Synthetic Aperture Radar.

either be achieved by IR sounders (provided they have good horizontal resolution) or improved IR imagers. Fire observation makes mandatory using the 3.7 μm wavelength. We have, similarly to Recommendation 27:

- **Recommendation 38** - ***Future geostationary satellites must have improved capability of observing land surface temperatures and fires. This may be achieved either by IR sounders with good horizontal resolution or IR imagers operating at appropriate wavelengths.***

Several vegetation parameters (NDVI, LAI, PAR, FPAR) will be observed from the NPOESS VIIRS, at a scale sufficient for global and regional applications. Smaller-scale applications, e.g. Vegetation type, require higher horizontal resolution, which can be provided from R&D and commercial satellites. These are anyway needed until NPOESS is operational. The recommendation is:

- **Recommendation 39** - ***In the near and mid term future, vegetation data from R&D and commercial satellites must be available for operational use. In the NPOESS era, continued access may be useful for small-scale applications.***

Land surface imagery and observations of Land cover, Soil type, Coastline and Land surface topography are required for small-scale applications (agrometeorology, hydrogeology, territory management, …). They imply high horizontal resolution, either in the optical field or by SAR. There are other user communities dominating the requirements on these issues, and satellite programmes are run as R&D in the initial phases and on commercial basis later. Similarly to Recommendations 33 and 37, we have:

- **Recommendation 40** - ***High-resolution optical and SAR imagery data of use for agrometeorology and hydrogeology should be procured from R&D and commercial satellites.***

Soil moisture is becoming an essential input for NWP and General Circulation Models. It is a difficult measurement, since it requires MW radiometry operating at very-low frequencies (typical, 1.4 GHz), implying very large antenna sizes to get good resolution. Good resolution as required for small-scale applications can be achieved by interferometry of thin stick antennas, such as in the ESA SMOS project. For meteo-climate, the horizontal resolution may be relaxed to several tens of kilometres, which may imply simpler antenna systems. Thus we have two recommendations, which can be taken together to Recommendations 35 and 36, due to the similarity of instrument requirements with what is needed for ocean salinity:

- **Recommendation 41** - ***A mission to observe soil moisture for meteo-climate applications, based on a SmallSat to provide limited horizontal resolution should be demonstrated, for possible operational follow-on.***

- **Recommendation 42** - ***Observations of soil moisture from R&D satellites with horizontal resolution suitable for small-scale applications should be made available for operational use.***

9. Strategy to implement recommendations

The analysis of Sections 2 to 8 have led to 42 Recommendations which can be implemented by one or more of the following approaches:

- by advanced geostationary satellites
- by updating the payload of medium-large meteorological operational satellites
- by small satellites, generally in low orbit (but also in GEO, in the case of MW/Sub-mm sounding)
- by constellations of minisatellites
- by a new R&D mission
- by acquiring data from R&D or commercial satellites.

Table 2 shows how the various Recommendations are spread versus the implementation approaches.

Table 2 - Strategy to implement recommendations

No.	Recommendation	Advanced GEO	Medium-large LEO	SmallSat GEO/LEO	Constel-lations	New R&D missions	Data from R&D sat's
01	Temperature/humidity IR sounding from GEO.	X					
02	MW/Sub-mm sounding from GEO	X		X			
03	Radio-occultation sounding				X		
04	Water vapour by DIAL					X	
05	Temperature profiles in limb mode						X
06	Improved imagery from GEO for improved winds	X					
07	Winds from overlapping images of LEO		X				
08	Water vapour sounding from GEO for wind profiling	X					
09	Wind profile data by passive Doppler spectroscopy						X
10	Technology development of Doppler lidar for winds			X			
11	Wind data from Doppler lidar demonstration missions						X
12	Winds by 4-D assimilation of soundings from GEO	X					
13	Ozone sounding from GEO	X					
14	Ozone profile and total-column trace gases from LEO		X				
15	Profiles of species other than ozone from LEO						X
16	Special effort on key species from LEO		X				
17	Cloud and water vapour growth from GEO images	X					
18	Accurate cloud top height and observation of cloud base						X
19	Global Precipitation Mission and operational follow-on				X		X
20	MW/Sub-mm radiometry for precipitation from GEO	X		X			
21	Precipitation by 4-D assimilation of soundings from GEO	X					
22	Clouds and radiation monitoring mission			X			
23	ERB observation from GEO and constellations	X			X		
24	Far IR spectroscopy for radiative processes in UT/LS					X	
25	Clouds and radiation data from process study missions						X
26	High-quality sea-surface temperature data from LEO						X
27	Improved sea surface temperatures from GEO	X					
28	Sea surface winds fully operational on LEO		X				
29	Interim sea-surface winds from R&D satellites						X
30	Ocean topography fully operational on LEO			X			
31	Geodetic-class radar or lidar altimeters						X
32	Large-swath radar altimeters for frequent sea-state				X		
33	SAR for wave spectra and other ocean/ice observations						X
34	Ocean colour data for the interim and beyond						X
35	Ocean salinity for meteo-climate applications			X			
36	Ocean salinity for applications in coastal zones						X
37	SAR observation of land snow and ice						X
38	Improved land surface temperatures and fire from GEO	X					
39	Vegetation data for the interim and beyond						X
40	High-resolution optical and SAR imagery of land						X
41	Soil moisture for meteo-climate applications			X			
42	Soil moisture for small-scale applications						X

The first four approaches are based on developments and demonstrations to be carried out with the possible help of R&D space agencies, to be taken over by CGMS partners for long-term follow-on. The second two approaches represent a sort of "data buy" policy of CGMS partners (or WMO at large) from R&D or commercial programmes. As anticipated, the ultimate purpose of this document is to draw two "manifests" listing the required developments/demonstrations to be taken over for operational follow-on and the data of operational interest to be procured from R&D or commercial programmes, respectively.

10. Developments/demonstrations to be taken over for operational follow-on

10.1 Advanced geostationary satellite and possible SmallSat in GEO

Geostationary satellites to be operational in the post-2015 should comply with the following recommendations:

- Recommendation 1 - *In the 2015 timeframe, all meteorological geostationary satellites in GOS should be equipped with spectrometers for frequent temperature/humidity sounding in IR.*
- Recommendation 6 - *Imagers of future geostationary satellites should have improved spatial resolution and much improved observing cycle, at least for those channels relevant for wind information retrieval.*
- Recommendation 8 - *Sounders from future geostationary satellites must be designed in such a way as to enable wind profiling by water vapour profiling with conveniently high resolution (horizontal, vertical and time).*
- Recommendation 12 - *Frequent temperature/humidity sounding from geostationary satellites should be implemented also to circumvent (by 4-D assimilation) the difficulty of directly measuring the wind profile.*
- Recommendation 13 - *IR sounding spectrometers from geostationary orbit should contribute to frequent ozone profiling to follow diurnal variations and as an input to 4-D assimilation models intended to improve determination of the wind field.*
- Recommendation 17 - *Depending on the characteristics of the envisaged temperature/humidity sounder, the imagery mission from GEO can be based on different number of channels. The minimum should enable monitoring cloud development and water vapour growth at time intervals in the range of 1-2 min.*
- Recommendation 21 - *Frequent temperature/humidity sounding from geostationary satellites should be implemented also to derive (by 4-D assimilation) precipitation fields to complement actual observations not easy to be performed from space.*
- Recommendation 23 - *In order to make ERB measurements effective for operational radiation climatology, broad-band radiometers should be introduced on each geostationary satellite and on a constellation of LEO.*
- Recommendation 27 - *Future geostationary satellites must have improved capability of observing sea surface temperatures for use in coastal zones. This may be achieved either by IR sounders with good horizontal resolution or IR imagers with a convenient number of channels.*
- Recommendation 38 - *Future geostationary satellites must have improved capability of observing land surface temperatures and fires. This may be achieved either by IR sounders with good horizontal resolution or IR imagers operating at appropriate wavelengths.*

It is easy to recognise that the basic tools to comply with these recommendations are as follows.

- Introduction on all geostationary satellites of frequent IR sounding by spectroscopic means. This would enable retrieval of temperature, humidity and ozone profiles (Rec. 1 and Rec. 13), improved wind profiling by tracing water vapour 3-D features (Rec. 8), and would provide input to 4-D assimilation models to generate wind profiles (Rec. 12) and precipitation fields (Rec. 21).
- The imagery mission should be improved by providing better resolution and much higher frequency to improve the accuracy of winds (Rec. 6) and monitoring of cloud development and water vapour growth (Rec. 17).
- Improved sea surface temperatures (Rec. 27) and land surface temperatures and fires (Rec. 28) could either be provided by the sounder (if the horizontal resolution is good) or by the imager (which would imply more spectral channels to be included).
- Broad-band radiometers to contribute to global Earth Radiation Budget monitoring should be included (Rec. 23).

The IR sounder also would provide several other measurements, such as: Atmospheric stability index; Height and temperature of the tropopause; Height of the top of the Planetary Boundary Layer; Cloud cover, type, top temperature/height and emissivity. Also it would help to compute: Downwelling long-wave radiation at the Earth surface, and components of Outgoing long-wave radiation at TOA and Outgoing spectral radiance at TOA. The imager could be extended to perform observation of short-wave radiative surface and vegetation parameters, if required because of advantages in monitoring the diurnal cycle under changing illumination conditions.

The subject of MW/Sub-mm sounding from GEO has led to two recommendations:

- Recommendation 2 - *An early demonstration mission on the applicability of MW/Sub-mm radiometry for temperature/humidity and cloud sounding from geostationary orbit should be provided, in view of possible operational follow-on in the 2015 timeframe.*
- Recommendation 20 - *An early demonstration mission on the applicability of MW/Sub-mm radiometry for frequent precipitation observation from geostationary orbit should be provided, in view of possible operational follow-on in the 2015 timeframe.*

Implementing this recommendation could be made in two steps: first a demonstration mission by a dedicated SmallSat, in the timeframe < 2010; then operational implementation, which could either occur by adding the payload (characterised by a 2-3 m antenna) on the main optical GEO satellite, or by continuing with dedicated SmallSat's launched as piggy-back of the optical GEO.

In addition to the main payload, both the main optical satellite and the dedicated MW/Sub-mm SmallSat could host opportunity payloads to increase cost-effectiveness. Specifically, *lightning mapper* should be considered, to improve cloud nature analysis and precipitation estimates.

10.2 Medium-large and SmallSat's in LEO

In this document we have assumed that NPOESS will continue beyond 2015. As for the EPS programme after METOP-3, we could hypothise that there will be a MediumSat substantially smaller than METOP, complemented by SmallSat's. The essential mission of post-METOP, fully concurring with NPOESS, would be:

- temperature, humidity and ozone profiles, and total columns of several trace gases (specifically, "green-house" ones), by IR and UV/VIS/NIR spectrometers and MW sounder;
- multi-purpose VIS/IR imagery for clouds, surface temperatures, ice/snow, vegetation, and for polar winds extraction (which implies improved horizontal resolution and water vapour channels).

This, in association with NPOESS, will enable implementing:

- Recommendation 7 - *Imagers of future polar satellites should be designed as to enable trace motion wind determination in overlapping areas at high latitudes, similarly to what is done from geostationary satellites.*
- Recommendation 14 - *Operational observation of trace gases other than ozone should, in general, be limited to total columns of those species which can be observed by the spectrometers for temperature/humidity/ozone sounding in IR and ozone sounding in UV/VIS/NIR.*

In addition, if some key species is selected for focusing, it could be possible to implement:

- Recommendation 16 - *Special effort on key species of particular value for climate monitoring is possible to be made at operational level by small dedicated instrumentation, provided that the spectroscopic conditions are favourable.*

The post-METOP scenario also is committed, together with NPOESS, to continue implementing:

- Recommendation 28 - *In the 2010 timeframe, sea surface wind must be observed in a fully operational framework (i.e. by NPOESS and METOP/post-METOP). It is urgent to assess whether the multi-polarisation passive MW radiometry is competitive with scatterometry.*

However, if multi-polarisation passive MW radiometry is demonstrated effective for sea-surface wind vector determination, the instrument could better fit with one of the SmallSat's to succeed to METOP-3 in order to allow the main satellite in the post-METOP spread scenario to remain within the limits of a MediumSat. For instance, the MW radiometer could fit within a SmallSat to implement:

- Recommendation 22 - *A mission should be demonstrated, designed to meet operational requirements for atmospheric radiation observations as input to long-term NWP and GCM. Unlike process study missions, which single out a small number of parameters to enhance accuracy and vertical resolution aspects, this mission should provide frequent observation of a wide set of parameters which need to be measured in compliance with strict comprehensiveness and consistency criteria.*

Ocean topography is better measured by altimeters in relatively high orbits. Thus, though NPOESS includes consideration of altimeters, a more appropriate solution is to provide an operational follow-on based on dedicated MiniSat's such as those of the Jason programme. This would implement:

- Recommendation 30 - *Missions for ocean topography, implying a couple of SmallSat's in relatively high orbits, should gradually in the next decade become an integral part of the CGMS-supported operational system.*

As for clear-air wind profiling by Doppler lidar, we have:

- Recommendation 10 - *A long-standing technological programme to follow Aeolus is solicited, to improve coverage characteristics and reduce instrument size to the extent that a sustainable Doppler wind lidar system may become operational in due time.*

The reason to prefer a SmallSat concept for the wind Doppler lidar is that NPOESS is not considering it, and that the main element of the post-METOP scenario, if it would, could not be a MediumSat. Also, the optimal orbit for wind profiling might not be sunsynchronous (lower inclination could be better, and low altitude could favour affordability). Thus, the preference is for a SmallSat, but much technological development is necessary to make this possible.

Finally, we have:

- Recommendation 35 - *A mission to observe ocean salinity for meteo-climate applications, based on a SmallSat to provide limited horizontal resolution and great accuracy should be demonstrated, for possible operational follow-on.*
- Recommendation 41 - *A mission to observe soil moisture for meteo-climate applications, based on a SmallSat to provide limited horizontal resolution should be demonstrated, for possible operational follow-on.*

These two recommendations can be implemented contextually, since the same technology is used (low-frequency MW radiometry). The dedicated SmallSat approach is advisable, since the antenna size needs to be several metres (an embarrassing item to be integrated in a multi-purpose satellite).

10.3 Constellations

We have collected the following recommendations requiring a constellation:

- Recommendation 3 - *A large constellation of radio-occultation sounders should be implemented, designed to minimise running costs so as to make possible a long-term operational follow-on.*
- Recommendation 19 - *Data from the Global Precipitation Mission must be made available for operational use, and arrangements should be sought to ensure long-term continuity to the system.*
- Recommendation 23 - *In order to make ERB measurements effective for operational radiation climatology, broad-band radiometers should be introduced on each geostationary satellite and on a constellation of LEO.*
- Recommendation 32 - *Large-swath radar altimeters for frequent sea-state observation should be demonstrated, with the eventual aim of an operational constellation.*

An effective approach would be to combine all requirements in a single constellation, giving up with the objective of a MicroSat (< 100 kg) and accepting to enter the class of MiniSat (< 500 kg). An example of constellation could be as follows:

- four orbital planes with four satellites in each plane, for a total of 16
- a cluster of four satellites placed in each plane by a single launcher (4 x 500 kg = 2 tons)
- orbit: height 800 km, inclination 70°, period 100 min, dephasing between satellites 25 min
- observing cycle for instruments with 700 km swath: 3 h at the equator, less with increasing latitude
- possible payload:
  - radio-occultation sounder
  - MW (small) radiometer and lightning mapper for precipitation
  - broad-band radiometer for ERB
  - large-swath altimeter for sea-state
  - supporting VIS/IR imager.

10.4 The "manifest" of required developments

Table 3 reports the "manifest" listing the missions which should be developed and demonstrated (possibly by R&D space agencies) for successive handing over to CGMS members for operational follow-on. Indications on satellite class and possible time target, geophysical parameters whose determination would be improved, and the type of needed instrumentation are provided.

Table 3 - "Manifest" of developments/demonstrations to be taken over for operational follow-on
(Background: GOES, MSG, MTSAT, GOMS, F-2, INSAT, NOAA/NPOESS, METOP, METEOR, FY-1 in < 2015; NPOESS in > 2015)

System	Improved parameters	Instrumentation
All GEO's upgraded (> 2015) **+** **GEO SmallSat (> 2008).**	Temperature, humidity, ozone profiles, winds at specified heights. Atmospheric instability index, tropopause height/temperature, height of PBL top. Cloud pattern, cover, type, top temperature and height. Sea-surface temperature, land surface temperature, permafrost, fires. Short- and long-wave outgoing radiation at TOA. Earth surface short-wave radiation/reflectance, long-wave radiation/emissivity. Products from 4-D assimilation (specifically: wind profile and precipitation field).	Frequent-sounding IR imaging spectrometer exploiting Large Focal Plane Array detectors. Fast VIS/IR imager. ERB radiometer. Short-wave channels.
	Precipitation rate and index.	Lightning mapper.
	All-weather temperature and humidity frequent sounding. Cloud water, cloud ice and precipitation frequent sounding.	MW/Sub-mm radiometer.
MediumSat (post-METOP) (> 2015) **+** **SmallSat for Clouds and Radiation (> 2008).**	Temperature, humidity and ozone profiles; total columns of key trace gases. Cloud pattern, cover, type, top temperature and height. Sea/land/ice surface temperatures, sea-ice cover, icebergs, NDVI, fires. Profiles or total columns of selected key trace gases.	IR/MW sounder. UV/VIS/NIR spectrometer. Improved VIS/IR imager. Narrow-band spectrometer.
	Sea-surface wind and temperature, sea-ice cover and surface temperature. Icebergs, glacier cover, snow cover and melting conditions. Precipitation rate, precipitation index.	MW radiometer with multi-polarisation and multi-viewing.
	Cloud pattern, cover, type, top temperature, height, optical thickness, drop size. Cloud water, cloud ice and aerosol profiles; aerosol size. Short- and long-wave outgoing radiation at TOA. Earth surface short-wave radiation/reflectance, long-wave radiation/emissivity. NDVI, LAI, PAR, FPAR (large scale).	Imagers covering UV, VIS, NIR, SWIR, MWIR, TIR, FIR and Sub-mm, with multi-polarisation and multi-viewing.
MiniSat for ocean topography (> 2008).	Significant wave height, sea level, ocean topography, geoid. Polar ice thickness and sheet topography.	Medium-class altimeter (follow-on of Jason).
SmallSat for wind profile (> 2015).	Wind profile in clear air. Aerosol profile (large scale).	Doppler lidar (follow-on of Aeolus).
SmallSat for salinity & moisture (> 2008).	Ocean salinity (large scale). Soil moisture (large scale).	Low-frequency MW radiometer.
Mini-satellites constellation (> 2008).	Temperature/humidity profile, heights of tropopause and PBL top. Total Electron Content and Electron density profile. Precipitation rate, precipitation index. Short- and long- wave outgoing radiation at TOA. Significant wave height (sea-state).	Radio-occultation sounder. MW radiometer. Lightning mapper ERB radiometer. Large-swath altimeter.

11. Data of operational interest to be procured from R&D or commercial programmes

The "manifest" listing the information from R&D or commercial programmes, required to be made available for operational use, is shown in ***Table 4***. To be noted that two items, Water-vapour profiling by DIAL (Recommendation 4) and Far IR spectroscopy for water vapour and radiative budget in UT/LS (Recommendation 24) represent a new development. They have not been included in Table 3 because:

- for DIAL, the performances achievable with the present instrument concept are too far from meeting official user requirements, particularly in respect of horizontal resolution and observing cycle; and the mission fails compatibility with the SmallSat condition; thus, technological progress is needed before a fully operational and affordable long-term mission can be defined;

- for FIR spectroscopy the present requirement is dominated by scientific motivations and it is too early to define a mission optimised for operational application.

The structure of Table 4 simply records the relevant recommendations discussed in Sections 2 to 8. Some remark is added, specifically to emphasise whether a new development is requested (Rec. 4 and Rec. 24), and whether the requirement is "*ad interim*" (e.g., waiting for NPOESS) or permanent.

Table 4 - "Manifest" of data of operational interest from R&D or commercial programmes

No.	Recommendation	Remark
04	Active sensing of water vapour by DIAL for high-vertical resolution profiling should be pursued, primarily for research purposes, procuring that data are accessible for operational use.	New development requested.
05	Temperature profiles in the higher stratosphere from missions oriented to atmospheric chemistry exploiting limb sounders should be made available for operational use.	Permanent requirement.
09	Any wind profile data available from experimental satellites, e.g., by passive Doppler spectroscopy of the upper atmosphere, should be made available for operational use.	Permanent requirement.
11	Wind profiles from Doppler lidar technology demonstration programmes must be made available for operational use.	Interim requirement waiting for a SmallSat
15	Profiles of species other than ozone, and total columns of species requiring instrumentation exceeding the operational one, as well as high-vertical resolution ozone by DIAL lidar, should be made accessible from scientific programmes for operational use.	Permanent requirement.
18	Accurate measurements of cloud top height and observation of cloud base height performed by research satellites should be made available for operational use.	Permanent requirement.
19	Data from the Global Precipitation Mission must be made available for operational use, and arrangements should be sought to ensure long-term continuity to the system.	Permanent requirement.
24	An exploratory mission should be implemented, to collect spectral information in the Far IR region, with specific emphasis on water vapour profiling significant of the UT/LS region, and on improved knowledge of the water vapour continuum.	New development requested.
25	Data from process study missions on clouds and radiation as well as from R&D multi-purpose satellites addressing Earth's surface characterisation and aerosol should be made available for operational use.	Permanent requirement.
26	Till the advent of NPOESS, high-quality sea-surface temperature data from R&D satellites must be made available for operational use, specifically for climate monitoring.	Interim requirement waiting for NPOESS
29	In the near and mid term future, sea-surface wind data from R&D satellites must be made available for operational use, and relevant satellites programmes should possibly be coordinated so that a two-satellite coverage is achieved.	Interim requirement waiting for NPOESS.
31	Data from geodetic-class radar or lidar altimeters from R&D satellites should be made available for operational use, specifically for the cryosphere.	Permanent requirement.
33	Data from SAR for wave spectra and other observations of ocean and ice should be acquired from R&D and commercial satellite programmes for operational use.	Permanent requirement.
34	In the near and mid term future, ocean colour data from R&D satellites must be available for operational use. In the NPOESS era, continued access may be useful for specific purposes, particularly in coastal zones.	Interim requirement waiting for NPOESS, continued in coastal zones.
36	Observations of ocean salinity from R&D satellites with horizontal resolution suitable for applications in coastal zones should be made available for operational use.	Permanent requirement.
37	SAR observation data of land snow and ice from R&D and commercial satellites should be made available for operational use.	Permanent requirement.
39	In the near and mid term future, vegetation data from R&D and commercial satellites must be available for operational use. In the NPOESS era, continued access may be useful for small-scale applications.	Interim requirement waiting for NPOESS, continued for small-scale applications.
40	High-resolution optical and SAR imagery data of use for agrometeorology and hydrogeology should be procured from R&D and commercial satellites.	Permanent requirement.
42	Observations of soil moisture from R&D satellites with horizontal resolution suitable for small-scale applications should be made available for operational use.	Permanent requirement.

12. Summary and conclusion

In this document a detailed analysis has been performed of the gaps of compliance of GOS current and near-future performances with WMO requirements, and recommendations have been put forward on how to fill or reduce the gaps within the 2015 timeframe. The analysis was carried out by geophysical parameters (nearly 100 as defined by CEOS/WMO) and by thematic areas (Atmospheric thermodynamics, Atmospheric dynamics, Atmospheric chemistry, Clouds and precipitation, Clouds and radiation, Ocean surface and sea-ice, Land surface and vegetation).

It has been found that certain gaps should be filled by full integration of appropriate tools into the operational satellite system whose long-term continuity is ensured by CGMS partners. This would require developments and demonstration missions possibly to be carried out with the help of R&D space agencies. A strategic approach has been applied to identify a limited number of missions based on satellites of different classes (MediumSat, SmallSat, MiniSat) to be added to a backbone of very few large satellites already committed for the post-2015 timeframe (e.g., NPOESS and presumably GOES follow-on). A "manifest" of such missions is reported in Table 3. On the other hand, it has been found that, for one or another reason (technological/scientific maturity, affordability, developmental nature, existence of a different driving user community, …), certain data are better procured on the base of a sort of "data-buy policy" from R&D or commercial programmes. A "manifest" of recommendations for data to be procured in this way is reported in Table 4, which also includes a couple of recommended new R&D developments.

This document is the (provisional) result of about three iterations occurred in about two years, starting with CGMS-XXVII in Beijing in October 1999, through CGMS-XXVIII in Woods Hole in October 2000, and culminated with the CGMS Workshop in WMO in April 2001, leading to this issue presented at CGMS-XXIX in Capri in October 2001. The two "manifests", obviously, are evolutionary and will never be perfect, but it is felt that their present version could constitute a useful basis for focusing discussions at the Second "Consultation meetings on high-level policy on satellite matters" between WMO, CGMS and R&D space agencies.

Difficulties in implementing the two "manifests" should not be hidden. For instance:

- as regards the manifest of Table 3, the present mechanisms of R&D space agencies to select new missions to be developed, based on "Call for Ideas" and "Announcements of Opportunity" open to widest scientific communities and controlled by Peer Review Panels, is not favourable to implement comprehensive long-term strategies based on international/interagency understandings;
- as for the manifest of Table 4, the difficulty of getting easy access to data from R&D satellites is well known. R&D space agencies do not have the undertaking of providing user-friendly data circulation schemes (including direct-read-out), standard formats and coding, fast processing and delivery, and product assurance of the level usual for data to be used in operational applications. Therefore, if CGMS partners want to serve their user community by procuring data from R&D satellites, they must set up appropriate arrangements, e.g., true programmes (i.e., budgeted) for the utilisation of third party missions.

Therefore, the two "manifests", in addition to their role for focused technical/scientific and strategic considerations, also offer the opportunity to address the policy and organisational aspects on the base of specific issues.