STATEMENT OF GUIDANCE FOR AERONAUTICAL METEOROLOGY

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Principally Aeronautical Meteorological services support air traffic *safety* in the first place. The other major activity is to support efficiency and capacity resulting in *economic* and *environmental* benefits. These services will have objectives to support take off and landing (local Air Traffic Management, typically in terminal area,*i.e.* the upper air area around the aerodromes and at surface level on the airfield and with short time frames) and to support the *en route* (level flight) flight planning (typically global Air Traffic Management).

The basic requirements expressed as Standards and Recommended Practices are documented in the WMO Technical Regulations (WMO - No. 49), Vol. II, Chapter C.3.1, which is identical to ICAO Annex 3. This document and related ICAO Manuals provide further details on observational variables necessary for forecasting and now casting and for instantaneous support of local Air Traffic Control. To improve Performance-based Navigation (PBN[1]) ICAO is working towards a new global concept of interoperable, consistent and harmonized Air Traffic Management (ATM), which will result in a significant upgrade of this set of requirements[2]. Also terminal area ATM is subject to improved PBN, covered by the CAeM Expert Team on Information and Services for Aviation (ET-ISA). Other CAeM expert teams involved with e.g. scientific or educational matters related to requirements are Expert Team on Aviation, Science and Climate (ET-ASC) and the Expert Team on Education, Training and Competency (ET-ETC)[3].

Aeronautical Meteorology has a global role, its users range from pilots, air traffic control and management to airline dispatch offices as well as airport authorities. *En route* forecasts for Instrument Flight Rules (IFR) flight planning purposes are mostly based on the International Civil Aviation Organization (ICAO) World Area Forecast System (WAFS), whereby fixed-time forecasts of wind, temperature and significant weather information are provided. The accuracy of upper wind and temperature forecasts is crucial for optimal flight planning, which apart from direct economical consequences also has an impact on the climate impact of aviation, i.e., its fuel consumption and resulting Greenhouse Gas (GHG) emission. This forecast accuracy critically depends in turn on highly accurate observations of these parameters, in particular near jet streams where sharp gradients of wind speed and temperature lead to large absolute errors where such systems are incorrectly positioned.

Significant Weather Charts as defined by ICAO are presented by the so-called SIGWX forecasts. These forecasts are issued by the two World Area Forecast Centers London and Washington at a high degree of automation, containing information on phenomena, with impact on safety, such as:

- convective activity (Cb cloud areas);
- icing in clouds
- clear air turbulence, both in the vicinity of jet streams and near convection;
- mountain wave activity;
- tropical cyclone (name and position only);
- volcanic eruption;
- accidental release of radioactive materials, and
- sand- and dust storms.

Many of these phenomena occur on a scale of a few km in the horizontal and less than 1 km in the vertical, and persist in time from minutes to a few hours. They need to be derived from ground- and satellite-based observations as well as larger-scale information in the NWP models by algorithmic methods, depending heavily on correct information of horizontal and

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[1] See ICAO Doc 9613, Performance-based Navigation (PBN) Manual, available at www.icao.int (4th edition, 2013)

[2] For an actual overview of the status on the further development of PBN, see http://www.icao.int/APAC/Meetings/2016%20PBNICG3/IP02_ICAO%20AI.%202%20-%20PBN%20Update.pdf

[3] See http://www.wmo.int/aemp/caem_experts for Terms of References.

vertical shear, moisture (including super-saturation) and Super-cooled Liquid Water Content (SLWC), and sometimes boundary layer information, such as low-level moisture content or depth of a stagnant layer upstream of mountains or hills generating gravity waves. Details on the use of NWP for Aeronautical Meteorology are provided as online training modules and publications, by organizations like COMET, ECMWF and NCEP.

Individual Flight Information Regions (FIR) are served by Meteorological Watch Offices (MWO) with a responsibility to issue SIGMET information giving precise location, intensity and movement of these phenomena when they occur. For route forecasts in Visual Meteorological Conditions (VMC), highly detailed information on visibility, cloud ceiling height and topographically induced features (coastal stratus, upslope fog, orographic cloud), needs to be provided to clients. For Terminal Aerodrome Forecasts (TAF), landing forecasts (TREND) and warnings as well as emerging new forecasts for the terminal area, nowcasting and very-short-range forecasting of local conditions such as visibility, cloud base height,convection, 3-D wind and vertical temperature profile is required.

Apart from forecast information, aircraft based observations (ABO) can be used in real time to inform other aircraft flying relatively nearby (aircraft typically fly in specified corridors and altitudes during level flight and during ascent and descent, so the other aircraft will experience similar weather phenomena like turbulence an dicing). This information exchange in real time mode on dangerous phenomena is an essential service to reduce risks by modifying the planned routes during flight.

In addition to the phenomena indicated above (convective systems, heavy precipitation, icing - both in-flight and on the ground -, and high winds), particular emphasis is placed on the following issues, relevant for landing and take off, inclusive ascent and descent:

- low-level wind shear and turbulence (including wake vortices);
- lightning and microbursts, gust fronts;
- heavy, solid (hail) and freezing precipitation;
- super cooled large cloud droplets ("freezing drizzle droplets");
- poor visibility and low ceiling situations (low stratus); and,
- snow fall and black ice formation on the runway.

For the benefit of air traffic management, airline dispatch offices and airport authorities, short-range forecasts of weather phenomena affecting airways or the acceptance rate of hub airports are required. These include deep convection, lightning, strong winds including crosswinds and gusts, low-level wind shear and turbulence, snow and sand storms, and very low ceiling and visibility values. For these phenomena, information on onset and cessation is also required. Decisions on de-icing activities before take off affecting PBN rely strongly on the air and runway temperature forecast (at some airports pavement temperature, measured by sensors installed in the runway, are used for decisions related to runway de-icing activities.

The key variables to be observed and forecast in aeronautical meteorology (beyond those already addressed in the NWP and Nowcasting and Very Short Range Forecasting SoGs and not repeated where requirements are considered identical) are briefly discussed below. Aeronautical Meteorology requirements for these variables are in the WMO database of user requirements[4]. This WMO database of user requirements (OSCAR) is to be regarded as the 'master' source, *i.e.* to be up-to-date. A number of variables are recently identified to be entered in this database: "Atmospheric Stability Index", "Vertical Visibility (surface)", "Super-cooled Liquid Water Content" (to replace Icing Potential) and "Ice Crystal Content". The appropriate variable representing Turbulence is under discussion. At present there is a preference for the Eddy Dissipation Rate (EDR) over the Derived Equivalent Vertical Gust Velocity (DEVG). This section provides estimates of how well existing and planned instruments and observing systems meet the requirements for Aeronautical Meteorology, concentrating on those parameters not already covered by previous sections of this document:

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[4] See http://www.wmo.int/oscar

Local observations at aerodromes

Apart from the global Aeronautical Meteorological services, local nowcasting services for take off and landing require specific local observations, in particular relevant for weather behaviour above and around runways and taxiways. These observations are reported and used in *real time*. Requirements are stated as standards in the WMO Technical Regulations (WMO - No. 49), Vol. II, Chapter C.3.1, which is identical to ICAO Annex 3. Reports shall contain:

- surface wind direction and speed (inclusive its variations);
- visibility (prevailing), expressed as 'aeronautical visibility' and 'runway visual range' (which requires background luminance and runway light intensity values);
- present weather (type and intensity of precipitation, freezing precipitation, fog, thunderstorm and other relevant phenomena, state of the runway);
- cloud amount, cloud type (only for cumulonimbus and towering cumulus) and height of cloud base or vertical visibility;
- air temperature and dew-point temperature;
- atmospheric pressure (expressed as QNH, *i.e.* pressure reduced to MSL using the International Standard Atmosphere (ISA)).

Apart from these observations it is recommended to provide supplementary information like wind shear and volcanic ash reports.

Further to local observations i.e. observations at the aerodrome reference point and along runways, there is an emerging need for observations in the vicinity of the airport (radius of ~10 km). This is useful for anticipating advection fog, snowfall, etc., which may help in estimating the onset of some of those critical phenomena.

Studies with numerical methods based on small-scale model physics have successfully demonstrated its usefulness to improve short term local weather forecasts. Examples are the *1D Boundary Layer Model COBEL*[5] (in particular for low visibility conditions) and *The Weather Research and Forecasting Model WRF*[6] (in particular for icing). These models require an extensive set of observational variables, like soil moisture, but these sets are comparable with requirements stated in the Very Short Range Forecasting SoGs.

Observations by satellites

Meteorological low-earth-orbiting (LEO) and geostationary (GEO) satellites provide observational data currently being the major source for NWP, also for Nowcasting and Very Short Range Forecasting. Recently launched GEO satellites already meet the required temporal resolution around 5 minutes. However to determine the localization of expected active updraft zones by automated algorithmic methods further updates and improvements are required.

In situ observations by aircraft

On board aircraft a number of meteorological quantities are measured and derived. Variables like air temperature, wind speed and wind direction are observed by default, together with the derived variables on turbulence, like EDR, and ice accretion.

During the recent decades new humidity sensors are developed and installed providing accurate mixing ratio. Although humidity observations will be of most interest for NWP in the first place, it is considered to have potential to derive supercooled liquid water content, a variable useful to indicate icing potential. In particular, reports on (clear air) turbulence and icing are of interest for immediate warnings to other aircraft nearby, flying the same routes. Most of these aircraft based observations (ABO) are reported using the Aircraft Meteorological

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[5] see "Adaptation of a particle filtering method for data assimilation in a 1D numerical model used for fog forecasting", by S. Remy et al, Q. J. R. Meteorol. Soc. 138: 536–551, January 2012 B,http://onlinelibrary.wiley.com/doi/10.1002/qj.915/pdf

[6] see http://wrf-model.org/

Data Relay (AMDAR) system. Details on ABO are available on the AMDAR website[7] . In particular the WIGOS Technical Reports on impacts and benefits of ABO to operational weather forecasting are of interest[8]. (See also under "Humidity Fields" in this SoG below)

Development on requirements for observations and forecasts.

The further development of requirements for observations and forecasts, in particular with a focus on automation, were carried out until 2014 by the ICAO Aerodrome Meteorological Observation and Forecast Study Group (AMOFSG)[9]. The further development of requirements for warnings is carried out by the ICAO Meteorological Warnings Study Group (METWSG). Both study groups were established to work on task, to be carried out under the ICAO strategic objective "Safety". These groups developed ICAO documents providing requirements on observational topics. To reduce the number of expert and study groups ICAO reorganized its structure and a new Meteorology Panel (METP) was established in 2015. Within this panel is a Working Group on Meteorological Requirements & Integration (WG-MRI) with the task to consider modernization documents related to observational requirements. First results were expected mid 2016.

- 3-D Wind and Temperature Fields and Profiles

For upper level wind forecasts supporting flight planning, the requirements stated in the NWP section apply. In practice, use is made of WAFS wind and temperature charts.

At busy airports introducing continuous descent approaches, arrival metering and sequencing operations for fuel saving and more efficient ATM, higher accuracy in the wind forecasts may be achieved by an enhanced collection of aircraft based observational data (*e.g.* down linked from AMDAR, ADS-B (Automatic Dependent Surveillance) and Mode-S systems) and observed in the terminal areas. For SIGWX information on turbulence, which is based on algorithmic methods, very high spatial resolution in temperature, moisture, and wind fields are required for calculation of non-dimensional parameters such as Richardson number, Froude number, Ellrod indices, divergence and deformation. The required vertical resolution is increasingly available both from aircraft (AMDAR / ADS-B / Mode-S), particularly from ascent / descent profiles, but also from en-route aircraft, as the recent introduction of RVSM (Reduced Vertical Separation Minima) have resulted in a closer spacing of flight paths in the vertical (1000 ft instead of 2000 ft). Although wind and temperature profiles generated with a high update frequency from AMDAR / ADS-B / Mode-S are becoming increasingly in practice for nowcasting in the terminal area, radiosonde network data would still be able to provide significant input to turbulence forecasting if the full vertical resolution of the sounding (about 50 m in the vertical) is transmitted instead of significant and standard levels only. Moreover the number of humidity observations by aircraft are limited and only performed in northern America. Improvement of upper air information can be found in reporting aircraft observations with an increased vertical resolution (50 m), together with humidity data. A relatively high vertical resolution is a constraint because these profiles provide the height of the boundary layer and significant inversions layers, which are essential for nowcasting services in the terminal area.

Multiple Doppler wind measurements from at least two radars can provide accurate 3D winds within precipitating areas. Such wind fields are retrieved thanks to the two (or more) non-collinear wind measurements along the beams and the use of an additional constraint such as the wind continuity equation. Furthermore, scanning weather radars often face problems for near surface measurements because of the presence of many non-meteorological artefacts which heavily contaminate the signal.

- Surface and near-surface wind

In the vicinity of airports, wind shear, turbulence, wake vortices and sudden changes in

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[7] see http://www.wmo.int/amdar

[8] see WIGOS Technical Report 2015-1, Impact and Benefits of AMDAR Temperature, Wind and Moisture Observations in Operational Weather Forecasting and WIGOS Technical Report 2014-2,The Benefits of AMDAR Data to Meteorology and Aviation,availble on the AMDAR website.

[9] see http://www.icao.int/safety/meteorology/amofsg/Pages/default.aspx

wind speed or direction (e.g. increase in crosswind including gusts) are very important for landing/departing aircraft and air traffic management (such as change of runways). Local observing meso-scale networks,Doppler lidars, and terminal Doppler weather radars are providing good wind information at selected locations in the developed world. Boundary-layer wind profilers provide useful information on vertical shear and turbulence but are limited in sampling the horizontal wind changes over the flight paths for alerting wind shear. Nevertheless improved cloud radar and lidar techniques for use in the terminal area are available and promising to improve the situation. Buildings and other artificial constructions may influence the wind behaviour on runways, in particular due to Venturi effects causing turbulences and variable crosswinds on the runways, and near embarking/disembarking gates causing turbulence and "no ground operations" areas. Present information on the wind behaviour in real time can be provided with acceptable uncertainty based on small-scale model case studies on the aero dynamical behaviour of such constructions.

Scatterometer data from satellites provide highly valuable surface-wind data for oceans and seas with improved performance around islands and coastal areas. Cloud-motion winds are rarely capable of providing data continuously in the planetary boundary layer over land.

- Surface pressure

Surface pressure at airport for reporting QNH/QFE is usually measured today by automatic digital barometers and on site, providing more reliable measurements (assuming instabilities and biases by wind impacts are avoided by the use of static tubes). The reported QNH is required for altimeter settings of the aircraft, so a local observation fulfils. Use of the historical mercury-in-glass barometers shall be discontinued[10]. Relevant here is that reduction to MSL (to generate QNH) follows an ISA-based calculus different from that done to derive $p_{\mathrm{MSL}}$for synoptical purposes.

- Humidity fields

Humidity fields play a critical role in forecasting icing and convection and, as in NWP; they are currently under-sampled by existing in situ-systems except in densely populated areas. Where ground-based systems provide temperature and dew point, the values reported in the METAR have a limited resolution (1 °C) to determine RH with sufficient resolution, indicative of the need for reporting of temperature and dew point to tenths of a degree Celsius in METAR reports. This would further benefit other application areas such as climate. Satellite sounding systems (microwave sounders) are beginning to have a positive impact over oceanic areas when such data is used in data assimilation for NWP, but vertical resolution and regular availability are still considered insufficient for the purposes of aeronautical meteorology. Ground-based microwave radiometers are also beginning to provide a significant contribution in monitoring the vertically integrated cloud liquid water. For *in situ* observations the introduction of improved humidity sensors on commercial aircraft is expected to have a positive impact on humidity analyses and atmospheric profiles at the terminal area[11].

Moisture information at higher flight levels may become very important if current research pointing to a significant impact of aviation generated cirrus cloud on radiative forcing, and thus contributing to global warming, is confirmed. For that reason, moisture sensors on AMDAR aircraft will become very important if the problem of sensitivity and accuracy at very low humidities at Upper Tropospheric and Stratospheric levels can be resolved[12]. These applications would also necessitate improved radiosonde humidity sensors at higher levels in the atmosphere. Reports of flame-outs on jet engines in very cold situations above deep convection, where melting and re-freezing of icicles is suspected, re-emphasizes the need for enhanced moisture data at high altitudes. In fact, jet engines are very sensitive for ingesting so-called "High-Altitude Ice Crystals". The AMSU, multi-spectral sensors on research satellites,

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[10] see http://www.wmo.int/pages/prog/www/IMOP/publications/Flyers/Mercury_flyer.pdf

[11] At present (2016) a number of 149 commercial aircraft provide humidity profiles, predominantly over USA and Europe.

[12] It is demonstrated that the new WVSS-II mixing ratio sensor on board 149 aircraft provide high accurate data down to 0.1 mg/kg around an altitude of 10 km.

and sensors on the newer geostationary satellites that include more spectral resolution in the water vapour band, are expected to have an increasing clear positive impact.

- Cloud and liquid / ice water content

Detection of large convective systems from cloud top height information is accomplished from multi-spectral infrared satellite sounding systems with acceptable horizontal and vertical resolution. Cycle times in the order of 10 to 15 minutes for the geostationary satellites are helping to satisfy the requirements for higher temporal resolution. Ground-based scanning Doppler radar and lightning detection networks provide acceptable detection and have good temporal and spatial resolution and accuracy over densely populated land areas in the developed world. Data exchange across national boundaries is beginning to provide information for larger areas, but it is far from covering entire continents, particularly in the developing world. The emerging deployment of ground-based polarimetric weather radars (also referred to as dual-polarization weather radars) contributes to improved estimates of rain and snow rates, better detection of large hail location in summer storms, and improved identification of rain/snow transition regions in winter storms – all of them highly relevant to accurate forecast and warning of severe weather impacting on air traffic near busy airports.

Cloud drop size information for icing forecasts is currently not directly observed; satellite remote-sensing methods and ground based (cloud) radar techniques are under development and should be closely followed. Observations from satellites are at the top of a cloud layer, and then only when this layer is viewable from space. Indirect methods for deriving this information are based on moisture supply, temperature inversions, and wind shear near cloud tops. Only radiosonde and aircraft data could provide acceptable vertical resolution of these parameters, but cycle times and horizontal resolution are marginal to poor. Dual-polarization weather radars, particularly if operated in the X-Band, again holds promise for acceptable accuracy in determining the amount and distribution of SLW droplets, but while now common in some countries are still far too rare to have a significant global impact.

- Visibility and cloud amount / cloud base height

These variables are well observed at most aerodromes both by human observers and automated systems. However, due to the nature of the current technology used (point measurements in the vertical only), automatic determination of cloud amount / cloud base height from single ceilometer measurements could be challenging at locations with complex topography (e.g. valleys, coastal stations and large cities with high aerosol loading). Apart from instrumented measurements of runway visual range (RVR) and visibility along runways, automatic determination of the prevailing visibility would typically require a suite of visibility meters installed at suitable locations within / near the airport. Although reporting Slant Path Visual Ranges (SVR) will have a positive impact on safety and efficiency, no operational technology is recommended so far. For en route forecasts of VFR flights, both the horizontal resolution and cycle time of existing observing stations reporting aeronautical weather information in METAR code are acceptable only in densely populated areas, and poor over most of the globe. Use of additional observations from synoptic weathers stations is recommended.

- Gravity waves

Gravity waves and their potential for breaking appear to depend very much on upstream wind and temperature profiles at high vertical resolution. Observation targeting by requesting ascent/descent data from AMDAR / ADS-B / Mode-S aircraft as well as full resolution in radiosonde profiles would be beneficial. The cycle times and availability of radiosondes immediately upstream of mountain ranges have to be considered acceptable only in a few densely populated areas and poor elsewhere.

Stratospheric intrusions associated with steepening and breaking gravity waves are detected in water vapour satellite imagery from geostationary satellites, where shorter wavelengths are resolved the required scale of motion (10-15 km) of gravity waves. Also,GNSS (like GPS) radio occultation measurements by satellites have proven to have potential to measure gravity waves as is shown by various studies[13].

- Volcanic Ash

Reliable detection and tracking of Volcanic Ash clouds are essential to the functioning of the International Airways Volcano Watch (IAVW) operated under ICAO regulations in close cooperation with WMO. WMO, together with ICAO and the International Union of Geodesy and Geophysics, frequently organize workshops on volcanic ash to keep its Members up to date. These workshops are International Workshops on Volcanic Ash (IWVA), the Ash Dispersal Forecasts and Civil Aviation Workshops and the VAAC Workshops. Moreover the Volcanic Ash Scientific Advisory Group (VASAF) meets frequently to provide advice and recommendations. Reports of meetings are provided on the WMO website of the Aeronautical Meteorology Programme[14]. Relevant documents containing details on what observations are used in forecasting volcanic ash are the reports of the "VAAC 'Inputs and Outputs' (Ins and Outs) Dispersion Modelling Workshop" (2012)[15] and the WMO VAAC "Best Practice" Workshop (2015)[16]. Within ICAO the International Airways Volcano Watch Operations Group (IAVWOPSG)[17] provides guidance concerning the operation of the AIVW and develop proposals for requirements to be published in ICAO Annex 3 (equivalent to WMO-No. 49, Vol. 2). The newly established ICAO Meteorology Panel (METP)[18] will continue to provide recommendations related to observations and forecasts, to be published in ICAO Manuals and the ICAO Annex 3.

A reference manual on volcanic ash is published by ICAO, entitled "ICAO Manual on Volcanic Ash, Radioactive Material and Toxic Chemicals (ICAO Doc 9691)". This document provides details on the particular chemical components and materials, to be considered as relevant for observations[19].

After the eruption at the Eyjafjöll volcano in South Iceland (2010), ESA and Eumetsat started together a series of workshops on the Monitoring of Volcanic Ash from Space. Reports from these workshop contain requirements for observation practices.[20]. More details are available on the Volcanic Ash Strategic initiative Team (VAST) website[21].

Many volcanoes are found in remote and scarcely populated areas, where reliable eruption detection and determination of the nature of the eruption can only be based on remote-sensing methods.

An integrated real time volcanic ash observing capability is vital to:

- Improve the initialisation of dispersion models;
- Verify dispersion model output;
- Improve the forecaster's capability in 'adding value' to raw dispersion model outputs;
- Facilitate ongoing and future research and development.

The sub-headings below provide a summary of the various observing resources that are currently available or undergoing development:

Satellite

The following satellite products are routinely generated in near real time and provide the basis for satellite detection:

1. Products based on 15-minute SEVIRI data from Meteosat-9 including the following:

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[13] see presentation by Torsten Schmidt at recent ROM SAF / ECMWF Workshop: http://www.ecmwf.int/en/rom-saf-workshop-presentations

[14] see https://www.wmo.int/aemp/; for final reports, see https://www.wmo.int/aemp/archive

[15] see https://docs.google.com/file/d/0B50bTmQtOwH6dUFkcjZzaG9UYlk/edit?usp=sharing

[16] see https://drive.google.com/open?id=0B50bTmQtOwH6TEtJMG5aekpqYkE&authuser=0

[17] see http://www.icao.int/safety/meteorology/iavwopsg

[18] see http://www.icao.int/airnavigation/METP/Pages/default.aspx

[19] an excerpt from this doc is available at http://www.knmi.nl/samenw/geoss/wmo/RRR/AeroMet/icao9691.pdf

[20] report (Monitoring volcanic ash from space -ESA-EUMETSAT workshop on the 14 April to 23 May 2010 eruption at the Eyjafjoll volcano, South Iceland; ESA-ESRIN, 26-27 May 2010) can be downloaded from http://earth.eo.esa.int/workshops/Volcano/. The report of the 2013 workshop (Earth observations and volcanic ash. A report from the ESA/Eumetsat Dublin workshop, 4-7 March, 2013, ESA, 2014, see http://www.nilu.no/Default.aspx?tabid=62&ctl=PublicationDetails&mid=764&publicationid=27591) contains the result of the VAST User Requirements Survey, see http://vast.nilu.no/meetings/workshops/dublin2013/ .

[21] see http://vast.nilu.no/en/

   - Two-channel Brightness Temperature Difference (BTD) product based on 10.8 µm – 12.0 µm (thresholds kept under review to maximise useful signal);
   - Three-channel BTD product based on the two-channel version but using also SEVIRI 8.7µm data to further exclude false alarm pixels;
   - “Dust” RGB based on SEVIRI channels [(10-9), (9-7), 9]. Also a variant of this product, with some colour scale manipulation to allow better colour discrimination (following inputs from H-P Roesli, EUMETSAT);
   - HRV imagery, in particular at the dawn & dusk periods where low sun angles sometimes reveal the ash plume;
   - Cloud Top Temperature (CTT) and Cloud Top Height (CTH) based on multi-spectral analysis.
   - Ash-layer height, ash loading and particle size[22]

2. Products based on AVHRR / MODIS direct broadcast data from polar orbiting satellites (satellites currently available are METOP-A, NOAA-15, -16, -17, -18, -19, FY-1D, TERRA, AQUA) including the following:
   - Two-channel BTD ash products based on the same theory as the SEVIRI product described above;
   - False colour RGB products (based on VIS channels) which sometimes show~~s~~ the ash plume coloured differently from cloud, especially if dense and especially at low sun angles.
3. Products based on IASI global coverage data from Metop-A including the following:
   - SO_2 plume detection product.

In addition, products generated externally, most on an experimental or ad hoc basis, are routinely monitored to check their availability with appropriate timeliness, and also to check the information revealed by them, for possible future case studies and product improvements. These products include:

   - Multi-spectral SEVIRI data analysis provided by Mike Pavolonis at CIMSS/SSEC[23]
   - Expedited analysis of CALIPSO data from NASA LARC[24]
   - Analysis of OMI data from AURA by NOAA/NESDIS[25]
   - Volcanic ash plume concentration levels from SEVIRI London VAAC (Met Office)[26]

Issues

   - Satellite products are most useful where there are significant concentrations of volcanic ash, although for certain phases of the current event clear signals at long downwind ranges have also been readily detected;
   - Further satellite application research is required to determine more accurate quantitative assessments of volcanic ash plume concentration levels;
   - Satellite products can be affected by the presence of underlying, overlying or shrouding clouds, especially ice clouds.
   - Satellite 'inverse modelling' techniques to better constrain the eruptive source term are currently only available in post-event research mode

Radar

A fixed C-band weather radar is the primary means by which the eruptive column height is estimated for Icelandic volcanoes. It should be recognized that this method is significantly more advanced than the visual or satellite-based estimates used in most other parts of the world. Scientific algorithms are then used to translate eruptive column heights into an ESP for

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[22] see publication “Retrieval of physical properties of volcanic ash using Meteosat: A case study from the 2010 Eyjafjallajökull eruption”, by Peter N. Francis, Michael C. Cooke and Roger W. Saunders on http://onlinelibrary.wiley.com/doi/10.1029/2011JD016788/full

[23] see http://cimss.ssec.wisc.edu/goes_r/proving-ground/geocat_ash/loops/iceland.html

[24] see http://www-calipso.larc.nasa.gov/products/lidar/browse_images/production/ .

[25] see http://satepsanone.nesdis.noaa.gov/pub/OMI/OMISO2/iceland.html

[26] see http://www.metoffice.gov.uk/aviation/vaac/process for general information on the London VAAC processes and products using satellites; see http://www.metoffice.gov.uk/media/pdf/4/3/FRTR592.pdf on “The sensitivity of NAME forecasts of the transport of volcanic ash clouds to the physical characteristics assigned to the particles.” (in Forecasting Research Technical Report No: 592, Met Office, August 18, 2014)

model initialization. During the Grímsvötn eruption in May 2011, use was also made of a mobile, X-band dual-polarization Doppler radar in addition to the C-band radar. Benefits of this radar are that it is deployable for optimum locational effectiveness and the dual-polarization capability should allow improved discrimination between water droplets and ash.

Meteorological Research Aircraft
Aircraft equipped with aerosol remote sensing instrumentation (LIDARs – see below) as well as aerosol sampling instruments (to measure concentrations and particulate characteristics) have provided some of the most reliable, real-time information, of ash cloud extent and concentrations.

Issues

- Primarily research-based.
- Spatial coverage is compromised by the limited availability of these specialised and very expensive resources.
- Subject to the same aviation safety considerations (engine ingestion of volcanic ash) as other aircraft and therefore generally cannot fly into areas of high ash concentration.
- Further development of appropriate instrumentation necessary.

LIDARs (LIght Detection And Ranging)
Although generally operated by the research community and therefore not always available operationally, the most effective surface based measurement system for detecting the presence of volcanic plumes are suitably calibrated LIDAR systems. They emit pulses of laser light and detect the backscattered signal.

Issues

- Detect low and high level cloud as well as volcanic ash and other aerosols. Using different observing channels (and other observations) cloud and aerosol can be distinguished.
- LIDAR signals cannot penetrate through thick clouds so low level clouds can obscure detection of aerosol/ash plumes higher up in the atmosphere.

Laser Cloud Base Recorders
Laser cloud base recorders (LCBRs - also known as ceilometers) are simple, low power forms of LIDARs designed to measure the height of cloud bases. They can be retuned to measure changes in aerosol concentration and hence ash cloud.

Issues

- Usually ‘tuned’ to detect clouds but some models can be recalibrated to detect aerosol layers.
- As with LIDARs, LCBRs signals are unable to penetrate thick cloud layers.
- Effective ash layer detection height range of approximately 4km above the ground.
- Raw data currently requires interpretation by LCBR experts.
- Coordination with and enhancement of existing LIDAR networks, including advanced, airport-installed Ceilometers are currently being actively pursued by WMO in close cooperation with research institutions, projects and operational operators of such systems[27].

Lightning Location
The ash plumes from some volcanic eruptions produce frequent lightning discharges in the immediate vicinity of the volcano, which are an indication that an eruption is taking place and generating ash clouds to sufficient altitude to trigger lightning events.

Issues

- Subjective information on the magnitude of some eruption activity only.

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[27] see http://www.knmi.nl/samenw/geoss/wmo/RRR/AeroMet/CAS_ceilometer_network.pdf

Aerosol Probes onboard Unmanned Aerial Vehicles
Particle measurement system (PMS) probes are frequently fitted to aircraft and can measure aerosol particle size from which it can be deduced whether the particle is volcanic ash or not. They can be mounted on UAV (Unmanned Aerial Vehicle) aircraft.

Issues

- Size distributions are derived in research mode requiring laboratory analysis.
- No prototype currently available for testing.

Aerosol Sondes
Similarly, particle measurement system (PMS) probes have been developed which can fly together with balloon mounted meteorological radio-sondes. These can also measure aerosol particle characteristics from which it can be deduced whether the particle is volcanic ash or not and an estimate of the concentration levels calculated. A drop-sonde version could potentially be an ideal way of obtaining accurate volcanic eruption source data for the initiation of dispersion models if dropped into the ash plume a nominal distance (100 km) downstream of the volcano

Issues

- Limited availability of the probes: development of the capability is ongoing and only a small number of the probes currently exist. A drop-sonde version, capable of being dropped from aircraft into volcanic ash plumes has, subject to confirmation, not yet been developed.

-Sand-and Dust Storms:

Sand- and dust storms have been recognized as significant hazards to aviation and comparable to volcanic ash impacts. While detection of such phenomena in a qualitative sense appears mature in Visible satellite imagery, automated detection outside daylight hours remains an issue, and surface observations in areas prone to suffer these phenomena are scarce. In addition, aviation meteorology is currently tackling the question of defining objectively the intensity of such phenomena as the presence of a severe sand-or duststorm would preclude planning of flights to an affected destination. Visibility, in particular Aerosol Optical Depth (AOD) and wind speed/gustiness are being explored as indicative parameters in the absence of any measurements of aerosol loading. Aircraft based observations in combination with dedicated products derived from satellite imagery are expected to be most promising[28]. Of interest here are the International Workshop on Sand/Dust storms and Associated Dust fall[29]. Moreover, in the last ten years dust models have developed[30] providing improved sand and dust storms forecast. To improve capabilities for more reliable sand and dust storm forecasts the WRCP programme has initiated the WMO Sand and Dust Storm Warning Advisory and Assessment System (SDS-WAS)[31]. An interesting regional SDS-WAS website[32] is provided by the Asia/Central Pacific Regional Centre.

The ICAO Aerodrome Meteorological Observation and Forecast Study Group (AMOFSG)[33] provided recommendations related to observations and forecasts on sand- and dust storms, to be published in ICAO Manuals and the ICAO Annex 3.

- Space Weather

Requirements stated in the SoG for Space Weather section apply also for aviation. Solar and extra-terrestrial radiation events (solar storms) have been recognized to cause disruption to HF radio communications and thus navigation. They may also pose health hazards to air crew and passengers in extreme cases, especially for cross-polar flights. A new initiative is underway in collaboration with ICAO to incorporate these "Space Weather Events" into regular warnings to

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[28] For an detailed overview, see http://www.atmos-chem-phys.net/12/10649/2012/acp-12-10649-2012.pdf
[29] see http://dustworkshop2013.enea.it/
[30] For example, see http://www.metoffice.gov.uk/research/news/dust-forecasting
[31] see http://www.wmo.int/pages/prog/arep/wwrp/new/Sand_and_Dust_Storm.html
[32] see http://www.wmo.int/pages/prog/arep/wwrp/new/DustforecastsAsianregion.html
[33] see http://www.icao.int/safety/meteorology/amofsg

aviation. New data sets for radiation levels and particle flow are being investigated as sources of information.

3.6.1 Summary of Statement of Guidance regarding Aeronautical Meteorology

The following key points summarize the SoG for Aeronautical Meteorology:

1. For upper-level temperature and wind forecasts the SoG for global NWP apply for operational forecast production, locally higher vertical resolution is required for development and verification of turbulence forecast algorithms as well as in support of future 4D trajectory planning of aircraft. Enhanced collection of aircraft data (*e.g.* AMDAR / ADS-B / Mode-S) may improve accuracy in support of more efficient ATM in the terminal areas of busy airports.

2. For Meteorological Watch purposes (issuance of warnings), satellite imagery, and higher-level products such as multi-spectral images, provide good guidance for location and intensity of convection. However scanning radars in networks combined with lightning detection systems currently have the cycle times of less than 10 min required for air traffic control and supporting air traffic management. Newer geostationary satellites with more frequent scanning capabilities in conjunction with improved lightning imagers are getting closer to these requirements.

3. For turbulence and gravity wave detection and prediction, current *in-situ* instruments have acceptable vertical resolution, but are not available in sufficient density for all areas of the globe. The AMDAR / ADS / Mode-S is a data source with a high potential to fill existing data gaps in the medium term, water vapour imagery is beginning to show potential for subjective detection of steepening waves, leading to Clear Air Turbulence.

4. For forecasts and warnings in the wider terminal area, *in-situ* and ground-based remote-sensing technology has the potential to meet requirements, but its high cost inhibits general, global availability. In particular, the possible extension of data requirements for new terminal forecasts and warnings for the larger approach-and departure areas, to be developed in close collaboration with ICAO, meso-networks, including lightning detection, LIDAR and Doppler RADAR (increasingly with dual-polarization functionality) coupled with Nowcasting algorithms, may become necessary for larger airports. The deployment of automatic instruments for measuring conventional parameters at airports such as surface wind, pressure, visibility and cloud will also need continuous improvements considering the evolving user needs and changing operational environment. In support of winter operations, runway pavement temperature measurements should be envisaged. Freezing point depression and runway (surface) condition measurements could be envisaged as well.

5. For *en route* forecasts for VFR flights, ground based observations are not meeting the required data density except for some densely populated areas. Satellite imagery and specialized products have acceptable horizontal resolution, but lack the information on visibility and ceiling height for low cloud.

6. For forecasts and *real time* nowcasting in the terminal zone ground based observations shall be as required and documented in the WMO Technical Regulations (WMO-No. 49, Vol. II). In practice these requirements are fully met, although the transition from human (visual) observations to fully automated observations is challenging resulting in a reconsideration of observational requirements. To improve short-term forecasts high resolution (in time and space) NWP models are being introduced, modelling in real time the atmosphere above the aerodrome and its vicinity. This practice requires new observation technologies to be developed in support of atmospheric processes and remote sensing for model initialization.

7. For the detection of volcanic ash clouds and eruptions, satellite and ground based

remote-sensing has significant detection and quantitative determination capability. Close cooperation with the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) in using seismic and sonic data is improving the detection of volcanic eruptions in remote areas.

SPECIAL NOTE: The accuracy requirements are based on the stated requirements expressed as Measurements Uncertainty (WMO-No. 49). Measurement Uncertainty is based on the definition adopted by WMO (see WMO-No. 8) and confirms to the international standard, issued by Bureau International des Poids et Mesures (BIPM)[34], ISO, and international scientific bodies (ICSU)[35].

For many physical quantities the measurement errors follow Gaussian statistics (*e.g.* temperature). Measurement Uncertainty is defined as the extended standard error from the true value which in this case is twice the standard error (k=2), which equals largely the standard deviation with respect to the true value.

This practice is based on a 95% confidence level (*i.e.* 95% of all possible observations will be within the range indicated by this measurement uncertainty). So for quantities with a linear Gaussian behavior we may assume that the expected RMS error is half the required measurement uncertainty. A number of quantities follow a exponential Gaussian behavior and errors should be expressed as relative errors (in %). In such cases the accuracy should be quantitatively expressed as relative values. Some quantities have no Gaussian behavior (*.e.g*. magnitude of the wind vector, or wind speed, always to be >0) in which case the type of the error distribution function and the stated confidence level shall give the relationship with RMSE. Uncertainty estimates based on the standard error only (k=1) will generally confirm to a 67% confidence interval.

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[34] WMO is member of CIPM and will follow its recommendations by general agreement

[35] See the Guide to the Expression of Uncertainty of Measurement (GUM) and the International Vocabulary of Basic and General Terms in Metrology (VIM), both issued by BIPM (http://www.bipm.org/)