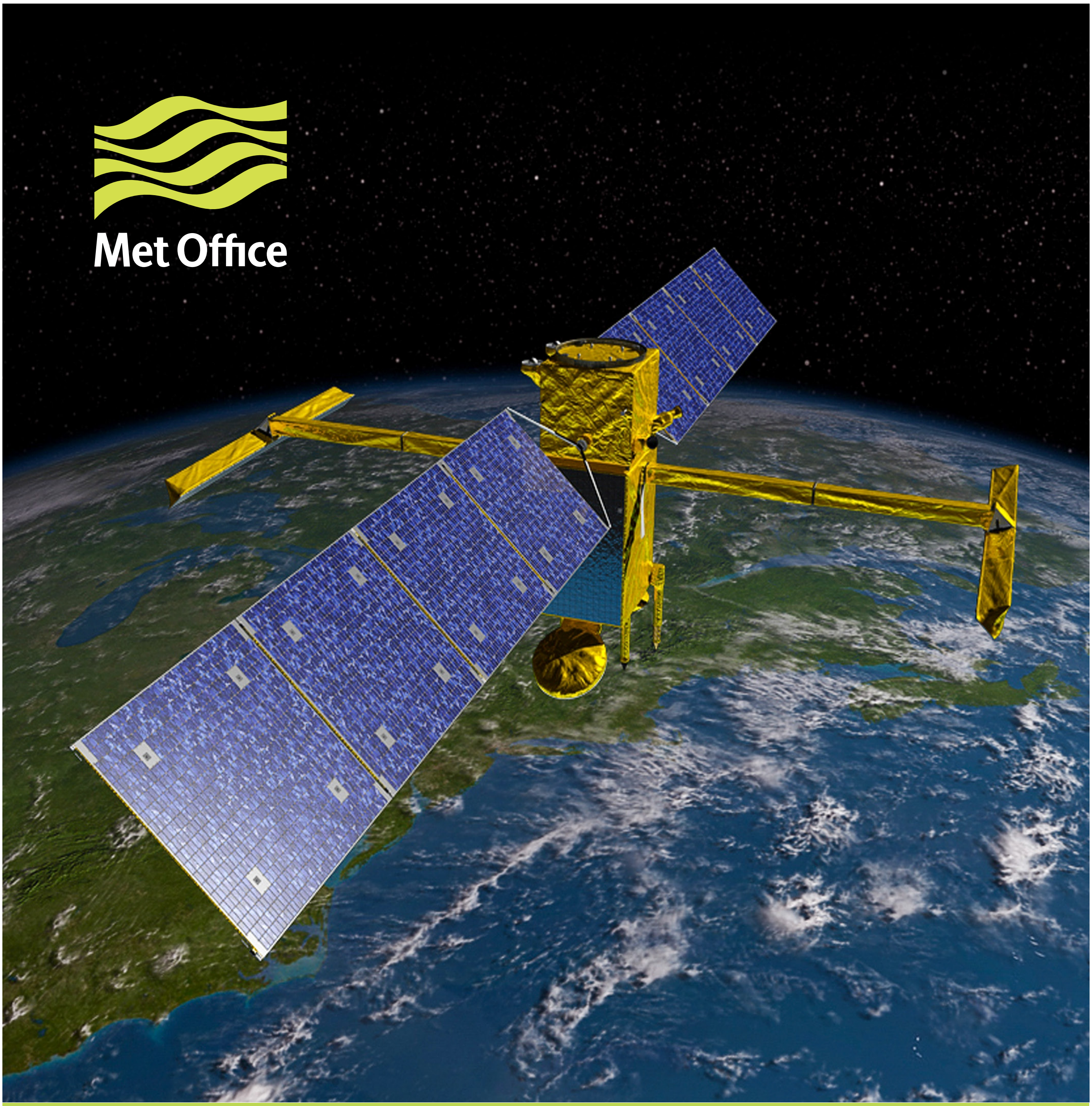

Satellites

National Meteorological Library and Archive
Factsheet 18 — Weather satellites

The National Meteorological Library and Archive

Open to everyone

The library was first mentioned in the 1870 Annual Report of the Meteorological Office.

In 1914 the archive was established as the official custodian of meteorological related records. It holds historic weather records on behalf of the nation and is an approved place of deposit under the Public Records Act.

The National Meteorological Library and Archive is a National Archive (TNA) Accredited Service.

The National Meteorological Library and Archive are open by appointment.

All of the images used in this fact sheet along with many others covering all aspects of meteorology can be obtained from the National Meteorological Library and Archive. For further information including our opening times please visit our web page at https://www.metoffice.gov.uk/research/library-and-archive
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Brief history

Until the 1960s measurements of the Earth's atmosphere and surface were all made by in-situ measurements from weather stations on land, ships and balloon ascents. The first satellites which observed the atmosphere were the TIROS class of satellite which imaged the Earth from a low Earth orbit showing the position of clouds in rather fuzzy images. TIROS-1 was launched in 1960 and was the first dedicated meteorological satellite but only covered the tropics and mid-latitudes providing images twice a day. Polar orbiting satellites in the NOAA series which are now widely used were developed from the TIROS satellites and regular launches were made of NOAA satellites from 1970 with increasingly sophisticated instrumentation onboard. Polar satellites are ideal for providing global coverage twice a day. The last in the NOAA series, NOAA-19, was launched in 2008 and is still providing imagery for our forecasters and sounding data for our numerical weather prediction models. Europe launched its own polar orbiter, Metop-A, in 2006 with enhanced instrumentation over the NOAA series, to cover the mid-morning orbit. The US has now developed a follow-on to the NOAA series, the Joint Polar Satellite System (JPSS) and its instruments are already flying on a precursor satellite Suomi-NPP.

Satellites in geostationary orbit (see below), provide more frequent imagery, albeit over a fixed view of the Earth's disk, but did not become a reality until 1975 when the Americans launched GOES-1. Since then several nations have joined the geostationary satellite 'club' enabling a ring of geostationary satellites around the equator giving good coverage, every 30 minutes or better, except for latitudes close to the poles (see Figure 1). In addition to the operational meteorological satellites there are many research satellites flown by the space agencies (e.g. NASA, ESA and JAXA) which although they don't have ensured continuity or backup have still proven valuable and have often been used for weather forecasting applications.

The Met Office contributes to the European operational meteorological satellite programme through EUMETSAT which launch geostationary (Meteosat) and polar orbiting (Metop) satellites as part of the global observing system on behalf of the European meteorological agencies. Links to the European Space Agency are also maintained to input to the research satellite programme which demonstrates the technology before it becomes operational.

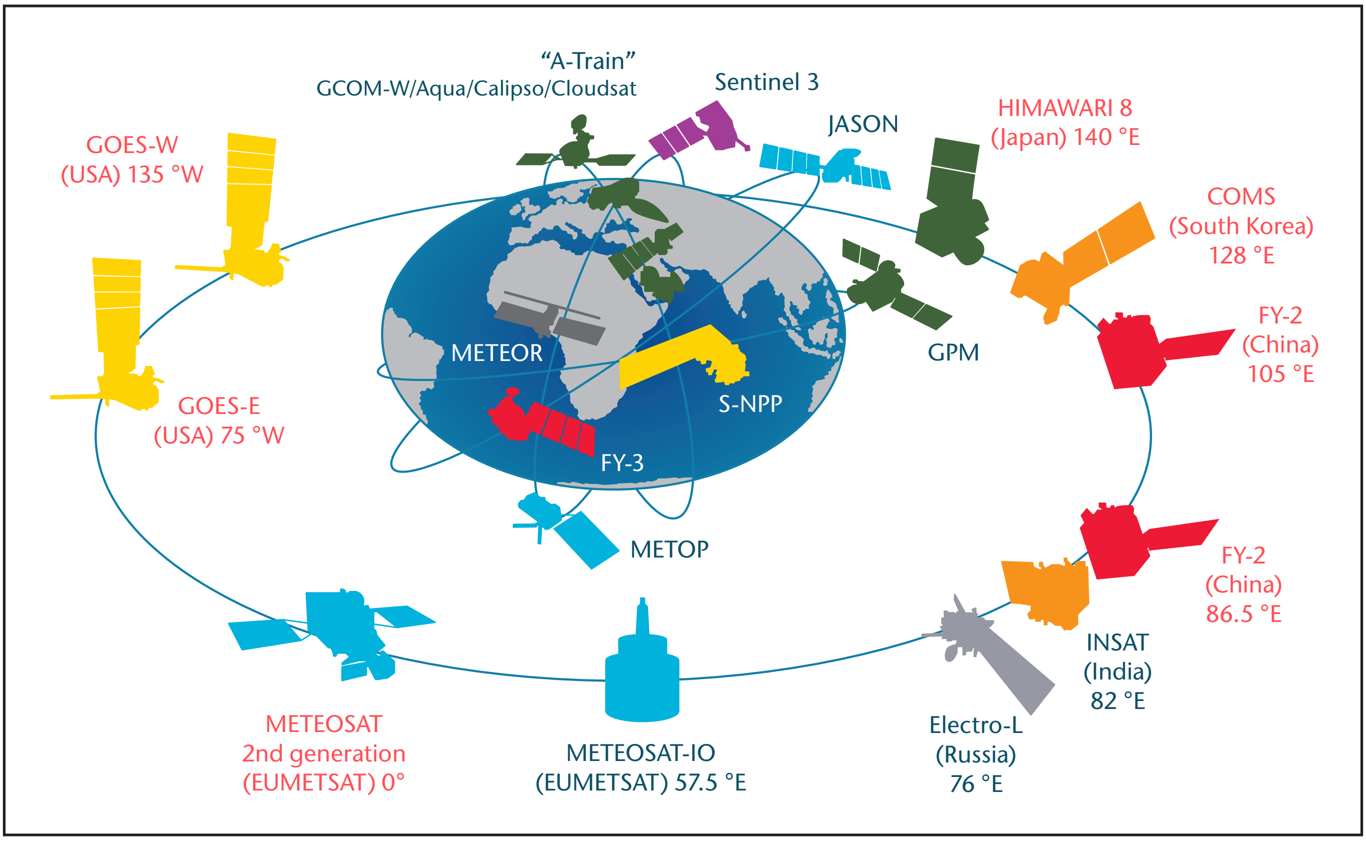


Figure 1. The current configuration of the meteorological satellite system.

Satellites for observing the atmosphere, ocean and land surface

Satellites provide a wealth of observations of the Earth's atmosphere and surface which in principle provide good coverage. Typically more than 10^5 measurements for a specific satellite observation type are received every day at operational weather centres. There are two distinct types of satellites in operation; those in geostationary orbit at an altitude of 35,786 km and those in a polar orbit generally at 800 km altitude as shown in Figure 1. The geostationary orbit allows the full disk of the Earth to be sampled typically every 10 minutes centred on the longitude of the satellite. There are more than 10 meteorological satellites in geostationary orbit at present. These are primarily used to provide high resolution imagery at visible and thermal infrared wavelengths for nowcasting applications. A typical example of full disk images from the Meteosat-10 satellite is shown in Figure 2(a)-(c) where images at wavelengths of 0.6, 10.8 and 6.7 microns are shown for one particular time slot.

However due to difficulties in using the data over land, cloud and sea-ice, and the need to thin the data to reduce horizontal error correlations between measurements, only about 20% of most satellite data are actually assimilated (see Table 1). The primary measurement of the atmosphere and surface properties from space is from the top of atmosphere radiation emitted by the surface, atmosphere and clouds. The atmosphere is sensed across the electromagnetic spectrum from the microwave to ultra violet wavelengths. The variable spectral absorption of atmospheric gases allows profiles of atmospheric temperature, water vapour and other gases to be inferred from the measured radiances.

Observation group	Observation sub-group	Variables	% assimilated
Ground-based vertical profiles	Radiosondes Pilot balloons Wind profilers	Temp, wind, humidity Wind Wind	96, 95, 76 21 17
Satellite-based vertical profiles	Polar radiances AIRS, IASI, CrIS, HIRS AMSU-A, MHS, ATMS, MWHS, Saphir, AMSR-2 Geostationary radiances GOES, Meteosat, Himawari Radio-occultation COSMIC, GRAS Aerosol optical depth MODIS AQUA	Radiances directly assimilated with channel selection dependent on surface instrument and cloudiness. Influences temperature and humidity Profiles of refractive index Aerosol optical depth	10 20 7 80 15
Aircraft	*Manual* AIREPS (incl. ADS) *Automated* AMDAR, TAMDAR	Temp, wind Temp, wind, humidity	77, 62 24, 24, 0
Satellite atmospheric motion vectors	Geostationary Meteosat, GOES, Himawari Polar Terra/Aqua MODIS NOAA, Metop	Wind Wind	10 8
Satellite-based surface winds	METOP-A/B ASCAT Coriolis WindSAT	Surface wind	4 1
Ground-based surface	Land SYNOP Ship Fixed buoy and rigs Drifting buoy METAR Mobile SYNOP	Surface pressure, wind, temperature, humidity	88 80 80 80 30 20
Ground-based satellite	GPS receivers	Zenith total delay influences water vapour	0.3

Table 1. Observations assimilated into the Met Office global Numerical Weather Prediction (NWP) model in 2014 with percentage of data used compared to that received in the right hand column.

Bending angles from GPS radio occultation measurements have become available in near real time to the meteorological community since the early 2000s and the constellation of satellites has increased to give reasonable global coverage. The advantage of these bending angle measurements is that they do not rely on any calibration, in contrast to the radiometers, and so can be considered as an absolute reference measurement of upper tropospheric and stratospheric temperature. This makes these measurements attractive for climate monitoring and investigating biases in radiosonde temperature profiles.

Scattering of microwaves from the sea surface measurements provide important information about the sea surface wind strength and provide some information on direction giving several preferred directions which the assimilation system can then select. These marine winds can improve forecasts of tropical cyclone tracks. These active microwave measurements have also proven useful over land surfaces to infer soil moisture in the upper surface levels and these data are now assimilated in land surface models.

Atmospheric Motion Vectors (AMVs) or cloud motion winds are a product derived from tracking clouds or water vapour features in geostationary image sequences and successive overlapping polar orbiter passes. They give good coverage for low and high cloud features but are sparse at mid-levels.

How do satellites measure atmospheric and surface properties?

The primary measurements of the atmosphere are provided by satellite sounders operating in the microwave and infrared part of the spectrum with cross-track nadir views. These sounders measure radiation which has been emitted from different levels in the atmosphere by choosing the regions of the spectrum which have strongly varying gaseous absorption primarily at microwave and infrared frequencies.

For the microwave, Figure 3 shows the different contributions to atmospheric absorption as a function of frequency. The main feature is the strong oxygen absorption band at 50–60 GHz which is used to infer the temperature profile of the atmosphere by using bands measured with a microwave radiometer that sense both the strong absorption part of the band and weaker part. As is illustrated in Figure 3 the strong absorption regions provide information in the upper atmosphere whereas weaker absorption bands see lower down in the atmosphere and even to the surface. Weighting functions shown in Figure 4 can be computed to determine at which levels the peak of the radiation measured originates from in the atmosphere. The advantage of using the microwave part of the spectrum is that the radiation is insensitive to most cloud types allowing a much better coverage down to the surface than in the infrared which is affected by all cloud types. There are also water vapour absorption lines at 22 GHz and 183 GHz which enable water vapour profiles to be inferred.

At infrared wavelengths the carbon dioxide band at 15 microns wavelength and the water vapour band at 6–7 microns are used to sound the temperature and water vapour profiles of the atmosphere albeit only in cloud free regions. The new generation of infrared sounders have good spectral resolution which allows more detail on the vertical distribution of temperature and water vapour to be inferred than with the microwave sounders. Infrared sounders can also infer estimates of cloud top pressure and surface temperature but infrared imagers are normally employed. Cloud top pressure and amount are assimilated into the UK model to better describe the 3D representation of cloud in the model.

Visible and infrared imagers which have a better spatial resolution (0.5–5 km) than sounders provide an accurate depiction of the cloud cover and top height and from geostationary orbit can provides images every 15 minutes allowing rapidly developing cloud systems to be monitored.

Active microwave instruments are also used to monitor the sea surface where a pulse of microwave radiation is emitted and the back scattered pulse is analysed to provide information on the ocean surface wind direction and strength. The strength is directly measured but four solutions for the wind direction are retrieved and all are provided to the NWP assimilation which chooses a wind most consistent with the model field and any nearby observations. Scatterometers operating in the C-Band (i.e. 5.25 GHz) and Ku-Band (i.e. 13.4 GHz) have been flown since the early 1990s and provide valuable information which can improve tropical cyclone forecasts.

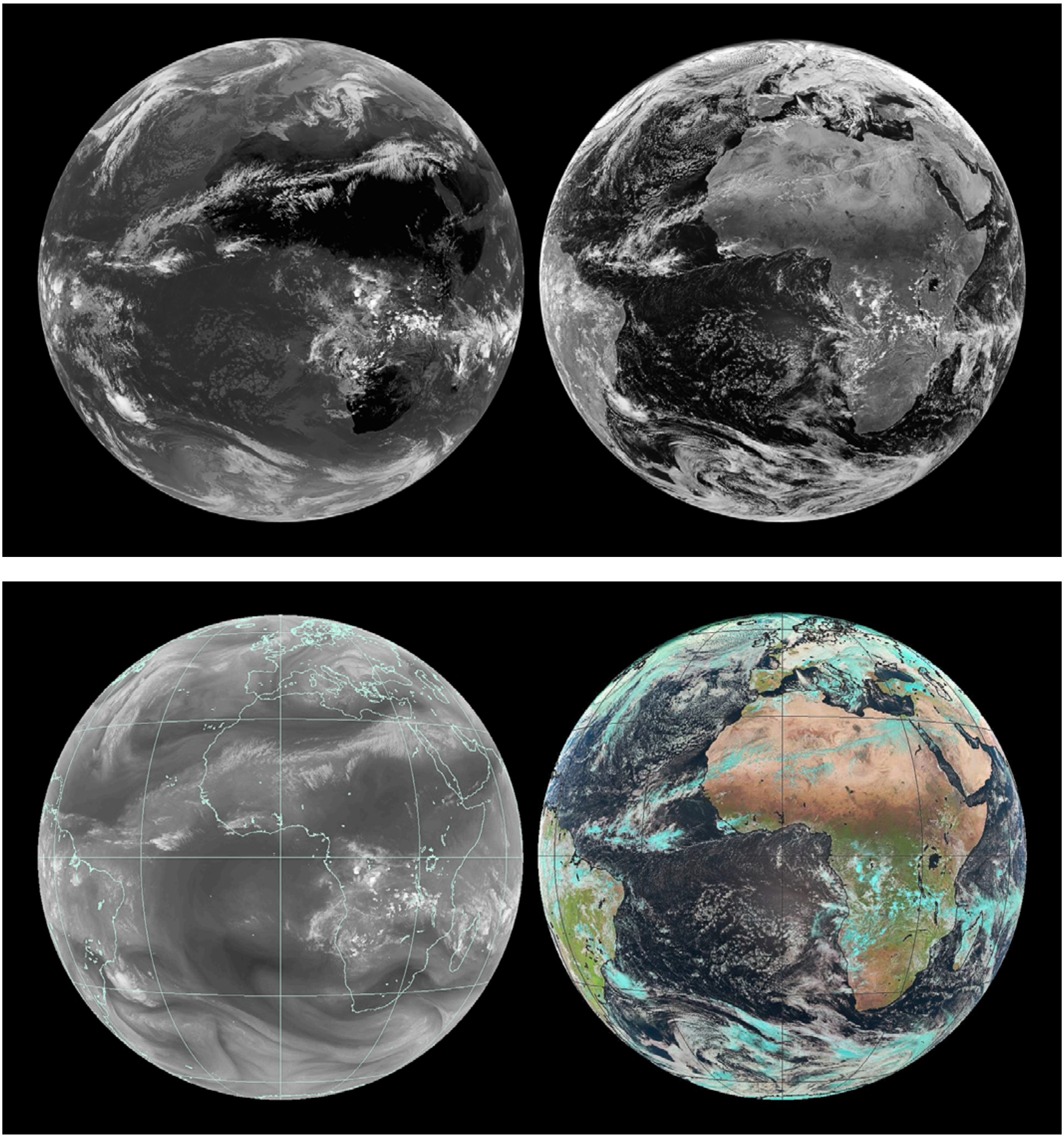
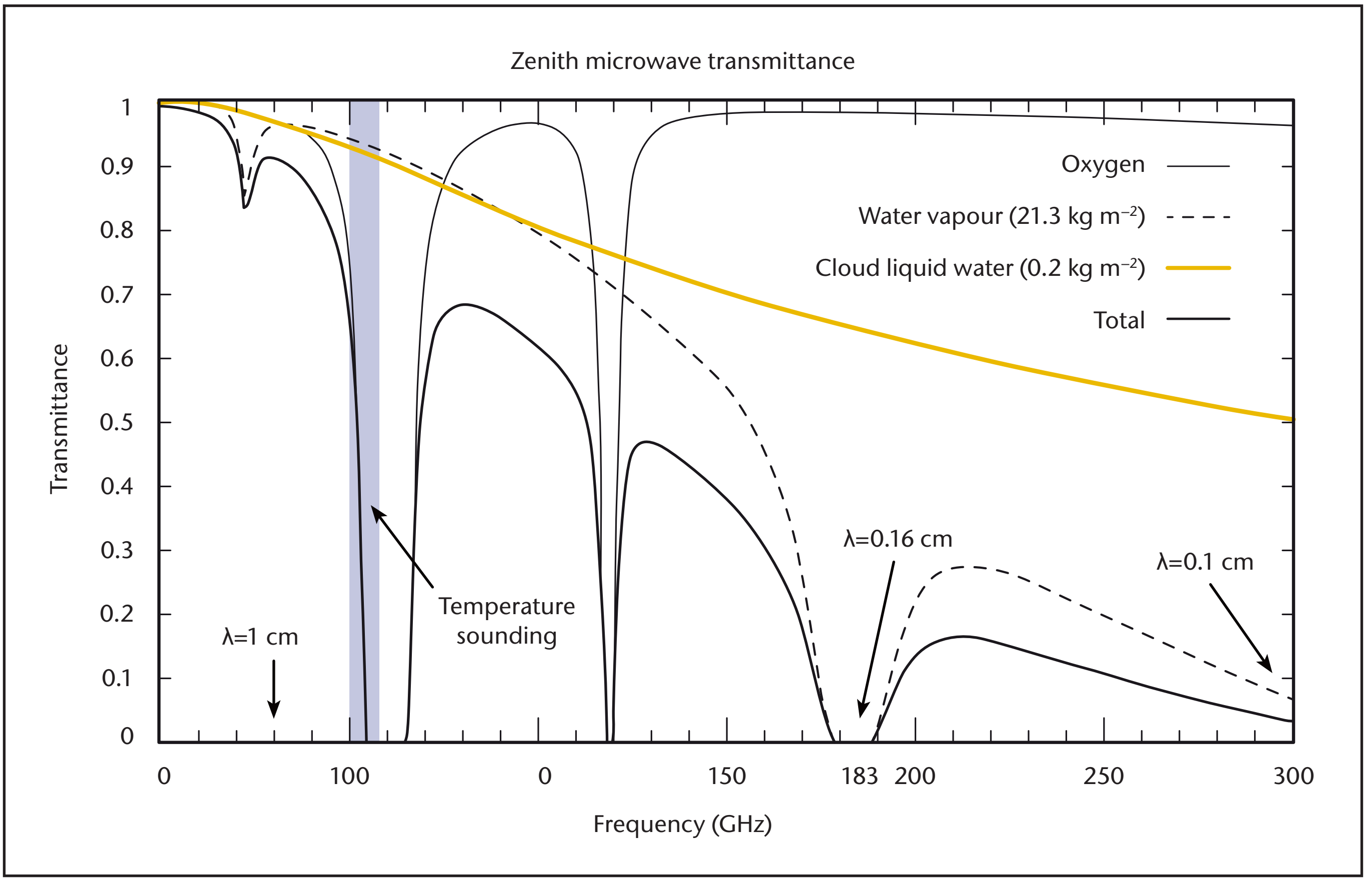


Figure 2. Meteosat-10, infrared (top left), visible (top right), water vapour (bottom left) and false colour (bottom right) images for 12Z on 23 January 2015.

Since the advent of the Global Navigation Satellite System (GNSS) satellite constellations several techniques have been exploited to make use of the data for meteorological purposes.
The radio-occultation technique pioneered with planetary science has been employed to measure the bending angle of a ray received from the GNSS satellite which is a function of the temperature and water vapour in the path (see Figure 5). Assimilating these bending angles in the NWP model allows the upper atmosphere temperature to be better defined with good vertical resolution but poor horizontal resolution. Another application is the measurement from the surface of zenith total delay of the signal to the GNSS satellite which is a measure of the total column water vapour. This relies on a good network of GPS receivers and the data being disseminated in real time. Recently a new potential application is being investigated where the reflected GNSS signal from the sea surface is measured to infer parameters related to the sea surface state.



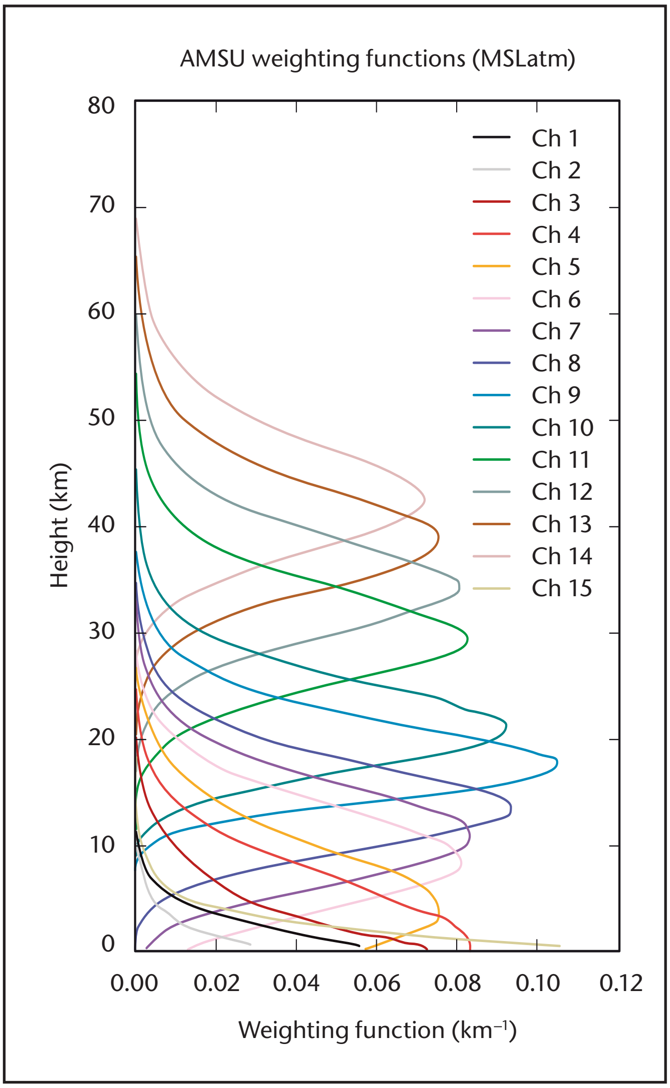


Figure 3 (above). Atmospheric absorption at microwave frequencies showing the different components in the atmosphere.

In addition to the atmospheric parameters which are retrieved several surface fields are also used to define the lower boundary of the model. Infrared imagery is used to define the sea and land surface temperatures in cloud free regions. Snow cover and sea ice are inferred from a mix of microwave and visible imagery and these are important fields for the model to represent accurately.

Soil moisture, or more accurately surface wetness can be measured with C-Band scatterometers and the ASCAT product is now assimilated in the global NWP model at the Met Office. The representation of surface albedo, lakes and vegetation in the model is also important and satellites play an important role in defining these variables and how they change during the year.

Figure 4 (left). Atmospheric weighting functions for the AMSU-A sounder channels.

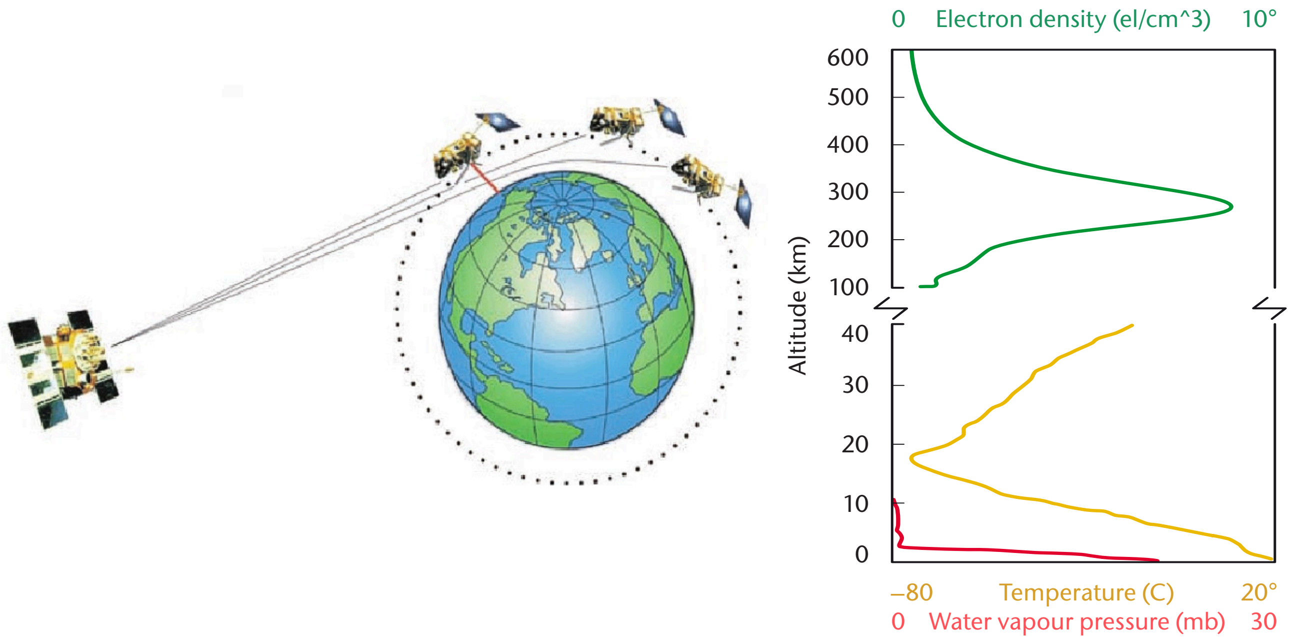


Figure 5. The geometry for GNSS radio occultation (left) and the retrieved profiles (right).

Satellite imagery products

Geostationary and polar satellites both have imaging radiometers onboard which provide a range of imagery that can be tailored for a variety of diverse applications as illustrated in Figure 6. The primary application is to support the forecasters by providing a “real world” representation of the atmosphere and surface which they can compare with the model analyses and recent predictions. Single channel imagery is often used by the forecasters to identify the positions of clouds, fronts and other features.
For more subtle features (e.g. dust storms) false coloured composites derived from several different channels are useful. For the geostationary satellite imagery the ability to run animations from the data updated every 15 minutes is also a useful tool.

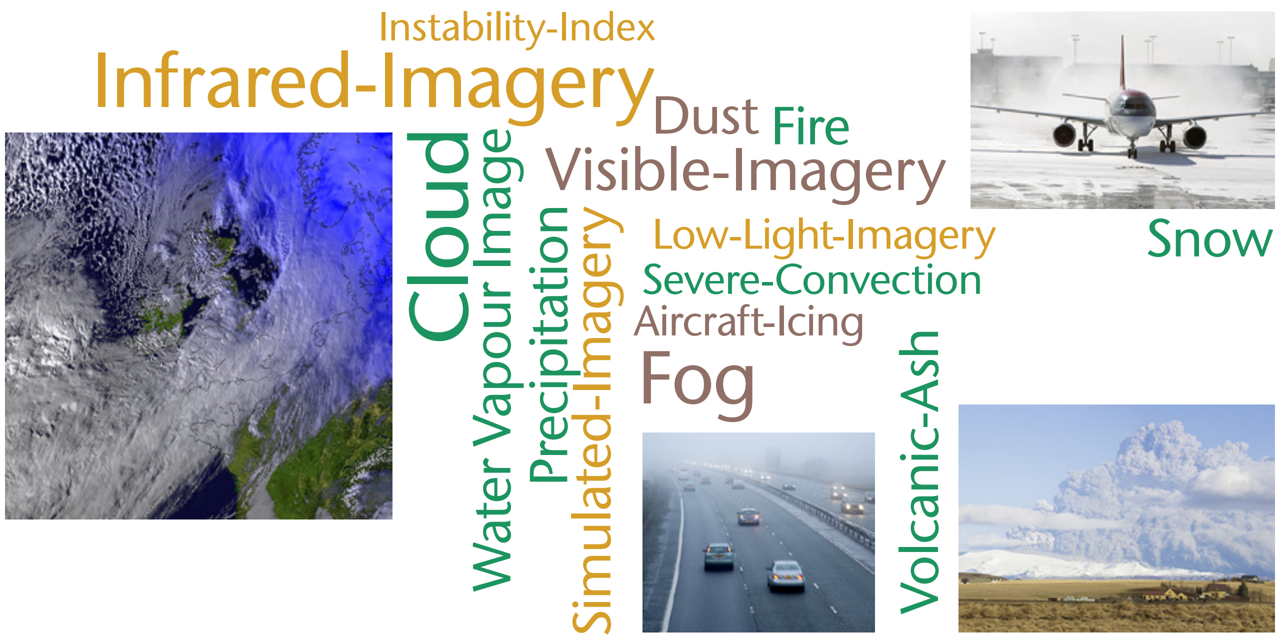


Figure 6. The variety of satellite imagery products produced at the Met Office to support the forecasters and Met Office hazard centre.

For some applications more complex methods are used to derive products from the imagery. For example the coverage of low cloud or fog is crucial for road and aviation warnings and so imagery has been developed to show the coverage night and day to assist in the guidance from models as illustrated in Figure 7. The Meteosat image shown can be displayed in animation mode with 15 minute updates showing how the fog evolves through the night. This product relies on using the difference in low cloud/fog top emissivity at the different infrared wavelengths measured by Meteosat.

Polar orbiter imagery is also used which can give more detail and enhanced detection but is only available from one overpass at night so is unable to guide on the evolution of the fog. Another product used for aviation is the cloud top pressure imagery which can be used as guidance to the pilots. More specialised aviation products detecting areas of severe icing or convection are also produced.

Some of the imagery products are produced for the Hazard Centre in the Met Office. Volcanic ash detection is a good example of this as shown in Figure 7 which provides guidance on areas of high ash concentrations and estimates can be made of the ash top height and total column amount. These data are also used to refine the ash forecasts from the dispersion model. If high ash concentrations are detected in the vicinity of airports they can be advised to close for the duration of the ash being advected over them. Other related products such as sulphur dioxide concentrations from volcanic eruptions, which can influence air quality, are also under development.

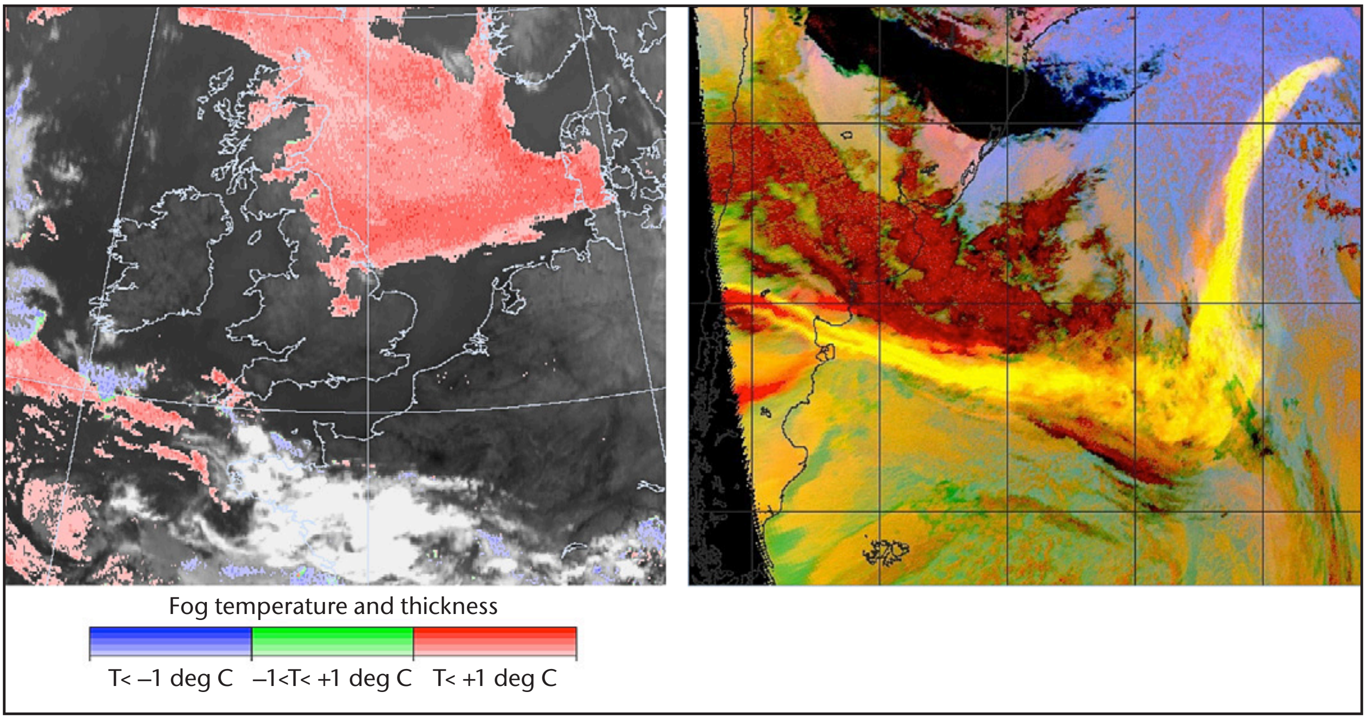


Figure 7. Left hand panel shows the depiction of fog in red over North East UK and North Sea as observed by Meteosat-8 on 1 May 2007 at 23Z. The right hand panel shows the extent of the ash cloud (light yellow colour) over the South Atlantic from the Cordón Caulle eruption in Chile at 09Z on 6 June 2011 which was 39 hours after the initial eruption using Meteosat-9 infrared imagery.

A recent innovation has been the use of simulated imagery as illustrated in Figure 8 where NWP model analyses or forecasts are used to produce a simulated satellite image at visible or infrared wavelengths. Comparing simulated imagery with the real image can give confidence in the model forecasts if the satellite data matches the model fields or conversely provide evidence that the model guidance should be viewed with caution.

Figure 8 shows an intense area of low pressure to the west of the British Isles which appears to be well modelled in the global model as compared with the visible satellite imagery. However convection in the Tropics and over the US often show differences between the model and satellite images.

Assimilation of satellite data in weather forecast models

The use of observations from satellites for assimilation into weather forecast models and for evaluating weather and climate models has increased significantly over the last two decades. One reason is the number of satellite instruments and satellites, on which they are mounted, has increased over the years as illustrated in Figure 9. More nations are now contributing to the global observing system which increases the number of satellites but also the robustness of the system.

Figure 10 shows the coverage of ATOVS sounding for one six hour analysis cycle and also Atmospheric Motion Vectors (AMVs) from five geostationary satellites showing for these data types a good global coverage is obtained allowing a more accurate description of the atmosphere to be obtained.

Note however that over land the satellite sounding data cannot be used at low levels due to current limitations in modelling of the land surface. For the GPS Radio Occultation bending angles the coverage is more sparse but the launch of new satellites to receive the signals and also new GNSS systems becoming operational (e.g. Galileo, GLONASS, Beidou) should improve this.

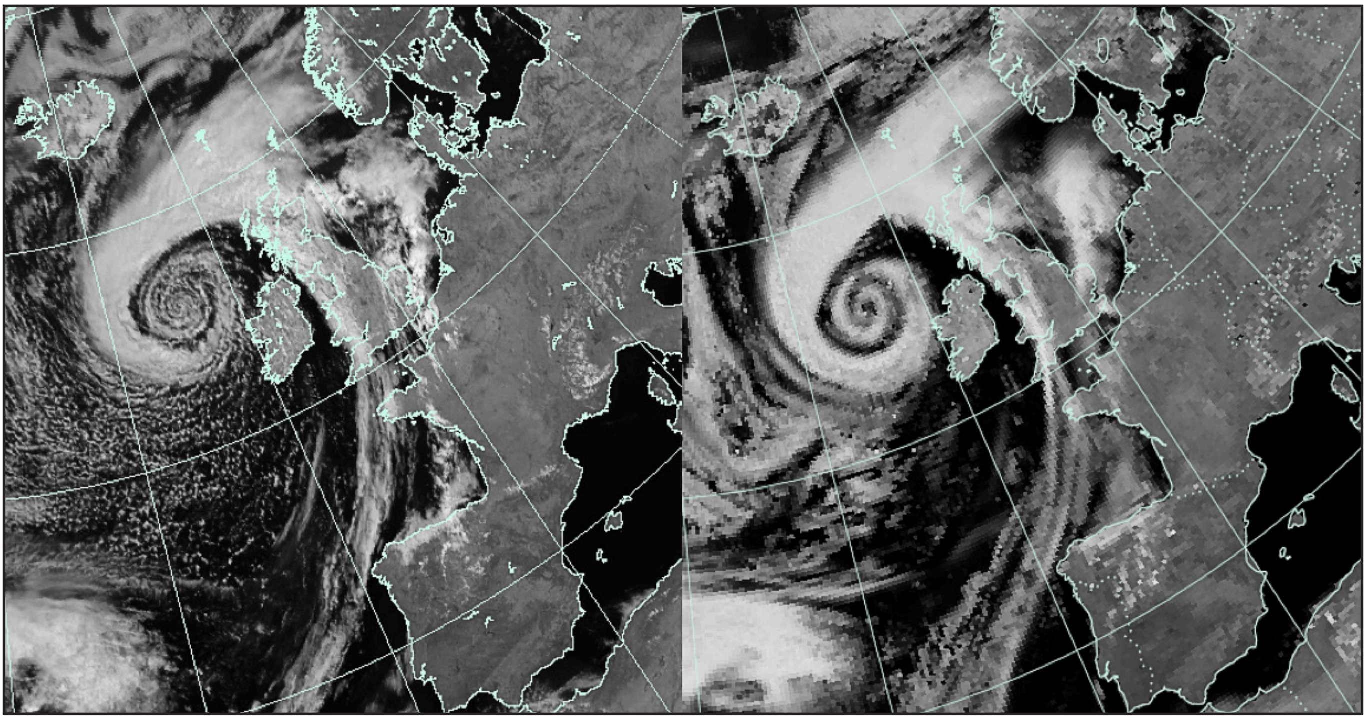


Figure 8. A Meteosat-10 visible image (left panel) for 12Z on 5 June 2015 and a simulated image (right panel) for a 12 hour forecast valid at 12Z from the Met Office global model.

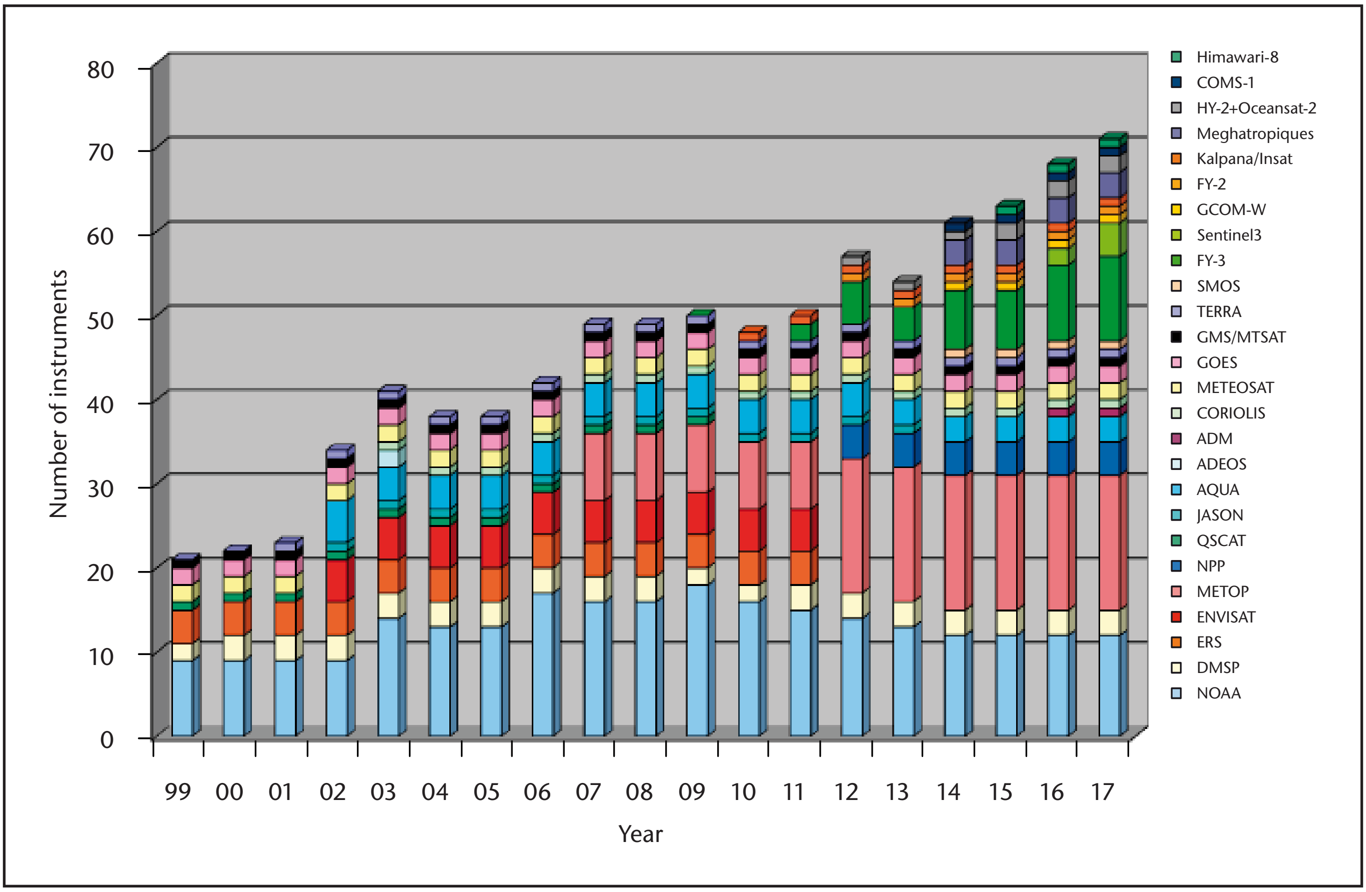


Figure 9. The growth in number of satellite instruments which can be considered for assimilation in NWP models.

Table 1 lists the radiances received from many sensors in polar and geostationary orbit which were assimilated in NWP models in 2014. Both advanced infrared sounders with high spectral resolution and radiometers with broader spectral responses are used to modify the NWP fields of temperature and humidity to better fit the observations. Assimilation of radiances over cloud and land surfaces is still an area of research but increasingly the data are being exploited in these areas.

Microwave radiances give a much better global coverage compared to the infrared radiances as they are not affected by non-precipitating cloud. Visible and near infrared radiances are not assimilated at present but work is in hand to enable this. The total column amounts of trace gases (e.g. ozone, nitrous oxide, methane and carbon dioxide) and aerosol optical depths can also be inferred from the radiances which are exploited in atmospheric composition models.

Only a small percentage of satellite data received are actually assimilated into the NWP models as shown by the right hand column of Table 1. This is after a series of quality control checks are applied to the data to make sure the measurements are realistic and not too far from the model's simulation of the satellite measurement. If the satellite data pass all the checks then they are passed, along with the other in-situ observations, to the 4D-Var assimilation system where each measured observation is compared with the model simulation of the same observation and all the differences are minimised taking into account the errors assigned to each observation. This process creates an analysis of the initial conditions from which the model forecasts are run from. Methods developed for assimilating observations in global-scale NWP over the last two decades are now being extended down to finer scale models where the model grid is smaller than the satellite field of view.

In recent years satellite observations have become the most important contribution to initialise current operational NWP models and hence impact the accuracy of the forecasts as shown in Figure 11. Satellite sounders have the most impact with IASI, an infrared sounder, having the most impact (there are two assimilated) followed by AMSU-A a microwave sounder (about 5 are assimilated). The AMVs are next on the list followed by radiosondes, aircraft and surface observations. The good coverage of the satellite observations obviously contributes to their large impact.

Use of satellite data for climate research

Satellite data are being increasingly used for climate research both for monitoring of the climate over decadal time periods and for comparing with the climate model predictions of the past climate. The Global Climate Observing System (GCOS) has defined a list of Essential Climate Variables (ECVs) which need to be monitored, by whatever means, to measure quantitatively climate change.

Satellites play an important role here as they give global coverage but their drawback is they have only been in existence for around 40 years so long term changes are still hard to infer. Recently there have been several initiatives to reprocess the original raw satellite data using the latest knowledge of instrument calibrations etc to provide uniform datasets from which climate quality products can be derived.

Climate or Earth System models are an indispensable tool for climate scientists to understand the climate system for the past, present and future. The model simulations utilise both observations of the past and present and climate prediction theory to simulate the state of the Earth System into the future. Current state of the art climate models include representations of the atmosphere, land surface, marine environment and the cryosphere to help reduce the uncertainty of the model predictions.

They include representations of many physical processes such as the forcing from changes in solar energy, atmospheric radiative effects from carbon dioxide and other greenhouse gases, the terrestrial carbon cycle; ocean biology, and tropospheric chemistry. HadGEM2 is the Met Office Hadley Centre model which includes these components as standard.

The increasing complexity of climate models mean it is not always easy to determine how closely the simulations represent reality. Satellite observations are one way to confront the models with reality at least for the present and past simulations which can give confidence in future projections. There are two different types of uncertainty inherent in climate models.

Parametric uncertainty is about the correct value of a specific variable, such as how much rain fell in a certain place in a given year. This type of uncertainty stems from a scarcity of data which satellite data with their continuous global coverage can now provide at least for the past 30 years for many Essential Climate Variables. Structural uncertainty is about the relationship between two or more variables in the model. The way that clouds influence and are influenced by temperature change and aerosol concentrations, for example, is not yet completely understood. Satellites can provide coincident measurements of the related variables for a wide range of different conditions to help climate scientists understand the interactions between them.

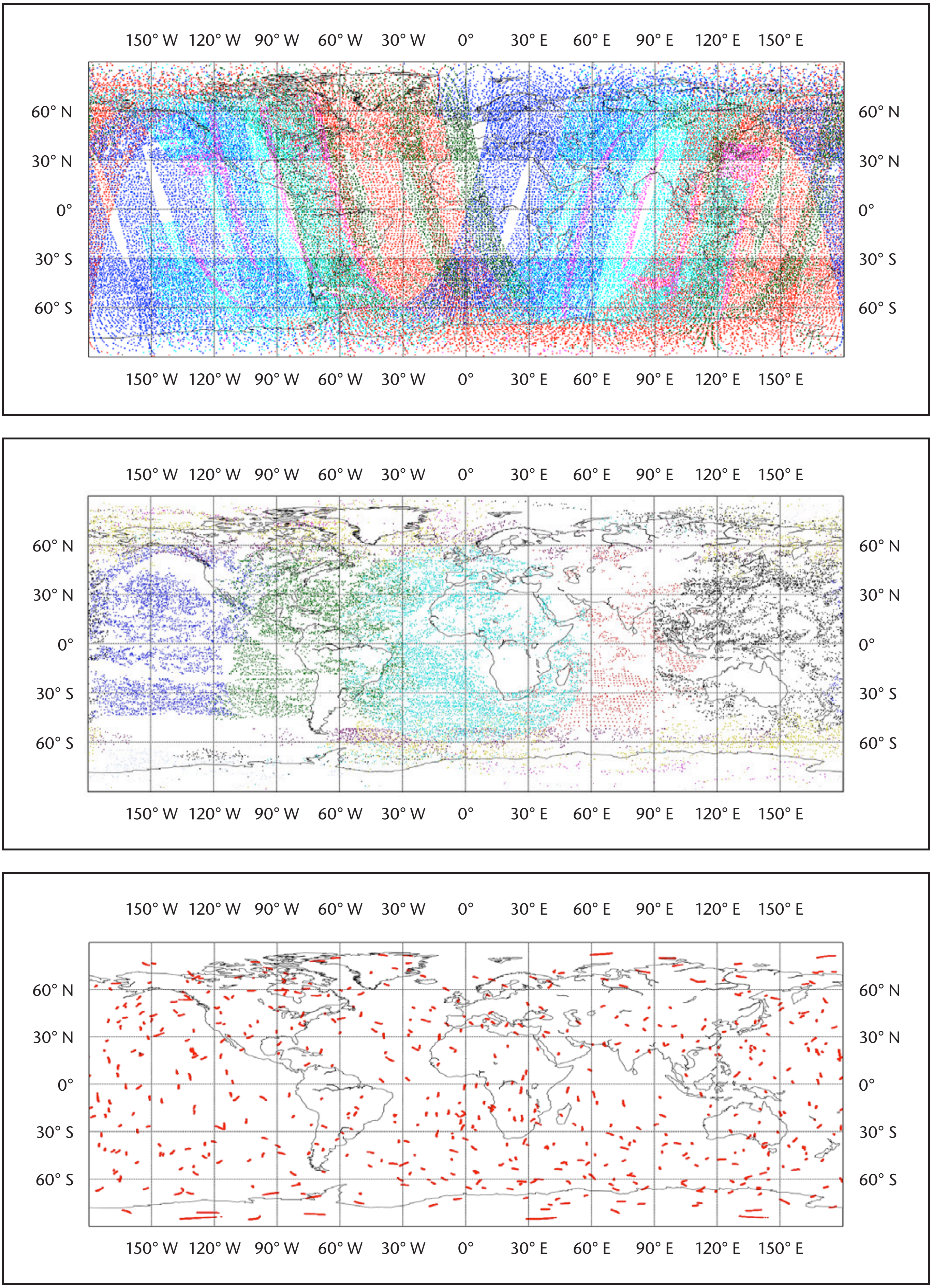


Figure 10. Coverage of ATOVS soundings from polar orbiters (top panel) and geostationary cloud motion winds (mid panel) and GNSS bending angles (bottom panel) for a six hour analysis cycle at 0Z on 18 August 2015. The different colours denote different satellites.

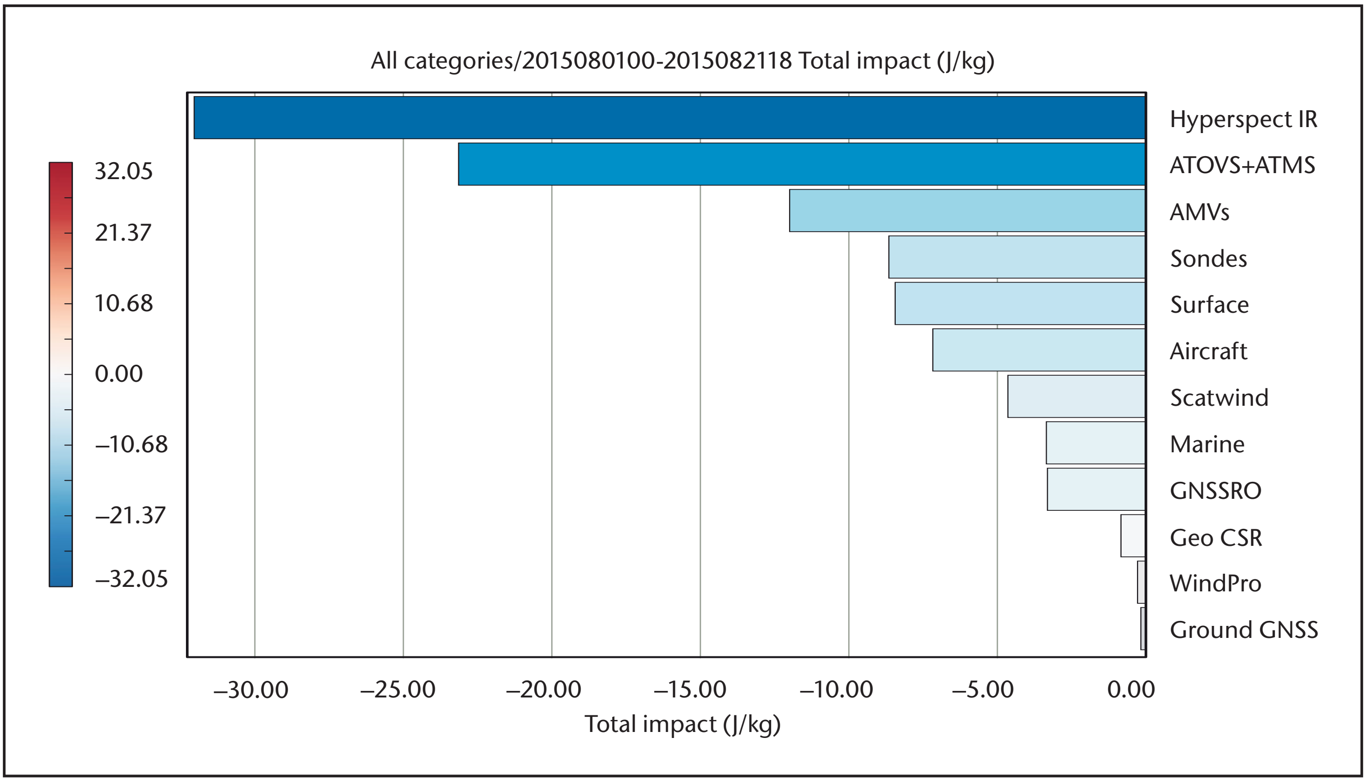


Figure 11. Mean impact of different observation types on the 24 hour forecast for August 2015 where negative values are where the observation type has improved the forecast.

There are several different applications that satellite climate datasets are being used to support climate modelling. To improve our understanding of the atmospheric chemistry processes in the model, satellite derived global ozone, greenhouse gas and aerosol concentration datasets are being compared with model simulations to assess the model uncertainties. For the marine domain the sea surface temperature climate data record (CDR) is being used to define the sea surface temperature for initialising model predictions. The sea-ice, glacier and ice sheet datasets together with the sea-level record contribute to improving models of the hydrological cycle and hence improve predictions of rising sea-level. The terrestrial ECVs such as land cover, fire and soil moisture are now allowing modellers to improve estimates of land use change and the carbon cycle. This will help to constrain the predictions of global warming from carbon dioxide. As the satellite datasets are extended in time and updates to their quality for climate research are made they will become a standard by which climate model simulations can be benchmarked.

Satellite CDRs are also increasingly being used for assimilation and comparison with reanalyses of the atmosphere and ocean as they are based on a stable processing system unlike the original datasets which were subject to changes in time as upgrades were made to the processing during the operational use of the data. Reanalyses can also be used to identify anomalies with satellite datasets when simulations from the reanalysis are compared with the raw uncorrected observations as shown in Figure 12.

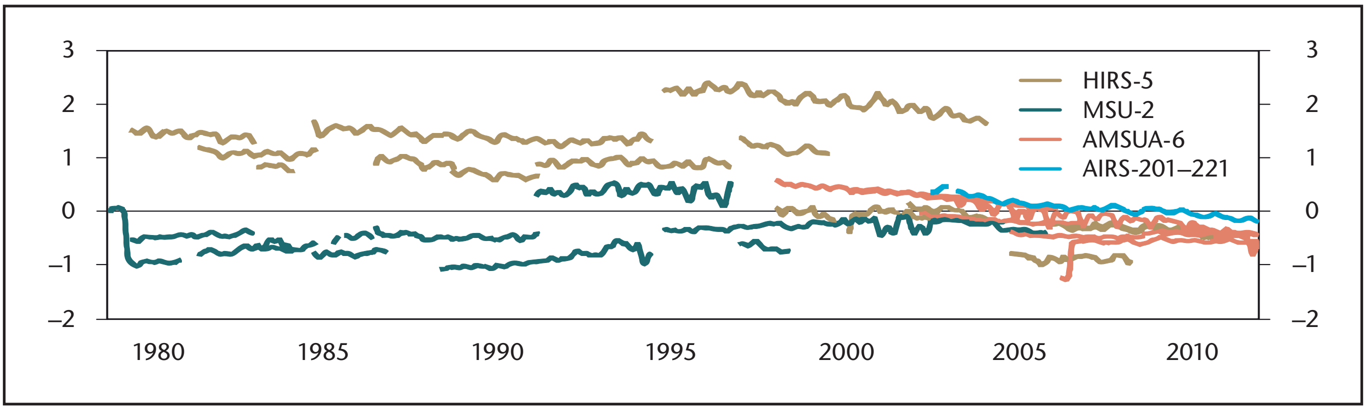


Figure 12. Brightness temperature (K) biases for measurements of the upper-tropospheric layer by infrared and microwave sounders compared to the ERA-Interim reanalysis. (Copyright ECMWF).

Future developments in satellite meteorology

Space agencies are continuing to develop new satellite instruments to monitor the Earth to provide continuity of existing measurements or enhance the global observing system with new measurements. One trend is that more countries are launching satellites for the Global Observing System, with China, Korea and India making significant contributions in recent years. This helps to share the cost overall. Another trend is the development of “nanosat” or “cubesat” technologies where the instruments are much smaller allowing them to be launched in a standard bus along with several other satellites. This new technology still needs to be proven but potentially could reduce costs for future missions.

To ensure continuity of the existing measurements both Europe and the US are planning future operational satellite series both in geostationary and polar orbits. New geostationary satellites (MTG, GOES-R) will include lightning imagers and the second satellite of the MTG series will also have a high spectral resolution infrared sounder on board similar to those on polar orbiters. The follow-on to the US NOAA polar system is JPSS-1, planned to launch in 2018. The Suomi-NPP satellite already flying is filling the gap between NOAA-19 and JPSS-1 with similar instruments to those planned for JPSS-1 and already being used by NWP centres. The European Metop satellite series will be succeeded by a second generation series with more instruments than on Metop split between two platforms.

For monitoring of the Earth system the European Union has funded the Sentinel series which are now being launched by the European Space Agency to monitor the land and ocean surface and atmospheric composition. A doppler wind lidar (ADM-Aeolus as shown in Figure 13) is planned for launch in the next few years to give observations of the three dimensional wind field and plans are already in place to assimilate these observations. EarthCARE is a new mission to measure clouds and aerosols and their impact on the radiation budget. Measurement of precipitation from space is a key requirement for modellers and the new Global Precipitation Mission satellite is showing some promise to improve the accuracies of this important ECV following on from the Tropical Rainfall Monitoring Mission which only observed at low latitudes.

Figure 13. Illustration of Aeolus Doppler Wind Lidar in orbit. (Copyright ESA).

Other more speculative innovations, including a satellite in a highly elliptical orbit which can view the polar regions for long periods, is under consideration by several high latitude nations. Having infrared hyperspectral sounders and microwave sounders on a geostationary platform will be an exciting new development and the former are being considered for the next generation of European satellites. This will enable atmospheric features to be tracked more frequently than is currently possible.

Acronyms

ADM	Atmospheric Dynamics Mission
AMSU	Advanced Microwave Sounding Unit
AMV	Atmospheric Motion Vector
ASCAT	Advanced Scatterometer
ATOVS	Advanced TIROS Operational Vertical Sounder
CDR	Climate Data Record
ECMWF	European Centre for Medium-range Weather Forecasts
ECV	Essential Climate Variable
ERA	ECMWF Reanalysis
ESA	European Space Agency
EarthCARE	EarthCARE Satellite
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
GCOS	Global Climate Observing System
GNSS	Global Navigation Satellite System
GOES	Geostationary Operational Environmental Satellite
GPS	Global Positioning System
HadGEM2	Met Office Climate Model
JAXA	Japanese Aerospace Exploration Agency
JPSS	Joint Polar Satellite System
METOP	Meteorological Operations Satellite
MSG	Meteosat Second Generation
MTG	Meteosat Third Generation
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
NPOESS	National Polar-orbiting Operational Environmental Satellite System
NPP	NPOESS Preparatory Project
NWP	Numerical Weather Prediction
TIROS	Television Infrared Observation System

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