# ANNEX A:	DETAILED ASSESSMENT OF EACH ECV

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A.a Atmosphere

A.a.i Surface Atmosphere

Wind speed and direction (surface)	
ECV Products covered by this sheet	Near surface wind speed and direction
Adequacy of the Observational System Assessment	3 Coverage of in situ measurements of near surface wind speed and direction over land and ocean is excellent in some regions, but sparse or non-existent over large areas of some continents, over most ice-covered regions and for oceans with few shipping routes. Satellites have provided measurements of wind speed over the ocean since the late 1980s, and wind vectors since the early 1990s.
Availability and Stewardship Assessment	4 Several NMHS and other organizations maintain datasets of sub-daily observations and daily and monthly averages. Work by NOAA NCEI and C3S is improving sub-daily global holdings. The most complete archive for in situ marine wind speed and direction is ICOADS at NOAA NCEI.
Networks	Global synoptic stations for surface wind speed and direction Voluntary Observing Ships (VOS) for wind speed and direction Global Tropical Moored Buoy Arrays (wind speed and direction) National networks of moored buoys, typically coastal (wind speed and direction).
Satellites	Wind speed and direction are available over the ocean from satellite scatterometers and wind speed from microwave sensors and radar altimeters. Gridded datasets for the global ice-free ocean have been constructed starting in 1987.
Models, Reanalysis etc.	Global atmospheric reanalyses provide useful estimates of surface winds when there are sufficient surface pressure observations and the sea surface temperature boundary conditions are accurate. Before 1979 winds in data sparse regions such as the southern hemisphere are poorly constrained. Reanalyses do not presently provide a consistent picture of large -scale long-term wind variability.

Discussion:

Wind speed trends are hard to quantify accurately as mean values are much smaller than their variability, requiring good coverage with small systematic errors. Consequently, there is much discussion in the literature as to whether winds are increasing in recent decades as surface air temperature has increased.

Observations over land: Most wind-speed and direction measurements from the nineteenth century and earlier were made using Beaufort estimations and compasses. Instruments began to be developed, but standardization took time, and a standard measuring height of 10 m was not accepted until the twentieth century. The height often depended on the use of the data, with agricultural purposes favouring lower heights of 2 m. Spatial coverage improved gradually with the peak in coverage and counts of observing sites since the 1950s. Antarctica was the last continent to get measurements. Coverage here is still limited mostly to coastal sites with only about 30 sites providing series from the late 1950s. Coverage is sparse in other remote regions as with Surface Air Temperature. Since the 1980s, automation has gradually spread across the world with most observations taken now by Automatic Weather Stations (AWSs) giving a much greater potential for more readings per day, but this has not been fully realized in archives. The changes in instrumentation since the nineteenth century means that centennial-scale series are generally not homogeneous

Observations over the oceans: Historically most marine wind observations were derived from visual assessment of sea state. From the 1960s onwards direct measurements became more prevalent. Wind measurements from either ships, buoys or other platforms are subject to air-flow distortion, making it hard to construct a consistent record. Historically, wind speed and direction were recorded alongside other ECVs (pressure, air and sea temperatures, humidity and cloud) and the ship's position in the ship's log book. More recently measurements are available from moored buoys, typically located in tropical or coastal regions. As ship observations have declined in coverage since the 1990s there has been a decline in coverage for marine winds. Constructing a homogeneous historical record requires knowledge of the measurement method as observations derived from anemometers and from visual reports of sea state are not consistent.

Wind is measured at different heights above sea level on different platforms, typically 20 metres or more on ships and a few metres on the autonomous platforms. The construction of consistent wind speed records requires the measurement height to be known, along with an estimate of the wind gradient between the observation height and the chosen reference height. Accurate adjustment requires estimates of local air-sea temperature difference and humidity.

Data and metadata stewardship: Much more data has historically been taken across the world's land areas than is currently available in global datasets. The National Oceanic and Atmospheric Administration (NOAA) National Climate Environmental Information (NCEI) and the Copernicus Climate Change Service (C3S) have made significant progress in the stewardship of global observations as work towards fulfilling GCOS Implementation Plan 2016 (GCOS IP 2016) Action A2, although much work remains to be done. Several NMHS maintain datasets of sub-daily observations and daily and monthly averages. The climate record for in situ winds from ships for recent decades is based largely on observations exchanged in near real time (NRT) in support of weather forecasting. Availability of observational metadata will improve if BUFR templates are diligently completed, supplementing metadata catalogued by OceanOPS (https://www.ocean-ops.org/). Archives of NRT observations are retained by several NMHS, but there is no dedicated archive specifically responsible for their direct acquisition and stewardship. Moored buoy observations are typically available in both near real time and at higher resolution with calibration following mooring visits. Global Collecting Centres provide added-value data for Voluntary Observing Ships (VOS) data, but only a subset of VOS reports become available through this route. The most complete archive for in situ wind speed and direction is the International Comprehensive Ocean-Atmosphere Data Set (ICOADS) at NOAA NCEI. Improvements to ICOADS data formats and processing are urgently needed to provide access to observations at their full resolution with WIGOS-compliant metadata along with improvements to quality control and duplicate handling (Kent et al., 2019).

Large volumes of all types of surface wind speed and direction observations are available in paper records or on archaic media or obsolete formats such as proprietary binary. Wind direction in particular is valuable very early in the record (pre 1850) for use in the construction of indices that document the prevailing flow. Resources to identify, catalogue, image and rescue this data would enhance and extend the surface wind speed and direction record, recognising that incorporating newly rescued data into the climate archives also requires substantial effort and resources.

Networks: Wind speed and direction measurements are transmitted using standard messages (SYNOP, CLIMAT) over the WIS. Most countries maintain more stations than are listed in RBON, and a small number (e.g. United States, Canada, Australia, Fennoscandian countries, Netherlands) make these data available on their websites. For many countries the number internationally exchanged is limited, sometimes because of resources, but sometimes due to there being few stations in remote regions.

The WMO Voluntary Observing Ships (VOS) program coordinates measurement and NRT transmission of marine meteorological and oceanographic measurements made aboard ships recruited to national or regional observing VOS networks. Many VOS reports include wind speed and direction alongside other near-surface observations required for adjustment of winds to a common reference height (air-sea temperature difference, humidity). Limited observational metadata (observing methods and heights) is available within the reports, and more extensive metadata elements reports can be accommodated in new BUFR templates. The metadata is supplemented by a metadata database which was established by JCOMM[40] based on WMO Publication No. 47.

Research vessels have the potential to make high-quality observations of many surface ECVs including wind speed and direction, but their observations are not consistently used for global monitoring as there is no internationally coordinated management system for their data.

Global Tropical Moored Buoy Arrays provide the broadest range of ECVs including wind speed and direction since the late 1970s in the Tropical Pacific and more recently extended to the Tropical Atlantic and Indian Oceans. Observations are transmitted in NRT, and these are supplemented with delayed mode observations from on-board logging retrieved when the moorings are replaced which also provides the potential for post-calibration if the instruments have survived.

National operational networks of moored buoys, typically in coastal locations, provide measurements of a range of ECVs in NRT including wind speed and direction. These buoys have not historically been managed for climate applications, so some archived records have limited metadata and provenance.

Surface Drifters have provided NRT measurements of wind speed derived from acoustic sensors, but these are not typically used for climate monitoring applications.

Satellite observations (ocean only): Satellite wind measurements started in the late 1980s for microwave wind speed with a succession of scatterometers providing in addition estimates of wind direction from the early 1990s. Sparse wind speed estimates are also available from satellite altimeters since the mid 1980s. The many different types of sensor, and frequencies of operation, mean that constructing a homogenous record, even using measurements from the same broad class of sensor, requires careful cross-comparison and adjustment among satellites and moored buoy measurements may be used as a reference.

Reanalysis: Several state-of-the-art global reanalyses provide information about surface wind, namely u and v components. Reanalysis data assimilate conventional data and

[40] The Joint WMO-IOC Commission for Oceanography and Marine Meteorology (JCOMM) was superseded in 2019 by the Joint WMO-IOC Collaborative Board.

satellite observations, however they do not ingest surface wind from land stations with problems in the representation of wind over not-homogeneous terrain. Surface wind in reanalyses (the 10 m wind) is parametrized in planetary boundary layer schemes. Information of wind components is available back to 1950 from a set of reanalyses, with a resolution up to 1 hour in the most recent ones, and back to the nineteenth century for a few reanalyses, at a lower space and time resolution. Data before 1979 are poorly constrained in data sparse region, as the southern hemisphere. The largest disagreement in wind speed mean, variability and trends across different reanalyses is found over land and in continental areas, with better wind speed performances from new generation products. Near surface wind and, in a few cases, instantaneous wind gust are also available in most recent reanalyses.

References:

Kent, E. C., N. A. Rayner, D. I. Berry, R. Eastman, V. Grigorieva, B. Huang, J. J. Kennedy, S. R. Smith and K. M. Willett, 2019: Observing requirements for long-term climate records at the ocean surface, Frontiers in Marine Science. 6:441. doi: 10.3389/fmars.2019.00441

Temperature (surface)	
ECV Products covered by this sheet	Surface air temperature (SAT) over land, sea surface temperature (SST[41]), marine air temperature (MAT) and global average temperature products[42]
Adequacy of the Observational System Assessment	4 Coverage of in situ measurements of air temperature over land and ocean is excellent in some regions, but sparse or non-existent over large areas of some continents, over most ice-covered regions and for oceans with few shipping routes.
Availability and Stewardship Assessment	4 For surface air temperature over land several NMHS and other organizations maintain datasets of sub-daily observations and daily and monthly averages. Work by NOAA NCEI and C3S is improving sub-daily global holdings. The most complete archive for in situ MAT and SST is ICOADS at NOAA NCEI but since 2014 ICOADS has only been updated with a subset of near real time data with no additions from GDACs or data rescue. Improvements to ICOADS data formats and processing are urgently needed to provide access to observations at their full resolution with WIGOS-compliant metadata along with improvements to quality control and duplicate handling. There is no dedicated data centre for the archival of marine observations from the GTS. Separate archives exist for the tropical moored buoys, surface drifters and Argo. A substantial amount of surface temperature observations (MAT, SST and SAT) are still to be digitized and are vital to extend the record further back in time and to sparsely sampled regions.
Networks	GCOS Surface Network for SATs Global synoptic stations for SATs Voluntary Observing Ships (VOS) for SST and MAT Global Tropical Moored Buoy Arrays (SST and MAT) National networks of moored buoys, typically coastal (SST and MAT). Surface Drifters (SST) Argo Profiling Floats (sparse but accurate SST)
Satellites	Neither SAT nor MAT can be retrieved from satellites with sufficient accuracy for global monitoring. The most accurate SSTs are from the ATSR/SLSTR series (early 1990s ->) SSTs are also available from other infrared (e.g. AVHRR, MODIS, VIRS) and microwave (e.g. SSM/I, TMI, GMI, AMSU) satellite sensors in various combinations starting in 1979.
Models, Reanalysis etc.	Global atmospheric reanalyses are much improved, particularly ERA5 (since 1979 but to be extended back to 1950) and JRA-55 (since 1958), but they are dependent on blended SST fields such as HadISST2 and COBE-SST2.

Discussion:

The ECV product - Global surface temperature climate record: The most widely used surface temperature ECV products are gridded products that combine Surface air temperatures over land (SAT) with sea surface temperatures (SST) across the world's

[41] SST is an ocean ECV and is covered in the Ocean Section A.2. However, as SST is used to compute the global average temperature, and often observing systems measure SST and MAT, information on SST can also be found here.

[42] LST (Land Surface Temperature) is a terrestrial ECV and is covered in the Terrestrial Section A.3.

surface at monthly and more recently at daily timescales. It is these gridded products that provide the key metric in climatology that shows that the world has warmed by over a degree Celsius since the late nineteenth century. A more consistent global temperature product would combine SAT with marine air temperatures (MAT) but this has not yet been attempted. The gridded temperature products are also essential for adaptation to climate change and to the study of changes in extremes.

Observations over land: Surface air temperatures (SATs) have been measured in parts of Europe since the seventeenth Century. Spatial coverage improved gradually with relatively stable counts since the 1950s although this hides regional improvements /degradations in the observing system. Apparent performance over time can be misleading owing to data policies and archival ingest latencies. Antarctica was the last continent to get measurements, with about 30 sites in Antarctica reporting daily and monthly instrumental climate observations since the International Geophysical Year (IGY) in 1958, and a few having records beginning in the 1940s, with variable consistency and confidence. Coverage is also sparse in other remote regions, such as the Arctic, desert regions and all tropical rain forests. Much more data has historically been taken across the world's land areas than is available in global datasets. Some of this is down to digitized data not being shared globally, while much data in some countries remains to be made digitally available. How SATs have been measured has changed over the centuries. The standard since the middle-to-late nineteenth century has been using thermometers protected from the sun in a white louvred screen, generally 1.25 to 2 m above the ground, and read manually. Since the 1980s, automation has gradually spread across the world with most observations taken now by Automatic Weather Stations (AWSs) giving a much greater potential for more readings per day, but this has not been fully realized in archives. There is no accepted WMO standard for how the average daily or monthly SAT should be measured.

Observations over the oceans: For ocean regions there are two different measures, air temperature (marine air temperature, MAT) and the temperature of the sea just below the sea surface (sea surface temperature, SST), which is covered in detail in the Ocean Section (Section C). Historically, temperatures were recorded alongside other ECVs (pressure, wind, humidity and cloud) and the ship's position in the ship's log book. As ship observations have declined in coverage since the 1990s there has been a decline in coverage for MAT as ships are presently the only widely distributed source of MAT, with an increase for SST which is supplemented by the autonomous platforms. (Kent et al., 2019). More recently measurements of both MAT and SST are available from moored buoys, typically located in tropical or coastal regions. Surface drifters make a substantial contribution to the SST observing system since the 1990s, but do not typically measure MAT. A contribution for SST comes from the sparse but highly accurate Argo profiling floats.

MAT is measured at different heights above sea level on different platforms, typically 20 m or more on ships and a few metres on the autonomous platforms. The construction of consistent MAT records requires the measurement height to be known, along with an estimate of the temperature gradient between the observation height and the chosen reference height. Accurate adjustment requires estimates of local wind speed, air-sea temperature difference and humidity. Likewise, for SST, development of corrections for large differences between SST measured on different platforms, with different methods and at different depths also requires observational metadata and information on ambient conditions.

Data and metadata stewardship: The climate record for in situ MAT and SST from ships and surface drifters for recent decades is based largely on observations exchanged in near real time (NRT) in support of weather forecasting. Availability of observational metadata will improve if BUFR templates are diligently completed, supplementing metadata catalogued by JCOMMOPS. Archives of NRT observations are retained by several NMHS, but there is no dedicated archive specifically responsible for their direct acquisition and stewardship. In contrast for surface drifters and Argo there are dedicated global centres to collect, process and add-value to the real time observations. Moored buoy observations are typically available in both near real time and at higher resolution with calibration following mooring visits. Global Collecting Centres provide added-value data for Voluntary Observing Ships (VOS) data, but only a subset of VOS reports become available through this route.

The ISTI databank provides access to an array of monthly resolution SAT over land. GHCND provides access to many long-term daily records globally. Work by NOAA NCEI and C3S is increasing accessibility to synoptic resolution data. Several NMHS and non-NMHS organizations maintain datasets of sub-daily observations and daily and monthly averages in addition.

Large volumes of all types of surface temperature observations (SAT, MAT, SST) are available in paper records or on archaic media or obsolete formats such as proprietary binary. Resources to identify, catalogue, image and rescue this data would enhance and extend the surface temperature record, recognising that incorporating newly rescued data into the climate archives also requires substantial effort and resources.

Networks: SAT measurements are transmitted using standard messages (SYNOP, CLIMAT) over the WIS network and about 1000 have been designated as the GCOS Surface Network. Most countries maintain more stations than are listed on GBON, and a small number (e.g. United States, Canada, Australia, Fennoscandian countries, Netherlands) make these data available (but often not in NRT) on their websites. For many countries the number internationally exchanged is limited, sometimes because of resources, sometimes due to there being few stations in remote regions and other times due to national data policy.

The WMO Voluntary Observing Ships (VOS) program co-ordinates measurement and NRT transmission of marine meteorological and oceanographic measurements made aboard ships recruited to national or regional observing VOS networks. Many VOS reports include SSTs and MATs alongside other near-surface observations required for adjustment of temperatures to a common reference height (wind speed, humidity). Limited observational metadata (observing methods and heights) is available within the reports, and more extensive metadata elements reports can be accommodated in new BUFR templates. The metadata is supplemented by a metadata database being established by JCOMM based on WMO Publication No. 47. Decline in the VOS network has resulted in a decline in the number of ships reporting MAT giving a decline in coverage (Kent et al., 2019) and presently only SST and surface pressure are included as marine ECVs for the GBON.

Research vessels have the potential to make high-quality observations of many surface ECVs, including SST and MAT but their observations are not consistently used for global monitoring as there is no internationally coordinated management system for their data.

Global Tropical Moored Buoy Arrays provide the broadest range of ECVs including both SST and MAT since the late 1970s in the Tropical Pacific and more recently extended to the Tropical Atlantic and Indian Oceans. Observations are transmitted in NRT, and these are supplemented with delayed mode observations from on-board logging retrieved when the moorings are replaced which also provides the potential for post-calibration if the instruments have survived.

National operational networks of moored buoys, typically in coastal locations, provide measurements of a range of ECVs in NRT including SST and MAT. These buoys have not historically been managed for climate applications, so some archived records have limited metadata and provenance.

Surface Drifters provide NRT measurements of SST and SLP, but some also record MAT. They are capable of providing accurate measurements of SST at high temporal resolution but may drift off-calibration during deployment so require careful QC. Observations are sparse in upwelling and divergence regions. The surface drifter program was established in the late 1970s and reached its design goal of 1250 drifters in 2005 – although sampling density has recently declined.

Argo Profiling Floats provide sparse but accurate SST from approximately 3000 floats which surface approximately every 10 days.

Satellite observations: Satellite measurements began to be used in the 1970s for SSTs, measuring the surface skin temperature (the top 1mm of the sea) by a variety of means. The combination of in situ measurements from ships, drifters and floats with satellite estimates, provides high temporal and spatial resolutions fields of SSTs, essential for weather forecasts and Reanalyses. Satellites cannot accurately measure MAT or SAT, but over terrestrial areas they measure the temperature of the land surface.

Reanalysis: Atmospheric reanalysis requires gridded fields of SST as a lower boundary condition, this places a requirement for higher resolution both spatially and temporally. Some atmospheric reanalyses assimilate MAT and SAT in addition to pressure observations. Modern reanalysis products (such as 20CRv3 since 1851, JRA55 since 1958 and ERA5 since 1979) produce estimates of surface temperatures that are in broad agreement with other estimates. Coupled reanalyses assimilate SST rather than using gridded fields as boundary conditions, but surface temperature estimates are required either for assimilation or validation. Ocean reanalyses or state estimates are not typically used for surface temperature monitoring.

Pressure (surface)	
ECV Products covered by this sheet	Station level pressure (STP), which is generally expressed as sea-level pressure (SLP) by correcting for elevation, temperature and gravity if required.
Adequacy of the Observational System Assessment	4 Coverage of in situ measurements is excellent in some regions generally excellent, but sparse or non-existent over large areas of some continents, over most ice-covered regions and for oceans with few shipping routes. The ocean coverage would be increased if a greater proportion of drifting buoys were fitted with pressure sensors.
Availability and Stewardship Assessment	5 A specific dataset of sub-daily STP and SLP for sparse-input Reanalyses has been developed by the International Surface Pressure Databank (ISPD) for land regions and includes data from ICOADS for marine areas. This is being integrated into the holistic holdings being prepared by NOAA NCEI and C3S but since 2014 ICOADS has only been updated with a subset of near real time data with no additions from GDACs or data rescue.
Networks	Global synoptic stations for STPs and SLPs Voluntary Observing Ships (VOS) for SLP over the oceans An increasing number of surface drifters measure SLP over the ocean National networks of moored buoys, typically coastal, a subset of the tropical buoy network.
Satellites	None
Models, Reanalysis etc.	Global Reanalyses are much improved, particularly ERA5 (since 1979) and JRA-55 (since 1958), but they are dependent on blended SST fields such as HadISST2 and Cobe-SST. STP and SLP are important input data for Reanalyses, and extended Reanalyses (e.g. 20CRv2/3) which rely on STP and SLP measurements to provide extensions back to the mid-nineteenth century (1851 for 20CRv2 and 1836 for 20CRv3). Reanalyses are essential datasets for the development of circulation indices

Discussion:

ECV Components: Station-level pressure (STP) measurements have been taken in parts of Europe since the late-seventeenth century. It was soon recognised that measurements of STP were lower at higher elevations and also depended on the air temperature. Standards were gradually developed during the eighteenth century, so STP values were reduced using formulae to 0m and 0°C and referred to as sea-level pressure (SLP). In the nineteenth century an additional correction was made for differences in gravity at different latitudes at the Earth's surface (the standard being chosen at 45°N). Formulae for these reductions have improved through time, so historic barometric measurements of STP require the temperature of the associated thermometer, the elevation of the site and the barometer above sea level and the latitude, to recalculate SLP with a consistent and modern formula. Even with improved formulae, the correction of STP measurements for high-elevation sites (> 2500 m) is not always recommended nor often undertaken. Instead reductions in high-elevation regions are made to a recognized level such as 850 or 700 hPa.

Observations over land: Spatial coverage improved gradually with the peak in coverage and counts of observing sites since the 1950s. Antarctica was the last continent to get measurements. Coverage here is still limited mostly to coastal sites with only about 30 sites providing series from the late 1950s. Coverage is sparse in other remote regions as with Surface Air Temperature.

Observations over the oceans: Historically, ships measured STP, first on research vessels, but more widely on merchant and navy ships since the 1830s. SLP is typically reported by ships requiring adjustment on board. Measurements were recorded with other surface ECVs (air temperature, sea surface temperature, wind, humidity and cloud) in the ship's logbook, which also recorded the position of the ship at sea, although position was often reported less frequently. Logbooks were and still are important documents providing vital information about the journey and of life at sea. They have been archived at a variety of centres in many maritime countries around the world. The information in some of these logbooks began to be digitized in the 1970s and much has found its way into the ICOADS since that time.

Use for weather and storm forecasting: The primary reason for pressure measurement has been weather and storm forecasting from the mid-nineteenth century, both on land, but also at sea to reduce the number of ships lost to adverse weather. Measurements at sea became a requirement from the Brussels congress in 1853 and when possible ships began to transmit SLP measurements by radio to shore in real time. SLP data are also used to track tropical and mid-latitude storm tracks and intensities. Century-scale variability in indices of storminess and wind speeds in mid-latitudes can be assessed using sub-daily and daily SLP data.

Circulation indices: SLP measurements at key stations have historically been used for many circulation indices (e.g. the North Atlantic Oscillation and the Southern Oscillation to name but two). A few climatologists noticed out-of-phase relationships between somewhat distant sites which explained features of temperature and precipitation variability. Series for many indices are still derived from key stations, but modern studies base analyses on modes of circulation variability derived from mathematical analyses (e.g. EOF, PCA etc.) of the sequence of circulation maps from the nineteenth century to the present. Gridded SLP datasets such as HadSLP2 have been widely used, but Reanalysis datasets are more commonly used today.

Data and metadata stewardship: Until the advent of reanalyses, historic measurements were considered less important than air temperatures or precipitation totals. For marine regions, much effort has been undertaken in to locate, scan and digitize more of the logbook information that it is still believed to lie dormant in archives around the world. Similarly for land, sub-daily SLP and STP measurements have been digitized, specifically with extended reanalysis in mind. All the data makes its way into ISPD and ICOADS, but neither are official archives. ICOADS has only added a subset of near real time data to its archive since 2014 and ISPD is maintained through small contributions from research budgets. Recognising this, NOAA NCEI and C3S are incorporating and extending land observations in ISPD via their work to address IP Action A2.

Large volumes of STP and SLP data are available in paper records or on archaic media or obsolete formats such as proprietary binary. Resources to identify, catalogue, image and rescue this data would enhance and extend the pressure records, recognising that incorporating newly rescued data into the climate archives also requires substantial effort and resources.

Networks: SLP and STP measurements are transmitted using standard messages (SYNOP, CLIMAT) on the WIS. Most countries maintain more stations than are listed in the Global Basic Observing Network (GBON), and a small number (e.g. United States, Canada, Australia, Fennoscandian countries, Netherlands) make these data available on their websites. For many countries the number internationally exchanged is limited, sometimes because of resources, but sometimes due to there being few stations in remote regions.

The WMO Voluntary Observing Ships (VOS) program co-ordinates measurement and NRT transmission of marine meteorological and oceanographic measurements made aboard ships recruited to national or regional observing VOS networks. Most VOS reports include SLP alongside other near-surface observations. Limited observational metadata (observing methods and heights) is available within the reports, and more extensive metadata elements reports can be accommodated in new BUFR templates. The metadata is supplemented by a metadata database being established by JCOMM based on WMO Publication No. 47.

Research vessels have the potential to make high-quality observations of many surface ECVs, including pressure but their observations are not consistently used for global monitoring as there is no internationally co-ordinated management system for their data.

Global Tropical Moored Buoy Arrays have only recently begun to report pressure on a subset of moorings.

National operational networks of moored buoys, typically in coastal locations, provide measurements of a range of ECVs in NRT including pressure. These buoys have not historically been managed for climate applications so some archived records have limited metadata and provenance.

Surface Drifters provide NRT measurements of SST and SLP. They are capable of providing accurate measurements of SLP at high temporal resolution. Observations are sparse in upwelling and divergence regions. The surface drifter program was established in the late 1970s and reached its design goal of 1250 drifters in 2005 – although sampling density has recently declined.

Reanalyses: All Reanalysis products are very dependent on STP and SLP measurements, particularly so for 20CRv3/2 since 1835/1851, slightly less so for JRA55 since 1958 and ERA5 since 1950. Reanalyses have improved since the 1990s, and a simple metric of this is to calculate the average sea-level pressure of the dry mass of the atmosphere (Hersbach et al., 2020) across the world. This metric should be relatively constant from year to year. Assessments are also essential for their use in data sparse regions such the Antarctic, the central Arctic and the Southern Oceans.

References:

Hersbach,H., B. Bell, P. Berrisford, S. Hirahara, A. Horányi, J. Muñoz-Sabater, J. Nicolas, C. Peubey, R. Radu, D. Schepers, A. Simmons, C. Soci, S. Abdalla, X. Abellan, G. Balsamo, P. Bechtold, G. Biavati, J. Bidlot, M. Bonavita, G. De Chiara, P. Dahlgren, D. Dee, M. Diamantakis, R. Dragani, J. Flemming, R. Forbes, M. Fuentes, A. Geer, L. Haimberger, S. Healy, R. J. Hogan, E. Hólm, M. Janisková, S. Keeley, P. Laloyaux, P. Lopez, C. Lupu, G. Radnoti, P. de Rosnay, I. Rozum, F. Vamborg, S. Villaume and J.-. Thépaut, 2020: The ERA5 global reanalysis. Q. J. R. Meteorol. Soc., 146:1999–2049. https://doi.org/10.1002/qj.3803

Surface Water Vapour	
ECV Products covered by this sheet	Near-surface relative humidity and dewpoint temperatures. Note: specific humidity was included in the most recent set of requirements. It is not typically measured but derived from the measurements discussed here.
Adequacy of the Observational System Assessment	3 Coverage of in situ measurements of humidity over land and ocean is excellent in some regions, but sparse or non-existent over large areas of some continents, over most ice-covered regions and for oceans with few shipping routes.
Availability and Stewardship Assessment	4 Several NMHS and other organizations maintain datasets of sub-daily observations and daily and monthly averages. Work by NOAA NCEI and C3S is improving sub-daily global holdings. The most complete archive for in situ marine humidity is ICOADS at NOAA NCEI but since 2014 ICOADS has only been updated with a subset of near real time data with no additions from GDACs or data rescue. Improvements to ICOADS data formats and processing are urgently needed to provide access to observations at their full resolution with WIGOS-compliant metadata along with improvements to quality control and duplicate handling.
Networks	GCOS Surface Network Regional Basic Observing Network (RBON) Voluntary Observing Ships (VOS) Global Tropical Moored Buoy Arrays National networks of moored buoys.
Satellites	Near surface humidity cannot be retrieved from satellites with sufficient accuracy for global monitoring.
Models, Reanalysis etc.	Global atmospheric reanalyses do not presently give a consistent picture of global surface humidity trends.

Discussion:

The ECV product: Global surface humidity climate record: Near surface humidity is measured as several different parameters, and different applications also require different near surface humidity parameters. Any needed conversion between the required parameter and the measured parameter establishes requirements for co-located measurements of temperature and pressure.

Observations over land: Near surface humidity has only been extensively measured since the early twentieth century. Early measurements were from wet and dry bulb thermometers housed in either screens or from psychrometers, and expressed using tables as vapour pressures or more commonly as Relative Humidity (RH). Conversion, also using tables, took place in some parts of the world to Dewpoint (DP) temperature and DP and RH are the two most commonly used humidity variables today. Data only began to be exchanged internationally in the 1950s. Coverage is sparse in remote regions, such as the Antarctic, Arctic and desert regions. Measurement is also more problematic in extremely cold or extremely dry regions. Since the 1980s, automation has gradually spread across the world with most observations taken now by Automatic Weather Stations (AWSs) giving a much greater potential for more readings per day, but this has not been realized in archives. Most AWSs measure RH and calculate DP from this additionally using air temperature and pressure.

Observations over the oceans: Surface humidity measurements over the ocean comprise a mixture of parameters. Until recently most ship-board measurements were from wet and dry bulb thermometers housed in either screens or psychrometers. Dewpoint temperature was calculated on board ship using tables or by electronic logbook software. Both measures were typically recorded and transmitted. More recently relative humidity (RH) sensors have become common as part of Automatic Weather Station (AWS) installations. Historically, humidity observations were recorded alongside other ECVs (pressure, wind, temperatures and cloud) and the ship's position in the ship's logbook. More recently humidity measurements are also available from moored buoys, typically located in tropical or coastal regions. As most of the coverage of near surface humidity measurements over the ocean comes from VOS, the decline in the number of VOS since the 1990s, combined with a decrease in the proportion of VOS reports containing humidity, there has been an overall decline in coverage for marine humidity (Kent et al., 2019). Humidity is measured at different heights above sea level on different platforms, typically 20 metres or more on ships and a few metres on the autonomous platforms. The construction of consistent humidity records requires the measurement height to be known, along with an estimate of the humidity gradient between the observation height and the chosen reference height. Accurate adjustment requires estimates of local wind speed, air-sea temperature difference and humidity. Differences have been found between humidity measured using different methods, so homogenisation requires metadata giving measurement method and ideally other parameters such as airflow near the sensor.

Data and metadata stewardship: NOAA NCEI and C3S have made significant steps towards a global collection of near-surface humidity data measured over land, but much work remains to be done. Several National Meteorological and Hydrological Services (NMHS) and non-NMHS organizations maintain datasets of sub-daily observations and daily averages. As the conversion between humidity variables is non-linear and additionally requires air temperature and pressure, it is better that datasets maintain the original sub-daily measurements.

The most complete archive for in situ marine humidity is ICOADS at NOAA NCEI. Improvements to ICOADS data formats and processing are urgently needed. There is no dedicated data centre for the archival of marine observations from the GTS. A separate archive exists for the tropical moored buoys. The climate record for in situ surface humidity from ships for recent decades is based largely on observations exchanged in near real time (NRT) in support of weather forecasting. Observational coverage has declined over the past decade as some ships have ceased measurement or operation. Availability of observational metadata will improve if BUFR templates are diligently completed, supplementing metadata catalogued by JCOMMOPS. Archives of NRT observations are retained by several NMHS and some progress has been made toward global stewardship by NCEI and C3S. Moored buoy observations are typically available in both near real time and at higher resolution with calibration following mooring visits. Global Collecting Centres provide added-value data for Voluntary Observing Ships (VOS) data, but only a subset of VOS reports become available through this route.

Large volumes of all types of surface humidity observations are available in paper records or on archaic media or obsolete formats such as proprietary binary. Resources to identify, catalogue, image and rescue this data would enhance and extend the surface record, recognising that incorporating newly rescued data into the climate archives also requires substantial effort and resources.

Networks: Over land near-surface humidity measurements are transmitted using standard messages (SYNOP, CLIMAT) over the WIS. Most countries maintain more stations than are listed in RBON, and a small number (e.g. United States, Canada, Australia, Fennoscandian countries, Netherlands) make these data available (but often not in NRT) on their websites. For many countries the number internationally exchanged is limited, sometimes because of resources, but sometimes due to there being few stations in remote regions.

The WMO Voluntary Observing Ships (VOS) program co-ordinates measurement and NRT transmission of marine meteorological and oceanographic measurements made aboard ships recruited to national or regional observing VOS networks. Many VOS reports include humidity alongside other near-surface observations required for adjustment of temperatures to a common reference height (near-surface wind speed, air and sea temperatures). Conversion between different measures of humidity may additional require co-located measurements of temperature or pressure. Limited observational metadata (observing methods and heights) is available within the reports, and more extensive metadata elements reports can be accommodated in new BUFR templates. The metadata within reports is supplemented by a metadata database being established by JCOMM based on WMO Publication No. 47.

Research vessels have the potential to make high-quality observations of many surface ECVs, including humidity but their observations are not consistently used for global monitoring as there is no internationally co-ordinated management system for their data.

Global Tropical Moored Buoy Arrays provide the broadest range of ECVs including humidity since the late 1970s in the Tropical Pacific and more recently extended to the Tropical Atlantic and Indian Oceans. Observations are transmitted in NRT, and these are supplemented with delayed mode observations from on-board logging retrieved when the moorings are replaced which also provides the potential for post-calibration if the instruments have survived.

National operational networks of moored buoys, typically in coastal locations, provide measurements of a range of ECVs in NRT, some including humidity. These buoys have not historically been managed for climate applications so some archived records have limited metadata and provenance.

Reanalysis: Reanalysis products include near-surface humidity output which has been used in BAMS State of the Climate series, C3S monitoring and compared to data in Simmons et al. (2010) and ECMWF Tech Memo 881. Humidity suitability from reanalysis is dependent upon the reanalysis system and is regionally dependent.

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Surface precipitation	
ECV Products covered by this sheet (group as much as possible)	Surface precipitation (accumulated precipitation)
Adequacy of the Observational System Assessment	3 Ground-based networks and satellite together provide a quasi- global coverage (lacking polar coverage).
Availability and Stewardship Assessment	3 Most ground-based network archives are well stewarded, although often only shared at regional or NMHS scale. Satellite and reanalysis data are curated by their producers.
Networks	Rain gauges (in situ) are available and many but by no means all, of these data are provided to GPCC or other international centers Citizen science networks such as CoCoRAHS Commercial microwave links (CML) Radar
Satellites	Polar orbiting satellites (DMSP-Satellite Series) Low-latitude orbiters (GPM, TRMM, MEGA-TROPIQUES)
Models, Reanalysis etc.	Reanalyses provide precipitation as an output rather than being used as an input. Reanalyses can have large departures from point gauge measurements particularly in convective precipitation regimes where they tend to disagree on location, phasing and intensity.

Discussion:

The accumulated precipitation amount is observed in situ by rain gauges. Also in situ instruments exist to measure snapshot precipitation rates. Precipitation rates are commonly measured by satellites, radar systems or commercial microwave links (CML) and translated to precipitation amounts. As satellites, radar and CML are indirect measurements, these need to be adjusted to in situ observations by means of rain gauges.

A global estimation of accumulated precipitation is possible and done on an operational basis by combining in situ data with remotely sensed data from satellites, radar and CML. Sub-daily temporal resolutions are possible as well at spatial resolutions below 1 km x 1 km, especially by combining in situ and radar data. This is limited to regions were these measurement systems are operated, which is regional and not global. There are limitations in areas of significant orography.

Over the last few decades, the data availability has increased due to modern remote sensing systems becoming available: satellite data are available since 1979, radar data since the early 1990s and in recent years CML has become available.

Conversely, in certain regions the number of rain gauges operated decreases as more remote sensing systems have become available. Going further back in time, rain gauge data become increasingly sparse, as fewer stations were operated and/or data were either not digitalized or have been lost in the interim. There is substantial scope to rescue old data and improve the situation.

The surface observing capability remains deficient over certain regions, most notably Africa and the Oceans and the High Asia Mountain, and the situation has not improved since GCOS IP 2016. Precipitation observations taken at synoptic stations are generally shared in near real time as part of the global SYNOP data stream. But this is solely a small component of the total observing system. In addition, data are provided to the international data centre GPCC and to NOAA NCEI, with a focus on daily and monthly aggregations. The citizen science Community Collaborative Rain, Hail and Snow Network (CoCoRAHS) network and similar networks such as weather WOW have greatly increased daily coverage over some regions. Concerning the citizen science networks their governance, sustainability, archival, accessibility, representativity, and uncertainty needs to be evaluated in a more thorough way.

RADAR remotely sensed precipitation data are only sparsely located and shared.

Weather radars have been widely used to detect and quantify precipitation and nowcast severe weather for more than 50 years. But, they are often patchy and heterogeneous. In recent years some progress has been made to provide guidance to the NMHSs. A dedicated task team from GCOS-AOPC has addressed this topic and a few recommendations by Saltikoff et al. (2019) have been published, to preserve the datasets for the future climatologists.

From MW imagers and microwave soundings with satellite instruments precipitation can be determined. They are in an operational sustained status and have good continuity into the 2040s, which is assured by the space agencies. The satellite precipitation data is generated, archived, and distributed by the responsible space agencies in near-real time.

Extremes can be captured by the observing system and are evaluated e.g. by the NHMS's and the WMO. However, the capturing capability is subdued to a large spatial variability. This shrinks the ability to evaluation the simulation of extreme precipitation on the global scale at a comparable quality. Agreed methods based on guidance by WMO are applied.

For reanalyses and global modelling precipitation remains a major challenge. as reported by several authors (Kaiser-Weiss et al., 2019; Lockhoff et al., 2019; Steinke et al., 2019; Kaspar et al., 2020; Rustemeier et al., 2019, when comparing reanalyses or results from global models with the surface-based observation on a global scale. It is reported that the global reanalyses are often not able to capture for example the occurrence of heavy precipitation events. Overall is noted that model evaluation is hampered by a general inconsistency between observed data sets of precipitation. However, taking the more recent high-resolution reanalyses, the matches are getting better with an improved coherence with independent observations (see review paper by Kaspar et al., 2020).

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Surface Radiation Budget	
ECV Products covered by this sheet	Surface downwelling and upwelling longwave (LW) radiation, Surface downwelling and upwelling shortwave (SW) radiation
Adequacy of the Observational System Assessment	4 Ground-based networks and satellite together provide almost global coverage (except poles).
Availability and Stewardship Assessment	3 Most ground-based network archives are well stewarded. Satellite and reanalysis data are well curated by their producers.
Networks	Surface observations available from national networks and archives, often maintained by national weather services. International networks: Baseline surface radiation network (BSRN) World Radiation Data Center (WRDC) Ocean moored buoys: TAO/TRITON (Pacific), PIRATA (Atlantic) RAMA (Indian) Global Energy Balance Archive (GEBA)
Satellites	Meteorological satellite instruments (SW / LW) allow the retrieval of the surface radiation budget; global coverage using polar orbiting and geostationary satellites. Data are available since about the 1980s. CERES EBAF and SYN surface radiation products (Ed.4) GEWEX SRB (Release 3) CM SAF CLARA-A2
Models, Reanalysis etc.	Recent global and regional reanalyses provide data of the surface radiation budget (e.g. ERA5, NCEP, MERRA-2)

Discussion:

In situ and ground-based network capabilities are currently broadly stable in terms of measurement frequency statistics. They are well maintained by the National Meteorological Services. Several countries run networks with extended capacity (e.g. US with the Atmospheric Radiation Measurement (ARM, US) or SURFRAD[43] (NOAA, US) sites, Germany, France, China and other).

The measurements of surface radiation are mostly done for the solar radiation and to a lesser extent for the longwave component. The data are globally shared via the World Radiation Monitoring Center for the Baseline Surface Radiation Network (WRMC-BSRN) archive hosted at the Alfred Wegener Institute (AWI), the World Radiation Data Center (WRDC) and the Global Energy Balance Archive (GEBA). The progress in distributing surface radiation data in a regular way is still slow.

The in situ capability is deficient over certain regions, most notably Africa, Central Asia, the deep tropics, and over the oceans, even though the buoy-based measurements and their provision have improved over recent years. Existing gaps in the surface network can be filled by surface radiation estimates based on satellite data.

Although the BSRN network has expanded to cover many new climatic regions and is providing a useful reference for satellite observations, site closures are unavoidable. Since 2008, ten BSRN sites have been closed. Nevertheless, the BSRN overall performance has been largely stable and the data are provided with additional auxiliary data in order to support their analysis. It is worth noting, however, that some sites are not representative of their surrounding regions, which bears limitations when comparing to satellite pixels, and that only very few current / former BSRN stations are / have been located in Africa. Further reductions in the BSRN network density in Africa should be avoided. Currently, BSRN is considering nine candidate stations in India, Taiwan and other countries.

Under the guidance of WMO the WRDC collects, archives and distributes global in situ radiometric data to ensure the availability of these data for research by the international scientific community. The data have been provided to the WRDC by National Meteorological Services since the 1960s at predominantly daily and monthly temporal resolution.

The Global Tropical Moored Buoy Array (GTMBA) covers three buoy networks in the Pacific (TAO / TRITON), the Atlantic (PIRATA) and the Indian (RAMA) ocean. While these buoys are not primarily designed to measure surface radiation at the highest quality, they do provide very valuable radiation data at the ocean surface with high quality.

The Global Energy Balance Archive (GEBA) is meant to serve as a central database for the worldwide instrumentally measured energy fluxes at the surface, maintained by the Institute for Climate and Atmospheric Sciences at ETH Zürich, Switzerland. The GEBA database stores and provides monthly means of the various energy flux components observed at surface stations. The GEBA is based to a wide extent on data provided by the BSRN and the WRDC.

Satellite-derived data sets provide global coverage. Most satellite-derived data sets, in particular those provided by satellite agencies, are well curated by their producers and provide historical data sets up to 30 to 40 years.

The surface radiation can be estimated from SW/LW satellite measurements from meteorological satellites in the geostationary (e.g. Meteosat, GOES) and polar-orbiting (e.g. Terra, Aqua, the NOAA-satellite series, Metop) orbits, providing high temporal and spatial resolution (geostationary) and global coverage (polar-orbiting).

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[43] https://gml.noaa.gov/grad/surfrad/

It is important to note the Surface Radiation Budget from satellites measurements is estimated through an inversion process from the top of the atmosphere (ToA) radiance measurement or through radiative transfer calculations using observed surface and atmospheric properties as input and the ToA irradiances as a constraint. As for the solar radiation components a direct relationship exists between the surface radiation and the ToA radiation, this part of the surface radiation budget is often generated and distributed by the responsible satellite agency. For the solar radiation component, a strong market (Photovoltaic power generation) exists. However, the maturity and availability of satellite-derived data sets of the longwave surface radiation is much less pronounced and only a few agencies provide products in an operational mode.

Recent regional and global reanalysis data sets using the latest developments of modern reanalysis systems also provide data of the surface radiation budget with acceptable quality.

A.a.ii Upper Air

Upper-air temperature	
ECV Products covered by this sheet	Tropospheric temperature profile, stratospheric temperature profile and temperature of deep atmospheric layers.
Adequacy of the Observational System Assessment	4 Coverage between in situ and remotely sensed is quasi-global with exception of poles
Availability and Stewardship Assessment	5 Satellite data is well curated and in situ data recent developments lead to improved redundancy in data stewardship.
Networks	GCOS Reference Upper-Air Network GCOS Upper-Air Network (subset of full WWW/GOS radiosondes network) Full WWW/GOS radiosonde network Commercial aircraft Capable of measurement by various remote-sensing techniques which are both sparse and lack global governance (FTIR, MWR, Lidar)
Satellites	MSU/ AMSU / ATMS (1979 ->) Hyperspectral sounders (2002 ->) (AIRS, IASI, CRIS) GNSS-RO (2000 ->)
Models, Reanalysis etc.	Global reanalyses. Regional reanalyses.

Discussion:

In situ and ground-based network capabilities are currently broadly stable in terms of measurement frequency statistics. Locations where observations have long been sparse have not improved, despite continued efforts to the contrary. Aircraft observations, with the exception during COVID-19, have been increasing with some incremental improvements in coverage. Measurements continue to be made by a broad range of remote sensing techniques but tend not to be shared in near real time and often are not shared broadly even in delayed mode. The in situ and remotely sensed capability is deficient over certain regions, most notably Africa, South America, and SE Asia. With the exception of major air traffic corridors, in situ observations are completely absent over the global oceans, including the Arctic Ocean.

Measurement quality from radiosondes has continued to improve, particularly with the switch to newer models by a number of the major manufacturers. The move to BUFR providing full high-resolution profiles yields improved information although several Members are encoding TEMP as BUFR still, and work is required to remedy this. Work by The GCOS Reference Upper-Air Network (GRUAN) to qualify traceable data products has yielded improved understanding of measurement biases and uncertainties. The GRUAN network has expanded to cover many, but not all, previously identified gaps. The GCOS Upper-Air Network (GUAN) performance has been largely stable with some station issues remedied via the GCOS Cooperation Mechanism but performance remains below 100%.

All-sky deep-layer sounding products continue to be generated from AMSU/ATMS style instruments, and there are several satellites in continuous operation in several polar orbiter slots making such measurements. Recently, hyperspectral measurements from several of the same observing platforms have been shown to be suitable for inferring clear-sky and partial all-sky temperature profiles. Limb-sounder techniques, such as MLS can also provide useful information above the upper troposphere.

The availability and exploitation of Global Navigation Satellite System Radio Occultation (GNSS-RO) profiles has improved. GNSS-RO provides all sky profile information with several hundred to thousand profiles measured per day. The fundamental measurement of phase delay is both stable and fully SI traceable. The returned profiles have high vertical resolution but require a priori information to disentangle temperature and humidity components in the troposphere and rarely extend to the lower troposphere.

Recent improvements in upper-air temperature measurement capabilities cannot address historical shortcomings. The latest generation of reanalysis products generally do a better job of accounting for the changing nature of the observational constraint although continue to show somewhat lower performance and more reanalysis-to-reanalysis dependency in and above the upper troposphere than at lower altitudes. All reanalyses struggle to varying extents in the pre-GNSS-RO era in regions distant from radiosonde stations. There is questionable timeseries behaviour in 'sparse-input' reanalysis products that solely ingest surface observations, particularly above the lower troposphere.

Wind speed and direction (upper-air)	
ECV Products covered by this sheet	Upper-air wind retrievals
Adequacy of the Observational System Assessment	3 Ground-based networks and satellites together provide a quasi- global coverage in the troposphere (lacking polar coverage). The coverage in the stratosphere is sparse.
Availability and Stewardship Assessment	4 Most ground-based network archives are well stewarded. Satellite and reanalysis data are well curated by their producers.
Networks	GCOS Upper-Air Network (subset of full WWW/GOS radiosondes network) Full WWW/GOS radiosonde network PILOT balloons Wind profilers Commercial aircraft
Satellites	Atmospheric motion vectors from geostationary and polar orbiters Doppler Wind Lidar
Models, Reanalysis etc.	Global reanalyses Regional reanalyses

Discussion:

The WWW/GOS radiosonde network is the backbone of global upper-air wind observations. A BUFR radiosonde template, which became operational in 2007 in parallel to the alphanumeric TEMP code, offers many advantages such as the original sampling resolution with actual time and balloon position during ascent (Ingleby et al., 2016), but transition from TEMP to BUFR is still underway. Quite a few countries are reporting BUFR codes with no balloon drifting position information (i.e. reformatted from TEMP) or still reporting TEMP codes only[44]. A general trend in wind-finding technologies has been a switch from radiotheodolite or radar to GNSS, which significantly reduced measurement uncertainty (Ingleby, 2017).

Observations from commercial aircraft supplement the coverage provided by the WWW/GOS radiosonde network around major commercial air routes such over the United States, North Atlantic, Europe and North Pacific. The total number of observations increased by about 50 % from 2014 to 2019[45]. The coverage over South America has especially improved through a new AMDAR program. Also, lower tropospheric observations over some islands in the tropical Indian Ocean and western Pacific became available since GCOS IP 2016.

Another source of wind information are the Atmospheric Motion Vectors (AMVs) obtained by tracking cloud elements between successive satellite images and assigning their height by measuring their temperature to provide "satellite winds". Since this technique has been continuously improved to provide better observations for NWP (e.g. Santek et al., 2019), use of AMVs produced operationally in earlier periods is not adequate for climate applications such as reanalysis. In order to produce AMVs with homogeneous quality in time, reprocessing has been undertaken by European, Japanese and the United States producers. How far reprocessing can go back in time is subject to availability of successive images needed as input (typically < 1-hr interval) and the quality of those images (such as geolocation and calibration errors).

Another noteworthy development since GCOS IP 2016 is a successful launch of ESA's long-awaited Aeolus mission, which carries a doppler lidar on board to measure wind profiles in the troposphere and lower stratosphere globally from a polar orbiter configuration (Witze, 2018). The doppler lidar instrument makes single-line-of-sight wind measurements, from which horizontal winds are derived through data assimilation or retrieval techniques. The satellite doppler lidar greatly improves the sampling over data sparse regions for the conventional observing systems such as the tropics and Southern Ocean.

Reanalyses can estimate wind fields for the whole atmosphere with data assimilation techniques, which combine model forecasts with information from a variety of observations and generate analysis fields as the most probable state of the atmosphere in a spatiotemporally regular manner. Changes in observing systems are better handled in the latest-generation reanalyses than previous ones, but still remain an issue in improving their temporal consistency. Therefore, care should be taken when reanalysis is used for investigating low-frequency variabilities and trends in the climate system.

Observations in the upper stratosphere and mesosphere are sparse, but there are some available from research-based radar wind profilers (e.g. Sato et al., 2014), which are useful for evaluating wind fields from reanalysis.

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Upper Atmospheric Water Vapor	
ECV Products covered by this sheet	Total column water vapor, tropospheric and lower stratospheric profiles of water vapor, upper tropospheric humidity
Adequacy of the Observational System Assessment	4 The global observing system of multiple satellite- and ground-based instruments can adequately monitor multi-decadal trends except in the troposphere over regions with persistent clouds and/or precipitation.
Availability and Stewardship Assessment	4 Tropospheric data and metadata are available through links on the GEWEX Water Vapor Assessment webpage and from various institutions (e.g. WMO) and networks (e.g. GRUAN and NDACC). Stratospheric profiles from different ground- and satellite-based instruments are independently archived in a variety of file formats.
Networks	• WWW/GOS: Radiosonde • GCOS Upper-Air Network (GUAN, subset of WWW/GOS): Radiosonde • Commercial aircraft: TAMDAR, IAGOS: TDL, Capacitive polymer • GCOS Reference Upper-Air Network (GRUAN): Radiosonde, Lidar, Microwave radiometer, FTIR, Frost point hygrometer (FP), GNSS • NDACC: Lidar, Microwave radiometer, FTIR, Frost point hygrometer • Various GNSS networks
Satellites	Hyperspectral sounders: IR, clear-sky and partly cloudy scenes; 2002 ->; AIRS, IASI, CRIS Visible/near infrared: total column water vapor over land; cloud-free scenes; 2000 ->; MERIS, OLCI, MODIS Microwave: primarily over oceans; 1987 ->; SSMI/S, global; AMSU, ATMS, GMI GNSS (1998 ->) and GPS/GNSS-Radio Occultation (2000 ->) Aura MLS (2004 ->) SciSat ACE-FTS, ACE-MAESTRO (2003 ->) SAGE III/ISS (2017 ->)
Models, Reanalysis etc.	NWP models CCMs: GEOS, CESM Lagrangian models: CLaMS, WACCM Reanalysis: MERRA-2, ERA5, JRA-55, NCEP-DOE AMIP II

Discussion:

Regardless of the measurement technique used, the observation of complete water vapor vertical profiles from the surface to the mesosphere is hampered by the large dynamic range of water vapor number densities in a complete profile, which can easily exceed six orders of magnitude. As a result, no single instrument presently exists that is capable of accurately measuring such a profile. Surface instruments looking up must be able to see through the thick layer of tropospheric moisture to observe the very dry stratosphere and mesosphere. Balloon- and aircraft-borne instruments optimized to measure dry stratospheric air must first pass through the wet tropospheric layer and possibly clouds without becoming fatally contaminated. Water vapor sensors must have detection limits low enough to measure stratospheric humidity, but at the same time not be too sensitive to measure high humidity in the lower atmosphere without saturating. Instruments on space-borne platforms typically have some stratospheric observing capability but have to see through the entire atmospheric column, and past clouds, to measure lower tropospheric water vapor. Furthermore, instrument calibration is complicated by the tendency of water vapor to adhere to every surface it contacts.

Despite these difficulties, significant improvements have been made in the spatial coverage and reliability of water vapor measurements. To date, however, no singular measurement technique exists with sufficient accuracy, record length, coverage, resolution, and temporal stability to monitor multi-decadal trends on a global scale at all levels of the atmosphere (free troposphere up into the mesosphere). An adequate assessment of water vapor trends on a global scale requires the use of observations from multiple instruments and platforms, each of which has unique advantages and shortcomings that require special attention in any trend analysis.

For the globe, the upper atmospheric humidity records useful for climate monitoring extend back to the 1950s for balloon-borne radiosondes, the 1980s for infrared-based and microwave-based satellite observations, 1994 for UTLS observations from long-haul aircraft, 1995 for total column precipitable water (PW) estimates based on the tropospheric delay of radio signals from Global Navigation Satellite System (GNSS) satellites to GNSS ground receivers, 2006 for PW estimates derived from GNSS Radio Occultation (RO), and 2014 for higher density tropospheric observations from a small number of regional service aircraft. Near-global coverage is provided by satellite-based observations, while vertical profiles from radiosondes, balloon-borne frost point hygrometers (FPs), and aircraft are concentrated on continents and islands. Vertical resolution varies widely among observing systems. It is highest, on the order of a few meters, for GNSS-RO, radiosonde and FP humidity profiles; passive microwave and infrared nadir-sounding systems provide a vertical resolution that is lower than the vertical scale of water vapor variability; and the GNSS-IWV technique only yields estimates of total column PW. Furthermore, the quality of water vapor data from different sensors varies under different atmospheric conditions. Infrared nadir-sounding systems cannot observe within and beneath clouds, passive microwave measurements can be contaminated by variations in surface emissivity and cannot penetrate precipitating clouds, and humidity sensors on radiosondes are least accurate under the dry and cold conditions of the upper troposphere and lower stratosphere.

All observing systems are, at least to some extent, affected by measurement and sampling biases and have undergone changes in instrumentation and processing algorithms over their respective periods of record. Atmospheric reanalyses, which generally provide the spatial coverage and record length needed for assessing the state of the climate over the past several decades, are impacted by these non-climatic signals as well as by temporal changes in the types and numbers of observations being assimilated.

Some observing systems with particular advantages and shortcomings are described in more detail below.

Other information: Balloon-borne measurements of relative humidity (RH) by radiosondes are made at least twice daily at several hundred locations around the globe, about 150 of which are part of the GCOS Upper Air Network (GUAN). These measurements are usually reported together with simultaneously observed temperature and either pressure or altitude, allowing for the derivation of vertical profiles of absolute humidity. Spatial coverage is concentrated on continents and islands, particularly in the mid-latitudes of the Northern Hemisphere. The vertical resolution of these profiles varies with altitude, but is generally 5-10 m from the surface to at least the middle troposphere. In cold and dry conditions of the upper troposphere and above, the quality of radiosonde RH measurements is significantly reduced by the sensor's decreased sensitivity and increased response time to changes in moisture.

Operational radiosondes are predominantly launched to obtain meteorological data for input to numerical weather prediction models, leading to spatial and temporal inconsistencies and changes in radiosonde RH sensor types, radiosonde manufacturers and models, instrument calibrations, and manufacturer-supplied instrument corrections that make it very difficult to merge the 80 years of radiosonde RH profile data into reliable climate records. To assist with the quantification of resulting biases and uncertainties in the operational radiosonde network as well as with the calibration of instruments from various observing platforms, the GCOS Reference Upper Air Network (GRUAN) provides sites distributed in various climatic conditions around the globe. GRUAN sites are certified to follow standardized operating procedures, employ careful management of instrumental or procedural changes, and utilize the centralized processing of sounding data. Several GRUAN sites also launch frost point hygrometers on the same balloons as radiosondes to extend high-quality water vapor measurements above the middle troposphere to the middle stratosphere. GRUAN measurement understanding has been used to drive improvements in several commercial sonde models.

More commercial aircraft than ever before are now being used to measure upper atmospheric humidity (among other meteorological variables and trace gases). The IAGOS program, a follow-on to the older MOZAIC program, provides both upper tropospheric and lower stratospheric measurements over long horizontal distances, depending on the cruise altitude and track of commercial airline flights. IAGOS collects data predominantly during long-haul flights between six continents. TAMDAR utilizes smaller regional aircraft flying shorter routes in North America, Asia and Europe, and with a higher frequency of take-offs and landings, provides more vertical profiles in the free troposphere. Both programs, but especially TAMDAR, contribute valuable humidity and other meteorological data to NWP, complementing humidity data from the radiosonde network.

Satellite-based measurements of water vapor vertical profiles from the upper troposphere through the mesosphere are performed by limb-viewing instruments (e.g. microwave limb sounders, solar occultation spectrometers), but only the *Aura* Microwave Limb Sounder currently produces near-global (82°S-82°N) coverage every day with >3500 profiles. Other limb-viewing satellite instruments generate only 30-40 profiles per day. The *Aura* MLS has been operational since late 2004 and has now exceeded its "expected 5-year lifetime" by 11 years. Presently there is only one plan in progress to deploy another limb sounder (ESA's Altius) with similar capabilities as the *Aura* MLS for water vapor profile measurements in the upper troposphere, stratosphere and mesosphere. At this point in time, the loss of MLS would reduce the global coverage of water vapor profile measurements above the middle troposphere by more than 90%. This is, of course, a concern.

Satellite-based measurements of water vapor vertical profiles from the mid- to lower troposphere are performed by nadir-viewing instruments. Specifically, the hyperspectral infrared and microwave sounders on polar-orbiting platforms namely, AIRS/AMSU on Aqua (2002–present), IASI/AMSU on the MetOp series (2006–present) and CrIS/ATMS on Suomi-NPP and the JPSS series (2011–present). Radiance channels sensitive to water vapor absorption are assimilated into some reanalysis models, e.g. ECMWF, but this is an evolving application with room for growth. The retrieval algorithms for all three sounder suites are mature and produce water vapor profiles, along with temperature and other atmospheric gases, globally from ascending and descending orbits (12 hours apart). From

AIRS/AMSU and CrIS/ATMS alone, the CLIMCAPS retrieval system generates > 200,000 successful retrievals at 01h30 and 13h30 every day for the full instrument record and will continue to do so well into the ~2040s with CrIS/ATMS on JPSS-2 through JPSS-4.

The Medium Resolution Imaging Spectrometer (MERIS) and Moderate-resolution Imaging Spectroradiometer (MODIS) provide measurements in the visible to near-infrared absorption bands from which total column water vapor for cloud-free scenes above land can be derived at a spatial resolution as high as 1 km x 1 km. The approach addresses the contamination effect of heterogeneous, and usually unknown, surface types on IR-based TCWV values over land because all surface types are sufficiently bright in the region between 0.1 and 1 µm.

Earth Radiation Budget	
ECV Products covered by this sheet	Top-of-atmosphere longwave radiative flux, top-of-atmosphere shortwave radiative flux (reflected), total solar irradiance, solar spectral irradiance
Adequacy of the Observational System Assessment	4 Broadband short and longwave irradiance is provided by CERES-like record. Continuity of this record is ensured by Libera, the recently selected NASA Earth Venture Continuity mission, to be launched in 2027 on JPSS-3. TSI and SSI continuity is maintained with TSIS-1.
Availability and Stewardship Assessment	4 TSI and SSI daily products are published with a latency of 4 days and 3 days, respectively. CERES data are available at different temporal resolutions, and updated regularly.
Networks	No in situ networks. ECV can only be measured from space
Satellites	Nimbus-7 ERB (1978-1988) ERBE (1985-1998) CERES (1998 ->) SCARAB-3 (2011 ->) GERB (2006 ->) ACRIM/TIM/VIRGO (1980 ->) SORCE TSI/SSI（2003 ->） ISS TSI/SSI（2018 ->） FY-3A/B/C ERM/SIM (2008 - >)
Models, Reanalysis etc.	Global reanalyses. (for example, ERA5, MERRA-2, NCEP) Regional reanalyses. (for example, NRLTSI,NRLSSI,SATIRE)

Discussion:

Satellite capabilities are currently stable in terms of measurement frequency statistics. Measurements continue to be made by several satellites. The data often are shared broadly but tend not to be shared in near real time.

For the Earth Radiation Budget (ERB) shortwave and longwave radiation fluxes, time series began with the Nimbus 7 ERB (calibrated from 11/1978 to 12/1988) and the ERBE WFOV Edition4.0 from ERBE MEaSUREs (Wong et al., 2006; Shrestha et al., 2019). The Clouds and the Earth's Radiant Energy System (CERES) instruments on NASA's Terra and Aqua, NOAA-20 and S-NPP satellites have provided and continue to provide global coverage for more than 20 years (Wielicki et al., 1996; Loeb et al., 2016). The suite of CERES instruments will be followed by the Libera mission to be launched on JPSS-3 (~2027) and is designed to provide seamless continuity to the CERES ERB data record. The Earth Radiation Measurement (ERM) is the similar instrument mounted on FY-3 series to provide the ERB shortwave and longwave radiation fluxes since 2008 (Yang et al., 2012). GERB ERB measurements are made on a geosynchronous platform covering Europe/Africa region (Harries et al., 2005). SCARAB has flown on multiple satellites through the years most recently on Megha-Tropiques.

For the Solar Spectral Irradiance (SSI), measurement quality from TSIS-1/SIM has improved in solar spectral irradiance products with an uncertainty of 0.25% compared to 2-8% in SORCE/SIM. SI traceability of TSIS-I/SIM is ensured by the Spectral Radiometer Facility (SRF) at LASP, but more work is required to assess its on-orbit performance. SSI also will be monitored by SSIM/FY-3E which is scheduled to be launched in 2021.

For the TSI, new measurements of total solar irradiance from NORSAT-1/CLARA and TSIS-1/TIM have continued the low values as SORCE/TIM and TCTE/TIM. The TCTE satellite and SORCE mission are phased out, TSIS-1/TIM on ISS (international Space Station) is the only high-quality record during the solar cycle minimum 24-25. TSI has also been monitored by the Solar Irradiance Monitor (SIM) mounted on FY-3 series since 2008. More missions are needed to keep measurement continuity and capture the decadal climate signal. TSIS-2 as the successor of TSIS-1 is planned to operate on a cubesat platform. The long-term stability of new compact instruments requires assessment. The accuracy of solar spectral irradiance may not match the ECV requirements based on the instrument character parameters.

Numerous other satellite analysis-based data products provide estimates of ERB parameters: ISCCP FD (Zhang et al., 2004), GEWEX SRB (Stackhouse et al., 2011) using both AVHRR and GEO imagers. The CMSAF CLARA product based on AVHRR-only product (Karlsson et al., 2017). TOA Longwave (or Outgoing LW radiation – OLR) products are provided through NOAA HIRS and NASA AIRS (Moy et al., 2010).

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Cloud Properties	
ECV Products covered by this sheet	Cloud properties include the following sub variables: Cloud Cover, Cloud Top Height, Cloud Top Temperature, Cloud Optical Depth, Cloud Liquid Water Path, Cloud Ice Water Path, Cloud Drop Effective Radius
Adequacy of the Observational System Assessment	4
	Ground-based networks and satellite together provide a quasi- global coverage depending on the sub-variable
Availability and Stewardship Assessment	4
	Most ground-based network archives are well stewarded. Satellite and reanalysis data are well curated by their producers.
Networks	Surface observations (GSN, WWW/GOS, VOS) Research Cloud radar and lidar network
Satellites	VIS, IR and MW radiances from geostationary and polar orbiting satellites used to derived cloud properties. Cloud-top temperature, microphysical properties and coverage are all operational and have good continuity. Cloud radar and lidar are on research satellites and not secured.
Models, Reanalysis etc.	Global reanalyses Regional reanalyses

Discussion:

In situ and ground-based network capabilities remain stable in terms of measurement frequency statistics. The surface observing capability is deficient over certain regions, most notably Africa and Oceans, and has not improved.

Surface based observation of Cloud cover (or cloud fraction) is often a human-made observation, but for other sub-variables of the ECV clouds measurements continue to be made by a range of remote sensing techniques (LIDAR, RADAR, Microwave radiometer).

Cloud information is generally shared in near real time as part of the global SYNOP data stream. However, the SYNOP data stream does not contain all ECV sub-variables (e.g. Ice Water path/ Liquid water path). Surface observations of cloud cover provide a historical record. How cloud observations have been made has changed considerably through time at many locations introducing the propensity for large inhomogeneities.

From the VIS, IR and MW radiances from geostationary and polar orbiting satellites cloud-top pressure, temperature, microphysical properties and coverage can be determined. They are in an operational sustained status and have good continuity into the 2040ies, which is ensured by the space agencies. The derived cloud properties data are generated and distributed by the responsible space agencies in near-real time either through direct broadcast or via terrestrial network links.

High-resolution infrared and microwave soundings contribute to improve understanding of optical cloud properties with a long period of record. In addition, hyperspectral measurements from several of the same observing platforms have been shown to be suitable for inferring certain cloud properties.

VIS instruments on geostationary platforms (e.g. ABI, SEVIRI) with their high spatial resolution provide excellent real-time imagery of cloud structure within evolving storms to support weather forecasting.

In terms of dedicated satellite missions with active instruments (e.g. RADAR, LIDAR system) no continuity is assured as these instruments are flown on the research satellites. Nevertheless, decadal-long data records do exist. in the public domain at various national data centres. One such record is the International Satellite Cloud Climatology Project (ISCCP) that began in 1982 to build a record of satellite observations of cloud radiative properties from a large array of instruments and algorithms. The latest ISCCP H Series is maintained by the NOAA National Centers for Environmental Information (NCEI). Another state-of-the art long-term cloud record is generated and maintained within the ESA Climate Change Initiative (CCI).

Extremes can be captured by the observing system and are evaluated e.g. by the NHMS's and the WMO. Agreed methods based on guidance by WMO Expert Team on Climate Change Detection and Indices (ETCCDI) are applied.

For reanalyses and global modelling cloud properties remain a major challenge and shortcoming in modelling today. A part of this story are shortcomings in radiative transfer modelling through clouds. No two cloudy radiative transfer models agree consistently. Without robust, good cloudy radiative transfer models, we are limited in our ability to retrieve the more difficult cloud properties.

Lightning	
ECV Products covered by this sheet	Global Lightning stroke density
Adequacy of the Observational System Assessment	5 The globe is covered by at least two real time high resolution commercial lightning networks, regional-continental scale real-time precision commercial networks, a NASA real-time lightning imager on the International Space Station (ISS), and two GEO lightning imagers on GOES-E and GOES-W covering much of the western hemisphere.
Availability and Stewardship Assessment	4 The commercial data are available, but not free since the networks are private. The space-spaced data are public and freely available from NASA and NOAA.
Networks	WWLLN (World Wide Lightning Location Network) ENGLN (Earth Networks Global Lightning Network) GLD360 (by Vaisala) Plus many regional lightning location networks (NLDN, EUCLID, Starnet, NZLDN, ADTnet, etc.)
Satellites	Global coverage: OTD (70 deg N/S latitude) TRMM/LIS (38 deg N/S latitude) ISS/LIS (54 deg N/S latitude) Plus regional coverage (NOAA GOES-R Series with GLM – geostationary lightning mapper - imaging) FY-4A LMI
Models, Reanalysis etc.	N/A

Discussion:

Lightning observed from space and ground have been useful for climate studies with the extended period of record making these data ever more valuable in recent years. Global coverage from space (OTD/LIS) began in 1995 and real time instantaneous coverage starting in 2004 (WWLLN). There are now other networks which also cover much of the earth in real time. These networks provide instantaneous lightning location information and at present claim to locate up to 80% or more of all lightning depending on the strength of the strokes (higher energy/peak current strokes are detected with the best detection efficiency globally). For climate research the stroke density can be accumulated on any time and space scale needed, with the suggested parameters of 10 x 10 km resolution on a Monthly, Daily or Hourly time resolution. At present only the raw ground-based commercial lightning network data sets (stroke by stroke, high time resolution data) are generally available at a cost. No metadata have been published which would support these time and space series. The goal is to get the private networks to provide climate data for lightning on these spatial and temporal resolutions for free to the public, along with adequate metadata. The space-based OT/LIS and GLM data are provided with metadata. However, there is a desire to use consistent metadata standards for all the lightning data sets.

Global lightning information is also available through proxy data such as thunder day data and Schumann Resonance data. Thunder day data are available for many decades from specific locations and specific countries and there is an active effort underway sponsored by GCOS to accumulate these thunder day data for climate studies. Schumann Resonances are the electromagnetic ringing of the earth-ionosphere cavity caused by lightning. The sum total of all global lightning keeps the cavity oscillating at the Schuman Resonant frequencies (~7, 14, 21, and higher resonances) and this total power is being monitored by a few global stations. The spectral amplitude at these resonant frequencies is proportional to the total global lightning activity, with little or no knowledge of exact location of the strokes.

There are no satellites which locate lightning globally in real time. Low earth orbit satellites instruments such as the OTD, TRMM/LIS and ISS/LIS detect lightning optically with resolution of about 4-8 km pixels, but only observe a small patch under the satellite at any instant. Global lightning climatology data are developed by integrating stroke counts over weeks and months to obtain near global coverage. The coverage region depends on the orbit parameters and generally does not cover the entire full disk of the earth.

Recent developments of lightning imagers at geostationary altitudes hold great promise, as they can observe lightning in continental-sized regions with high space and time resolution. Individually these satellites also do not cover the globe, but a WIGOS GEO-Ring network could do so in the next decade or so. These geostationary satellite instruments have only a few years of total data so far (only over the Americas and adjacent oceans), but will become important sources for regional lightning climatology studies. Data from the geostationary lightning mappers (GLMs) operated by NOAA (jointly developed by NASA/NOAA) are freely available for download for North and South America.

There is another method which has been demonstrated to provide information on global lightning through the fair weather return current, as the charged atmosphere (charged up by thunderstorms) electrically discharges through the conducting atmosphere. Thus, monitoring the vertical return current in fair weather can also provide temporal variation information about global lightning and thunderstorm activity. At present only demonstration projects have shown this technique to work, but no real time monitoring exists. It is possible to monitor the return current from selected ground-based locations, or by using stratospheric balloon borne payloads.

It is useful to note that all these data sets use different techniques, which continue to be compared and cross correlated. Optical satellite instruments easily detect the lightning radiation which penetrates the tops of clouds, but often miss the lightning optical emissions from low altitude strokes below clouds, or between layers within clouds. Ground based VLF (very low frequency electromagnetic radiation) networks detect the electromagnetic signal at frequencies between 1 and 50 kHz (about) which are generated by individual lightning strokes, and located by multi-station triangulation. There is not a simple, constant relationship between the stroke densities determined by these techniques, or with the information from the other (e.g. Schumann Resonance) techniques.

A.a.iii Composition

Carbon Dioxide, Methane & other Greenhouse Gases	
ECV Products covered by this sheet	Tropospheric CO_2 column; Tropospheric CO_2 profile; Tropospheric CH_4 column; Tropospheric CH_4 profile; Stratospheric CH_4 profile
Adequacy of the Observational System Assessment	3 Column values of CO_2 and CH_4 are not temporally and spatially adequately sampled. despite the global coverage achieved with satellites. Vertically resolved measurements are very sparse.
Availability and Stewardship Assessment	3 Satellite and some ground-, aircraft- and balloon-based datasets are well curated and accessible, while ground-, balloon- and aircraft-based datasets are in various formats and spread among several data repositories.
Networks	TCCON / NDACC: total column CO_2 and CH_4 and some in situ balloon based measurements ICOS, GAW: surface in situ CO_2 and CH_4 NOAA GGGRN: global flask network CO_2 and CH_4 with sparse in situ ground-, aircraft- and balloon-based measurements of CO_2 and CH_4 IAGOS/CARIBIC: CO_2 and CH_4 measurements from commercial aircraft Regional and national in situ and flask networks: surface values
Satellites	MetOp IASI, Aqua AIRS, Suomi-NPP CrIS, JPSS-1 CrIS, Sentinel-5P TROPOMI, GOSAT and GOSAT-2 TANSO, OCO-2, ISS OCO-3, OCO-2, SCISAT ACE-FTS, TANSAT
Models, Reanalysis etc.	CAMS (forecast, (re)analysis, inverse modelling) C3S (reanalysis) MERRA-2 (reanalysis) NOAA Carbon Tracker (data assimilation/model) Carbon cycle and Earth system models

Discussion:

The global coverage of total column observations of both CO_2 and CH_4 has improved during the last decade with the addition of several satellite instruments dedicated to GHGs that complement GOSAT, the first GHG-dedicated satellite mission. After the demonstration with SCIAMACHY/Envisat, dedicated CO_2 observations have recently been made by OCO-2, OCO-3, TANSAT, GOSAT, GOSAT-2, and CH_4 by ACE-FTS, S5P/TROPOMI and GOSAT-2. AIRS, IASI and CrIS observe mid-tropospheric variations of both CO_2 and CH_4 but at coarser spatial and vertical resolutions. OCO-2 has a relatively narrow swath of ~10 km, while TROPOMI and CrIS measure top of atmosphere radiance with >2000 km-wide swaths to achieve near-global coverage daily. None of the satellite instruments provide presently tropospheric column observations and this is reflected in the updated ECV requirements and the tropospheric column ECVs have been replaced by total column ECVs. The data from the satellite instruments are generally well-documented, easily accessible from online archives and distributed with a range of error and uncertainty metrics to facilitate transparency in downstream data processing applications. The required uncertainty limits when interpreted as total column uncertainties, are achieved with satellite observations. The spatial resolution requirements are met with satellite. The sampling frequency CO_2 observations is strongly limited by the narrow swath of present satellites. For CH_4 the situation is better with S5P/TROPOMI providing nearly daily sampling frequency. Hover, the temporal sampling requirement of 4h is not met with present satellites.

Ground based measurements of total columns of CO_2 and CH_4 are obtained by Fourier Transform Infrared (FTIR) spectrometers as part of the TCCON and NDACC. High measurement quality is achieved through coordinated activities like inter-comparison campaigns at network sites. New networks include COCOON, a collection of mobile FTIR instruments that have been deployed at urban sites to measure CO_2 emissions. Observations from other more regional networks or individual institutions are coordinated by the Global Atmosphere Watch Programme; data are available in the World Data Centre for Greenhouse Gases[46].

Profiles of CO_2 and CH_4 obtained from aircraft- and balloon-based measurements meet the vertical resolution requirements but are spatiotemporally sparse, especially in the stratosphere and over the oceans.

Tropospheric profiles of CO_2 and CH_4 are obtained by the IAGOS/CARIBIC program of in situ measurements from commercial aircraft. One recently-realized vulnerability in the program was a significant reduction in IAGOS data due a drastic decline in commercial aircraft flights driven by the COVID-19 global pandemic. In a few places, balloon-borne observations of CH_4 and CO_2 profiles are obtained by AirCores - whole air samplers with an altitude-dependent vertical resolution of 0.1-1 km. Developments are ongoing to further improve and simplify tropospheric profile measurements using more automated technologies including drones and return gliders.

High-quality, ground-based observations of CO_2 and CH_4 are made in Europe by the ICOS network, and worldwide by NOAA's Global Greenhouse Gas Reference Network, which includes a global array of flask sampling sites and less dense networks of in situ measurements at the surface, from tall towers, and from aircraft.

Stratospheric CH_4 profiles are currently measured by only the ACE-FTS satellite instrument using the solar occultation technique. ACE-FTS provides about 30 measurements/day, predominantly at high northern latitudes. The need for continuation of satellite-based instrument that measures stratospheric CH_4 profiles also around the globe is critical.

[46] www.gaw.kishou.go.jp

Ozone	
ECV Products covered by this sheet	Mole fractions in the troposphere, UTLS, middle and upper stratosphere, and mesosphere, total column, tropospheric column, stratospheric column
Adequacy of the Observational System Assessment	3 Good for stratospheric and mesospheric observations, but for tropospheric ozone is poor in terms of both the spatiotemporal density and quality
Availability and Stewardship Assessment	3 Satellite and some aircraft- and balloon-based datasets are well curated and accessible, while in some instances ground-, balloon- and aircraft-based datasets are in various formats and spread among several data repositories.
Networks	GAW: Dobson, Brewer, Lidar, Ozonesonde, Microwave Radiometer NDACC: Dobson, Brewer, Lidar, Ozonesonde, Microwave Radiometer, UV/VIS MOZAIC/IAGOS: Measurements from commercial aircraft NASA SHADOZ: Ozonesonde Surface ozone: GAW, regional and national AQ networks
Satellites	SCISAT ACE-FTS and ACE-MAESTRO, Aura OMI and MLS, MetOp GOME-2 and IASI, Aqua AIRS, Suomi-NPP and JPSS OMPS and CrIS, Odin OSIRIS, Sentinel-5P TROPOMI, ISS SAGE III
Models, Reanalysis etc.	TOMCAT/SLIMCAT (CTM) CLaMS (CTM) CAMS (forecast and reanalysis) MERRA-2, ERA-5 (reanalysis)

Discussion:

The global coverage of ozone profile measurements above the tropopause has improved during the last decade with the addition of several nadir- and limb-viewing instruments on polar orbiting satellites. Several satellite-based instruments (e.g. ACE-FTS, ACE-MAESTRO, MLS) continue to add to their multi-decade measurement records of stratospheric and mesospheric ozone mole fractions. Along with tropospheric ozone measurements by the more mature OMI instrument, the TROPOMI instrument now provides measurements of the tropospheric column in the tropics. It is anticipated that TROPOMI tropospheric profile data will soon be released, as well as extra-tropical data. Unfortunately, data from different satellite sensors produce disparate trends for tropospheric ozone columns. The hyperspectral infrared sounders, AIRS, IASI and CrIS, together provide nearly two decades of global ozone measurements as column layer densities with lowest uncertainty (maximum information content) in the stratospheric region.

In situ measurements of ozone mole fractions are made from commercial aircraft, starting in 1994 by the MOZAIC program and now continuing by the IAGOS program. The measurements are predominantly made at cruise altitudes, spanning large horizontal domains of the UTLS, although profiles from the surface to cruise altitudes are also obtained during aircraft initial climbs and final approaches near major airports. Expansions in the number of airlines and aircraft participating in IAGOS during the last decade have helped to fill some gaps in geographical coverage, especially over the central and south Pacific regions, but there are still many regions with no measurements. One recentlyrealized vulnerability in the program was a significant reduction in IAGOS data due a drastic decline in commercial aircraft flights driven by the COVID-19 global pandemic.

The global network of sites measuring ozone profiles with balloon-borne electrochemical concentration cell (ECC) ozonesondes declined somewhat during the early 2010s as Environment and Climate Change Canada decided to consolidate its ECC and Brewer networks. Fortunately, growth of the SHADOZ, NDACC and GRUAN networks since that time has increased the number of global sites routinely launching ECCs. In some regions, namely South America and Africa the geographical coverage of ECC sounding sites remains poor. Recent, world-wide efforts by ECC sounding networks have focused on the standardization of pre-flight instrument preparation and testing procedures, and the homogenization of data processing methods. GRUAN is developing a climate quality product for ozonesonde data that is centrally processed and includes error estimates for every measurement.

Ground-based measurements of ozone profiles and total columns are made around the globe using Dobson and Brewer spectrophotometers, Fourier-transform Infrared (FTIR) spectrometers, microwave radiometers, and various UV-visible spectrometers. The networks of these ground-based instruments are stable and together provide adequate global coverage, including several polar sites in both hemispheres. However, the balloon soundings at many of these sites are only weekly, so the temporal density of observations is low. The WMO-coordinated network of Dobson spectrophotometers, first introduced in 1926, has produced the longest records of total column ozone and continues to operate globally. Regional campaigns to Inter-calibrate Dobson and Brewer instruments have been performed regularly for many years, with absolute calibrations tied to WMO World Reference Standard instruments.

Surface ozone has been measured by regional and national networks for many years, mainly for the purpose of air quality monitoring near urban areas. The more recent WMO GAW network was developed with the monitoring of background tropospheric ozone levels in mind. Strengths and inadequacies of the global coverage of surface ozone monitoring sites were recently addressed in the IGAC Tropospheric Ozone Assessment Report. Though there is some evidence that surface ozone levels are higher today than 40-50 years ago, there is no clear global pattern for changes in surface ozone mole fractions since 2000. It is hoped that new, higher quality satellite-based products for tropospheric ozone, including profile information, with better global coverage can supplement the limited coverage of surface observations and permit the determination of statistically significant trends. Unfortunately, it is likely that new satellite-derived tropospheric ozone products will be spatially limited to North America and Europe in the foreseeable future.

Precursors (to support Aerosol and Ozone ECVs)	
ECV Products covered by this sheet (group as much as possible)	NO_2 tropospheric column; SO_2,HCHO tropospheric columns; CO tropospheric column; CO tropospheric profile
Adequacy of the Observational System Assessment	4 Global coverage is adequate but temporal sampling is insufficient except for at sparse in situ sites.
Availability and Stewardship Assessment	4 Satellite and some ground-based datasets are well curated and accessible, but ground-based data are spread among several data repositories.
Networks	MAX-DOAS network: NO_2, SO_2 Padonia/Pandora network: NO_2, (SO_2, HCHO) TCCON network: CO Surface observations: regional and national AQ networks MOZAIC/IAGOS: Measurements from commercial aircraft
Satellites	*Aura* OMI, *MetOp* GOME-2, *Suomi-NPP* and *JPSS* OMPS, Sentinel-5P TROPOMI, *GEMS*
Models, Reanalysis etc.	CAMS (forecast and reanalysis) MERRA-2 (reanalysis)

Discussion:

The global coverage of precursors for ozone and aerosol ECVs have further improved during the last years thanks to the new satellite instrument TROPOMI which measures all the constituents (NO_2, SO_2, HCHO, CO). Its small pixels (5,5 x 3,5/7 km) are suitable for detecting local enhancements of precursors. Most importantly, these new observations provide CO column data which was not available from satellites before. In addition to the new observations, the existing instruments OMI, GOME-2, OMPS have continued making good quality observations of SO_2 and NO_2. Tropospheric column observations are obtained with satellites and ground based remote sensing instruments or profiling instruments with adequate accuracy.

The temporal sampling does not yet fulfil the requirement globally, but is met locally with ground-based remote sensing instruments. However, the temporal sampling of measuring precursors from satellites entered a new level thanks to the Korean GEMS Geostationary mission, which measures several times per day NO_2 and SO_2 and HCHO over Asia.

The ground-based observations of precursors rely strongly on Pandora and MAX-DOAS spectrometers.

The tropospheric profiles of CO and NO_2 are measured on-board commercial aircrafts by MOZAIC/IAGOS network. NO_2 profile observations are made by one aircraft. One recentlyrealized vulnerability in the program was a significant reduction in IAGOS data due a drastic decline in commercial aircraft flights driven by the COVID-19 global pandemic.

Aerosol Properties	
ECV Products covered by this sheet	Multi-wavelength Aerosol Optical Depth, Aerosol light extinction vertical profile (Troposphere, including Aerosol Layer height), Aerosol light extinction vertical profile (stratosphere), Chemical Composition of aerosol particles, Number of Cloud Condensation Nuclei, Aerosol Number Size Distribution, Aerosol Single Scattering Albedo
Adequacy of the Observational System Assessment	3 The ground-based networks and satellite systems together provide a quasi- global coverage for some of products, but not all products meet threshold requirements, for both spatial and temporal coverages in particular. The accuracy and precision of all aerosol products need to be improved in the future observing system.
Availability and Stewardship Assessment	3 Satellite and reanalysis data are well curated by their producers. Access to some Ground-based network archives could be improved. Observations in some regions are simply not available due to lack of organized network stewardship. The ground-based networks still suffer limited interoperability.
Networks	AOD and derived products: Networks for the detection of Aerosol Optical Depth (AOD): AERONET (https://aeronet.gsfc.nasa.gov/), GAW Precision Filter Radiometer (PFR) (http://www.pmodwrc.ch/worcc/), CARSNET (China Aerosol Remote Sensing NETwork), Skynet radiometer Network (https://www.skyner-isdc.org/index.php) Aerosol light extinction profile (Troposphere and Stratosphere) and derived parameters including Aerosol Layer height: European Atmospheric Lidar Network - EARLINET/ACTRIS, ADNET in Asia MPLNET , NDACC (Network for the Detection of Atmospheric Composition Changes - https://www.ndaccdemo.org/data) Aircraft-based networks: In-service Aircraft Global Observing System IAGOS - https://www.iagos.org Surface-based networks (under the Global Atmosphere Watch), NOAA-Federated Aerosol Network (N-FAN, https://www.esrl.noaa.gov/gmd/aero/net/), The Aerosol, Cloud and Trace Gases Research Infrastructure ACTRIS (https://actris.eu), The European Monitoring and Evaluation Programme' EMEP (https://www.emep.int), the IMPROVE network (http://vista.cira.colostate.edu/Improve/), The Canadian Air and Precipitation Monitoring Network (CAPMoN- https://www.canada.ca/en/environment-climate-change/services/air-pollution/monitoring-networks-data/national-atmospheric-chemistry-database/data.html), the Acid Deposition Monitoring Network in East Asia (EANET- https://www.eanet.asia)
Satellites	AOD and derived products can be retrieved from Standard multi-spectral passive sensors orbiting LEO or GEO, such as MODIS, POLDER, MERIS, GOMOS, OMI, SeaWiFS, AVHRR, IASI, ABI, MERSI, VIIRS, AHI, AGRI. Typical datasets can be found at https://atmosphere-imager.gsfc.nasa.gov/documentation/collection-6 Extinction coefficient including ALH can be derived from Space-lidars (CALIOP), relatively narrow for multi-viewing sensors (MISR ATSR) and TROPOMI Space-based observations for other Aerosol ECV products such as number of Cloud Condensation nuclei, or aerosol chemical composition are generally retrieved. Aerosol CCI http://cci.esa.int/aerosol https://atmosphere-imager.gsfc.nasa.gov/sites/default/files/ModAtmo/ATBD_MOD04_C005_rev2_0.pdf
Models, Reanalysis etc.	CAMS (forecast and reanalysis) AEROCOM (evaluation, reanalyses) https://aerocom-evaluation.met.no/main.php?project=aerocom

Discussion:

Generally, the global observation system for aerosol ECVs have further improved in the past decade thanks to both availability of new satellite-based observations and the development of the in situ observations from the ground and from commercial aircraft. In addition, efforts to promote access to information and development of interoperable information systems have facilitated access to data and data products retrieved from both space, ground and aircraft-based observations.

However, despite evident progresses, the aerosol observing system still does not fully meet the expected requirements for a Global Observing System. The wide spatial coverage of space-borne sensors generally provides sufficient information at Threshold for most ECV products that are suited for many applications (evaluations, analyses), however, smaller retrieval areas should be explored in future satellite missions to respond to requirements at breakthrough and goal levels. Only the threshold temporal resolution of AOD products is met for space-borne sensors which are taken from polar orbiters with repeat measurement times outside the polar regions that are quite long. This is compensated for in many regions but not all by a dense ground-based network for AOD and derived products retrieval.

Most aerosol products in satellite remote sensing can only address column averaged (or integrated) properties. However, vertical distributions are useful constraints for the evaluation of transport in global models. A smart use of in situ observations, space observations and models may compensate for sparseness and limitations of information on vertical distribution, but this only applies to regions where lidar networks are operational with seamless access, as for the United States and Europe. Access to vertical profiles remains a limiting factor to a global aerosol observing system.

The ground-based system has also significantly improved mostly for its spatial coverage that is now close to threshold in several regions (North America, Europe, some parts of Asia) for several aerosol parameters. AERONET and other AOD networks (Skynet, PFR, etc.) provide a dense network of observations over land, responding to threshold requirements (and breakthrough in some areas) for GCOS. Threshold in Timeliness is only met by a few networks.

For other aerosol parameters, despite the fact that e.g. NOAA-FAN in the US, ACTRIS in Europe have extended their networks beyond US and Europe political boundaries, many areas in the world remain undersampled and data access remains an issue.

The tropospheric profiles of aerosol particle size distribution and the number concentrations are measured as part of the IAGOS CARIBIC package and is planned to be implemented on the IAGOS Aerosol Package on-board commercial aircrafts in the future, providing key information on both profiles and concentration along aircraft routes. Interest of some countries to join the IAGOS association, and development funding for adapting IAGOS packages to new aircraft, including on shorter routes, will be of key importance. One recently realised vulnerability in the program was a significant reduction in IAGOS data due a drastic decline in commercial aircraft flights driven by the COVID-19 global pandemic.

The development of the in situ observing system for Aerosol ECV products has been paralleled with great efforts to ensure traceability and provenance of data, joint data management procedures and data policies, under the GAW program. The information system remains, however, managed regionally, and in some countries/regions, operated by different research organisations, leading to difficulties to fully respond to user requirements of an integrated observing system.

Record length of aerosol products should be at least 10 to 15 years for trends to be derived. Continuity of operations and consistency in the time series for both space-based and in situ observing systems are key to many downstream applications and must remain high on the agenda.

A.b Oceans

A.b.i Physical Parameters

Sea Level	
ECV Products covered by this sheet	Global Mean Sea Level Regional Mean Sea Level
Adequacy of the Observational System Assessment	3 Satellite altimetry generally meets requirements and provides reliable trends. While there is a subset of high-quality tide gauges coordinated by GLOSS, the wider tide gauge network is extremely heterogenous in terms of sampling, reliability and capability.
Availability and Stewardship Assessment	3 Satellite altimetry and GLOSS tide gauge sites have good data availability and data stewardship, but a substantial fraction of tide gauge data records is not publicly available.
Networks	Tide Gauges (Coordination: Global Sea-Level Observing System – GLOSS). Moorings (Coordination: OceanSITES, DBCP) Tsunami Moorings (Coordination: DART Network)
Satellites	Satellite Altimetry (Coordination: Ocean Surface Topography Science Team - OSTST); GRACE gravity measurements (NASA and DLR)
Models, Reanalysis etc.	Permanent Service for Marine Sea Level (PSMSL) GLOSS + SONEL Global Navigation Satellite System service Copernicus Marine Environmental Monitoring Service Sea Level products Global Extreme Sea Level Analysis initiative Satellite products: AVISO(Copernicus), JPL-PODAAC, NOAA, ESA Sea Level CCI Argo data products for steric component of global sea level Flanders Marine Institute GLOSS real-time network Uni. Hawaii Sea Level Center quality-controlled sea level data International Association of Geodesy Joint Working Group 3.2 on Global GPS VLM fields at tide gauges

Discussion:

Satellite altimetry generally meets requirements and provides reliable trends (scale 4), although the records only began in 1993, limiting their use for the climate record at present. Satellite altimetry has good spatial and temporal resolution but is restricted to the open ocean, excludes the very high latitudes, and is limited in coastal areas. While there is a subset of high-quality tide gauges coordinated by GLOSS, the wider tide gauge network is extremely heterogeneous in terms of sampling, reliability and capability with potentially important consequences for understanding local observed sea-level change. Tide gauges provide coastal data, but the quality and data records are highly mixed, and temporal gaps in the data records limit their use for climate studies. In addition to that, tide gauges provide relative (not absolute) sea levels that need to be corrected for vertical land motions for certain applications such as climate studies.

Sea Surface Temperature	
ECV Products covered by this sheet	Sea Surface Temperature (SST)
Adequacy of the Observational System Assessment	4 The global temporal and spatial coverage of SST meet requirements for global 7-day averages (satellite spatial resolution) but do not meet requirements in regions of persistent high cloud cover and coastal regions.
Availability and Stewardship Assessment	5 Satellite and in situ data are readily available and systems are in place to track data quality and availability.
Networks	Volunteer Observing Ships Moorings (OceanSITES, DBCP) Drifters (DBCP) Profiling Floats (Argo) Tagged Animals (AniBOS) Ice-tethered profiling systems (International Arctic Buoy Program)
Satellites	Infrared satellite radiometers Microwave satellite radiometers Infrared ship radiometers
Models, Reanalysis etc.	Gridded satellite SST products Gridded gap-free satellite products Native in situ products Gridded in situ products Gridded gap-free in situ products Gridded gap-free merged satellite / in situ SST

Discussion:

While SST is the ocean variable with the greatest spatial and temporal coverage owing to the combination of satellite and in situ networks, we are still some distance from having a complete network to meet requirements. Data do not meet requirements in areas of persistent high cloud cover (satellite limitations, limited in situ network coverage) and coastal zones.

Satellite SST observations provide the most comprehensive spatiotemporal coverage of all platforms that measure SST. Satellite SST data are routinely calibrated with in situ measurements, from other platforms (including surface drifting buoys and Argo), demonstrating the importance of integrated multi-platform observing. Analysis and provision of satellite SST observations has benefitted from a very active and engaged community, under the Group for High Resolution SST (GHRSST; https://www.ghrsst.org). This is an international team of SST experts who meet regularly to assess SST data sources, monitor data quality, maintain data standards, and produce many data products.

Over the years, the instrumentation on satellites has changed – making it somewhat challenging to synthesise a consistent data record, with known error. AVHRR data, for example, is known to be high-quality, but does not return a measurement in the presence of cloud. Microwave SST is less accurate than AVHRR, but produces an observational estimate even in the presence of cloud. These differences mean that sampling of the ocean surface has been inconsistent, with microwave-based measurements available for some years (since 2009, with a gap in 20120-2014). SST observations are also sensitive to local time-of-day. For many applications (particularly gridded products), only measurements at night-time are used, because of the difficulties quantifying diurnal variability (which measures warm during the day, but depends on wind-speed and sea-state). The precise definition of SST measurements that are available is requires precise understanding of the various data products, that discriminate between skin SST and foundation SST, and that ascribe to strict definitions about data processing (e.g. LP2, L3, L4 products).

SST data provision has benefited from the efforts of several groups, who have taken responsibility for processing and disseminating SST databases that include quality-controlled SST data from multiple platforms. This includes NOAA's Pathfinder Project (www.nodc.noaa.gov/SatelliteData/pathfinder4km53/), US Naval Oceanographic Office (NAVO), and most recently CCI-AVHRR and CCI-ATSR, under Copernicus (www.copernicus.eu).

Subsurface Temperature	
ECV Products covered by this sheet	Subsurface Temperature
Adequacy of the Observational System Assessment	3 The open ocean data above 2000 m is good (scale 4) but adequacy is poor (scale 2) below 2000 m in the open ocean, in boundary regions, in marginal ice zones, in shelf areas, and in enclosed, marginal seas.
Availability and Stewardship Assessment	3 Argo data are available in real time on the GTS (scale 5), and other products, near-real time and delayed mode vary in availability. Data availability in the EEZs is problematic, and there are significant delays (up to several years) where data release is dependent on individual principal investigators. In the Arctic, observations by autonomous in situ profiling system (ice-tethered buoys / profilers) are limited to about the top 700 m. Data coverage is sparse and constrained by seasonal accessibility of the Arctic basin for deployments and ice drift (in particular, the Transpolar Drift stream). Full-depth CTD profiles obtained by research ships are largely limited to the months June/July/August/September.
Networks	Profiling floats (International Argo Steering Committee) Repeat Hydrography (GO-SHIP) SOOP-XBT Moorings (OceanSITES) Drifters (DBCP) Ocean Gliders (Oceangliders) Tagged Pinnepeds (AniBOS network) Ice-tethered profiling systems (International Arctic Buoy Program)
Satellites	Not applicable.
Models, Reanalysis etc.	Coordinating data centers, NOAA, and Coriolis, for gridded in situ products IQuOD (www.iquod.org) - Long term, highest quality, most complete and internally consistent global ocean subsurface temperature profile data (and metadata), from 1800s onwards, including (intelligent) metadata and attached uncertainties.

Discussion:

There is a large range in adequacy of the subsurface temperature data. During the period from 2000-2005, global-scale data sampling started to grow due to the Argo Profiling Float Program. Since the year 2005, open ocean data coverage above 2000 meters is good, but below 2000 meters, where Argo does not sample, data availability from combined other observing platforms is low. Many regions, such as the boundary regions, marginal ice zones, shelf areas and enclosed/marginal seas, are still poorly observed. In the Arctic, observations by ice-tethered profiling systems give year-round measurements of T and S to about 700 m, but coverage is sparse. Before the year 2000, data are limited and inhomogeneous, and often limited to 300 or 700 m depth layers. Sparse data are available from the beginning of the century, and starting in the 1950s and 1960s, data sampling increased due to technological developments, but with large gaps and irregular sampling. Since 2005, global 3-monthly resolution in the open ocean is good (above 2000 m). There is still substantial spread in global ocean heat content estimates for the 0-2000 m layer, even at annual timescales. Since 2000, availability and stewardship of data collected as part of global observing systems is very good, but the data collected in Exclusive Economic Zones can be hard to track and to make openly available. Data quality control can vary between automatic instantaneous (real time) for operational use, real-time data combined with additional QC for assimilation (near-real-time), and near-real time data combined with scientific QC (delayed-mode). There are some issues with the delayed mode data being made available in a timely manner where data release is dependent on the PI, where delays of several years have been known to occur.

Sea Surface Salinity	
ECV Products covered by this sheet	Sea Surface Salinity (SSS)
Adequacy of the Observational System Assessment	3 In situ SSS do not meet the resolution requirements but target accuracy is marginally met by in situ based gridded products. There are reliable regional decadal trends over much of the open ocean, but sampling is poor in coastal regions, marginal seas, and polar oceans.
Availability and Stewardship Assessment	4 Most SSS data are publicly available.
Networks	Profiling Floats (Argo) Moorings (OceanSITES) Repeat Hydrography (GO-SHIP) Drifters (DBCP) Underway Thermosalinograph (VOS / TSG) Gliders (Oceangliders) Ice-tethered profiling systems (International Arctic Buoy Program)
Satellites	SMOS Aquarius SMAP
Models, Reanalysis etc.	Satellites: gridded maps of SSS (e.g. PODAAC/JPL, IFREMER, BEC/Spain) In situ: World Ocean Atlas products Argo or Argo+other in situ gridded fields Blended satellite and in situ products: NESDIS / NOAA

Discussion:

In situ SSS do not meet the resolution requirements of 100 km and monthly sampling for the open ocean, and are far from meeting the 10 km weekly / monthly requirements for coastal oceans. The requirement for target accuracy of 0.1 on 100 km, monthly scales is marginally met by in situ based gridded products (with root-mean-square differences of different in situ based gridded SSS products being close to 0.1 when averaged spatially). There are reliable regional decadal trends over much of the open ocean, but not for the coastal ocean, marginal seas, and polar oceans, where sampling is poor. Satellite SSS meet the resolution requirements of 100 km, monthly sampling (observing capacity is 40 km, weekly or better), but they do not meet the 10 km resolution requirement for the coastal ocean. Some satellite products meet the accuracy requirements as well, but the records are too short to depict decadal trends. Satellite SSS in the polar oceans have much larger uncertainties and thus do not meet the requirements. In the Arctic, observations by ice-tethered profiling systems give year-round measurements of T to about 700 m, but coverage is sparse.

Subsurface Salinity	
ECV Products covered by this sheet	Interior Salinity
Adequacy of the Observational System Assessment	3 The open ocean data above 2000 m is good but adequacy is poor below 2000 m in the open ocean, in boundary regions, in marginal ice zones, in shelf areas, and in enclosed, marginal seas.
Availability and Stewardship Assessment	3 Argo data are available in real time on the GTS, and other products, near-real time and delayed mode vary in availability. Data availability in the EEZs is problematic, and there are significant delays (up to several years) where data release is dependent on individual principal investigators.
Networks	Profiling Floats (Argo) Moorings (OceanSITES) Repeat Hydrograhy (GO-SHIP) Drifters (DBCP) Gliders (Oceangliders) CTD tagged pinnepeds (AniBOS) Ice-tethered drifters (International Arctic Buoy Program)
Satellites	Not applicable.
Models, Reanalysis etc.	World Ocean Database / NODC Coriolis Gridded salinity climatology

Discussion:

The open ocean above 2000 m is relatively well sampled by the Argo profiling float program. Deep ocean, boundary region above the 1500 m isobath, coastal regions, and marginal seas are less sampled or show smaller number of open data. The open ocean above 2000 m is sampled monthly with 300 km resolution. Availability and stewardship of data from global ocean observing networks are good. Some of boundary currents systems and coastal regions and marginal seas are less well observed. The resolution for waters below 2000 m is also low. In the Arctic, observations by ice-tethered profiling systems give year-round measurements of S down to a depth of 700 m. Note: ARGO-style correction kicks out the bottom few hundred metres due to calibration with historical data (i.e. any signal will be lost due to the conductivity correction.)

Surface Currents	
ECV Products covered by this sheet	Surface geostrophic current
Adequacy of the Observational System Assessment	3 Meets requirements for geostrophic and Ekman currents in the open ocean at large spatial and weekly time scale, but the spatial and temporal resolution and the coverage in boundary and coastal regions is not adequate. Observations of total surface current velocity below 300 km scales are non-existent.
Availability and Stewardship Assessment	4 Surface drifter and satellite altimeter and scatterometer data are readily available and systems are in place to track data quality and availability. HF radar data is accessible for some networks (e.g. US) but can be difficult to access in other regions.
Networks	Moorings (Coordination: OceanSITES) Drifters (Coordination: DBCP) Coastal HF radar
Satellites	Sea Surface Height anomalies Dynamic topography Surface vector winds SST SAR Interferometry SAR range Doppler
Models, Reanalysis etc.	OSCAR surface currents products ESA GlobCurrent Satellite products: NASA PODAAC, CNES / CLS, EUMETSAT, SALTO/DUACS

Discussion:

Surface current observations in the open ocean are dominated by satellites (altimetry + scatterometry) which provide good estimates of the geostrophic and Ekman components of the total currents on scales greater than 100km and away from boundary and coastal regions. In situ observations are very sparse, limited to underway ship data and dedicated research campaigns. Surface drifters and Argo provide observations of the total ocean surface circulation but the spatial and temporal resolution remain coarse (>300km). There are presently no observations of total ocean surface current velocity in the open ocean and polar regions at shorter scales. HF networks can provide continuous maps of ocean surface currents within 200 km of the coast at high spatial (1–6 km) and temporal resolution (hourly or higher) (Roarty et al., 2019). However, and although HF radar networks have been growing and HF radar systems are and have been operated in 25% of the countries with an ocean coastline, considered globally, the coverage of coastal regions is poor. The observing system meets requirements for geostrophic and Ekman currents in the global ocean at large spatial and weekly time scales. The spatial and temporal resolution and the coverage in boundary and coastal regions is not adequate. Observations of total surface current velocity below 300 km scales are non-existent.

Surface drifter and satellite altimeter and scatterometer data are readily available and systems are in place to track data quality and availability. HF radar data is accessible for some countries/networks (e.g. see http://global-hfradar.org/) but can be difficult to access in other regions.

References:

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Subsurface Currents	
ECV Products covered by this sheet	Interior currents
Adequacy of the Observational System Assessment	2 Adequate in some regions of the world's oceans but at a global scale the observing system is not adequate with very few observations in the ocean interior.
Availability and Stewardship Assessment	3 Availability and stewardship is very much region dependent
Networks	Moorings (OceanSITES) Drifters (DBCP) Profiling floats (Argo) Ocean Gliders (Oceangliders) Repeat Hydrography (GO-SHIP) Electromagnetic (floats and fixed cables)
Satellites	Not applicable.
Models, Reanalysis etc.	Gridded 1000 m current (Argo Information Center) OceanSITES Underway ADCP and station lowered ADCP (GO-SHIP)

Discussion:

Observations of subsurface ocean velocity contribute to estimates of ocean transports of mass, heat, freshwater, and other properties on local, to regional and basin to global scales. Subsurface velocity observations are obtained via direct measurements of the ocean velocity or indirectly from observations of temperature, salinity and pressure using the geostrophic approximation. The best available tool for estimating the long-term variability of the large-scale full-depth velocity/transport are purposely-designed transport mooring arrays. Subsurface boundary currents, equatorial currents, and other constrained intense currents are observed directly using moored Acoustic Doppler Current Profilers (ADCP) at hourly time resolutions. Gliders, using similar techniques, are used to monitor boundary currents and ocean eddies for periods of days to a few months. Shipboard ADCP and Lowered ADCP provide surface and subsurface current data from boundary current scale to basin scale depending on horizontal resolutions and tracks of research voyages. While the vertical shear of the component of horizontal velocity perpendicular to each station pair of a hydrographic section is straightforward to calculate from geostrophy, determining the absolute velocity field to sufficient accuracy for transport estimates is more problematic. An important contribution to subsurface velocity observing are Lagrangian subsurface current measurements derived from the drift at 1000 dbar of Argo profiling floats. These data can be combined with other ocean current observation to obtain gridded basin-scale full depth geostrophic velocity estimates. However, Argo floats are not deployed at shelf/shelf break areas inshore the 2000 m isobaths, where a large part of western boundary currents occur.

Velocity estimates can be combined in data assimilation models to provide gridded global estimates of ocean circulation at varying temporal and spatial scales. Gridded time varying ocean velocity observations provide the estimates of local and global mean and eddy kinetic energy. These products are used to assess and improve the reliability of numerical ocean models. The range of technologies available to measure sub-surface currents has increased in the last decades and in particular HF radars have seen a great development in the last 15 y. Measurements are adequate in some regions of the world's oceans, but at a global scale the observing system is not adequate, with very few observations in the ocean interior. The resolution of observations might meet user requirements for specific regions of the ocean, but global coverage is very poor and there are few observations in the ocean interior. Availability and stewardship are very much region dependent.[1]

[1] Key Performance Indicators for global ocean networks such as Argo can be found in OceanOPS (ocean-ops.org)

Surface Stress	
ECV Products covered by this sheet	Ocean surface stress
Adequacy of the Observational System Assessment	3 Satellite ocean-surface wind stress meets some of the accuracy requirements. In situ wind stress meets all accuracy requirements, but coverage is extremely sparse. Satellite wind stress measurements, with typical spatial resolution of 25 km, are close to meeting the 10-100 km spatial resolution requirements. But they do not meet the hourly sampling requirement for certain phenomena. In situ wind stress does not meet the resolution requirements of 10-100 km, but mooring wind stress meet the hourly sampling requirement.
Availability and Stewardship Assessment	4 Most wind stress data are available publicly.
Networks	Research vessels (GO-SHIP) Surface Buoys (DBCP) Air-sea Flux Moorings (OceanSITES)
Satellites	Scatterometers Polarimetric passive microwave radiometers
Models, Reanalysis etc.	CCMP wind analysis, IFREMER wind analysis, ERA-Interim, ERA5, CFSRv2, MERRA2, JRA-55

Discussion:

Satellite measurements of ocean-surface wind stress are derived from scatterometers and polarimetric radiometers. While the typical spatial resolution is 25 km. Products generated at 12.5 km are also available with higher noise level. There are very few of these satellites currently operating in orbit and with the ASCAT series being the only operational mission. Because of this, there are significant temporal sampling gaps on diurnal time scales (not meeting the hourly temporal sampling requirement). Resolving diurnal wind stress are important for many science and application areas, such diurnal convection and its effect on variability of longer time scales including synoptic storms and Madden-Julian Oscillation. International coordination among space agencies is critical to improve the ability to sample diurnal surface stress. Satellite scatterometers are typically on sun-synchronous orbits with fixed local equatorial crossing times. This may cause aliasing of diurnal signal into the long-term mean. There are insufficient in situ surface stress measurements over the global ocean to understand the extent of the diurnal aliasing in satellite surface stress. Satellite scatterometers use both Ku- and C- band microwave frequencies. Ku-band sensors are more susceptible to rain effect than C-band sensors. Inter-calibration of different satellite scatterometers using long-term in situ measurements is important, especially in climatologically rainy regions. In such regions, the evaluation of satellite surface stress using in situ measurements need to take into account small-scale wind variability that are averaged within satellite footprints but sampled at point-wise locations by in situ sensors. Such small-scale wind variability, which can be stronger under rainy conditions (e.g. associated with transient convective rain cells), can contribute the difference between satellite and in situ surface stress measurements. Effect of surface currents can also contribute to the difference between surface stress derived from satellites and in situ sensors.

Sea State	
ECV Products covered by this sheet	Significant Wave Height, Directional wave spectrum
Adequacy of the Observational System Assessment	2 The system provides highly accurate and precise buoy and satellite altimeter measurements but spatial coverage for both satellites and buoys are limited. Use of buoy data for climate monitoring is low due to problems in continuity, consistency, and stability. Directional wave spectra from buoys is good in the northern hemisphere but sparse elsewhere. Directional wave spectra from satellites have issues with quality.
Availability and Stewardship Assessment	3 SWH data are well organized and publicly available from satellites and most (but not all) buoy networks. Access and use of consistent quality flags, metadata and common compact definition for directional spectra are needed. Directional spectra data not always accessible.
Networks	Moorings (Coordination: OceanSITES, JCOMM DPCP, NDBC, CDIP) Research vessels (Shipboard motion recorders and X-band radar) Drifting wave buoy under development but quality still unknown
Satellites	Altimetry (Coordination: OSTST, CEOS) SAR CFOSAT and Lidar Altimeters
Models, Reanalysis etc.	Real-time forecasts (All maritime weather offices as well as Global centers including ECMWF, UK-MetOffice, NOAA/NCEP, Meteo-France, Env. Canada, DWD, ...) Reanalyses/hindcasts (ERA5, Copernicus-CMEMS, NCEP-EMC)

Discussion:

Significant Wave Height (SWH) for near-real time (scale 3) is obtained from highly accurate and precise buoy and satellite altimeter measurements, but spatial coverage for both buoys and satellites is limited. SWH in the open ocean where the altimeter constellation provides global coverage at roughly 100km and 3-day (i.e., not yet meeting the 3 hr 25 km goal) is good (scale 3 to 4), but poor for capturing extreme SWH in open oceans, frequently missed due to satellite undersampling (scale 2). SWH from buoys for climate applications (scale 1) is poor because there are no requirements for buoy networks to ensure long-term continuity, consistency or stability. Sea state monitoring in the coastal zone, where sea states are highly variable due to bathymetry and current interactions, requires new and dedicated means. Swell from SAR and directional wave spectra from CFOSAT and buoys is fair (scale 2 to 3). Directional wave spectra from the buoy network (scale 3) shows good quality but the network is very limited, mainly in North Hemisphere. Directional wave spectra from satellites (SAR, CFOSAT) has interesting coverage but the data have issues with quality (scale 1).

SWH data are well organized and publicly available from satellites and most (but not all) buoy networks. Access and use of consistent quality flags, metadata and common compact definition for directional spectra are needed. Directional spectra data are not always accessible.

Sea Ice	
ECV Products covered by this sheet	Sea Ice Concentration Sea Ice Extent Sea Ice Thickness Sea Ice Drift
Adequacy of the Observational System Assessment	3 Sea Ice Concentration is mature, but improvements needed in the summer melt season. While Climate Data Records (CDR) for sea-thickness are mature in Northern Hemisphere they remain experimental in Southern Hemisphere. Too few sustained CDRs exist for Sea Ice Drift, overall, they are limited form and at coarse resolution, but existing CDRs are useful. Polar satellite altimetry missions are science missions: not ideal for long-term monitoring
Availability and Stewardship Assessment	4 In Europe, ESA CCI, EUMETSAT OSI SAF, and Copernicus (C3S and CMEMS) are committed to fulfil this role. North America: NSIDC DAAC and NOAA CDR programme. However In situ monitoring is driven by research agencies, and data is scattered across many data portals.
Networks	Moorings (Coordination: OceanSITES, but many polar sites are inactive or closed.) Drifters: somewhat coordinated Arctic (and some Antarctic) data access by DBCP, IABP and IPAB. No coordinated or sustained deployment programme. AUVs (no network; propelled AUV and gliders are used only locally / regionally, and not for long-term monitoring) Aircraft (e.g. Operation Ice Bridge - now terminated), ESA CryoVeX.
Satellites	US SSMIS and ICESat-2, JAXA AMSR2, ESA SMOS and Cryosat-2. Also, scatterometers (Metop ASCAT), and SARs (Sentinel-1, RCM).
Models, Reanalysis etc.	Daily sea ice products (extent, concentration): NSIDC CDR, EUMETSAT OSI SAF, ESA CCI, EU C3S and EU CMEMS TB (brightness temp): NSIDC, JAXA, CLASS, RSS inc, CM SAF. Ice Motion: NSIDC, IFREMER/CMEMS, EUMETSAT OSI SAF (2021), JPL Ice Thickness: ESA CCI and EU C3S, NSIDC Ice Edge: EU C3S.

Discussion:

Sea Ice Concentration observations for climate are mature but improvements are needed in the summer melt season (melt-ponds). For Sea Ice Thickness, the threshold is satisfied (0.5 m per month and 25 km) but not the target. The Climate Data Record (CDR) is mature in Northern Hemisphere, but experimental in Southern Hemisphere. Polar satellite altimetry missions are science missions, which are not ideal for long-term monitoring. For Sea Ice Drift, too few CDRs exist, and are overall provided in limited form and at coarse resolution, but the existing CDRs are still useful. The adequacy of Sea Ice observations from satellites depends heavily on which ECV Product is considered. Microwave radiometry for sea-ice (concentration, drift, type) is generally well covered and secured at a coarse resolution, but securing higher resolution and lower frequencies is required (EU CIMR, AMSR3, WSF-M, etc.). SAR (C-band) is well covered (Sentinel-1, RCM, Sentinel-1NG) in the Arctic. In Antarctic, the coverage is not as good, but dedicated missions (e.g. NISAR) can help in the future. High-inclination altimetry is still problematic with only two research satellites flying (CryoSAT2 and ICESat2). In the future, European missions CRISTAL & CIMR would bring operational monitoring capabilities out to the late 2020s (if confirmed). Likewise, Sentinel-3A/B altimeter data may be optimised for sea ice in the future (not usable up to now). As long as CRISTAL is not confirmed, the high-latitude sea-ice thickness monitoring is at risk (when CryoSat and ICESat2 stop working) and a gap might occur if CRISTAL is delayed. Visible and IR are generally well covered although twilight acquisitions are not always secured (e.g. S3 OLCI). Data availability and stewardship are very good. In Europe, ESA CCI, EUMETSAT OSI SAF, and Copernicus (C3S and CMEMS) are firmly committed to fulfil this role and in North America, the NSIDC DAAC and NOAA CDR programmes provide valuable services. In situ monitoring is currently driven to a great extent by research agencies, and there is not a single-entry point to the data, they are scattered across many data portals.

Ocean Heat Flux	
ECV Products covered by this sheet	Net Surface Heat Flux; Latent Heat Flux; Sensible Heat Flux; Net Shortwave Radiation; Downward Shortwave Radiation; Upward Shortwave Radiation; Net Longwave Radiation; Upward Longwave Radiation; Downward Longwave Radiation; Photosynthetically Available Radiation
Adequacy of the Observational System Assessment	2 Satellite-based net surface heat flux is limited by present inability to measure near-surface and boundary layer temperature and humidity with required accuracy. Global products of air-sea heat fluxes generally must rely upon NWP model output for near-surface air-temperature and humidity. In situ bulk heat fluxes meet all accuracy requirements, but coverage is extremely sparse
Availability and Stewardship Assessment	3 Some global products are publicly available with good documentation. In general, in situ fluxes are available through individual projects and some are publicly available and well documented, and other in situ fluxes are not.
Networks	Underway Marine Meteorology (Coordination: Volunteer Observing Ships network / JCOMM) Flux moorings: OceanSITES, PMEL GTMBA; In Situ Direct Covariance Fluxes: SeaFlux for R/V and older buoy datasets, and OOI for direct covariance fluxes from current operational moorings
Satellites	Radiation: CERES, EBAF; Bulk turbulent: HOAPS3.2; IFREMER V4; J-OFURO3; OAFlux HR; SEAFLUX V3
Models, Reanalysis etc.	NWP: CFSR; ERA-Interim; ERA5; JRA-55; MERRA2; Blended: CORE.2; JRA-55-do; OAFlux; Ship-based: NOC 2

Discussion:

Satellite-based net surface heat flux is limited by present inability to measure near-surface and boundary layer temperature and humidity with required accuracy. This affects both radiative fluxes and derived bulk latent and sensible heat fluxes. Thus, global products of air-sea heat fluxes generally must rely upon NWP model output for near-surface air-temperature and humidity. In situ bulk heat fluxes meet all accuracy requirements, but coverage is extremely sparse. Direct covariance heat flux estimates have better accuracy than bulk fluxes but are much sparser than the sparse bulk flux observations. While some supporting variables meet the resolution requirement, ocean surface heat flux products can only meet the required resolution through use of a NWP model. In situ ocean surface heat flux observations meet the temporal resolution requirement, but not the spatial resolution. Some global products are publicly available with good documentation. SeaFlux acts as a partial repository for in situ direct covariance and bulk surface fluxes. In general, in situ fluxes are available through individual projects and some are publicly available and well documented, and other in situ fluxes are not.

A.b.ii Biogeochemistry

Inorganic Carbon	
ECV Products covered by this sheet	Surface ocean partial pressure of CO_2 (pCO_2) Subsurface ocean carbon storage (DIC/TA, pH) Ocean acidity (pH)
Adequacy of the Observational System Assessment	2 There is a large range in adequacy of the data. The coverage and accuracy of inorganic carbon in surface layers in the open ocean of the northern hemisphere is good but is low in others.
Availability and Stewardship Assessment	4 Availability and stewardship of data collected as part of global observing systems is good, but their QC rely largely on voluntary services.
Networks	Ship-based Repeat Hydrography: GO-SHIP Ship-based Underway Observations: SOOP-CO_2 Ship-based Fixed-point Observations Moored Fixed-point Observatories: OceanSITES Profiling floats: Biogeochemical Argo Autonomous Underwater Vehicles: OceanGliders Autonomous Surface Vehicles: no coordinated network
Satellites	None
Models, Reanalysis etc.	Global Ocean Data Analysis Project (GLODAPv2): http://glodap.info/ Surface Ocean CO_2 Atlas (SOCAT): http://www.socat.info Lamont-Doherty Earth Observatory (LDEO) Climatology: https://www.nodc.noaa.gov/ocads/oceans/LDEO_Underway_Database/ Biogeochemical Argo: http://biogeochemical-argo.org/data-access.php

Discussion:

Collections of surface ocean pCO_2 data have been made largely by ship-based underway measurements and augmented with fixed-point measurements by moorings. Coverage of data in space and time is good in the open oceans of the northern hemisphere but is low in many regions of the vast oceans in the southern hemisphere and in coastal zones in light of the resolutions required. These data have been submitted by Principal investigators, quality-controlled, compiled in SOCAT (the data product of CO_2 in surface ocean endorsed by the Global Ocean Observing System), opened to the public, and updated regularly. However, the activity of data quality control has been made voluntarily and its continuation is thus vulnerable. Several gridded data products of global monthly pCO_2 have been reconstructed from SOCAT with a variety of interpolation-extrapolation methods including neural network-based ones. These data products are also publicly available and have been used to capture phenomena such as the variability of air-sea CO_2 flux and ocean acidification. Data of inorganic carbon sub-variables (DIC, TA, pH) in the ocean interior have been collected through the ship-based hydrographic observing network GO-SHIP and at shipboard fixed-point time-series stations with high quality. Data coverage by GO-SHIP is global, from surface to near-bottom, and resolution on selected repeat sections are good, but their temporal resolution is typically low. Their data have been integrated, quality-controlled, compiled in GLODAP (the data product of ocean carbon and biogeochemistry in the ocean interior endorsed by the Global Ocean Observing System), opened to the public, and updated regularly. However, the activity of data quality control of GLODAP has been made with research funding and is not sustainable. There are several ship-based time-series stations around the world that provide high-quality data of inorganic carbon with high-frequency that meet the goal of temporal resolution. The coordination of these time-series measurements is in progress, but data sets have not been integrated in a certain data base. Development of the observing network of BGC-Argo, which enables high frequency measurements of pH that meet the goal of required temporal resolution, is in progress on a research basis and in pilot stage. To date, the total number of active BGC-Argo profiling floats installed with pH sensor is growing but remains 170, which is less than half of total active BGC-Argo (399) (April 2020). It has been proposed to deploy more BGC-Argo floats globally and keep the total of 1000 profiling floats installed with BGC sensors, including that of pH, in operation to complement largely the existing observing networks collecting data of biogeochemistry. Data management of pH observations performed by BGC-Argo is yet to be established for Data Assembly Centres. Sensor pH measurements on other emerging autonomous vehicles such as ocean gliders and Saildrones that are capable of monitoring from the coastal zone to the open ocean are currently at the concept level and in progress.

Nitrous Oxide	
ECV Products covered by this sheet	Interior ocean N_2O Air-sea N_2O flux
Adequacy of the Observational System Assessment	2 Data are available globally but their number is very limited. Uncertainty of measurement needs improvement by networking the observations.
Availability and Stewardship Assessment	3 Availability of data collected is good, but resources to process these data are insufficient.
Networks	Ship-based Repeat Hydrography: GO-SHIP Ship-based Fixed-point Observatories: no coordinated network Ships of Opportunity: no coordinated network
Satellites	None.
Models, Reanalysis etc.	MarinE MethanE and NiTrous Oxide (MEMENTO) database: https://memento.geomar.de

Discussion:

Measurements of N_2O have been made globally in the ocean surface layer and in the interior of both the open ocean and in coastal zones. However, they are limited to small number of underway measurements on research vessels and on Voluntary Observing Ships, measurements at depths in a very small number of GO-SHIP sections, a small number of time-series stations, and some research campaign observations, showing severe under-sampling in many regions and in time. Extensive measurements of N_2O over the global ocean have been precluded by the constraints of human and financial resources. An underwater sensor for N_2O has become available recently. These data sets of shipboard measurements or sampling have been archived in a quality-controlled data base "MarinE MethanE and NiTrous Oxide (MEMENTO)" and made open to the public. However, the data sets are not yet cross-calibrated. Technological improvement has enabled the uncertainty of underway N_2O measurements to potentially meet the goal of the required measurement uncertainty, but a mechanism for inter-calibration, standard post-processing operations and so on are needed to make the data sets comparable to each other within the required uncertainty. Standard operating protocols for measuring N_2O in discrete seawater samples and with continuous underway systems are available. The establishment of a harmonized N_2O Observation Network (N_2O-ON) combining surface data of underway measurements and discrete data at depths from various platforms have been proposed (Bange et al., 2019). The network will help enhance the high-quality measurements with calibrated techniques and their availability both in open ocean and in coastal zones, facilitating the understanding of variability of N_2O in space and time and thereby its air-sea flux and the impact of climate change on it.

References:

Bange, H. W., D. L. Arévalo-Martínez, M. de la Paz, L. Farías, J. Kaiser, A. Kock, C. S. Law, A. P. Rees, G. Rehder, P. D Tortell, R. C.Upstill-Goddard and S. T. Wilson, 2019: A harmonized nitrous oxide (N_2O) ocean observation network for the twenty-first century, Frontiers in Marine Science, 6.

Nutrients	
ECV Products covered by this sheet	Nitrate Silicate Phosphate
Adequacy of the Observational System Assessment	3 Data are available from global oceans with increasing level of quality but their temporal resolution is generally low in most regions.
Availability and Stewardship Assessment	4 Availability of data collected as part of global observing systems is good, but resources to process these data are insufficient.
Networks	Ship-based Repeat Hydrography: GO-SHIP Ship-based Underway Observations: SOOP-CO_2 Ship-based Fixed-point Observatories: no coordinated network Moored Fixed-point Observatories: OceanSITES Profiling floats: Biogeochemical Argo Autonomous Underwater Vehicles: OceanGliders
Satellites	None
Models, Reanalysis etc.	Global Ocean Data Analysis Project (GLODAPv2): http://glodap.info/

Discussion:

Data of nitrate, nitrite, phosphate, and silicic acid have been collected in the ocean interior through discrete water sampling at depths in the ship-based hydrographic observing network GO-SHIP and at shipboard fixed-point time-series stations. There were initially data quality issues with analyses of these nutrients. However, development of Reference Material for nutrients analyses has raised the level of data quality control and is improving the compatibility of nutrient data collected in different regions and times. As discussed for the Inorganic-Carbon Requirements, data coverage by GO-SHIP is global, from surface to near-bottom, and spatial resolution on selected repeat sections is good, but temporal resolution is typically low. The data have also been submitted together with other variables by Principal investigators, quality-controlled, compiled in GLODAP, opened to the public, and updated regularly. However, the activity of data quality control of GLODAP has been made with research funding and is not sustainable. Sensors for nitrate measurements are commercially available, and the observing network of BGC-Argo installed with nitrate sensors is in progress on a research basis and is now at pilot stage. BGC-Argo enables high-frequency measurements of nitrate in the open ocean and in marginal seas that meet the goal of the required temporal resolution. The total number of active BGC-Argo floats installed with nitrate sensor is growing but remains 180, which is less than half of total BGC-Argo (April 2020). It has been proposed to deploy more BGC-Argo floats globally and keep the total of 1000 floats installed with BGC sensors, including that of nitrate, in operation to complement the existing observing networks collecting data of biogeochemistry. Data management of nitrate observations performed by BGC-Argo is yet to be established for Data Assembly Centres. Observing nitrate by ocean gliders network is also technically feasible but is still at concept level.

Ocean Colour	
ECV Products covered by this sheet	Chlorophyll-a concentration Water leaving radiance
Adequacy of the Observational System Assessment	3 Data is generally within requirement. Comparison across satellites sometime suggest larger uncertainties.
Availability and Stewardship Assessment	4 Data is available and is free. Uncertainties are still lacking for some products.
Networks	Moored Fixed-point Observatories: MOBY/BOUSSOLE + other Tower Fixed-point Observatories: AERONET-OC Profiling floats: Biogeochemical Argo
Satellites	Ocean Colour Radiometry Virtual Constellation (OCR-VC)
Models, Reanalysis etc.	Ocean Biology Processing Group (OBPG): https://oceandata.sci.gsfc.nasa.gov/ Ocean Colour Climate Change Initiative (OC-CCI): https://www.oceancolour.org/ CMEMS Ocean Color Thematic Assembling Center: http://marine.copernicus.eu/about-us/about-producers/oc-tac/ GlobColour: http://www.globcolour.info/

Discussion:

The state of ocean colour observations is good with several missions covering the globe and providing data within day of measurements. Data is available on near daily and ~1km^2 resolution particularly when merging several satellite products (e.g. Sentinel 3, MODIS and VIIRS). Cloud cover reduces coverage, particularly in regions and season of high cloudiness. For chlorophyll, products at 4 km and 8-day resolution are covering the majority of the glob (except at time regions of winter night.) Data quality is assessed regularly via supported in situ network dedicated to validation. Data in time/regions where the sun angle is low (near and at polar night) are currently not available. This could be resolved via ocean Lidar. Nearshore data (within 4 km of coasts) is currently not routinely available (the top of the atmosphere data IS available) despite exiting sensors (Sentinel 2ab and Landsat 8) which have been shown to be able to provide quality near shore data.

Oxygen	
ECV Products covered by this sheet	Dissolved Oxygen concentration
Adequacy of the Observational System Assessment	3 High-quality data are available from global oceans but their temporal resolution is generally low in most regions.
Availability and Stewardship Assessment	4 Availability of data collected as part of global observing systems is good, but resources to process these data are insufficient.
Networks	Ship-based Repeat Hydrography: GO-SHIP Profiling floats: Biogeochemical Argo Moored Fixed-point Observatories: OceanSITES Autonomous Underwater Vehicles: OceanGliders Ship-based Fixed-point Observatories: no coordinated network Ship-based Underway Observations: no coordinated network
Satellites	None.
Models, Reanalysis etc.	Global Ocean Data Analysis Project (GLODAPv2): http://glodap.info/

Discussion:

High-quality data of dissolved oxygen (DO) in the ocean interior that fulfil the threshold level of the required measurement uncertainty have been collected through discrete water sampling at depths and subsequent Winkler titration in the ship-based hydrographic observing network GO-SHIP and at shipboard fixed-point time-series stations. As discussed in Inorganic-Carbon Requirements, data coverage by GO-SHIP is global, from surface to near-bottom, and spatial resolution on selected repeat sections is good, but temporal resolution is typically low. The data have also been integrated with other variables collected together, quality-controlled, compiled in GLODAP, opened to the public, and are updated regularly. However, the activity of data quality control of GLODAP has been made with research funding and is not sustainable. On the other hand, several time-series stations provide high-frequency data that are good enough to assess the trend of DO, although they are yet to be coordinated among each other. The DO sensor is the most mature sensor among those to measure biogeochemical variables in the ocean. The number of vertical high-resolution profiles of DO measured with sensor installed with Conductivity-Temperature-Depth profilers on hydro-casts, being calibrated with data from discrete samples, is increasing. Development of the observing network of BGC-Argo installed with DO sensor is in progress on a research basis and is now at pilot stage. BGC-Argo enables high-frequency measurements of DO in the open ocean and in marginal seas that meet the goal of required temporal resolution. Many of the BGC-Argo floats have been deployed in regional programs, such as those in the Southern Ocean, North Atlantic, Indian Ocean and Mediterranean Sea. The total number of active BGC-Argo floats is 399 (April 2020), which is 10% of core Argo array, and DO sensors have been installed with most of these floats. The calibration technique of DO sensor that uses oxygen measurements in the atmosphere has been developed for practical use, and data management of DO observations performed by BGC-Argo has been established for Data Assembly Centres. It has been proposed to deploy more BGC-Argo float globally and keep the total of 1000 profiling floats installed with BGC sensors, including that of oxygen, in operation to complement largely the existing observing networks collecting data of biogeochemistry. However, human and financial resources to deploy 1000 of BGC-Argo floats and process their data are currently not available. Observing networks of ocean gliders are also developing from concept to pilot level. The gliders installed with biogeochemical sensors including that of DO are commercially available and a DO observing network is technically feasible. A data portal that enables DO data from variety of observing networks to become more accessible is in preparation under the auspices of IOCCP/GOOS BGC Panel to help better assess the changes in DO in global oceans including both open oceans and coastal zones.

Transient Tracers	
ECV Products covered by this sheet	CFC-12 CFC-11 SF_6 ^{14}C
Adequacy of the Observational System Assessment	2 Data are available from global oceans but their uncertainty is higher than that required.
Availability and Stewardship Assessment	4 Availability of data collected as part of global observing systems is good, but resources to process these data are insufficient.
Networks	Ship-based Repeat Hydrography: GO-SHIP
Satellites	Nond
Models, Reanalysis etc.	Global Ocean Data Analysis Project (GLODAPv2): http://glodap.info/ Tritium and helium data compilation: https://www.nodc.noaa.gov/ocads/data/0176626.xml

Discussion:

Data of chlorofluorocarbons (CFC-12, CFC-11), sulfur hexafluoride (SF6), and radiocarbon isotopic ratio (Δ14C) of dissolved inorganic carbon have been collected in the ocean interior through discrete water sampling at depths in the ship-based hydrographic observing network GO-SHIP. As discussed in Inorganic-Carbon Requirements, data coverage by GO-SHIP is global, from surface to near-bottom, and spatial resolution on selected repeat sections is good. Temporal resolution, usually decadal, meets the threshold temporal resolution assigned for these variables. No sensor measurements are available for transient tracers. Their data have also been collected together with other variables, quality-controlled, compiled in GLODAP, opened to the public, and updated regularly. However, the activity of data quality control of GLODAP has been made with research funding and is not sustainable. For CFC-12 and CFC-11, uncertainty of data in GLODAP is 5% after second level quality control, which is still larger than the required measurement uncertainty of 1%.

A.b.iii Ecosystems

Plankton	
ECV Products covered by this sheet	Zooplankton biomass, Zooplankton diversity
Adequacy of the Observational System Assessment	2 Spatial and temporal resolution very low. From in situ sampling only.
Availability and Stewardship Assessment	2 Some good zooplankton datasets are available including the Continuous Plankton Recorder program but coverage patchy and biased away from tropical areas. New automated imaging and genomic technologies plus greater diversity of mobile platforms anticipated to lead to major changes over next 10 years.
Networks	Ship-based: Global Alliance of Continuous Plankton Recorder Surveys (GACS; http://www.globalcpr.org/). Autonomous platforms (Biogeochemical Argo; https://biogeochemical-argo.org); Monitoring Networks (HAEDAT; http://haedat.iode.org) Phytoplankton data available from ocean time series stations: HOT, BATS, CARIACO, others
Satellites	Ocean Colour Virtual Constellation
Models, Reanalysis etc.	Data products: NOAA Coastal and Oceanic Plankton Ecology, Production, and Observation Database (COPEPOD) GACS CalCOFI JFRA HAEDAT OBIS

Discussion:

Plankton is a broad category that includes both plant-like photosynthetic organisms and all animal or animal-like organisms whose dispersal in the ocean is dominated by physical processes such as ocean currents. The zooplankton includes protozoans and metazoans. Many of the ecosystem services supporting human activities in coastal ocean waters depend on photosynthetic microorganisms representing the lowest trophic levels in the ocean, fixing carbon and producing oxygen. High-biomass and/or toxic proliferations of some specific cells (or "Harmful Algal Blooms" or HABs), are known to cause harm to aquatic ecosystems, including plants and animals, and to humans via direct exposure to water-borne toxins or by toxic seafood consumption. Zooplankton are the food for many mammals, birds, fish, corals and other invertebrates including zooplankton. They are consumers of the phytoplankton and can also be carnivorous. They are an intermediary between primary productivity and higher trophic levels. They also play a key role in defining the chemistry of the ocean by recycling nutrients and carbon in near-surface waters of the ocean and by delivering these materials to deeper ocean waters through defecation and through daily and ontogenetic migration. Phytoplankton and zooplankton biomass are important and commonly used variables to evaluate trophic state, fisheries potential, and ecosystem health. Today, it is still impractical to monitor the number and diversity of organisms in mid- to upper trophic levels of the food web. Yet, the abundance of many fish species, sea birds, and marine mammals on continental shelves is critically tied to fluctuations in the abundance of smaller planktonic organisms driven by climate-scale changes. The plankton can be extremely diverse. Phytoplankton diversity is often based on functional groupings and traits (e.g. nitrogen fixing, toxic, prokaryotic vs. eukaryotic), but species diversity becomes critical when for example identifying HABs. Plankton diversity refers to the number of species, taxonomic composition, or community structure within a region. Zooplankton diversity influences ecosystem health and productivity through trophic links. In turn, zooplankton diversity is sensitive to environmental pressures such as climate change, including ocean acidification, warming and deoxygenation. The abundance and functional types of zooplankton, even their presence or absence, are accepted indicators of marine ecosystem responses to climate change. Ichthyoplankton surveys, focussing on larval fish species, can also be informative for zooplankton diversity. Phytoplankton biomass is inferred from the presence of chlorophyll-a, allowing for global synoptic assessments using ocean colour as well as routine deployment of fluorometers in situ. Zooplankton biomass is most commonly measured as wet weight, dry weight, and also as carbon content, nitrogen content, protein and lipid content. Recent approaches also include acoustic and optical detection of zooplankton biomass. Observation and measurement of phytoplankton and zooplankton abundance and diversity are obtained through various methods, which traditionally have involved the use of vertically or horizontally towed nets (with mesh sizes ranging from less than 100 μm up to 500 μm) but more recently include instruments such as imaging flow cytobots and video plankton recorders which collect an image of the organisms in situ. In terms of consistent and most extensive sampling effort, the best example to date is that of the Continuous Plankton Recorder (CPR) which collects observations along the track of ships of opportunity in some areas of the world. CPR surveys are brought together through the Global Alliance of CPR Survey (GACS). Net tow sampling is conducted in extensive and long-standing projects by various regional fisheries and oceanography surveys (e.g. the California Cooperative Oceanic Fisheries Investigations, CalCOFI). Some collections are conducted as part of research and fisheries programs, some of which are part of regional Ocean Observing Systems (OOS). There are also numerous national plankton monitoring programs, but international coordination such as the Harmful Algae Event Database (HAEDAT) is limited and typically targets high-impact species such as HABs. With respect to specific methods/tools, there is a need for coordination and standardization of data for global comparisons. Techniques may be developed that can bring together the different approaches and methodologies and may yield useful metrics despite challenges in merging differently acquired data. A challenge for this EOV to become fully mature is to secure funding to fill the geographical observation gaps and support capacity building for sample processing, since taxonomic skills are necessary to generate diversity measurements.

Marine Habitat Properties	
ECV Products covered by this sheet	Coral reefs
Adequacy of the Observational System Assessment	2 There remains uncertainty around global shallow tropical hard coral reef cover. There are no reliable global coral diversity estimates. Visual surveys, moored instrument arrays, spatial hydrographic and water quality surveys, satellite remote sensing, and hydrodynamic and ecosystem modelling that was collectively referred to as the International Network of Coral Reef Ecosystem Observing Systems (I-CREOS). Efforts are more advanced in wealthy developed nations. Cold water coral communities are an emerging area of concern given potential human impacts (fisheries, mining), climate change (deep water warming, acidification).
Availability and Stewardship Assessment	3 Coral Reef data reporting coordinated globally by Global Coral Reef Monitoring Network through International Coral Reef Initiative. Updated global assessment due 2020 has had to deal with regional differences in data collection. Ongoing collaboration with Allen Coral Atlas will improve global consistency of future assessments. Cold water coral communities are the focus of plans for a deep ocean observing strategy and initiatives
Networks	GCRMN NOAA NCRMP NOAA Pacific RAMP The Global Coral Reef Monitoring Network International Network of Coral Reef Ecosystem Observing Systems (I-CREOS).
Satellites	Skysat imagery (Planet Labs: https://www.planet.com), Sentinel-2, GOES-R satellite series and NOAA-20's Visible Infrared Imaging Radiometer Suite (VIIRS), Landsat-8 and GF-1, Millennium Global Coral Reef Map (WCMC)
Models, Reanalysis etc.	Data products: NOAA's Coral Reef watch program

Discussion:

Hard corals are the principal architects of coral reefs, supporting the high biodiversity and productivity of shallow, tropical coral reef systems. Coral reefs are among the most biodiverse and highly valued ecosystems worldwide for their ecosystem goods and services. They are also one of the most threatened ecosystems of the world. Many people that depend on coral reefs live in low-income tropical countries. Healthy reefs are a foundation for their livelihood and food security; some products derived from coral reefs have global markets, including ornamental fish, cement, and tourism and recreation.

Climate change, ocean acidification, fisheries, pollution, and coastal development are all significant threats to coral reefs. Hard corals are particularly vulnerable because they are slow-growing and susceptible to stress, particularly when there are synergies between natural and anthropogenic stresses. The health and areal extent of the hard coral community within a reef are direct indicators of the ability of a system to sustain the diversity of associated species, productivity, and valuable ecosystem services. Multiple measures give fundamental information on the health of a coral reef: live hard coral cover and the areal extent of a reef are the most important indicators of whether a reef is in a coral-dominated state or not; the composition and diversity of coral taxa is an important index of reef health; coral condition (e.g. bleaching, disease) gives fundamental information on the health of a reef; the size class structure (and recruitment) of hard corals gives fundamental information on the resilience, disturbance history and recovery potential of a reef. 'Hard' and 'soft' corals are key taxonomic groups dominating hard and some soft substrates in subtidal habitats from the shallows to the deep ocean, and from the equator to polar regions. This wide range of habitats can be grouped into three principal assemblages: tropical hard coral communities (coral reefs), soft coral-dominated habitats, and deep- or cold-water coral communities. This specification sheet is focused on the former – tropical hard coral communities – to meet the immediate need there. Parallel specification sheets have been developed for other hard- and soft-coral dominated habitats.

Marine Habitat Properties	
ECV Products covered by this sheet	Mangrove Forests
Adequacy of the Observational System Assessment	2 Giri et al. (2011) estimate that mangrove forests are approximately 12% smaller than the most recent estimate by the FAO
Availability and Stewardship Assessment	3 Remote sensing data coordinated globally by Global Mangrove Watch. Additional data reported by 223 countries (133 with mangroves) as part of FAO's Global Forest Resource Assessment 2020. In situ calibration and verification generally lacking. Regional and global diversity assessments are lacking.
Networks	Global Mangrove Watch Global Mangrove Alliance Ramsar Convention on Wetlands CGMFC-21 National Commission of Biodiversity Mexico Australian Mangrove and Salt Marsh Network GEO-Wetlands working group on mangroves French Mangrove Observation Network The K&C Global Mangrove Watch
Satellites	Landsat TM Imagery, GF-1, Worldview3, SPOT, ASTER, PolSER, IKONOS-2, QuickBird, LiDAR, OBIA, InSAR, Sentinel 1 and 2
Models, Reanalysis etc.	Data products: Global Mangrove database (FAO 2007) CGMFC-21 (Hamilton 2016) https://www.globalmangrovewatch.org/ Ramsar Convention on Wetlands. (2018). Global Wetland Outlook: State of the World's Wetlands and their Services to People. Gland, Switzerland: Ramsar Convention Secretariat. https://www.global-wetland-outlook.ramsar.org/

Discussion:

Mangroves are intertidal, tree-dominated wetlands distributed along tropical and subtropical coastlines and estuaries around the world. Under the influence of ocean tides, these forests are periodically inundated with waters ranging from slightly brackish to hypersaline. Trees in this environment must survive in dynamically flooded, anoxic, and saline soils, and the adaptations that they employ to tolerate the physiological challenges provided by these conditions distinguish the evolutionarily diverse mangrove plant taxa (McKee 1996; Scholander et al., 1962). Mangroves mediate key biogeochemical fluxes (Kristensen et al., 2008), are highly productive (Bouillon et al., 2008), and support rich biological communities (Nagelkerken et al., 2008). The functions performed by these ecosystems often translate into valuable services for humans. They protect coastal communities from erosion and damage from storm surges (Das and Vincent 2009), filter terrestrial run-off (Ewel et al., 1998), supply timber, and generate significant revenue through ecotourism and biodiversity conservation (Costanza et al., 1997). Mangroves provide critical nursery habitat for marine species around the world (Hutchinson et al., 2015). This nursery function adds considerable value to coastal fisheries, with each hectare of fringe mangrove in the Gulf of California, Mexico, estimated to provide $37,500

(U.S.) per year in fisheries production (Aburto-Oropeza et al., 2008). Globally, mangroves sequester and store more carbon than almost any other type of ecosystem (Donato et al., 2011). Estimates of the total amount of carbon stored by mangroves range from 3 Pg C (Hutchinson et al., 2014) to 20 Pg C (Donato et al., 2011 estimate of 1,000 tons C/ha). Despite growing appreciation for the economic value of mangroves, these forests are severely threatened, with about 1% destroyed each year globally (Duarte et al., 2013). Unsustainable coastal forestry, agriculture, aquaculture, and urbanization and infrastructure development, along with increasing sea level, have already resulted in the cumulative loss of more than 35% of global mangrove cover (Valiela et al., 2001). In addition to these rapid anthropogenic declines, mangrove forests are naturally dynamic, made up of species adapted to aggressive colonization of open intertidal habitat and capable of shifting their distributions with changes in coastal geomorphology (Thom, 1967). Taking into account their ecological and social value, dynamic distributions, and severe recent losses to human impacts, mangroves require urgent management, including restoration, and monitoring. Several studies have estimated mangrove area (Giri et al., 2011, Hamilton & Casey 2015) and biomass (Hutchinson et al., 2014), but the dynamic distribution of this biome requires a globally integrated and consistent approach based on high temporal and spatial resolution data. Global mangrove area was estimated in the year 2000 to cover 137,760 km2 in 118 countries, with more than 50% of this area in six countries (Indonesia, Australia, Brazil, Mexico, Nigeria, and Malaysia) (data from the year 2000; Giri et al., 2011). In a more recent analysis, global forest area was recently estimated in the year 2012 as 81,684 km2 in areas delineated as mangrove forest and 167,387 km2 within wider mangrove biome with only 20 countries containing greater than 80% of the global mangrove holdings. (Hamilton & Casey 2016). While researchers in the countries with large areas of mangroves are contributing valuable information, the value of this information could be extended with support from international initiatives.

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Marine Habitat Properties	
ECV Products covered by this sheet	Seagrass beds
Adequacy of the Observational System Assessment	2 There is high uncertainty around how much seagrass exists globally, especially in sub-tidal environments and particularly within the tropics. "The spatial extent of seagrass remains difficult to assess using conventional remote sensing tools, particularly in either turbid, deep environments or shallow waters where density can be low. " Hays et a. 2018
Availability and Stewardship Assessment	3 Efforts are underway to enable global coordination of in situ data and dataflows. At present there are no reliable global estimates of seagrass cover and health. The expectation is coordination between different seagrass monitoring groups will produce substantial improvement over previous 2018 global dataset from 128 countries available through WCMC. Gaps remain in regional and global coverage.
Networks	Seagrass-watch SeagrassNet Smithsonian MarineGEO Local and regional programs Ocean Heat Index MarineGEO
Satellites	Landsat-8TM/EM, EO-1 ALI and Hyperion and IKONOS, Sentinel 2; others
Models, Reanalysis etc.	Data products: ZosTDB - the first open access transcriptomics portal for the Australian seagrass Zostera muelleri eATLAS Seagrass Dataset – CAMRIS Effrosynidis, 2019 for seagrass from the Mediterranean Sea. Ramsar Convention on Wetlands. (2018). Global Wetland Outlook: State of the World's Wetlands and their Services to People. Gland, Switzerland: Ramsar Convention Secretariat. https://www.global-wetland-outlook.ramsar.org/ United Nations Environment Programme, 2020. Out of the Blue: The Value of Seagrasses to the Environment and to People. Nairobi: UNEP.

Discussion:

Seagrasses are vascular plants that that can reproduce by flowering (sexually) and also spread asexually through rhizome extension. They can form dense, submerged meadows in coastal and estuarine waters. There are approximately 72 seagrass species that belong to four major groups. Seagrasses are often highly productive and provide essential habitat and nursery areas for many finfish, shellfish, charismatic megafauna, and species of concern, including sea turtles, dugongs and manatees. Seagrasses also help stabilize and protect coasts by binding underlying sediments. They contribute to good water quality by trapping sediment and absorbing nutrient runoff. Seagrasses are recognized as a “blue” carbon storage system, by fixing inorganic carbon via photosynthesis and storing and sequestering it in seagrass rhizomes and associated sediments. Although coastal vegetated habitats comprise only 0.2% of the world ocean, they contribute >10% of all carbon buried annually in the sea. Vigorous photosynthesis by seagrasses can also reduce the acidity of surrounding water by removing dissolved carbon dioxide. Seagrasses are declining worldwide as a result of coastal development, nutrient loading that leads to poor light conditions on the sea floor, climate change, and cascading impacts of fishing. Loss of resources, including biological habitats such as seagrass meadows, is a major concern for governments worldwide and emerges as a major societal pressure motivating international conventions and bodies focused on ocean environment and resources. Regular monitoring of seagrass cover and ecosystem structure will be useful to modelling coastal and reef fishery production, the global carbon cycle, and tracking impacts of climate change and coastal eutrophication.

Marine Habitat Properties	
ECV Products covered by this sheet	Macroalgal canopy cover and composition
Adequacy of the Observational System Assessment	3 Global at concept level; Regional at pilot level. Spatial and temporal resolution typically low.
Availability and Stewardship Assessment	3 Regional datasets in good condition. Work identified to develop global data systems and workflows.
Networks	GOMON KEEN PISCO SARCE IMOS
Satellites	No oversight group established. Satellite data have been used for offshore floating macroalgae (e.g. Sargassum) but may be of insufficient resolution for coastal macroalgae.
Models, Reanalysis etc.	Data products: KelpTime database. http://bit.ly/kelptime

Discussion:

Macroalgal forests (dominated by kelp and fucoid brown algae) are iconic on rocky reefs around the world's temperate coasts. These highly diverse ecosystems provide many important functions and services including high primary production, provision of nursery areas, human food resources, and protection from coastal erosion. Macroalgal forests are vulnerable to global threats such as ocean warming and to regional stressors resulting from intensifying human activities along the coast, including habitat degradation, pollution, eutrophication, and spread of invasive species. The compounded effects of global and regional stressors are eroding the resilience of these systems, making regime shifts and population collapses more likely. Regime shifts such as the replacement of macroalgal canopies by less productive, low-diversity assemblages of turf-forming algae and barren habitat are increasingly observed on many reefs around the world. Vulnerability begets sensitivity and macroalgal forests respond quickly to deteriorating environmental conditions, potentially allowing the early detection of impending regime shifts. Furthermore, their broad distribution from boreal to temperate regions allows for comparison of latitudinal trends and the tracking of geographic shifts in species ranges.

Macroalgal forests provide a sensitive and well understood indicator of changing coastal marine environments, and are also models for understanding more complex interactions influencing marine communities, building on the detailed experimental knowledge and basic ecological understanding accumulated for these systems over decades.

A.c Terrestrial

A.c.i Hydrology

Evaporation from Land	
ECV Products covered by this sheet	Evaporation from Land (latent heat flux or '*evapotranspiration*') Evaporation Components: Transpiration Bare Soil Evaporation Interception Loss
Adequacy of the Observational System Assessment	3 Uncertainties are frequently unreported, validation data are scarce, indirect retrievals based on model assumptions and there is a frequent reliance on reanalysis forcing
Availability and Stewardship Assessment	4 Most datasets are available in the corresponding data archives of the development teams. Most datasets are only occasionally updated. Lag time of a t least a few months.
Networks	FLUXNET (evaporation measurements from eddy-covariance sensor) SAPFLUXNET (transpiration measurements from sap flux sensors)
Satellites	Aqua, Terra, CERES, SMOS, SMAP, AVHRR, etc.
Models, Reanalysis etc.	The following observational global datasets exist (non-exhaustive): Moderate Resolution Imaging Spectroradiometer (MODIS) Penman–Monteith approach (PM-MOD) Global Land Evaporation Amsterdam Model (GLEAM) Priestley and Taylor Jet Propulsion Laboratory (PT-JPL) model Surface Energy Balance System (SEBS) model Breathing Earth System Simulator (BESS) FLUXCOM Penman–Monteith–Leuning (PML) model

Discussion:

Terrestrial evaporation is the phase change of (liquid or solid) water inland into the vapour phase, and its subsequent transport into the atmosphere. Often the terminology 'evapotranspiration' as equivalent to 'terrestrial surface latent heat flux'. The evaporation from land may comprise several sources or individual components, the most important being: transpiration (plant water consumption), bare soil evaporation (direct evaporation of water from soils), and interception loss (evaporation of water from wet canopies, typically during and after precipitation events). Each of these components are considered as a separate ECV product. Terrestrial evaporation amounts to approximately two-thirds of the precipitation falling inland. As such, the ability to monitor land evaporation dynamics is critical, as it governs the distribution of hydrological resources inland, spanning catchment to continental scales. This monitoring is also critical in climatological applications, since evaporation (1) uses incoming radiation, indirectly attenuating air temperature; (2) influences air humidity and cloud formation, plays a strong role in driving atmospheric feedbacks and precipitation; and (3) is intrinsically connected to photosynthesis, echoing changes in biospheric carbon fixation.

Terrestrial evaporation cannot be observed directly from space, yet a range of approaches have been proposed to indirectly derive this flux by applying models that combine the satellite-observed environmental and climatic drivers of the flux. Several international activities have advanced the study field in recent years, including the European Union Water and global Change (WATCH) project, the LandFlux initiative of the Global Energy and Water- cycle Exchanges (GEWEX) project, and the European Space Agency (ESA) Water Cycle Multi-Mission Observation Strategy (WACMOS)-ET project. Inter-comparison of the emerging observation-based global evaporation datasets brought to light large discrepancies among them (Miralles et al., 2016). To date, areas of particularly low accuracy still exist. In semiarid regimes and tropical forests, the divergence among existing datasets and low agreement against in situ measurements suggest higher uncertainties. For semiarid regions, this relates to difficulties to reflect the response of evaporation to drought stress. For tropical forests, large part of the uncertainty relates to the high error in interception loss estimates. Interception loss remains in relative terms the most uncertain component in terrestrial evaporation models. This also affects the quality of the evaporation data in temperate and boreal forests. Boreal regions are further affected by two large sources of uncertainties: (a) the poor representation of sublimation processes in current models, (b) the difficulties to mimic evaporation under conditions of severe radiation limitation. Moreover, long-term trends in the existing datasets need to be interpreted with caution, since the effects of CO_2 fertilization on transpiration via stomatal conductance and biomass changes, or the regulation of stomatal conductance by atmospheric aridity, remain poorly represented in current evaporation retrieval models. Nonetheless, the separate estimation of any of the evaporation components remains challenging, and the uncertainty in the individual evaporation components (i.e. transpiration, bare soil evaporation, interception loss) remains higher than that of total evaporation (Talsma et al., 2018).

Therefore, progress in the field of global terrestrial evaporation monitoring remains indispensable to reduce uncertainties, and even just to adequately estimate and report these uncertainties. Nonetheless, one decade after the start of the first approaches to derive evaporation from satellite data at global scales, current methods appear relatively well developed, and the ongoing progress in satellite technology has the potential to improve these datasets (McCabe et al., 2019). Just recently, Fisher et al. (2017) provided clear guidelines to the scientific community in order to address some of grand challenges currently faced to improve global evaporation estimates. Among others, these challenges included the improvement in accuracy, and highlighted the need for higher spatiotemporal resolution, multi-scale coverage, and long-term monitoring. A roadmap for the future was recently proposed by McCabe et al. (2019), aiming to bring evaporation estimates one step closer to their observational nature, and one step away from the influence of model assumptions. Potential pathways include the use of new types of satellite observations, such as solar induced chlorophyll fluorescence, and novel platforms, such as CubeSats and unmanned aerial vehicles. These advances are expected to deliver new means to increase our ability to estimate terrestrial evaporation at global scales.

Terrestrial evaporation cannot be observed directly from space; this flux is estimated by applying models that combine the satellite-observed environmental and climatic drivers of evaporation. Most models are based on different modifications of traditional local-scale formulations, that are usually process-based or semi-empirical. A few apply satellite data within statistical approaches, sometimes in combination with ground meteorological measurements of evaporation. The majority of these formulations use reanalysis input data for variables that are difficult to retrieve from satellite sensors. Although many of these models were originally intended for climatological-scale studies, some have evolved to provide estimates of evaporation in near operational mode, with ongoing efforts aiming to reduce product latency and improve spatial resolution. This opens up a range of possible applications, from regional drought monitoring to irrigation management. Some examples of evaporation datasets targeting near-real-time simulation at continental scales include the Land Surface Analysis Satellite Applications Facility (LSA-SAF) evaporation dataset, the Atmosphere–Land Exchange Inverse (ALEXI) and the Global Land Evaporation Amsterdam Model (GLEAM). The scarcity of in situ evaporation measurements at global scales, despite the efforts by the FLUXNET and SAPFLUXNET communities, remains bottleneck for the improvement of global satellite-based evaporation datasets, which rely on in situ measurements for validation or parameterisation of the underlying retrieval models.

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Groundwater	
ECV Products covered by this sheet	Groundwater storage change, groundwater level
Adequacy of the Observational System Assessment	3 There is no global coverage. Groundwater level monitoring networks usually depend on national authorities, so they are concentrated in countries with more resources.
Availability and Stewardship Assessment	3 Data are collected in many places, but they are not publicly available.
Networks	GGMN (Global Groundwater Monitoring Network) from IGRAC is the only open global repository of groundwater level data, containing data provided by national authorities. Other networks are the national networks established by each country.
Satellites	Gravity measurements from satellites (GRACE, GRACE-FO) can be used to estimate changes in land water storage, from where groundwater changes at large spatial scales can be derived.
Models, Reanalysis etc.	

Discussion:

Groundwater monitoring, i.e. measuring groundwater levels on a regular basis, is until now the best way to assess the status and trends of groundwater, a resource that can be impacted by overexploitation, drought, climate change, changes in irrigation patters, and more.

Countries interested in managing their groundwater resources in a better way have already established a groundwater monitoring network. From a country perspective, this is enough, and there is no need to make their data available to the wide international community, since most of groundwater issues and solutions have a local or regional dimension (in the case of transboundary aquifers). For this reason, collecting data to be part of GGMN (or any international programme or project) is a difficult task.

Regarding "Adequacy of the Observational System" and in the case of monitoring groundwater levels, there is no "observational system to produce adequate datasets for users" since data are disaggregated per country, and to aggregate them requires a considerable effort (either by collecting data and storing it in one place, or by connecting databases, whose difficulty resides in the fact that there is no widely used standard to store and share time series data).

With respect to "Availability and Stewardship", this depends entirely on the attitude of each country regarding "open data". In many parts of the world, groundwater data is considered strategic, or at least, data that should not be easily shared given the effort put to collect it in the first place. Criteria as "freely available, discoverable, accessible with QA/QC and adequate metadata" vary largely per country, but in most of the cases data are not easily discoverable and lack adequate metadata.

Time-variable gravity data of the satellite missions of the Gravity Recovery and Climate Experiment (GRACE) and GRACE-Follow On (GRACE-FO) provide data on the Earth's gravity field, which can be used to estimate changes in total land water storage (ΔTWS). When other water storage compartments (e.g. soil moisture, surface water, snow and glaciers) are calculated at the same resolution and subtracted from ΔTWS, groundwater storage change can be obtained since 2002. The main limitations of this approach are the low spatial resolution of these data (large aquifers to continental scales) and significant uncertainty. The uncertainty in groundwater change results from the accumulation of uncertainties in the water compartments and the satellite observations.

Lakes	
ECV Products covered by this sheet	Lake water level (LWL), Lake water extent (LWE), Lake surface water temperature (LSWT), Lake water leaving reflectance (LWLR), Lake ice cover (LIC)*, Lake ice thickness (LIT). *Sometimes referred to as lake ice extent (LIE)
Adequacy of the Observational System Assessment	Large lakes 4, small to medium lakes 2 to 3 Both in situ and satellite observations for above-mentioned Lakes ECV products generally meet user requirements and reflect reliable global trends. In some cases, satellite observations need to be adjusted or further interpretative algorithm research is needed.
Availability and Stewardship Assessment	3 Available data for ECV-Lakes products are useful and reliable from a user perspective. For some thematic variables (Lake water-leaving reflectance, Lake ice thickness, lake surface water temperature) not all originators of in situ data participate in organised stewardship systems.
Networks	Global Terrestrial Network – Hydrology (GTN-H) HYDROLARE, St.Petersburg, Russia (In situ: lake water level, lake surface water temperature, lake ice thickness), National Snow and Ice Data Center (NSIDC), Boulder, Colorado, USA (In situ: lake water level, lake ice phenology) National in situ hydrological networks (Lake water level, lake surface water temperature, lake ice thickness, lake ice phenology) A network is lacking for Lake water-leaving reflectance
Satellites	Satellite constellation for lake water level, lake water extent, lake surface water temperature, lake water-leaving reflectance, lake ice extent have been in operation for more than one decade and up to several decades. The ESA CCI project included the lakes ECV in 2019. A Climate Research Data Package (CRDP V1.0) on 250 lakes is accessible on: https://catalogue.ceda.ac.uk/uuid/3c324bb4ee394d0d876fe2e1db217378
Models, Reanalysis etc.	User groups working on the uses of CCI datasets for regional studies in 5 use cases: Use case 1: Analysis of ECVs for Lakes in Greenland: joint analysis of LSWT, LIC, LWL and glacier CCI Use case 2: Analysis and interpretation of ECVs for larger lakes (LSWT, LWST) Use case 3: Exploiting ECVs in long term ecosystem Research Use case 4: Brownification in Scandinavian lakes Use case 5: Consistency of ECVs in the Danube river lake-lagoon system Lakes are represented within the land-tiling schemes of some re-analysis systems such as at ECMWF. ISI-MIP climate change scenarios have been successfully applied to run simple lake models for projecting future lake climate changes (e.g. https://doi.org/10.1038/s41561-019-0322-x).

Discussion:

Terrestrial and satellite observations of the products that make up the ECV-Lakes are carried out on all continents and provide relevant data for a variety of data consumers (water, shipping, science and education, environmental protection, etc.). All thematic ECVs included in the Lakes ECV are sensitive to climate change.

In situ observations provide data (albeit scarce) on lake water level, lake surface water temperature, lake ice phenology (ice-on/ice-off dates and ice duration), lake water leaving reflectance. Satellite data provide information on lake water level, lake water extent, lake surface water temperature, lake water leaving reflectance, lake ice extent.

In situ observations of lake water level, lake surface water temperature and lake ice thickness are usually part of complex hydrological observations carried out by national hydrological networks. Most countries in their hydrological observations on lakes are guided by WMO regulations - Technical Regulations, volume III, Hydrology, 2006 edition, WMO-No.49 Guide to Hydrological Practices, sixth edition, 2008, WMO-No.168. In this regard, the data of in situ observations of the products considered within the Lakes ECV in international exchange have the necessary accuracy. The most complete regime information on the results of in situ observations of lake water level, lake surface water temperature, lake ice thickness is concentrated in the international HYDROLARE database. Nevertheless, some originators of data for LSWT do not openly share data or participate in organised stewardship systems: presently the Lake CCI project attempts to collect additional in situ data on an annual basis for annual climate assessment activities.

In situ observations of lake water leaving reflectance are not carried out within any context of stewardship and are relatively costly to obtain. Several properties of lake water quality that can also be derived from lake water-leaving reflectance are routinely monitored in national monitoring programmes (Chlorophyll-*a*, Turbidity, Dissolved Organic Matter). In the latter cases, protocols are embedded in ISO standards meeting adequate accuracy targets. For Reflectance, some networks include inland water platforms (AERONET-OC) but these do not meet all requirements for satellite validation, lacking essential wavebands and reference measurements. The foremost international database for collective lake optical measurements of research quality is LIMNADES hosted at the University of Stirling (UK). This initiative only covers data sharing and not quality control.

Satellite observations of the above-mentioned Lakes ECV products are carried out, as a rule, as part of integrated international projects carried out under the auspices of ESA, NASA and other agencies launching satellites for the scientific study of the planet’s natural resources. Currently, the study of the hydrological properties of lakes is carried out as part of international missions (Sentinel1/2/3, Radarsat, Landsat, Jason, MODIS, AVHRR, etc.). In the near future, new missions are planned. The Sentinel programme from the EU will allow monitoring very large number of variables related to the water cycle, including lakes variables. The ESA CCI programme gathers experts in different domains to create global data records of ECVs. Observations of lake water extent and lake ice extent are made only by satellite. The accuracy of these observations provides a study of the dynamics of these products, including within the framework of GCOS. Satellite observation data for lake water level and lake surface water temperature are less accurate than in situ observations but due to scarcity of in situ observations, satellites provide highly valuable and unique information on these variables worldwide. Moreover, the technical capabilities of new satellites and the improvement of methods for adjusting satellite observation data based on in situ observations can constantly improve the accuracy of satellite measurements of these products.

The most complete information on the results of satellite observations of lake water level and lake water extent is concentrated in the international database HYDROWEB. Satellite observation data for lake water leaving reflectance and lake surface water temperature are provided in the Copernicus Global Land Service and Copernicus Climate Service (only LSWT). Lake ice extent products are also recorded in national archives (internationally accessible). Global databases of these observations now exist within the framework of the CCI project (see CRDP V1.0, link given above) for an initial set of 250 lakes.

Adaptation:

- Lake water level – shipping, fisheries, coastal infrastructure.
- Lake ice thickness, Lake ice extent - transportation (shipping and ice roads), leisure activities (e.g. ice fishing and snowmobiling), food security (northern communities via ice roads).
- Lake water leaving reflectance – water extraction, ecosystem health, fisheries and aquaculture, drinking water supply, recreation.

Extremes:

- Highest lake water level, largest lake water extent – inundation.
- Extremely high or low lake water temperature – fisheries and aquaculture issues.
- Extremes in lake water leaving reflectance due to episodic events such as harmful phytoplankton blooms, aquatic vegetation, erosion – fisheries, aquaculture, drinking water supply, recreational value.
- Low and high ice years – transportation, leisure activities, food security.
- There is a lack of studies on lake temperature extremes, including lake heatwaves – these may be expected to affect ecological and fishery systems, and societal exploitation.

River discharge	
ECV Products covered by this sheet	River discharge, water elevation
Adequacy of the Observational System Assessment	3 In situ observations with gaps and highly variable Satellite data: measure water elevations, no direct measurement of discharge. Global monitoring but weak temporal resolution depending on the satellite orbit cycle (several days). The use of constellations (with 10 satellites or more) could improve the temporal resolution.
Availability and Stewardship Assessment	3 In situ data quality and availability dependents on national hydrological service Satellite data: all freely available, long-term monitoring foreseen with the Copernicus program, QA/QC but dependant on in situ data, and adequate metadata. Water elevation accuracy less precise than in situ (few decimetres accuracy).
Networks	Global Terrestrial Network for River Discharge (GTN-R) managed by Global Runoff Data Centre (GRDC). National hydrological services from currently 28 countries are contributing QA/QC data from 326 gauging stations. Discharge data are provided to GRDC at varying intervals. National hydrological services from approximately 60 countries are not contributing to GTN-R. Spatial gaps exist in parts of Africa, Asia, South-eastern Asia, Central America and the Mediterranean
Satellites	Altimeters can estimate rivers water elevation at the intersections between the satellite track and a river (= virtual stations) and only use of ancillary data/models (like rating curve with nearby in situ discharge or model outputs, assimilation of altimetry water elevations into numerical models) allow to infer river discharge (with potentially important errors). Note that water elevation corresponds to the distance between the top of the water surface and a given reference surface (geoid or ellipsoid), it is not the water depth. The estimation of water elevations with altimetry is already operational through the HYDROWEB website for instance, where about 10,000 virtual stations will be soon available and with a potential of more than 30,000 virtual stations worldwide. The improvement of algorithms and on-board processing makes it possible to have now good accuracy and to see smaller rivers (50 m wide). Temporal series are available from 1992 and a long-term monitoring is foreseen (up to 2030). Moreover, with the future SWOT (Surface Water and Ocean Topography) mission jointly developed by NASA and CNES, to be launched in early 2022, dedicated algorithms will infer discharge from SWOT measurements (water elevation, surface slope and river width) and using, among other algorithms, mass conserved flow law inversion. This discharge estimation should be done along river reaches wider than 100 m at each SWOT observation time.
Models, Reanalysis etc.	A specific hydrological/hydraulic modelling with assimilation of altimeter-based data or the use of a rating curve (discharge as function of water elevation) is needed to infer river discharge. It is a tough task to retrieve it with a good accuracy due to the model calibration phase. It is still an on-going scientific research but there will be an official discharge product generated with SWOT mission measurements. Currently there is no requirement on SWOT discharge accuracy.

Discussion:

River discharge is defined as the volume of water passing a measuring point or gauging station in a river in a given time. For station calibration both, the flow velocity and the cross-sectional area has to be measured a few times a year. River-discharge measurements have essential direct applications for water management and related services, including flood protection. They are needed in the longer term to help identify and adapt to some of the most significant potential effects of climate change. The flow of freshwater from rivers into the oceans also needs to be monitored because it reduces ocean salinity, and changes in flow may thereby influence the thermohaline circulation.

GRDC is managing the Global Terrestrial Network for River Discharge (GTN-R). The idea of the GTN-R is to draw together the already available QC/QA discharge data within a year after measurement. National Hydrological Services (NHS) are asked to provide these data to GRDC so that the data can be redistributed in a standardised way. Core component are gauging stations located near the mouth of the World's major rivers. This network assists in determining freshwater fluxes to the world's oceans and determining the volumes of the hydrological cycle. In cooperation with the Hydrological Services of the WMO Member States this network is continually being extended with additional stations. The GTN-R is a project in progress with a currently 326 gauging stations worldwide.

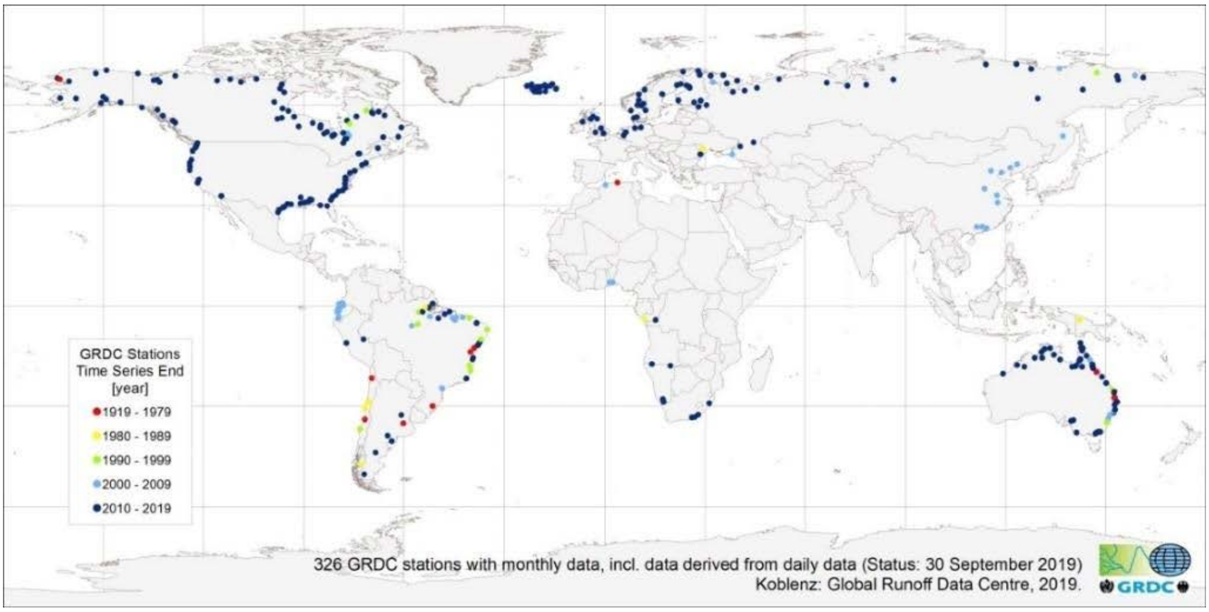

Figure 10. Global Terrestrial Network for River Discharge (GTN-R): Status September 2019

Satellite data cannot see directly river discharge but water elevations. And this information can definitely complement the in situ network thanks to its numerous data and improving accuracy. Currently only water elevation along the satellite track is measured (nadir altimetry).

Figure 11. Virtual station network on HYDROWEB database
http://hydroweb.theia-land.fr/

The future SWOT mission to be launched in 2022 is considered as a breakthrough, as it will provide images (and not just a sampling along the satellite orbit) of water elevation (with 10cm accuracy) and extent. It will therefore provide the very first comprehensive and quasi-global view of Earth's freshwater bodies from space and will characterize changing volumes of fresh water across the globe at an unprecedented resolution. Discharge variations in rivers will also be inferred from SWOT, globally. These measurements are key to understanding surface water availability and in preparing for important water-related hazards such as floods and droughts.

Constellation of altimeter satellites is also under consideration as it should improve the temporal resolution with a revisit time of one day on each virtual station (>15,000 virtual station for the SMASH mission project for instance).

Networks, Satellites, reanalysis, models:

Discharge and water level measurements are affected by a number of changing conditions and uncertainties due to complex calibration needs such as river cross section flow velocities, changing channel conditions, siltation, scour, weed growth, ice conditions. Well established standards and regulations exist for the monitoring of these variables. Selection of standards and references are listed:

- WMO Technical Regulations of Hydrology (WMO-No.49) and Guide to hydrological practices (WMO-No.168).
- ISO 1100-1 (1996) Measurement of liquid flow in open channels-Part I: Establishment and operation of a gauging station.
- ISO 748 (1997) Measurement of liquid flow in open channels-Velocity area methods.
- WMO (WMO-519) Manual on stream gauging Volume I-Fieldwork and Volume II-Computation of discharge.
- ISO Technical Committee 113 is dealing with all standards related to Hydrometry.
- ISO/TS 24154 (2005) The principles of operation, construction, maintenance and application of acoustic Doppler current profilers (ADCP).

Hydrological and hydraulic modelling is also mandatory to give access to river discharge worldwide by assimilating in situ and satellite-based data and so further developments and research work are still needed.

Soil Moisture	
ECV Products covered by this sheet	Surface soil moisture, root-zone soil moisture + ancillary variables vegetation optical depth, surface state (frozen/unfrozen), and surface inundation for quality characterisation
Adequacy of the Observational System Assessment	3 Meeting requirements in semi-arid regions and crop lands, issues still in dense vegetation, organic soils, and regions of strong topography as well as seasonally frozen ground and permafrost
Availability and Stewardship Assessment	5 Most datasets are open access, including doi and validation reports and many are produced operationally
Networks	International Soil Moisture Network; SMAP cal/val reference sites, North American Soil Moisture database; Copernicus GBOV sites, USCRN
Satellites	Nimbus7-SMMR, DMSP SSM/I, TRMM MI, Aqua AMSR-E, CGOM-W1 AMSR2, Coriolis Windsat, SMOS MIRAS, SMAP, FengYun 3B, GPM MI, ERS1/2 AMI WS, MetOp-A/B/C ASCAT, Sentinel-1, ALOS-1, ALOS-2
Models, Reanalysis etc.	ERA5, ERA5/Land, MERRA2, GLDAS2.1, Earth2observe ensemble,

Discussion:

Major recent developments:

- A lot of ongoing research on developing high-resolution soil moisture products.
- Community efforts to establish validation good practices:
  - Montzka, C. e.t al., (2020): Soil Moisture Product Validation Best Practice Protocol. Version 1.0.
  - Gruber, G. et al., (2020): Validation practices for satellite soil moisture retrievals: What are (the) errors?
- Data and metadata are becoming more and more available according to FAIR data principles (e.g. containing DOIs, and following transparent validation protocols (e.g. QA4SM).
- Retrieval issues:
  - Availability and quality of retrievals under dense vegetation.
  - No widespread reliable retrievals possible when soil is frozen, masking of frozen soils not always adequate.
  - Difficulty in mountainous areas.
  - Quality in circumpolar regions is still uncertain.
- Quality assurance issues:
  - Insufficient high-quality and representative in situ network data are available for validation.
  - No clear protocol and insufficient reference data for assessing stability.
  - Validation of high-resolution products requires new approaches and novel reference data.

    - Consistency with other hydrological variables not yet systematically assessed.
- Data availability issues:
    - Climate and agricultural communities require root-zone soil moisture products.
    - Datasets contain spatial and temporal gaps because of limited sensor availability and data retrievals issues.
    - Continuation of L-band data record threatened by absence of follow-on missions for SMOS and SMAP.
    - Radio Frequency Interference remains an issue for passive microwave observations and is increasingly affecting C-band radar observations.

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A.c.ii Cryosphere

Glacier	
ECV Products covered by this sheet (group as much as possible)	Glacier Area, Glacier Elevation Change, Glacier Mass Change
Adequacy of the Observational System Assessment	3 The in situ network for long-term monitoring remains limited to a few hundred glaciers. Improvement in the global coverage from space-borne geodetic surveys with decadal resolution.
Availability and Stewardship Assessment	5 In situ data and remote sensing data is collected and published by prevailing networks with high quality and efficacy. Users can access and use most data easily.
Networks	World Glacier Monitoring Service (https://wgms.ch) GLIMS: Global Land Ice Measurements from Space (https://www.glims.org) National Snow and Ice Data Center (https://nsidc.org)
Satellites	Landsat – 8, ASTER, GF – 3, ICESat, SRTM Sentinel-1/2, Cryosat-2, ICESat2, used to extract different glacier products and DEMs (e.g. AW3D30, ArcticDEM and the global DEM from TanDEM-X)
Models, Reanalysis etc.	To produce regional and global glacier mass change, Degree-Day Model, simple Energy Balance Model and Energy Balance Model were used.

Discussion:

It is never easy to make in situ observations of glaciers. For most large glaciers, it may be impossible. Thus, only a limited number of small glaciers in each region can be continuously monitored. There is risk of biased data because large glaciers and glacier surfaces at high elevation (where crevasses are generated) cannot be measured. For glacier area and glacier elevation change, data can be obtained from remote sensing images, however, the spatial and temporal resolution is too low to extract useful annual information and cannot detect the occurrence of extreme events. For glacier mass change, in situ observation is necessary because the snowpack density above the glacier surface is highly temporally and spatially variable. Without in situ observation of snow density, the glacier mass change results deduced by glacier elevation changes are only reliable at decadal scales. This is too low a time resolution for some glaciological studies.

Ice Sheet and Ice Shelves	
ECV Products covered by this sheet	Surface elevation change, ice velocity, ice mass change, grounding line location and thickness
Adequacy of the Observational System Assessment	4 Great achievements cover vast and ca. inaccessible area.
Availability and Stewardship Assessment	4 Data product efforts were done, and information was compiled, and dissimilation have been progressing.
Networks	Field observations are limited in the ice sheets and ice shelves. Coordination of international campaign are needed.
Satellites	Laser, radar altimeters and gravity measurements for ice sheet mass change. Frequent satellite observations have provided ice velocity data.
Models, Reanalysis etc.	Combined with laser and radar altimeter observation, modelling snow density enables to estimate mass change. Modelling of Ice sheet instability – ocean interaction is required to reduce uncertainty.

Discussion:

As the impacts of climatic change is clear in the polar cryosphere, ice sheets and ice shelves must be monitored. There have been continuous retreats and sporadic extreme events by the disintegration of ice shelves in the Antarctic and calving of glacier fronts in Greenland.

Continuous and effective observations are needed to monitor this vast and remote area. Surface conditions were well monitored by satellite. Ice sheet/ice shelf and ocean contacting zone are a new focus for monitoring ice sheet and ice shelf instability.

Satellite gravity measurements are very useful for Ice mass change monitoring. This program should be continued.

ECV products are not independent. These components are dependent on the flow of ice sheets and ice shelves with spatial and temporal variability. Holistic observations, including field observations, are required to support the satellite observations of vast and remote areas.

Improvements in the monitoring of ice sheet ECV is necessary for the future projection of the ice sheets. According to the IPCC "Uncertainty related to the onset of ice sheet instability arises from limited observations, inadequate model representation of ice sheet processes, and limited understanding of the complex interactions between the atmosphere, ocean, and the ice sheet." (IPCC SROCC (2019) SPM. A3.3)

The IPCC SROCC (2019) also discussed the instability of marine terminated ice sheets. Again, the modelling performance requires improvement with improved understanding of grounding line conditions needed. This is also important evidence of changes. Thus the improvements in the observations can reduce the uncertainty of decadal change of ice sheet and centennial change of sea level.

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Permafrost	
ECV Products covered by this sheet (group as much as possible)	TSP – Thermal State of Permafrost ALT – Active Layer Thickness
Adequacy of the Observational System Assessment	4 Mean reference sites provide fully reliable and consistent datasets, and allow derivation of regional and global trends. Many other sites have irregular reporting.
Availability and Stewardship Assessment **Class (5 – 1)** **short text**	4 A sufficient number of reliable datasets is available for all regions of the world. Spatial coverage could be improved in some regions (e.g. Siberia) but difficult due to remoteness. Reported data are fully accessible on the GTN-P database but its sustainability is not assured.
Networks	Data collection and database are coordinated by the GTN-P (Global Terrestrial Network). GTN-P relies on a network of National correspondents and of Young National correspondents, who are in charge of coordinating data collection in their country. All data are in situ measurements, made either manually or through automated logging. Most data are retrieved manually on an annual basis. Very few sites are equipped for real-time data transmission.
Satellites	No satellite data. The new product proposal on RGK – Rock Glacier Kinematics – will include satellite based InSAR data.
Models, Reanalysis etc.	No model outputs.

Discussion:

The GTN-P is a well-structured and wide monitoring network, covering most of the world's permafrost regions: Arctic, Antarctica, Qinghai-Tibet Plateau, temperate mountain ranges of Europe, Asia, North and South America, New Zealand. Only the few isolated high mountains of Africa are lacking permafrost monitoring. The spatial distribution is however uneven, and there are some large spatial gaps, especially in Central Siberia and in Central-Northern Canada.

The network is predominantly based on academic research sites, followed by often small research teams on a voluntary basis. Few sites are integrated in institutional measurement stations. Despite these characteristics and the remoteness of many sites, most of the monitoring sites are regularly monitored and provide almost continuous data series. The relatively low tech, robust and simple measurement procedures allow the production of continuous, consistent and reliable datasets despite the very harsh climate conditions leading to consecutive technical failures and logistical constraints.

Data are provided annually to the GTN-P database, by the data producers themselves. There are discrepancies in the regularity of data updates. For some sites, data are provided irregularly. This should be improved.

Discussions are ongoing on two main topics:

- A proposal for a new product, RGK – Rock Glacier Kinematics, elaborated by an IPA Action Group. This is a major indicator for mountain permafrost, and proved to be highly sensitive to atmospheric warming, which induces strong accelerations of surface movements. It may include satellite based InSAR data which allows detection of surface movements in the centimeter range for various time-steps, and allows systematic coverage over large areas, whereas in situ measurements are possible only on a limited number of sites due to remoteness. RGK concerns mainly mountain permafrost, where RGK measurements become routine in some national networks.
- Surface subsidence measurements, which is an important component of seasonal thawing and needs to be measured in order to correct ALT data for ice-loss at the permafrost table.

Networks: The global GTN-P network is now well organized and structured. The professional secretariat is hosted and supported since several years at AWI (Alfred Wegener Institute) at Potsdam/Germany.

A meeting of National Correspondents takes place every two years during International or Regional Permafrost Conferences. A few countries have a structured national network, who collects data and provides them to GTN-P, and/or have their own data portal (i.e. Switzerland, France, Norway).

Data are stored and distributed through the GTN-P database. The GTN-P database is hosted at the Arctic Portal in Akureiry/Iceland. This is a private organization, which has periodical financial issues, and doesn't provide therefore sufficient guaranties of sustainability. A duplicate of the database exists at AWI in order to secure data, and applications for another solution are ongoing. Decisions for the future of the database should be made by end of 2020.

Satellite data: The new product proposal RGK – Rock Glacier Kinematics – will include satellite based InSAR data.

Large spatial coverage of surface subsidence measurements could be best achieved by satellite altimetry

Another proposal for a satellite-based surface temperature product was made by the ESA-CCI community. This is however not considered currently reliable by the GTN-P Steering Committee, because it is a model calculation derived from indirect satellite measurements, and not a direct measure of permafrost temperature, with considerable uncertainty. Similarly, there have been attempts to retrieve ALT from P-band SAR.

Snow	
ECV Products covered by this sheet (group as much as possible)	Snow cover area, snow depth, snow water equivalent
Adequacy of the Observational System Assessment	4 Globally covered by the combination of In situ data, remote sensing data and reanalysis data
Availability and Stewardship Assessment	4 Remote sensing, reanalysis data and (part) in situ data are fully available to users
Networks	No global network especially focuses on snow, but several organizations/institutes/websites collect and publish high quality and globally covered snow data, exp: http://nsidc.org/data/g02156.html https://lpdaac.usgs.gov/products/modis_products_table GlobSnow (http://www.globsnow.info/index.php?page=Data) https://disc.gsfc.nasa.gov/datasets/ ERA Interim (https://apps.ecmwf.int/datasets/data/interim-full-daily/)
Satellites	Aqua/Terra - MODIS, AMSR-E DMSP - SSM/I, SSMI/S POES-AVHRR
Models, Reanalysis etc.	MERRA2, ERA-Interim

Discussion:

For in situ observation of snow, several countries, such as the USA, Russia, and China. have monitoring networks (monitoring the snow depth and water equivalent and other meteorological parameters). However, the global network of in situ observations is still insufficient, and it is difficult to collect the data: the Global Cryosphere Watch is endeavouring to fill this gap.

Potentially, remote sensing data provides global coverage. The snow cover area and its trends are well monitored. However, the uncertainties of the snow depth dataset produced by remote sensing are significant, resulting from both the methodology and the lack of in situ observation for data calibration and validation. The snow depth bias between modelled and reality data cannot be ignored in several mountainous areas. The main reasons for this difference are: (1) it is difficult to perform continuous in situ measurement on snow in mountainous areas, and (2) some of those areas are nearby/at country borders, where data is not available for international, or even domestic, scientific communities. Although scientists have attempted temporal and spatial analysis of snow depth, without enough in situ data, the improvement/progress is very limited. The IPCC did not give a determination on the interannual trend of snow depth either. However, significant progress was recently made in determining trends in non-mountain snow water equivalent from both satellites combined with in situ data [47]and reanalyses datasets.

Snow thickness on sea ice is poorly measured. Monitoring snow thickness on sea ice and snow on land ice are as they are substantial control of ice beneath.

[47] See DOI: 10.1038/s41586-020-2258-0 and DOI: 10.5194/tc-14-2495-2020)

A.c.iii Biosphere

Surface Albedo	
ECV Products covered by this sheet	Bidirectional reflectance factors (BRF), Reflectance anisotropy (bidirectional reflectance distribution function (BRDF) model parameters), bidirectional hemispherical reflectance under isotropic illumination or white-sky albedo (BHRiso), directional hemispherical reflectance or black-sky albedo (DHR) and bidirectional hemispherical reflectance or blue-sky albedo (BHR).
Adequacy of the Observational System Assessment	3 Whereas the entire products listed above are needed. Some datasets provide only DHR and BHR.
Availability and Stewardship Assessment	3 Satellite data with good stewardship are available. BSRN in situ data also freely available form the World Radiation Monitoring Center hosted by DWD.
Networks	BSRN, Surfrad, Fluxnet
Satellites	ECV datasets from space were operationally available from 2002 at global scale. Over Europe and Afrique, EUMETSAT provide a largest past period.
Models, Reanalysis etc.	ERA5 recently provides seasonal (monthly?) albedo values.

Discussion:

Global surface albedo products at a medium spatial resolution are operational and supplied by space agencies (NASA, EUMETSAT) and the Copernicus Climate Change Service.

There is a strong limitation in terms of long-term operational archives, since none covers the years before 2002, with the exception of those of EUMETSAT, but only on the METEOSAT disc. Research projects, such as QA4ECV, have also published daily products for a longer past period. The Copernicus C3S service should soon publish data from 1981. Some research projects design and deliver this ECV at higher resolution mainly over ice cap or glaciers, but they are not operational.

Only a few products include the anisotropic spectral and broadband parameters that are necessary to derive the surface albedo and assess its quality. Uncertainties may or may not be part of the products, but progress has been observed following the spread of the error budget.

The quality of the albedo spatial measurements decreases during the fall and winter when the incoming solar irradiance and the angle of solar incidence decrease, which occurs especially at high northern latitudes. Cloud cover is one of the main problems with optical remote sensing of the Earth's surface, especially for surfaces covered with snow and ice (Davaze et al., 2018; Gunnarsson et al., 2019).

For Iceland, for example, data are generally not available from mid-November to mid-January due to polar darkness.

The biases existing between the different products of several sensors have an impact on confidence in their use in the analysis of climate trends. This bias may come from calibration problem or atmospheric correction methods.

Despite the accuracy problem, applications can be made through changes and trends in relative values. In climate modelling studies, the climatology of the surface albedo of the functional types of plants (PFT) is often used as a reference or constraint.

Baseline Surface Radiation Network (BSRN) and SURFace RADiation Budget Measurement Network (SURFRAD) provides shortwave broadband albedo only (not spectral) over several sites. Despite BSRN uses pairs of secondary standard pyranometers to retrieve the albedo, the installation height is not homogeneous across sites as it varies from 3 m to 30 m. Only few sites implement tower observations, which are the most representative for monitoring purposes. US BSRN sites (most SURFRAD) perform homogeneous measurement from a nominal height of 10 m. To include upwelling components as basic requirements for future BSRN candidate stations, and to provide products for albedo in black-sky and white-sky conditions, are under discussion. Despite its wider distribution and tower implementation FLUXNET do not measure the irradiance with the same quality instruments and BSRN/SURFRAD and do not provide information of the diffuse component, which is useful in the process of cloud screening and reduction of the albedo to white-sky and black-sky components (see Copernicus Ground-Based Observation for Validation Service).

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Above-ground biomass	
ECV Products covered by this sheet	Maps of Above-ground biomass
Adequacy of the Observational System Assessment	4 Biomass maps are being produced but so far little consistency in time for assessing biomass change. Challenges remain for estimating high biomass values. Ground reference networks are also not well distributed globally for validation.
Availability and Stewardship Assessment	5 Satellite data with good stewardship are available.
Networks	GFOI: http://www.gfoi.org BiomassCCI: http://cci.esa.int/biomass ESA-Globbiomass: www.globbiomass.org WRI Global Forest Watch: https://www.globalforestwatch.org/ FOS: https://forest-observation-system.net/
Satellites	SAOCOM Sentinel 1 GEDI JERS-1, ALOS, ALOS-2 Geoscience Laser Altimeter System (GLAS) mission onboard the Ice, Cloud, and land Elevation Satellite (ICESat) NISAR (expected 2021) ALOS-4 (expected 2021) MOLI (expected 2021) Tandem-L (expected 2022) BIOMASS (expected 2022)
Models, Reanalysis etc.	Long-term biomass data records are evolving but not widely available yet. Reprocessing might be required based on the accuracy and stability of the prototype products that should be available soon.

Discussion:

Radar / Lidar space-based data are most commonly used to estimate AGB are available, but consistent time-series are not. Based on such data, there is significant progress for providing large area forest biomass data derived from a series of active and upcoming space-based missions.

Many of them provide open data targeted at large area and better spatial resolution (100-1000 mk) biomass monitoring than has previously been achieved. For examples, the Climate Change Initiative Biomass (CCI Biomass) project of the European Space Agency (ESA) is providing multiple global biomass data and information mainly for climate modelling and assessments. There are also first time-series biomass maps (at coarse spatial resolution) becoming available from NASA Carbon Monitoring Systems (10 km) and from passive microwave observations (25-50 km).

Current efforts are on the way to look into such new biomass products and their uncertainties by comparison and integration with plot based reference data sources from research plot networks, high-resolution LIDAR data and national forest inventory (NFI) datasets. The CEOS WGCV is in the process of finalizing a community-consensus protocol for global biomass validation.

FAPAR	
ECV Products covered by this sheet	
Adequacy of the Observational System Assessment	3 ECV datasets from space were operationally available from 2002 and one using past AVHRR data from 1980. In situ network is not well represented at global scale. Only a few of them meets accuracy and stability requirements
Availability and Stewardship Assessment	5 Satellite data with good stewardship are available.
Networks	Long-term infrastructural networks, e.g. TERN, NEON, ICOS, Fluxnet.
Satellites	ECV datasets from space were operationally available from 2002 and one using past AVHRR data from 1980. In situ network is not well represented at global scale.
Models, Reanalysis etc.	

Discussion:

ECV FAPAR data are produced by national space agencies (e.g. NASA and ESA) and Copernicus services at global scale. EUMETSAT also provides operational daily products for Europe and Africa. In addition, some research products are also available but only cover a limited period. ECV FAPAR products on a higher spatial scale (around 20-30 m), which could be used for adaptation, are not yet operational but feasible.

The 'in situ' measurement networks include less than a hundred local sites which do not sample all types of vegetation. The sites are almost missing on the South American and African continents. The traceability of measurements and standard methods across networks has not yet been achieved, but recent progress has been seen. We must also highlight the disparities between the available products in term of temporal and spatial scale, different geographic projection that implies often a post-processing by final users.

The main default for the applications relating to climate change concerns the non-compliance with the requirement of long-term temporal stability. This failure affects the confidence of interannual variability and the analysis of trends. This is mainly due to the following problems: poor calibration or drift for the older sensors but also for a series of same sensors on board different platforms, such as AVHRR / NOAA; use of a non-physical algorithm on different optical sensors. (See the example in Gobron et al., 2019).

This implies that the analysis of trends in the FAPAR ECV is not reliable and can only be carried out over a short and recent "climatic" period (last 18 years).

In addition, the uncertainties (when present) of various products are either missing or do not represent a correct mathematical quantity. Thanks to research projects, such as QA4ECV and FIDUCEO, progress has been made to have a full budget of uncertainties but has not always been implemented operationally. Long-term reprocessing of archives using state-of-the-art retrieval algorithm and handling of uncertainties must be considered to overcome these problems.

The current products available represent also different definitions, as the products can represent either instantaneous or diffuse values and can represent either the total, mixed or green leaves absorption.

This implies that the documentation is necessary for their use in certain applications. For example, Zhang. and. al. (2020) has shown that certain products are better suitable for the calculation of GPP. In addition, consistency with other terrestrial ECVs should be improved.

In situ sensors across the several networks can be different and sometimes non-standard. Progress has been made regarding the use of PAR sensor networks which has proven to be more appropriate to represent this ECV at the local scale. However, research is still needed to infer the 'green' values instead of the total absorption. In vegetation and climate models, the parametrization of the radiative transfer is often based on a 1-D model which establishes the physical link between LAI, FAPAR and surface albedo. This means that the assimilation of these ECVs must be taken with caution.

MODIS and MISR instruments on board TERRA have been flying since 2002 and will stop in a few years. VIRSS can replace MODIS even if its performance is not at the same level. Fortunately, Copernicus Sentinel 3A and its twin Sentinel 3B have been launched in the past four years. However, their main area of application concerns the oceans. In addition, Sentinel 2A and Sentinel 2B provide data that can be used for LAI at higher resolution, although geographic coverage at global scale may be limited.

The recent Earth Polychromatic Imaging Camera (EPIC) on the Deep Space Climate Observatory (DSCOVR) platform, which was launched into the Sun–Earth's first Lagrange Point (L1) orbit, provide spectral images of the entire sunlit face of Earth with 10 narrow channels (from 317 to 780 nm). As EPIC can provide high-temporal resolution data, it is beneficial to explore the feasibility of EPIC to estimate high-temporal resolution FAPAR.

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Fire Disturbance	
ECV Products covered by this sheet	Burned Area
Adequacy of the Observational System Assessment	3 Omission and commission errors higher than required
Availability and Stewardship Assessment	5 Datasets incorporate all standards and are easily accessible.
Networks	NASA MODIS standard products ESA CCI standard products EU Copernicus Climate Change Service GOFC-GOLD Fire Implementation Team Global Wildland Information System (JRC)
Satellites	Terra-Aqua MODIS (>2000) Sentinel-3 SLSTR-OLCI (>2018) NOAA-VIIRS (>2013) NOAA-AVHRR (>1982) limited interest
Models, Reanalysis etc.	Several Fire modules within DGVM (Spitfire, GlobFIRM, CASA, CTEM, Orchidee)

Discussion:

Several global BA (burnt area) products have been released in the last years, mainly derived from sensors providing frequent temporal coverage (daily), such as MODIS, MERIS or VEGETATION, but coarse spatial detail (>300 m). A recent review by Chuvieco et al. (2019) shows the strengths and limitations of existing global products. The most reliable ones estimate total worldwide BA in the range of 3.5 to 4.5 Mkm^2, but this estimation is likely to be conservative since comparison of global and regional products show an important underestimation from the former (Roteta et al. 2019, Hawbaker et al.2017). Now the most used global BA product is the MCD64A1, produced by NASA based on MODIS 500 m reflectance bands guided by active fires. The last version is collection 6 (Giglio et al. 2018), which has superseded other NASA BA products. The ESA's Climate Change Initiative Fire Disturbance project (FireCCI) has developed an alternative global BA product, based on MODIS 250 m reflectance bands, which provides similar accuracy to the NASA product but seems more sensitive to small burn patches (Chuvieco et al. 2018, Lizundia-Loiola et. al., 2020). A prototype for generating BA products from long-term series of AVHRR products has also been recently published, but it is still unstable and provides low accuracy for Boreal and temperate regions (Otón et. al. 2019)

These global BA products have been extensively used for the analysis of fire activity, determining characteristics of fire regimes, such as average BA and temporal persistency (Abatzoglou et al. 2018), and spatial variations of BA trends (Andela et al. 2017). These trends are then related to the main drivers of fire, including climate changes and human activity. The analysis of agricultural fires is particularly challenging since they tend to be small and low intensity and are therefore difficult to map using standard remote sensing approaches. However, considering these cropland fires is important to better account for atmospheric emissions, particularly in some regions where they have a relevant impact on air pollution (Wu et al. 2019)

A growing recent trend in remote sensing of fire effects is the use of BA products for parameterization of Dynamic Global Vegetation Models (DGVM). Most DGVM include a fire component, which tries to estimate the impact of fire over vegetation and soils (Lasslop et. al. 2018). These fire modules generally use stochastic processes to estimate fire ignition and standard fire propagation models to estimate BA (Hantson net al. 2016). Several studies have found a tendency towards underestimation of actual BA by these models (Kloster et al. 2017). For this reason, recent studies tried to improve them by better understanding the spatial variation of fire characteristics. The most analysed in the last few years are fire size, shape and orientation (Laurent et.al 2018). Once fire events have been individualized, several analyses can be conducted, such as fire –size distribution (Hantson et al. 2015) or relations between fire size and fire radiative power (Laurent et al. 2019). In addition, the use of BA products in DGVM requires a better characterization of product uncertainty, which is a novel field of research that requires further efforts (Brennan et al. 2019).

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Leaf Area Index	
ECV Products covered by this sheet	Leaf Area Index (LAI) (effective) values from EO and LAI from ground-based measurements.
Adequacy of the Observational System Assessment	3 ECV datasets from space were operationally available from 2002 and one using past AVHRR data from 1980. Only few of them meets accuracies and stability requirements. In situ network is not well represented at global scale.
Availability and Stewardship Assessment	3 Only few of them meets accuracies and stability requirements.
Networks	Long-term infrastructural networks, e.g. TERN, NEON, ICOS, Fluxnet.
Satellites	MISR, MODIS, VIRSS, AVHRR, Vegetation, Sentinel-3 OLCI
Models, Reanalysis etc.	Parameterization of LAI is done either with climatic variable or through phenological model. More assimilation of EO LAI was developed.

Discussion:

ECV LAI global data are operational and produced by space agencies (NASA, ESA) and by both the Copernicus global land and climate change services. EUMETSAT also supplies daily and operational products in Europe and Africa. Some research products are available but only relate to a limited period. LAI products on a higher spatial scale (around 20-30 m) which could be used for adaptation purposes are not yet operational but they are feasible.

Terrestrial networks include less than a hundred local sites that do not sample all types of plant cover. Sites on the South American and African continents are almost missing. The traceability of standard measures and methods across networks is not yet operational, but recent progress exists.

We must also highlight the disparities of end-user products in terms of time and space scale within different geographic projections, which means that post-processing always seems mandatory when used in climate or land global model.

The main issue for climate change analyses concerns the non-compliance with long-term temporal stability requirements.

This defect affects the confidence of interannual variability and the analysis of trends. This is mainly due to the calibration and drift problem, such as AVHRR / NOAA, or to the use of algorithm not based on physics and applied on different sensors. (See example in Jiang C. et al., 2017). This implies that the reliability of the LAI ECV trends can only be realized over a short and recent "climatic" period (last 18 years). In addition, their uncertainties can be either missing or do not represent a correct mathematical quantity.

Thanks to research projects, such as QA4ECV and FIDUCEO, progress has been made to infer a full budget of uncertainties but has not always (never?) been implemented operationally. The reprocessing of the archive using adequate calibration and advanced retrieval method together with uncertainties should be considered to overcome these problems.

In land and climate models, the LAI parameterization is done either with a dynamic relationship between the climatic variables or with a phenological model. Progress has nonetheless been made to assimilate EO LAI products in order to improve these parameterizations.

Most of these products represent effective values compared to a true measurable value. Converting geometric measurements to real values, or vice versa, is an essential step and requires additional information on the structure and architecture of the canopy, e.g. the distribution of scattering elements at appropriate spatial resolutions.

This has a huge impact on the biases between the available LAI datasets and can also lead to ambiguities for users, as was the case, for example, in estimates of gross primary production (BPP) through models of 'ecosystem.

In addition, consistency with other terrestrial ECVs must be improved.

In situ network should be extended geographically to provide a better coverage in the southern hemisphere. This requires more international cooperation and resources. In addition, the measurement protocol should be based on that of the FRM.

The structure and architecture of the canopy, necessary to improve the conversion to geometric measurements from actual values, are often lacking.

MODIS and MISR instruments on board TERRA have been flying since 2002 and will stop in a few years. VIRSS can replace MODIS even if its performance is not at the same level. Fortunately, Copernicus Sentinel 3A and its twin Sentinel 3B have been launched in the past four years. However, their main area of application concerns the oceans. In addition, Sentinel 2A and Sentinel 2B provide data that can be used for LAI at higher resolution, although geographic coverage at global scale may be limited.

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Land Cover	
ECV Products covered by this sheet	Maps of land cover (1), Maps of high resolution land cover (2), Maps of key IPCC land use, related changes and land management types (3)
Adequacy of the Observational System Assessment	4 Coverage is global, and reliable global historic trends can be derived
Availability and Stewardship Assessment	5 Satellite data with good stewardship are available globally.
Networks	The Global Terrestrial Observing System (GTOS) http://www.fao.org/geospatial/projects/detail/en/c/1035185/ GLC-SHARE http://www.fao.org/geospatial/resources/detail/en/c/1036591/ ESA-CCI Land Cover data http://www.esa-landcover-cci.org/ MODIS global land cover data: https://modis.gsfc.nasa.gov/data/dataprod/mod12.php Copernicus Global Land Monitoring Service https://land.copernicus.eu/global/products/lc GOFC-GOLD (Global Observation for Forest Cover and Land Dynamic) http://www.gofcgold.wur.nl CEOS (Committee on Earth Observation Satellites) Working Group on Calibration and Validation Land Product Validation Subgroup https://lpvs.gsfc.nasa.gov/
Satellites	Sentinel 1 & 2 Landsat MODIS ALOS-Palsar Proba-V
Models, Reanalysis etc.	Reprocessing of historical land cover data records is occasionally done but no common. Land cover is classified globally and routinely, but land use and land use change are only occasionally done and often at local scale, making the function of maps for IPCC land use types limited.

Discussion:

In general, there is a wide range of relevant long-term well curated satellite data, at a range of horizontal and temporal resolutions, and also for appropriate temporal extents (required for the three relevant products). The Landsat archive and Sentinel satellites in particular now provide many opportunities for more detailed land cover mapping. High-temporal resolution (10 m) observations however are only available globally since 2015.

The availability of long and consistent historical data is most relevant and requires novel remote sensing time series approaches to utilize these data for global and regional level assessments.

Reference data are also available globally (for example through the GOFC-GOLD Reference Data Portal, although the last update was in October 2015). Experts can be accessed in the networks to support validation of results. Validation of global land cover change remains a challenge both in terms of (standard) approaches and available reference data.

The availability of satellite-based products on land use change and attributions following IPCC guidelines are limited. Satellite products provide maps of land cover and land cover change. More work is required to develop land use change products (e.g. agriculture, pasture, agroforestry, natural vs plantation forests etc.) to allow for IPCC recommended attributions to emissions and removals.

Land Surface Temperature	
ECV Products covered by this sheet	Land Surface Temperature
Adequacy of the Observational System Assessment	4 Satellite data is global, but in situ networks are sparse
Availability and Stewardship Assessment	4 Satellite data is well curated and freely available. In situ data have different stewardships for different networks with differing accessibility
Networks	Surface Radiation (SURFRAD) Network Atmospheric Radiation Measurement (ARM) Network Baseline Surface Radiation Network (BSRN) U.S. Climate Radiation Network (USCRN) Institute managed networks (data not publically available): Karlsruhe Institute of Technology, University of Leicester, NASA JPL, University of Valencia Copernicus Ground-Based Observations for Validation of Copernicus Land Products (GBOV) Network Copernicus Space Component Validation for Land Surface Temperature, Aerosol Optical Depth and Water Vapour Sentinel-3 Products (LAW) Network
Satellites	ATSR-2 (1995 – 2003) AATSR (2002 – 2012) Terra MODIS (1999 ->) Aqua MODIS (2002 ->) MSG SEVIRI (2004 ->) GOES (GOES-12 to GOES-16) (2004 ->) Sentinel-3 (2016 ->) SSM/I (F-13 to F-18) (1998 ->) MTSAT / Himawari (2010 ->) VIIRS (2011 ->) AHVRR (NOAA-15 to NOAA-19) (1998 ->) AVHRR (Metop) (2007 ->)
Models, Reanalysis etc.	Global reanalyses of skin temperature: ERA-Interim ERA5 MERRA

Discussion:

Collection of requirements

The approach to defining LST requirements for climate is based on the work carried out within the LST CCI project, which undertook the largest survey of climate users of LST data to date. Questions focused on gathering information about user applications, current data use, user concerns surrounding satellite LST products, dataset specification (e.g. temporal and spatial resolution, stability, accuracy, etc.), data format, quality and uncertainty information, requirements for validation and inter-comparison information, and issues concerning clouds. The information obtained through the surveys and interviews has been synthesised and used to define LST user requirements for climate applications with recommendations on updates to existing requirements. This included an evaluation of requirements for the parameters specified in the GCOS Implementation Plan: LST spatial and temporal resolution, data set length, accuracy, precision and stability. In addition qualitative user consensus on requirements for spatial domain, observation times, temporal and spatial resolution, dataset length, accuracy, precision and stability are:

- LST data should be provided globally
- Observations should be provided at all times of day
- . User priorities for dataset specification are:
    - High quality data more important than spatially complete fields
    - High temporal resolution more important for global studies, whilst high spatial resolution is more important for local studies
    - Dataset length is more important for global studies, whilst high data resolution is more important for local studies

Adequacy/inadequacy of current holdings

Single-sensor Infrared (IR) LST data-products from satellite have greatly improved:

- High accuracy of IR LST data – validation shows majority of biases < 1.0 K from MODIS, AATSR, Sentinel-3, and VIIRS, with high accuracy of emissivity <0.015 (1.5%) available from MODIS, ASTER, and VIIRS products.
- Full- pixel uncertainty budgets from first principles categorised by effects whose errors have distinct correlation properties: random, locally-correlated and (large-scale) systematic following a consistent approach with the SST community; these are applicable to all processing levels and products
- Advances in cloud detection (dynamic probabilistic and confidence-level approaches)
- Global LST data which resolve the diurnal cycle becoming available
- Merged geostationary (GEO) and low earth orbit (LEO) data sets are for the first time giving high spatial resolution, sub-diurnal sampling.:
- Inter-calibrated merged GEO (SEVIRI, GOES, MTSAT) and merged LEO (ATSR, MODIS, AVHRR) being produced at 3- hourly resolution

Quantification of the infrared LST clear-sky bias by using microwave LST measurements

Improved validation protocols are being applied to LST data:

- Community- driven standardised LST validation protocol from CEOS LPV using both temperature- and radiance-based methods being applied across several existing and proposed for new projects.
- Accurate and highly highly-stable in situ instruments, with documented calibration at dedicated sites
- Validation of LST uncertainty in line with SST approaches
- Increasing confidence in traceability and stability of LST:
- LEO IR time series length being increased with ATSR back to 1991
- LEO IR time series length being increased with AVHRR back to 1991 and potentially back to 1981
- GEO IR time series length being increased with Meteosat-MVIRI back to 1983
- Microwave (MW) time series length being increased with SSM/I back to 1998
- Quantitative assessments of biases between consecutive instruments such as ATSR-2/AATSR and MODIS/VIIRS.

Satellite instruments and satellite datasets

- Fundamental Climate Data Records (FCDRs) of appropriate TIR and microwave imagery (top-of-atmosphere radiances), as a basis for LST CDRs, with appropriate global and diurnal coverage.
- Sustained IR and microwave sensors, capable of supporting climate accuracy global LST analyses.
- Geostationary Earth Orbit (GEO) platforms, which allow regional coverage and high temporal resolution and therefore frequent observations under clear-sky conditions to resolve the diurnal cycle, since surface temperature changes significantly over periods ranging from hours to years and beyond
- Low Earth Orbit (LEO) satellites, which can provide observations for all regions up to twice- daily, acquire data for more or less narrow swaths during each orbit. These platforms are able to deliver sub-daily observations over the high latitudes thereby resolving the diurnal cycle for clear-sky over these regions
- High-accuracy and high temporal stability observations, which merge together LST coverage by LEO and GEO instruments in the IR to provide diurnal and high high-spatial spatial-resolution capability, and microwave observations to understand the clear-sky bias and to deliver all-sky datasets
- FCDR generation capabilities which are independent from in situ measurements and are consistently applicable to different satellite instruments which observe LST, involving such measures as inter-instrument harmonisation of brightness temperatures, detailed uncertainty analysis, aerosol detection and assessment of stability (older AVHRR data being reprocessed to guarantee consistency with MODIS, and (A)ATSR and VIIRS-derived LST)
- Instrument calibration involving prelaunch characterization, on-board calibration, and in-orbit calibration campaigns. This is important also to allow inter-calibration of data retrieved from different sensors and platforms before being merged
- Reprocessing of archives of LEO and GEO LST observations in a consistent manner to community agreed data formats
- Assessment of FCDR maturity with respect to the system maturity matrices; and to include full metadata traceability for improved data provenance
- Production of long-term, stable data sets free from non-climatic artefacts.

In situ validation and data archiving:

- The objective of validation and inter-comparison is to provide an assessment of the quality of LST products and assessments of instrument stability including current data from operations as well as long- term datasets from archives. Such an assessment is of utmost importance for the acceptance by the user community
- Validation and inter-comparison should follow a clear and transparent protocol for assessing the various LST data sets
- A comparison against in situ data is generally regarded as the most accurate and reliable LST validation technique. However, this is the most resource-demanding method requiring utmost care in determining accurate LST over sufficiently representative sites, and ensuring radiometers are well-calibrated, and appropriate understanding of the mismatch in spatial scale between the point-level in situ observations and the satellite LST pixels
- The in situ network of permanent high quality IR radiometers for dedicated LST validation is being expanded, but still need to work with in situ data providers to ensure validation data is collected according to set guidelines and is publicly available to the research community.

- In addition to in situ validation, a comprehensive validation on a global scale following standard protocols is also being incorporated: i) radiometric-based validation, which does not require measurements of LST on the ground, and can provide a viable alternative for long-term, semi-operational LST product evaluation at the global scale; ii) inter-comparisons with similar LST products from other instruments, which give important quality information with respect to spatial patterns in LST deviations; iii) time series analysis to quantify trends and to identify potential instrument drift or persistent cloud contamination.
- Increased use of in situ instrument uncertainty and knowledge of the spatial and temporal context of matching satellite LST data within situ measurements to validate the uncertainty model of the satellite LST data.

Soil Carbon	
ECV Products covered by this sheet (group as much as possible)	Soil carbon organic content (in g kg^{-1}) in different soil layers Soil organic carbon stock (t ha^{-1})
Adequacy of the Observational System Assessment	3 While maps of current soil carbon content have improved significantly in quality and accessibility, long-term monitoring is not available globally
Availability and Stewardship Assessment	4 Good stewardship by the mentioned organisation. Includes standardisation efforts and capacity building. FAO/Global Soil Partnership World Data Centre for Soils (WDC-Soils) at ISRIC
Satellites	No product available.
Models, Reanalysis etc.	ISRIC works with machine learning. Within the scientific community several soil carbon models have been developed and improved over decades (e.g. CENTURY, RothC, Yasso). They can provide information on soil carbon changes depending on climate, land use and land management.

Discussion:

Soil surveys including carbon are run repeatedly in many countries usually by governmental agencies. Global data integration efforts resulting in global maps or open data products are run by FAO/Global Soil Partnership (product: Global Soil Organic Carbon Map) and the International Soil Reference and Information Centre (ISRIC, products: soil organic carbon stock map, soil organic carbon content maps, 250 m resolution).

While maps of current soil carbon content have improved significantly in quality and accessibility, Soil Carbon Dynamics (changes in time) are not available globally due to low amount of systematic repetition of the observations (costly, only available from few countries). Future tasks should focus on supporting this, since changes in soil carbon have a high relevance for land-atmosphere fluxes.

A.c.iv Anthropogenic

Anthropogenic Water Use	
ECV Products covered by this sheet	Terrestrial water use for household, industry, livestock and irrigation
Adequacy of the Observational System Assessment	2 In situ coverage for most nations of annual data, but not for every year or for every relevant variable.
Availability and Stewardship Assessment	4 Good availability and well-curated data at the FAO level; more varied stewardship and availability at individual country level.
Networks	Data at the national level (200 countries) provided to the United Nations Food and Agriculture Organisation who then publish at http://www.fao.org/nr/water/aquastat/data/query/index.html?lang=en
Satellites	Not applicable
Models, Reanalysis etc.	Not applicable

Discussion:

This is a data set that is dependent on in-country tabulations of a range of anthropogenic water use statistics that are then provided to the UN Food and Agriculture Organisation (FAO) for uploading to their AQUASTAT database/website. The quality of data is therefore highly dependent on in-country collection from a range of sources and quality control that is highly variable across the 200 contributing countries. The FAO website is well organised and compiled with clear attempts to homogenise the data. Depending on the variable, some annual data are available from ~1960, but often for data in the last year of five-year blocks.

This data set does not lend itself to automated, satellite or modelling so is unlikely to evolve much more than its current form.

Anthropogenic greenhouse-gas fluxes	
ECV Products covered by this sheet	National annual CO_2, CH_4 and N2O emission inventory time series and their uncertainty per sector and covariance matrix; also disaggregated spatially (e.g. to 0.1degx0.1deg) and temporally (monthly, daily, hourly) and their gridmap uncertainties
Adequacy of the Observational System Assessment	2 Considerable differences between bottom up (inventory based) and top down (atmospheric inversion based) are still not well explained
Availability and Stewardship Assessment	3 Emissions estimates are available but without a data centre or data stewardship.
Networks	For CO_2 and CH_4: TCCON, COCCON, For CO_2 and CH_4 and N2O: ICOS Ref: https://www.copernicus.eu/sites/default/files/2019-09/CO2_Green_Report_2019.pdf
Satellites	For CO_2: GOSAT2, OCO-2, and in the future OCO-3, GOSAT3, and CO_2M Sentinel For CH_4: GOSAT2, Sentinel 5P, and in the future GOSAT3, CO_2M Sentinel Ref: http://ceos.org/document_management/Virtual_Constellations/ACC/Documents/CEOS_AC-VC_GHG_White_Paper_Publication_Draft2_20181111.pdf
Models, Reanalysis etc.	e.g. Ensemble models of the Copernicus Atmospheric Monitoring Service (incl. IFS model of ECMWF)

Discussion:

Estimates of anthropogenic global greenhouse gas (GHG) emissions have a number of issues with considerable differences between bottom up (inventory based) and top down (atmospheric inversion based, see Balsamo et al. 2018) still not well explained. In particular regions which are poorly equipped with in situ stations or which are subject to less well-managed land-use changes or less well confined (less well characterised or less well regulated) human activities (e.g. exploratory drilling, shale gas fracking, waste incineration or disposal) could benefit from additional in situ measurements (Pinty et al., 2019). The space borne observations (e.g. GOSAT2 or OCO-2) do provide useful and reliable information and spotted emission sources which were neglected or missing (e.g. fugitive CH_4 emissions from coal mines, which are now taken up in the 2019 Refinement of the IPCC 2006 guidelines for national emission; the Indian coal power plant missing in the CARMA database) and CEOS is working towards a better constellation architecture (Crisp et al., 2018, CEOS 2018) to produce datasets for users, atmospheric modellers, national inventory compilers, policymakers, citizens. A fair and transparent monitoring of the nationally determined contributions to GHG reductions which the UN Parties have to report under the enhanced transparency framework of the Paris Agreement could benefit of observation-based evidence when discrepancies arise in reviews or stock takes (such as the biennial Facilitative Multilateral Consideration of Progress and the five-yearly Global Stock Take).

Given better coverage, the observational system can provide evidence for the level of GHGs in the atmosphere and its trends, in particular supporting the monitoring of the desired GHG emission reductions, which is pursued with the Copernicus CO_2 Monitoring system (Janssens-Maenhout et al., 2020). However, it will not replace national inventories with disaggregated sector-specific information, but it can complement these with very valuable information, in particular on those emissions of activities with human-nature interactions and feedbacks, such as the agriculture, forestry, other land-use (AFOLU) sector. The AFOLU sector is still showing the largest uncertainties in the national inventories and will need to provide a sink for the remaining emissions that cannot be cut to zero.

Moreover, the extra spatially disaggregated information of the observational system will allow for identifying emission hotspots, displacements or accidental releases, which need to be under control. We call for the provision of emission gridmaps in addition to the national annual inventories because they support the tracking of GHG reduction actions, which take place at local level. Also the higher temporal resolution of the observational system allows for a more efficient follow-up and action in those regions where derailing is monitored or where a green recovery should be planned (in particular after a disruptive event such as COVID-19, as indicated by Le Quéré, 2020). Of course, the large variability in the spatially and temporally disaggregated information needs an assessment with robust uncertainties. However, visualisation of the problem with near-real time maps might be part of the climate change solution.

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ANNEX B: ASSESSMENT OF PROGRESS ON IMPLEMENTATION PLAN ACTIONS