Satellite Observations in Support of the Copernicus Climate Change Service

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ABSTRACT

The Copernicus Climate Change Service (C3S), operated by ECMWF on behalf of the European Commission, provides climate services built around a comprehensive suite of data products. These products include multi-decadal estimates of the atmospheric state, based on atmospheric reanalysis, and a range of observational datasets on Essential Climate Variables (ECVs).

Atmospheric reanalyses are now regarded as valuable sources of information for monitoring trends in the global atmospheric state and employ highly optimised methods for combining observations of meteorological variables, both *in-situ* and satellite. The most recent C3S global atmospheric reanalysis, ERA5, covering the period 1979-2019 (to be extended to 1950) is now available and since its release in early 2019 has a rapidly growing user base, currently numbering more than 30,000. It uses a recent version of the ECMWF Numerical Weather Prediction (NWP) system to assimilate observations (87 billion for the period 1979 - 2018) in order to analyse the atmospheric state. Satellite observations are a key input to reanalyses and the range of observations assimilated are reviewed.

ECVs derived from satellite and *in-situ* observations, spanning land, atmosphere, ocean and biosphere domains, produced as part of international collaborations, are available via the C3S Climate Data Store (CDS). The aspiration of C3S is to further develop the CDS to include a wider range of ($\sim$ 35) ECVs in the next phase of the Copernicus programme (2021-2027).

Keywords: Copernicus, C3S, Reanalysis, ERA5, ECMWF

1. INTRODUCTION

In the context of the present session, *Solutions at Scale (in Earth Observation)*, this paper aims to address the specific question: as the satellite component of the Earth observing network continues to grow in complexity and capability, how can we make optimal use of the vast amount of data produced ? Two important aspects of this question are: scientifically, how can we efficiently extract information on the Earth System from these observations ? and; how can we make this information readily available to users ? The paper will show that within the EU's Copernicus Climate Change Service (C3S), operated by the European Centre For Medium Range Weather Forecasts (ECMWF) on behalf of the European Commission, satellite data play a key role in two important elements of the service: firstly, in supporting the production of climate reanalyses; and secondly in the production of climate data records of Essential Climate Variables (ECVs). Furthermore the first of these elements, climate reanalyses, employ a sophisticated data assimilation system which efficiently extracts information on the atmospheric state from a large and diverse array of satellite sensors, as well as a comprehensive network of conventional meteorological instruments. As such it serves as a useful model for the more general challenge of how Earth observations from diverse sources can be combined to provide a single coherent analysis of the state of the Earth system. Indeed, the approach has already been extended to the assimilation of atmospheric composition observations in another Copernicus Service, the Copernicus Atmospheric Monitoring Service (CAMS, https://atmosphere.copernicus.eu/), also operated by ECMWF.

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The Copernicus Climate Change Service (C3S) is one of six services (https://www.copernicus.eu/en/services) operated as part of the larger EU Copernicus Programme. The first phase of C3S commenced in 2015, and was declared operational in July 2018. The service aims to support climate adaptation and mitigation by providing authoritative climate information to policy makers, researchers and the commercial sector. This information comprises a comprehensive suite of data products made openly available through a web portal (the C3S Climate Data Store, https://cds.climate.copernicus.eu). These products include climate reanalyses, observational records of ECVs, seasonal weather forecasts, climate projections and bulletins as well as a series of data sets and diagnostic tools tailored to the requirements of specific commercial sectors with significant sensitivities to climate change (including water, energy, agriculture, infrastructure, health and insurance).

As part of the first phase of C3S, ECMWF have produced a *state-of-the-art* global climate reanalysis, ERA5, spanning 1950-present. ERA5 continues in near real time, and provides data to a growing user base, currently numbering more than 30,000, 5 days behind real-time. Some of the key features of the Numerical Weather Prediction System, and specifically the data assimilation system, used to produce ERA5 are described in Section 2 below. The range of ECV datasets addressed by C3S are described briefly in Section 3.

2. THE C3S CLIMATE REANALYSIS, ERA5

2.1 Background: Numerical Weather Prediction and Reanalysis

The success and steady ongoing improvement of weather forecasting based on Numerical Weather Prediction (NWP) in recent decades has, in part, been due the evolution of sophisticated data assimilation systems which provide the initial conditions (or *analyses*) for forecast models (see Figure 1). These data assimilation systems combine information on the atmospheric state from previous short range forecasts, together with new information on the atmospheric state from observations.

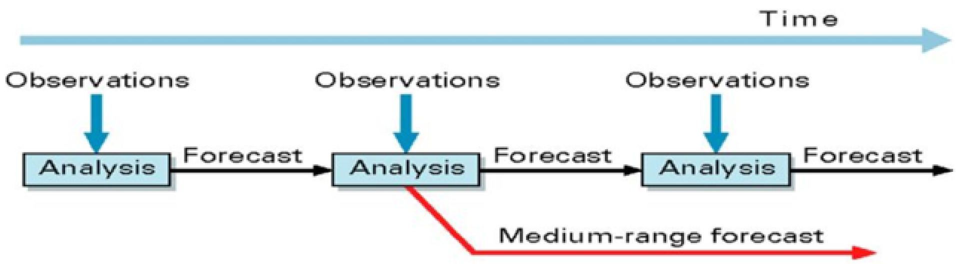

Figure 1. In Numerical Weather Prediction (NWP) Data Assimilation (DA) systems the initial conditions, or *analysis*, for a forecast model run are derived by combining new information on the atmospheric state from: (i) observations, together with (ii) the estimate of the atmospheric state based on a previous short range forecast. In reanalysis the resulting sequence of analyses, often spanning timescales of many decades, provides a coherent record of the evolution of the atmosphere.

These observations are produced from conventional components of the observing network as well as from satellites. The satellite observing system has advanced significantly over the last 40 years. The ECMWF operational model currently uses a diverse array of satellite data from the main meteorological satellite agencies (see Figure 2).

In the ECMWF operational NWP system (as it stands in early 2020) data from around 95 satellite instruments is currently processed in the Integrated Forecasting System (IFS). This level of utilisation is set to continue in the near future (see Figure 3) and most probably, given historical trends in the evolution of the observing system, increase in the longer term. Notable aspects of the recent evolution have been the steadily growing contributions from Europe (through EUMETSAT's polar and geostationary programmes, as well as ESA's Earth Explorers and the Sentinel missions) and from China (through CMA's polar [FY-3] and geostationary [FY-4] programmes).

Reanalyses use the same framework employed for NWP, except in the case of reanalyses the primary output is *the sequence of analyses themselves*. When run over periods of several decades, these reanalyses provide a

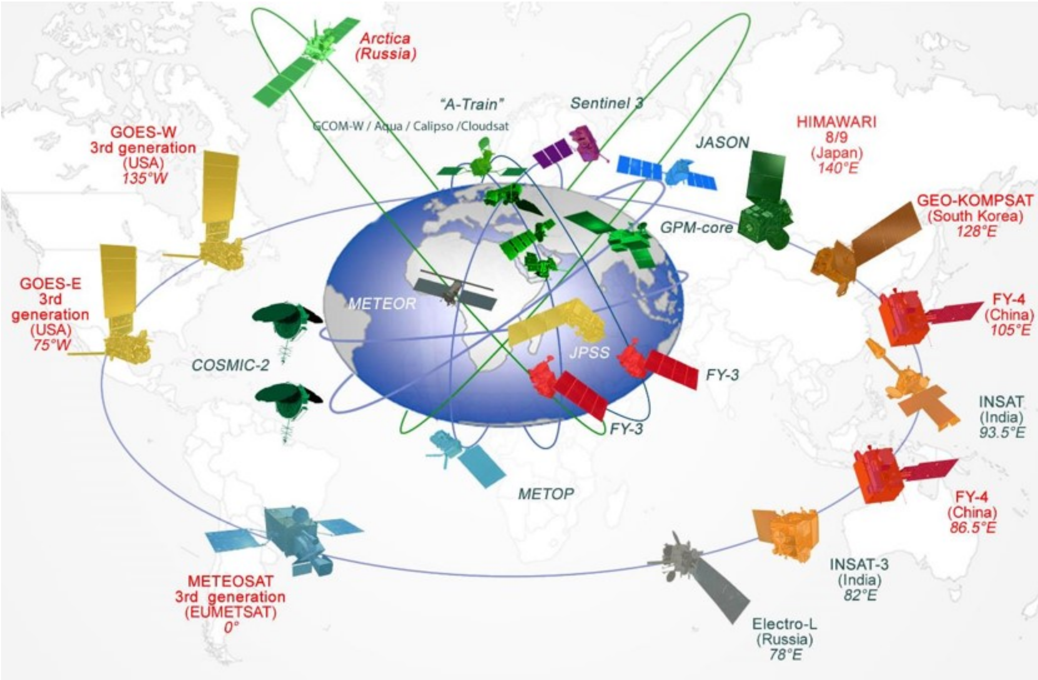

Figure 2. An illustration of the diversity of meteorological satellite missions operating in 2020, showing the contribution of the major agencies: the US (yellow); Europe (blue and purple); China (red); Japan (green); India (orange); South Korea (brown) and Russia (grey and light green). Geostationary, polar and highly elliptical-orbit satellites are shown.

coherent estimate of the atmospheric state, making best use of all available observations and employing a single, state-of-the-art, data assimilation system.

Such reanalyses support a broad range of applications spanning inter-governmental assessments of global climate change[1] at one extreme, to specific and unique use cases requiring accurate representations of local weather at the other. Accordingly, reanalyses aim to provide homogeneity and accuracy in the depiction of global and regional climate variables over multi-decadal timescales, as well as accuracy in the representation of synoptic scale events at sub-daily temporal resolution.

Reanalyses are produced at several institutes worldwide, mainly operational weather centres, and are typically updated every five to ten years to take advantage of continuous developments in data assimilation systems, forecast models and available computing power. Therefore successive reanalyses typically offer higher resolution as well as improved accuracy in representing weather and climate. ERA5 is the fifth generation of atmospheric reanalysis to be produced at the European Centre for Medium Range Weather Forecasts (ECMWF), now as part of the Copernicus Climate Change Service. It replaces its widely used predecessor, ERA-Interim.[2] ERA5 is produced in operational mode and is expected to continue for the next 5-10 years. More detailed information on ERA5 including comparisons to other contemporary reanalyses, focusing on the period 1979-2019, is given in [3] and summarised in Table 1 below.

As part of C3S high resolution regional reanalyses, for both the European and Arctic domains, are being undertaken and for these satellite data also play a key role. The focus of this paper, however, is the ERA5 global reanalysis.

2.2 Data Assimilation

ERA5 employs a 4D-Var assimilation system which can be considered a more general and powerful form of optimal estimation methods commonly used to produce retrievals from satellite observations in remote sensing applications. The objective of 4D-Var is to find the best estimate of the state of the atmosphere within an assimilation time window (the timescale over which a batch of new observations are used to derive a new set of

Table 1. Characteristics of ERA5 relative to its predecessor, ERA-Interim. Reproduced from Hersbach *et al* (2020)[3]

	ERA-Interim	**ERA5**
Publicly available, expected in 2020	1979 - August 2019	1979 - onwards 1950 - 1978
Availability behind real time	2-3 months	2-3 months (final product) 5 days (preliminary product)
Model cycle (year)	Cy31r2 (2006)	Cy41r2 (2016)
Atmospheric DA window for 00, 12 (UTC)	12h 4D-Var $(15_{\mathrm{day}-1}, 03]$, $(03,15]$	12h 4D-Var ensemble $(21_{\mathrm{day}-1}, 09]$, $(09, 21]$
Model input *(radiation and surface)*	as in ERA-40, inconsistent SST and sea ice	appropriate for climate, e.g., evolution greenhouse gases, aerosols, SST and sea ice
Spatial resolution	79(TL255) 60 levels to 10 Pa	31(TL639), HRES 137 levels to 1 Pa
Ocean waves	1 degree	0.36 degree
Inner-loop resolution	TL95, TL159	TL95, TL159, TL255
Land-surface model	TESSEL	HTESSEL
Soil moisture DA	1D-OI	SEKF
Snow DA	Cressman	2D-OI
Uncertainty estimate	none	from the 4D-Var ensemble, EDA 10 members at 63(TL319) ocean waves 1 degree TL127, TL159 inner loops
Output frequency	6-hourly for analyses, 3-hourly for forecasts	hourly throughout (uncertainty 3-hourly)
Output parameters	84 (sfc), 25 (wave), 27 (ua)	205 (sfc), 46 (wave), 30 (ua)
Extra observations	following ERA-40, GTS	in addition, latest instruments
Reprocessed FCDRs	some	many more (see Table **??**)
Radiative transfer model	RTTOV v7 clear-sky assimilation	RTTOV v11 partly all-sky assimilation
VarBC	radiances only	also ozone, ground-based radar-gauge composites, aircraft temperature, surface pressure
Radiosonde corrections	RAOBCORE	RICH
Other corrections	Scatterometer, altimeter	Scatterometer, altimeter

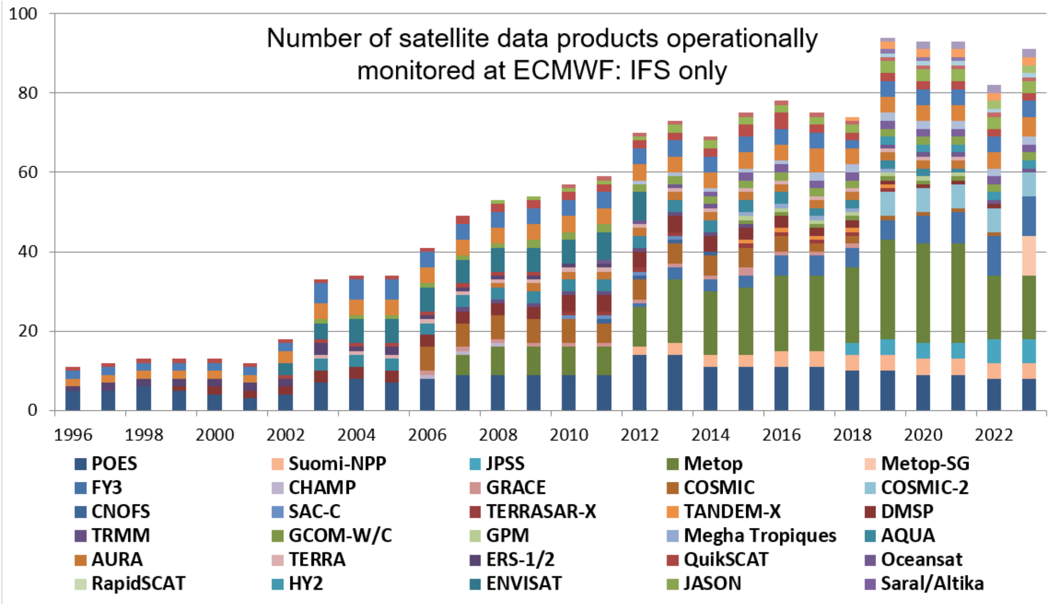

Figure 3. Evolution of the number of satellite instruments processed (or expected to be processed) in the ECMWF Integrated Forecasting System (IFS) during the period 1996 - 2023.

initial conditions), given a background forecast x^b valid at the start of the window and observations y^o falling within that window. Here, approximately following the unified notation proposed by Ide *et al*[4] , any x contains the model data at one particular time across all locations, levels and variables, and any y contains all the available observations in the window. The aim is to reduce the misfit d between the observations and their modelled equivalents y, i.e.,

$$d = y^o - y, \tag{1}$$

consistent with the estimated uncertainty of the background and observations. This is done by adjusting the state of the atmosphere at the start of the assimilation window x and, recognising the possibility of bias in observations, by adjusting a vector of parameters β that describe such biases b in observation space. Hence the vector of simulated observations is computed as

$$y = H(x) + b(x, \beta). \tag{2}$$

In 4D-Var the observation operator $H()$ and bias model $b()$ include the model integration from the start of the window to the time of the observation, as well as interpolation to the observation location and simulating of the observed quantity (such as radiance) from the model state. The bias parameter vector consists of a large number of small subsets (containing between 1 and 12 elements), each of which determines the bias estimate for a particular sub-group of observations, a 'bias group'. Bias groups contain anything from a handful to tens of thousands of observations, collecting for example all the data from one aircraft flight or from one channel of one satellite instrument on one satellite. In ERA5 all bias models are linear[5] , i.e.,

$$b_i(x, \beta) = \sum_{j \in S} p_j(x) \beta_j \tag{3}$$

with p_j the linear predictors and where the sum is limited to the small subset S of bias parameters that relates to the bias group to which one observation i belongs. Each observation enters either exactly one bias group, or none at all, in which case $S = \emptyset$ and no bias correction is applied. Such latter observations are also called anchors. The simplest predictor is a constant, while others can depend on characteristics of the observations and/or the model state at the observation location and time. ERA-Interim was the first ECMWF reanalysis to include variational bias corrections[6] . It was applied to radiance data. In ERA5 this has been extended to Ground-based radar-gauge composites, total column ozone, aircraft temperature and surface pressure observations. The bias correction for radiosonde temperatures, scatterometer backscatter and altimeter wave height is prescribed independently of the data assimilation.

4D-Var minimizes the following cost function

$$\begin{aligned} J(\delta x, \delta\beta) &= J_b(\delta x) + J_p(\delta\beta) + J_o(d) = \\ &\frac{1}{2}\delta x^T B^{-1}\delta x + \frac{1}{2}\delta\beta^T {B_\beta}^{-1}\delta\beta + \frac{1}{2}d^T R^{-1} d. \end{aligned} \quad (4)$$

Here $\delta x = x - x^b$ and $\delta\beta = \beta - \beta^b$ are the deviation, or increment from the model and bias parameter backgrounds x^b and β^b. T is the transpose operator. While x^b is the result of a model integration starting from the previous analysis, there is no bias evolution model, so β^b are simply the final values from the previous analysis. Covariance matrices B, B_β and R express the second-order moment error characteristics in the background model state, bias parameter and (bias-adjusted) observations, respectively. For simplicity in Equation 4 one term with minor effect, J_c, has been omitted - this is a digital filter for reducing gravity waves in the increments.[7]

2.3 Satellite Data

ERA5 assimilated large volumes of satellite data spanning the modern satellite-era. The launch and operation of the TOVS satellites, from 1979 onwards, saw the first use of significant numbers of high quality microwave and infrared sounding data. Some sounding data (from the VTPR infrared sounding instrument onboard NOAA-2 to -5) was assimilated in an earlier period (1972-1979). The number of observations assimilated in ERA5 increases from approximately 0.75 million per day on average in 1979 to around 24 million per day by January 2019. In the 40 years from 1979 to 2018 inclusive, 86.6 billion observations were actively assimilated in 4D-Var.

The 4D-Var component of ERA5 uses observations from over 200 satellite instruments or types of conventional data over the period 1979-2019. It extracts information from in situ observations on 10m wind over sea and 2m humidity over land, and pressure over land and sea. Upper-air observations of wind, temperature and humidity are obtained from PILOT, radiosonde, dropsonde and aircraft measurements. Upper-air wind is also obtained from atmospheric motion vector winds (AMV) from a number of polar and geostationary satellites. In addition, ERA5 uses information on rain rate from ground-based radar-gauge composite observations from 2009. ERA5 uses measurements from many satellite platforms. These include radiances sensitive to upper-air temperature, humidity and ozone from (clear-sky) HIRS, MSU, SSU, AMSU-A, AMSU-B, ATMS, and (all-sky) MWHS, MWHS2, MHS, and from microwave imagers (also all-sky) SSMI, SSMIS, TMI, AMSR-2, AMSRE, GMI, and (hyperspectral infrared radiances) from IASI, AIRS, CRIS and (mixed clear-sky and all-sky) from geostationary satellites. ERA5 uses level 2 ozone from a range of instruments. ERA5 also benefits from GNSS-Radio Occultation bending angles (from 2001, but large quantities from 2006), providing information on upper-air temperature and humidity. Information on ocean vector wind (4D-Var) and land soil moisture is obtained from scatterometers, while information on ocean-wave height (OI) is obtained from altimeters (both types of instruments from 1991).

Radiances are the dominant and growing source of measurements throughout the period (see Figure 4). Major developments for this class of observations have included the transition from the TOVS (HIRS-2, MSU, SSU) to ATOVS suite (HIRS-3/-4, AMSU-A, AMSU-B) of sounding instruments in 1998, the introduction of hyperspectral infrared radiances from 2003 and the increasing availability of observations from a growing constellation of microwave imagers. Relative to ERA-Interim there has been a marked increase in the number of other satellite observations assimilated, notably GNSS-RO, scatterometer wind observations and Level-2 ozone products.

2.4 Long term trends

ERA5 represents the evolution of meteorological variables, including temperature, humidity, surface pressure, winds, cloud and precipitation from the surface to the model top (at 0.01 hPa) at hourly intervals over the period from 1979-2020. It also includes a range of other parameters including sea surface temperatures, sea-ice,

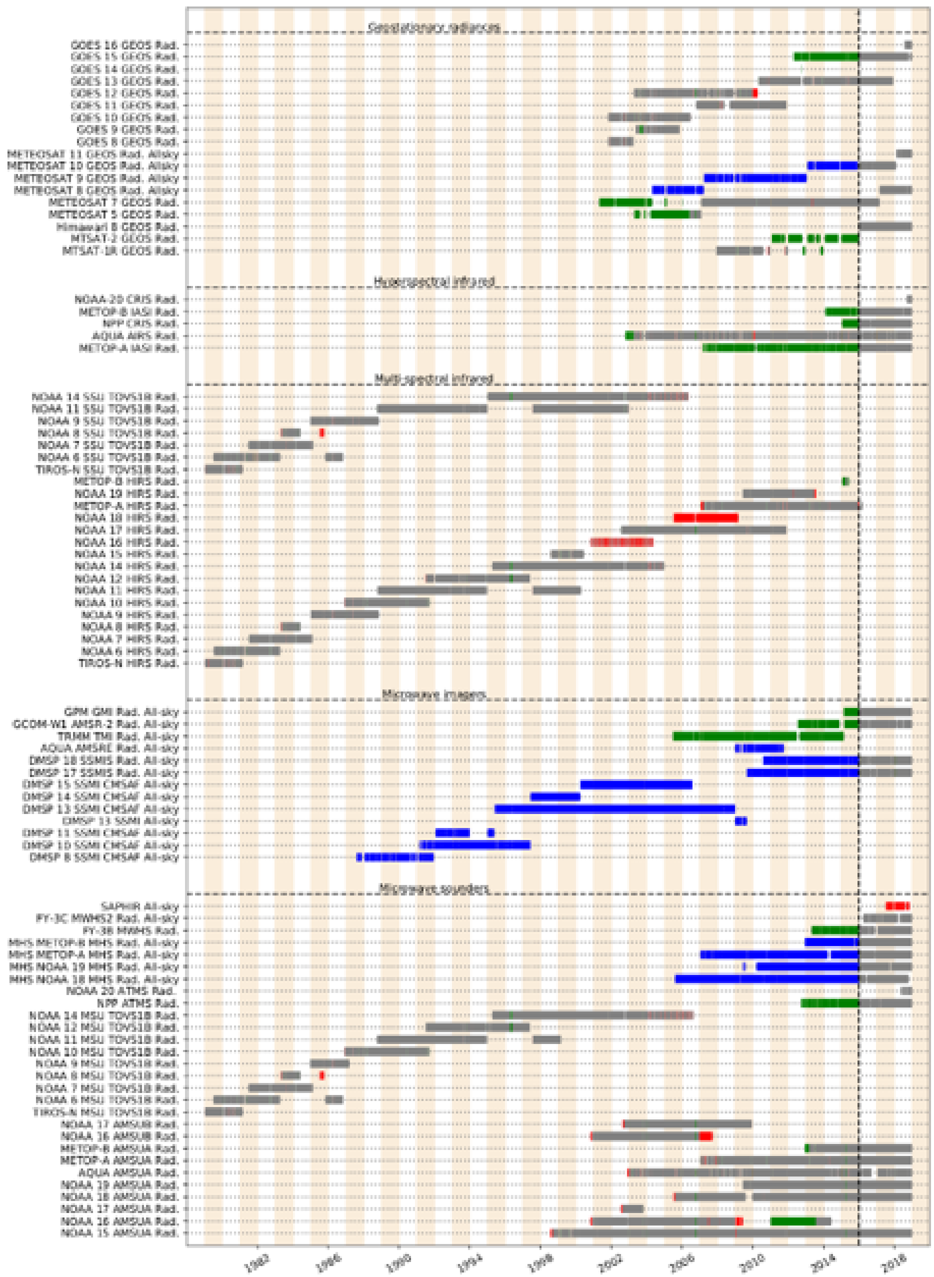

Figure 4. Satellite radiance data assimilated in the ERA5 reanalysis during the period 1979-2019. Grey bars indicate observations assimilate in both ECMWF operations and ERA5; blue bars indicate reprocessed datasets have been used in ERA5, or the treatment of observations is significantly changed relative to the treatment in previous reanalyses (ERA-Interim); red indicates the observations are not assimilated in ERA5, but are assimilated in operations; and green indicates the observations are assimilated in ERA5 but not in ECMWF operations.Reproduced from Hersbach *et al* (2020)[3]

significant wave heights as well as radiative fluxes. The extension back to 1950 has been produced and will be released later in 2020. As an example of the trends derived from ERA5, Figure 5 shows the evolution of global temperatures at 2m together with those derived from ERA-Interim and a number of other observational data sets. In general there is good agreement across the data sets which all show a warming trend, evident since the mid-1980s.

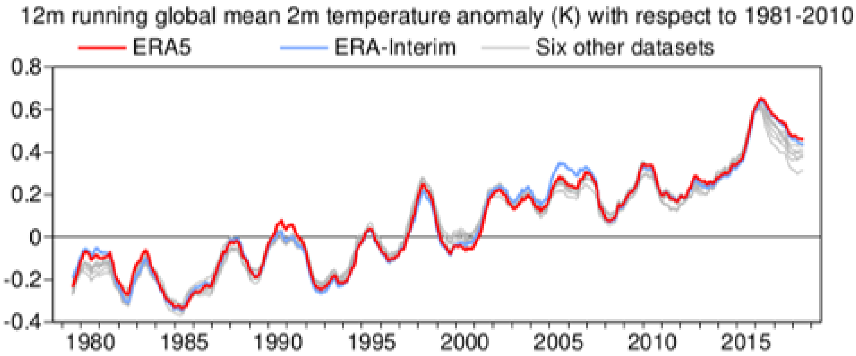

Figure 5. Trends in (global) 2m temperatures based on ERA5 (red) and ERA-Interim (blue). Six other datasets are shown in grey: JRA-55[8] ; GISTEMP version 4[9] ; HadCRUT4[10] ; NOAA GlobalTemp v5[11] ; HadCRUT4[12] and Berkeley Earth Surface Temperature Project. Reproduced from Hersbach *et al* (2020)[3]

2.5 Synoptic representation

A large subset of the ERA5 user community is interested in the accuracy of the representation of synoptic scale events in ERA5. As an example of this Figure 6 shows the representation of Hurricane Florence which struck the East coast of the continental US on 14th September 2018, killing 24 people and causing an estimated $24 billion worth of damage. Also shown is the representation of Hurricane Florence in ERA-Interim. Clearly the higher resolution of ERA5, coupled with the much improved forecast model and data assimilation system has resulted in a more accurate depiction of the storm in ERA5.

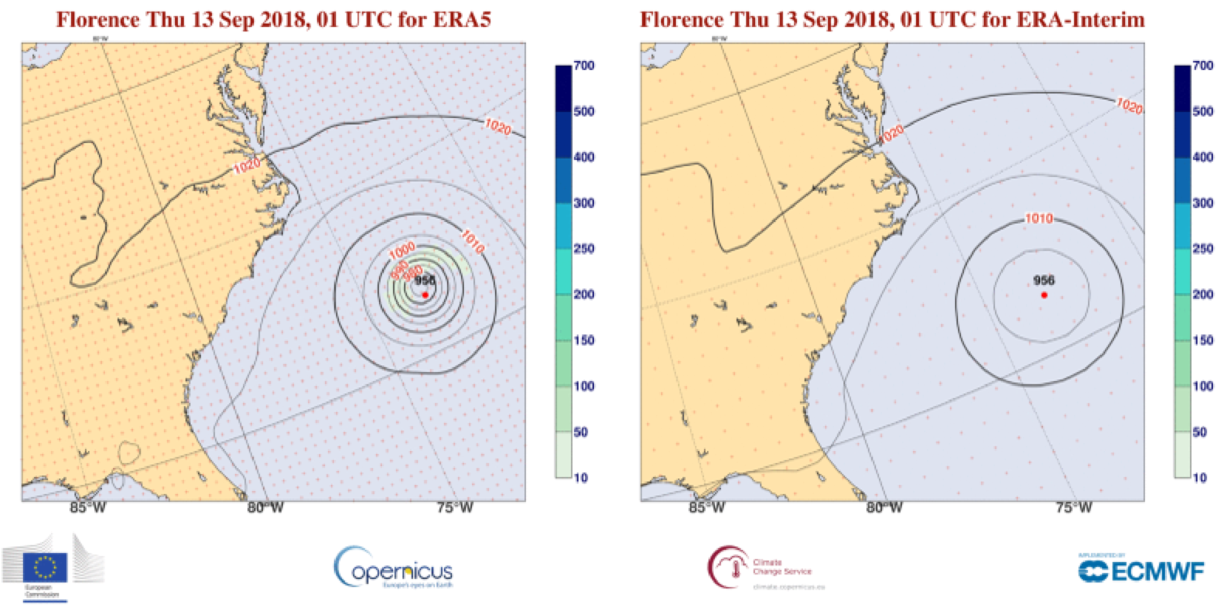

Figure 6. The representation of Hurricane Florence in (left) ERA5 and (right) ERA-Interim. Also shown (orange dot) is the measured central pressure in hPa.

3. ESSENTIAL CLIMATE VARIABLES (ECVS)

An Essential Climate Variable (https://public.wmo.int/en/programmes/global-climate-observing-system/essential-climate-variables) is a physical, chemical or biological variable or a group of linked variables that critically contributes to the characterization of Earth' s climate. C3S aims to provide users with full and timely access to observational records of ECVs derived from satellite observations. The objective is to provide products which are: *state-of-the-art*; cover long periods of time, are consistent and complete (Climate Data Records, CDRs); are regularly updated (through the provision of Interim-CDRs, ICDRs); and are accessible and traceable.

The satellite-derived ECVs are produced through collaborative activity within C3S (C3S_312a) which builds upon, and involves, a number of external partners including EUMETSAT (through the Satellite Application Facilities, or SAFs), ESA's Climate Change Initiative (CCI) as well as NOAA and NASA. The 22 ECVs addressed in the current phase of C3S are partitioned into five themes: atmospheric physics; atmospheric composition; ocean; land hydrology and cryosphere; and land biosphere and are illustrated in Figure 7. The current expectation is that this list will be extended to around 35 ECVs in the next phase of C3S, due to commence 2021.

			C3S_312a				
					C3S_312b		
		GCOS	2017	2018	2019	2020	2021
Atmospheric physics							
	Precipitation	4.3.5					
	Surface Radiation Budget	4.3.6					
	Water Vapour	4.5.3			Lot 1		
	Cloud Properties	4.5.4					
	Earth Radiation Budget	4.5.5					
Atmospheric composition							
	Carbon Dioxide	4.7.1	Lot 6				
	Methane	4.7.2	Lot 6		Lot 2		
	Ozone	4.7.4	Lot 4				
	Aerosol	4.7.5	Lot 5				
Ocean							
	Sea Surface Temperature	5.3.1	Lot 3				
	Sea Level	5.3.3	Lot 2		Lot 3		
	Sea ice	5.3.5	Lot 1				
	Ocean Colour	5.3.7					
Land hydrology & cryosphere							
	Lakes	6.3.4					
	Glaciers	6.3.6	Lot 8		Lot 4		
	Ice sheets and ice shelves	6.3.7					
	Soil moisture	6.3.16	Lot 7				
Land biosphere							
	Albedo	6.3.9	Lot 9				
	Land Cover	6.3.10					
	Fraction of Absorbed Photosyntheti	6.3.11	Lot 9		Lot 5		
	Leaf Area Index	6.3.12	Lot 9				
	Fire	6.3.15					
			2017	2018	2019	2020	2021

Figure 7. Essential Climate Variable (ECV) data sets addressed in C3S through activities in C3S_312b.

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Reanalysis touches on a large number of activities at ECMWF and its success relies on the efforts from many, many people across ECMWF and from many collaborations. ECMWF implements the Copernicus Climate Change Service on behalf of the European Union, and ERA5 was produced with funding from this Service. The EU, through the 7th Framework Programme, supported the ERA-CLIM and ERA-CLIM2 projects which served as precursors to the ERA5 reanalysis. The efforts of the many scientists involved in these projects is gratefully acknowledged. ERA5 benefits from the usage of a large number of reprocessed datasets that were prepared by CIMMS, ESA, EUMETSAT Satellite Application Facilities (SAF), JMA, NASA, NASDA, NOAA, TU Wien

and UCAR. The provision of satellite-based ECV datasets is also dependent on the efforts of many external programmes, most notably the ESA CCI programme and the EUMETSAT Satellite Application Facilities (SAFs).

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