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Some aspects on the use and impact of observations in the ERA5 Copernicus Climate Change Service reanalysis

András Horányi

European Centre for Medium-Range Weather Forecasts,
Shinfield Park, Reading, RG2 9AX, United Kingdom

Author E-mail: Andras.Horanyi@ecmwf.int

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Abstract—The latest reanalysis at the European Centre for Medium-Range Weather Forecasts is the ERA5 system, which is produced in the framework of the European Union's Copernicus Climate Change Service. ERA5 is primarily going to cover the satellite era, i.e. 1979 to near real-time and will be publicly available for the users during 2018. The present article provides information about the observation usage of ERA5 together with an impact assessment of the assimilated data. Though all this is based on some test (scout) ERA5 experiments, however, they are providing a good overview of the evolution of the Global Observing System. The impact assessment is based on the Degree of Freedom to Signal adjoint diagnostic tool. There is a continuous data amount increase from the beginning of the ERA5 period, which is reaching more than 30 times of the assimilated data amount today than that of the 1979s. The data increase is mostly attributed to the satellite measurements, particularly lately to the hyper-spectral infrared observations. Though at every period the satellite data amounts are larger than that of the conventional observations, their impact is not getting larger until the late 1980s. At the same time the per observation impact of the conventional observations always remain larger than the satellite ones, which means that the conventional observations, though small in quantity, still remain essential ingredients of the Global Observing System.

Key-words: ERA5 reanalysis, Copernicus Climate Change Service (C3S), Degree of Freedom to Signal (DFS), Observation Influence (OI), conventional and satellite observations

1. Introduction

Copernicus is a European Union (EU) flagship programme, which focuses on Earth observations from satellites and additionally provides various related environmental services to the European citizens. One of such services is the Copernicus Climate Change Service (C3S), which is coordinated by the European Centre for Medium-Range Weather Forecasts (ECMWF) on behalf of the European Union. C3S consists of various aspects of the climate as climate observations, reanalysis, seasonal predictions, and climate projections. All the related datasets are going to be organized into the Climate Data Store (CDS), which will be publicly accessible.

One of the elements of the CDS, which is directly produced by ECMWF is the reanalysis, which is called ERA5 referring to the fact that it is the 5th generation ECMWF reanalysis (*Hersbach* and *Dee*, 2016). This name also highlights the fact that ECMWF has a long experience dealing with reanalysis, and ERA5 is heavily building on that. In the past, ECMWF produced the ERA-15 (*Gibson et al.*, 1997), then ERA40 (*Uppala et al.*, 2005), and afterwards the ERA-Interim (*Dee et al.*, 2011) reanalyses. ERA5 is relying on all the reanalysis experiences gathered in the last few decades and will surpass ERA-Interim in the very near future. In principle, reanalysis should be done in one go from the beginning to the end of the covered time period. However, in practise, the reanalysis production is split into parallel streams running simultaneously in order to have a timely production. This is a practical necessity, which is facilitated with the use of 1-year spin-up periods at the beginning of each production streams. These spin-up years permit the proper warm up of the data assimilation system and ensures smooth transition between the consecutive streams. Typically these streams for ERA5 cover 5-10 years periods. The entire ERA5 dataset from 1979 to real-time will be available to the users during 2018.

Reanalysis is a relatively modern field of Numerical Weather Prediction (NWP), where the past climate system is described with a state-of-the-art NWP data assimilation system and model using all available observations from the examined period. These observations are the ones, which were already routinely used in numerical modeling, but also ones which are reprocessed since then. A reanalysis system provides consistent and coherent global description of the atmosphere, which is very valuable to various user communities interested in the precise description of the past climate.

Since the aim of this paper is not to describe the ERA5 system in details, hereafter we are only going to provide some details of the main differences (improvements) of ERA5 with respect to its predecessor ERA-Interim. Both reanalyses are covering the so called satellite era (from 1979 onwards), where the satellite observations are dominating as compared to the conventional ones. Though it is noted here that the plan is to extend ERA5 backwards until the 1950s. ERA5 is using a very new assimilation and modeling system of the ECMWF's

Integrated Forecasting System (IFS), since it is using the state-of-the-art version (as it is in 2016), which is around 10 years younger than it is the case for ERA-Interim. Therefore, ERA5 includes 10 years of new NWP developments, which are not available in ERA-Interim (for instance at the time of ERA-Interim, various satellite observations like for instance IASI was not available, and consequently the code was not prepared for its use, and therefore the data was not assimilated). Naturally, the horizontal and vertical resolutions are increased in ERA5 as opposed to ERA-Interim: 32 km and 137 levels compared to 79 km and 60 levels, respectively. New feature of ERA5 is the use of the Ensemble of Data Assimilations (EDA, *Bonavita et al.*, 2012) system essentially for the computation of the flow-dependent background error co-variances for the ERA5 data assimilation system. Additionally, EDA can be used to provide uncertainty estimates to the final reanalysis products. This EDA-based uncertainty estimation will be part of the publicly available dataset in the Climate Data Store. EDA is based on a 10-member ensemble with 64 km horizontal resolution. The output frequency of ERA5 is also improved with hourly outputs provided for the users. Beside all these differences, ERA5 is assimilating significantly more data than ERA-Interim thanks to the wide variety of newly reprocessed datasets. All these improvements give a good platform to ERA5 to have superior reanalysis quality than it is the case for ERA-Interim.

It is very important to underline that the experiments used in this study are not the final ERA5 production suites, but tests experiments, which were mainly used to understand the behavior of the Global Observing System (GOS) as it is to be used for ERA5. Particularly, these test (so called “scout”) experiments have reduced horizontal resolution (~64 km), and they are using static background errors. This latter means that climatological background errors were used instead of the information from EDA. Therefore, the information given hereafter is in a very good approximation valid also for ERA5, but it is not exactly the same.

In this article, we are going to give a snapshot of the main aspects of the observation usage in ERA5. Additionally, some information is going to be provided on the impact of observations using an adjoint data assimilation diagnostics tool. In the next chapter, we briefly introduce the methodology applied particularly the main elements of the impact assessment. Section 3 deals with the evolution of the Global Observing System for ERA5 and discusses the impact of the various observations. Finally Section 4 provides summary and conclusions.

2. Impact assessment methodology

There are various ways to assess observation impacts in a data assimilation system. The most widely used method is Observing System Experiments (OSEs), where data assimilation (and ensuing weather forecasts) is run with and without the investigated observations and the observation, impact is deduced based on the performance differences between the two systems (*Kelly* and *Thépaut*, 2007). OSEs can provide impact of given sets of observations to any forecast metric. In the last few decades, adjoint diagnostic tools were developed in order to get a general assessment of the impact of assimilated observations. These tools are able to provide the impact of any observations used in the assimilation system to one specified forecast performance aspect. This forecast performance aspect is typically the reduction of the forecast error, which is attributed to the assimilated observations. Typically there are two such adjoint diagnostics tools (*Cardinali*, 2013): Degree of Freedom to Signal (*DFS*, *Cardinali et al.*, 2004) or Forecast Sensitivity to Observation Impact (*FSOI*, *Cardinali,* 2009). In this study the DFS tool will be used, which is briefly explained hereafter.

As mentioned above, the main question is how the observations can contribute to the decrease of forecast errors. For this, first a forecast error measure has to be defined, which is denoted by J_e. In the ECMWF system, the dry energy norm is used to provide a unique metric (norm) to the different components of the model state variables. The impact of observations on the forecast error can be described as

$$\frac{\partial J_e}{\partial y} = \frac{\partial x_a}{\partial y}\frac{\partial J_e}{\partial x_a}, \tag{1}$$

where y refers to the observations and x_a to the analysis.

The second term in the right hand side is the forecast error sensitivity to the analysis (*Rabier et al.*, 1996), which can be projected to the observations as Forecast Sensitivity Observation Impact (*FSOI*; *Cardinali*, 2009). The first term is the Degree of Freedom to Signal (*DFS*, *Cardinali et al.,* 2004) or Observation Influence (*OI*, which is the *DFS* per datum, i.e., *DFS/n*, where *n* denotes the number of observations for a given observation type), and it can be written using classical data assimilation notations (*Ide et al.*, 1997) as

$$DFS = Tr\left[\frac{\partial Hx_a}{\partial y}\right] = Tr\left[K^T H^T\right] = Tr\left[HK\right], \tag{2}$$

where K is the Kalman gain, which is

$$K = (B^{-1} + H^T R^{-1} H)^{-1} H^T R^{-1}, \tag{3}$$

R is the observation error covariance matrix, B is the background error covariance matrix, and H is the observation operator.

It is important to mention that the Observation Influence is complementary to the Background Influence, since it is related to the weight (impact) of observations in the analysis. Hereafter the *DFS* and *OI* results will be presented in the ERA5 reanalysis context. It should be stressed that the impact of observations is not absolute, since it depends on the entire assimilation and modeling system and also on the use of other observations. *DFS* (*OI*) provides information about the influence of the observation in the analysis and not about the fact that this influence is positive or negative. It is strictly speaking true although experiments show that the *DFS* and *FSOI* fractional impacts are generally similar (*Cardinali*, 2013), pointing to the fact that the direction of the impact can be also anticipated.

3. Observations in the ERA5 reanalysis

Prior to the reanalysis production, intensive experimentations are performed in order to make sure that all the expected observations are assimilated, and the reanalysis quality is superior to that of the previous reanalyses. For the case of the Copernicus/C3S/ERA5, the benchmark (reference) reanalysis is ERA-Interim (*Dee et al.,* 2011), and indeed in most aspects ERA5 has a better performance than that of ERA-Interim. One essential way of the abovementioned testing is the preparation and exploitation of "scout runs", which are simplified versions of the final reanalysis. The main simplifications are the lower horizontal resolution and the use of climatological background errors (instead of EDA). This reanalysis test is capable to assess all the observations to be used in the reanalysis production and spot any observation-related problems prior to the more sophisticated and expensive reanalysis production. In this article, we are going to highlight some of the aspects of observations usage in ERA5 using the results of these scout runs. It is believed that this gives a very good idea about the observations assimilated in ERA5, though it is certainly not exactly the same. Additionally, some impact results will be shown using the Degree of Freedom to Signal (*DFS*) diagnostics (*Cardinali et al*., 2004), which provides information on the impact of observations in the analysis (see details in the previous section). Hereafter some snapshots of the Global Observing System were taken at the beginning of each planned ERA5 production streams. These years are 1979, 1989, 1999, 2009, and 2015, respectively.

3.1. Evolution of the observing system in ERA5

First, the temporal evolution of the global observing system as used in ERA5 will be demonstrated. It is no surprise that there is a continuous increase in data amounts from 1979 onwards. *Fig. 1* shows the 6 months data amounts of the representative ERA5 years. Steady and massive increase can be seen particularly from the beginning of the 21st century onwards. This is due to the rapid increase of satellite observations. In 2015, there are more than 30 times more data assimilated than in 1979.

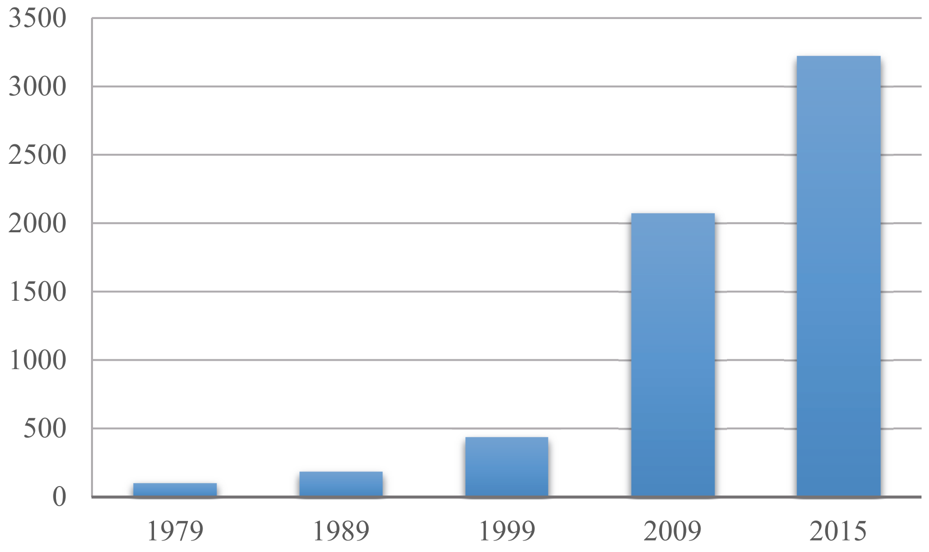

Fig. 1. 6 months of assimilated observation amounts (in million) for the representative ERA5 years.

Fig. 2 shows the absolute amount of conventional and satellite observations. This figure confirms that ERA5 is indeed focusing on the satellite era, i.e., the satellite observation amounts are always larger than that of the conventional ones although the relative amounts are very much different at the beginning and at the end of the reanalysis time window. In 1979, the satellite observations are 65% of the total data amount, while for 2015 it is 90% (though lately there is a sharp increase in conventional data amounts too).

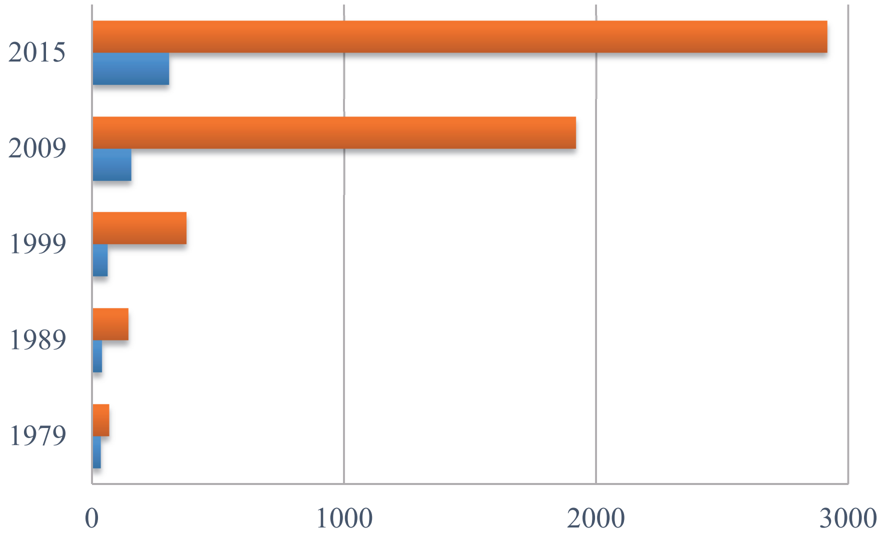

Fig. 2. The absolute amount (in million) of conventional (blue) and satellite (orange) observations in the representative ERA5 streams.

Fig. 3 shows more details of the satellite observations assimilated. It can be seen that the main reason for the huge increase of satellite data is the appearance of infrared radiances, particularly the hyper-spectral data. This covers more than 50% of the total observation amount in the modern Global Observing System. Microwave radiances are the first major satellite data sources, and they are dominating in data amounts until the beginning of the 21st century. SATOB and scatterometer wind data became also essential, particularly due to the fact that with the increase of the satellite data, mostly temperature-related measurements have been added, and the value of the wind observations is getting increased (*Horányi et al.*, 2015). Additionally, there is increased amount of ozone observations (which are strongly enhanced with respect to ERA-Interim). From mid-2000s, the GNSS-RO observations are assimilated, and they are essential due to the fact that they are bias free observations, which can be used (beside radiosondes) for anchoring other satellite data (i.e., to be used for satellite bias correction).

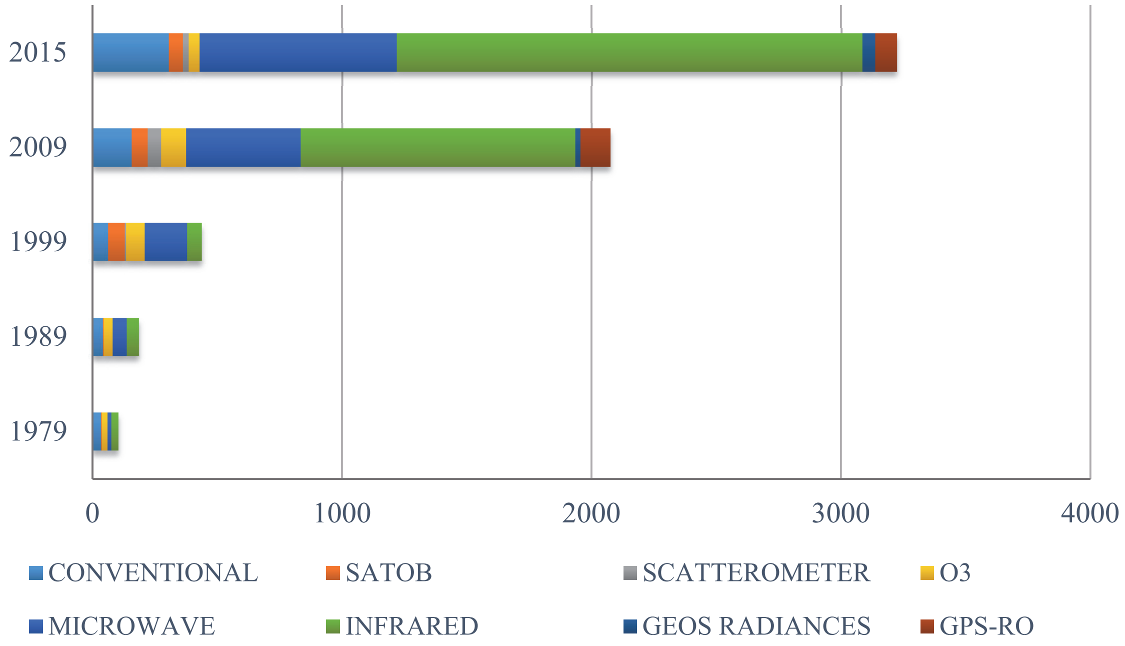

Fig. 3. 6 months observation amounts (in million) for the different observation categories (light blue: conventional, orange: SATOB satellite atmospheric motion vectors, grey: scatterometer winds, yellow: ozone, darker blue: microwave radiances, green: infrared radiances, dark blue: geostationary radiances and brown: GNSS-RO).

Regarding the conventional observations (*Fig. 4*), they are still essential (see some results described in the next section), in spite of their decreasing relative amount compared to satellite data. At the beginning of the time window the radiosondes were dominating, while today the aircraft data are the most dominant conventional data sources. The SYNOP surface observations are relatively unchanged, and the (wind) profilers are getting more in numbers from the 2000s onwards (when the PILOT data is decreasing).

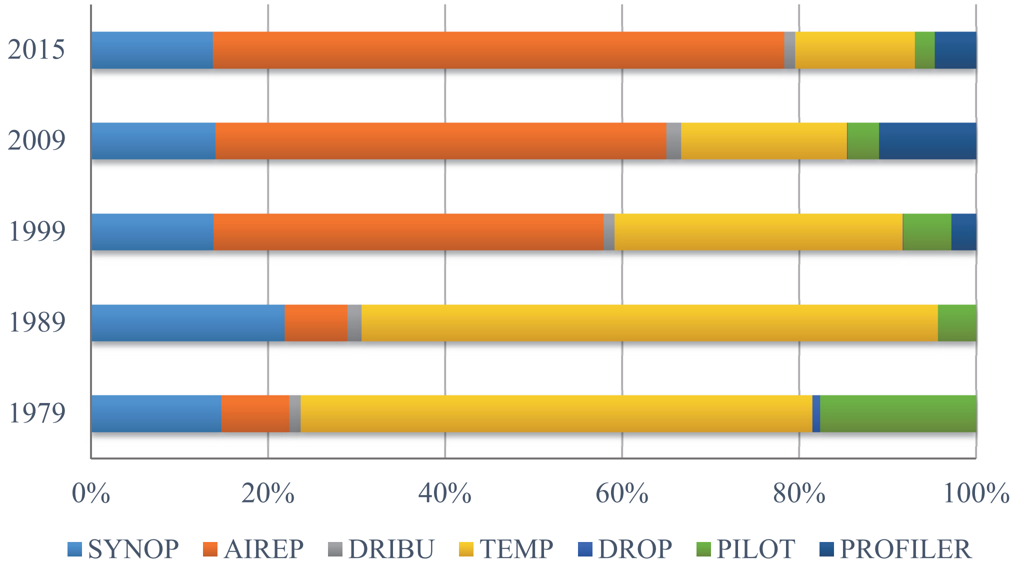

Fig. 4. The relative amounts of the main conventional data sources for the various ERA5 streams (light blue: surface, orange: aircraft, grey: buoy, yellow: radiosonde, darker blue: dropsonde, green: PILOT wind and dark blue: wind profiler observations).

3.2. *Observation impact*

As described in the methodology section, the DFS (OI) diagnostics can give information about the impact of observations in the analysis. Certainly, there are limitations attributed to this tool (*Cardinali*, 2013), nevertheless it provides a valuable insight on the (relative) merits of the various observations. Hereafter the observation impacts will be assessed for the five selected periods. The figures show fractional observation amounts (in %), DFS (in %), and also OI values. The latter measure provides information on the per observation impact of the given observation type.

1979 suite (*Fig. 5*): It was already mentioned that the fractional observation amount is 65%-–35% in favor of the satellite data. On the other hand, the fractional DFS is 25%-–75% (having larger contribution by the conventional observations). This shows that overall, in spite of the larger satellite observation quantity, the total impact is larger for the conventional data. It is particularly clear for the radiosondes, but also for the other conventional observations, i.e., the DFS proportions are larger than that of the observation amount. It is especially striking in the OI values (right panel), where the per observation impact (the impact of one piece of observation) is significantly larger for every conventional data. It is remarkable that the largest OI is for the buoy observations, which indicates that although they are very small in numbers, but very large in impact (*Horányi et al.*, 2017).

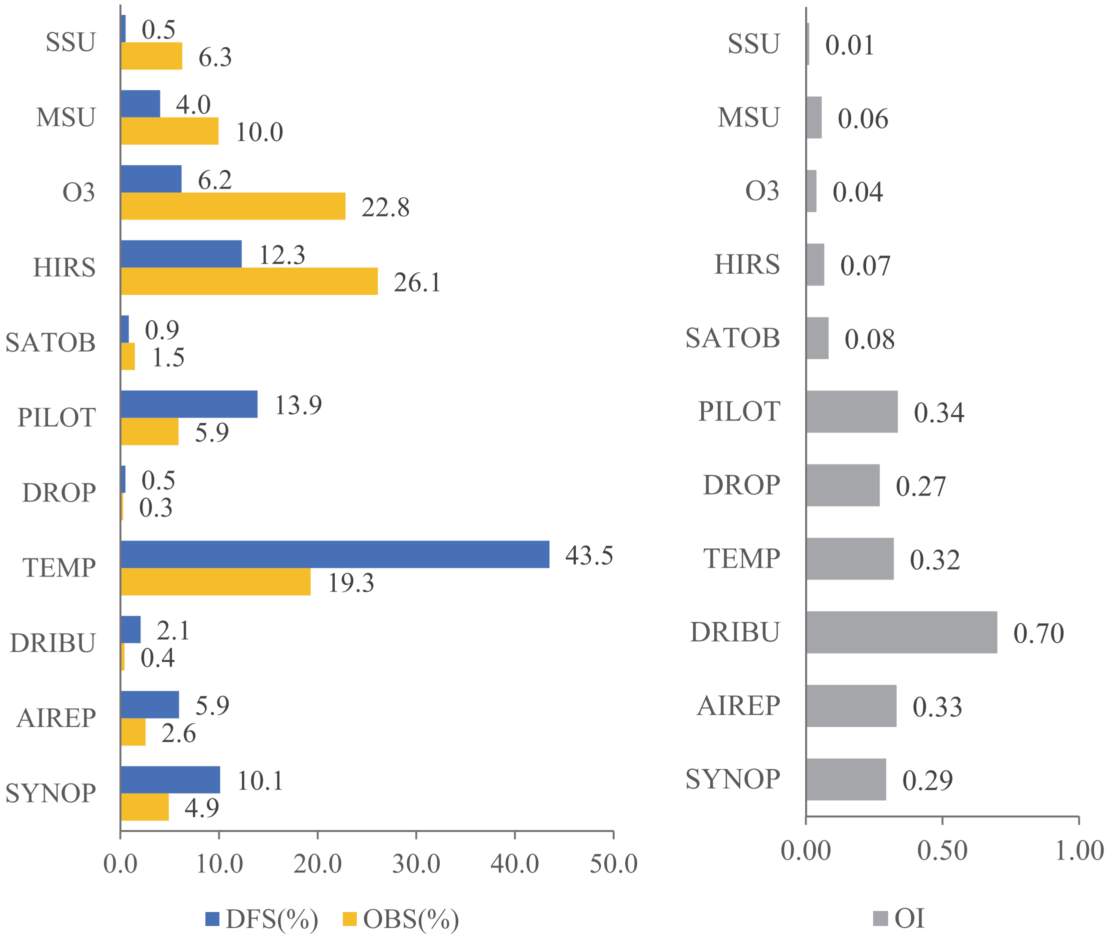

Fig. 5. DFS (blue) and observation (yellow) relative amounts (in %, left) and OI (right). Period: 1979. Observation types: surface (SYNOP), aircraft (AIREP), buoys (DRIBU), radiosondes (TEMP), dropsondes (DROP), PILOT winds (PILOT), satellite atmospheric motion vectors (SATOB), High-resolution Infrared Sounder (HIRS), ozone (O3), Microwave Sounding Unit (MSU) and Stratospheric Sounding Unit (SSU).

1989 suite (*Fig. 6*): The relative satellite observation amount in this period grows to 78%. The respective relative DFS is 60%, i.e., the impact of satellite observations overall is larger than that of the conventional data. This is as expected with the increased amount of satellite data. The discrepancy between the observation amount and DFS is much smaller in this period compared to 1979. Moreover, now the largest impact is for the HIRS data (and its DFS percentage is larger than its fractional observation amount). The OI (per observation impact) values had been dramatically increased for the satellite observations (particularly MSU and HIRS), but they are still smaller than the ones for the conventional observations. There are several factors, which might contribute to the OI increase of MSU and HIRS, for instance, improvements in satellite instrument technology or changes in the GOS, like the rapid increase of satellite data amounts. The total radiosonde impact is just slightly smaller than the HIRS impact.

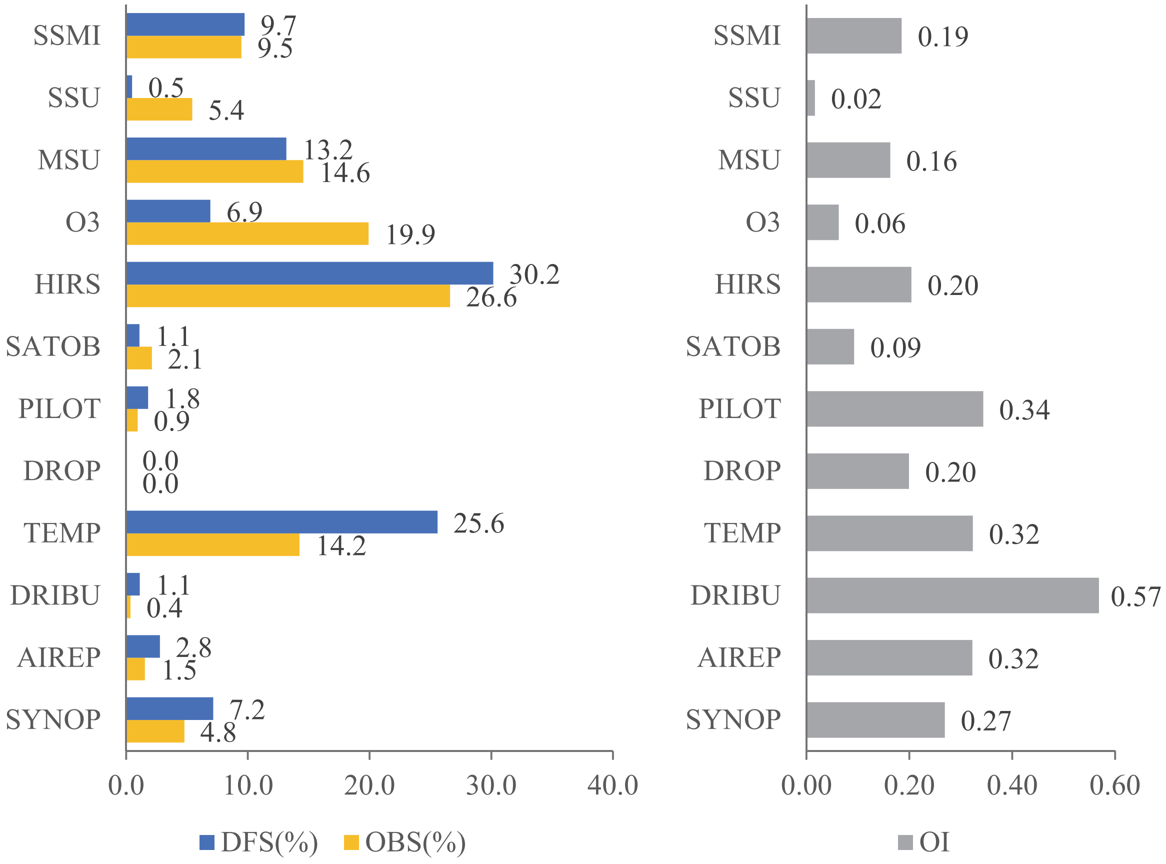

Fig. 6. DFS (blue) and observation (yellow) relative amounts (in %, left) and OI (right). Period: 1989. Observation types: surface (SYNOP), aircraft (AIREP), buoys (DRIBU), radiosondes (TEMP), dropsondes (DROP), PILOT winds (PILOT), satellite atmospheric motion vectors (SATOB), High-resolution Infrared Sounder (HIRS), ozone (O3), Microwave Sounding Unit (MSU), Stratospheric Sounding Unit (SSU) and Special Sensor Microwave Imager (SSMI).

1999 suite (*Fig. 7*): For this period, the satellite observations provide around 85% of the total assimilated data. The impact of the satellite data increased further to 72%. Therefore, from this period onwards, the satellite observations are dominating not only in quantity, but in impact too. The most influential satellite observations are AMSU-A followed by SSMI, HIRS, and SATOB. Among the conventional observations, the aircraft data are getting equally important than that of the radiosondes (the aircraft data amount is larger than the data count for radiosonde observations). Regarding the per observation impact, it is rather similar to the previous period: the conventional observations are much more influential (though the satellites are not that dramatically far behind), and the buoys are the most important observing system in terms of value per observation.

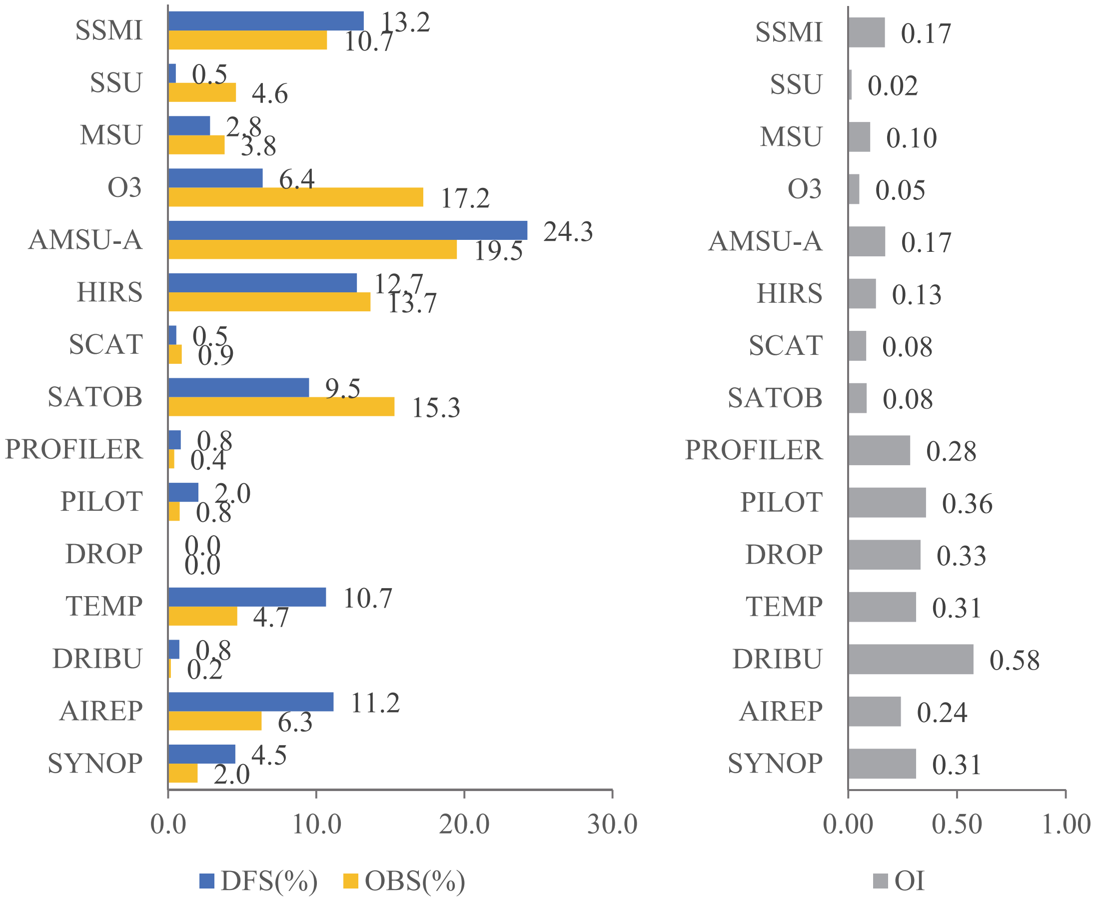

Fig. 7. DFS (blue) and observation (yellow) relative amounts (in %, left) and OI (right). Period: 1999. Observation types: surface (SYNOP), aircraft (AIREP), buoys (DRIBU), radiosondes (TEMP), dropsondes (DROP), PILOT winds (PILOT), wind profilers (PROFILER), satellite atmospheric motion vectors (SATOB), scatterometer winds (SCAT), High-resolution Infrared Sounder (HIRS), Advanced Microwave Sounding Unit (AMSU-A), ozone (O3), Microwave Sounding Unit (MSU), Stratospheric Sounding Unit (SSU) and Special Sensor Microwave Imager (SSMI).

2009 suite (*Fig. 8*): The relative amount of satellite data reaches its present state with around 90%. This is corresponding to 80% of impact, suggesting that still the conventional observations have significantly larger relative impact than their quantity would suggest. The largest satellite impact contributors are AMSU-A, AIRS, IASI, and GNSS-RO, respectively. It shows the emerging of the hyper-spectral infrared instruments and the important introduction of GNSS-RO measurements. In the conventional observations, now the aircraft data have the largest impact surpassing radiosondes. It is worth mentioning that the use of all-sky technology (*Bauer et al*, 2010; *Geer et al.*, 2010) for the satellite data improves their impact in the analysis, indicating that improved data assimilation methods can result in better data usage and larger observation impact.

2015 suite (*Fig. 9*): The main change with respect to the previous period is that the largest overall impact is coming from the IASI data, which is not surprising, since they contain around 37% of the total data. Overall, the infrared instruments provide around 40% impact (the other two largest contributions are AIRS and CRIS). Microwave (particularly AMSU-A) are still essential as the conventional observations too. For the conventional data, the influence of SYNOP observations is matching the ones for radiosondes. The Observation Influence (OI) is more homogeneous, though the conventional data are still clearly standing out.

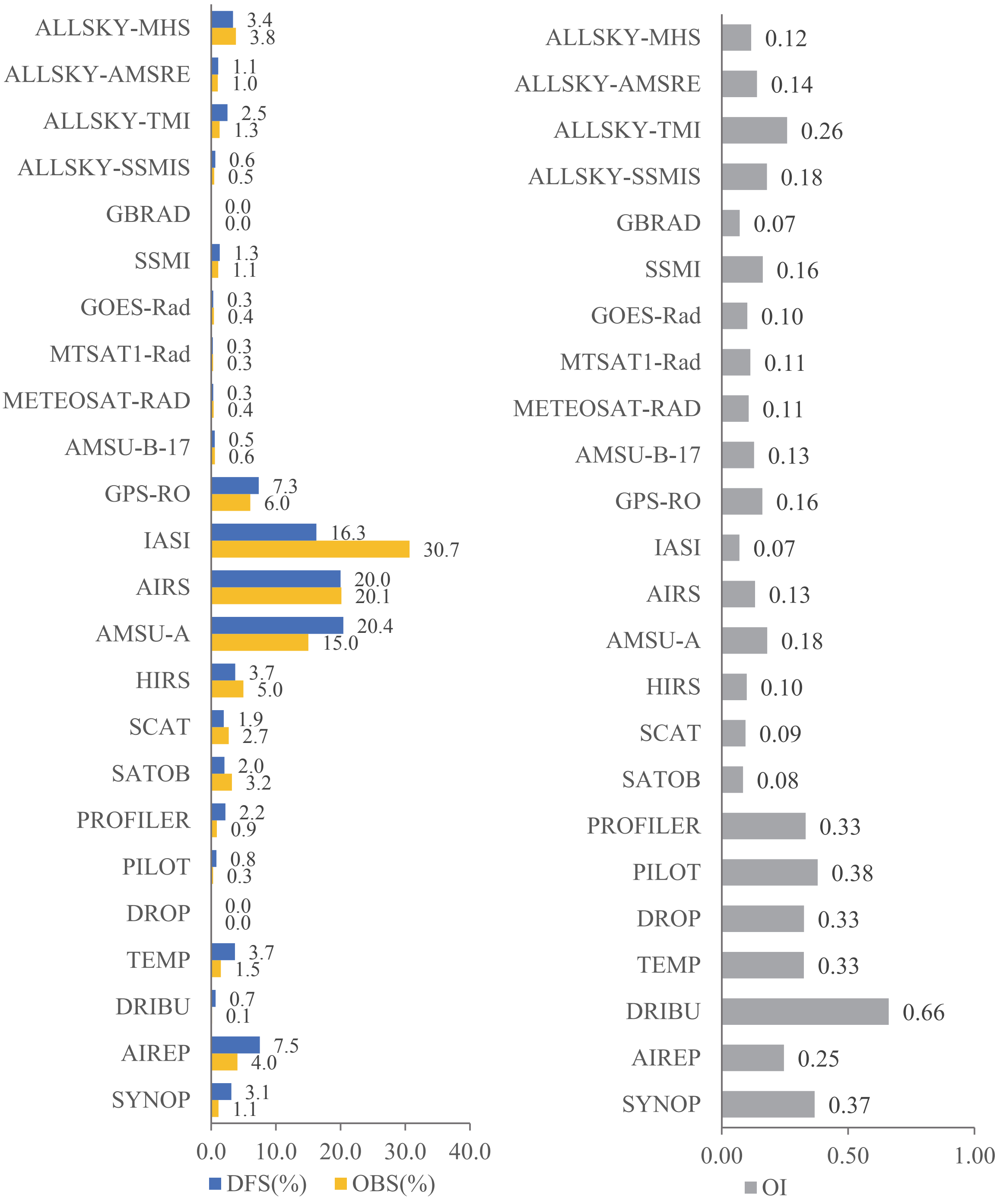

Fig. 8. DFS (blue) and observation (yellow) relative amounts (in %, left) and OI (right). Period: 2009. Observation types: surface (SYNOP), aircraft (AIREP), buoys (DRIBU), radiosondes (TEMP), dropsondes (DROP), PILOT winds (PILOT), wind profilers (PROFILER), satellite atmospheric motion vectors (SATOB), scatterometer winds (SCAT), High-resolution Infrared Sounder (HIRS), Advanced Microwave Sounding Unit-A (AMSU-A), Atmospheric Infrared Sounder (AIRS), Infrared Atmospheric Sounding Interferometer (IASI), GNSS-RO (GPS-RO), Advanced Microwave Sounding Unit-B (AMSU-B-17), METEOSAT geostationary radiances (METEOSAT-RAD), MTSAT1 geostationary radiances (MTSAT1-Rad), GOES geostationary radiances (GOES-Rad), Special Sensor Microwave Imager (SSMI), ground based radar (GBRAD), Special Sensor Microwave Imager/Sounder (ALLSKY-SSMIS), TRMM Microwave Imager (ALLSKY-TMI), Advanced Microwave Scanning Radiometer (ALLSKY-AMSRE) and Microwave Humidity Sounder (ALLSKY-MHS).

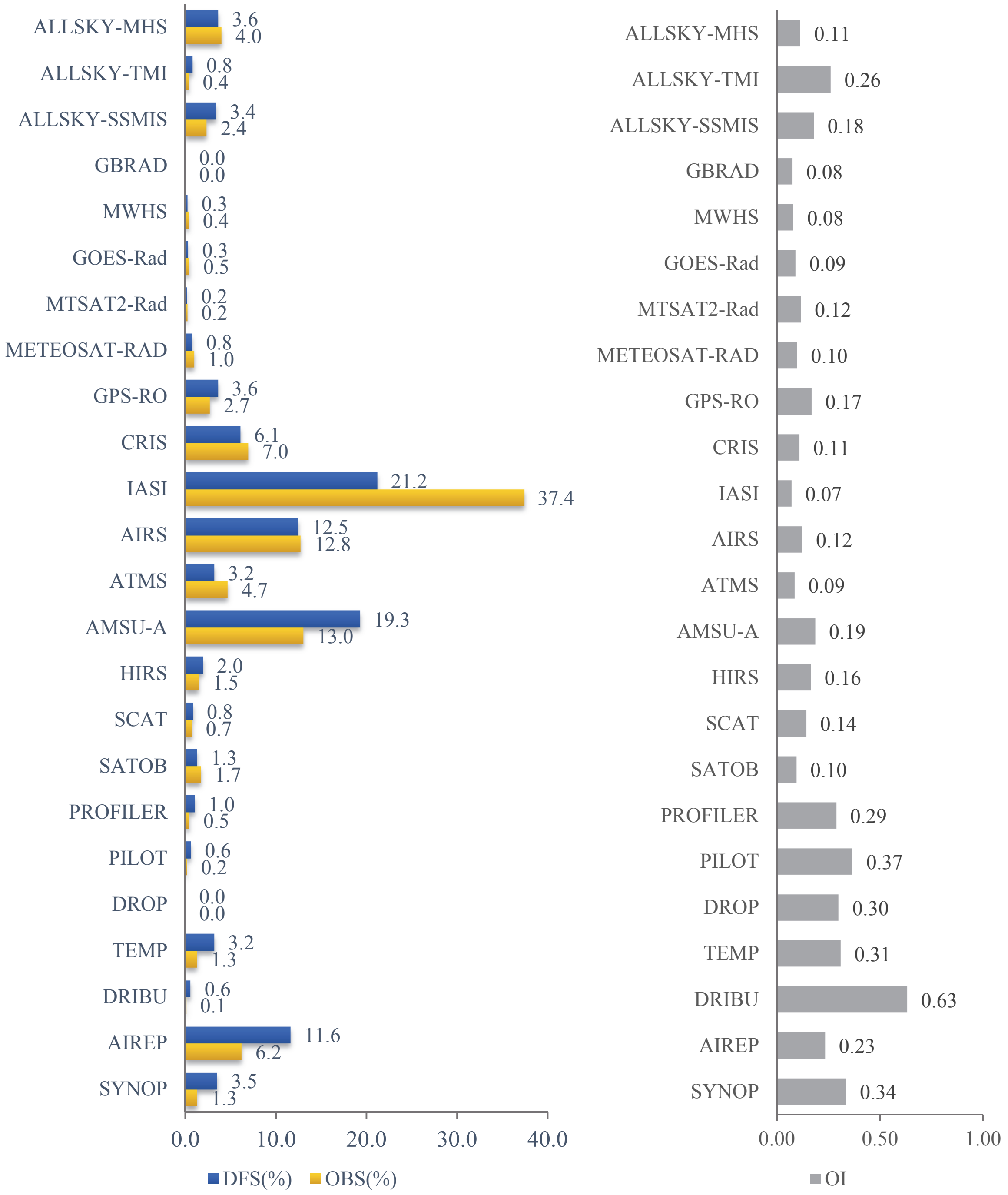

Fig. 9. DFS (blue) and observation (yellow) relative amounts (in %, left) and OI (right). Period: 2015. Observation types: surface (SYNOP), aircraft (AIREP), buoys (DRIBU), radiosondes (TEMP), dropsondes (DROP), PILOT winds (PILOT), wind profilers (PROFILER), satellite atmospheric motion vectors (SATOB), scatterometer winds (SCAT), High-resolution Infrared Sounder (HIRS), Advanced Microwave Sounding Unit-A (AMSU-A), Advanced Technology Microwave Sounder (ATMS), Atmospheric Infrared Sounder (AIRS), Infrared Atmospheric Sounding Interferometer (IASI), Cross-track Infrared Sounder (CRIS), GNSS-RO (GPS-RO), METEOSAT geostationary radiances (METEOSAT-RAD), MTSAT2 geostationary radiances (MTSAT2-Rad), GOES geostationary radiances (GOES-Rad), Microwave Humidity Sensor (MWHS), ground based radar (GBRAD), Special Sensor Microwave Imager/Sounder (ALLSKY-SSMIS), TRMM Microwave Imager (ALLSKY-TMI) and Microwave Humidity Sounder (ALLSKY-MHS).

4. Summary and conclusions

ERA5 is prepared under the umbrella of the Copernicus Climate Change Service of the European Union. ERA5 is the 5th generation atmospheric reanalysis at ECMWF, which has important additional features with respect to its predecessor ERA-Interim. The final ERA5 product will have significantly higher horizontal and vertical resolution, and the assimilation system will include cca. 10 years of Numerical Weather Prediction (NWP) development work. The background error co-variances will be based on a 10-member EDA system, which is also going to be used to provide uncertainty estimations to the reanalysis product. Such a modern, high resolution reanalysis system provides an excellent opportunity to study the evolution of the Global Observing System and the varying impact of the various components of it. In this article, a short overview is given about some aspects on the use and impact of observations in the test versions of the ERA5 reanalysis system. These experimental versions have lower horizontal resolution and use climatological (static) background errors.

Not surprisingly, the assimilated observation amounts had been dramatically increased since 1979 having more than 30 times data today than at the first years of ERA5. While the satellite observation amounts are always larger than the conventional ones, their impact is smaller at the very beginning of the period. The conventional observations remain always essential in the GOS, however in the last decades, the fast growing number of satellite observations can counter-balance their overall impact. The other consequence of the increased amount of satellite observations is that information about the mass variables (temperature, humidity) of the atmosphere is overwhelming with respect to the wind measurements. Therefore, additional wind measurements would be welcome in the GOS. Other interesting aspect is that the per observation impact of the satellite data can be further increased. For instance, the use of all-sky radiances (instead of the clear-sky only) can help to better exploit satellite information and further enhance their impact to the reduction of the forecast error. In the last 10 years or so, GNSS-RO observations became essential in the GOS, since they are bias free observations and therefore, they can be used as anchor measurements for satellite bias corrections. In spite of the emergence of huge amount of satellite observations, the conventional observations will have still crucial role in the modern NWP systems. Particularly, the highest influence of one piece of observation is always belonging to the buoy observations.

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