Sixth WMO Workshop on the Impact of Various Observing Systems on Numerical Weather Prediction Shanghai, China, 10-13 May 2016

Workshop Report

Edited by Yoshiaki Sato, JMA, and Lars Peter Riishojgaard, WMO

Introduction

The sixth WMO Workshop on the Impact of Various Observing Systems on Numerical Weather Prediction (NWP) was held 10-13 May 2016 at the Shanghai Meteorological Service (SMS) Headquarters in Shanghai, China. The Workshop was hosted for the WMO Commission for Basic Systems by the China Meteorological Administration (CMA) and SMS, and additional financial support was provided by the World Weather Research Program and the World Climate Research Program. The WMO Inter Programme Expert Team on the Observation System Design Evolution (IPET-OSDE) had proposed topics for NWP impact studies (Appendix II) relevant to the evolution of global observing systems (GOS) and participants were encouraged to present results on those topics in particular.

The workshop was attended by roughly 80 participants from 14 countries (see list of participants in appendix III), and it included experts on data assimilation and observation impact, experts on climate change and seasonal forecasting, representatives from space agencies and from private industry, as well as managers of observing networks. The scientific organization committee comprised Erik Andersson (Co-Chair, ECMWF), Yoshiaki Sato (Co-Chair, JMA), Carla Cardinali (ECMWF), John Eyre (Met Office, UK), Ron Gelaro (GMAO, NASA), Jianjie Wang (CMA), Jochen Dibbern (DWD), Thibaut Montmerle (Météo-France), Lars Peter Riishojgaard (WMO) and Wenjian Zhang (WMO). At the workshop the WMO Secretariat was represented by the Director of Observations and Information Systems, Dr. Wenjiang Zhang and the WIGOS Project Manager, Dr. Lars Peter Riishojgaard.

The workshop was organized in three oral sessions and one joint poster session:

1. Global forecast impact studies (chaired by J. Eyre and C. Cardinali);
2. Regional forecast impact studies (chaired by R. Gelaro and Jiangdong Gong (CMA));
3. Sensitivity forecast impact studies (chaired by J. Dibbern and T. Montmerle);
4. Poster session.

There were roughly 15 presentations in each oral session, for a total of 43 oral presentations and 41 poster presentations (see the program in Appendix I). Each oral session was followed by a dedicated discussion period. In order to lead off the discussions the Session Chairs presented their draft summary reports capturing the salient points, statements about observation impact and recommendations, taking into account also related material from the joint poster session. These summary reports were then discussed by all participants and subsequently amended by the Session Chairs. Overarching messages from the Workshop, tentative answers to the Science Questions, and any modifications to the Science Questions for the impact work in the future, were all discussed during the wrap-up session on the final day. This report includes highlights from the presentations and it captures the main points agreed on during the workshop. Where appropriate, the conclusions are stated in terms of formal recommendations that are addressed either to WMO, to various observing system operators (both on the conventional and on the space-based side), or to the NWP community itself.

Session 1. Global forecast impact studies.

In general, the major NWP centers tend to see less evidence of redundancy of observations or saturation of the impact than was reported at the previous WMO Impact Workshop in Sedona in 2012 (henceforth referred to as Sedona 2012). It was now reported that adding new observations to the assimilation would almost always lead to a positive impact on forecast skill. This could be due to either an improvement in quality of the observations or improved assimilation techniques. The Workshop was not in a position to make an unequivocal statement about the relative importance of these two factors (see also below regarding progress in assimilation).

In terms of the most important observing systems contributing to forecast skill of global NWP models, the top five system were, in no particular order, microwave sounders (AMSU-A, ATMS), hyperspectral infrared sounders (AIRS, IASI, CrIS), radiosondes, aircraft data and atmospheric motion vectors (AMVs). The list was thus similar to the findings from Sedona 2012. GNSS radio occultation (RO) data are also important, and the general sense was that if a larger number of soundings could be provided, this type of observation would become even more important. Among the notable changes with respect to Sedona 2012 was the emergence of ocean surface winds from scatterometers as a significant contributor to NWP skill at all major centers.

Most of the reports shown at the Workshop included results given in terms of Forecast Sensitivity Observation Impact (FSOI) statistics. However, also some classical data denial studies were reported. Among the notable results:

- So-called secondary (or back-up) satellites within a given orbital plane have a substantial impact on skill – their data are thus not redundant with those provided by the primary satellites;
- Removing the NOAA PM orbit coverage has a substantial negative impact on skill;
- Removing polar GNSS RO also has a substantial negative impact, but not as much as removing the PM coverage.

Scientific progress on assimilation was reported in a number of different areas. One area showing very significant improvement was the use of microwave radiances affected by cloud and precipitation, i.e. all-sky radiance assimilation. This has been made possible by much improved modelling of radiative transfer in these situations, especially in the water vapor absorption band at 183 GHz. The additional microwave data ingested in all-sky mode has been found to improve the wind analysis when assimilated using 4D-VAR, which demonstrates the dynamical adjustment of the model to the new data.

Several new satellite data types have entered operational assimilation during the past four years, all with positive impacts. Among them are: MetOp-B (in addition to MetOp-A); CrIS and ATMS on Suomi-NPP; Megha-Tropiques/SAPHIR (microwave sounder in low-inclination orbit); ISS Rapidscat (scatterometer in low-inclination orbit); FY-3C/MWHS-2 183 and 118 GHz channels; GCOM-W/AMSR-2; GPM-core/GMI; LEO-GEO AMVs. In addition, assimilation experiments with both AMV and Clear Sky Radiances from the Korean geostationary COMS satellite are underway. Generally positive impacts of surface-sensitive microwave channels over land and over sea-ice was noted, and the impact was found to be increased when using retrieved microwave emissivity. MWHS-1 data from FY-3B have been used over land and over snow surfaces with some positive impact. On the infrared side, it was pointed out that several sensors (e.g. IASI) are still under-utilized over snow-covered surfaces.

Several centers reported results obtained using explicit modeling of observation error correlation. Due to technical limitations, observation errors had been assumed to be uncorrelated in most assimilation systems until relatively recently, and instead some level of thinning of the observations had been employed to at least partly account for the existing correlations. Generally good impact was obtained for microwave and infrared radiances using inter-channel correlated observation errors. Studies regarding temporally correlated errors of ground-based GNSS data found negligible correlations beyond 1.5 hours. Further work on the modelling of correlated observation errors would be beneficial especially to high density and high volume data provided by nadir-looking satellites and by ground-based radars. Further pursuit of such work was strongly encouraged.

Recommendation 1
All NWP centers are encouraged to include explicit models of observation error correlations, in particular for satellite and radar data.

Recommendation 2
The constellation of scatterometers should be improved (better orbital spacing) in order to provide better spatial and temporal coverage. Generally the impact of adding observations in data void areas is significantly higher than the impact of adding additional data in areas where observations already exist.

Recommendation 3
NWP centers rely on high-quality level 1 data. Space agencies are encouraged to make every effort to improve the quality of their level-1 data, including via the Global Space-based Inter-Calibration System (GSICS).

In addition to the level 1 radiance products mentioned above, NWP centers also rely on high-quality level 2 processing undertaken by the space agencies, e.g. for AMVs and scatterometer ocean surface winds. For the AMVs in particular, the space agencies were commended for the recent improvements in quality control and product quality, including improved height assignments.

Recommendation 4
Additional data impact studies for new AMV products (e.g. LEO-GEO winds, IR sounder winds, MISR winds) are strongly encouraged.

The positive direct impact of GNSS-RO data on global NWP skill was confirmed, as well as the indirect impact of these data through their contribution to bias correction of radiance data from other satellite sensors. In similar fashion these data have the potential to also help improve the radiosonde bias correction. It was noted that the Taiwan-US COSMIC-1 constellation had entered a phase of decreased capabilities (fewer observations than previously due to fewer satellites still operating). The FORMOSAT-7/COSMIC-2 constellation as planned would consist of two components, namely COSMIC-2A: Six satellites in low inclination orbits, and COSMIC-2B: Six satellites in high inclination orbit. Only the first segment (COSMIC-2A), providing soundings primarily over the tropical regions is currently funded. The Workshop stressed the importance of also having GNSS-RO data available over the extratropical regions.

A study based on an ensemble of data assimilations (EDA) regarding the expected impact of a substantially enhanced future RO system demonstrated no saturation of impact (but a gradual decrease in incremental impact) even at ~100,000 profiles per day. Observing System Simulation Experiments (OSSEs) on future GNSS-RO systems are still ongoing and will focus on issues such as data quality and vertical coverage in the future.

Recommendation 5
(first proposed by the IROWG and supported by this Workshop in slightly modified form)
The deployment of an operational constellation of GNSS-RO satellites capable of providing at least 20,000 high quality soundings per day, at near-uniform global coverage and extending well into the lower troposphere is strongly recommended.

An OSSE study demonstrated the potential impact on tropical cyclone track forecasting of a geostationary hyperspectral IR sounder. Compared to an instrument - or even to a moderately sized constellation of instruments - flying in LEO, a GEO sounder can provide higher temporal resolution. Such GEO hyperspectral IR sounders are planned as FY-4A/GIIRS and MTG-S1/IRS to be flown by China and by EUMETSAT, respectively. The potential impact of a 183 GHz multispectral GEO radiometer concept has been the subject of an OSSE study focusing on improving the analysis of humidity. So far this study has shown that it may be difficult to make significant improvements using the data from this proposed instrument concept, unless the accuracy of the data can reach the same level as those of the typical LEO MW sounders. However, this was found to be far from unusual for new space-borne technologies, so the Workshop adopted the following recommendation:

> ***Recommendation 6***
> *The CGMS space agencies operating GEO satellites are encouraged to continue the development and deployment of hyperspectral IR GEO sounders. Further studies of GEO MW sounders and imagers and their potential impacts are encouraged.*

Regarding the impact of aerosol observations on NWP it was noted that case studies under the auspices of the WMO Commission for Atmospheric Science Working Group on Numerical Experiments (WGNE) were underway. Data assimilation for these observations continues to be a challenge due to the large uncertainties regarding the actual quantities being observed. It was noted that not enough high-quality data sets are available for assimilation and for validation of the assimilation products.

The positive impact of aircraft observations, both flight-level and profile data, on skill continues to be very substantial. The quantity of profile observations made available through the AMDAR program and used for NWP has increased significantly with respect to the status in 2012. All NWP centers were encouraged to further increase the use of profile data from ascending and descending aircraft. Moisture observations from the Water Vapor Sensing System (WVSS) now operating on 135 US and 8 European AMDAR-equipped aircraft were shown to be of equal or better quality than radiosonde measurements. The largest impact on skill is over the CONUS region, where the impact is 50% larger than that of the twice-daily radiosondes. It was noted that ascent profiles tended to have slightly larger impact than data observed during aircraft descent. The assimilation of WVSS data in the NCEP Global Forecast System improved moisture forecasts out to 66 hours and had positive effects on the 12-36 hour precipitation forecasts at all thresholds.

> ***Recommendation 7***
> *WMO is strongly encouraged to investigate and publicize the benefits of aircraft observations in general and of humidity observations in particular, in order to help sustain and further expand the AMDAR program.*

During the workshop the scheduling of radiosonde launches was introduced as a topic of substantial interest to the WMO Commission for Basic Systems and the WMO community as a whole. Currently the radiosondes are launched simultaneously (primarily at 00 UTC and 12 UTC) by national weather services all over the world as part of their commitments to the WMO RBSN (Regional Basic Synoptic Network). However, both for climate applications and for certain local forecaster applications, some flexibility in the launch schedule may be desirable. In addition, alternative launch schedules might prove to be beneficial to regional limited area NWP activities. No studies pertaining to this topic were presented, but the Workshop agreed on the following two recommendations for future work:

> ***Recommendation 8***
> *WMO to develop specific alternative scenarios for radiosonde launch schedules; NWP centers were encouraged to perform data impact experiments for such scenarios.*

> ***Recommendation 9***
> *Recent CMA field experiments with augmented launches has provided a useful dataset that could be used by other NWP centers for impact experiments; CMA is encouraged to make the extra sounding data available to the international NWP community for study purposes.*

The Workshop took note of the current development in the space sector regarding commercial data providers proposing to put privately funded GNSS-RO constellations in space with an aim to sell these observations to national governments, and it was emphasized that unless the data are procured with a clear aim to continue respecting existing principles on international data sharing, these data will not be fully utilized, since their main application is in the area of global numerical weather prediction. Similar issues regarding proprietary data was raised several times during the discussions also for other observing systems.

> ***Recommendation 10***
> *All data providers are encouraged to continue to share all observations internationally, especially those observations that are essential for numerical weather prediction, e.g. all GNSS-RO soundings.*

During the Workshop, concerns about inconsistent use of terminology which might lead to misinterpretation of the results were expressed. Therefore, the following recommendation was agreed:

> ***Recommendation 11***
> *All NWP centers are strongly encouraged to use standard data assimilation terminology (e.g. Ide et al., 1998 and similar references) in their presentations; measures of statistical significance should be included in all forecast skill charts.*

Session 2. Regional forecast impact studies.

(Some of the presentations in this session were reporting primarily on global impact studies; this material is included below, but resulting formal recommendations consistent with those provided in Section 1 are not repeated here).

The utilization of observational data in regional NWP - and therefore also the level of knowledge about observational data impact in regional NWP - had progressed very significantly since Sedona 2012. In the previous two impact workshops in 2008 and 2012, many limited area NWP systems had shown only limited impact of local observations, and had in fact received much of their information from observations assimilated into the global systems providing the background and boundary conditions. In contrast during this (2016) workshop all presenters showed significant impact of local observations assimilated into the limited area model itself.

Several presenters demonstrated that assimilating observations at increased temporal resolution improved short to medium range forecast skill. This was assumed to be at least in part caused by a significant increase in the number of assimilated observations that are asynoptic in nature, e.g. satellite radiances, ground-based GPS, wind profiler data.

Radiosonde information above 100 hPa was found to be an important contributor to forecast accuracy in the stratosphere in both the NH and SH extratropics. While aircraft observations continue to have substantial positive impact on forecast skill, these observations cannot be expected to fully replace the vertical profile information of wind, temperature and humidity provided by the radiosonde network.

A discernible positive impact of assimilating data from up to four scatterometers simultaneously was shown. It was noted that all NWP centers were now showing positive impacts, not only in selected cases of high impact weather as was the case in Sedona 2012, but also on average forecast skill. The Workshop attributed this positive development primarily to improved assimilation techniques rather than to any increase in observation counts for these observations.

The addition of AMVs from MISR to the standard suite of satellite winds already used for operational assimilation was found to provide a modest additional positive impact on skill. This was nonetheless considered a significant result, since the spatial coverage of MISR AMVs is extremely limited compared to the existing AMV coverage.

A temporary reduction in the number of daily Russian radiosonde launches (only one ascent per station per day from January 1 to February 12 2015) had led to a demonstrated significant degradation in medium-range forecast skill over Northeast Asia and the North Pacific. The Russian soundings (amounting to well over 10 % of total number of global radiosonde ascents, even after the temporary reduction) were found to be essential, especially during the northern hemisphere winter season when the use of satellite observations is rendered difficult due to snow and/or sea ice on the surface. It was noted that WMO had reacted to this reduction and that Russia had since resumed its twice-daily launch schedule.

The data types currently being studied or tested for assimilation at the finest scales (meso- to convective-scale NWP) were broadly classified as follows in terms of their usage:

a. Maturing data types
- Radar reflectivity, radial wind, and retrieved observations from radars such as relative humidity profiles;
- MODE-S wind and temperature (more observations than AMDAR available over Europe, especially the extra wind observations are useful);
- AMDAR measurements of water vapor;
- Ground-based GNSS slant total delay, zenith total delay;
- Space-based radar observations (e.g., GPM/DPR).

b. Emerging data types
- Ground-based MW radiometers, focus on brightness temperatures rather than retrievals;
- Temperature and water vapour from rotational Raman lidars (TRRL, WVRRL);
- Water vapour differential absorption lidar measurements;
- Radar refractivity.

c. Improved or enhanced usage of conventional data types
- Supplemental radiosonde launches;
- Surface mesoscale networks; e.g., China Automatic Weather Station (AWS) network.

It was noted that some regional NWP systems show significant impact from data that are not shared internationally (not disseminated via the GTS). Since the impact has been demonstrated and since regional model domains are set up largely irrespective of national borders, increased international distribution of these observations is required in order to make further progress in regional NWP.

> ***Recommendation 12***
> *WMO to articulate the requirement for international sharing of all observations used in NWP systems, e.g. via the new RBON (Regional Basic Observing Network) development; data providers (including NMHSs and space agencies) are encouraged to make these data available to all NWP centers.*

It was noted that the observational data requirements for convective scale NWP are very challenging in terms of both accuracy and data latency. There is a need for higher vertical resolution observations of temperature, wind and humidity in the boundary layer in order to help improve convective scale forecast skill. A systematic set of OSSEs would be useful to help define the requirements for these observations. Passive measurement techniques alone are not likely to be able to satisfy these requirements, so active sensing techniques and assimilation in test mode of the data provided by them should be pursued.

> ***Recommendation 13***
> *NWP community to carry out impact studies regarding proposed observing systems for high-resolution sensing of the atmospheric boundary layer; WMO to document and record the requirements for such observations through its Rolling Review of Requirements.*

Convective scale NWP is now showing impact from assimilation of radar reflectivities and Doppler winds, but there is still much potential for further exploitation of these data. At this point in time, the data assimilation effort is still mostly focusing on the use of fairly high level products, but it was noted that in line with previous successful efforts in assimilation of satellite data, direct assimilation of radar reflectivity should be the goal. Assimilation of radar reflectivity provides significant skill improvement, either via the use of a latent heat nudging approach (e.g. in the NOAA RAP/HRRR,in the Met-Office UK4 or in the DWD COSMO-DE systems), or by considering a 1D Bayesian inversion method to retrieve profiles of relative humidity that are considered as pseudo profiles in the Var (e.g in Météo-France AROME or in the JMA MSM systems). Radar polarization information has proven to be useful for the quality control of radar data and for the correction of the signal attenuation due to precipitation. Including this information directly in the assimilation itself may provide additional benefits, but the experimental evidence for this was unclear at the time of the workshop. Further investigation is encouraged.

Recommendation 14
The radar data assimilation community is encouraged to move gradually toward assimilation of lower level products, in line with the methodologies first pioneered for satellite radiance assimilation.

Recommendation 15
Further investigation into the use of radar polarization information is encouraged.

It was pointed out that perhaps even more than for other observing systems, attention to quality control is absolutely vital for any radar data assimilation effort due to the effect of clutter and various non-meteorological sources of back-scatter. The sheer volume of data provided by the radars poses significant technical and scientific challenges. Further investigation into various approaches for handling this issue is needed. It was noted that thinning removes mesoscale features, and therefore may not be desirable. Super-obing (horizontal averaging) will not remove the correlated errorw, and direct investigation into the modeling of correlated observation errors is therefore needed (additional support for ***Recommendation 1***).

Both the radar and the ground-based meso-network communities would benefit from increased organization, standardization of data formats and data quality control procedures, and from increased data sharing on an international basis. WMO has initiated such efforts but increased emphasis on this issue is strongly recommended.

Recommendation 16
WMO is encouraged to continue and strengthen its efforts on the development of protocols and formats for both national and international exchange of weather radar data.

Support was expressed again here for ***Recommendation 13.*** The challenges of using 3D-VAR assimilation techniques for high-frequency assimilation due to spin-up issues, and the need for additional tuning, point to the need to exploit 4D techniques for mesoscale data assimilation. This would also facilitate a more efficient use of high temporal frequency observations.

There has been much progress in the validation of the AWS mesoscale ground network over China, and experimental evidence showing the positive impact of these data on regional NWP was presented.

MODE-S observations were found to give a small additional positive impact in the early part of the forecast range (reduced RMS errors in temperature and wind speed) in the DWD KENDA. GPS slant delay data provide a positive impact during the first 12 hours of the forecast range in DWD KENDA. Ground-based Microwave radiometers (MWR) were shown to have a modest positive impact on the precipitation forecast (but not on the model dynamical fields) during the early part of the forecast range in the Météo-France AROME system. There was some indirect evidence that MWR data might have more impact if radiances instead of retrievals were used and if the instruments are placed away from radiosonde sites; the likely explanation for the latter was thought to be mostly related to the general advantage of improved horizontal distribution of the observations rather than to any unique relationship between the measurements from radiosondes versus MWRs.

Session 3. Sensitivity forecast impact studies

(In some cases there was significant overlap in subject matter between studies presented in this session and the two previous ones; for the benefit of readers who did not attend the workshop the results and recommendations are generally grouped and reported under the session of primary relevance).

Drifting buoys were found to have a very substantial positive impact at the global level. A data impact study aimed at investigating the relative contributions from VOS (the WMO Voluntary Observing Ships) and the drifting buoys in the Atlantic showed that both are important, their relative contribution depending on weather situations and the specific geographic area considered.

For some data assimilation systems using very short observation cut-off times, aircraft observations taken during ascent/descent are the most important data, together with radiosondes and geostationary satellite data products. Over the Arctic regions, buoys and LEO satellite observations are essential, but additional in situ vertically resolved data (soundings) are needed.

> ***Recommendation 17***
> *WMO and the Global Cryosphere Watch (GCW) to investigate possibilities of obtaining additional soundings over the Arctic.*

Some radar wind profilers have shown good accuracy, and with the use of efficient QC algorithms these now appear to have the potential to be as informative as radiosonde winds over the vertical extent of their coverage.

The requirements for observations to support climate studies and climate monitoring were discussed during the workshop, and it was noted that the requirements differ significantly across different sub-disciplines within the general area of climate. Detection of long-term climate trends depends less on extensive horizontal coverage and more on calibration and long-term stability of measurement accuracy. Process studies and detection of extreme events on the other hand lead to requirements that are more similar to the requirements for the weather-related WMO application areas. The development of OSSE methodologies to address specific climate-related observing network design issues was recognized as an emerging area, and further work in this area was encouraged.

> ***Recommendation 18***
> *Further investigation into the use of impact studies for the design of climate observing networks is encouraged.*

It was noted that for seasonal to decadal-range prediction performed with coupled models, additional observations would be needed, e.g. sub-surface ocean observations, more detailed sea ice observations (additional parameters needed), additional aerosol and gaseous atmospheric constituents (greenhouse gases), solar irradiance measurements. No impact studies of this nature were presented at the Workshop, but it was recommended that this be done in the future.

> ***Recommendation 19***
> *Longer range (seasonal to decadal range prediction) observation impact studies are encouraged.*

The quantitative influence of satellite observations on reanalysis has been growing during the last several years, but reanalyses are still heavily influenced by individual conventional data types (e.g. aircraft, SYNOP). The relative ("per observation") impact of the conventional data is roughly twice the impact of the satellite data. It should be noted that since the concept of forecast skill does not apply to reanalysis data (unless a corresponding hindcasting effort is included), these results are stated in terms of the so-called DFS (Degrees of Freedom for Signal) diagnostics, which cannot be directly compared to the FSOI (Forecast Sensitivity Observation Impact) diagnostics typically reported for forecast impact studies.

Concerning the FSOI diagnostics, it was noted that different methodologies are used for different data assimilation systems:

- FSOI using model adjoint
- EFSO using ensemble FSOI for EnKF
- Hybrid FSOI for 4DEnVar

These differ in their respective approaches to the backward propagation of sensitivities and in the ways in which the adjoint of the analysis gain matrix is computed. The ensemble-based EFSOI diagnostics were found to be strongly dependent on technical details such as ensemble size, methods for localization and accounting for model error, and it was therefore difficult to directly compare FSOI and EFSO diagnostics.

Different subjective norms were used as a basis for computing the sensitivities. Dry or moist total energy norms are based on evaluating the forecast error in model space and can therefore be sensitive to model biases. Normalized forecast departures with respect to observations are based on evaluating the forecast error in observation space. This methods leads to diagnostics that are more similar to DFS diagnostics.

> ***Recommendation 20***
> *Cost functions formulated in observation space should be used as a complement to the currently prevailing energy norms.*

The general sentiment expressed at the Workshop was that FSOI continues to be a very useful diagnostic with its well recognized and well publicized possibility to rank the NWP impact of the different data types and different network components with respect to the chosen norm. FSOI diagnostics can therefore be used by observing network operators to help them optimize the design of their networks, but the results must be interpreted carefully and they should preferably be complemented with OSEs (data denial/addition experiments) in select cases. Since the FSOI diagnostics are usually based on 24-hour forecast errors due to linearity assumptions, they may at times point to conclusions that differ from those drawn from data denial experiments. However, the consistency of the results obtained using the two methodologies was found to be reasonably good overall.

Since the FSOI diagnostics provide quantitative partitioning of the contribution to error reduction between the various types of observations, they naturally lend themselves also to cost/benefit studies. One such study undertaken by the Met Office in the United Kingdom was presented at the Workshop. Among other things this study provided a rather striking illustration of the fact that while national observations can have quite unfavourable cost/benefit numbers when used and costed in isolation, the cost effectiveness becomes very favourable once the benefits of international data exchange are taken into account.

As also noted under Session 1, the recurring theme in all major studies presented was that the following five observing types provided the most significant contributions to error reduction for global NWP: Microwave sounders (AMSU-A, ATMS) hyper spectral IR sounders(AIRS, IASI, CrIS), radiosondes, aircraft data and satellite winds (AMVs). On a per observation basis, the impact was dominated by buoys, radiosondes, AMVs and aircraft observations.

Intercomparisons between similar impact studies undertaken by different NWP centers are of great interest both for the NWP community and for the observing system operators. One such intercomparison was presented by the US Joint Center for Satellite Data Assimilation on behalf of a broad international group of NWP centers. The work carried out under this study toward developing a common framework for classification of observations, data formats etc. was commended.

Recommendation 21
WMO is strongly encouraged to foster further coordination between impact studies undertaken by different NWP centers; this should extend also to issues such as common methodologies and diagnostics and common quantities used when presenting the results.

It was also noted that the research and development regarding the use of FSOI-like diagnostics at the regional scale were necessary. Adjoint models could be used if available, although they may be less reliable at these scales. The use of ensembles looks promising. The development of new norms that would capture the role of convection should be investigated.

Recommendation 22
Development of FSOI methodologies applicable to regional and convective scale is encouraged.

Finally, concerning future work, strong support was expressed for the ocean observing networks for climate, and the NWP community was encouraged to further develop coupled modeling and assimilation efforts necessary to make use of the profile observations provided by e.g. the moored buoy arrays, and to undertake relevant sensitivity/impact studies as the methodologies mature.

Recommendation 23
NWP and modelling communities to continue to develop modeling and assimilation approaches relevant to surface flux measurements and sub-surface ocean observations and to undertake relevant data sensitivity and impact studies when possible.

(APPENDIX I)

SIXTH WMO WORKSHOP ON THE IMPACT OF VARIOUS OBSERVING SYSTEMS ON NUMERICAL WEATHER PREDICTION

Shanghai, China
10-13 May 2016

CHINA METEOROLOGICAL ADMINISTRATION
中国气象局

Programme

Tuesday 10 May 2016

08:00	Continental breakfast and registration
09:00	Welcome and opening remarks *(Moderator: Lars Peter Riishojgaard, WMO)* Mr. Heng ZHOU, Director-General , Dept. of International Cooperation, CMA Mr. Yinmin YANG, Deputy Director-General, Shanghai Meteorological Service Dr. Yoshiaki Sato, Science Organizing Committee, JMA Dr. Wenjian ZHANG, Director, WMO Observing and Information Systems Department
10:00	Break

Session 1: Global forecast impact studies

Co-chairs: Carla Cardinali and John Eyre

10:15	John Eyre, Met Office, UK	WS6-2016-022 Impact studies with satellite observations at the Met Office
10:40	Simon Pellerin, Meteorological Service of Canada	Global data impact studies using Canadian 4DEnVar system
11:05	David Groff, NCEP/EMC, USA	WS6-2016-021 Infrared and Microwave Data Addition Observing System Experiment Impacts Using the NCEP Global Forecast System
11:30	Sid Boukabara, NOAA/NESDIS, USA	WS6-2016-034 Impact Assessment of Potential Gaps in the Satellite Constellation on NOAA's Global NWP
11:55	Lunch	
13:00	Niels Bormann, ECMWF, UK	WS6-2016-030 All-sky assimilation of microwave sounder radiances (v2)
13:25	Keyi Chen, Department of Atmospheric Sciences, Chengdu University of Information and Technology, China	WS6-2016-010 Assimilating MWHS-FY-3B data over land
13:50	Cristina Lupu, ECMWF, UK	WS6-2016-012 The impact of satellite observations over land and sea-ice surfaces within the ECMWF system
14:15	Chris Burrows, Met Office, UK	WS6-2016-008 Radio occultation and its use in NWP
14:40	Break	
15:10	Lidia Cucurull, NOAA	WS6-2016-025 Global OSSEs to Assess New Sensors Potential Impacts on NOAA Systems

15:35	Jun LI, University of Wisconsin, Madison	WS6-2016-060 Value-added Impact from FengYun-4 hyperspectral IR sounder observations on regional NWP
16:00	Philippe Chambon, Météo-France/CNRS, CNRM/GAME, France	WS6-2016-087 Data impact of a microwave sounder onboard a geostationary satellite through Observing System Simulation Experiments
16:25	Jae-gwan Kim, KMA/NMSC, Republic of Korea	Current Maximization Impact of the COMS Data Assimilation on the KMA NWP System
16:50	Georg Grell, NOAA	The impact of aerosols on numerical weather prediction and the importance of assimilating atmospheric composition data to get it right
17:15	John Eyre, Met Office, UK and Lars Peter Riishojgaard, WMO	Potential impact of changes to WMO radiosonde launch schedules
17:40	Visit SMS	
19:00	Welcome dinner hosted by Ms. JIAO Meiyan, Deputy Administrator of CMA (Jianguo Hotel)	

Wednesday 11 May 2016

Continuation of Session 1

09:00	Ralph Petersen, University of Wisconsin-Madison, Cooperative Institute for Meteorological Satellite Studies, USA	WS6-2016-032 Impact Tests of Aircraft Moisture Observations in several Global-Scale NWP systems
09:25	Discussion session 1	
10:50	Break	

Session 2: Regional forecast impact studies

Co-chairs: Ron Gelaro and Jiandong Gong

11:20	Alexander Cress, Deutscher Wetterdienst, Germany	WS6-2016-011 Global and Regional Impact Studies at the German Weather Service (DWD)
11:45	Olivier Caumont, CNRM/GMME/MICADO, Meteo France	WS6-2016-057 Assimilation of humidity and temperature observations retrieved from ground-based microwave radiometers into a convective-scale NWP model
12:10	Lunch	
13:10	Poster Session (poster area outside the conference room)	*The poster viewing time is joint for all three sessions; poster contributions are listed at the end of the program*
14:45	Break	
15:05	Jean-Francois Mahfouf, CNRM/GMAP/OBS, Meteo France	WS6-2016-085 Recent experience at Météo-France on the assimilation of observations at higher temporal frequency
15:30	David Simonin, Met Office, UK	WS6-2016-014 Assimilation of weather radar observations at the UK Met Office
15:55	Hong LIANG, CMA, China	WS6-2016-020 Meteorological applications of precipitable water vapour measurements retrieved by the national GNSS network of China
16:20	Volker Wulfmeyer, University of Hohenheim, Germany	New Observations of Lower Tropospheric Water-Vapor and Temperature Fields and Their Impact of Short-Range Weather Forecasting
16:45	Wenjian Zhang, WMO	Vision for the space-based component of WIGOS in 2040

17:45 Adjourn

Thursday 12 May 2016

Continuation of Session 2

09:00	Yoshiaki Sato, JMA/NPD, Japan	WS6-2016-041 Global and regional impact studies at JMA
09:25	Eric Wattrelot, CNRM/GMAP/OBS, Meteo France	WS6-2016-086 Higher density radar assimilation in the operational AROME model at 1.3 km of horizontal resolution
09:50	Zhifang XU, National Meteorological Center, China (presented by Dr. Jiandong GONG)	WS6-2016-076 Extra Radiosonde Observations at 06UTC in China Mainland and Their Impact Study on Mesoscale Numerical Weather Prediction
10:15	Jianxia GUO, CMA, China	WS6-2016-018 Implementation of RRR in China
10:40	Break	
11:10	Kefeng Zhu, Nanjing University, China	WS6-2016-023 Initial Assessment of Traditional and Meso-scale Network Datasets Impact on the NJU Real-time Forecasts During May - August 2015 Warm Season over China
11:35	Min SUN, Shanghai Central Meteorological Observatory, Shanghai Meteorological Service, China	WS6-2016-047 Observation Strategy on Yangtze River Delta Region and Its Impact Study
12:00	Lunch	
13:00	Luiz Fernando Sapucci, INPE/CPTEC, Brazil	Assessing observation impacts on the INPE/CPTEC global data assimilation system
13:25	Discussion session 2	
14:50	Break	

Session 3: Sensitivity forecast impact studies

Co-chairs: Jochen Dibbern and Thibaut Montmerle

15:20	Carla Cardinali, ECMWF, UK	WS6-2016-005 FSOI diagnostic tool with an observation-based objective function
15:45	James Cotton, Met Office, UK	WS6-2016-024 "Comparing Data Denial Trials to FSOI Results: Reduced Russian Radiosonde Reports"
16:10	Chris Tingwell, Bureau of Meteorology Research & Development Branch	WS6-2016-009 Forecast Sensitivity to Observations in ACCESS

16:35	Thomas Auligne, USA	WS6-2016-081 Forecast Sensitivity and Observation Impact (FSOI) Inter-comparison Experiment
17:00	Stan Benjamin, Earth Modeling Branch, NOAA, USA	Observation sensitivity experiments with the hourly rapid fresh(RAP) using hybrid-ensemble/variational data assimilation
17:25	Simon Pellerin, Environment Canada, Canada	WS6-2016-028 Forecast sensitivity to observations in the Canadian global EnVar as computed with an ensemble-variational approach to FSOI

17:50 Adjourn

Friday 13 May 2016

Continuation of Session 3

08:45	Elizabeth Weatherhead, University of Colorado, USA	Designing the Climate Observing Systems of the Future
09:10	David Groff, NCEP/EMC, USA	Observing System Forecast Impact for the FY16 GFS Based on Ensemble Forecast Sensitivity to Observation (EFSO) Calculations
09:35	John Eyre, Met Office, UK	WS6-2016-033 Steps towards evaluating the cost-benefit of observing systems
10:00	Roger Randriamampianina, MET Norway	Observing system experiments and observing system simulation experiments using mesoscale model in Arctic
10:25	Yuhei Takaya, Climate Prediction Division, JMA, Japan	Observation requirements for sub-seasonal to decadal predictions
10:50	Break	
11:10	Andras Horanyi, ECMWF, UK	WS6-2016-003 The impact of observations in the ECMWF latest reanalysis system
11:35	Peng ZHANG, National Satellite Meteorological Center/CMA (presented by Dr. Lei YANG)	WS6-2016-058 Fengyun-3E: An early morning orbit mission and its impacts on NWP
12:00	Lunch	
13:00	Volker Lehmann, Germany	Overview on wind profiler networks worldwide and review of impact results
13:25	Discussion session 3	
14:50	Break	
15:20	Discussion, overall Workshop conclusion and recommendations	
16:20	Closure	

16:30 Adjourn

POSTER PRESENTATIONS

1	Agnes Lim, Cooperative Institute for Meteorological Satellite Studies, USA	WS6-2016-001 Development of An OSSE Framework in Support of Impact Analysis of LEO Hyperspectral Sounder Field of View Size on Forecast Performance
2	Byung-Ju Sohn, Seoul National University, Republic of Korea	WS6-2016-004 New IASI channel selection for Unified Model data assimilation system
3	Baode CHEN, Shanghai Typhoon Institute of CMA, China	WS6-2016-015 Applying radar and satellite observations in the physical (cloud) initialization for convection permitting NWP models
4	Yunchang CAO, CMA, China	WS6-2016-019 Quality control and quality assessment of the surface observations from China Automatic Surface Observation Network
5	Ruixia LIU, National Satellite Meteorological Center, CMA, China	WS6-2016-026 The Influence of Initial cloud Condition Adjustment using FY-2 Satellite Data on Precipitation Forecasting
6	Maria Eugenia Dillon, University of Buenos Aires, Argentina	WS6-2016-027 Toward the implementation of an Ensemble based Data Assimilation System including satellite retrievals over Southern South America
7	Novvria Sagita, Indonesian Agency for Meteorology, Climatology and Geophysics (BMKG)	WS6-2016-031 Using The Atmospheric Boundary Layer Height As The Peak Height Of Weather Research And Forecasting (WRF) Model For The Analysis Of Tornado Events In Bogor
8	Sue Grimmond, University of Reading, UK	WS6-2016-035 Boundary Layer Observations in the Shanghai area to inform high resolution NWP
9	Jie TANG, Shanghai Typhoon Institute, CMA, China	WS6-2016-036 Preliminary Evaluation of the First Rocket-Deployed Dropsonde Observations in an Offshore Typhoon: A Project EXOTICA Case Study in STY Mujigae (1522)
11	Hong WANG, Guangzhou Institute of Tropical and Marine Meteorology, China	WS6-2016-038 Application of the dual-polarization radar data in numerical model: Construction of simulator (NB same as 066)
12	Juxiang PENG, Institute of Heavy Rain, CMA, China	WS6-2016-039 Variational Assimilation of Cloud Optical Depth and Its Impact on NWP

13	Yali WU, Guangzhou Institute of Tropical and Marine Meteorology, CMA, China	WS6-2016-040 On use of LHN method to assimilate the intensified surface precipitations for GRAPES Meso model initialization (NB same as 069)
14	Yasutaka Ikuta, JMA, Japan	WS6-2016-042 Impact of appropriate consideration of observation time in the meso-scale hybrid 4D-Var system
15	Yuefei ZENG, Meteorological Institute of Ludwig Maximilian University of Munich, Germany	WS6-2016-043 Assimilating radar volume data into the COSMO model using an LETKF approach
16	Min SUN, Shanghai Central Meteorological Observatory, Shanghai Meteorological Service, China	WS6-2016-048 Nowcasting and Shot-term Heavy Rain Forecast of Typhoon Fitow (2013) using GSI with Radar Radial Wind Assimilation
17	Hongli LI, Institute of Heavy Rain, Wuhan,CMA, China	WS6-2016-049 Application of FY stationary satellite data in the cloud analysis of a heavy rainfall
18	Jihang LI, Key Laboratory of Regional Numerical Weather Prediction, Guangzhou Institute of Tropical and Marine Meteorology, China	WS6-2016-050 Utilizing Doppler Radar Observations with the Preferred-Multi-Scale/Block Batch-wise Variational Data Assimilation for Super Typhoon Rammasun Initialization and Prediction
19	Nan SAN, Meteorological Observation Center, CMA, China	WS6-2016-054 Comparative Analysis on Errors of Temperature Advection Between T639 Model and Wind Profile Radar
20	Qiyun GUO, Meteorological Observation Center, MA, China	WS6-2016-055 The development and test of sounding system of the stratosphere
21	Yang LI, Meteorological Observation Center, CMA, China	WS6-2016-056 Comparative analysis of air sampling equipment of unmanned helicopter with ground sampling
22	Jianmin XU, National Satellite Meteorology Center, CMA, China(Introduced by Dr. Xiaohu ZHANG)	WS6-2016-059 FengYun-2 Atmospheric Motion Vectors Data Quality Improvement and their Impact Study
23	Qifeng LU, China	WS6-2016-061 FY-3 evaluation in NWP: overview from CMA, ECMWF and UKMO

24	Heng HU, China	WS6-2016-064 Analysis on the effect of precipitation from ground-based GPS for the numerical forecast
25	Jiqin ZHONG, Institute of Urban Meteorology, CMA, China	WS6-2016-067 Research on quality control and assimilation of ground-based GPS ZTD in North China
26	Xubin ZHANG, Key Laboratory of Regional Numerical Weather Prediction, Institute of Tropical and Marine Meteorology, CMA, China	WS6-2016-068 Impacts of assimilating wind-profiling-radar data on QPF during SCMREX-2013
27	Xiaolong CHENG, Institute of Plateau Meteorology, CMA, China	WS6-2016-071 A comparative experimental study of an extreme rainstorm caused by the Southwest China vortex during the intensive observation period
28	Duming GAO, Institute of Plateau Meteorology, China Meteorological Administration, China	WS6-2016-072 Influence of southwest radiosonde data assimilation on the prediction of a vortex precipitation in Sichuan Basin
29	Xiumei MA, Institute of Desert Meteorology, CMA, China	WS6-2016-073 A Study of the Application of C-band Radar Observation in Numerical Forecasting System in Xinjiang Region
30	Xinghua BAO, State Key Laboratory of Severe Weather, Chinese Academy of Meteorological Sciences, China	WS6-2016-074 Assimilation of Doppler Radar Observations with an Ensemble Kalman Filter for Convection-permitting Prediction of the Mesoscale Convective System over South China on 8 May 2013
31	Xiangde XU, State Key Laboratory of Severe Weather, Chinese Academy of Meteorological Sciences, China	WS6-2016-075 The Warning and Prediction of downstream weather by Assimilating Plateau Observational Data
32	Xingying ZHANG, National Satellite Meteorological Center, CMA, China	WS6-2016-077 Study on satellite aerosol observation and assimilation to improve air quality forecast in CMA
33	Lily LIU, Tianjin Meteorological Service, China	WS6-2016-080 The Research of the Distribution of the Ocean Meteorological Observation Stations Over the Bohai Sea and Yellow Sea
34	Bin WANG, Institute of Heavy Rain, CMA, Whuan, China, HE Wenhuang, Xianning Meteorological Bureau, CMA, China	WS6-2016-082 Analysis of characteristics of precipitation vertical structure detected by a C-POL radar in a Mei-yu frontal heavy rainfall case

35	Muyun DU, Hubei Key Laboratory for Heavy Rain Monitoring and Warning Research, Institute of Heavy Rain, CMA, China	WS6-2016-083 Image Identification of Downbursts with WSR-88D Doppler Weather Radar
36	Chunguang CUI and Rong WAN, Institute of Heavy Rain, CMA, Hubei Key Laboratory for Heavy Rain Monitoring and Warning Research, China	WS6-2016-084 The Mesoscale Heavy Rainfall Observing System (MHROS) over the Middle Region of the Yangtze River in China
37	David Crisp, JPL, USA	Space Based Surface Pressure Estimates from the Orbiting Carbon Observatory-2
38	Xy ZHANG, Chinese Academy of Meteorological Sciences, China	WS6-2016-078 Observational data application in Haze-fog and SDS forecasts in CMA
39	Xudong LIANG, China	WS6-2016-063 Wind profiler network and data assimilation in China
40	Neville Smith, Co-Chair TPOS 2020 SC, Australia	The Tropical Pacific Observing System and NWP
41	Andras Horanyi, ECMWF, UK	WS6-2016-002 The global numerical weather prediction impact of mean sea level pressure observations from drifting buoys
42	Anne-Lise Doerenbecher, Meteo-France	WS6-2016-097 Impact on weather prediction of in-situ atmospheric observations at the surface of Northern Atlantic Ocean

(APPENDIX II)

Proposed topics for NWP impact studies relevant to the evolution of global observing systems

Short name: Full name	**Science question**
	Surface-based
S1Marine: Surface pressure over ocean	What density of surface pressure observations over ocean is needed to complement high-density surface wind observations from satellites? What is the required coverage of SCAT winds?
S2AMDAR: Coverage of AMDAR	What are the priorities for expansion of the AMDAR network? How does the impact vary over the globe? Provide guidance for AMDAR optimisation. Evaluate the impact of MODE-S data in high-resolution NWP.
S3Radar: Radar observations	What are the impacts of current radar observations, including radial winds and reflectivities?
S4Strat: In situ observations of the stratosphere	What network of in situ observations is needed in the stratosphere to complement current satellite observations (including radio occultation)? Assessments addressing the tropics are encouraged.
S5PBL: Observations of the PBL for regional and high-resolution NWP	What should be the focus of improvements for observations of the planetary boundary layer (PBL) in support of regional and high-resolution NWP? Which variables and what space-time resolution?
	Space-based
S6SatLand: Satellite sounding over land and ice	What is the impact of new developments in the assimilation of radiance data over land and sea ice?
S7Sounders: Impact of multiple satellite sounders	What benefits are found when data from more than one passive sounder are available from satellites in complementary orbits, e.g. the current unprecedented availability of four hyper-spectral sounders?
S8AMVs: Atmospheric Motion Vectors	Based on evidence from current AMV impacts, which AMV characteristics should be enhanced for the next generation of GEO satellites? What are the impacts of recent new types of AMVs such as MISR-AMV?

General	
S9UA: Regional upper-air network design studies	Upper-air network design studies such as those performed for the European composite observing system (EUCOS) are required also in other Regions, especially in Region I where the basic networks are under pressure. Assessments of recent changes in the networks, including the impact of launching radiosondes once per day.
S10AdjEns: Application of adjoint and ensemble methods	What insights can be gained from adjoint and ensemble-based impact measures tailored for applications such as severe weather, aviation and energy? Specific impact metrics may be required.
S11Ocean: Impact in ocean-coupled assimilation	Whic ocean observations are particularly important for NWP? Investigate the role of ocean observations in coupled atmosphere-ocean data assimilation with a focus on the 7-14 day range.
S12Land: Impact in land-coupled assimilation	Which land-surface observations are particularly important for NWP at all forecast ranges? Investigate the role of surface observations in coupled atmosphere-land data assimilation with a focus on the 7-14 day range.
S13 Time frequency	What is the required time frequency of observations? Consider AMDAR, GEO satellites and ground-based remote sensing observations (such as Doppler radar, wind profiler, ground based GNSS receivers) for regional and global NWP.
S14 Atmospheric composition	Study observation impact in atmospheric composition and air quality applications and the impact of atmospheric composition observations (e.g. aerosol) on NWP.
S15 OSSEs	Observing system simulation experiments are encouraged in support of satellite system decision making, e.g. regarding orbit optimization for GPS-RO satellites, or configurations for hyper-spectral IR sounders on geostationary orbit.

(APPENDIX III)

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