Observing System Simulation Experiments: Justifying new Arctic Observation Capabilities

White paper on OSSE Optimized Modelling submitted to the Arctic Observing Summit (AOS), Vancouver, Canada (April 30 to May 2, 2013)

[1]Michiko Masutani, [2]Louis Garand, [3]William Lahoz, [4]Erik Andersson, [5]Yves Rochon, [6]Lars Peter Riishøjgaard, [7]Mikhail Tsyrulnikov, [8]John McConnell, [9]Lidia Cucurull, [10]Yuanfu Xie, [11]Shoken Ishii, [12]Robert Grumbine, [13]Gilbert Brunet, [14]John S. Woollen, [15]Yoshiaki Sato

[1] NOAA/NWS/NCEP/EMC, College Park, Maryland, USA, Michiko.Masutani@noaa.gov
[2] Environment of Canada, Dorval, Qc, Canada, Louis.Garand@ec.gc.ca
[3] NILU, Norwegian Institute for Air Research, Norway, William.A.Lahoz@nilu.no
[4] European Centre for Medium-Range Weather Forecasts (ECMWF), Reading, UK, erik.andersson@ecmwf.int
[5] Environment of Canada, Toronto, On, Canada, Yves.Rochon@ec.gc.ca
[6] Joint Center for Satellite Data Assimilation, College Park, MD, USA, Lars.P.Riishojgaard@nasa.gov
[7] Hydro Meteorological Centre of Russia, Moscow, Russia, tsyrulnikov@mecom.ru
[8] Department of Earth and Space Science and Engineering, York University, Canada, jcmcc@yorku.ca
[9] NOAA/NWS/NCEP/EMC, Boulder, CO, USA, lidia.cucurull@noaa.gov
[10] NOAA/Earth System Research Laboratory, Boulder, CO, USA, Yuanfu.Xie@noaa.gov
[11] National Institute of Information and Communications Technology (NICT) Tokyo, Japan, sishii@nict.go.jp
[12] NOAA/NWS/NCEP/EMC, College Park, MD, USA, Robert.Grumbine@noaa.gov
[13] Met Office, Exeter, UK, gilbert.brunet@metoffice.gov.uk
[14] NOAA/NWS/NCEP/EMC, College Park, MD, USA, Jack.Woollen@noaa.gov
[15] Japan Meteorological Agency, Tokyo, Japan, y-sato@met.kishou.go.jp

Executive Summary:

The Arctic is recognized as one of the key areas of the globe, both in terms of its sensitivity to climate change, and by the increasing economic activity that is expected with the opening up of Arctic areas in a warming climate. In addition, Arctic weather can have important influences in winter cold outbreaks of air which can affect Northern Hemisphere countries as far south as the subtropics with serious economic implications. Therefore, a revised assessment of Arctic satellite and surface observation capabilities and requirements is warranted, especially given the Arctic surface and upper air network is sparse. Observing System Simulation Experiments (OSSEs) are a powerful tool to assess added value of planned or hypothetical observing systems for weather analysis and prediction. This white paper reviews the current state of OSSE science with respect to the Arctic, and provides lines of investigation for the future, with a focus on weather and air quality observations in the Arctic. Recommendations are based on perceived observation gaps in the Arctic, and the experience gained by the WWRP-THORPEX Polar Prediction Project and the broader OSSE scientific community.

1. Definition and motivation of OSSEs

Observing System Simulation Experiments (OSSEs) are designed to use data assimilation ideas to investigate the potential impact of future observing systems (observation types and deployments). They may also be used to investigate current observational and data assimilation systems by testing the impact of new observations on them. The information obtained from

OSSEs is generally difficult, or in some contexts impossible, to obtain in any other way. OSSEs require significant resources in computing power and human resources.

In an OSSE, simulated rather than real observations are the input to a data assimilation system (DAS); an extended review of the observation types comprising the Global Observing System (GOS) and state-of-the-art data assimilation systems is provided in Lahoz *et al.* (2010). OSSEs are closely related to Observing System Experiments (OSEs), which test the value of current observation types using data denial experiments. An OSSE is formally similar to an OSE with one important difference: OSSEs assess *new* data, *i.e.*, data obtained by hypothetical observing systems that do not yet exist. The OSSE methodology consists of:

- Generation and verification of reference atmospheric states. This is usually done with a good-quality, realistic atmospheric model in a free-running mode without data assimilation. This is the Nature Run (NR), providing the "truth," from which observations are simulated and against which subsequent OSSE assimilation experiments are verified;
- The NR is then used to generate simulated observations, including realistic errors, for existing observing systems and for the hypothetical future observing system;
- A control experiment in which current observational data are included;
- A perturbation experiment in which simulated candidate observations under evaluation are added;
- Comparison of forecast skill between control and perturbation runs.

The first two items above require significant resources (Marseille *et al.,* 2003; Reale *et al.*, 2007; Andersson and Masutani, 2010; Masutani *et al.,* 2011; McCarty *et al.*, 2012; Zhu *et al.*, 2012; Heilliette *et al.,* 2013). The OSSE approach was first adopted in the meteorological community to assess the impact of prospective observations, *i.e.*, not available from current instruments, and test potential improvements in numerical weather prediction (NWP; Nitta, 1975; Atlas *et al.*, 1985; Lord *et al.*, 1997; Masutani *et al.*, 2010a). In a review paper, Arnold and Dey (1986) summarized the early history of OSSEs and presented a description of the OSSE methodology, its capabilities and limitations, and considerations for the design of future experiments. OSSEs have been used to assess trade-offs in the design of observing networks and to test new observing systems, particularly costly instruments such as Space-Based Doppler Wind Lidars (DWL; *e.g.* Stoffelen *et al.*, 2006; Tan *et al.*, 2007; Masutani *et al.*, 2010b; Riishøjgaard *et al.*, 2012). In more recent developments, OSSEs have been used to assess satellite platforms to monitor air quality (Edwards *et al.*, 2009; Timmermans *et al.*, 2009; Claeyman *et al.*, 2011; Lahoz *et al.*, 2012; Rochon *et al.*, 2012) and assess HEO (highly elliptical orbit) satellite platforms to fill wind observation gaps over the Arctic (Garand *et al.*, 2012).

By running OSSEs, current operational data assimilation systems can be tested, and upgraded to handle new data types and volume, accelerating the use of future instruments and observing systems. However, the impact of additional observations on the GOS depends on the quality of the DAS and its constituent model (Lahoz *et al.,* 2010; Masutani *et al.*, 2010a, b) and the information content of the new observations. Thus, for OSSEs for the Arctic, the DAS should have a realistic representation of high latitude conditions such as sea ice coverage, albedo, low humidity, and thin clouds. The Arctic poses additional challenges to the DAS owing to the scarcity of in situ observations, and relatively small spatio-temporal scales. In particular, low observability and high variability may give rise to highly flow-dependent background error covariances.

This white paper is a contribution to the Arctic Observing Summit (AOS) due to be held in Vancouver, Canada, 30 April - 2 May 2013. The AOS will provide a forum for assessing the science basis for Arctic observing activities and improving co-ordination and optimal resource allocation for the International Network of Arctic Observing Systems (INAOS). The AOS will bring together the actors involved in Arctic observing activities, including academia, government agencies and Arctic stakeholders. This white paper presents the views of the OSSE science community on OSSE developments, with particular application to weather and air quality observations over the Arctic. Challenging aspects of OSSEs are discussed: production of the NR (Section 2); extraction of simulated observations from the NR (Section 3); evaluation and interpretation of the results (Section 4); and calibration of the OSSE (Section 5). Examples of OSSEs for the Arctic are discussed (Section 6), and recommendations for an improved NR and an improved Arctic observing system provided (Section 7).

2. The Nature Run

The NR is a long, uninterrupted forecast (free run) by a NWP model. The preparation of the NR and the simulation of data from it consume significant resources. Because the real atmosphere is a chaotic system governed mainly by conditions at its lower boundary, the NR diverges from the real atmosphere a few weeks after the simulation begins. This does not matter *provided that* the climatological statistics and structure of weather systems in the NR match those of the real atmosphere. In this white paper, the term OSSE refers to a simulation experiment with a NR generated from a NWP model significantly different from that used for data assimilation. In the early years of OSSEs, "identical twin" or "fraternal twin" OSSEs (using the same NWP model and/or DAS for the NR and OSSE) were often conducted due to the paucity of state-of-the-art NWP models. This has been noted to lead to overly optimistic forecast skill for the OSSE DAS (Masutani *et al.*, 2010a).

The primary specifications of a NR based on past experience of OSSEs are:

- Employ a NWP model with demonstrated forecast skill; Kinter *et al.* (2012) evaluate two of the most important state-of-the-art global NWP models. There should be a trade-off between the resolution and the complexity of the physical (and chemical) processes included in the model;
- Since data impact depends on the season, it is important that NRs cover long periods, preferably a whole year to allow selection of interesting sub-periods for closer study;
- Data archiving should be user-friendly and shareable with the community;
- Simulation should agree with the real analyses in a statistical sense at all spatio-temporal scales;
- A temporal resolution higher than the OSSE analysis cycle. Simulation should resolve spatio-temporal scales compatible with the main observing systems;
- It is desirable that the NR should be based on an atmosphere-ocean coupled model; or at least, the NR must be forced by an analysis incorporating frequently updated SST (sea surface temperature) and sea ice data. It is not recommended to force the lower boundary condition to match exactly that of the NR. However, attention should be given to limit

significant biases between the SSTs of the NR and the OSSE;

- Chemistry and aerosol information which affect the data should be evaluated when appropriate.

The International Joint OSSE Collaboration community has developed a state-of-the-art NR based on the global ECMWF (European Centre for Medium-Range Weather Forecasts) NWP model (Andersson and Masutani, 2010). The best available temporal (3-hr) and spatial (~40 km) resolutions of this NR have proved suitable for many OSSE studies. However, this does not match the current resolution of global models (~10-15 km), and does not include gases other than water vapour and ozone. A higher horizontal resolution is also desirable for improved simulation of satellite radiances. For application to the Arctic, it appears important to ensure that the NR reproduces well key specific characteristics such as temperature and humidity inversions, boundary layer cloudiness, and seasonal sea-ice variations (Beesley *et al.*, 2000). Another important issue is the need for an NR which includes key air quality variables, aerosols, and additional greenhouse gases. How to proceed with these developments remains to be determined, as assimilation of air quality variables, notably from space, is much less developed than that of temperature, wind and humidity (see, *e.g.*, Lahoz *et al.*, 2012). Finally, if the focus of the OSSE is optimizing the surface network, it becomes important not to force the lower boundary condition in the OSSE with input that is too close to the NR. These issues are being debated in the OSSE community (Masutani *et al.*, 2010a).

3. Simulation of observations

Several major issues must be considered regarding the simulation of observations from the NR:

(i) ***Inclusion of complex effects such as horizontal error correlations in the observational errors.*** These issues are discussed in Errico *et al.* (2012). Providing realistic errors for simulated observations is a non-trivial task. It is thus desirable to design OSSEs whose results do not depend strongly on the observational errors assigned. The work of Riishøjgaard *et al.* (2012) suggests that observational errors do not show a significant impact at the larger spatial scales, but may show significant impact at the smaller spatial scales.

(ii) ***Selection of forward model.*** Various observation simulators are available for calculating radiances (Tanelli *et al.*, 2012; Matsui *et al.*, 2012). Ideally, the forward model used in simulation of observations should be more accurate than the forward model used in the data assimilation step. Development of forward models for new observation types is a challenging task. The impact of errors in the forward model on OSSE results has been recently studied by Gorin and Tsyrulnikov (2011). Their work suggests that using *different* forward models in simulating observations and assimilating them, will give rise to error correlations, which is desirable for simulating the real Earth System. However, if the forward models used to create the NR and perform the OSSE are different, radiance bias correction methods (as done in operational NWP) may need to be applied. This is feasible but complicated.

(iii) ***Handling clouds in the simulation of radiances.*** Use of sophisticated forward models to simulate radiances (for the infrared and the microwave) in all sky conditions is desirable. Radiative Transfer Models which include clouds are now used regularly (Han *et al.*, 2006; Heidinger *et al.,* 2006; Liu *et al.,* 2006; Weng *et al.,* 2007; Garand *et al.*, 2011; Collard, 2012). Simulation and assimilation using clear sky radiances with sampling adjusted by cloud cover remains a practical approach (Zhu *et al.*, 2012). However, all-sky simulated radiances generally agree well with real data, and can be used in OSSE studies (Heilliette *et al.*, 2013). This has the advantage that the same quality control procedures used operationally for radiance assimilation can be applied to OSSEs. Furthermore, deficiencies of the real system can be evaluated, *e.g.*, the level of cloud contamination present in assimilated radiances.

(iv) ***Consistent definition of surface variables (temperature, albedo, sea ice fraction/thickness, snow cover, and surface emission sources and sinks).*** Inappropriate use of surface variables could affect OSSE results. Surface variables defining the NR, including topography, should be used in a consistent manner in the simulation of observations. Some surface variables could come from NWP analyses; others from climatology. For the Joint OSSE NR (Andersson and Masutani, 2010), analysed SST and sea ice are used; surface types affecting variables such as surface emissivity come from climatology.

4. Evaluation of OSSE results

Data impact in an OSSE varies with spatio-temporal scales. Below we discuss two commonly used methods to test data impact in an OSSE.

4.1 Data denial experiments

The most common method used to test the impact of specific data is to compare the analysis and forecast skill with and without the specific data. With real data (as for an OSE) the impact is measured as the forecast skill without the specific data compared against the best analysis or fit to observations. Usually, the analysis with the most data is considered to be the best and used as the control experiment (see Section 1). Note that within an OSSE, comparing forecasts with analyses and observations is only done for calibration (see Section 5). Once calibration has taken place, the results of the OSSE are evaluated against the NR as well as against the analyses generated by the OSSE cycles.

Many diagnostic techniques used to evaluate the NR can also be used to evaluate the OSSE results. Examples include:

- Root Mean Square Error (RMSE);
- Anomaly correlation (AC). Anomaly correlation is affected by the climatology used, so it is important to use the same climatology for all skill comparisons. Traditionally, the AC of the 500 hPa geopotential height is used, but Masutani *et al.* (2010b) showed that other levels and variables need to be evaluated. Calculating ACs for different spatial scales is also crucial;
- Storm track and intensity;
- Fit to observations;

- Evaluation of the realism of the NR by assessing likelihood of extremes lying outside the normal range of analysed or measured values;
- Amplitude, wavelength and propagation speed (or phase) of waves;
- Comparisons which may shed light on the realism of disturbances in the model and identify possibly unrealistic or spurious scales of motion;
- Evaluating the analysis and forecast of precipitation using the statistics of analysis increments (Errico *et al.*, 2007).

4.2 Adjoint–based techniques

The adjoint–based technique to estimate the impact of observations on NWP analyses is described in Langland and Baker (2004). It is a powerful method that quantifies the relative contribution from different observations. Its advantages and disadvantages compared with data denial experiments are discussed in Zhu and Gelaro (2008) and Gelaro and Zhu (2009).

5. Calibration of OSSEs

Calibration of OSSEs consists in verifying that the simulated data impact is similar to the real data impact. One way of calibrating an OSSE is to use a data denial experiment to find out whether the assimilation of a specific type of observation has the same statistical effect on a forecast within the simulation as it does in the real world. This calibration has been done for the current joint OSSE system using the ECMWF T511 NR (Privé *et al.*, 2012, 2013). An alternative method of calibration is to use the adjoint-based technique to adjust the observational error so as to achieve a similar data impact with real observations. The simulation of the data has to be repeated until a satisfactory agreement is achieved. Ideally, a complete calibration of OSSEs would be performed every time the DAS changes. However, this is time consuming, and there is a need to be selective in what experiments are used for calibration and for verification.

6. Examples of OSSEs for high latitude observations

The Arctic is recognized as a key area of the globe in terms of its sensitivity to climate change. The Arctic environment will be under pressure from the increasing economic activity associated with the exploitation of natural resources and the opening of new sea routes in a warming climate. Understanding these changes and providing an informed societal response to these changes requires observational information. In Sections 6.1-6.8 we provide examples where OSSEs could play an important role in supporting the case for future observation capabilities in the Arctic. The examples address gaps in the GOS for the Arctic, consistent with the gap analysis described by Eyre *et al.* (2013).

6.1 Addressing spatio-temporal observational gaps in the GOS

It is highly desirable to observe high latitudes from space in a continuous fashion, as available from geostationary satellites (GEOs) for latitudes equatorward of 60^{o}N and 60^{o}S. For that reason, both Canada and the Russian Federation are proposing 2-satellite constellations in a highly elliptical orbit (HEO) to observe the Arctic. The Canadian mission is Polar Communications and Weather (PCW). Using two HEO satellites, seamless imagery with a 15-min repeat cycle can be obtained northward of 60°N (Trishchenko and Garand, 2012). Obtaining the equivalent of 15-min imagery at 60°N/80°N would require 23/10 low orbiting satellites (LEOs), respectively. The need to combine information from different satellites (*e.g.* GEOs and LEOs) raises issues linked to differences in time, viewing angle, channel characteristics, and timeliness. These issues are avoided with HEO satellite platforms.

Environment Canada has performed an OSSE to evaluate the impact of assimilating atmospheric motion wind vectors (AMVs) provided by PCW, and which fill a severe high latitude observational gap (especially over 55°-70°N). The added value of this potential new source of AMV data has been demonstrated (Garand *et al.*, 2012). OSSEs could also be performed to test the potential of other instruments on HEO, *e.g.*, a hyperspectral sounder (similar to *e.g.* IASI) and a UV-VIS-NIR instrument for air quality and aerosol column measurements (McConnell *et al.,* 2012). A relatively new type of AMV, termed LEO-GEO or LEO-LEO (*e.g.* using METOP-A and METOP-B), is being designed to at least partially fill the above-mentioned observational gap at high latitudes (Hoover *et al.*, 2012).

6.2 Optimizing the use of GPS RO observations

GPS RO (GPS Radio Occultation) observations, with sensitivity to temperature and humidity, have been proven to significantly improve weather forecast skill, in particular in the Southern Hemisphere (Cucurull and Derber, 2008; Cucurull *et al.*, 2012). Weather analyses and forecasts in the Arctic should thus benefit from assimilation of additional GPS RO data. GPS RO observations provide all-weather and global coverage information on the state of the atmosphere. Over the Polar Regions where humidity is low, GPS RO can probe the atmosphere down to the surface; for example, ~100% of all COSMIC-1 soundings in the Polar Regions penetrate to within 2 km of the Earth's surface. In recent years, the quality of lower troposphere GPS RO retrievals has improved in Polar Regions. These measurements have very small instrument errors so that, potentially, they can be assimilated as uniquely precise observations. Thus, the Arctic is an ideal region to evaluate the benefit of the assimilation of GPS RO data.

The COSMIC-1 platform is deteriorating - one of the satellites has stopped functioning and others have limited energy left. To address this, a follow-up mission (COSMIC-2) is being planned, with the first launch expected in 2016. COSMIC-2 will fly more receivers than COSMIC-1, which will double the number of soundings per payload. Currently, only the first launch with six satellites in equatorial orbit has been funded, although various options to fund the second set of six satellites, to be deployed in polar orbit in 2018, are being considered. This second launch should enhance the Arctic observing system and improve information on weather and climate over the region. OSSEs with COSMIC-2 data would help characterize their potential benefit over the Arctic region.

6.3 Optimizing the surface and upper air network in the Arctic

The density of surface and upper air observations in the Arctic is very sparse due to the challenging environment. Surface buoys are lacking from large areas, resulting in considerable uncertainty in determining the position and intensity of weather systems. Additional in situ surface and upper air observations would help improve short term forecasts, and longer-term forecasts in all areas affected by influences from the Arctic. OSSEs could be designed for the optimization of an Arctic surface and upper air network. This could include simulated deployment of additional buoys, and testing the benefit from additional commercial aircraft data over the Arctic, and potential Russian Arctic RAOB sondes. Owing to the importance of surface conditions (SSTs, albedo, and ice conditions) for the Arctic, careful sensitivity experiments would be required prior to the OSSE experiments.

6.4 Unmanned Aircraft System observations

The NOAA Unmanned Aircraft System (UAS) programme includes an Arctic testbed (Privé *et al.,* 2009). In collaboration between NOAA OAR/ESRL and NCEP/EMC, an OSSE is being planned to help design a future observation system for the Arctic based on LEO satellite platforms and UAS observations. This observing system would contribute to monitoring and predicting Arctic weather and climate. Other benefits of this OSSE include an assessment of the importance of various processes that drive sea ice, namely, cloud-boundary layer-surface processes and their interactions, and wind stress.

6.5 Air Quality

Air quality, defined by the atmospheric composition of gases and particulates near the Earth's surface, will be affected by changes in the Arctic. As a result of increased shipping and resource extraction activities in the Arctic and northern regions, atmospheric pollution in the Arctic is likely to increase. The frequency of biomass burning events and other natural disturbances at nearby high latitudes could also increase, adding further pollutants to the Arctic atmosphere. These factors will affect the environment and human society both locally and globally (by long-range transport of pollution). The importance of the Arctic is recognized by countries with territories that border it. As an example, Norway has initiatives such as SIOS (Svalbard Integrated Arctic Earth Observing System; http://www.sios-svalbard.org/*),* designed to ensure Norway is a leading player in Arctic environmental science and related policy. Similar initiatives and activities are expected to be undertaken by other countries with an interest in the Arctic.

OSSEs would help quantify the relative value of satellite data and in situ data for monitoring air quality in the Arctic, with focus on measurements of key near-surface pollutants such as ozone, SO_2, CO, NO_x and aerosols. This could also extend to greenhouse gases and short-lived-climate-pollutants (such as black carbon), and quantifying their emission sources even though longer time scales are involved. The ability of observing systems to quantify changes to the natural cycles of CO_2 and CH_4 associated with climate change (*i.e.*, emission of these gases from thawing permafrost) is desirable. While OSSEs for greenhouse gases, short-lived-climate pollutants, and emissions, should be conducted using the global NR resolution, OSSEs for assessing observations of pollutants and their impact on air quality would need a NR with spatio-temporal scales of less than ~10 km and less than 1 hr (Lahoz *et al.*, 2012); this could be accomplished using limited area models embedded in a coarser resolution model providing the boundary conditions. Expected outcomes of these OSSEs would be: (i) improved monitoring of the Arctic environment; and (ii) improved information for decision makers; and Arctic society, including the public, government, and industry.

6.6 Use of lidars for aerosol, ozone and water vapour profiling

The Arctic ecosystem is sensitive to sunlight, surface temperature, ocean heat-transport, and atmosphere-ocean interactions. Various gaseous and particulate aerosols are transported to the Arctic over several thousands of km in the atmosphere from Northern Hemisphere anthropogenic pollution sources as well as boreal forest fires; they play an important role in the atmospheric radiation budget through their spatial distributions and optical properties, and cloud-aerosol interactions. Water vapour is transported poleward from the North Atlantic and the North Pacific (via the Bering Strait). This presence of aerosols, clouds, and water vapour in the Arctic has an impact on chemical cycles and global climate change.

Lidars are active remote sensing techniques that offer very good capabilities for aerosol, cloud, ozone and humidity profiling in terms of accuracy and vertical resolution (10% error and 100m vertical resolution for ground-based and airborne measurements; Donovan *et al.*, 1995; Doyle *et al.*, 2011; Nott *et al.*, 2012). Ground-based and airborne lidar measurements in the Arctic are limited owing to its remoteness and cloud cover. An example of an Arctic lidar platform which could be included in impact assessment OSSEs is the Rayleigh/Mie lidar at the Lidar Research Laboratory, Chatanika, Alaska. Although space lidar platforms are expensive, new OSSEs testing its benefit for improving the Arctic observing system would be warranted for better understanding of atmospheric transport in the Arctic; couplings between the Arctic region and lower-latitude regions; aerosol-cloud interactions in cold atmospheres; and stratospheric intrusions of dry air. Measurements of the low humidity levels found in the Arctic are very challenging, and lidars onboard satellites offer the best way forward (ESA, 2001).

6.7 Ice Observations

Major parameters of the Arctic ice pack which may affect the global circulation include albedo (Grumbine, 1994), ice concentration, ice thickness, and ice velocity. Arctic ice observations are primarily obtained by satellite observations. Albedo can be measured by AVHRR, MODIS, and other visible sensors. Sea ice coverage is mainly obtained from passive microwave instruments (*e.g.* SSMI, SSMI/S, and AMSR). Ice thickness can be measured by altimetry to some degree, *e.g.*, from Cryosat and Icesat. Ice concentrations can affect heat and air-sea aerosol exchange, and lower atmosphere chemistry. However, the impact of ice and snow on the global circulation has not been thoroughly evaluated (Randall *et al.*, 1998; Wu *et al.*, 2005). OSSEs represent a powerful tool for the evaluation of this impact, and that from various observations on the quality of analyses.

6.8 Polar wind from Space-Based Doppler Wind Lidar

A number of OSSEs have been performed to evaluate the benefit of Space-Based DWL in polar orbit (Stoffelen *et al.*, 2006; Tan *et al.*, 2007; Masutani *et al.*, 2010b; Riishøjgaard *et al.*, 2012). In a recent development, and to reduce costs, the International Space Station orbit, which covers 50^{o}S-50^{o}N, is now being considered as a platform for the DWL. OSSEs could assess that impact.

7. Summary and concluding remarks

There is ample evidence that OSSEs can be used to realistically evaluate the impact of prospective observations. However, differences between the Nature Run (NR) and the real atmosphere, the process of simulating the data, and the estimation of observational errors, all impact on the results. Using appropriate evaluation metrics is also important to infer meaningful conclusions. The position of the authors of this white paper on OSSEs, including their application to an Arctic observing system, is summarized as follows:

- **Advancing OSSE science**

  OSSEs are a challenge to weather services and there are immediate costs to develop and perform OSSEs. Funds must be engaged requiring significant computer and human resources. Strong leaders with a clear vision are needed, because OSSE science aims at long-term rather than short-term benefits. The NR has to be produced using state-of-the-art global NWP models at the highest resolution. Simulating data from a NR is a significant task, and assimilation cycles have to be repeated with various configurations. OSSEs also require extensive knowledge of many aspects of the NWP system. In particular, expert knowledge is required for each instrument. Effective and efficient collaborations are thus essential.

- **Collaboration in OSSE experiments**

  There are several levels of possible collaboration with regard to OSSEs, particularly if they have one point in common, *e.g.*, the use of the same NR. Having a common NR is fundamental because the synthetic observations are then derived from the same “truth”. Cooperation on data simulation is another clear benefit. Close co-ordination with the WMO WWRP-THORPEX Polar Prediction Project, PPP (Fairall *et al.*, 2013) is highly desirable. OSSEs will be conducted by scientists with different interests, such as promotion of particular instruments and improved design of the Global Observing System (GOS). Operational centres can help find a balance among conflicting interests to seek improvement in weather predictions. They can be regarded as unbiased and best placed for this role; however, difficulties in finding resources may hamper their effort. With current financial constraints for the development of space technologies, presenting a very strong case for future instruments is more challenging than ever. It is recommended to proceed with OSSEs in support of future missions as early as possible in the development phase, *i.e.*, at Phase A level when mission requirements and instrument characteristics are known.

- **Conclusions**

  Data assimilation systems are now evolving toward coupled ocean-atmosphere systems and cloud resolving models. It appears too early to propose a long NR with such characteristics. Nevertheless, the time has come to produce a new global NR at resolution of order 10-15 km and hourly output for a whole year. The current resolution of the ECMWF model, 16 km, would be sufficient for several years to come. The development of a NR which includes key air quality variables and greenhouse gases provides new challenges. Efforts should be directed toward the definition of a NR with characteristics satisfying a broad range of scientists. Embedding the air quality NR into an atmospheric NR offers obvious advantages. Specific issues related to the Arctic observation network and relevant to the Arctic Observing Summit are presented in this paper. Several satellite missions and new or upgraded observation capabilities are being proposed to address well recognized spatio-temporal observation gaps in the Arctic. OSSE studies will be invaluable to decision makers by providing objective, scientific information on these new observing capabilities.

Acronyms

AMSR: Advanced Microwave Sounding Radiometer
AVHRR: Advanced Very High Resolution Radiometer
AOS: Arctic Observing Summit
COSMIC: Constellation Observing System for Meteorology, Ionosphere and Climate
GPS: Global Positioning System
IASI: Infrared Atmospheric Sounding Interferometer
MODIS: MODerate resolution Imaging Spectroradiometer
OSE: Observing System Experiment
OSSE: Observing System Simulation Experiment
PPP: Polar Prediction Project
RAOB: Radiosondes (RAwinsonde OBservation)
SSMI: Special Sensor Microwave Imager
SSMI/S: Special Sensor Microwave Imager/Sounder
THORPEX: THe Observing system Research and Predictability EXperiment
WMO: World Meteorological Organization
WWRP: World Weather Research Programme

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