Met Office

Observing system studies proposed for GNSS-R ocean surface wind data

Forecasting Research
Technical Report No: 629

June 2018

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ESA contract TGScatt, 4000116699/16/NL/CT

Abstract

This report was prepared as a contribution to the ESA-funded project, "Scientific assessment of TDS-1 GNSS-R scatterometric measurements" (TGScatt). It summarises various observing system studies that could be undertaken to assess the impact, and potential future impact, of GNSS Reflectometry (GNSS-R) observations of ocean surface wind on numerical weather prediction (NWP).

General methods for assessing the impact of current and future observations on NWP are described. For each of these methods, its potential for assessing the impact GNSS-R ocean surface wind observations is reviewed.

1. Introduction

Observations of many different types, both space-based and surface-based, are used in numerical weather prediction (NWP) to deliver global weather forecasts. The observations are assimilated into NWP models through data assimilation (DA) systems. These systems undergo continuous development, both to improve the exploitation of currently-available observations and to prepare for observations from planned new observing systems. These DA systems can also be used to assess the potential of proposed future observing systems.

Methods for assessing the impacts and potential impacts of observations, referred to here as "observing system studies", are of a number of generic types. In section 2 of this report we summarise these generic methods together with their strengths and weaknesses.

In section 3, we consider how each of these generic methods might be applied to understand the potential impact of GNSS-R ocean surface wind observations in global NWP.

In section 4, we present conclusions and recommendations.

2. Methods for assessing the impacts of observations

2.1 Observing System Experiments (OSEs)

These are also called Data Denial Experiments (DDEs). They use real observations and they measure the effect of removing them from a NWP system. Usually they make use of a NWP DA system that is the same as or similar to an operational system, assimilating the full range of observations types that are currently used operationally, and then examining the impact of removing one observation type. Impact is assessed using a range of metrics available to operational centres. These include the impact on the skill of short/medium-range forecasts made using the NWP system, using either observations or NWP analyses as the "truth" against which the forecast is verified. Another commonly-used and sensitive metric is the fit of the short-range forecast (e.g. 6 hours) to the next batch of observations.

Operational centres have the facilities to do such experiments, as they are necessary tools for testing the assimilation of any new observation set before it is used operationally.

The OSE method is the "cleanest" way of assessing impact on NWP; it measures what you really want to know. However, it can only be done with observations that are available from existing observing systems; it cannot be used to estimate the impact of future observing systems.

The results of OSEs tend to be noisy. This is because even "good" observations, with small observation errors that are well understood, will degrade the NWP analysis (and subsequent forecasts) in some areas, i.e. those areas where the NWP background field is, by chance, more accurate than the observations. This is a consequence of the inherently statistical nature of the DA problem. Moreover, statistics available from the complementary FSOI (Forecast Sensitivity to Observation Impact) technique (see, for example, Lorenc and Marriott, 2013) show that, for most observation types, the percentage of observations that improves the analysis (rather than degrading it) is usually in the range 51-55%. This result, which at first sight is rather alarming, can be shown to be consistent with the expectations of statistical theory.

Because of these considerations, experience shows that global OSEs need to be run for at least two months, and often several months, before they provide estimates of impact that are statistically significant. Also, the lower the impact of a given observation type, the longer the experiment must be run before results become significant.

As a consequence, although such experiments are "easy" for an operational NWP centre to perform, they can be demanding in terms of computational cost, particularly if many different combinations of observation type or of observation processing method need to be tested.

2.2 OSEs with modified observations

In NWP DA, whenever an observation is assimilated, assumptions must be made about its uncertainty (i.e. about the error statistics of the set of observations from which it is drawn). Best results are obtained when the assumed characteristics are consistent with the real error characteristics of the observation type. Therefore, when assimilating real observations, efforts are made to assess their error characteristics as accurately as possible.

Within this framework, therefore, it is also possible to simulate hypothetical observations of a lower quality, by modifying the real observations: either by adding random noise or by degrading them in some other way (e.g. by converting observations of wind vector into observations of wind speed only).

In this way the impact of hypothetical observations can be assessed but only if they are simulated at the same times/locations as the real observations, or at a sub-set of these times/locations. To test the impact of hypothetical observations at different times/locations, other methods are required - see below.

This type of study may therefore be suitable for observation types for which the characteristics are known (or can be assumed) but which are not yet available, or not available with the space/time coverage suitable for an OSE. It does however rely on the existence of observations of high quality of the same geophysical variable(s) and of suitable space/time coverage from some other technology.

2.3 Observing System Simulation Experiments (OSSEs)

In an OSSE, the whole observing system is simulated – not only the new observation type in which we are interested, but also all the other components of the observing system expected to be important when the new observation type becomes available. A hypothetical "true" state of the atmosphere is generated by running a NWP model without assimilating any observations for several months. The output of this model is called the "nature run". It is desirable that this model is state-of-the-art and is run at the highest feasible resolution. Taking the nature run as the true state of the atmosphere, observations of all types are simulated using state-of-the-art observation operators. Realistic observations errors are then added, taking account of state-dependent effects (e.g. the effects of cloud and precipitation) on both observational errors and useful observational coverage. These simulated observations are then assimilated into a NWP system (preferably independent of the system used to generate the nature run) and forecasts from this system are compared with the "truth" (i.e. the nature run). By performing experiments in which different combinations of simulated observation types are assimilated, the impact of these observation types can be assessed.

In principle, this is the best way to study the impact of future observing systems but it is very expensive. At present, as far as we are aware, there is no centre in Europe that is maintaining a system to do this adequately, and only one centre in the USA (Errico *et al*., 2013). Not only is much effort (both human and computational) needed to accomplish all the steps of an OSSE outlined above, but it is important to put considerable effort into calibrating the system, i.e. to ensure that the impact of simulated observations is comparable with the impact of real observations for observation types that currently exist. It is also important that the error characteristics of the new observation types are simulated realistically; **the estimated impact of new observations depends critically on their assumed errors.**

To underline the difficulty and cost of establishing an OSSE system, it should be recalled that an effort was made to establish a European capability, at ECMWF and funded by ESA, in the mid-1990s (Becker *et al*., 1996). This system was built primarily to simulate ADM/Aeolus data and to allow other centres to study the NWP impact of these data. However, all other observing systems used operationally in NWP at the time were also simulated. Despite the success of the project in developing a system to simulate observations, it was not found possible to maintain the resources to establish a long-term European OSSE capability.

Although the OSSE approach is very powerful, it is limited by the extent to which the characteristics of the simulations are realistic. This can be checked to some extent using the "calibration" method described above. The approach has another fundamental limitation; ideally one would like to test the impact of a simulated future observing system using the DA systems that will be in available in the future. Unfortunately, one is limited to using today's DA systems.

2.4 Intermediate methods

Some intermediate methods have been developed which are significantly cheaper to use than OSSEs. They combine the properties of an OSE, using real observations for currently available systems, with those of an OSSE for simulated observations from hypothetical future systems.

Some approaches have used the framework of an ensemble data assimilation (EDA) system to perform these studies. The EDA approach provides an estimate of the theoretical analysis and short-range forecast error statistics, based on the ensemble ‘‘spread,’’ which is the standard deviation of the ensemble members about the ensemble mean. This approach can be used to estimate the impact of hypothetical future measurements through their ability to reduce the ensemble spread. It can therefore be used to study how the impact scales as a function of observation number or of some other property of the new observing system. Examples of this approach are the study of the impact of Aeolus (Tan *et al*., 2007) and the impact of various configurations of GNSS-RO data (Harnisch *et al*., 2013).

Studies of this type have the potential to show not only the impact of new observation types but also the tendency of the impact to saturate (or not) as the observation numbers are increased. However, just as with OSSEs, they are very sensitive to the assumptions made about the error characteristics of the simulated observations, including the spatial correlations of their errors.

2.5 Simple information content studies

A surprising amount of insight into the likely impact of new observations can be obtained from highly simplified calculations, in which the information content of the new observations is assessed relative to the system into which they will be assimilated. Such studies use the basic equations that describe the error characteristics of the variational DA problem, or of DA systems with properties approximately equal to those of an idealised variational system (e.g. see Kalnay, 2003).

Within each cycle of a DA system, the observations act to add information to the system in the following way. In the limit of a linear system, the error covariance of the analysis, **A**, is related to the error covariances of the observations, **R**, and of the background field, **B**, as follows:

$$\mathbf{A}^{-1} = \mathbf{B}^{-1} + \mathbf{H}^{T}\mathbf{R}^{-1}\mathbf{H} \quad , \qquad (1)$$

where **H** is the Jacobian of the observation operator, i.e. the gradient of the operator, describing the physical relationship between the analysed geophysical variables and the “observed” variables, with respect to the analysed variables, and **R** and **B** are assumed to be uncorrelated with each other. The “observed” quantities can, in principle, be raw instrument measurements, or retrieved geophysical variables, or any convenient intermediate variables.

By defining the inverse of the error covariance of a quantity as its “information content”, eq.(1) can be interpreted as saying that the information content of the analysis is the sum of the information contents of the background field and of the new observations (when the latter are projected into the same space as the analysis).

In a real global NWP system, **A** and **B** typically have a dimension of several million and also complex off-diagonal structure describing how the analysis/background errors are correlated, both in space and between analysis variables (e.g. between temperature and wind). However, insight can be obtained by considering problems of much lower dimension. For example, consider the problem of a single variable at a single location with a background error of 1 unit. Now consider an observation of the same variable at the same location. In this case **H** is unity. If the standard deviation of observation error is 1 or 2 or 3 units, then the analysis error will be given, through eq.(1), by the following table:

B	**B^{-1}**	**R**	**R^{-1}**	**A^{-1}**	**A**	**$A^{½}$**
1x1=1	1	1x1=1	1	2	1/2	0.71
1x1=1	1	2x2=4	1/4	5/4	4/5	0.89
1x1=1	1	3x3=9	1/9	10/9	9/10	0.95

Table 1. Illustrating the application of equation (1) to a simple example.

From this table it can be seen that a single observation with the same error as the background (and when unaffected by other nearby observations) will, on average, reduce the analysis error by 29%. However, when the observation error is increased to 2 or 3 times the background error, then the reduction in analysis error is only 11% or 5% respectively.

To take account of the cycling of a DA system, it is necessary to add a further equation to represent the evolution of background error, i.e. how the analysis error covariance from one assimilation cycle is amplified by the forecast process and becomes the background error for the next assimilation cycle.

This type of simple study has been used to assess some aspects of future observing systems, e.g. the effect of the number of satellites and/or their equator crossing times on the analysis accuracy (e.g. Eyre and Weston 2014).

3. Possible methods for assessing GNSS-R ocean surface wind observations

In section 2, we have introduced generic methods for assessing the impact of observations. In this section, for each generic method, we assess its applicability to GNSS-R observations of ocean surface wind.

3.1 OSEs

OSEs could be conducted on ocean surface wind retrievals available from TechDemoSat-1 (TDS-1). However the conclusions that could be drawn from such experiments are likely to be very limited because of two factors: the limited temporal coverage of TDS-1 data (up to July 2017, only one day in four) and their large errors relative to scatterometer observations. (Their errors are a limiting factor because of the arguments presented in section 2.5). Because of these limitations, it is unlikely that an OSE of less than one year would yield statistically significant results.

Therefore the steps needed to make such experiments more worthwhile would be one, or preferably more, of the following:

(a) Extend the TDS-1 mission to provide continuous temporal coverage for at least 3 months.
(b) Continue efforts to understand and to reduce the errors in the wind retrievals.
(c) Perform OSEs on equivalent retrievals from CYGNSS data, to take advantage of the multi-satellite coverage.

Concerning (b), it may be that the errors in the wind speed retrievals are fundamentally limited by the information content of the observations themselves. If this is the case, then efforts to improve the accuracy of these retrievals are likely to be fruitless, or to suffer from rapidly diminishing returns for the R&D effort put in. For this reason, it is important to conduct some basic simulation studies to understand the information content of the observations and hence the limiting accuracy of the retrievals. All uncertainties should be understood and propagated through a realistic simulator, and all available knowledge should be employed to reduce these uncertainties. Moreover, efforts should be made to correct all systematic errors, e.g. on transmitter or receiver conditions (gain, pointing), since they substantially complicate observation error covariances.

It is possible that the information potentially available on wind is degraded by retrieving only wind, without simultaneous consideration of wave information. If this is the case, then other assimilation approaches could be considered: assimilating mean square slope (MSS) retrievals, or assimilating observations as delay-Doppler maps (DDMs). Such approaches are unlikely to give any improvement unless the observation operator mapping from geophysical variables (i.e. the surface wind from NWP field and other relevant geophysical variables) to the observed variables is sufficiently complex as to address the separate effects of the instantaneous wind field and of other aspects of the wave field on the DDM or MSS.

3.2 OSEs with modified observations

The most straightforward application of this approach to the study of GNSS-R winds would be via scatterometer data: existing observations from scatterometers could be degraded to simulate GNSS-R data – degraded by converting wind vectors to wind speed only, and degraded by adding noise to simulate estimates of errors of GNSS-R winds, taking account of their wind speed dependence (e.g. see Cotton 2018) and any other known contributors to their error characteristics. Moreover, the error estimates could be varied: they could conform to the best estimates of GNSS-R products today, and they could also conform to hypothetical improvements in these products towards the theoretical limit of their accuracy (see section 3.1 above). Results from the ESA-funded project, “Scientific assessment of TDS-1 GNSS-R scatterometric measurements” (TGScatt), contribute to the quantification of current error characteristics and of their theoretical limit. For realistic simulations, scatterometer observations should also be degraded to take account of the lack of across-track sampling of GNSS-R winds or, more precisely, the number of specular points that can be tracked at the same time.

ASCAT observations could provide the main source of observations to perform such experiments. ASCAT observations from either Metop-A or Metop-B or both could be degraded to simulate GNSS-R observations in these orbits. Part of this set of experiments should include experiments with ASCAT winds themselves (as currently used operational) and with no ASCAT winds, to serve as a baseline for the GNSS-R experiments.

Alternatively, observations from RapidScat on the International Space station (ISS) could be used, as these may be more favourable for simulation of systems such as CYGNSS.

Scatterometer observations from other satellites in other orbits could also be used. OSCAT (available from 2009 to 2014) would be one possibility. Scatsat data have recently become available. In the near future, additional scatterometer observations will be available from Oceansat-3, Oceansat-3A, Metop-C and HY series satellites.

Of course, if more scatterometer observations are available, then the impact of observations from any given GNSS-R constellation will be lower, and so it will be useful to understand the impact of proposed GNSS-R constellations in the presence of varying scatterometer constellations.

3.3 OSSEs

For the reasons given in section 2.3, it would be a substantial and expensive undertaking to develop an OSSE system and to run it with believable results. It would be most practicable to perform such studies in collaboration with a centre that already has a mature OSSE capability. Collaboration with NASA or with the USA's Joint Center for Satellite Data Assimilation (JCSDA) could be considered.

Within such a framework it would be possible to simulate the GNSS-R constellation in a number of proposed configurations and with various assumptions about the quality of the retrieved winds or, indeed, using more sophisticated assimilation options discussed in section 3.1 (some of which are under development in the USA in the context of CYGNSS studies). These issues could be studied to some extent in the context of the studies described in 3.2, but they could be studied in a more complete way in a OSSE.

3.4 Intermediate methods

Such studies could be performed by a centre with an existing capability in this area, e.g. ECMWF. The study of GNSS-RO data conducted by Harnisch *et al.* (2013) is a good model for what could be done with GNSS-R winds.

In their study, Harnisch *et al.* found no saturation - the impact of increasing numbers of GNSS-RO data increased almost linearly with the number of observations. This result confirmed expectations that global GNSS-RO network is far from saturation. It is not clear whether a similar result with GNSS-R winds is expected or not. However, Stoffelen *et al*. (2014) found ASCAT at 9:30 and OSCAT at 12:00 local time to be complementary. This suggests one could cover the ocean in winds every 3 hours and maintain complementary benefit.

A crucial aspect of the problem, which would need careful consideration, is the spatial and temporal correlation of errors to be expected with GNSS-R winds (errors both in the observations themselves and in their observation operators). As can be seen from eq.(1), the information in observations with uncorrelated errors tends to add linearly, whereas strong correlations of error between observations will lead to a saturation of the information content. The biases and the correlations of error within the NWP system also restrict the information that can usefully be extracted from the observations, and these need to be considered in this type of observing system study (and also in other types of study).

Another aspect of the problem, and one which is not so clear for surface wind observations, is the extent to which they have impact on forecasts beyond a few hours, i.e., the extent to which other observations (primarily of the free troposphere) become dominant for successful forecasting of the surface wind fields. This was a major problem in the early days of scatterometer data assimilation. It is thought to be less of a problem now; assimilation of scatterometer data has been shown to benefit forecast skill at all forecast ranges. However, experiments using this approach may be able to add to the understanding of this question.

3.5 Simple information content studies

In section 2.5 we have already shown how very simple calculations of information content can be used to inform thinking about the potential impact of future observing systems. In fact the values in Table 1 were chosen to be relevant to the surface wind assimilation problem, where background errors are typically ~1m/s and observation errors for scatterometer winds are similar or lower.

4. Conclusions and Recommendations

In section 2 we have described a range of types of observing system study that may be used to assess the impact on global NWP of present and future observing systems. In section 3 we have considered how each type of study might be applied to assess the impact of ocean surface wind retrievals from currently available GNSS-R data and from possible future constellations of GNSS-R sensors.

We **recommend** that the following set of studies should be considered as options for taking forward the assessment of the impact of ocean surface wind information derived from GNSS-R observations:

(a) Much detailed work has already been performed within the TGScatt project to generate an “observation operator” for GNSS-R observations, i.e., a physical model for simulating GNSS-R observations, given knowledge of the values of relevant geophysical variables, observation geometry, instrument parameters, etc. The TGScatt project has also provided understanding of the error characteristics of TDS-1 observations. Taken together, this information provides a basis for assessing the information content of GNSS-R observations on ocean surface wind, and of its state-dependence. More specifically, it provides a model for **H** and statistics for **R** in equation (1), from which the theoretical errors in retrieved wind speeds, and their wind speed dependence, can be assessed. **It is recommended** that further studies are undertaken to improve understanding and to provide estimates of the theoretical limit of wind retrieval errors for a range of realistic assumptions on measurement error statistics.

(b) Assuming that the TDS-1 mission can be continued, **it is recommended** that a set of continuous observations of at least 3 months be acquired and processed to generate retrieved winds. **It is also recommended** that similar data sets be acquired or generated for the CYGNSS mission. These data could then be used in conventional OSEs to assess the impact of retrieved winds from currently available GNSS-R sensors.

(c) **It is recommended** that OSEs with modified observations should be performed. Scatterometer wind retrievals should be degraded to represent GNSS-R wind retrievals, with observation coverage and error characteristics of currently available TDS-1 retrievals and/or of idealised retrievals as assessed through study (a). The impact of these data would be assessed through OSEs and compared with the impact of scatterometer data, as described in section 3.2.

(d) Through collaboration with appropriate centres (e.g. JCSDA), **it is recommended** that a set of OSSEs could be conducted to assess the impact of proposed constellations of GNSS-R sensors, as described in section 3.3. The observation simulation tools developed during the TGScatt project could serve as the basis of the observation operator used in the OSSEs.

(e) Through collaboration with appropriate centres (e.g. ECMWF), **it is recommended** that a set of EDA experiments could be conducted to assess the impact of proposed constellations of GNSS-R sensors, as described in section

3.4. Again, the observation simulation tools developed during the TGScatt project could serve as the basis of the observation operator used in these experiments.

Acknowledgements

Thanks to James Cotton, Mary Forsythe, Marcos Portabella and Ad Stoffelen for valuable comments that have contributed to this report.

Acronyms

ADM	Atmospheric Dynamics Mission (of ESA)
CYGNSS	Cyclone Global Navigation Satellite System (of NASA)
DA	Data Assimilation
DDE	Data Denial Experiment
DDM	Delay-Doppler Map
EDA	Ensemble Data Assimilation
ECMWF	European Centre for Medium-range Weather Forecasts
ESA	European Space Agency
FSOI	Forecast Sensitivity to Observation Impact
GNSS	Global Navigation Satellite System
GNSS-R	GNSS Reflectometry
GNSS-RO	GNSS Radio Occultation
ISS	International Space Station
JCSDA	Joint Center for Satellite Data Assimilation (of the USA)
MSS	Mean Square Slope (of the ocean wave field)
NASA	National Aeronautics and Space Administration (of the USA)
NWP	Numerical Weather Prediction
OSE	Observing System Experiment
OSSE	Observing System Simulation Experiment
R&D	Research and Development
TDS-1	TechDemoSat 1

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