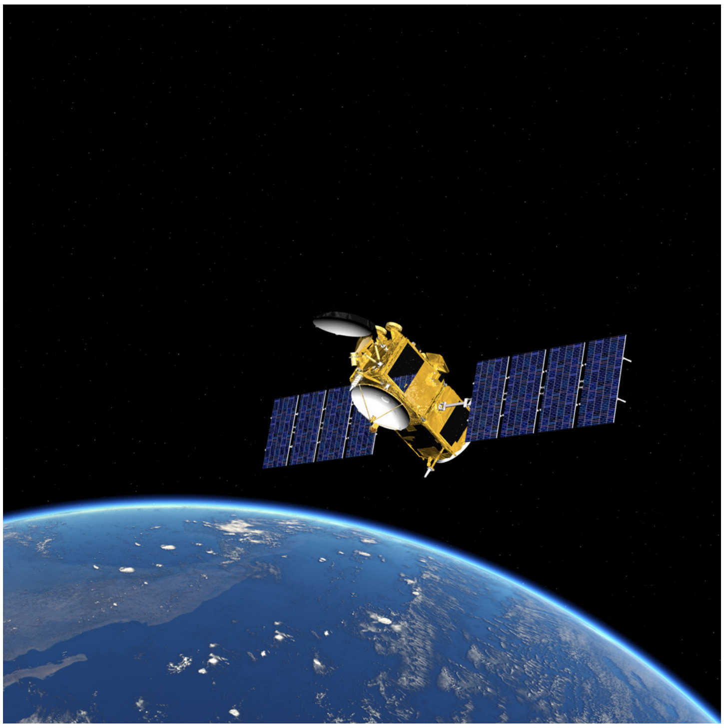
ECMWF Feature article

from Newsletter Number 149 – Autumn 2016

METEOROLOGY

The use of radar altimeter products at ECMWF



Artist's impression of Jason-3 satellite (© EUMWTSAT)

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doi:10.21957/m2cx1w

This article appeared in the Meteorology section of ECMWF Newsletter No. 149 – Autumn 2016, pp. 14-19.

The use of radar altimeter products at ECMWF

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Radar altimeters are satellite instruments which probe the Earth's surface by emitting a series of electromagnetic pulses and measuring their reflections. The measurements are used to derive information on near-surface wind speed over the oceans, mean sea level, and ocean wave height. Observation capabilities have recently been boosted by the launch of two new satellites carrying radar altimeters: Jason-3 (January 2016) and Sentinel-3A (February 2016).

ECMWF uses radar altimeter products both to help initialise forecasts and to monitor the performance of its Integrated Forecasting System (IFS). Experiments carried out at the Centre show that assimilating altimeter observations brings significant benefits for ocean reanalyses of sea level changes and for monthly and seasonal atmospheric forecasts as well as for wave height forecasts.

Altimeter products

For the time being, all radar altimeter products used at ECMWF are ocean products. The Centre's use of these products can be summarised as follows:

- Data assimilation, the process of using observations to help initialise forecasts, is the most important application of altimeter observations. Sea-level anomaly (SLA) and significant wave height (SWH) products are used for this purpose. A detailed description of these products and of the impact of assimilating them is given below.
- SLA, SWH and wind speed products are used to monitor the performance of the IFS and to assess model changes.
- SWH and wind speed products have been used to estimate the absolute random model error.
- Altimeter wind speed has been used to estimate the effective model resolution (*Abdalla et al.*, 2013).
- Altimeter products are also used for climate studies. In particular, the assimilation of SLA and SWH data is used in atmospheric and ocean reanalyses produced at ECMWF.

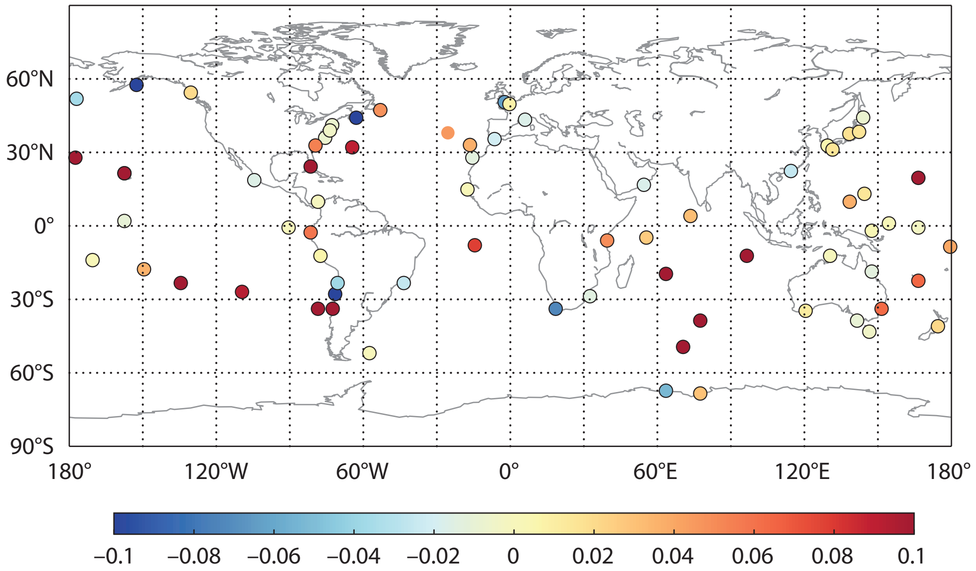

Figure 1 Differences in the correlation of the ORAP5 and CTRL SLA reanalysis with observations from 72 BADOMAR tide-gauge stations. Positive values indicate that ORAP5 is correlated better with the BADOMAR observations than the CTRL produced without the assimilation of SLA data. Statistics were computed using the monthly mean sea-level analysis from ORAP5 at the nearest model point to each tide gauge station between 1993 and 2011.

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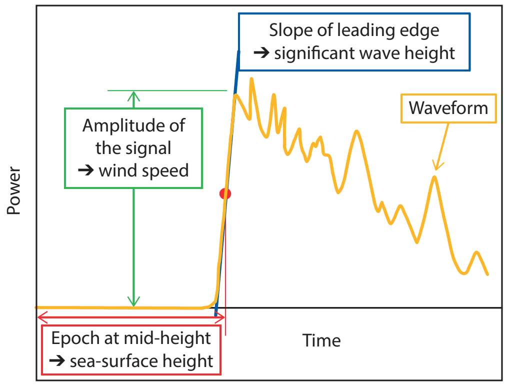
An explanation of how altimeter measurements are used to derive information on sea-level height, significant wave height and wind speed is given in Box A.

Most altimetry missions accommodate a microwave radiometer instrument to measure atmospheric humidity. The main purpose is to determine the impact of atmospheric humidity on altimeter measurements (delay and attenuation of the radar signal). A total column water vapour (TCWV) product is also derived from those measurements and is used at ECMWF to monitor the IFS's performance.

Reading the signal

A

Space-borne radar altimeters measure the radar echo reflected from the surface of the ocean. This is called the ocean waveform. Usually 100 waveforms within 50 milliseconds are averaged on-board, i.e. averaging takes place at a rate of 20 Hz. The figure schematically shows a typical altimeter ocean waveform of such an average. The mean waveforms are transmitted to ground stations where they are processed to retrieve geophysical observations. The 20 observations per second are averaged to produce the 1 Hz products which are usually used for practical applications, such as data assimilation. Typically, this corresponds to about 6 to 7 km along the satellite ground track.



Information extracted from a radar echo reflected from the ocean surface after averaging about 100 individual waveforms within 1/20 of a second.

The time lapse between emitting the signal and receiving the midpoint of the leading edge of the waveform is used to determine the distance between the altimeter and the ocean surface (also called the range) after correcting for the signal delay due to various environmental factors, such as dry air ('dry tropospheric correction'), humidity ('wet tropospheric correction') and the electron content in the atmosphere ('ionospheric correction'). The impact of fluctuations in the range measurements due to tides, atmospheric pressure and ocean waves is then filtered out to determine the sea-surface height (SSH). The deviation of SSH from its mean over a few decades, which is known as the sea-level anomaly (SLA), is an important indicator of climate change.

The slope of the leading edge can be used to compute significant wave height (SWH), which is an important measure for the ocean sea state. If the ocean surface has no waves, the reflection from the surface is specular and the waveform leading edge is vertical (change from no reception to full reception of the echo in a very short period of time). The existence of ocean waves causes the waveform leading edge to tilt. The part of the signal that is reflected from the wave crests reaches the altimeter before the part that is reflected from the wave trough, with a whole spectrum in between. The higher the waves, the smaller the slope of the waveform leading edge is. This slope is translated into SWH. These observations are very important for ECMWF as they are the only ones that are currently assimilated in the ocean wave model (ECWAM).

The amplitude of the waveform can be used to estimate the wind speed over the water surface. In the absence of surface wind (and assuming there are no other surface disturbances), the water surface is undisturbed, the radar signal is specular, and the maximum intensity is echoed back to the altimeter. The wind roughens the surface causing the scattering of the echo into different directions, and only part of the echo is received by the altimeter. The stronger the wind is, the rougher the surface is and the less signal is received back by the altimeter.

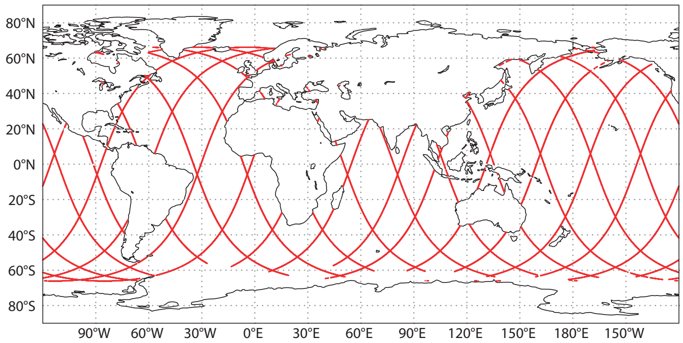
doi:10.21957/m2cx1w

The altimetry observing system

B

The radar altimeter instrument is part of the payload of a number of past and current polar-orbiting satellites, as shown in the table. For operational models, the observations need to be available in near real time, i.e. typically within three hours for ocean waves. Currently Jason-2/3, CryoSat-2, SARAL and Sentinel-3A provide these fast-delivery products. In general, two polar-orbiting satellites give good global coverage in the form of a mesh in about 6 hours, as shown below for Jason-3. However, having more operational altimeters not only improves model predictions but also adds resilience to the altimetry observing system.

One of the main recent advancements in radar altimetry is the use of the synthetic aperture radar principle, known as SAR altimetry, to make altimeter measurements. The backscattered echoes are collected coherently by making use of the Doppler information in the along-track direction, forming a synthetic aperture which results in higher-resolution data. This type of altimetry provides higher-precision measurements, which are useful for measurements in the cryosphere, for example in the presence of sea ice and ice sheets, and in coastal zones. SAR altimetry was first used in the pioneering CryoSat mission. This type of instrument has started to become the norm, as can be seen with Sentinel-3A as well as future altimeters on Sentinel satellites.



Coverage of Jason-3 on a typical day, showing the locations of ocean observations which have passed quality control.

The main electromagnetic frequency implemented for radar altimeters is between 13.5 and 14 GHz (Ku-band). This corresponds to a wavelength of about 2.5 cm. The only exception is SARAL, which operates at the electromagnetic frequency of 35.75 GHz (Ka-band), corresponding to a wavelength of about 0.8 cm. Most modern radar altimetry missions carry dual frequency altimeters to estimate the impact of the atmosphere on the radar signal (ionospheric impact). The C-band with a wavelength of about 5.5 cm is the most commonly used second frequency.

Missions providing operational radar altimeter products

Mission	Near real time	Organisation	Repeat Cycle (days)	1-Hz Product sampling (km)	Launch	End of operations
ERS-1	Yes	ESA	3, 35, 168	7	Jul 1991	Mar 2000
TOPEX/ Poseidon	No	CNES, NASA	10	6	Aug 1992	Oct 2005
ERS-2	Yes	ESA	35	7	Apr 1994	Sep 2011
GFO	No	US Navy	17	7	Feb 1998	Sep 2008
Jason-1	Yes	CNES, NASA	10	6	Dec 2001	Jul 2013
ENVISAT	Yes	ESA	35	7	Mar 2002	Apr 2012
Jason-2	Yes	CNES, NASA, NOAA, EUMETSAT	10	6	Jun 2008	current
CryoSat-2	Yes	ESA	369	7	Apr 2010	current
HY-2A	No	CNSA	14, 168	7	Aug 2011	current
SARAL	Yes	ISRO, CNES	35	7	Feb 2013	current
Jason-3	Yes	CNES, NASA, NOAA, EUMETSAT	10	6	Jan 2016	current
Sentinel-3A	Yes	EC, ESA, EUMETSAT	27	7	Feb 2016	current

CNES: Centre National d'Études Spatiales
CNSA: China National Space Administration
EC: European Commission
ESA: European Space Agency
EUMETSAT: European Organisation for the Exploitation of Meteorological Satellites
ISRO: Indian Space Research Organization
NASA: National Aeronautics and Space Administration
NOAA: National Oceanic and Atmospheric Administration

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Sea-level anomaly

Radar altimeter sea-level anomaly (SLA) observations have been assimilated in ECMWF's ocean data assimilation system using a variational data assimilation scheme developed in collaboration with CERFACS, the UK Met Office and Inria for the NEMO ocean model (NEMOVAR). SLA data is used in the production of the latest ocean conditions in the form of real-time analysis, and in the reconstruction of the history of the global ocean state in the form of ocean reanalysis products, such as ORAS4 (Ocean ReAnalysis System 4) and ORAP5 (Ocean ReAnalysis Pilot 5) (see *Zuo et al.*, 2015). The assimilation of SLA data improves the initialisation of the IFS, which has a positive impact on extended-range (monthly to seasonal) forecasts. The data used are along-track multi-mission altimeter SLA products from AVISO (Archiving, Validation and Interpretation of Satellite Oceanographic data) and include observations from ERS-1, ERS-2, ENVISAT, TOPEX/Poseidon, Jason-1, Jason-2, Jason-3, GFO, CryoSat-2, SARAL and HY-2A (Box B). Altimeter-derived global mean sea level (GMSL) variations are also assimilated in ECMWF's ocean analysis system to constrain the global freshwater budget and global mean sea-level trends.

To enable comparisons between the model and the SLA observations, a reference mean dynamic topography (MDT) is required. This MDT can be calculated as the mean sea-surface height (SSH) from an assimilation of only temperature and salinity, for an arbitrary period (for example between 2000 and 2009, when the world's oceans were adequately sampled by Argo float measurements). A spatially dependent correction factor is then added to take into account the different reference periods used by the model and AVISO SLA observations. A super-observation scheme, described by *Mogensen et al*. (2012), is used to reduce the correlation of the SLA observation error and to avoid oversampling of the satellite observations. In this scheme, a super-observation grid is constructed with a resolution comparable to that of the model. Altimeter observations are then binned in time and space to create super-observations. An alternative solution is to thin the SLA observations using a stratified random sampling method, which also accounts for representativeness error from observations and can be used for ensemble member generation.

Impact on ocean reanalysis

Altimeter sea-level data has much more uniform spatial coverage than in-situ data. It is a unique dataset for the analysis of large and small scales. In assimilation, careful treatment of the altimeter data and careful specification of background and observation error covariance parameters are required. Experiments carried out at ECMWF show that, as a result of assimilating satellite sea-level data, ocean (re)analyses provide much-improved estimates of seasonal and inter-annual variability of sea-level changes. Compared to a contol run (CTRL) in which SLA data were not assimilated, ORAP5 shows higher correlation with AVISO gridded data, particularly in the tropical regions. ORAP5 is also in general in closer agreement with BADOMAR tide-gauge measurements than CTRL (Figure 1). The assimilation of SLA data also improves the fit to subsurface temperature observations from buoys in the tropical ocean (Figure 2). In the future, improvements are expected from using absolute sea level together with the recently improved geoid (the hypothetical shape of the surface of the oceans under the influence of the Earth's rotation and gravitation alone) based on the GRACE (Gravity Recovery and Climate Experiment) and GOCE (Gravity field and steady-state Ocean Circulation Explorer) satellite missions, instead of using relative SLA defined with respect to an external MDT. The availability of additional high-resolution satellite altimetry data, from Sentinel-3 for example, will be beneficial for the assimilation of SLA near the coasts.

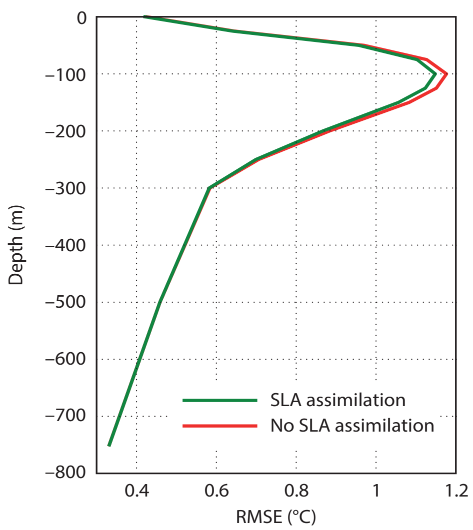

Figure 2 Root-mean-square ocean temperature error of ORAP5 reanalysis runs with and without SLA assimilation, compared to observations from buoys, averaged between 1993 and 2012, in tropical oceans (defined as oceans between 30°S and 30°N).

Significant wave height

Unlike atmospheric data assimilation, which started in the 1960s, ocean wave data assimilation emerged only in the 1980s, mainly as a result of the availability of altimeter ocean wave data. Satellite wave data are assimilated to improve the initial sea state for the wave forecast. Significant wave height (SWH), a parameter widely used to describe the ocean sea state, is defined as four times the square root of the integral of the wave spectrum. It closely corresponds to the average height of the highest one third of waves. The first operational implementation of altimeter SWH assimilation in ECMWF's global ECWAM wave model was realised on 15 August 1993. The SWH products that have been assimilated over the years are shown in Figure 3.

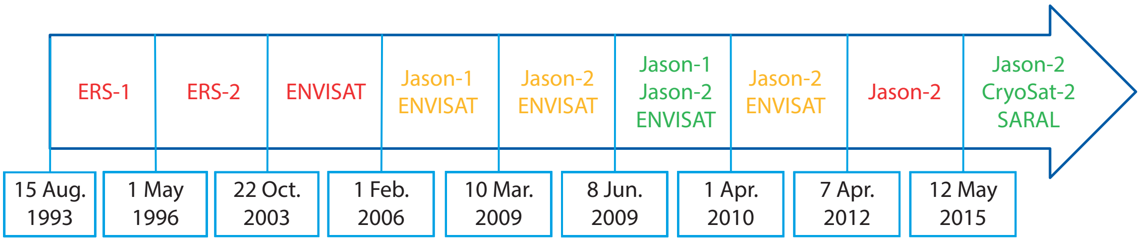

Figure 3 Timeline of altimeter SWH assimilation at ECMWF. There is currently good resilience in altimeter SWH observations as data are being provided by three satellites. Jason-3 and Sentinel-3A data are expected to be added in 2017. The colour coding indicates the degree of resilience.

ECWAM uses the optimal interpolation (OI) technique for the assimilation of satellite ocean wave data. However, information on the full wave energy spectrum is not available from the altimeter since it only provides SWH, which represents the total wave energy.

On the other hand, the wave energy spectrum is the prognostic variable in the wave model, while SWH is a diagnostic variable that is computed from the wave spectrum. In the OI assimilation, the model SWH values (the background) are combined with altimeter SWH measurements to create the SWH analysis increments.

The main challenge in ocean wave data assimilation is to distribute the SWH analysis increments across the whole wave spectrum. This is done by classifying the sea state as wind-sea dominated (with mainly active wave generation) or swell-dominated (mainly waves that are no longer under the influence of their generating wind). In wind-sea dominated conditions, the analysis increment is distributed over the whole background spectrum by adjusting its shape based on the model wave growth curves. In swell-dominated conditions, the increment is distributed over the background spectrum in a way that maintains wave steepness.

The assimilation procedure can be summarised as follows:

- The 1 Hz altimeter SWH data within 6-hour windows centred on major synoptic times are gathered and sorted by time.
- The data go through a quality control process: duplicate, wrong, noisy or questionable measurements are discarded.
- Super-observations of SWH are formed by averaging 11–13 consecutive measurements along the satellite ground track. Each super-observation represents data segments with a length of about 75 km.
- Bias correction is applied to harmonise the altimeter SWH data with the model counterpart.
- The OI scheme is applied to analyse the SWH.
- The wave spectrum is adjusted to incorporate the SWH increments as described above.

Finally, 10–15 day forecasts are calculated from the analyses at 00 and 12 UTC.

Impact on forecasts

The impact of altimeter SWH data assimilation can be assessed through comparison with independent in-situ data, the model's own analysis, and wave and atmospheric data from other instruments.

 doi:10.21957/m2cx1w

Figure 4 shows the mean difference between the SWH analysis when Jason-3, CryoSat-2 and SARAL observations are assimilated and the SWH analysis from a model run without any SWH data assimilation. Both are stand-alone wave model runs uncoupled with the atmosphere. Altimeter SWH data assimilation clearly affects the analysis, and detailed evaluation shows that it improves it. For example, the model is known to overestimate the SWH in the area in the Eastern Pacific off Central America. The data assimilation corrects this overestimation by reducing the wave height.

In-situ wave data are not assimilated and can therefore be used as independent data for data assimilation impact assessment. Figure 5 shows the percentage by which SWH random errors are reduced at analysis time and at various forecast ranges compared to in-situ measurements from buoys and platforms. The assimilation of one satellite alone (Jason-2) reduces the error by about 3.5% (about 5% in the tropics) at analysis time, while assimilating SWH from three altimeters (Jason-2, CryoSat-2 and SARAL) reduces the error by 6.5% (about 9% in the tropics). The impact of data assimilation decreases with forecast range and vanishes after about two days in the extratropics (latitudes higher than 20°), which is usually dominated by active wave generation. In the tropics, which is dominated by swell, the impact is larger and longer lasting.

In general, the assimilation of altimeter SWH also has a positive impact on the predicted wave spectrum. This translates into better agreement between model and measured sea-state-describing parameters derived from the wave spectrum, such as mean wave period (not shown).

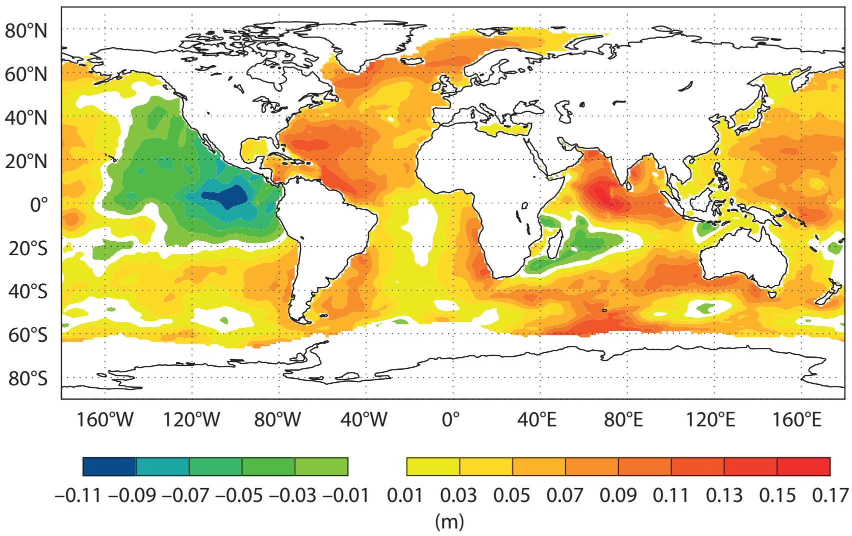

Figure 4 Mean impact, in June and July 2016, of assimilating Jason-3, CryoSat-2 and SARAL SWH data on the SWH analysis, expressed as the difference in SWH between an ECWAM stand-alone model run at a resolution of 0.25° (IFS Cycle 42r1) assimilating data from the three satellites and another model run without any data assimilation.

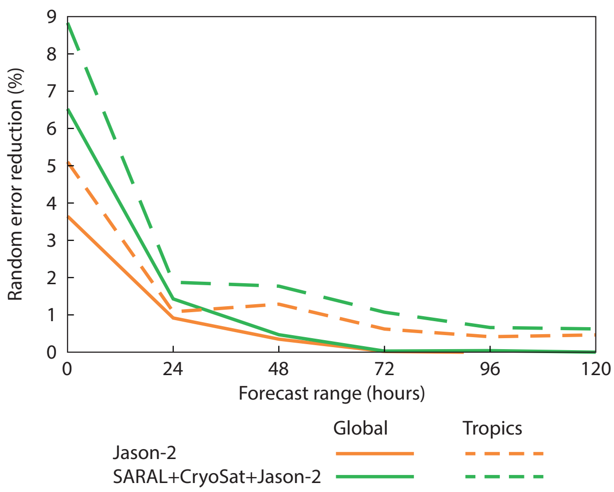

Figure 5 Impact of assimilating altimeter data on reducing the SWH random error in an ECWAM stand-alone model run at a resolution of 0.25° (IFS Cycle 40r1) as verified against in-situ buoy data, averaged over the period 14 February to 30 April 2013.

The tight two-way coupling between the atmospheric and ocean wave models in the IFS means that any wave model change, including data assimilation, affects the atmospheric fields. In another assimilation experiment, the results from a full IFS run (coupled wave-atmospheric model runs) using Jason-2, CryoSat-2 and SARAL SWH measurements were compared with the results of only assimilating Jason-2

SWH measurements. The experiment showed a positive impact on sea-state predictions in agreement with the results from the stand-alone wave model runs (not shown).

Furthermore, the additional altimeter SWH data from CryoSat-2 and SARAL have a small positive impact on some atmospheric fields. For example, Figure 6 shows the mean impact of assimilating SARAL SWH in addition to that of Jason-2 on the anomaly correlation of the 500 hPa geopotential height forecast in the northern hemispheric extratropics (latitudes higher than 20°) with respect to the operational analysis. The chart shows a generally positive impact although on most days the effect is not statistically significant at a confidence level of 95%.

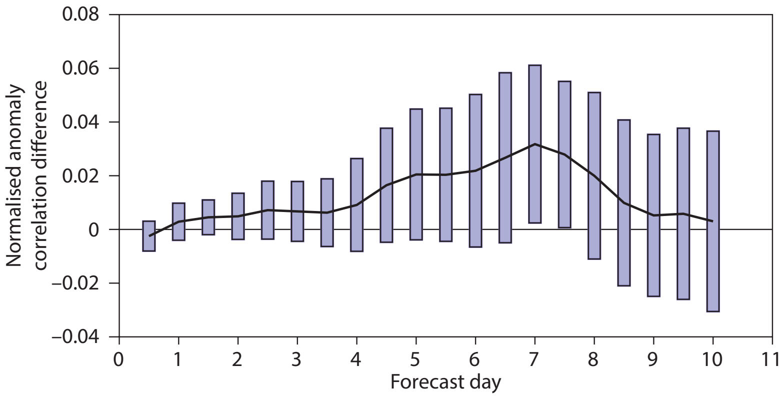

Figure 6 Mean impact of assimilating SARAL SWH on the geopotential anomaly correlation at 500 hPa in the extratropical northern hemisphere, for forecasts produced by IFS Cycle 40r1 (atmosphere and waves) at the resolution TL511 (corresponding to a grid spacing of about 40 km) between 14 February 2014 and 1 April 2014. Vertical bars show 95% confidence intervals.

Concluding remarks

Satellite altimetry provides a wealth of high-quality data for a wide range of marine applications. SLA, SWH and surface wind speed are of particular interest to ECMWF. The ECMWF ocean analysis system, which is part of the IFS, is initialised with SLA. The SWH is assimilated in the ocean wave model ECWAM, which is also part of the IFS. The assimilation of both SLA and SWH improves medium- to long-range forecasts. All altimeter measurements are also used for the verification of IFS predictions.

Further reading

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doi:10.21957/m2cx1w