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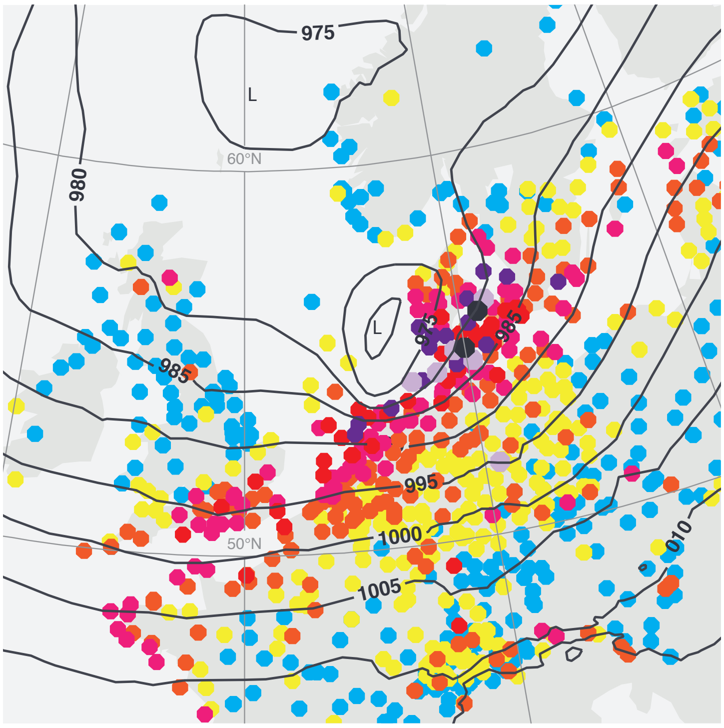
Effective spectral resolution of ECMWF atmospheric forecast models



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Effective spectral resolution of ECMWF atmospheric forecast models

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Very sharp atmospheric phenomena (e.g. frontal zones or tropical cyclones) with scales of 50–80 km or the equivalent of 3–5 model grid spacings are frequently seen in the forecasts from the ECMWF Integrated Forecasting System (IFS). Since 26 January 2010, the high-resolution forecasts (HRES) use a model with a spectral truncation of T1279 which corresponds to a horizontal grid resolution of 16 km (see Table 1 for a list of some of the common horizontal resolutions of ECMWF atmospheric forecast models). However, due to the nature of numerical solutions and parametrizations, the model effective resolution degrades to several grid spacings. It is of interest to estimate this effective resolution.

In this article we will estimate the effective model resolution at the ocean surface by comparing the spectrum of some model fields against a corresponding spectrum from the independent radar altimeter measurements. The restriction to the ocean surface is due to the fact that altimeter wind speed measurements are only possible over the water surface. It is found that the effective useful resolution of the current HRES is 3–5 grid spacings supporting the possibility of observing sharp phenomena at this scale.

Spectral analysis of surface wind speed

Spectral analysis using discrete Fourier transform is an attractive tool to resolve data series into their underlying simple sinusoidal functions covering all possible scales. This concept can be used to reveal the ability of numerical weather prediction (NWP) models in resolving various scales by comparison with available theoretical and empirical (mainly from satellite data) spectra. The first step is to establish a reference against which the model spectra will be compared.

Theoretical, experimental and observational studies show that atmospheric energy spectra follow a power law in the form of k^{-n} where k is the wavenumber (i.e. reciprocal of the horizontal scale). Theoretical studies (e.g. *Lilly*, 1989) suggest that in the upper atmosphere the exponent n has a value of 3 at large scales (small wavenumbers) changing down to 5/3 at smaller scales. There is little known about the shape of the spectrum at the surface. Oceanic surface wind observations (e.g. scatterometers) show agreement with the upper atmosphere theory as far as the exponent at small scales is concerned, i.e. n=5/3. However, it has been found by earlier studies that the value of n for larger scales varies between 2.4 and 2.6.

We have computed the spectra of the surface wind speed product from the radar altimeter (RA-2) aboard the European Space Agency (ESA) Environmental Satellite (ENVISAT). RA-2 surface wind speed measurements can be an attractive source of data to study the properties of the atmospheric spectra at the ocean surface. A typical RA-2 measurement covers a footprint of a few kilometres (typically below 10 km). This resolution is enough to resolve scales in the order of few tens of kilometres. RA-2 wind speed measurements are described further in Box A.

All continuous RA-2 data records of 7,168-km length (1,024 measurements sampled at 7 km) during a period of one year from 1 August 2010 to 31 July 2011 were extracted. There were 685 records in total. A Fast Fourier Transform (FFT) was used to compute the corresponding spectra after applying de-trending (i.e. removing linear trends) and windowing (i.e. ensuring the periodicity). The average of the 685 spectra is plotted in Figure 1. Comparing the average spectrum with the wavenumber power law, it is seen that the RA-2 spectrum follows a power law with n=2.5 for large scales and n=5/3 for smaller scales. The transition occurs at around 400-km wavelength. The spectral shape is in very good agreement with other (surface) wind spectra available in the literature from other instruments (e.g. *Nastrom & Gage*, 1985 and *Xu et al.,* 2011). Therefore, the mean RA-2 spectrum is used here as a reference against which the corresponding model spectra can be compared.

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Spectral solution	Grid spacing (km)	Operational at ECMWF		Notes
		Start	End	
T511	39	21 November 2000	31 January 2006	High-resolution forecast
T799	25	1 February 2006	25 January 2010	High-resolution forecast
T1279	15.6	26 January 2010	Current	High-resolution forecast
T639	31	26 January 2010	Current	Ensemble forecast
T255	78	–	–	ERA-Interim
T2047	10	Candidate for operational use in ~2015	–	Research forecast
T3999	5	–	–	Research forecast

Table 1 Recent and possible future resolutions of ECMWF atmospheric forecast models.

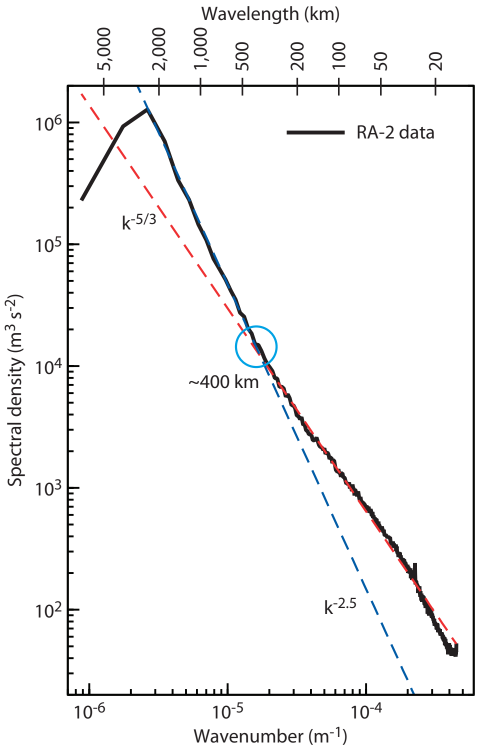

Figure 1 Globally averaged RA-2 surface wind speed spectrum during the period from 1 August 2010 to 31 July 2011. This consists of 685 spectra using data records of 7,168 km in length (1,024 measurements sampled at 7 km spacing). Best-fit power spectra are plotted for the large- and small-scale regimes.

Current model configuration of HRES – T1279

HRES uses the spectral transform method where some computations are done in the grid point domain and some in the spectral domain. Therefore, the global spectra are easily extractable from the model fields. Such spectra represent the atmospheric variability over the whole globe. Examples of surface kinetic energy spectra for four model grid spacings are shown in Figure 2. At large scales, the model spectra from all configurations follow the power law with n=3. At smaller scales, the model spectra follow the power law with n=5/3 with higher resolutions showing more success.

Some scientists claim that global energy spectra are significantly influenced by the variability of the orography. To eliminate this possibility and to get model spectra comparable with the altimeter data, it is necessary to consider only the model spectra over the ocean surface. However, there is no reliable method to separate the spectra over land and ocean from the global model spectra. Therefore, a FFT on the model's physical grid can be used instead. The irregular reduced Gaussian grid used by the model is not suitable for use by standard FFT algorithms which require evenly spaced data series. However, linear interpolation is ruled out as it smooths the structure of the data leading to spectra with steeper high frequency tails than the correct tails.

In order to mimic the ground tracks of polar-orbiting satellites like ENVISAT, model values at given meridians can be used. The FFT requires the meridians to be selected such that the model grid points are aligned perfectly on them. The best candidate is the prime (zero) meridian, where all grid points line up by design. However, this meridian contains a large fraction of land. This limits the ability to consider long sequences. The 180°-meridian can be used as the next best option, if about 8 km deviations in the locations of some of the model grid points are tolerated. 16,000-km record lengths (1,024 grid points) of model data along the 180°-meridian and centred around the equator are used.

ECMWF forecast fields beyond the first 24 hours (every 3 hours from 27 to 144 hours, both inclusive, then every 6 hours till 240 hours) from the analyses at 00 UTC during the period from 1 to 10 October 2011were used to compute the 10-metre wind speed. This resulted in a total of 560 records representing the surface wind speed over the ocean. The sequences were treated in a similar way to the altimeter data and the spectra were averaged to produce the model wind speed spectrum shown in Figure 3 (labelled T1279). The RA-2 average wind speed spectrum shown in Figure 1 is also plotted for comparison (labelled RA-2 data). The T1279 spectrum coincides well with that of the RA-2 and only starts to deviate at a wavelength of about 120 km, i.e. about 8 times the model grid spacing (16 km). This means that the model is able to fully resolve the same structures as does RA-2 for all scales in excess of 120 km. This scale is termed as the effective model resolution.

RA-2 wind measurements

A

RA-2 aboard ENVISAT is a nadir looking instrument that transmits radar pulses towards the Earth at the speed of light. The time elapsed from the transmission of a pulse to the reception of its echo due to the reflection from the surface is proportional to the altitude of the satellite. The power and shape of the echoes contain information on the characteristics of the surface that caused the reflection.

The backscatter of RA-2 signal from the ocean surface varies depending on the roughness of the surface. The rougher (or steeper) the surface is, the lower the returned signal is. Therefore, the total strength of the returned signal is inversely proportional to the surface roughness. Furthermore, it is possible to show that the sea surface roughness (or more precisely the mean square slope of the sea surface) can be related to the wind speed.

There are several (empirical) algorithms to relate the altimeter backscatter coefficient and the surface wind speed. ENVISAT RA-2 used the algorithm proposed by *Abdalla* (2012) for this purpose. RA-2 makes measurements at a rate of 18 Hz. To reduce the noise, 1-Hz measurements are produced by averaging over a period of 1 second which corresponds to about 7 km.

RA-2 wind speeds are not assimilated in the IFS atmospheric forecast model, but are used for independent verification instead.

Future model configuration candidates for HRES – T2047 and T3999

The horizontal resolution of the HRES increases typically every 5 years. The next model horizontal resolution planned for 2015 is expected to be T2047 which corresponds to a grid spacing of about 10 km. A number of runs using this higher resolution have been already carried out by the ECMWF Research Department.

A consistent experiment covering the period from February to November 2009 was carried out starting on the 15th of each month (i.e. 10 forecasts). Forecast fields at steps 24 to 240 hours every 12 hours (i.e. 19 fields) were used to extract a total of 190 records (i.e. 19 fields from 10 forecasts) along the 180°-meridian. A FFT was used for each of these 10,240-km long records (1,024 grid points with 10 km spacing). The average of the resulting 190 spectra is shown in Figure 3 (labelled T2047). It is clear that the wind speed spectrum from the coming high-resolution forecast is able to resolve the variability for scales in excess of about 75 km. So the model fully resolves scales in excess of about 8 times the grid spacing.

Finally, the wind speed spectra from one of the candidate resolutions for the high-resolution model expected to be implemented by the end of the decade are also investigated. The spectral resolution of this candidate is T3999, corresponding to a grid spacing of about 5 km. The T3999 runs are computationally very expensive on the current ECMWF computing facilities. Therefore, only a limited number of T3999 model runs have been carried out. The results of two experiments are used here.

- The first is a 24-hour forecast run starting from 12 UTC on 17 March 1998. Five forecast fields (12 to 24 hours with 3-hour intervals) are used.
- To increase the number of cases, the fields from another experiment are used as well. This experiment is a 48-hour forecast from 12 UTC on 15 October 2010. Four forecast fields (12, 24, 36 and 48 hours) are used.

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Records of lengths 10,240 km (2048 grid points) along the 180°-meridian from the 9 fields were extracted and a FFT was used to compute the spectra. The averaged spectrum of the T3999 model is shown in Figure 3 (labelled T3999). Irrespective of the noisiness of the spectrum (due to the limited number of spectra used in the averaging), it can be clearly seen that the model with a 5-km grid spacing is able to fully resolve scales as short as 30–40 km. Again, the model fully resolves scales in excess of about 8 times the grid spacing.

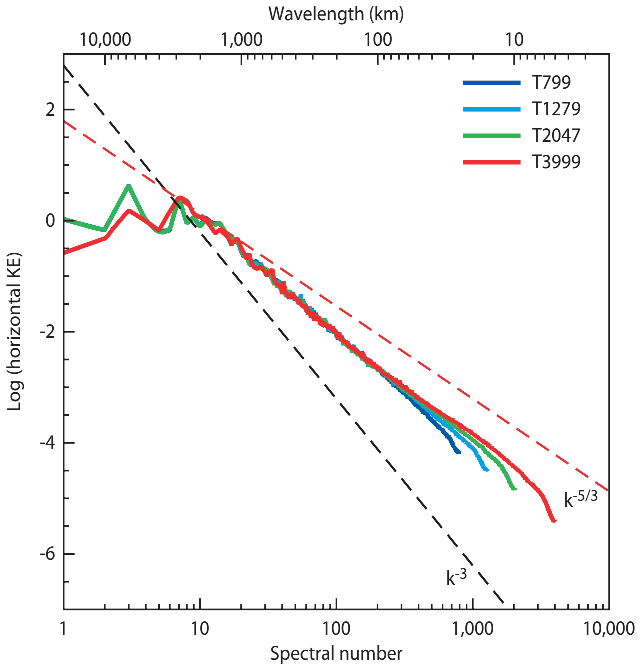

Figure 2 Typical global surface (10-metre height) kinetic energy (KE) spectra for 5-day forecasts for configurations at T799, T1279, T2047 and T3999 of the IFS atmospheric model.

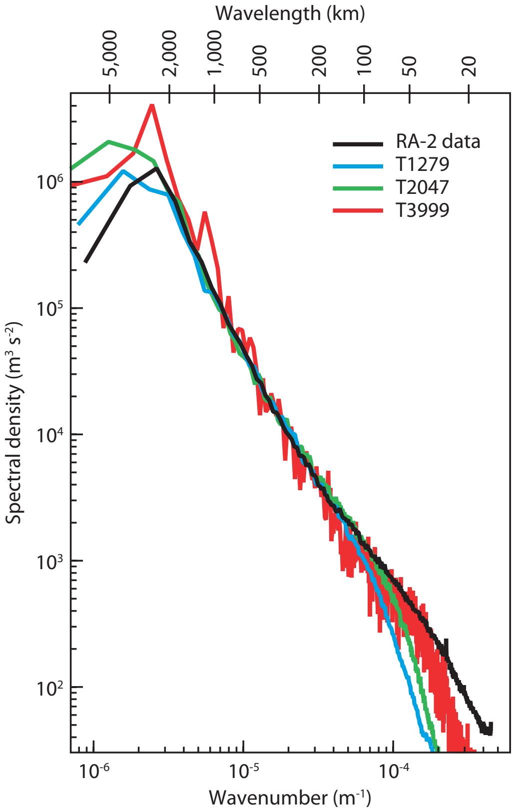

Figure 3 The surface wind speed spectrum of the current and candidates for future ECMWF model configurations compared to those of RA-2. The model configurations are T1279 (560 spectra using 512x15.6 km records), T2047 (190 spectra using 1,024x9.8 km records) and T3999 (9 spectra using 2,048x5 km records).

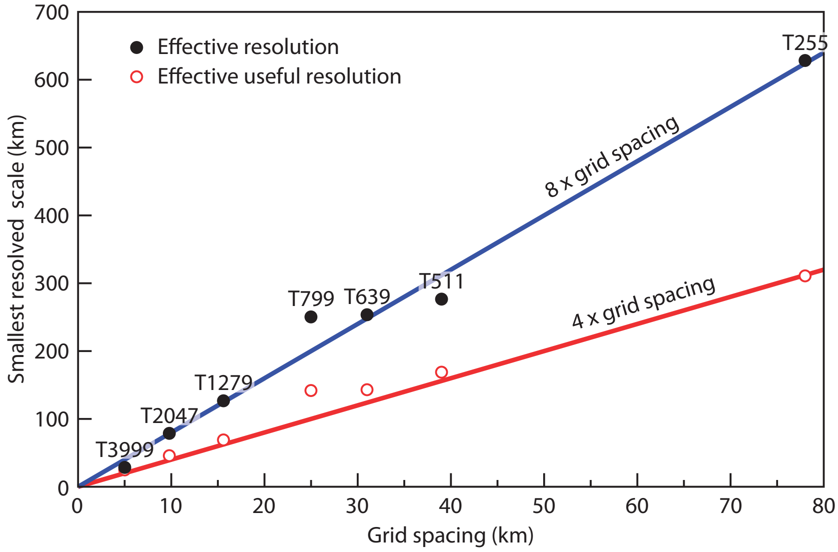

Figure 4 Effective resolution (i.e. model smallest fully-resolved scale) and effective useful resolution (i.e. model shortest scale with 50% resolution) as functions of the model grid spacing for several model configurations. The fixed ratios between the shortest resolvable scale and the used grid spacing of 4 and 8 are indicated by red and blue lines.

Effective model resolution

The effective model resolution represents the smallest scale the model is able to resolve fully. This can be found by comparing the model spectrum against a corresponding spectrum from independent measurements (or theory). Using RA-2 wind speed spectrum as a reference, it is possible to estimate the effective model resolution for the model configurations listed in Table 1. The effective model resolution as a function of the model grid spacing is shown in Figure 4.

It is clear that almost all model configurations considered in Figure 4 show effective full resolution as 8 times the model grid spacing. The model configuration T511, which was operational between 21 November 2000 and 31 January 2006, is the best cost-effective configuration as far as the effective resolution to grid spacing ratio is concerned, though of course the forecasts are less accurate than those with a higher resolution.

Beyond the full spectrally resolved energy, it is sensible to accept scales with partial spectral energy content to be quite useful information. If we relax the strict definition of the effective resolution to what can be termed as effective useful resolution by requiring the presence of at least 50% of the variability of that scale (open circles in Figure 4), the effective useful resolution of the current HRES configuration becomes 3–5 grid spacings. This needs to be taken into account when users of ECMWF products interpret the detailed information in the forecast fields.

Further reading

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