Assimilation of scatterometer data as equivalent-neutral wind

Hans Hersbach
Research Department

July 2010
Assimilation of scatterometer data as equivalent-neutral wind

Abstract

This document describes the assimilation of scatterometer data as equivalent-neutral 10m vector wind into the four-dimensional variational data assimilation (4D-Var) component of the integrated forecasting system (IFS) at the European Centre for Medium-Range Weather Forecasts (ECMWF). For given surface stress this quantity (also simply denoted by neutral wind) provides the wind at 10m height for which stability effects in the surface layer (SL) have been neglected. So far, at ECMWF, scatterometer data has been assimilated as 10m (non-neutral) wind, i.e., the actual wind at 10m height including stability effects. Since it is believed that scatterometer data relates more closely to surface stress than wind, the usage of an observation operator that is sensitive to neutral rather than to non-neutral wind should be more accurate.

Although it is straightforward to adapt the standard observation operator for surface wind, it is realized that the current assimilation system uses an estimation of exchange coefficients that is based on an old version of the ECMWF SL parametrization. Such coefficients are required to perform a proper vertical interpolation from the lowest model-level wind.

The reason for this is that only a limited set of model information is passed to the location where the observation operator is evaluated. In this document it is described how neutral wind can be included into this set, such that the correct information from the actual SL can be accessed. This also embraces the incorporation of the influence of the 4D-Var control vector in the minimization on this diagnostic surface field. Although not further explored here, this latter extension could be applied to other diagnostic surface fields as well.

Several assimilation experiments are performed at a resolution of T511 in early-delivery mode for 109 cases in the Autumn of 2009. From these it is verified that departures between scatterometer and model wind speed are slightly reduced when an observation operator for neutral wind is used. Impact on forecast skill is found to be relatively neutral, with some (not significant) positive impact over the Southern Hemisphere for the atmosphere and ocean surface waves. Most favourable results are obtained for an experiment in which neutral wind is fetched from the actual ECMWF SL.

The usage of scatterometer data as neutral wind has become the default configuration in IFS cycle 36r3, which represents the starting point of a future cycle (36r4) for the currently operational suite (36r2).

1 Introduction

Space-born scatterometer data provide accurate information on speed and direction of surface wind over the global oceans. Since the launch of the ERS-1 satellite in July 1991, global coverage of scatterometer data has been available without interruption. Applications vary from near-real time assimilation into numerical weather prediction models (NWP), the forcing of ocean models, to climate studies accessing the now 19-year data record.

At the European Centre for Medium-Range Weather Forecasts (ECMWF) scatterometer winds have been assimilated in the operational integrated forecasting system (IFS) from 30 January 1996 onwards. The four-dimensional variational assimilation system at ECMWF (4D-Var) allows for a dynamically consistent use of observations. In this way, information of scatterometer surface winds is propagated to the entire troposphere (Isaksen and Janssen, 2004). Currently (May 2010) data is used from the AMI scatterometer on-board the European Remote sensing Satellites ERS-2 (from June 1996 onwards), from the ASCAT instrument on the MetOp-A platform (from June 2007 onwards), and data from the SeaWinds instrument on-board QuikSCAT has been used from February 2002 until its failure in November 2009.

A scatterometer is a microwave radar that emits pulses at well-defined frequency and polarization to the Earth surface. A backscatter is recorded, from which over the global oceans information on the local surface wind conditions can be obtained. The main physical process is based on Bragg scattering where backscatter is related
Assimilation of scatterometer data as equivalent-neutral wind

to the intensity of surface water waves with wavelengths that are comparable to that of the emitted pulse. By choice of the scatterometer wavelength in the centimetre range, the strength of gravity-capillary surface waves is sensed. These in turn, are determined by the local surface stress \( \tau \), or in effect, the local surface wind condition. Since backscatter response also depends on the relative angle between the incident pulse and capillary wave direction, information on wind direction can be extracted as well. In practise, an empirical relation (called geophysical model function, GMF) is established between backscatter and 10m vector wind \( \mathbf{u}_{10} \).

The connection between stress and 10m wind depends among other quantities on the stability of the surface layer (SL). If one assumes a constant stress layer at the surface and a form of Monin-Obukhov stability theory ([Monin and Obukov, 1954]), this relation can be estimated as:

\[
\mathbf{u}(z) = \frac{u_*}{\kappa} \left\{ \log \left( \frac{z + z_0}{z_0} \right) - \Psi_M \left( \frac{z + z_0}{L} \right) + \Psi_M \left( \frac{z_0}{L} \right) \right\} + \mathbf{u}_{\text{oc}},
\]

where \( \tau = \rho_u u_* \), with \( \rho_u \) air density, \( u_* \) the friction velocity and \( u_* \) its magnitude, \( z = 10m \), and \( \kappa = 0.4 \) is the von Kármán constant. This relation in principle depends on variations in atmospheric stability (expressed by the stability function \( \Psi_M \) and Obukhov length \( L \)), air density, and ocean surface current \( \mathbf{u}_{\text{oc}} \). In the ECMWF formulation roughness length \( z_0 \) over the ocean depends for light wind on the kinematic viscosity \( \nu \) \( (1.5 \times 10^{-5} \text{m s}^{-1}) \) and on a Charnock relation ([Charnock, 1955]) for stronger winds

\[
z_0 = \alpha_M \frac{V}{u_*} + \alpha_{\text{ch}} \frac{u_*^2}{g}
\]

Here \( \alpha_M = 0.11 \), \( g = 9.80665 \text{m s}^{-2} \) is the gravitational acceleration, and \( \alpha_{\text{ch}} \) depends on the (ocean-wave) sea state ([Janssen, 1991]). This introduces a sea-state dependency on the relation between stress and surface wind as well.

At ECMWF scatterometer wind is assimilated as 10m wind \( \mathbf{u}_{10} \). Variations in stability, air density, ocean current and sea state (which affect the relation with stress) are, therefore, not accounted for. Although such fluctuations may be small on average, locally it may have a non negligible effect. For atmospheric stability, e.g., locally seasonally dependent differences appear. An estimation of such effects within the ECMWF framework can be found in [Hersbach, 2010a].

To address the issue of stability, the concept of equivalent-neutral wind is popular. It represents the relation between stress and wind in case stability effects are neglected. The neutral wind \( \mathbf{u}_n(z) \) at height \( z \) is given by:

\[
\mathbf{u}_n(z) = \frac{u_*}{\kappa} \log(1 + z/z_0).
\]

Such winds (from now on simply denoted by neutral), therefore, represent the wind (usually at 10-metre height) for given surface stress in case the marine boundary layer were neutrally stratified. On average, the marine boundary layer is weakly unstable, and the global average 10m neutral wind appears \( \sim 0.2 \text{m s}^{-1} \) stronger than the non-neutral wind (see e.g. [Brown et al., 2006]). For QuikSCAT, the empirical relation between scatterometer backscatter and wind has been trained on neutral wind (NSCAT-2, QSCAT-1 GMF, see [Wentz and Smith, 1999]; [Freilich and Dunbar, 1999]; [Ebuchi et al., 2002]). For ERS-2 and ASCAT such relation has been based on (non-neutral) wind (CMOD5 GMF, see [Hersbach et al., 2007]). Recently an extension for neutral wind has become available (CMOD5.N GMF, see [Verhoef et al., 2008]; [Hersbach, 2010a]).

In this manuscript it is described how scatterometer data can be assimilated as neutral wind in the ECMWF assimilation system. This can be achieved by an appropriate extension of the generic observation operator for surface wind. In Section 2 a brief overview of the ECMWF 4D-Var system is presented. Details on the extension of an observation operator for neutral wind are given in Section 3. While doing so, a few issues are addressed. Some technical complications are described in Section 4. All necessary modifications have
been compiled in a model branch from IFS cycle 36r1 (dal_CY36R1_neutral_full_dependencies ), which was later merged into IFS cycle 36r3. Some new features are discussed in Section 5, while a more extensive list is provided in Appendix B. The results of a number of impact studies are described in Section 6, and the document ends in Section 7 with a discussion.

A list of acronyms as used and IFS subroutines as mentioned in this document may be found in Appendix A.

## 2 Four-dimensional data assimilation (4D-Var)

ECMWF uses the method of incremental four-dimensional data assimilation (denoted by 4D-Var, Courtier et al. (1994)). For a given assimilation window, data is collected and compared to the model state via a cost function $J$ that is to be minimized with respect to an increment $\delta x$ that corrects the background $x^b$ at the start of the assimilation window. Schematically, $J$ is given by:

$$J(\delta x) = J_b + J_o = \frac{1}{2} \delta x^T B^{-1} \delta x + \frac{1}{2} (H\delta x - d)^T R^{-1} (H\delta x - d).$$

(4)

The background is a short forecast from the previous analysis cycle. The $J_b$ term expresses the confidence in this field via the background error covariance matrix $B$. At the end of the minimization, the final increment $\delta x^a$ is added to the background $x^b$ to provide the analysis $x^a = x^b + \delta x^a$.

The comparison between model and data is obtained via an observation operator $H$. It expresses what the value of observation should be according to the model. In 4D-Var the comparison between model and observation incorporates the timing of the observation as well. As a function of initial model state, $H$ therefore includes a model integration from initial time to observation time. In (4), $H$ is a suitable linearization of $H$ around the background. The covariance matrix of observation errors $R$ expresses the accuracy of the observational network. The innovation vector $d$, also called the first-guess departure, is given by:

$$d = y^o - H(x^b),$$

(5)

where the set of observations within the assimilation window is represented as a vector $y^o$. The model integration started from the background over the entire assimilation window, that is required to calculate $H$ and innovation $d$ for each observation in (5), is called the trajectory run (or outer loop). It is performed at the same resolution as the forecast model. Minimization of (4), though, is performed at a reduced resolution (inner loop). It requires tangent-linear (TL) and adjoint (AD) equations for the entire path from increment $\delta x$ to observation cost function (which embraces a model integration to appropriate time plus the translation from the resulting model state to observation equivalent). The sequence of outer and inner loop is iterated a few times, in which the high resolution trajectory is readily updated (currently there are three inner loops). In a final trajectory run analysis departures are evaluated:

$$d^a = y^o - H(x^a).$$

(6)

A more detailed description may be found in Part II of the IFS-documentation (2009).

### 2.1 Some relevant technical details

The evaluation of the non-linear observation operator $H$ is handled by the routine `hop`. Here, required model information is fetched from a set of arrays in memory. These GOM arrays include values from model fields at the appropriate time step which have been horizontally interpolated to observation location as well (in a routine `obshor`). Besides wind, temperature, humidity and a number of other quantities on model levels the
GOM arrays contain information on a number of model surface fields. During the integration of the non-linear trajectory, the GOM arrays are filled step by step. This is managed by routines cobs and cobslag, which are part of a routine scan2m. This latter routine also contains routine gp_model that takes care of all model computations in grid-point space. This includes the ECMWF physics parametrization (ec_phys/callpar). The actual computation of $H$ occurs at the end of the trajectory in one go for all observations, i.e., after all GOM arrays have been filled.

The evolution of TL and AD perturbations applied to linearization $H$ occurs in routines hoptl and hopad. For model quantities on model levels the influx of linear perturbations and the passing back of AD dependencies are channelled by associated GOM arrays. For model surface fields such arrays are not used, which effectively means that all perturbations and dependencies in these quantities are neglected. Since surface fields are not part of the control vector $\mathbf{x}$, this does make sense for 3D-Var (which was the operational environment when GOM arrays were introduced). In 4D-Var, however, where many surface fields are updated diagnostically each time step (in callpar), such fields are affected by changes in the control vector at initial time, and strictly speaking, dependencies should be incorporated.

Surface fields reside in memory via a dedicated module (surface_fields_mix) where they are bundled into specific groups. Routines are available (in su_surf_flds) that greatly facilitate the inclusion of a new field, its initialization, and its inclusion into the interpolated trajectory that is used in the minimization. Other operations, such as archiving at specified intervals, updating in ec_phys and communication with GOM arrays, is more tedious.

3 Observation operator for equivalent neutral 10m wind

For surface data the non-linear observation operator $H$ is handled in the routines preints and ppobsas, which are both called in hop (Cardinali et al., 1994; Vasiljevic et al., 1992). A flow diagram is presented in Fig. (1). Routine preints is responsible for the pre-calculation of a number of quantities, while the actual evaluation of $H$ takes place in ppobsas. At the start of preints required model information is fetched from the GOM arrays. From these horizontally interpolated quantities, exchange coefficients for momentum and heat are determined, which are required in the vertical interpolation from lowest-model level to observation height. This latter step is performed in ppobsas.
3.1 Vertical interpolation

For operators that involve observations of wind or temperature below the lowest model level \( l \) (currently around 10m) the interpolation method of Geleyn (1988) is used. It is based on Monin-Obukhov theory in which simplified versions for stability functions are chosen. For the interpolation of wind, this method requires the relative wind \( \mathbf{u}_l \equiv \mathbf{u}(z_l) - \mathbf{u}_* \) between the lowest model wind \( \mathbf{u}(z_l) \) at height \( z_l \) and surface current \( \mathbf{u}_* \), as well as the knowledge of the exchange coefficients \( b_N \) and \( b_D \). These are defined as:

\[
\begin{align*}
    b_N &= \log(1 + z_l/z_0), \\
    b_D &= \kappa(|\mathbf{u}_l|/|\mathbf{u}_*|),
\end{align*}
\]

and are calculated at an earlier point of the code (see next subsection). Here \( z_0 \) is the surface roughness length for momentum and \( \mathbf{u}_* \), the friction velocity. The interpolated model wind \( \mathbf{u}(z) \) at a height \( z \) is estimated as:

\[
\mathbf{u}(z) - \mathbf{u}_* = \frac{\mathbf{u}_l}{b_D} \left[ \log \left( 1 + \frac{z/z_l}{e^{b_N} - 1} \right) - S \right]
\]

where

\[
S = \begin{cases} 
    \frac{(z/z_l)}{e^{b_N} - b_D} & \text{stable case,} \\
    -\log \left( 1 + \frac{z/z_l}{e^{b_N} - b_D} \right) & \text{unstable case.}
\end{cases}
\]

Although based on simplified stability functions \( \phi(\eta) = 1 + \alpha_\epsilon \eta \) for stable and \( \phi(\eta) = (1 - \alpha_\epsilon \eta)^{-1} \) for unstable stratification, where \( \eta \) is the ratio between height and Obukhov length, Geleyn (1988) shows that (9) provides a good estimate for the near-surface wind profile, and has correct values for \( z = z_l \) and \( z = 0 \).

The neutral wind speed \( \mathbf{u}_*(z) \) at height \( z \) is connected with the logarithmic profile (3). Since in (9), substitution \( 1/z_0 = \exp(b_N - 1)/z_l \) had been made, it directly follows that interpolation (9) can also be used for the exact evaluation of neutral wind, where the lhs is replaced by \( \mathbf{u}_*(z) \) and \( S \) by:

\[
S = 0 \quad \text{for neutral wind.}
\]

For stable cases neutral wind \( \mathbf{u}_n \) will be weaker \((S > 0)\), while for unstable cases it will be stronger \((S < 0)\) than the relative real wind \( \mathbf{u} - \mathbf{u}_* \). Only for neutral stratification both coincide. Over the global oceans, the surface layer is typically weakly unstable, and 10m neutral wind speed is on average 0.2ms\(^{-1}\) stronger than real wind.

In IFS, the method of Geleyn is coded in the routine \texttt{ppuv10m} which is called by \texttt{ppobsas}. The extension (11) for neutral wind is simple, and was incorporated in cycle 35r2. The incorporation of surface current, which was not part of the original method of Geleyn (1988) was included here as well. A study on its potential effect on the ECMWF forecast and assimilation system can be found at Hersbach and Bidlot (2009). Note that in the operational configuration, and for all applications discussed in this document, surface current is set to zero.

3.2 Exchange coefficients as used in the operational observation operator

The method of Geleyn relies on the availability of the exchange coefficients \( b_N \) and \( b_D \). Evaluation of \( b_N \) (7) is straightforward, since it is directly related to surface roughness, which is in principle part of the GOM arrays. Quantity \( b_D \) depends in detail on stability, and requires knowledge of, e.g., friction velocity, surface stress or Obukhov length as it is calculated in the parametrization (within \texttt{callpar}). Neither of such quantities are available. As an alternative, \( b_D \) is based on an estimate from Louis et al. (1982), which was used in a previous physics package for IFS. In this method \( b_D \) is estimated from \( b_N \) and a stability-dependent correction factor \( f_M \) as:

\[
b_D = b_N / \sqrt{f_M},
\]

Assimilation of scatterometer data as equivalent-neutral wind

Technical Memorandum No. 629
3.3 Comparison with an offline calculation of the IFS surface-layer physics

The estimation of Louis et al. (1982) does not correspond to the latest version of the IFS surface layer (SL) parametrization that is used in the forecast model, where equations for the turbulent transfer of momentum, heat and moisture are addressed simultaneously. This latter occurs within the routine vdfmain (vertical diffusion), which is called under callpar. A concise description may be found in Part IV.3 of the IFS-documentation (2009). For the situation over water, a stand-alone version of the IFS SL physics is available, which can be used to test the similarity between the two schemes. Although this package, called OCFLX, addresses the same set of equations, these are solved in an iterative way, instead of the ‘more than implicit’ time-stepping method that is used in IFS. Input to OCFLX are the wind $u_l$, temperature $T_l$, humidity $Q_l$, geopotential height $\Phi_l$ and pressure $P_l$ at lowest model level, surface skin temperature and the ocean-wave Charnock parameter. Output are the surface fluxes for momentum ($\vec{\tau}$), heat and moisture, corresponding roughness lengths, and air density $\rho_a$.

Results from an offline extraction of Louis et al. (1982) from preints are compared to OCFLX on the basis of archived fields for the +6H T799 forecast component from the Daily-Archive (DA) analysis for 00UTC 20090801 of an analysis experiment with identifier fc01. For pressure, the exponent of the logarithmic surface pressure (LNSP) is used, and the geopotential height is determined from:

$$\Phi_l = \alpha R_l (1 + R_{lw} Q_l), \quad \text{where} \quad \alpha = 1 - \log\left(\frac{1}{B}\right) B (1 - B),$$  

(14)
with \( R = 287.0597 \ldots, R_w = 0.60777 \ldots \) and \( B = 0.997630119324 \). For a typical case \((T_l = 289K, Q_l = 0.01kg/kg)\) this corresponds to a height of \( z_l = \Phi_l/g = 10.093m \).

For OCFLX, exchange coefficients \( b_N \) and \( b_D \) are calculated from (7, 8), where friction velocity is determined as:

\[
||u_v|| = \sqrt{||\xi||/\rho_a}.
\]  

(15)

For exchco, the value for saturated humidity as calculated by OCFLX is used, while wetness is set to unity (as it is in surbound). An important point is that the GOM array for surface roughness does not contain the actual forecast surface roughness (archived as FSR) as calculated in the SL, but is filled with an analysis surface roughness field (SR), instead. This latter is based on climatology. Over the ocean, it contains a value of 1mm, which is typically an order of magnitude too high. A comparison between SR and FSR is presented in Fig. (2), which clearly demonstrates the difference between the two fields. For this reason, \( b_N \) (7) and \( f_M \) (13) are based on \( z_0 = 1mm \). For \( z_l = 10m \) this gives \( b_N = 9.2 \), while for the +6H forecast as indicated above, an average value of \( b_N = 11.3 \) is found from using FSR.

For both methods, the 10m neutral wind is calculated according to (9), with \( S = 0 \), and \( z = 10m \). As mentioned above, the lowest model level \( z_l \) is usually close to 10m, in which case (9) reduces to:

\[
u_n(z_{10}) \approx (b_N/b_D)\Phi_l.
\]  

(16)

For Louis et al. (1982) the ratio \( b_N/b_D \) is equal to the square root of correction factor \( f_M \) (13), and as a result, the effect on \( b_N \) by using SR rather than FSR is divided out for stable cases. For unstable cases there is a residual dependency.

The resulting 10m neutral wind is compared to the 10m wind as archived in the Meteorological Archival and Retrieval System (MARS). The difference is positive for unstable and negative for stable cases. Fig. (3) provides scatter plots for this stability correction for OCFLX (horizontal axis) versus exchco (vertical axis). The left panel shows that exchco as used in the operational model \((z_0 = 1mm)\) under estimates unstable corrections, and shows quite some scatter for stable conditions. On average, stability corrections are 0.06m/s lower, i.e. 0.14m/s versus 0.2m/s for OCFLX.

Surprisingly, the usage of FSR (middle panel) deteriorates the comparison with OCFLX. Reason for this may be that it seems that the Louis et al. (1982) scheme had been calibrated for a fraction \( z_l/z_0 = 5500 \). At the time that this formulation was used in the ECMWF SL, the lowest model level was located at about \( z_l = 30m \), which translates to \( z_0 \approx 5.5mm \). The right-hand panel of Fig. (3) shows results for \( z_0 = 5mm \), from which it is seen that the agreement is indeed improved for unstable cases. For stable cases, where \( f_M \) (13) does not depend on \( b_N \), all three choices give equivalent results.

The framework of Louis et al. (1982) may give reasonable results for 10m neutral wind because interpolation (16) mainly depends on the ratio \( b_N/b_D \). For vertical interpolation to other heights, however, the too high value for \( z_0 \) will introduce biases. An example is buoy wind, which is typically observed at a height of 4 to 5m. The situation for the vertical interpolation to 4m is displayed in Fig. (4). Depending on 10m wind speed, corrections vary from 0m/s to −2.5m/s, with an average of −0.6m/s. Interpolation based on Louis et al. (1982) with \( z_0 = 1mm \) overestimate the magnitude of the correction by on average 0.13m/s (left panel). For moderate winds the mismatch is largest. For winds stronger than 14m/s the sign changes (middle panel), which corresponds to the regime where the actual FSR becomes larger than 1mm. It is clear that a correct value for \( b_N \) is important for interpolation to heights other than 10m. Within the framework of Louis et al. (1982) best results are expected to set \( z_0 = 5mm \) in the correction factor (13), but to use \( z_0 = FSR \) in the definition (7) for \( b_N \). This is confirmed by the right-hand panel of Fig. (4), which shows a large reduction in the wind-speed dependent interpolation error. This would require that FSR is passed to the GOM arrays, rather than SR.
Figure 3: Scatter plots for the deviation of 10m neutral from 10m non-neutral wind over sea (T799 6-hour forecast from the 00 UTC 20090801 DA, fc01 analysis) between OCFLX (current SL formulation) and EXCHCO (Louis et al. (1982)), where the latter is based on a surface roughness of $z_0 = 1\text{mm}$ (left), $z_0 = \text{FSR}$ (middle), and $z_0 = 5\text{mm}$ (right panel).

Figure 4: Scatter plots for the correction of 4m non-neutral wind from 10m non-neutral wind over sea (T799 6-hour forecast from the 00 UTC 20090801 DA, fc01 analysis) between OCFLX (current SL formulation) and EXCHCO (Louis et al. 1982), using the standard choice of SR for surface roughness (left), the difference between Louis et al. (1982) and OCFLX (middle), and a similar difference for a blend between SR and FSR as explained in the text (right panel).

Figure 5: Scatter plots for the deviation of 10m neutral from 10m non-neutral wind over sea (T799 6-hour forecast from the 00 UTC 20090801 DA, fc01 analysis) for OCFLX with iteration (left) and without iteration (middle panel) versus EXCHCO, vdf, and the difference in the estimation of non-neutral 4m wind speed (right panel).
3.4 Extension of the non-linear observation operator

From the previous sub-section it emerges that it is desirable to have direct information on stability in the observation operator as it is calculated inside the SL. This can be established by an appropriate extension of the GOM arrays. One could pass on $b_D$ directly, or use friction velocity $u_s$, from which $b_D$ can be calculated from (8). Since the current goal is the construction of an observation operator for 10m neutral wind $u_n(z_{10})$, it is proposed to add neutral wind itself. From this, quantity $b_D$ can be reconstructed as:

$$b_D = \log \left( 1 + \frac{z_{10}}{z_0} \right) \frac{\| u_l \|}{\| u_n(z_{10}) \|}.$$  

(17)

By definition (of the constant stress layer) no wind turning occurs in the SL, and therefore, substitution of (17) into vertical interpolation (9) with $S = 0$, directly provides neutral wind again. In other words,

$$H(x) = u_n(z_{10}).$$  

(18)

Extension (17) together with (7), is implemented in a new routine called \texttt{exchco\_vdf}.

Besides the inclusion of neutral wind in the GOM arrays, it is desirable that for surface roughness $z_0$, SR is replaced by FSR. It should be noted, however, that over the ocean FSR has a dynamic range of a few orders of magnitude. For this reason, it can locally vary substantially, which may lead to inaccurate results in the horizontal interpolation (\texttt{obshor}). Over water, there is an alternative to reconstruct $z_0$ from (3, 2). For given neutral wind and Charnock parameter $\alpha_{sh}$, these equations can be solved for $z_0$ by iteration. In cycle 36r1, a routine is available \texttt{(z0sea)} that gives an accurate estimation of $z_0$ without the need of iteration (Hersbach, 2010c). The usage of this routine will result into more accurate estimates for $z_0$ over the ocean. Besides the neutral wind, this requires the inclusion of the wave Charnock parameter into the GOM arrays as well.

The Charnock parameter can be directly fetched from the ocean-wave model component of IFS, while the neutral wind is to be fetched from \texttt{vdfmain}. In the default version of cycle 36r1, neutral wind is not calculated, though. A logical place to include its computation is where the 10m (non-neutral) wind is determined (\texttt{sppcf1}). Originally, \texttt{sppcf1} was only called in the forecast model at time steps that required post-processing for archiving. Nowadays, it is called every time step inside the trajectory run as well, since the 10m wind is required for the assimilation of all-sky microwave radiances (Bauer et al., 2006). Routine \texttt{sppcf1} is called under \texttt{vdfmain} after the computations in the SL have completed. It has access to the same stability functions $\Psi_M$ and Obukhov length $L$. Over the ocean, the extension of \texttt{sppcf1} calculates neutral wind from lowest-model level wind $u(z_l)$ as:

$$u_n(z_{10}) = \frac{\log \left( 1 + \frac{z_{10}}{z_0} \right)}{\log \left( 1 + \frac{z_l}{z_0} \right) - \Psi_M \left( \frac{z_l + z_0}{L} \right) + \Psi_M \left( \frac{z_{10}}{L} \right)} \left( u(z_l) - u_s \right).$$  

(19)

Over land, the computation is somewhat more complicated, since here a 10m wind is returned that is representative for open terrain, rather than over the average landscape within the model grid box. Details may be found in Hersbach (2010a).

Like for \texttt{exchco} results from the new routine \texttt{exchco\_vdf} are compared to OCFLX offline, on the basis of the same +6-hour forecast as used in Section 3.3. For that forecast, the neutral wind (19) as calculated in \texttt{sppcf1} has been archived on the basis of the in MARS existing parameters (U10N,V10N). Together with archived FSR, $b_N$ and $b_B$ are calculated in \texttt{exchco\_vdf}, and substituted in (9). For 10m neutral wind, the result is, again, compared to the 10m (non-neutral) wind. In the left panel of Fig. (5), such obtained stability corrections (y-axis) are plotted against results from OCFLX (x-axis). From this it is seen that both the relative bias and scatter is smaller than for \texttt{exchco} (left panel of Fig (3)). Especially for stable cases the comparison between \texttt{exchco\_vdf} and OCFLX is excellent. For unstable cases, however (which are more common over
the ocean.\textsuperscript{3} \texttt{exchco\_vdf} somewhat under-estimates \textit{OCFLX}. Over all cases, the average stability correction is 0.03 m\textsuperscript{s\textsuperscript{−1}} weaker, i.e., 0.17 m\textsuperscript{s\textsuperscript{−1}} versus 0.20 m\textsuperscript{s\textsuperscript{−1}} for \textit{OCFLX}. Most of the scatter is found to occur for light winds (see \textit{Hersbach} (2010a)). As mentioned above, there is a difference in which the turbulent equations for momentum, heat and moisture are addressed. For \textit{OCFLX} these are solved in an iterative way, while a ‘more than implicit’ time-stepping is used in \texttt{vdfmain}. If instead of the default of three iterations, no iterations are performed in \textit{OCFLX}, the comparison with \texttt{exchco\_vdf} appears to improve for unstable cases (middle panel of Fig (3)). The fact that scatter is reduced considerably indicates that for part, differences between \textit{OCFLX} and \texttt{vdfmain} may indeed be connected to a difference in solution method.

Since routine \texttt{exchco\_vdf} provides good estimates for $b_N$ and $b_D$, it can also be used for vertical interpolation to other heights. The example for $z = 4$m is given in the right-hand panel of Fig. (5). From this it is seen that the comparison with \textit{OCFLX} is much better than what is found for \texttt{exchco} (see Fig. (4)).

For 10m neutral wind, Fig. (6) provides global maps for all stability corrections as regarded in this Section. From this it is seen that the regional patterns for less than average unstable (blue) and more than average unstable (red) areas are very similar for most approaches. Only for the usage of FSR in \textit{Louis et al.} (1982) (lower left), unstable patterns are largely missing. The similarity in patterns is not too surprising, since all are driven by the difference between air temperature and skin temperature. And this input is the same for all approaches. For the scheme that is used in the operational observation operator, i.e., \textit{Louis et al.} (1982) with $z_0 = 1$mm (top left), perturbations are clearly weaker than on the basis of the offline package \textit{OCFLX} (middle right). Better amplitudes are obtained for $z_0 = 5$mm (left middle). The usage of neutral wind from extension (19) in \texttt{vdfmain} (top right) produces unstable corrections that are slightly weaker than \textit{OCFLX}. It does corresponds much closer to results for \textit{OCFLX} without iteration in the solution method (bottom right).

### 3.5 Extension of the linearized observation operator

As mentioned above, perturbations in surface parameters are not incorporated in associated GOM arrays. For this reason any TL perturbation in $u_n$ is cut to zero, while any AD dependency that is accumulated in \texttt{hopad} is nullified later on. The combination of (17) and (9) exactly delivers $u_n$, as shown in (18). This means that the observation operator for neutral wind is independent on variations $\delta x$. Therefore its contribution to the cost $J_o$ is a constant, and effectively, the associated observations are not assimilated.

One way to avoid this problem is the assumption that a variation in neutral wind, due to a variation in model state is mainly driven by a change in the lowest model level wind, and not so much by a change in stratification. Since the effect of stability is largely contained in the ratio $b_D / b_N$ (as e.g. according to the approach by \textit{Louis et al.} (1982)), it is reasonable to keep this ratio constant. This means that for $b_D$ the TL of (17) can be approximated by:

$$
\delta b_D = \left( \frac{b_D}{b_N} \right) \delta b_N. \tag{20}
$$

For the usual case that the lowest model level $z_l$ is close to 10m, this leads to a perturbation in neutral wind (16):

$$
\delta H = \delta u_n \approx \left( \frac{b_N}{b_D} \right) \delta u(z_l). \tag{21}
$$

For the AD, similar equations apply. Perturbations in $u(z_l)$ are well propagated in the associated GOM arrays, so in effect approximation (20) and its AD analogue allow for a proper assimilation of neutral wind.

The more consistent way forward is to resolve the issue of the associated GOM arrays for diagnostic surface fields. For the TL this means that the calculation of perturbations are to be added to the TL of routines that calculate these parameters inside \texttt{callpar}, that these are horizontally interpolated to observation location,
Figure 6: Global maps of the deviation of 10m neutral wind minus 0.2 m/s from real wind (00 UTC 20090901 DA favr, 3-hour forecast) for several schemes.
and that they are stored into the responsible GOM array. In hop1 these perturbations are then read from memory, which then provide non-zero contributions to perturbations in H. For the AD, dependencies in surface parameters as built up in hopad are stored in the associated GOM array. These, in general non-zero values are read in the AD of the corresponding routines in callpar, and in this way contribute to the dependency of the initial control vector on the cost J.

For neutral wind, this extension appears to be possible. The necessary extensions in the TL (sppcflstl) and AD (sppcflsad) routines to sppcfls are made, which latter provides the simplified-physics version of sppcfl. For standard cycle 36r1, the associated GOM arrays are already allocated. They are just not used. Appropriate extensions in routines cobstl/ad provide the communication with the model physics, while extensions in the routines preintstl/ad provide the connection with the observation operator. The resulting proper flow of perturbations in neutral wind, now do allow for the exact TL and AD to (17). These are coded in exchco.vdftl and exchco.vdfad. These routines also contain an option for approximation (20), and depending on a logical in the argument list, one of the two methods is used. For z0 dependencies are effectively handled by the TL (z0seatl) and AD (z0seaad) of the estimation from neutral wind and Charnock parameter in z0sea. Variations in the Charnock parameter are neglected, since that would require the TL and AD of the ECMWF wave model (WAM).

4 Technical complications

4.1 Issues regarding the trajectory run

In Section 3.4 it was shown how information on stability could be fetched from the physics in callpar, by the inclusion of neutral wind in the GOM arrays. In Fig. (7) some detail is provided on the flow in the trajectory run. The high-level routine step0 takes care of all computations within one time step (NSTEP=0, 1, ..., NSTOP). From this it is seen that the horizontal interpolation and storage of surface fields into GOM arrays occurs before diagnostic surface fields are updated. For that reason, at initial time step (NSTEP=0) surface fields contain their initialized values. These are based on the +3-hour forecast surface fields from the previous DCDA analysis that had been read in by su_surf.flds. Those surface fields that are not supplied by this first-guess will remain un-initialized. This is, e.g., the case for FSR (z0) and neutral wind (un). As a result, the observation operator as discussed in Section 3.4 will fail since it will find un-initialized values in the GOM arrays for neutral wind.

Prior to the execution of 4D-Var, the set of required first-guess fields are retrieved from MARS, or if still on disk from the ECMWF Field Data Base (FDB). At script level, any extra fields can simply be added to a list of requested parameters. For FSR, i.e., this would be straightforward. For 10m neutral wind, however, the situation is more complex because it is not archived in the DCDA forecast. This is only done for the operational DA forecast. Here neutral wind does not, like other parameters, result from a calculation inside IFS, but is derived from other fields from FDB, instead. In Section 3.4 it was shown how the computation of neutral wind can be included in sppcfl. This paves the way for archiving from inside IFS which requires the extension of a set of relevant routines that takes care of the post-processing (FULLPOS). Details may be found in Hersbach (2010a). This then allows for the addition of neutral wind to the list of to be retrieved first-guess fields, and for the initialization of the relevant GOM arrays at the first time step.

Another consequence of the flow in the trajectory run is that the GOM arrays are filled with surface fields that have been updated the previous time step. As, e.g., can be seen from Fig. (7), the GOM arrays at NSTEP=1 rely on the results in the parametrization from NSTEP=0. This is not necessarily incorrect, since there are diagnostic fields that are strictly speaking valid for the next time step. For neutral wind and 10m wind, however, this is not the case, and for that reason, the values for neutral wind in the GOM arrays are out of sync with other variables.
(such as fields at model levels). The update of neutral wind at final time step NSTEP=NSTOP is not used in the observation operator.

4.2 Issues regarding the minimization

For one specific iteration in the minimization, the TL is run from initial time to final time, which is followed by a run of the AD code from final time back to initial time. Similar flow diagrams as shown in Fig. (7) apply to step0tl and step0ad.

Since for the first time step neutral wind is taken from a first-guess field, its value will not be affected by any perturbation $\delta x$ in the control vector at the start of the assimilation window. As a result, the cost $J_o$ will be a constant for all observations for neutral wind that fall inside this first time slot. When the full dependencies of neutral wind are correctly handled by the associated GOM array, this will lead to a zero gradient with respect to such data. Assumption (20) assumes that perturbations in neutral wind are dominated by perturbations in the lowest model level wind. Since these are influenced by the control vector, this approach will lead to a non-zero dependency for the first time slot. Therefore, to take full advantage of the incorporation of perturbations in neutral wind, one should use the full TL and AD for exchco_ydf for all time steps, except for the first one, where assumption (20) is to be used. The choice for which approach to take can be conveniently provided by the inclusion of a logical in the GOM arrays that indicates whether surface fields have been updated sofar.

When a quantity is calculated in a non-linear code, its adjoint value is usually to be nullified in the corresponding AD code. When this rule is not obeyed, there is a risk that erroneous dependencies leak into upstream parts...
of the code when the same variable is reused. A typical example is the calling of a certain routine for several
time steps. Although variables are reused, they physically represent quantities at different time steps, and for
that reason the adjoint of updated global variables need to be zero at the start of the call to the AD code. When
the nullifying rule has been used consistently, such adjoint variables will be zero automatically. As a safeguard
one could nullify all variables explicitly at the start of the adjoint routine, which eliminates any leaking from
un-careful adjoint coding.

At the start of ec physad such a reset is performed for all surface field perturbations. The risk is that this
could overdo the job, since it also resets perturbations of variables that have not been updated yet. An example
is the AD of the neutral wind that is read from the GOM arrays in the AD of cobs lag and cobs. These
quantities, which describe the influence of the control vector on the cost via the computation of neutral wind,
must not be nullified at the start of ec physad. The remedy is not to reset surface field perturbations anymore.
It was carefully checked that this did not have side effects, which effectively means that for surface fields the
adjoint has been properly coded.

In the minimization the same variables are used for TL and AD perturbations. To avoid interference, one should
ensure that all perturbations other than those for the control vector are zero at the start of a TL run (from 0 to
NSTOP), and similarly at the start of an AD run (from NSTOP to 0). This can be guaranteed by resetting
variables at the very start and at the very end of a run. For surface fields this is performed in ec physstl and
ec physad. With the incorporation of surface perturbations inside the observation operator, this has to be
done at a higher level of the code. The proper location is scan2mtl and scan2mad which encapsulate all
calculations for surface fields. For this reason the resetting of surface field perturbations is moved upwards to
these routines.

5 Implementation for cycle 36r3

All extensions as discussed in Section 3 have been coded in a branch dal_CY36R1_neutral_full_dependencies,
which was later merged into cycle 36r3 (for details, see Appendix B). Some had been prepared before and were
already present in cycle 36r1. These include the adaptation of ppuv10m, the inclusion of z0 sea, and their
TL and AD versions. The decision on the choice of the various options is handled from the following logicals,
which can be set at script level via the namelist NAMOBS:

- **LSCATT_NEUTRAL** (existing): If .true., for scatterometer wind vertical interpolation (9, 11) is used.
  Regarding the inversion from scatterometer observed backscatter to wind, 0.2ms⁻¹ is added to wind speed for QuikSCAT, while for ERS-2 and ASCAT geophysical model function CMOD5.N (Hersbach, 2010b), rather than CMOD5.4 (Abdalla and Hersbach, 2007) is used.
  If .false., scatterometer wind is assimilated as 10m non-neutral wind (currently operational).

- **LVDFTRAJ** (new): If true, for scatterometer data exchange coefficients are based on neutral wind from
  the ECMWF physics (exchco_vdf) and surface roughness is based on (z0_sea) Hersbach (2010c). In principle this new method could be used for other surface wind observations as well (such as buoys). It was decided, though, to concentrate on scatterometer data first. Also, if .true., the Charnock parameter, which is used to estimate z0 is placed in the full time-dependent trajectory (as returned by the coupled
  wave model) rather than in the constant trajectory (using a value of αch = 0.018).
  If .false., the method of Geleyn (1988) is used (exchco, currently operational).

- **LVDFMIN** (new): If .true., for scatterometer data the full dependency of perturbations δx via neutral
  wind is incorporated. If .false., the ratio (u_N/u_D) is kept constant in the minimization.
Assimilation of scatterometer data as equivalent-neutral wind

- **LZ0FC** (new): If .true., FSR is placed in the GOM arrays rather than SR (currently operational). This FSR is also used in *Louis et al.* (1982), which is not optimal, as discussed in Section 3.3. Therefore, this switch should not be used at the moment.

At script level, the value of **LSCATT**_NEUTRAL_ (set in prep ifs) is used for **LVDFTRAJ** as well. For that reason, the system remains bit-identical when **LSCATT**_NEUTRAL_ is .false. (which is the default in cycle 36r1). **LVDFMIN** is set to .true., **LZ0FC** is set to .false., and a script change is required in case this is not intended. Inside IFS, some quality control is performed (defrun). **LVDFTRAJ** is reset to .false. when **LECMWF** (configuration for ECMWF) or **L3DFGAT** (physics is run in trajectory) is .false..

### 5.1 Sanity checks

The AD and TL of the routines **ppuv10m**, **z0sea**, **exchco_vdf** and **sppcfls** were thoroughly tested. It was checked that the TL and AD code for individual routines match, and it was verified that finite differences convert to TL results in the limit towards zero perturbation size. In a reduced resolution of T42, a similar test on the match between the TL and AD was performed for the entire 4D-Var minimization. This option, which is provided in IFS by the setting of a variable **NTESTVAR**=3, was passed successfully for the configurations as described below, giving similar results to that for an experiment that was based on a clean 36R1 branch. This gives confidence on the move of nullifying statements for surface field perturbations at initial and final time from **ec_physst1** and **ec_physad** to **scan2mtl** and **scan2mad**, and the removal of such statements in **ec_physad** at all other time steps.

It was ensured that array boundaries were not violated and that non-initialized variables were not used in the rhs of any computation.

### 6 Impact studies

In order to test the various options as described in the previous Section, for the period from 15 July 2009 to 31 October 2009 a number of experiments are conducted at T511 in early-delivery mode. Details on configurations may be found in Table (6.1).

Except for a CONTROL run (experiment identifier f8tz), which used a clean version of cycle 36r1, all experiments are based on the branch **dal_CY36R1_neutral_full_dependencies**. The assimilation of scatterometer wind as neutral wind, using information from the ECMWF physics (both non-linear and linear) is explored in an experiment **EXCHCO_VDF**. The usage of a neutral wind observation operator on the basis of the estimation of $b_D$ by *Louis et al.* (1982) and the usage of SR into $b_N$ is investigated in an experiment **EXCHCO**.

The effect of the usage of FSR rather than SR in the standard configuration of cycle 36r1, i.e., assimilating scatterometer data as non-neutral wind, with *Louis et al.* (1982) is explored in an experiment **FSR**. Note that this change has virtually no effect on the assimilation of 10m wind data, since for that case vertical interpolation (9) is basically the identity operator. It does have an effect on the assimilation of wind at other observation heights, such as for buoy data. Prior to this experiment, two other experiments had been run that had used FSR rather than SR as well. These two experiments assimilated scatterometer wind in the new fashion (LVDFTRAJ=.true.), one, like **EXCHCO_VDF** taking account of neutral wind perturbations (LVDFMIN=.true.) and one neglecting them (LVDFMIN=.false.). Both appeared to give rise to very similar forecast skill, but, unfortunately performed worse (at a 95% significance level) than the CONTROL. It was only then realized that the usage of FSR rather than SR is not optimal for the *Louis et al.* (1982) scheme. By running experiment **FSR**, the effect of using forecast surface roughness can be isolated.
Assimilation of scatterometer data as equivalent-neutral wind

<table>
<thead>
<tr>
<th>Name</th>
<th>Expid</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CONTROL</td>
<td>f8tz</td>
<td>based on dah_CY36R1_backstitch</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LSCATT_NEUTRAL=.false.</td>
</tr>
<tr>
<td>EXCHCO_VDF</td>
<td>favr</td>
<td>LSCATT_NEUTRAL=.true.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LZ0FC=.false.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LVDFTRAJ=.true.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LVDFMIN=.false.</td>
</tr>
<tr>
<td>EXCHCO</td>
<td>fbk</td>
<td>LSCATT_NEUTRAL=.true.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LZ0FC=.false.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LVDFTRAJ=.false.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LVDFMIN=.false.</td>
</tr>
<tr>
<td>FSR</td>
<td>fxa</td>
<td>LSCATT_NEUTRAL=.false.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LZ0FC=.true.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LVDFTRAJ=.false.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LVDFMIN=.false.</td>
</tr>
</tbody>
</table>

Table 1: List of experiments as discussed in this document. All are in a T511 early-delivery assimilation environment and have been run from 15 July 2009 to 31 October 2009. The second, third and fourth experiment are based on dal_CY36R1_neutral_full_dependencies.

The default configuration for dal_CY36R1_neutral_full_dependencies (i.e., LSCATT_NEUTRAL=.false.) should give equal results to a clean cycle 36r1. This was confirmed by an experiment (favq), which was run for a number of days. Indeed, bit-wise identical results were obtained with respect to the CONTROL.

6.1 Condition numbers

For all experiments displayed in Table (6.1) very similar condition numbers were found in the minimization. This indicates that the fetching of AD and TL information for surface field perturbations is handled well, and does not affect the performance of the minimization scheme.

6.2 Departure statistics

In Hersbach (2010a) it was observed that for two one-month periods scatterometer wind first-guess departures (5) are slightly reduced when based on neutral rather than non-neutral wind. This is confirmed in the present study. For both the EXCHCO_VDF and EXCHCO experiment, first-guess (and analysis departures) are somewhat reduced for ERS-2, ASCAT and QuikSCAT. For ASCAT, results are presented in Fig. (8), from which it emerges that the largest reduction is found in the Northern Hemisphere. Statistics are very similar for both experiments.

For ASCAT and QuikSCAT, maps of average first-guess departures are displayed in Fig (9) for the CONTROL (left) and EXCHCO_VDF experiment (right panels), respectively. For EXCHCO maps are similar to EXCHCO_VDF (not shown). The blue patterns around Newfoundland and the Hudson bay indicate areas of stable conditions, which are typical for late Summer. They are reduced in the EXCHCO_VDF, and this is probably the reason why for this season the reduction in departure statistics is largest in the Northern Hemisphere.

Analysis departures (6) are in general much lower than first-guess departures (5), since this expresses that the data is assimilated. A similar improvement is observed for both experiments as shown Fig. (8) as well. It emerges that this occurs for all time slots. Also for the first time slot (not shown), where the model neutral wind results from a first-guess field, and, therefore, is not influenced by the control vector, this appears the case. For the EXCHCO_VDF experiment this means that linearization (20), which is only used for the first time step, is working well. When, in contrast, for this step the full dependencies in neutral wind are retained it appears that the analysis departure is only marginally smaller than the first-guess departure. This, which was checked by an experiment that was run for a few days, indeed reflects that in such case scatterometer winds that fall in the first
Figure 8: Statistics of first-guess (left) and analysis (right sub-panels) departures accumulated from 20090715 to 20091031, for ASCAT 10m wind as used in the observation operator H, i.e., neutral for EXCHCO

FULLDEP v CONTROL 2009071500-2009103112(12)
ALL ASCAT-U10m/V10mspeed N.Hemis
used wind data

<table>
<thead>
<tr>
<th>nb</th>
<th>rms</th>
<th>mean</th>
<th>std</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

EXCHCO v CONTROL 2009071500-2009103112(12)
ALL ASCAT-U10m/V10mspeed N.Hemis
used wind data

<table>
<thead>
<tr>
<th>nb</th>
<th>rms</th>
<th>mean</th>
<th>std</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

FULLDEP v CONTROL 2009071500-2009103112(12)
ALL ASCAT-U10m/V10mspeed Tropics
used wind data

<table>
<thead>
<tr>
<th>nb</th>
<th>rms</th>
<th>mean</th>
<th>std</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

EXCHCO v CONTROL 2009071500-2009103112(12)
ALL ASCAT-U10m/V10mspeed Tropics
used wind data

<table>
<thead>
<tr>
<th>nb</th>
<th>rms</th>
<th>mean</th>
<th>std</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

FULLDEP v CONTROL 2009071500-2009103112(12)
ALL ASCAT-U10m/V10mspeed S.Hemis
used wind data

<table>
<thead>
<tr>
<th>nb</th>
<th>rms</th>
<th>mean</th>
<th>std</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

EXCHCO v CONTROL 2009071500-2009103112(12)
ALL ASCAT-U10m/V10mspeed S.Hemis
used wind data

<table>
<thead>
<tr>
<th>nb</th>
<th>rms</th>
<th>mean</th>
<th>std</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Assimilation of scatterometer data as equivalent-neutral wind

Figure 9: Geographically time-averaged first-guess departures over the indicated period for ASCAT (top) and QuikSCAT (lower panels) 10m wind speed for the CONTROL (non-neutral, left) and the EXCHCO\_VDF (neutral, right panels) experiment.

time slot are effectively not assimilated.

6.3 Forecast skill

The impact on average global forecast skill on geopotential at 500 hPa (Z500) in the atmosphere, and on significant wave height (SWH) at the ocean surface is presented in Fig. (10). For the EXCHCO\_VDF and EXCHCO experiment, plots that indicate the statistical significance for Z1000 and Z500 are presented in Figs. (11, 12). In general the EXCHCO\_VDF exhibits the slightly better performance. Regarding the Northern Hemisphere, all experiments under-perform the control around day 8 for geopotential, although EXCHCO\_VDF is more comparable with the CONTROL. For EXCHCO and FSR, a negative impact which is significant on the 95% level is found for Z1000, while for EXCHCO\_VDF this is on the brink of significance. For ocean waves, impact is more neutral, with EXCHCO\_VDF giving a tiny (non-significant) improvement over the CONTROL. Over Europe (see Fig. (13)), similar results are found.

Over the Southern Hemisphere, a modest positive impact is found for EXCHCO\_VDF and EXCHCO (not significantly, though) on geopotential. For ocean waves, EXCHCO\_VDF clearly provides the best skill.

In general, the FSR experiment performs worst.

A more detailed view of the effect on forecast skill is presented in Fig (14), which shows the normalized average difference in day 3 forecast skill with respect to the CONTROL for Z1000. From this it emerges that no clear areas can be identified where forecast skill generally improves or deteriorates. The patchy patterns east of Japan are possibly the result of small scale and temporal fluctuations in atmospheric stability over the Kuroshio extension. At other levels, similar results are observed.
Figure 10: Anomaly correlation coefficient averaged over 109 cases over the Northern Hemisphere (left) and Southern Hemisphere (right panels) of the 500 hPa geopotential (top) and significant wave height (lower panels) for the CONTROL (red), EXCHCO_VDF (blue), EXCHCO (green) and FSR (brown) experiment. Higher values indicate a higher forecast skill.
Figure 11: Normalized difference in anomaly correlation coefficient averaged over 109 cases over the Northern Hemisphere of the 1000 hPa (top) and 500 hPa (lower panels) geopotential for the EXCHCO VDF (left) and EXCHCO (right panels) experiment. Positive values indicate an improvement, while the bars express the 95% confidence level.

Figure 12: Normalized difference in anomaly correlation coefficient averaged over 109 cases over the Southern Hemisphere of the 1000 hPa (top) and 500 hPa (lower panels) geopotential for the EXCHCO VDF (left) and EXCHCO (right panels) experiment. Positive values indicate an improvement, while the bars express the 95% confidence level.
**Figure 13**: Normalized difference in anomaly correlation coefficient averaged over 109 cases over Europe of the 1000 hPa (top) and 500 hPa (lower panels) geopotential for the EXCHCO-VDF (left) and EXCHCO (right panels) experiment. Positive values indicate an improvement, while the bars express the 95% confidence level.

**Figure 14**: Normalized 3-day forecast error differences for the geopotential height at 1000 hPa compared to the CONTROL for EXCHCO-VDF (left) and EXCHCO (right), averaged over the 109-day period 20090715-20091031. Negative values indicate an improvement.
6.4 Analysis differences

The effect on the average level of analysis fields was found to be very small (not shown). For surface wind, surface pressure, and significant wave height rather small-scale fluctuations appear over the Tropics. In general, no real coherent differences are found.

7 Discussion

In this document the assimilation of scatterometer data as equivalent-neutral 10m wind has been assessed in the ECMWF assimilation system. Rationale for the adaptation of the scatterometer observation operator is that scatterometer data is sensitive to surface stress, which is closer related to neutral than to non-neutral 10m wind. Indeed, it is found that the usage of an observation operator for neutral wind has a positive effect on departure statistics. Based on experiments performed at T511 in early-delivery mode for 109 cases in Autumn 2009, the impact on forecast skill appears rather neutral, although on the Southern Hemisphere some positive impact is found. The usage of scatterometer wind as neutral wind has become the default in cycle 36r3, and it is the objective to introduce this method in the operational suite for cycle 36r4.

The adaptation of the observation operator for surface (non-neutral) wind to neutral wind is in principle straightforward. One complication is that the method that extrapolates the available lowest-level model wind to observation height \textit{Geleyn} (1988) relies on the knowledge of neutral and non-neutral exchange coefficients $b_N$ and $b_D$, respectively. These quantities are not directly available at the relevant part of the code, and have to be reconstructed. Currently (cycle 36r1), they are recomputed on the basis of \textit{Louis et al.} (1982), which represents an old version of the ECMWF surface layer (SL) package. For both neutral 10m wind and non-neutral 4m wind (buoy data) differences are found with respect to a calculation based on the actual model SL. Although these differences are not large, they are not negligible with respect to the magnitude of the adaptations that are to be made to the observation operator for neutral wind. The neutral exchange coefficient is directly related to surface roughness. Rather than using of the actual model surface roughness (FSR) a climatological field (SR) is used, which is typically one order of magnitude too high over water. It appears, though that this constant climatological value (of 1mm) gives better results for \textit{Louis et al.} (1982) than FSR does, probably because this SL scheme was developed for a fixed ratio between lowest-model level and roughness length, and FSR sensitively depends on surface wind speed.

To improve on this situation, a method was described that allows for a recalculation of exchange coefficients from the current physics parametrization. It was shown that this can be achieved by the inclusion of 10m neutral wind in the GOM arrays, which provide the communication between the model and the observation operator. Besides for the obvious case of an operator for 10m neutral wind, this quantity also provides the correct determination of (non-neutral) wind at other heights.

The fetching of neutral wind from the model physics assimilation system, requires that account is taken of tangent-linear (TL) and adjoint (AD) perturbations. If not, such observation operator would not depend on the control vector in 4D-Var, and as a result associated observations are not assimilated.

Sofar, perturbations in surface fields have been neglected in the ECMWF assimilation system. This is the correct approach in the frame work of 3D-Var, where no model integration is performed and unless the control vector contains surface fields itself, this will not influence information at the surface. For 4D-Var, though, the situation is different. Many surface quantities are updated diagnostically every time step, and in this way the control vector does affect those fields. Neutral wind is a good example.

It appears possible to extend IFS in such a way that full account is given for perturbations in diagnostic surface
fields. For the case of neutral wind it is found that the assimilation system performs very similarly to the case where 10m wind is estimated from lowest model wind. Also, when perturbations in 10m neutral wind are neglected, departures for scatterometer data appear relatively unchanged, i.e., the data is not assimilated. As an alternative a simpler option is provided as well. It is argued that perturbations in neutral wind could be estimated from lowest (non-neutral) wind under the assumption that stability does not significantly change in the minimization. It was found that both methods led to similar results in the minimization.

One complication is that the storage of model quantities into GOM arrays occurs before the call to the physics package which updates such quantities. For the first time step, therefore, values have to be fetched from first-guess fields. For neutral wind this requires the provision of a (archived) model field, which required an appropriate extension in the FULLPOS part of the IFS code. Since such initial surface fields are not influenced by the control vector, for this first time step perturbations have to be fetched from lowest model level wind to guarantee the assimilation of associated observations. The complication at the first time step could be remedied by storing model-field information into GOM arrays after the call to the model physics. Such a change would make the system more transparent, and it is suggested that this could be taken into consideration for the follow-up of IFS.

Rather than the inclusion of neutral wind in the GOM arrays, one could also consider the fetching of the exchange coefficients themselves. Although surface roughness is a fast changing quantity over the ocean, the neutral coefficient $b_N$, which is directly related to this behaves much more mildly. This facilitates horizontal interpolation. The omission of TL and AD perturbations in $b_N$ and $b_D$ effectively result in the neglect of changes in stability during the minimization such as expressed in (21). In other words, an observation operator for neutral wind will in this case still be able to incorporate essential information from the control vector. Such a replacement of neutral wind implies that the exchange coefficients are to be added in the list of surface fields. In addition, in the current order in which the model physics is called, initial first-guess fields are to be provided, i.e., archiving into MARS.

The incorporation of perturbations in neutral wind in the minimization as discussed in this document could be applied to other diagnostic surface fields as well. One candidate could be the skin temperature. Cardinali et al. (1994) found that it was difficult to assimilate 2m temperature over land, because a change in this quantity was not accompanied by a dynamically consistent change in surface temperature. This could lead to unphysical changes in the lapse rate. It would be worthwhile to investigate whether the account of perturbations in the diagnostic skin temperature could improve on this situation.

**Acknowledgements**

The work presented in this document was funded by ESRIN (Project Ref. 22025/08/I-EC). The author would like to thank Anton Beljaars, Mats Hamrud, Yannick Tremolet, Deborah Salmond, Marta Janiskova, Philippe Lopez, Lars Isaksen and Peter Janssen for their useful discussions, advice and support, and Rob Hine for the creation of the flow chart diagrams.
A Acronyms and abbreviations

A.1 General acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>4D-Var</td>
<td>Four-dimensional variational data assimilation</td>
</tr>
<tr>
<td>AD</td>
<td>Adjoint</td>
</tr>
<tr>
<td>AMI</td>
<td>Active Microwave Instrument</td>
</tr>
<tr>
<td>ASCAT</td>
<td>Advanced SCATerometer</td>
</tr>
<tr>
<td>CMOD</td>
<td>C-band Geophysical MODel function</td>
</tr>
<tr>
<td>DA</td>
<td>Daily Archive</td>
</tr>
<tr>
<td>DCDA</td>
<td>Delayed-cutoff Daily Archive</td>
</tr>
<tr>
<td>ECMWF</td>
<td>European Centre for Medium-range Weather Forecasts</td>
</tr>
<tr>
<td>ERS</td>
<td>European Remote sensing Satellite</td>
</tr>
<tr>
<td>ESA</td>
<td>European Space Agency</td>
</tr>
<tr>
<td>ESRIN</td>
<td>European Space Research INstitute</td>
</tr>
<tr>
<td>FDB</td>
<td>Fields Data Base</td>
</tr>
<tr>
<td>FSR</td>
<td>Forecast surface roughness</td>
</tr>
<tr>
<td>FULLPOS</td>
<td>Part of IFS that handles the post-processing for fields</td>
</tr>
<tr>
<td>GMF</td>
<td>Scatterometer Geophysical Model Function, relating wind to backscatter</td>
</tr>
<tr>
<td>GOM</td>
<td>Set of arrays that provide horizontally interpolated model information to the</td>
</tr>
<tr>
<td></td>
<td>observation operator</td>
</tr>
<tr>
<td>IFS</td>
<td>ECMWF Integrated Forecasting System</td>
</tr>
<tr>
<td>L3DGFAT</td>
<td>IFS logical that indicates that the ECMWF model is run in the minimization</td>
</tr>
<tr>
<td>LECMWF</td>
<td>IFS logical that indicates the configuration for ECMWF</td>
</tr>
<tr>
<td>lhs</td>
<td>left-hand side</td>
</tr>
<tr>
<td>LSCATT NEUTRAL</td>
<td>IFS logical that controls whether scatterometer data is assimilated as neutral wind</td>
</tr>
<tr>
<td>LVDPMIN</td>
<td>New IFS logical that controls whether perturbations in neutral wind are to be included</td>
</tr>
<tr>
<td>LVDPTRAJ</td>
<td>New IFS logical that controls whether neutral wind is to be fetched from the IFS SL</td>
</tr>
<tr>
<td>LZ0FC</td>
<td>New IFS logical that stores FSR rather than SR in the GOM arrays</td>
</tr>
<tr>
<td>MARS</td>
<td>Meteorological Archival and Retrieval System</td>
</tr>
<tr>
<td>NAMOBS</td>
<td>IFS namelist relating to observation operators</td>
</tr>
<tr>
<td>NSCAT-2</td>
<td>GMF for the NSCAT scatterometer</td>
</tr>
<tr>
<td>NSTEP</td>
<td>Time step in IFS, ranging from 0 (initial) to NSTOP (final time step)</td>
</tr>
<tr>
<td>NSTOP</td>
<td>Final time step</td>
</tr>
<tr>
<td>OCFLX</td>
<td>Offline version of the IFS SL physics over water</td>
</tr>
<tr>
<td>QSCAT-1</td>
<td>GMF for the QuikSCAT scatterometer</td>
</tr>
<tr>
<td>rhs</td>
<td>right-hand side</td>
</tr>
<tr>
<td>SL</td>
<td>Surface Layer</td>
</tr>
<tr>
<td>SR</td>
<td>Analysis surface roughness, which is based on climatology</td>
</tr>
<tr>
<td>T511</td>
<td>A triangular spectral grid with 511 waves along the equator</td>
</tr>
<tr>
<td>TL</td>
<td>Tangent linear</td>
</tr>
<tr>
<td>UTC</td>
<td>Coordinated Universal Time</td>
</tr>
<tr>
<td>U10N</td>
<td>u-component for 10m neutral wind as archived in MARS</td>
</tr>
<tr>
<td>V10N</td>
<td>v-component for 10m neutral wind as archived in MARS</td>
</tr>
<tr>
<td>WAM</td>
<td>third-generation ocean-Wave Model</td>
</tr>
<tr>
<td>Z1000</td>
<td>Geopotential height at 1000 hPa</td>
</tr>
<tr>
<td>Z500</td>
<td>Geopotential height at 500 hPa</td>
</tr>
</tbody>
</table>
A.2 Relevant IFS subroutines

callpar Handles the ECMWF parametrization
cobs Prepares model fields for storage into GOM arrays
cobsflag Fills GOM arrays
defrun Defines and checks control parameters
defphys Handles the ECMWF physics
exchco Routine under hop that estimates exchange coefficients based on Louis (1979)
exchco_vdf New routine under hop that estimates exchange coefficients from vdfmain
gpmodel Handles model calculations in grid point space
hop Evaluates the observation operator
obshor Provides the horizontal interpolation from model fields to observation location
pppobsas Routine under hop that calculates the observation operator for surface observations
ppuv10m Routine under hop that handles the vertical interpolation of wind
preints Routine under hop that estimates exchange coefficients for surface observations
scan2m High-level routine that encapsulates all computations in grid-point space
sppcf1 Routine under vdfmain that computes 2m temperature and 10m wind
sppcf1s Simplified-physics version of sppcf1
step0 High-level routine that handles all operations for one time step
surbound Routine under hop that pre-calculates quantities that are required for exchco
surface_fields_mix Module that defines groups of surface fields
su_surf_flds Handles the initialization and setup for surface field
vdfmain Routine in the ECMWF physics that includes the calculation of the SL
z0sea Estimates surface roughness from neutral wind and Charnock parameter

Any associated tangent-linear and adjoint routines have the annex tl and ad, respectively.

B Overview of code changes

The changes that were made in dal_CY36R1_neutral_full dependencies, and which have been merged into cycle 36r3 are:

- The introduction of the diagnostic surface fields (group VDIAG), and their archiving into MARS of:
  - Neutral wind at 10 m x-component, y-component (131.228, 132.228)
  - Friction velocity (003.228)
- The calculation of 10-m neutral wind components and friction velocity in VDIAG (sppcf1_mod). For neutral wind, adaptations in simplified physics and its adjoint/tangent-linear code have been made as well (sppcf1s_mod, sppcf1sad_mod, sppcf1stl_mod).
- Usage of first-guess fields of 10-m neutral wind components, forecast surface roughness, and forecast surface roughness for heat as input to the analysis.
- The introduction of 10-m neutral wind components in the GOM arrays. A logical LUPD informs whether surface fields have been updated.
- The introduction of the logicals LVDFTRAJ, LVDFMIN and LZ0FC in YOMOBS.
• Communication of perturbations in 10m-neutral wind components to corresponding GOM arrays (cobsad/tl). It would be straightforward to extend this new structure to other surface fields.

• Regarding the horizontal interpolation from model fields to observation location (cobs), the bookkeeping on which fields behave like scalars of vectors, is made more transparent.

• The resetting of surface perturbations at start and final steps in the adjoint and tangent-linear code has been moved to a higher level from ecphysad/tl to scan2mdad/tl. In addition, only perturbations are reset, rather than the complete (un-necessary) reset of associated non-linear surface fields.

• Information on the magnitude of the neutral-wind GOM arrays is printed for scatterometer data (gathergom, prtgom).

• Similarly to the requirement of the assimilation of all-sky microwave radiances (LEMWAVE, Bauer et al. (2006)), it is ensured that the post-processing of surface wind is being called under ec phys when LSCATT_NEUTRAL=.true. (suphli).

• When LSCATT_NEUTRAL=.true., Charnock is saved in the high-res trajectory, which is then interpolated to the resolution of the minimization (KTRAJ=1 in su surf flds). Otherwise, a constant Charnock (value 0.018) is used in the minimization (KTRAJ=2).

References


Hersbach, H. (2010a). Calculation and archiving of friction velocity and 10m equivalent-neutral wind from ifs. Ecmwf research department memorandum, ECMWF, Shinfield Park, Reading, [R60.9/HH/1034].


