TOWARDS A HIGH-RESOLUTION GRIDDED OCEAN FORCING

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Abstract

Scatterometers estimate the relative atmosphere-ocean motion at spatially high resolution and provide accurate inertial-scale ocean wind forcing information, which is crucial for many ocean, atmosphere and climate applications. An empirical scatterometer ocean stress (SOS) product is estimated and validated using available statistical information. A triple collocation dataset of scatterometer, moored buoy and numerical weather prediction (NWP) observations together with two commonly used surface layer (SL) models are used to characterize the SOS. First, a comparison between the two SL models is performed. Although their roughness length and the stability parameterizations differ somewhat, the two models show little differences in terms of stress estimation. A triple collocation exercise is then conducted to assess the errors of both the observations and the SL models. The results show that the uncertainty in the NWP dataset is generally larger than in the buoy and scatterometer wind/stress datasets, but depending on the spatial scales of interest. The triple collocation analysis also shows that scatterometer winds are as close to real winds as to neutral winds, provided that we use the appropriate scaling. An explanation for this duality is that the small stability effects found in the analysis are masked by the uncertainty in SL models and their inputs. The triple collocation analysis shows that scatterometer winds can be straightforwardly and reliably transformed to wind stress. This opens the door for the development of wind stress swath (level 2) and gridded (level 3) products for the Advanced Scatterometer (ASCAT) onboard MetOp and for further geophysical development.

1. INTRODUCTION

Wind forces motion in the ocean and in turn the motion in the ocean determines the weather and climate in large portions of the world. Wind forcing is essential in the El Niño Southern Oscillation (ENSO) and other ocean-atmosphere interaction phenomena occurring in the Tropics, as well as in the modelling of the Antarctic circumpolar current, forcing of the southern oceans, research on the variability and occurrence of storms, and forcing in complex basins, e.g., the Mediterranean. A continuous wind stress time series of high temporal and spatial resolution would aid in the understanding of the unexplained variability of these wind events from year to year.

Wind information is available from conventional platform observations, such as ship or buoy. These systems measure the atmospheric flow at a measurement height that can vary between 4 m and 60 m, and are thus not a direct measure of surface 10-m wind or of stress. Stress computation requires the transformation of these winds by Planetary Boundary Layer (PBL) parameterisation schemes in order to represent the sea surface conditions. These PBL schemes and, more in particular, their embedded Surface Layer (SL) schemes have improved accuracy over the years although they still contain transformation errors. Furthermore, buoy wind observations and, by implication, the NWP analyses that exploit these data use a fixed reference frame. In contrast, scatterometer observations provide a measure of the relative motion between atmosphere and ocean, and therefore can potentially provide accurate high resolution wind stress information, essential to drive ocean models.

A scatterometer measures the electromagnetic radiation scattered back from ocean gravity-capillary waves and it is difficult to validate quantitatively the relationship between the roughness elements associated with gravity-capillary waves and the measurements. As such, empirical techniques are employed to relate microwave ocean backscatter with geophysical variables. The retrieved products from satellite scatterometers are generally validated by collocation with NWP model (e.g., European Centre for Medium Range Forecast, ECMWF) background winds, and/or buoy measurements. A multitude of wind observations is available at a reference height of 10 m, and as such scatterometer winds are traditionally related to 10m winds. For the Earth Remote Sensing (ERS) C-band (5.4 GHz) scatterometers, the so-called CMOD-5 (*Hersbach et al., 2007*) Geophysical Model Function (GMF), which relates the 10-meter wind to the backscatter measurements, is widely used nowadays for wind retrieval. For varying ocean wind conditions, the backscatter measurements vary along a well-defined conical surface in the 3D measurement space, i.e., the measurements depend on two geophysical variables or a 2D vector. CMOD-5 indeed well explains the coherent distribution of backscatter measurements in measurement space. In fact, scatterometers measure sea surface roughness (rather than 10-meter wind), which is highly correlated with the wind stress. So, if one collocates wind stress or its equivalent value at 10-meter height (i.e., 10-m neutral wind) to CMOD-5 winds and estimates their relationship, one would obtain a CMOD-5 stress model (or CMOD-5 neutral wind model) that potentially explains more of the backscatter variance than the CMOD5 wind model, since the disturbing effects of atmospheric stratification in the lowest 10m have been eliminated. The GMF would provide the same conical fits in 3D measurement space, since only an argument of the CMOD function has been transformed.

The aim of this paper is to define and validate a scatterometer wind-to-stress transformation. For such purpose, triple collocations of ERS-2 scatterometer observations, moored buoy observations and ECMWF model output are performed. Since the tropics and the extra-tropics have very different characteristics in terms of, e.g., wind variability, atmospheric stability or sea state, two different triple collocation datasets, one for each region, are used here.

2. DATA

The ERS-2 scatterometer 10-m winds are derived from the Royal Netherlands Meteorological Institute (KNMI) ERS scatterometer data processing (ESDP) package, developed in the context of the Ocean & Sea Ice (OSI) and the Numerical Weather Prediction (NWP) Satellite Application Facilities (SAFs) of the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT). The tropical moored buoy data used (kindly provided by Jean-Raymond Bidlot) correspond to the National Oceanic Atmospheric Administration (NOAA) TAO and PIRATA buoy arrays, which are located in the tropical Pacific and Atlantic oceans, respectively. Open ocean moored buoy data from the National Data Buoy Centre (NDBC), the Marine Environmental Data Service (MEDS), and the UK Met Office, which are located in the extra-tropical North Pacific and North Atlantic oceans, are also used. Hourly sea surface winds together with other surface layer relevant parameters, such as sea surface temperature (*SST*) and air temperature (*T*) are retrieved from the buoy data files. Additionally, first guess (FG) ECMWF ERA-40 lowest level (approximately 10 meter height) winds, *T,* specific humidity (*q*), pressure (*p*), *SST*, surface pressure (*sp*) and Charnock parameters are retrieved from the ECMWF MARS archive.

The triple collocations are performed with the following criteria: only observations separated less than 25 km in distance and 30 minutes in time are used. In practice, most of the collocations are within 12.5 km and 10 minutes, thus considerably reducing the collocation error, i.e., uncertainty due to spatial and temporal separation between collocated observations. Several Quality Control (QC) procedures have been applied to the dataset (see details in *Portabella and Stoffelen, 2007*). In total, we use data from 53 tropical buoy stations (for year 2000) and 41 extra-tropical buoy stations (for years 1999 and 2000), which produced 3471 and 3345 collocations (after quality control), respectively, over the mentioned periods.

3. SURFACE LAYER MODEL COMPARISON

The surface layer is assumed to be a constant flux layer and it extends up to a few tens of meters above the surface. In the bulk parameterization of the similarity theory, the fluxes are determined with the transfer coefficients which relate the fluxes to the variables measured, e.g., surface wind speed (*U*), *T*, *SST*, *q*. The bulk transfer coefficients can be determined by integrating the *U*, *T* and *q* profiles. Close to the surface, the distributions of *U*, *T* and *q* are governed by diabatic processes. As such, the wind profile can be written as:

$$u_* = \frac{k}{[\ln(\frac{z}{z_0}) - \psi(z/L)]}(U - U_s) \tag{1}$$

where k is the von Karman constant, $u_*^2 = \tau / \rho$ is the friction velocity, z is the height above the surface, z_0 is the roughness length for momentum, ψ is the stability function for momentum (positive, negative, and null, for unstable, stable, and neutral conditions, respectively) and L is the Monin-Obukhov length, which includes the effects of temperature and moisture fluctuations on buoyancy. The wind at the surface U_s is neglected. Similar profiles to the one in Eq. 1 are also derived for the scale temperature (T_*) and the scale humidity (q_*) (see *Liu et al., 1979*). Since stability (z/L) depends on T and q, the set of 3 dimensionless profiles (u_*, T_*, and q_*) have to be solved at the same time.

The discussion of air-sea transfer is not about the validity of the approach described above but generally about the details of parameter and function choices. As such, most SL models are based on the bulk formulation derivation (e.g., Eq. 1), and differences among them lie in the parameterization of L and/or z_0. This is the case for the two SL models used in this work, i.e., the LKB and the ECMWF SL models. Their similarities and differences are further discussed in the following section.

3.1 LKB versus ECMWF: formulation

The LKB and ECMWF SL models present the same roughness length function (see *Liu et al., 1979*, and *Beljaars, 1997*), which is written as:

$$z_0 = \frac{0.11 \cdot \nu}{u_*} + \frac{\alpha \cdot u_*^2}{g} \tag{2}$$

where ν is the kinematic viscosity of the air (1.5x10^{-5} m^2/s), g is the gravitational constant of the Earth (9.8 m/s^2), and α is the (dimensionless) Charnock parameter. However, the Charnock value, which is a sea-state parameter, is substantially different, i.e., 0.011 for LKB and around 0.018 for ECMWF SL (the latter is not a fixed value). The same happens with the formulation of the stability function $\psi(z/L)$, which is identical for both models, but where the computation of the L parameter (Monin-Obukhov length) differs from one another (see *Liu et al., 1979*, and *Beljaars, 1997*). Additional minor differences between the two models are reported in detail in *Portabella and Stoffelen* (2007).

3.2 LKB versus ECMWF: results

Figure 1a shows the two-dimensional histogram of LKB estimated u_* versus ECMWF SL estimated u_* for the second of the two available extra-tropical input datasets: GTS buoys and ECMWF model output. Since the two datasets contain different parameters (see discussion in section 2) and the two SL models allow somewhat different input (see section 3.1), we select the coincident parameters for all 4 combinations: U, T, and *SST*. As it is clearly discernible, the distribution lies close to the diagonal, it is very narrow, and the correlation is 1, meaning that the estimated u_* is very similar, regardless of the SL model used. Very similar results are found when using the GTS buoy dataset or the tropical datasets (GTS buoy or ECMWF model output) as input (not shown). In other words, the two models show very similar stresses. A 5% bias at high u_* values needs to be explained though. As described above, SL model differences must lie in the roughness length and the stability parameters. Therefore, we take a closer look at these.

Roughness and stability terms

Figure 1b shows the same as Figure 1a, but for the z_0 parameter. Again, the correlation between the two models is striking. However, a clear difference between the two model formulations is noted. As discussed in section 3.1 the Charnock parameter is substantially different for both models, i.e., 0.011 for LKB and 0.018 (default value) for ECMWF. Therefore, for very low u_* values, where the viscosity term (first right-hand side term of Eq. 2) is dominant, the distribution lies on the diagonal (same z_0 for both models), and for higher u_*, where the Charnock term is dominant (second right-hand side term of

Eq. 2), the distribution is off diagonal, with a slope which is given by the ratio between the Charnock values of both models.

Looking at Figures 1a and 1b, one can easily realize that in order to achieve such good agreement in u_* (Figure 1a), the stability term in Eq. 2 has to compensate for the difference in the roughness term between the two models. Since the stability term is relatively small in both models, there should be a bias of about 5% between ECMWF and LKB u_*, which is not present at low u_* values (see Figure 1a).

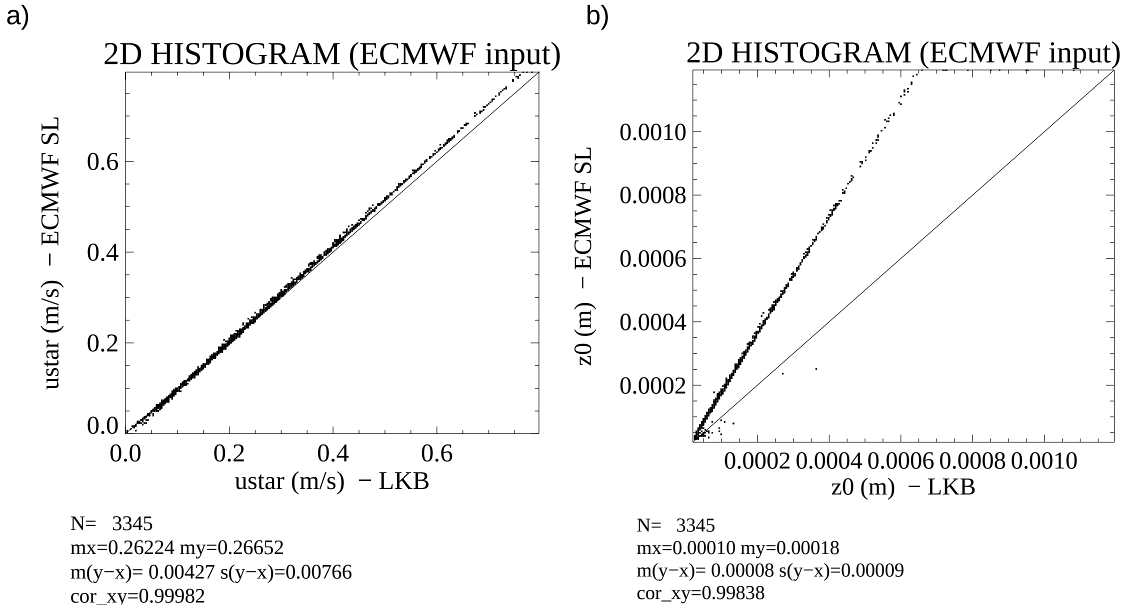

***Figure 1*: Two-dimensional histogram of LKB estimated u* versus ECMWF SL estimated u* (a) and of LKB estimated z_0 versus ECMWF SL estimated z_0 (b), using the ECMWF model output in the extra-tropics. N is the number of data; mx and my are the mean values along the x and y axis, respectively; m(y-x) and s(y-x) are the bias and the standard deviation with respect to the diagonal, respectively; and cor_xy is the correlation value between the x- and y-axis distributions.**

The relative weight of the stability term in the denominator of Eq. 1 is analysed for both the LKB and the ECMWF SL models. It turns out that the stability term is only relevant for low z_0 values (i.e., low winds) (not shown). Moreover, the LKB stability term is more relevant than the ECMWF stability term. Since most of the observations correspond to unstable ($\psi > 0$) situations (not shown), the more relevant stability term (thus producing larger instability) for LKB compensates the larger z_0 values from ECMWF SL model, such that the resulting u_* values are very similar for both models for low and medium winds. Overall, stability effects are small both in the tropics and the extra-tropics and in the order of ±0.5 m/s.

Sea state effects

The Charnock parameter is a measure of wave growth, hence wave age. As mentioned in section 3.1, the Charnock parameter is fixed for LKB but not for ECMWF SL model. The Charnock parameter, as formulated in the ECMWF Wave model (WAM), is a function of the so-called wave induced stress which in turn is function of the wind input source term. Such Charnock output is included in the collocated ECMWF dataset (section 2) and therefore can be used as input to the ECMWF SL model. Up to now, results have been produced with fixed Charnock values (default values) for both models, i.e. 0.011 for LKB and 0.018 for ECMWF. To show the impact of a variable Charnock (i.e., sea state dependency) Figure 1a is reproduced with ECMWF Charnock input. The resulting 2-D histogram (not shown) shows only somewhat larger spread than the one in Figure 1a, indicating that even if the sea state is relevant in the extra-tropics, it has little impact on the wind stress (u_*) estimation.

The triple collocated dataset can be used to better analyze the Charnock output from WAM. Figure 2 shows the scatterometer – ECMWF (left plot) and buoy – ECMWF (right plot) speed bias and standard deviation (SD) as a function of the Charnock parameter in the extra-tropics. ECMWF and GTS buoy speeds have been converted to 4 m height speeds using ECMWF SL model. Since the scatterometer actually observes sea surface roughness, which is directly affected by the wave induced stress, one would expect that for increasing Charnock (sea state) values, sea surface roughness and therefore the mean biases in the left plot increase. However, the bias is rather flat and very similar to the one in the right plot, where for the same set of points no explicit roughness effect is expected. Moreover, the spread in the data points could be different due to sea state effects, which is also not the case and the plots look very similar indeed. The wind vector cell, WVC, mean sea state roughness as observed by scatterometers thus appears mainly wind-driven and cases of substantial stress-wind decoupling appear exceptional. The slight bias increase at large Charnock values in the left plot may be an indication of stress-wind decoupling, although there is not enough data to support this statement. It is therefore concluded that, in general, Charnock is very much correlated to the WVC-mean wind and therefore has small impact in the quality of a global SOS. However, the Charnock parameter may contain some added value for exceptional conditions such as cases of extreme wind variability and/or air-sea temperature difference. A much larger dataset is needed however to further investigate this.

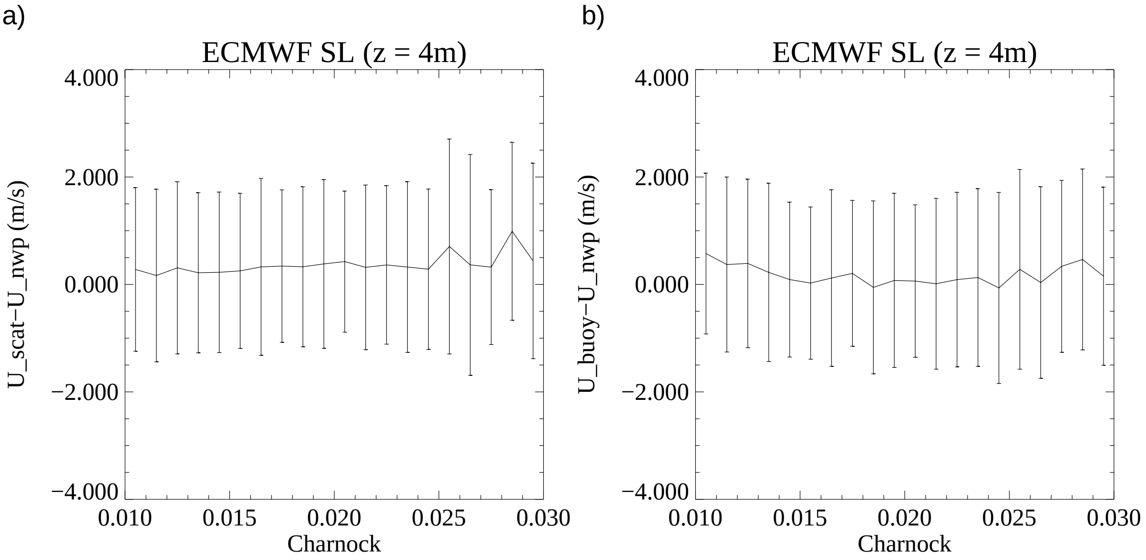

Figure 2**: ERS scatterometer – ECMWF (left plot) and buoy – ECMWF (right plot) wind speed bias (solid curve) and SD (error bars) as a function of the Charnock parameter (bins of 1).**

4. WIND-TO-STRESS CHARACTERIZATION

In remote sensing, validation or calibration activities can only be done properly when the full error characteristics of the data are known. In practice, the problem is that prior knowledge on the full error characteristics is seldom available. *Stoffelen* (1998) shows that simultaneous error modeling and calibration can be achieved by using triple collocations. Simultaneous error modeling and calibration can be used to compare triple collocation wind component datasets. In this section, the scatterometer winds are fixed in all datasets and used as reference. The two other wind observing systems (i.e., buoys and NWP) are presented at varying heights and stability conditions, such that the true and error variances can be evaluated for the different datasets. In this way, the interpretation of the different observing systems and the performance of the SL models are characterized in this section.

4.1 Error assessment using LKB and ECMWF SL models

The triple collocation exercise is used here to assess the random errors and scaling properties of the ERS scatterometer, buoy and ECMWF winds, using ERS scatterometer CMOD-5 winds as a reference system. As such, the performance of the two SL models compared in section 3, i.e., LKB and ECMWF, can be tested by using the SL models to convert buoy and ECMWF wind observations to different reference heights (e.g., 4 m, 10 m) and then estimating the errors of the buoy and NWP converted wind “observations”.

Table 1 shows the observation error (in terms of wind vector SD) for tropical and extra-tropical datasets at 50-km scales, when LKB is used to produce the (buoy and NWP) wind datasets at 10-m height. It is clear that the scatterometer errors both in the tropics and the extra-tropics are smaller than ECMWF errors at 50-km resolution. When ECMWF SL model is used (instead of LKB) to produce the (buoy and NWP) wind datasets at 10-m height, the triple collocation results (not shown) are almost identical to the ones in Table 1. That is, the performance of both SL models is comparable. These results are in line with the results of section 3.2, where both models were showing little differences. The same exercise is repeated using buoy and NWP winds at 4 m height, i.e., the approximate measurement height of buoys used in this work. In this case, no SL model transformation is required for the buoy winds. The results (not shown) are very similar in terms of errors of the different sources, denoting that the SL model does not introduce additional error when buoy winds are transformed from 4m to 10m. It also implies that scatterometer winds can be scaled equally well to 10m and 4m winds.

	Scatterometer	Buoy	ECMWF
Tropics (m/s)	1.17	1.48	2.04
Extra-tropics (m/s)	1.60	1.55	2.16

Table 1**: Estimates of the wind vector SD error of the scatterometer, LKB-derived 10 m buoy and ECMWF winds, for 50-km scale wind in the tropics and the extra-tropics.**

4.2 Scatterometer wind interpretation

As discussed in the introduction, scatterometers are essentially observing wind stress. Therefore, one may better interpret scatterometer-derived winds as equivalent neutral winds (i.e., stress) rather than real winds. In this section, we investigate the interpretation of scatterometer data by performing the triple collocation exercise for two different datasets:

a) ERS CMOD-5 winds, buoy real winds, and ECMWF real winds;
b) ERS CMOD-5 winds, buoy neutral winds, and ECMWF neutral winds.

The first dataset is the same as the one used in section 4.1. The second dataset is the same as the first one but for buoy and NWP converted neutral winds using either LKB or ECMWF SL model. The error scores of dataset a) (see Table 1) are very similar to the scores obtained with dataset b) (not shown), when using LKB model and 10-m conversion. The same conclusions are drawn when using ECMWF SL model and/or 4-m conversion. This indicates that scatterometer winds can explain the same true variability regardless of whether these are tested against real or neutral winds. In other words, provided that we use the appropriate scaling in the scatterometer GMF (e.g., CMOD-5), scatterometer winds are as close to real winds as to equivalent neutral winds (or stress).

This can be explained as follows: on the one hand, the stability effects are small, i.e., differences between real and neutral winds are subtle (see section 3); on the other hand, SL models and the different observations (wind, SST, air temperature) used by the models to compute height conversions and neutral winds contain errors, which in turn mask the already subtle differences between real and neutral winds. Although scatterometer winds can be interpreted as real winds from a statistical point of view, there may be special air-sea interaction situations where the scatterometer shows its real potential to measure stress. For example, in the extra-tropics, there are substantially more cases with stable stratification than in the tropics (not shown). For these single cases, the use of stability information may increase the true variability in a triple collocation exercise, therefore indicating that such scatterometer observations should be interpreted as neutral winds (or stress) rather than real winds. To prove this, further tests with a larger dataset are required.

4.3 Scatterometer wind-to-stress transformation

In order to obtain stress, first a well-calibrated scatterometer 10-m neutral wind is required. Then a SL model like LKB or ECMWF SL can be used to convert 10-m neutral winds to wind stress. In fact, since the most recently developed SL models have similar performance up to 16 m/s (*Bourassa, 2006*), either one of them can be used to do the neutral-to-stress conversion. Since no stability information is needed to do this conversion, an independent SOS product can be developed straightforwardly.

To obtain the calibrated scatterometer 10-m neutral wind, a scatterometer-to-buoy correction (calibration) and a real-to-neutral wind conversion need to be applied to CMOD-5 winds. Based on the triple collocation results, we recommend adding 0.7 m/s to CMOD-5 winds to obtain the scatterometer 10-m neutral winds (in line with *Hersbach et al., 2007*). Alternatively, one can derive stress from the 10-m real winds instead (see discussion on scatterometer wind interpretation in section 4.2). To obtain calibrated scatterometer real winds we recommend adding 0.5 m/s to CMOD5 (see Figure 3).

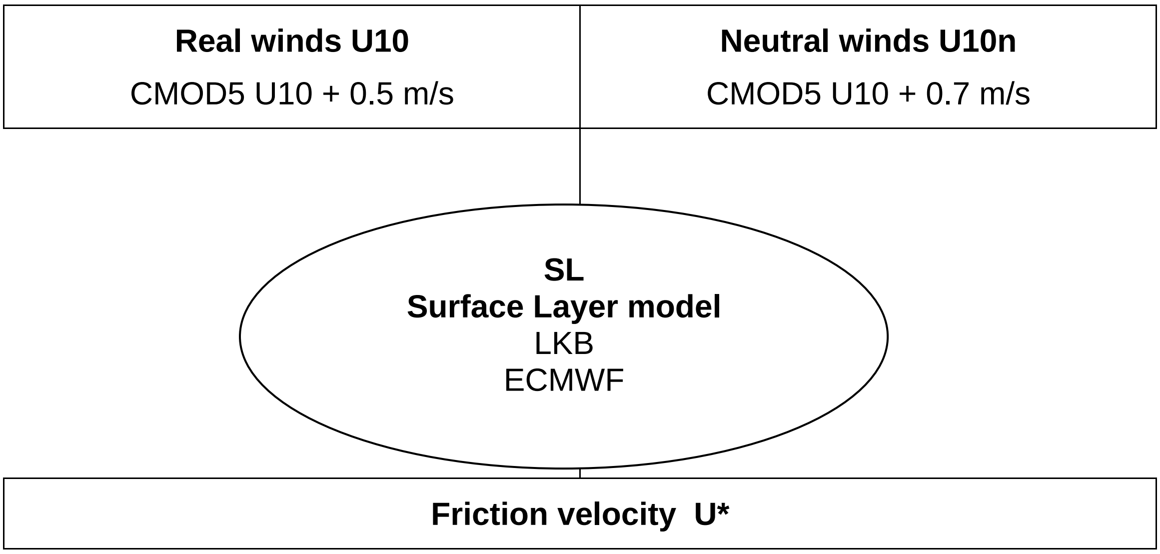

***Figure 3*: Schematic of recommended scatterometer wind and stress conversion. The well-validated CMOD5 winds at 10m height are used as basis for geophysical conversion to friction velocity. Either real or neutral 10m winds may be transformed to friction velocity by either LKB, ECMWF or any similar SL model.**

5. OUTLOOK

Although the results in this paper relate to the ERS scatterometer, the wind to stress conversion also applies to other scatterometers such as the new C-band scatterometer, i.e., ASCAT (onboard MetOp), which was launched on October 19 2006 and has more than twice the coverage of the ERS scatterometer. In the framework of a collaboration between NOAA and EUMETSAT OSI SAF, ASCAT underflights have been planned during the NOAA 2007 winter storm and tropical cyclone campaigns.

These extreme weather datasets could therefore be used to assess the quality of SL models at cases of extreme wind variability or air-sea temperature difference, where SL models may show large wind and stress discrepancies. Moreover, it would also be interesting to study the ability of scatterometers to measure stress in such extreme conditions.

The work presented here opens the door for the development of wind stress swath (level 2) and gridded (level 3) products for ASCAT and for further geophysical development. In the context of the European Commission initiative on Global Monitoring for the Environment and Security (GMES), a directive to provide Marine Core Services (MCS) has been issued. In particular, the GMES body has asked an oceanographic consortium (constituted by MERCATOR and MERSEA among others) of the 6th Framework Program (FP6) of the European Union to lead a proposal on MCS, the so-called *My Ocean*, for the next FP7. Within *My Ocean*, KNMI will lead the so-called Wind Thematic Assembly Centre (Wind TAC), which aims to provide spatially and temporally consistent high-resolution ocean wind forcing products, potentially very useful for ocean modelling and wave and surge forecasting.

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