

# Ocean Surface Vector Wind Observations



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**Abstract** Ocean surface vector winds (OSVW) play a fundamental role in the Asian Seas through air-sea interaction; this applies to the modest winds in the trades, the winds associated with the extensive areas of tropical convection, sea and land breezes and, of most direct human relevance, the winds associated with hurricane-force typhoons. Predicting the air-sea exchanges in the cold polar seas and the atmospheric dynamics of tropical mesoscale convective systems or the strength and track of typhoons remains equally a challenge, but is of fundamental importance for weather forecasting and climate change studies. It is briefly described how wind vector information is obtained from satellite microwave active and passive measurements off the wind-roughened ocean surface, and subsequently an evaluation of the wind vector product services, for example, in coastal areas, is provided. India, China, Russia and Japan, inter alia, have been, are, or will be contributing to a global virtual constellation of scatterometers that provide increasing temporal coverage of ocean surface vector wind information.

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The application of scatterometer winds for weather nowcasting, for mesoscale and global numerical weather prediction and for oceanography and climate studies is highlighted.

**Keywords** Scatterometer · Ocean surface vector winds · Virtual constellation  
Air-sea interaction · Typhoons · Moist convection · Mesoscale  
Nowcasting · Oceanography · Climate

## 1 Introduction

Scatterometer winds have proven to be very relevant in driving ocean circulation and air–sea interactions (Chelton et al. 2004; Tokmakian 2005; Blanke et al. 2005; Liu and Xie 2006), which in turn play a major role in the climate system (Xie et al. 2007; Tokinaga et al. 2009; Shimada and Kawamura 2006) and marine biology (Moore and Renfrew 2005). OSVW and wind stress force the ocean in many ways, where most uncertainty exists in these interaction processes at mesoscales and at extreme winds. High winds play a disproportionately large role in Earth’s weather and climate. Mid and high latitude, high wind events (cold air outbreaks) lasting several days, can remove what at typical wind speeds would be a month’s worth of the ocean’s heat and moisture, leading to the formation of “deep water” that helps drive global ocean circulation patterns. High winds also help exchange disproportionately large amounts of carbon dioxide. Moreover, long-term stable instrument records are essential to build confidence in the fidelity and limitations of model reanalyses and guide their application in trend analyses.

Understanding the peculiarities of such a large and varied collection of marine and coastal atmospheric dynamics requires the adoption of integrated systems of earth observation (EO), in which microwave remote sensing by satellite instruments, such as scatterometers (Bourassa et al. 2009), Synthetic Aperture Radars (SAR) and radiometers, plays an essential role.

This chapter reviews the current potential of EO wind in the assessment of the many Asian seascapes, using both passive and active microwave techniques, measuring emitted or scattered microwaves. An in-depth evaluation of the available microwave wind observation techniques, as well as of novel methods, ensures that suitable instruments are indeed accessible for managing and exploiting the wealth of resources that the Asian Seas have to offer. First, the physical regime of mesoscale winds is described to lead on to the application-based requirements and the EO-based capabilities for OSVW. The relationship between EO measurements, OSVWs and wind stress will be elaborated, before discussing the application of EO winds in the last section, including extreme winds (Yu et al. 2015).

## 2 Ocean Vector Winds and Stress

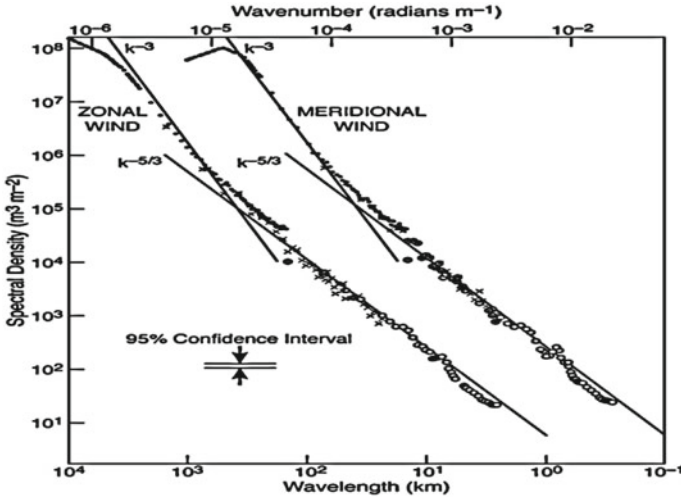
Though essential and relevant for a wide range of applications in economy and society, such as coastal protection, ship routing, off-shore wind energy, climate-scale circulation, water cycle and ocean forcing, only sparse coverage of the ocean surface by conventional anemometers exists. In particular, spatial gaps of several 1000 km exist, which clearly limit the capability to obtain detailed information on the winds and wind stress over the world oceans. The advent of EO satellites provides a leap forward to fulfil the requirements for wind and stress measurements over the oceans. On the large scales, wind measurements are mainly relevant in the tropics, since elsewhere large-scale wind circulations may be determined from the atmospheric mass field. However, as meteorological analyses more and more focus on mesoscale processes, wind measurements are needed globally as further discussed in the first subsection. Based on this basic need, user requirements are subsequently formulated in the different basic application areas and the associated EO capability on ocean winds. Finally, the relationship between these EO ocean measurements and both winds at 10 m height, which is a World Meteorological Organisation (WMO) standard height, and wind stress, which is the most relevant input parameter for ocean forcing, is discussed.

It is clear that in the next decades focus will be put on mesoscale weather phenomena and coastal dynamics, as these will be required in many off-shore and coastal applications and increasingly resolved by Numerical Weather Prediction (NWP) and ocean models.

### 2.1 3D Turbulence and Convection

Winds are associated with turbulence and convection, but also with mixing of air, dispersion, fluxes of momentum, heat and moisture, and cloud processes. For example, important exchanges appear due to downbursts of relatively dry and cool air near moist convection, which is widespread in tropical areas in particular. Given these important atmospheric and ocean exchange processes, detailed knowledge of wind fields and their dynamical evolution appears critical to understanding the earth system, since most of the earth surface is covered by water.

Nastrom and Gage (1987) supplemented large-scale experimental evidence to the ideas of Kolmogorov (1941) on atmospheric turbulence, as depicted in Fig. 1. For scales larger than 500 km, the spectral signature designates two-dimensional (2D) turbulence and geostrophic flow, while for smaller scales 3D turbulence appears. Although the depth of the troposphere is order 10 km, 3D turbulence starts to dominate on scales below about 500 km. So, the horizontal-to-vertical aspect ratio of the associated turbulent structures is about 100, with, for example, vortices of 1 km depth being spread 100 km horizontally.

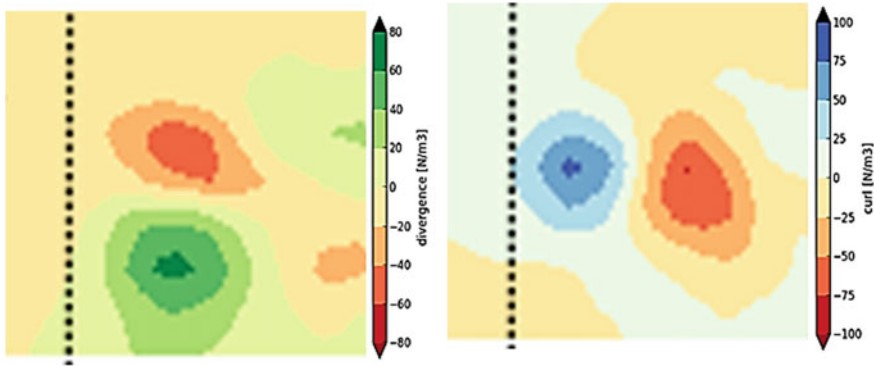


**Fig. 1** Spectral wind energy density as a function of wave length (bottom) and wave number (top) for measured upper air zonal and meridional winds, where the latter is shifted right by an order of magnitude for clarity. Nastrom and Gage (1985). © AMS

The spectra in Fig. 1 are determined statistically and the actual two-way spread ( $2\sigma$ ) around the climatological mean at small scales is about an order of magnitude in spectral energy. Meanwhile, many other studies confirmed these findings (e.g., Vogelzang et al. 2011). Note that the spectral turbulent energy in the meridional and zonal components in Fig. 1 is very similar and that mesoscale wind variations tend to be statistically isotropic, i.e., variations along the mean large-scale wind tend to be similar to variations across (Vogelzang et al. 2015).

The large-scale heating of the atmosphere results in large-scale circulation patterns, broken down to smaller scales (downscale propagation), until eventual dissipation on the molecular scale. On the other side, atmospheric instability and (moist) convection processes cause the generation of wind variability on the smaller scales, which leads in turn to so-called upscale propagation (King et al. 2015). Note that the dynamics of these small scales are steered by the local winds and that wind measurements are most effective to capture their evolution (Stoffelen et al. 2006).

Moist convection is widespread in the tropics and causes rapid changes in the ocean surface vector winds. Moist convective cells are identified by Meteosat Second Generation (MSG) geostationary imagery, notably the day-time KNMI MSG rain product. Collocated ASCAT winds show characteristic patterns in the wind convergence and curl, as illustrated in Fig. 2. The two panels are centred on the same location and the intense red blob in the left panel of Fig. 2 is closely overlapping the MSG rain pattern and designates a wind downburst due to rapidly descending rain-cooled air aloft. It may be clear that moist convection invigorates mixing of air, dispersion, air-sea fluxes of momentum, heat and moisture, and further lifting of air and cloud processes.



**Fig. 2** ASCAT wind convergence (left) and curl (right) around a deep moist convective cell in the tropics (as identified by KNMI MSG rain). The wind convergence and divergence (downburst) are clearly visible, depicting intense air-sea interaction. Moist convection is widespread in the tropics

Although advancing meteorological applications to resolve smaller scales appears natural, the interest in measuring mesoscale and convective-scale wind structures poses daunting challenges:

- Spatial resolution and coverage must be sufficient to capture these scales;
- Accuracy must be sufficiently high to measure the small amplitudes of the small scales (see Fig. 1);
- Temporal sampling must be enhanced to match convective time scales (30 min);
- Observation timeliness must be commensurate this time scale and also the warning horizon needed to take action to avoid societal impacts.

## 2.2 Wind Requirements

The WMO Observing Systems Capability Analysis and Review<sup>1</sup> tool is maintained by application experts, who specify consensus requirements for geophysical variables in diverse application areas, such as climate applications, global and regional NWP, (high-resolution) weather nowcasting, ocean applications, meteorological research (GEWEX, SOLAS), etc. Moreover, these basic meteorological requirements serve downstream applications, such as ocean wave and storm surge predictions, or more novel applications, such as energy production in off-shore wind farms (Dong et al. 2013).

The geophysical variable of interest here is the horizontal wind vector over water surfaces defined by WMO as: “Horizontal (2D) vector component of the 3D wind vector, conventionally measured at 10 m height”. Table 1 provides a brief summary

<sup>1</sup>WMO OSCAR: [www.wmo-sat.info/oscar](http://www.wmo-sat.info/oscar).

**Table 1** Summary of WMO OSCAR requirements defined for 2D wind vector over the surface

Application area	Uncertainty (ms <sup>-1</sup> )	Spatial resolution (km)	Observation cycle (h)	Timeliness (h)
Global NWP	2	100	6	1
Regional NWP	1	10	3	½
Nowcasting	2	10	½	½
Ocean	2	5–25	3	1–24
Climate	1–2	5–100	3–18	1–1000

of the so-called breakthrough requirements for the horizontal wind as provided in the OSCAR data base. This “breakthrough” would, if achieved, result in a significant improvement for the targeted application and is an intermediate level between a threshold requirement and an ultimate goal. The breakthrough level may be considered as an optimum from a cost-to-benefit point of view, when planning or designing observing systems. Since multiple entries exist in the data base in an application area, ranges are specified when needed. In Table 1 uncertainty is meant as vector error, i.e., the modulus of the vector difference between the observed wind vector and the true vector. Since the two horizontal wind vector components are assumed equally accurate, the wind vector component uncertainty requirement is a factor  $\sqrt{2}$  more stringent. Moreover, the “uncertainty” characterizes the estimated range of observation errors on the given variable, with a 68% confidence interval ( $1\sigma$ ).

All application areas require 1–2 ms<sup>-1</sup> vector wind quality. Biases are assumed negligible and, therefore, accurate (inter)calibration of instruments is necessary. The requirements for spatial resolution are more diverse, even within an application area. In this regard it is noted that wind spectra fall off exponentially and smaller scales contain less wind variance. Therefore, when small scale wind features are targeted, small uncertainty must be required, typically better than the integrated climatological wind variance on scales smaller than the targeted horizontal resolution. Similarly, small-scale wind structures evolve much faster than large-scale atmospheric structures and therefore a high spatial resolution generally implies a high observation frequency in order to be able to capture all small-scale variations. Finally, timeliness is critical for atmospheric, ocean wave and storm surge hazard forecasting applications, since it is generally directly compromising the timeliness of alerting economy and society.

Although WMO OSCAR also provides requirements on wind speed in a similar fashion, it may be clear, however, that wind vector information is generally more desirable, for example to obtain spatial wind derivatives, such as wind stress curl and divergence.

In addition to the quality parameters in Table 1, the WMO Global Climate Observing System section formulated a requirement on the stability of essential climate data records (GCOS 2011). In a report on Systematic Observation Requirements for Satellite-based Products for Climate, supplemental details to the satellite-based component of the Implementation Plan for the GCOS are provided and a stability of 0.1 m/s per decade for observational wind records is requested.

### 2.3 *Virtual Ocean Vector Wind Constellation*

Scatterometer instruments are part of so-called virtual constellations through international collaboration. The Committee on Earth Observation Satellites Ocean Surface Vector Wind Virtual Constellation (CEOS OSVW VC) interagency working group is making steps to align requirements and product standards to build a global constellation of scatterometers. Given the above-mentioned daunting challenges on spatial and temporal sampling, accuracy and timeliness, international collaboration appears extremely profitable for all space agencies involved. With more agencies now planning scatterometers (e.g., ISRO on ScatSat and OceanSat, the Chinese Meteorological Agency on the FY series of satellites, the Chinese State Ocean Administration on the HY series and CFOSAT<sup>2</sup> and Russia on the Meteor series) and scatterometers likely available from three<sup>3</sup> EUMETSAT Metop satellites at the same time, a virtual constellation is being built to address spatio-temporal coverage needs.

Scatterometers are usually mounted on polar satellites in sun-synchronous orbits, i.e., they pass a given location at approximately the same time every day, defined by the satellite's Local Time of equator Ascending Node (LTAN). By coordinating the LTAN of the different satellites, the CEOS OSVW VC may effectively cover all times of day and therefore for example the diurnal cycle of the ocean winds, which is particularly substantial near land masses.

Due to the polar orbits and different LTAN, close collocations between scatterometer measurements are relatively infrequent and mainly situated near the poles, where orbits cross. The NASA RapidScat scatterometer, mounted on the International Space Station, is neither sun-synchronous nor polar and provides scatterometer winds at different times of day. Moreover, in due time, close collocations with other operational scatterometers, notably ASCAT-A and -B and NASA's QuikScat (now only pointing at one fixed azimuth angle), which favours accurate intercalibration and geophysical interpretation (Wang et al. 2017).

In addition, the close RapidScat and ASCAT collocations provide an excellent data base to further improve the wind retrieval from scatterometer data, both at Ku and C band, in terms of quality control, wind speed scale, wind direction biases, and ambiguity removal (Stoffelen et al. 2017) and moreover fosters the opportunity of international collaboration towards wind scatterometer retrieval improvement as elaborated in the International Ocean Vector Winds Science Team (IOVWST).

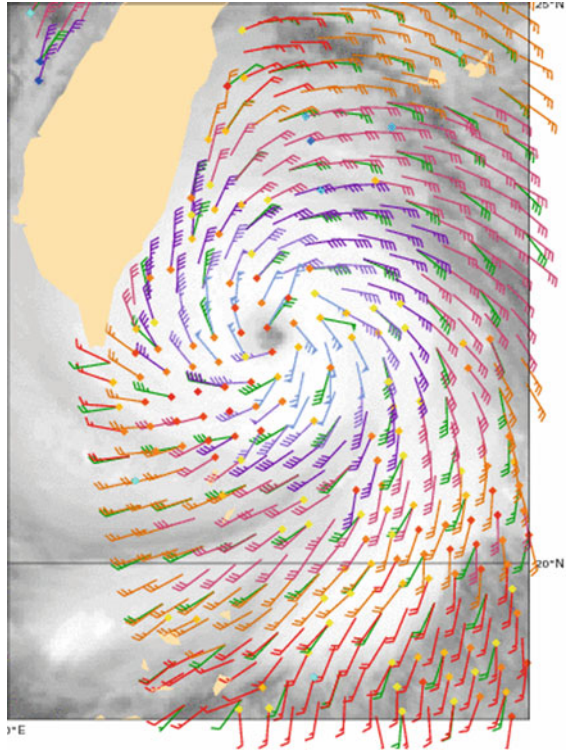
A new asset to the virtual constellation is the recently launched ScatSat mission by ISRO, which has higher incidence angles than RapidScat and will initially provide abundant collocations with ASCAT to provide further intercalibration and processing advancements of C- and Ku-band scatterometers. Figure 3 shows a depiction of a typhoon by ASCAT.

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<sup>2</sup>Chinese-French Ocean Satellite SCAT wind scatterometer.

<sup>3</sup>Scatterometers (ASCAT) on board the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) Metop satellites A, B and C.

**Fig. 3** Acquisition of typhoon Nepartak on the 8th of July 2016 before hitting Taiwan; the typhoon shows 25-km scale eye wall winds up to  $35 \text{ ms}^{-1}$  in ASCAT (blue and red), but, while the 12-hour forecast position is excellent, considerable weaker winds in the collocated ECMWF winds (green)



## 2.4 Stress-Equivalent Winds

Scatterometer, SAR and radiometer measurements relate to the ocean surface roughness and kinematic wind stress, while their wind products are represented by a wind vector at 10 m height over a Wind Vector Cell (WVC). How can this be consolidated? It is important to realize that in the approach followed, the radar backscatter measurement  $\sigma^0$  is related to the wind at 10 m height above the ocean surface, simply because such measurements are widely available for validation. This implies, however, some geophysical error. In particular, air stability and mass density are not directly sensed by the wind scatterometer, SAR nor radiometer and should be compensated in the derived 10 m wind, which is affected by these air properties.

Fortunately, in moored buoy and NWP model validation sources, the 10 m wind may be corrected for air stability and mass density with good precision. Therefore, scatterometer winds are validated and compared as so-called stress-equivalent 10 m winds, abbreviated as  $\mathbf{U}_{10S}$ . To avoid atmospheric stability effects, the 10-m equivalent-neutral wind vector,  $\mathbf{U}_{10N}$ , has been defined in the past, to replace the actual 10-m wind vector,  $\mathbf{U}_{10}$ . Using Monin-Obukhov similarity scaling, the equivalent-neutral wind vector amplitude is simply given by



$$U_{10N} = \frac{u_*}{\kappa} \ln\left(\frac{10}{z_0}\right) \tag{1}$$

where  $z_0$  is the aerodynamic roughness length, the friction velocity is defined by the equation for the kinematic wind stress  $u_*^2 = \tau/\rho$  and  $\kappa$  is von Karman’s constant. The aerodynamic roughness length

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

is approximated from the geophysical variables  $\nu$  (kinematic viscosity of air,  $1.5 \times 10^{-5} \text{ m}^2/\text{s}$ ),  $\alpha$  (dimensionless Charnock parameter, see Charnock 1955), and  $g$  (gravitational constant,  $9.81 \text{ m/s}^2$ ). The Charnock parameter, which depends on sea-state, varies substantially for different surface layer schemes, from 0.011 to around 0.018, and affects wind stress  $\tau$ , while it does not much affect  $U_{10N}$  (Portabella and Stoffelen 2009), such that  $U_{10N}$  may be used as a standard. To obtain  $\tau$  from  $U_{10N}$  one needs information on the stability of the atmospheric boundary layer, which may be obtained from moored buoys or NWP models with sufficient precision, and apply it in one’s favorite atmospheric surface layer scheme.

For the same  $U_{10N}$ , cold heavy air will produce more stress (and roughness) than lighter (warmer or dryer) air. This effect is expressed by the surface stress equation. The surface wind stress  $\tau = \rho u_* \mathbf{u}_*$  depends on the air mass density  $\rho$  and NWP and buoy winds may be converted to so-called stress-equivalent winds

$$U_{10S} = \sqrt{\frac{\rho}{\langle\rho\rangle}} U_{10N} \tag{3}$$

where  $U_{10S}$  is the 10 m-height stress-equivalent NWP or buoy winds that may be compared to scatterometer wind retrievals and  $\langle\rho\rangle$  is the average air density as defined in a standard atmosphere ( $1.225 \text{ kg/m}^3$ ).  $\rho$  variations, which depend on surface pressure, air temperature, and humidity, are generally small (1–2%) and can exceptionally increase locally in cases such as cold air outbreaks. These straight-forward corrections for air stability and mass density reduce geophysical errors when validating and applying scatterometer, SAR and radiometer wind retrievals. Equation (3) suggests that the global mean  $U_{10S}$  and  $U_{10N}$  are equal, but differ locally. It implies further that validated scatterometer products of  $U_{10N}$  can be interpreted as  $U_{10S}$  with improved geophysical accuracy (de Kloe et al. 2017).

Kinematic wind stress may now be easily obtained from  $U_{10S}$ , since

$$\tau = \langle\rho\rangle \cdot \left(\kappa / \ln\left(\frac{10}{z_0}\right)\right)^2 U_{10S} \cdot \mathbf{U}_{10S} = \langle\rho\rangle \cdot C_{DN} U_{10S} \cdot \mathbf{U}_{10S} \tag{4}$$

where it is noted that  $U_{10S}$  already includes the effect of varying air mass density on the stress exerted on the ocean surface to create roughness.  $C_{DN}$  is the neutral air drag coefficient.

However, wind scatterometers may be sensitive to more parameters than only those that relate (correlate) with  $U_{10S}$ . For example, the appearance of surface slicks, suppressing the amplitude of small-scale ocean waves and thus microwave-sensed roughness, is associated with low winds and may, to some degree, be fitted by a GMF (Stoffelen 1998; Chap. I). However, abundant surfactants, generated by natural or human causes, may render the nominal wind-to-backscatter relationship, as captured by the GMF, less accurate. Other variable effects, such as rain (mainly for Ku-band scatterometers), extreme wind variability, complex sea states, SST, etc., may affect GMF accuracy too, but only to a small degree.

## 2.5 Accuracy

Scatterometer winds are averaged over a WVC and do not spatially represent buoy nor NWP winds, which complicates calibration. Stoffelen (1998; Chap. IV) discusses a unique method to determine the accuracy of scatterometer, buoy, and NWP model  $U_{10S}$  winds: triple collocation. The method takes into account the different spatial representations of local winds from moored buoys, scatterometer (25 km WVCs) and global NWP winds (>100 km) (Vogelzang et al. 2011).

Table 2 provides some typical wind error standard deviations (SDE) of scatterometer, buoy and ECMWF winds for the same collocation criteria, though (necessarily) over different years. All verification is naturally provided on the spatial aggregation scale of the scatterometer, which here is either 12.5, 25 or 50 km. As may be expected, a larger aggregation to a 50 km scale, suppresses noise and slightly improves the SDE. However, at the same instance, the buoy SDE

**Table 2** Triple collocation results for KNMI scatterometer winds in subsequent months of November, December and January, starting in 2007 for ASCAT, 2015 for RapidScat, and 2009 for OSCAT and QuikScat

Product	Scatterometer		Buoys		ECMWF	
	$\sigma_U$	$\sigma_V$	$\sigma_U$	$\sigma_V$	$\sigma_U$	$\sigma_V$
	[m/s]		[m/s]		[m/s]	
12.5 km ASCAT	0.7	0.8	1.2	1.2	1.7	1.7
25 km ASCAT	0.6	0.7	1.2	1.2	1.6	1.6
25-km QuikScat	0.6	0.5	1.4	1.4	1.3	1.3
25-km RapidScat	0.6	0.7	1.3	1.4	1.2	1.2
50-km RapidScat	0.6	0.5	1.4	1.5	1.1	1.1
50-km OSCAT	0.7	0.5	1.5	1.6	1.0	1.1

The zonal (u) and meridional (v) wind component error standard deviations are provided on the scatterometer scale (e.g., Verhoef et al. 2015)

slightly increases at 50 km, indeed suggesting that the scatterometer 50-km products are a worse representation of the local buoy winds than their 25-km equivalents. Note that the 50-km products are a better representation of the ECMWF winds (ECMWF has lower SDE on the 50-km scale), which do not resolve 50-km scales.

It is clear from these results that moored buoys are not a good validation reference for scatterometer winds, due to their relatively large SDE on the scatterometer scale. However, the triple collocation method takes into account the SDE in estimating the calibration of scatterometers with respect to buoys and thus enables to exploit the main asset of moored buoys, which is their absolute calibration. As such, scatterometers are calibrated with respect to moored buoys and thus moored buoys are absolutely critical in scatterometry (Stoffelen et al. 2015).

### 3 Applications of Stress-Equivalent Vector Winds

Satellite stress-equivalent vector winds are used in a wide variety of applications from weather and climate to oceanography, as outlined below.

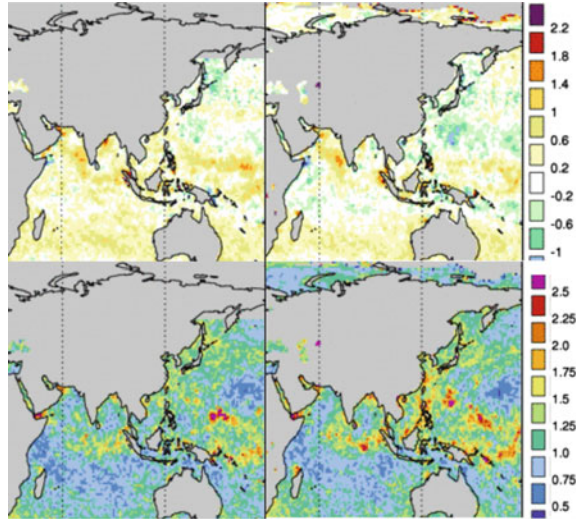
#### 3.1 *Global NWP*

Scatterometer winds have proven to be very useful for the forecasting of dynamic weather (Isaksen and Stoffelen 2000) using the 4D-Var data assimilation system, which is capable of assimilating winds with dual ambiguity (Stoffelen and Anderson 1997) and propagating the scatterometer surface information vertically (Isaksen and Janssen 2004). Increased coverage clearly improves forecasts of extreme events (Stoffelen et al. 2013). Severe storms often originate from ocean areas, where only sparse meteorological observations are available. Consequently, the initial stages of severe storms are often poorly analyzed and their development poorly predicted (ESA 1999) and occasional devastating ocean or coastal wind and wave conditions remain a major challenge for global NWP. Due to cut-off times in NWP, particularly in cases of fast weather developments, which often have large societal impacts, the timely use of satellite observations is complicated.

Figure 4 depicts regular monitoring statistics in the EUMETSAT NWP SAF. Note that larger biases and standard deviations of the differences between scatterometer and NWP model appear in the same regions: near the ITCZ, in regions with ocean currents, and near land masses. These areas correspond to areas with large atmospheric dynamics and substantial speed and systematic wind direction biases (Sandu et al. 2011).

Similar NWP biases occur in most global NWP models and are due to fast or mesoscale processes resolved by the scatterometer, but not by models, such as

**Fig. 4** Speed bias (top) and SD (bottom) of differences (O-B) of scatterometer winds (O) with respect to the Met. Office global model (B) for RapidScat on ISS (left) and ASCAT-A on MetOp (right) for July 2015 (note different legends). Different scattermeters produce similar local mean and variability of differences with respect to weather models. © EUMETSAT NWP SAF



(moist) convection (Lin et al. 2015), atmospheric turbulence (King et al. 2017), gravity waves and systematic errors in boundary layer parameterisations or the lack of ocean currents. These biases seasonally evolve, but tend to persist over time. The occurrence of these biases is however ignored in data assimilation and their existence prevents the correct assimilation of observed dynamical weather features. Whereas variational bias correction is quite common for satellite observations, the local model biases of Fig. 4 are not corrected yet, but may be estimated and prevented to a large extent, thus facilitating improved dynamical wind data assimilation.

All aspects of global NWP apply to regional NWP as well, but in regional NWP higher spatial and temporal resolution is attempted, as well as faster cycling.

### 3.2 Regional NWP

Although for regional NWP similar objectives hold as for global NWP, these applications will need faster observations, higher resolution, and improved coverage. Nevertheless, insufficient observations exist to initialise the fast-evolving turbulent scales. Therefore, while these mesoscale wind structures perhaps may be realistic, they are not real. Over the ocean and in the upper air they are generally not in phase with the real structures as observed by, for example, a scatterometer. This leads to a so-called double penalty in the scatterometer minus first guess departures and thus to larger departures than in global NWP.

Such large departures, dispersed over a range of spatial scales, are challenging in data assimilation and weather-dependent background error covariances will be

needed to obtain appropriate and balanced distributions of the innovations over the broad spectrum of background error scales. Such background error covariances may be provided by ensemble techniques, but also scatterometer OSVW provide information on NWP model error structures (Lin et al. 2016). Moreover, improved initialisation may be achieved by assimilating a constellation of wind scatterometer instruments (see also, e.g., Žagar et al. 2016).

### 3.3 *Nowcasting*

Scatterometer winds are widely used for nowcasting, e.g., to depict the evolution of typhoons, tropical cyclones or mesoscale complex systems (MCS), but also in case of marine and coastal forecasting for traffic, off-shore activities, wind energy, etc. Scatterometer data are furthermore used for typhoon warnings over extratropical seas (Von Ahn et al. 2006; Chang et al. 2009). Moreover, also the depiction of coastal features and moist convection warrants high spatio-temporal resolution.

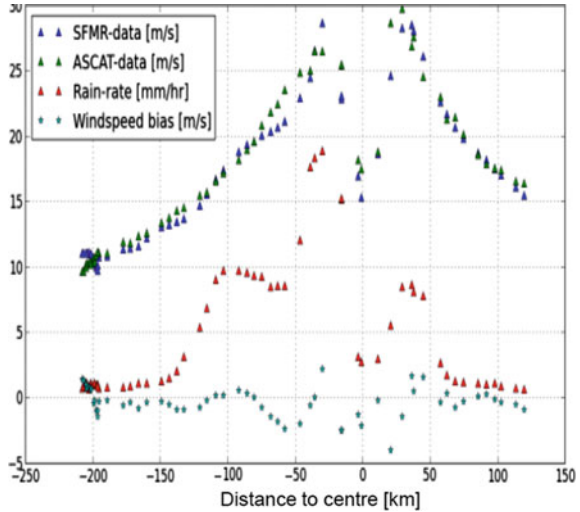
Recently, further progress has been made in the quality assessment of ASCAT winds near rain (Portabella et al. 2012) and in associating the inversion residual, called MLE and as depicted in Fig. 3, with local wind variability (Lin et al. 2015). It is very useful when scatterometer winds and wind variabilities should be part of advanced NRT integrated visualization in meteorological work stations, where mesoscale weather information from satellites, in situ observations and models can be compared. Furthermore, on-the-fly warning systems may be developed to effectively focus attention on areas where large discrepancies exist between observed and modelled weather phenomena.

Typhoons cause much havoc in the Asian waters, where its winds are devastating and occasionally cause water levels to surge to catastrophic heights. A particularly pressing requirement at most participating CEOS OSVW agencies is therefore to obtain extreme winds in hurricanes (>30 m/s) from scatterometers, since extreme weather classification, surge and wave forecasts for societal warning are a high priority in nowcasting (van Zadelhoff et al. 2014).

### 3.4 *Extreme Winds, Waves and Storm Surges*

However, measuring extreme winds is challenging as vicarious calibration is needed. The NOAA hurricane hunters go into hurricanes to drop sondes, and thus obtain wind profiles in the lowest few kilometers of hurricanes, and mount dedicated microwave instrumentation on aircraft, to obtain detailed wind patterns in hurricanes, such as the Stepped-Frequency Microwave Radiometer (SFMR). Ideally, local dropsonde winds may be statistically used to calibrate SFMR, which in turn is used to calibrate satellite scatterometers and radiometers in overflights. Given the scale of typhoons and the footprint of radiometers and scatterometers,

**Fig. 5** Illustration of modified (2012) SFMR wind speeds (blue), rain rate (red), collocated ASCAT speed (green) and SFMR-ASCAT speed difference (light blue). SFMR speeds have been ad hoc modified to match ASCAT over a large number of typhoons by subtraction of  $\ln(\text{RR})$  and  $\ln(V)$  and provides an estimate of current typical calibration uncertainty. The ASCAT depiction of typhoon structure appears faithful and not much affected by rain



satellite typhoon speeds are expected to be less extreme than in situ measured extremes, due to the implicit spatial aggregation of the satellite-based winds. The calibrated spatial wind patterns measured by SFMR may however be averaged to approximately match the satellite footprints and thus provide a calibration reference and an estimate of local wind variability (see Fig. 5). Using similar tracking and collocation procedures, van Zadelhoff et al. (2014) used SFMR to obtain a C-band cross-polarisation geophysical model function (GMF).

Although this approach is credible in principle and physically more consistent than any other global method to obtain maximum winds in typhoons, research is ongoing to understand the exact physical interpretation of dropsonde winds and SFMR in the inherently extremely variable conditions in typhoons and to obtain more hurricane flight data to relate to satellite scatterometer overpasses.

## 4 Wind Energy and Other Coastal Applications

Offshore wind energy is a sustainable technique in development in an attempt to reduce the burning of fossil fuel and temper anthropogenic climate change. It however results in a demand for observed off-shore wind information to

1. estimate long-term wind production,
2. aid in the design of the wind mills,
3. plan the occurrence of maintenance time windows and
4. continuously forecast the electrical input to the grid of available wind farms.

Scatterometer winds are helpful in all these aspects since they are being carefully intercalibrated (e.g., KNMI Wind Atlas). For points 2 and 3 wave or storm surge

information is relevant, which is usually based on wind vector input to wave or storm surge models.<sup>4</sup>

Not only wind energy, but also shipping, e.g., on the northern route from China to Europe, and other economic activities in coastal areas will increase as the world population grows, as well as coastal protection. Improved scatterometer wind and sea ice (Belmonte Rivas and Stoffelen 2011) processing in coastal areas will thus remain a high priority in the years to come. The developments in regional NWP, Nowcasting and Wind Energy above, all apply to the coastal area in particular.

## 4.1 *Climate Data Records*

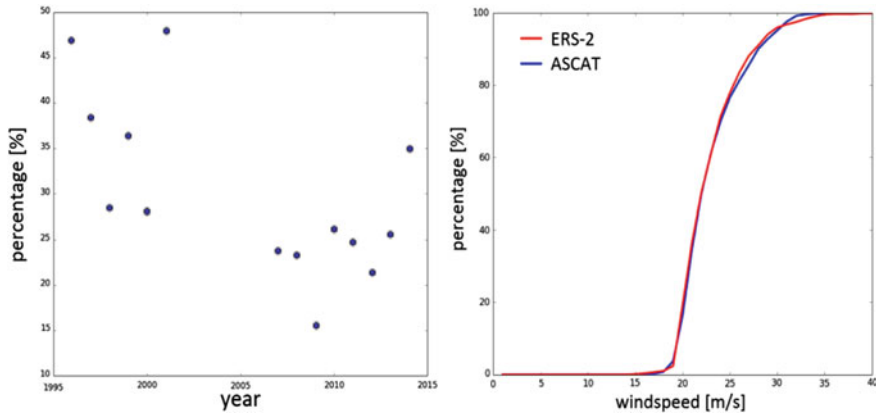
Wind and stress climatologies, based on a long heritage of scatterometer measurements, are considered essential climate variables (ECV) and used for the design of structures at sea, by policy-makers, in wind energy applications, climate change adaptation, etc. In particular, improvements in the coastal region brought by increased resolution will be beneficial for many climatological applications.

Alternatively, model reanalyses are conveniently used for wind climatologies at regular and high temporal resolution. However, the observational inputs to these reanalyses vary in time, which may affect the climatology artificially. An example is provided in Fig. 6 for the ECMWF reanalysis ERA. Here, a detection algorithm has been used to find typhoons in ERS-2 and ASCAT scatterometer winds and, subsequently, another detection algorithm uses a radius of 800 km to search for that typhoon in ERA. While the statistical characteristics of the typhoons found in ERS-2 and ASCAT are quite similar (e.g., right panel of Fig. 6), the ERA hit rate is quite different (left panel). A plausible reason for this difference may be that ERS-2 winds have been assimilated in ERA, while ASCAT winds were not assimilated. Although the skill is generally low, one may conclude that a change of observational input, clearly has changed the skill of ERA to represent typhoons over time. Climate data records of essential climate variables, such OSVW or wind stress, based on long-term stable instrument records are thus essential to build confidence in the fidelity and limitations of reanalyses based on general circulation models, and identify and possibly correct their time-dependent biases.

The construction of OSVW ECV CDRs consists in the reprocessing of scatterometer data, which profits from the strict automated monitoring developed in near-real time (NRT), since very similar procedures are implemented for reprocessing. In addition, ocean calibration methods and triple collocation are used for long-loop instrument and parameter performance monitoring (e.g., calibration stability) on a monthly and yearly basis. Triple collocation (TC) with moored buoys, scatterometers and GCMs is performed to establish the accuracy and intercalibration of the scatterometer winds and the GCMs at the available moored buoy

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<sup>4</sup>eSurge: [www.storm-surge.info/](http://www.storm-surge.info/).



**Fig. 6** Left: Tropical hit rate of typhoons in the ECWWF reanalysis (ERA) for cases where a typhoon has been detected in ERS or ASCAT scatterometer winds. Right: PDF of typhoon winds for ERS-2 from 1995 to 2000 and for ASCAT from 2007 to 2015. Although ERS and ASCAT typhoon detection behaves very similar, the ERA typhoon representation appears quite different in the 1990s and 2000s

positions. By physical inference, it is assumed that the spatial sample of buoys is sufficient to obtain a globally representative absolute calibration for scatterometers. This can obviously not be proven, as no globally representative in situ wind network is available (Stoffelen et al. 2015). However, given such plausible inference, it appears possible to reach the 0.1 m/s per decade stability in a representative global metric from scatterometers (Verhoef et al. 2015).

Recent publications indeed suggest that observation of OSVW variability in the tropics is quite relevant, e.g., Sherwood et al. (2014) or Sandu et al. (2011), suggesting that spread in climate model sensitivity and model bias can be related to subtle dynamical model aspects, such as moist convection. More work is needed on dynamical meteorological atmospheric and oceanographic interaction processes, relevant for the realism of climate models, and may be addressed by measurement capability in the satellite era. Scatterometer OSVW can play a relevant role here (Lin et al. 2015; King et al. 2017).

## 5 Conclusions

An overview of satellite Ocean Surface Vector Winds, physical phenomena, observation requirements, capabilities and applications is provided. OSVWs contribute to weather and climate analyses and forecasts, which in turn serve many applications in economy and society, related to coastal hazard warnings, off-shore marine applications, such as shipping, exploration, infrastructure, wind energy and tourism. Besides these applications of winds, sea waves and storm surges,



near-surface wind conditions drive the ocean circulation, which in turn plays a major role in the climate system and in marine ecosystems (e.g., fisheries).

OSVW play a fundamental role in the Asian Seas through air-sea interaction. This applies to the modest winds in the trades, the winds associated with the extensive areas of tropical convection, sea and land breezes and, of most direct human relevance, the winds associated with hurricane-force typhoons.

Accurate wind vector information is obtained from satellite microwave active measurements off the wind-roughened ocean surface, and wind speed information from passive microwave sensors. India, China, Russia and Japan, inter alia, have been, are, or will be contributing to a global virtual constellation of scatterometers that provide increasing temporal coverage of ocean surface vector wind information. This much facilitates the application of scatterometer winds for weather nowcasting, for mesoscale and global numerical weather prediction and for oceanography and climate studies.

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