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Innovations in metocean sensors

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Abstract— Real-time observations are critical to understand, predict and estimate the impact of extreme weather events such as extratropical hurricanes and storms. Remote sensing, moored wave buoys and advances in predictive models have greatly advanced understanding and predictive capability of extreme ocean weather. However, due to cost and complexity of traditional moored buoys, in-situ networks are typically sparse and often close to shore and not well suited to drive predictive models over meaningful geophysical scales. Here we will discuss ongoing efforts to extend the capability of the Sofar Spotter to measure marine boundary layer dynamics. With the advancement to more portable metocean buoys such as Spotter, free-drifting strategies can be deployed, including fast-moving vessels and airplanes. This opens up opportunities for rapid deployment to improve predictive capabilities of extreme weather events and provide continuous data for validation of theoretical models.

1. Introduction

Real-time observations of marine boundary layer dynamics are critical to understanding and predicting the evolution of ocean weather, in particular the development and impact of extreme weather events such as extratropical hurricanes and storms. Currently, real-time ocean weather data is mostly provided by moored buoy networks (deployed mostly in limited water depth on the continental shelf) and satellite, vessel or land-based remote sensing. Advances and expansion of buoy networks and remote sensing technology have led to improved weather forecasting through calibration of models and progress in data assimilation. As a result, wave forecasting models such as WaveWatch III (WWIII hereafter, [1]) are now routinely used to forecast waves up to ten days in advance with reasonable skill. More in-situ weather observations and expansion of sensor networks beyond the continental shelf would immediately enable considerable improvements in predictive skill. However, due to cost and complexity of traditional moored buoys, in-situ networks remain sparse and generally not available in open ocean regions.

For extreme weather events such as extratropical hurricanes, real-time and accurate in-situ data along the track of the storm greatly improves predictive capabilities. However, traditional ocean instruments are difficult to deploy in an agile manner, and rapid deployment of instruments from vessels is difficult and dangerous in the presence of rapidly moving and accelerating storm systems.

Recent advances in weather buoys have resulted in platforms that are more lightweight and compact, making them highly suitable for rapid and agile deployments,

either from fast-moving vessels or airplanes. Moreover, the combination of solar-powered and autonomous operations, real-time satellite connectivity, integrations with modern APIs, and cost efficiency, enable free-drifting array deployments that can cover larger areas, collect synoptic information, and drive effective assimilation strategies.

To improve our ability to collect data to constrain ocean weather models, expanding the capabilities of low-cost instrumentation is important. For instance, modern technology enables the design of compact and highly robust wave buoys. These types of devices are specifically designed to have superior surface-following properties. If we want to include wind measurements, then in a traditional approach we would add an elevated anemometer. However, this would reduce surface-tracking capabilities, make the instrument considerably larger, more vulnerable, and more cumbersome to deploy. Surface wind speeds can however also be derived directly from the surface roughness, which can be measured in great detail by a compact wave buoy. Since short waves in a random sea state are strongly forced by wind (see e.g. [2,3]), such a proxy measurement can be obtained from a compact surface-following buoy without the need of mast-mounted anemometer. The principle of using the equilibrium range in the wave spectrum as a proxy for wind speed and direction is not unlike satellite scatterometer estimates, which uses sea-surface roughness to estimate wind magnitude and direction. In fact, recent research based on collocated observations of waves and wind at (NDBC National Data Buoy Center) stations ([4]) demonstrates that the accuracy of these wave-derived estimates is similar to satellite remote sensing observations.

Here we will discuss ongoing efforts to extend the capability of the Sofar Spotter to measure marine boundary layer dynamics. Specifically, we discuss the development, implementation and validation of a wind inversion technique from the equilibrium range in the wave spectrum, which provides an accurate proxy estimate of wind speed and direction. Further we will discuss the development of air-deployment capabilities, and the addition of a sea surface temperature sensor. Finally, we hypothesize how large-scale array deployments with these types of sensors will impact our forecasting skill and provide unprecedented detail on long-distance wave propagation characteristics.

2. Estimating wind speed and direction from spectral wave observations

In general, energy densities in the tail of the wave spectrum evolve under the action of generation by wind, dissipation by white-capping, and redistribution of

energy through nonlinear wave interactions (see e.g. [5]),

$$D_t E = S_{non-linear} + S_{dissipation} + S_{generation},$$

with E the energy as a function of frequency, space and time. For exposed (open ocean) sites, the tail of the wave spectrum responds relatively fast to changing wave conditions, and develops an equilibrium between generation, dissipation, and nonlinear re-distribution of wave energy. In this wave equilibrium range observed spectra consistently scale proportionally to f^{-4} (with f frequency), with a proportionality factor that is linearly dependent on the friction velocity determined from the wind stress [6].

If the conditions are assumed to be locally homogeneous and stationary, (empirical) approximations for dissipation due to whitecapping, generation due to wind, and nonlinearity are substituted, and an explicit (first suggested by [2]) dependency between friction velocity and the wave spectrum is found

$$E(f) = \frac{4g\beta I u_*}{(2\pi)^3} f^{-4}$$

Here g is gravitational acceleration, u_* the friction velocity, I is an empirical constant that accounts for the directional spreading of the wave field, and β is a tuning coefficient (here referred to as the Phillips parameter). Consequently, if locally the wave spectrum is known, the friction velocity may be approximated through a least squares fit of a f^{-4} shape to the observed spectrum in the equilibrium range. Observations show that using literature values of $\beta = 0.01$ and $I = 2.5$, wind stress estimates from spectra compare favorably to direct estimates [3].

To relate stress estimates to wind speed at a reference height we assume that the atmospheric ocean boundary layer is stable, and the horizontal wind speed magnitude $U(z)$ as function of height above the sea-surface z follows a logarithmic profile

$$U(z) = \frac{u_*}{\kappa} \log\left(\frac{z}{z_0}\right),$$

Here $\kappa = 0.4$ the von Karman constant and z_0 the oceanic surface roughness length scale which may be related to friction velocity through the Charnock parametrization

$$z_0 = \alpha \frac{u_*^2}{g},$$

with $\alpha = 0.01$ the Charnock parameter.

To estimate the wind direction we observe that the mean wave direction is typically aligned with the mean wind direction. However, wave buoys do not directly observe the complete directional properties of the wave field. Instead only the lowest four Fourier moments of the directional distribution are directly observable. Following [8], the mean wave direction θ (and consequently mean wind direction) may be approximated as

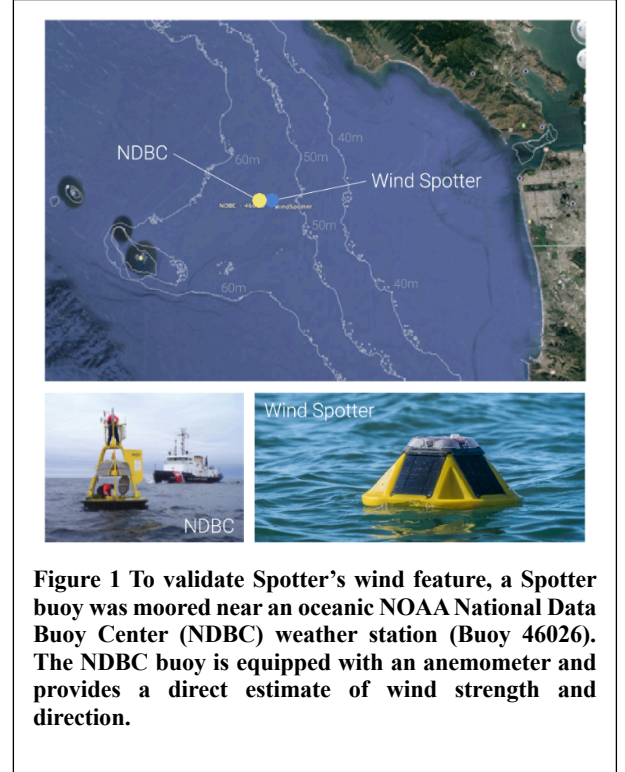


Figure 1 To validate Spotter's wind feature, a Spotter buoy was moored near an oceanic NOAA National Data Buoy Center (NDBC) weather station (Buoy 46026). The NDBC buoy is equipped with an anemometer and provides a direct estimate of wind strength and direction.

$$\theta = \frac{180}{\pi} \tan^{-1}\left(\frac{b_1}{a_1}\right)$$

where b_1 and a_1 are the first sine and cosine Fourier coefficients averaged over the equilibrium range.

If parametrizations for the Charnock and Phillips parameter are substituted, and with more advanced descriptions of the relation between wind stress and spectral observations, it was shown in [4] that wind estimates from spectra observed by NDBC buoys compare well to direct collocated observations. Here, we consider the even simpler model using literature constants that can easily be implemented in the firmware of a wave buoy.

3. Observations

To validate the wind inversion from the wave equilibrium range, and verify its accuracy, a Spotter wave buoy was moored approximately 25 km (15 miles) westward of San Francisco, near NDBC site 46026 (moored at less than a kilometer away, Fig. 1). This site is well exposed and sufficiently far from land so that finite growth effects due to fetch limitation were small for conditions encountered. Further, the nearby NDBC buoy has a full SCOOP layout that includes collocated observations of both wind speed and direction and directional wave spectra. This allows us to use wind observations as validation, and compare the difference between NDBC buoys and Spotter wave-derived wind estimates. The buoy was deployed for approximately 6 months (from November 2018 onwards), and collected hourly spectral wave information at approximately 0.01 Hz resolution (from 0.03 Hz to 1Hz). Data was sent back through Iridium satellite telemetry in

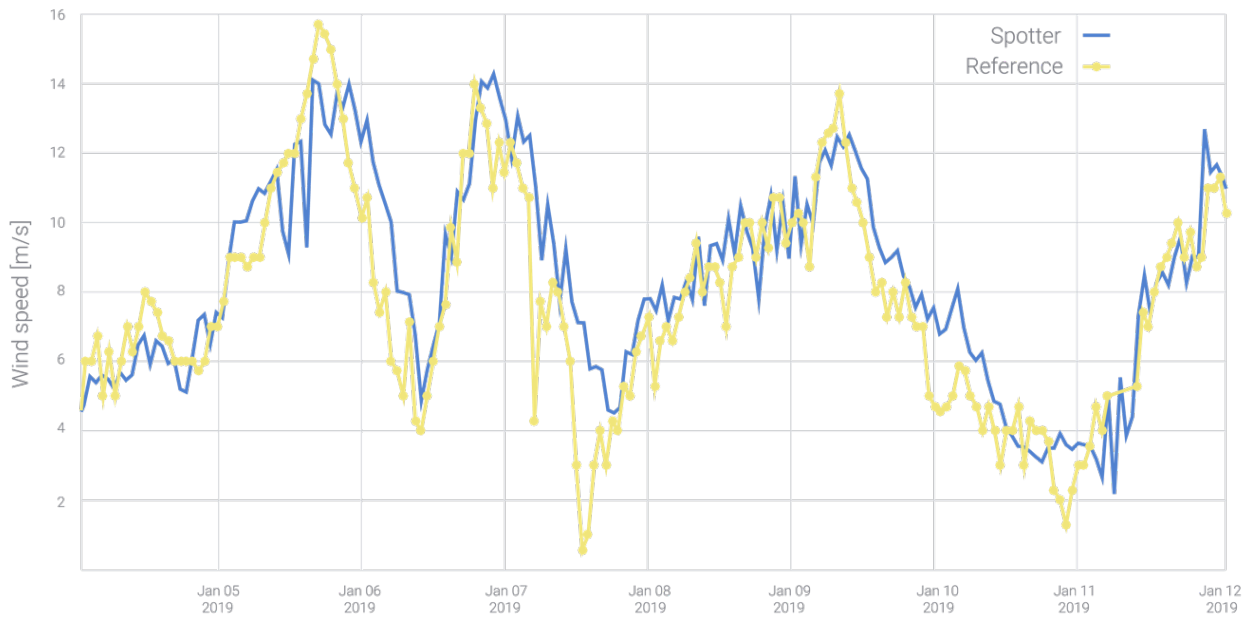


Figure 2 Wind speed estimated by Spotter compared to direct observations from a close-by (under 1 km) NOAA weather station (46026).

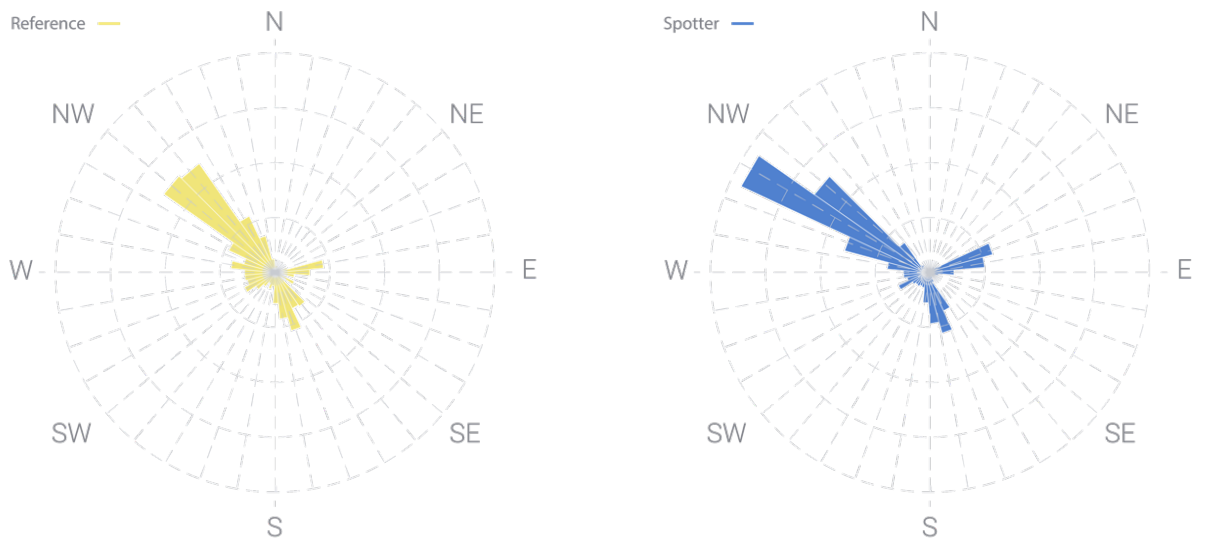


Figure 3 During testing, northwesterly winds dominated and wind was onshore for approximately 70% of the time. The distribution of wind directions derived from Spotter wave data (right panel) is very similar

real-time and stored at the Sofar backend for further processing. All wind speeds were extrapolated to 10m height (including those of the reference NDBC site) using a logarithmic velocity profile approximation.

4. Results

Maximum observed wind strength in the observational period at the reference NDBC site was about 16 m/s. Spotter-derived estimates of wind speed and direction

show excellent agreement to direct wind observations from the NDBC site (Fig. 2). Observational errors in wind speed are typically smaller than 1 to 2 m/s (RMS error over entire deployment 1.8 m/s). A slight lag in response to changing winds can usually be observed (e.g. downward trending winds are usually lagged by a few hours), likely due to persistence of energy in the wave field even though the winds have already decreased. For growing conditions lag seems to be fairly small.

During the deployment, winds were predominantly from the North, though winds were directed offshore for about 30 percent of the time. Directions derived from the equilibrium tail usually match up well with directly observed directions, and the roughness-derived distribution of wind directions matches direct observations well (Fig. 3). Errors can be large (order 40 degrees) for very low wind speed conditions (under 3 m/s winds) where equilibrium theory does not hold. However, once the wind picks up (>5 m/s) the RMS error is constrained to about 15 degrees. Note that there is no observable difference in errors between offshore and onshore directed winds, confirming that fetch limitations did not play a role under the present conditions.

Surface winds estimated from Spotter-derived wave have much smaller errors than those derived from wave spectra estimated by the NDBC buoy (not shown). This is due the fact that the small form factor of the Spotter buoy makes it very responsive to short waves, and is better able to resolve the short waves in the equilibrium range.

5. Ongoing development efforts

Future developments of the Spotter platform include expanding the sensor package and developing rapid deployment options for the platform. Specifically, integration of a Sea Surface Temperature (SST) sensor into the platform is completed, which will allow for real-time updates (through satellite telemetry) of sea-surface temperature. Future developments may include expanding the platform to include observations of atmospheric pressure, salinity, and other parameters of interest in the ocean boundary layer.

All these developments are guided (and to a certain extent constrained) by the philosophy that the Spotter platform should provide an affordable, easy-to-use and globally connected sensor package. This not only allows easy deployment from small vessels (and by untrained personnel), it also allows for the development of rapid deployment strategies. For instance, to allow for deployment from the air we developed Spotter Airdrop: a compact parachute accessory with release harness that is optimized for aerial deployments over water. This allows Spotter to be deployed from any altitude and speed from fixed-wing airplanes and helicopters. The parachute is designed to be robust and provide enough drag for a safe landing in the water, but small enough to limit drift and enable precise delivery. Upon touch-down in water the quick release harness detaches from Spotter,



Figure 4 (top panel) Buoys being loaded into the airplane prior to deployment. (bottom panel) Spotter descending on parachute toward ocean surface near Monterey (CA, USA).

releasing the ballast chain and dropping free the parachute harness. This way Spotter is immediately operational and without the risk of the parachute covering the solar panels or affecting data collection. The parachute and quick release-harness are completely biodegradable, ensuring that no unnecessary litter is left behind in the ocean.

6. Discussion and Conclusion

Expanding observational capabilities of affordable, mass-producible and easy to deploy wave buoys such as Spotter to include wind and SST observations, will help increase our capabilities of monitoring the world's oceans. Specifically, it will allow for higher density moored observational networks in developed regions and allow e.g. small island nations to deploy assets where previously none were available due to cost and operational constraints. Further, it will enable deployment of large-scale, high-density, free-drifting arrays of metocean sensors. Not only because individual units are relatively affordable, but - more importantly - ease of deployment and small deck footprint implies that no specialized equipment is needed to deploy instruments (the buoy can easily be deployed by a single person). As a consequence, vessels of opportunity can be used for deployment.

A free-drifting network may considerably improve our capabilities to predict ocean weather. For wave observations in particular, which at present are predominantly constrained along the coast, this would provide unprecedented new data that can help significantly improve forecasts through data assimilation. Moreover, it will help improve our understanding of wave physics through direct observation of long distance propagation – e.g. to determine the influence of sub-mesoscale currents on swell propagation [9]. Further, combined with rapid deployment options such as airdrop, sensors can be deployed in the path of extreme weather events to help better constrain model predictions.

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