Wind and Wave Extremes over the World Oceans From Very Large Forecast Ensembles

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ABSTRACT

Global return value estimates of significant wave height and 10-m neutral wind speed are estimated from very large aggregations of archived ECMWF ensemble forecasts at +240-h lead time from the period 2003-2012. The upper percentiles are found to match ENVISAT wind speed better than ERA-Interim (ERA-I), which tends to be biased low. The return estimates are significantly higher for both wind speed and wave height in the extratropics and the subtropics than what is found from ERA-I, but lower than what is reported by Caires and Sterl (2005) and Vinoth and Young (2011). The highest discrepancies between ERA-I and ENS240 are found in the hurricane-prone areas, suggesting that the ensemble comes closer than ERA-I in capturing the intensity of tropical cyclones. The width of the confidence intervals are typically reduced by 70% due to the size of the data sets. Finally, non-parametric estimates of return values were computed from the tail of the distribution. These direct return estimates compare very well with Generalized Pareto estimates.

1. Introduction

Return value estimates of significant wave height and 10-m wind speed over the oceans are fundamental to risk assessments. Long observational records are scarce, making global return value estimates impossible, with the exception of altimeters Vinoth and Young 2011, which to date represent rather short and heterogeneous time series. Reanalyses and hindcasts (Kalnay et al. 1996; Uppala et al. 2005; Weisse and Günther 2007; Dee et al. 2011; Reistad et al. 2011; Wang et al. 2012) serve as proxies for observations where there are none. But even long reanalyses will normally be substantially shorter than the return period sought, leaving wide error bars on the return values computed from them (Wang and Swail 2001, 2002; Caires and Sterl 2005; Sterl and Caires 2005; Breivik et al. 2009).

The Integrated Forecast System (IFS) of the European Centre for Medium-Range Weather Forecasts (ECMWF) has produced daily ensemble forecasts (ENS) since 1992 (Molteni et al. 1996; Buizza et al. 2007; Hagedorn et al. 2008) and has been coupled to the WAM wave model since 1998 (Janssen 2004, 2008). Even though the ECMWF forecast skill has steadily been improving over the years (Richardson 2010), +240-h lead time ensemble forecasts of wind and waves still tend to be weakly correlated, and their upper percentiles are virtually uncorrelated (Breivik et al. 2013). Such weak correlations are in fact a necessity when utilizing ensemble forecasts for extreme value estimation since the data must be independent and identically distributed. This may appear as something of a paradox since it means the forecasts can only be used for estimating return values if the skill is low.

Aggregating large amounts of virtually uncorrelated ensemble forecasts to estimate 100-year return values of wave height was first explored by Breivik et al. (2013). They found that the estimates matched observed upper percentiles well in the Norwegian Sea. The results were also found to agree fairly well with estimates based on the high-resolution hindcast NORA10 (Reistad et al. 2011; Aarnes et al. 2012;

Semedo et al. 2013). In this study we extend the analysis to 10-m wind speed and compare global 100-yr return values with return values computed from the ERA-I reanalysis. We also evaluate the upper percentiles against buoy measurements and ENVISAT altimeter wind speed observations.

2. Methods

ENS forecasts at +240 h lead time were interpolated onto a regular $1 \times 1°$ grid. All forecasts (two per day, 00 and 12 UTC) between March 2003 and March 2012 were used. Model values were collocated with buoy observation locations using a bilinear interpolation. ERA-I fields (1979-2012) were interpolated onto the same grid as ENS. The current spectral truncation of ENS is T639 for the atmospheric model, corresponding to approximately 32 km, with the wave model run at approximately 55 km. Previous model cycles had coarser resolution (see Fig 1 by Breivik et al. 2013).

The two daily ensembles of +240-h forecasts from 50 perturbed ensemble members plus the unperturbed control member aggregated over 9 years amount to

$$51\,\text{members} \times\ 2\,\text{daily forecasts} \times 6\text{h}\ \times\ 9\ = 229.5\,\text{yr} \quad (1)$$

under the assumption that each forecast is representative of a six-hour interval (Breivik et al. 2013).

The 10-m neutral wind speed was extracted for both ENS and ERA-I. This is the field used to force the wave model and is thus consistent with the significant wave height fields investigated. Grid points with less than 80% ice-free forecasts were excluded from the analysis when computing the return values for significant wave height. No such filtering was required for the wind speed.

The wave height from 24 buoys (see Fig 1), averaged over a period of ±2 hours, were collocated with model data for verification (Bidlot et al. 2002; Breivik et al. 2013). Only wind and wave measuring buoys in deep water (> 70 m) were selected since coarse resolution forecasts are ill-suited for simulating near-shore conditions. Furthermore, ENVISAT RA2 altimeter observations of wind speed and wave height were averaged into along-track "super-observations" of comparable resolution to the WAM grid (Abdalla and Hersbach 2004). This procedure makes data and model values more comparable, which is important when assessing the upper percentiles of the model climatology for wind and waves.

The return estimates from ENS were found using the Generalized Pareto (GP) distribution for data exceeding a threshold u such that $y = X_i - u$, $y > 0$. The GP distribution reads as (Coles 2001)

$$H(y) = 1 - \left(1 + \frac{\xi y}{\tilde{\sigma}}^{-1/\xi}\right). \quad (2)$$

Here ξ is the shape parameter and $\tilde{\sigma}$ is a scale parameter. In the limit as $\xi \to 0$ Eq (2) tends to the exponential distribution. The threshold was set to the 1000 highest forecasts, corresponding to the 99.7% percentile. Since ensemble forecasts are assumed uncorrelated, all data points exceeding the threshold were used. For ERA-I, the threshold was also set to 99.7% and a standard peaks-over-threshold (POT) technique where data must be separated by 48 h was used to assure that points are independent and identically distributed (Mathiesen et al. 1994; Lopatoukhin et al. 2000; Coles 2001; Aarnes et al. 2012; Breivik et al. 2013). Confidence intervals were estimated using the *Delta method* (Coles 2001, p 33).

Extreme value distributions are parametric estimates of the underlying distribution of the theoretical maxima based on modelled or observed values, usually in the form of one or more continuous time series with a fixed temporal resolution. However, under the assumptions that a forecast represents a temporal period we may convert our collections of nearly independent ensemble forecasts into an equivalent time series which is significantly longer than 100 years (229 years). In other words, we can make non-parametric direct return estimates (DRE) from the ensemble of the 100-yr return value, H_{100}^{DRE}, without invoking an extreme value distribution. However, some care has to be taken when interpreting the upper percentiles of even quite large data sets since the nature of extremes is such that the true return value for a given extreme value distribution will only have a certain probability of appearing in any given period. The probability of exceeding the 100-year return value in any given 100-year period is about 63% for the Gumbel distribution. Complementary, there is still a certain probability (∼10%) that the 100-year return value does not appear in our data set. The DRE method interpolates the tail of the cumulative distribution, For a data set of ∼229 years a linear interpolation between $X_{(2)}$ and $X_{(3)}$ (the second and third highest values in an ordered series) yields the following weighting,

$$r_{100}^{\text{DRE}} = 0.67X_{(2)} + 0.33X_{(3)}, \quad (3)$$

where r_{100} is the 100-yr return value.

3. Results and Discussion

The tail of the forecast distribution should closely resemble the observed distribution. Fig 2 shows good agreement at the 99.7 percentile level for significant wave height and wind speed throughout the northern hemisphere oceans (buoy locations shown in Fig 1). Fig 3 compares the $P_{99.1}$ of ENVISAT altimeter wind speed. As can be seen ENS240 has less bias than ERA-I at the tail of the distribution.

The 100-yr return estimate of 10-m wind speed, U_{100}, with 95% confidence intervals, are shown in Fig 4. The most salient feature is the striking difference between ERA-I and ENS240 in the subtropics (> 10 m s^{-1} difference, see panels b in Fig 4 and Fig 5. This is clearly related to tropical cyclone activity (see e.g. Oouchi et al. 2006 for an overview of geographical distribution of tropical cyclones) Although ENS is still far from capturing the strength of tropical cyclones, it represents a substantial improvement over ERA-I. ENS240 also yields significantly higher return values (> 2 m s^{-1} difference) in the extratropics (Panel b of Fig 4).

The same general features are found for the 100-yr return estimate of the significant wave height, H_{100} (Fig 5). In the extratropics we find differences in excess of 2 m, while in regions of the tropics and subtropics with high tropical cyclone activity the differences exceed 6 m (east of Madagascar and in the Arabian Sea in particular).

The ensemble forecasts represent the equivalent of about 229 years, and under this assumption the confidence intervals are reduced dramatically compared with the 30 years of ERA-I data. Clearly, as pointed out by Breivik et al. (2013), the model bias persists, but the uncertainty under the assumptions are much lower for the ensemble data set than for ERA-I. This is clearly seen by comparing Panels c-d in Fig 4 and Fig 5.

Thus it may seem that throughout the extratropics ERA-I underestimates the 100-yr return values for wind speed and wave height by about 10%, while in the regions with tropical cyclones the underestimation reaches 25%. Since the return values are computed from coarse resolution model simulations, the ENS240 estimates for the subtropics will be biased low and should be considered low-end brackets of the real return estimates.

Our H_{100} estimates are broadly geographically consistent with previous estimates of the return values of wind speed and wave height by Caires and Sterl (2005); Sterl and Caires (2005), based on the ERA-40 (Uppala et al. 2005) reanalysis. However, Caires and Sterl (2005) report as much as 7 m higher wave heights in the storm tracks in the North Atlantic and the North Pacific. Vinoth and Young (2011) aggregated 30 years of satellite altimeter wind and wave observations. Of the various extreme value distributions fitted to their data they concluded that the initial distribution method (IDM) gave the most reliable fit to the upper percentiles of buoy observations. Their estimates are generally much higher in the extratropics, and typically 2-4 m higher than ENS240 in the North Atlantic and the North Pacific. No confidence intervals were provided by Caires and Sterl (2005) although estimates for different decades of ERA-40 were computed. Vinoth and Young (2011) likewise offer no estimates of the confidence intervals, but judging by the large spread between the different methods employed it is likely to be high.

To investigate the impact that the exponential fit has on the return estimates we have computed the non-parametric direct return estimates outlined in Sec 2. As seen in Fig 6 the results are very similar to the return values computed using the exponential distribution in Fig 4 and Fig 5.

4. Conclusion

Return value estimation based on very large aggregates of ensemble forecasts at advanced lead times was first reported by Breivik et al. (2013) for wave height in the Norwegian Sea and the North Sea. We have extended the analysis here to produce global maps of return values for wind speed and wave height. We find that the ensemble yields estimates of wave height and wind speed that are signifcantly higher than ERA-I, but much lower than the estimates reported by Caires and Sterl (2005) and Vinoth and Young (2011). The upper percentiles show good agreement with buoys and the ENVISAT altimeter. The confidence intervals for ENS240 are much narrower than for ERA-I due to the much larger data sets (see Figs 4 and 5). We note that there is substantially more tropical cyclone activity in the ensemble at long lead times than in ERA-I, which seems to correspond better with ENVISAT altimeter observations of wind speed and wave height. However, it is clear that the model is still too coarse to realistically model wind speed maxima around tropical cyclones and the estimates for the subtropics are likely to be biased low (but less so than ERA-I). The return values found in the extratropics seem reasonable and represent a valuable addition to previous estimates, especially given the much narrower confidence intervals.

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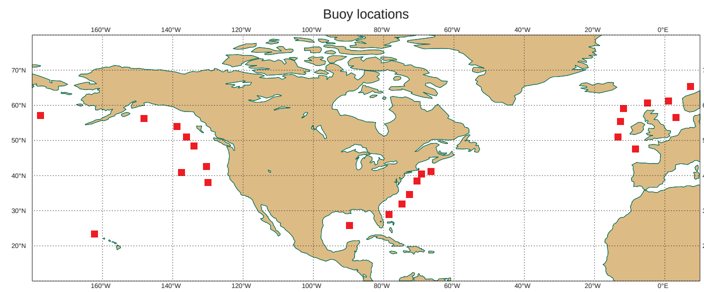


FIG. 1. 24 wind and wave-measuring buoys were used to assess the upper-percentile climatology of the ENS forecasts.

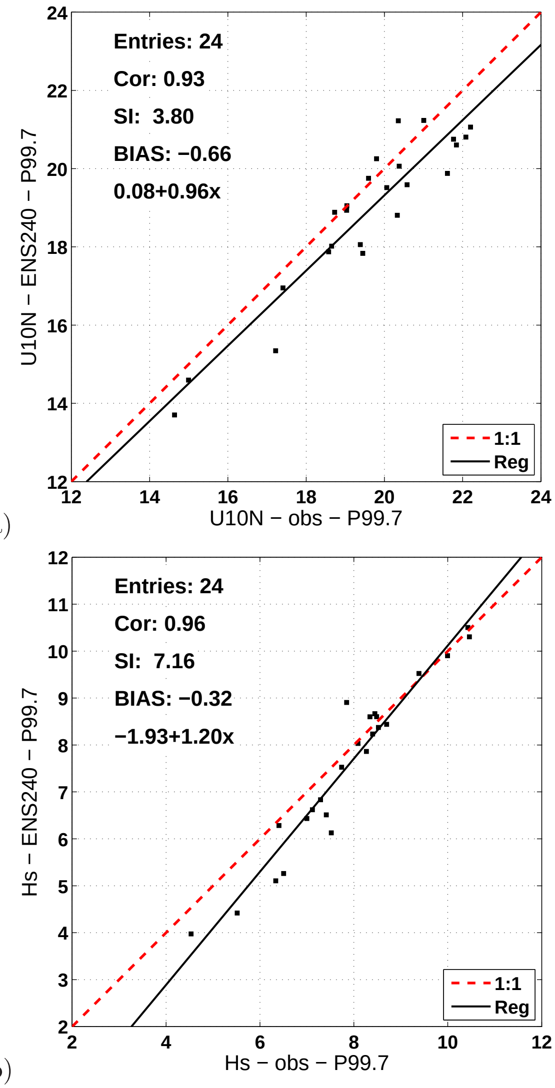
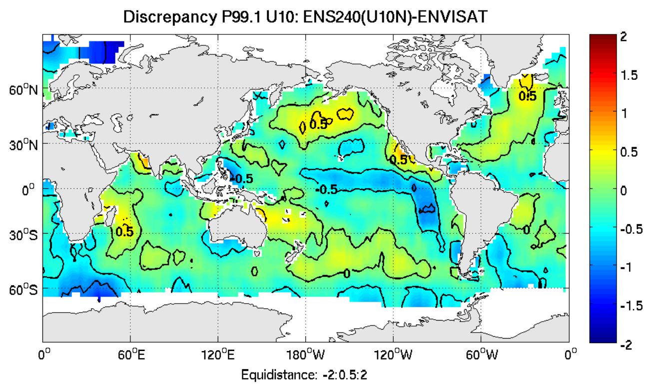
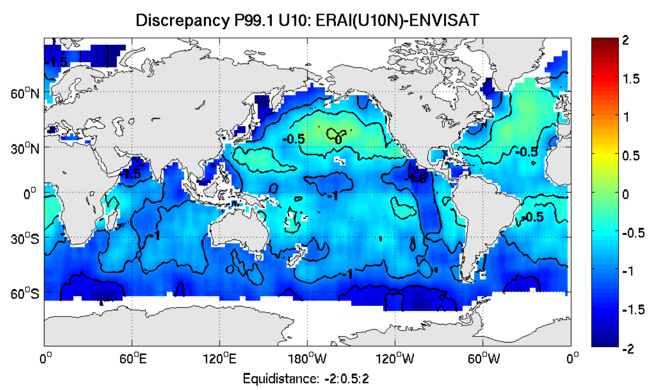


FIG. 2. Panel a: Observed v modelled 99.7 percentiles ($P_{99.7}$) of 10-m neutral wind speed [m s^{-1}]. Panel b: Significant wave height [m].

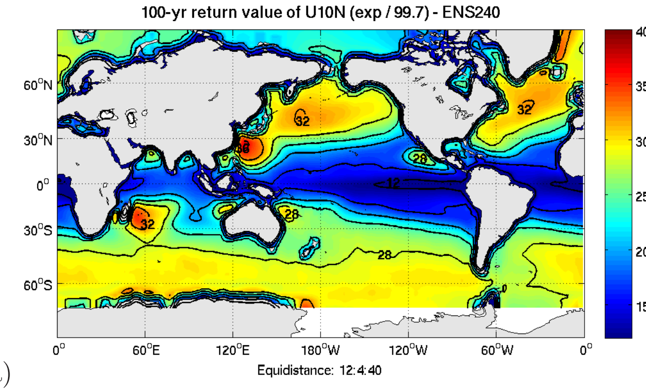


(a)



(b)

Fig. 3. Panel a: The difference between the ENVISAT altimeter 99.1 percentile ($P_{99.1}$) 10-m wind speed (2002-2012) and ENS240 neutral 10-m wind speed [m s^{-1}] (positive when ENS240 is larger than ENVISAT). Panel b: Difference between ERA-I and ENVISAT wind speed. The differences between ERA-I and ENVISAT at $P_{99.1}$ are generally larger (ERA-I biased low) than for ENS240.



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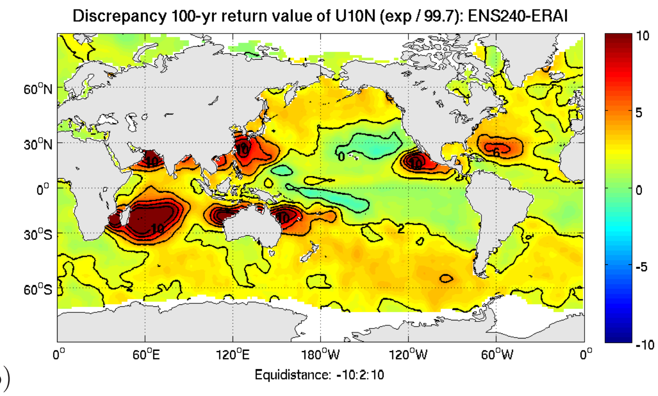

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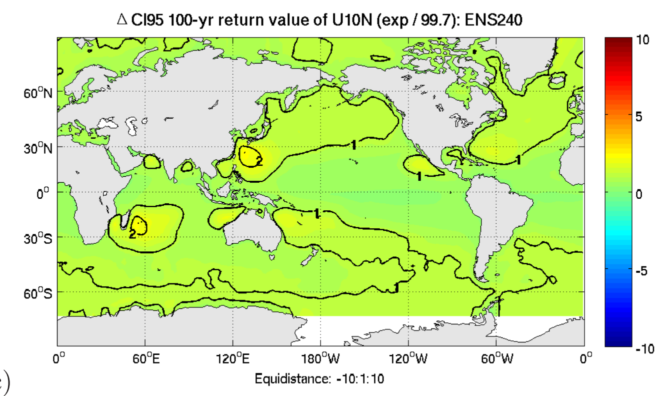
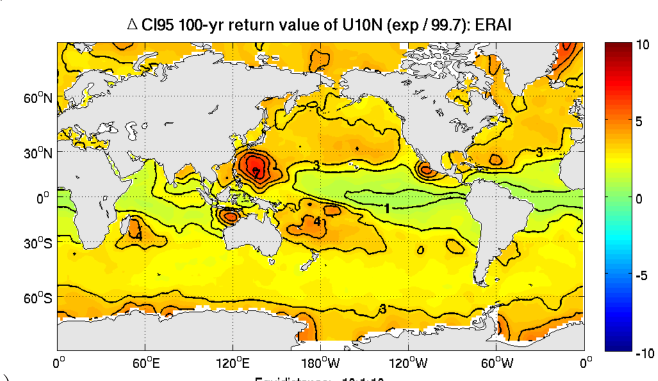


(c)



(d)

Fig. 4. 10-m wind speed 100-yr return values, U_{100} [m s^{-1}]. Panel a: ENS estimate. Panel b: Difference between ENS and ERA-I. Panels c-d: width of 95% confidence intervals for ENS240 and ERA-I, respectively.

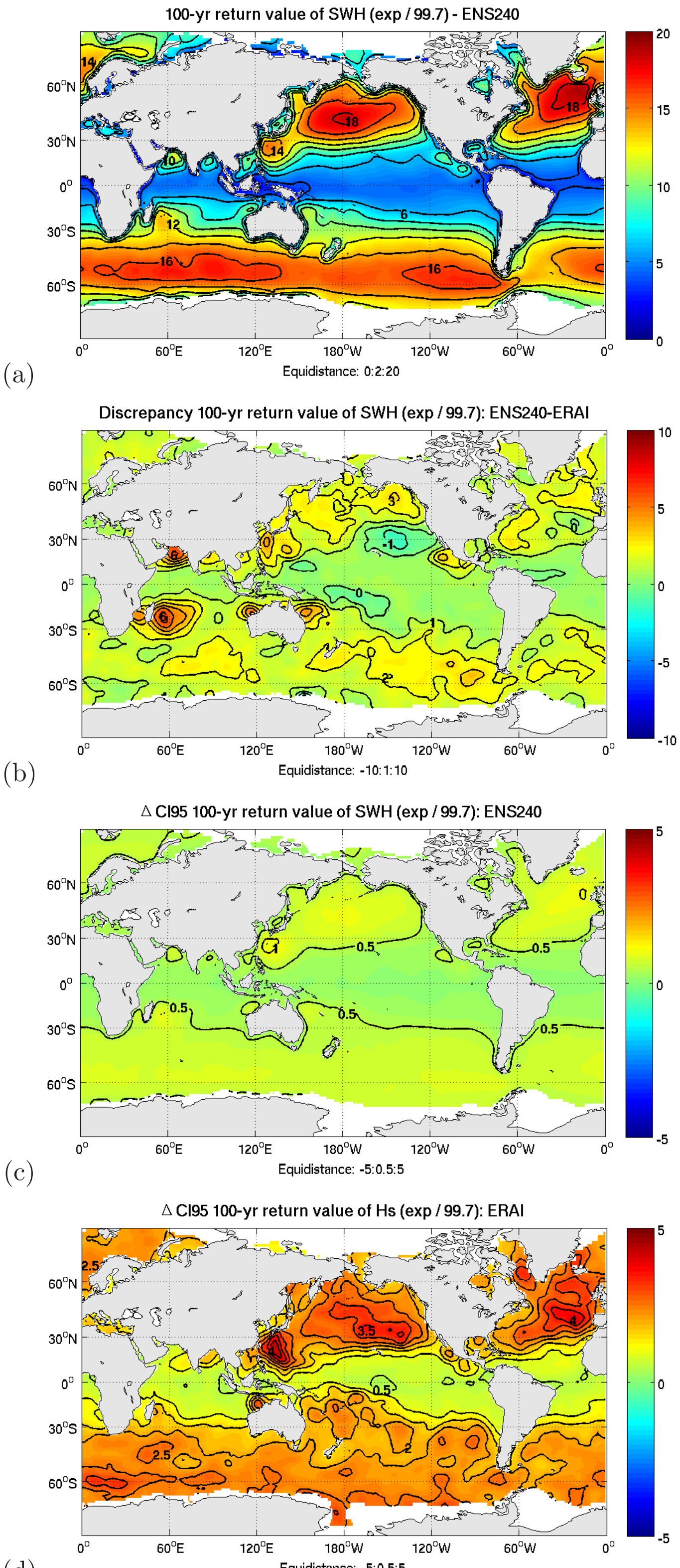


FIG. 5. 100-yr return values of significant wave height, H_{100}^{ENS} [m]. Panel a: ENS estimate. Panel b: Difference between ENS and ERA-I. Panels c-d: Width of the 95% confidence intervals for ENS240 and ERA-I, respectively.

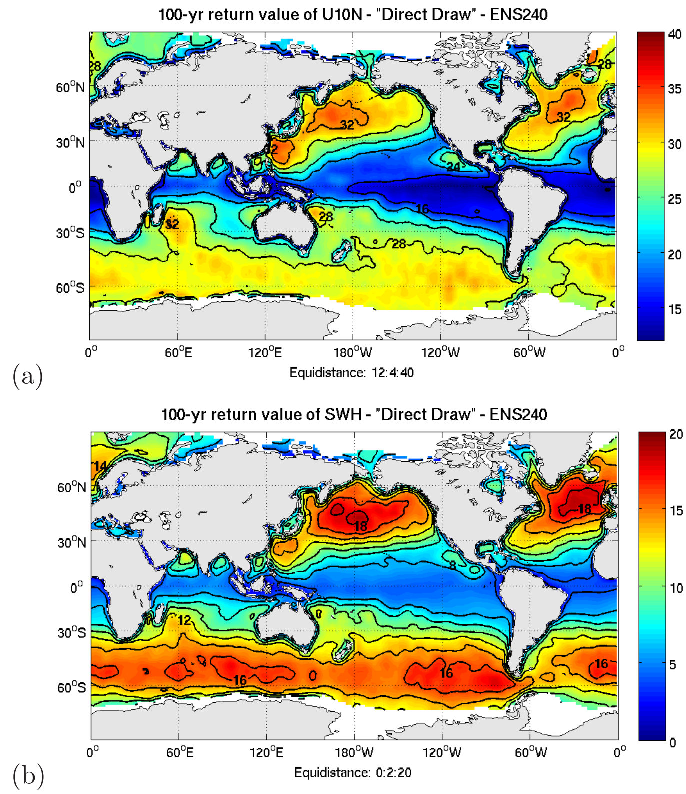


FIG. 6. Direct return value estimates (DRE). Panel a: Direct return estimates of the 100-yr wind speed, U_{100}^{DRE} [m s^{-1}]. Panel b: Similar for significant wave height, H_{100}^{DRE} [m]. The return value estimates are very similar to those estimated using the exponential distribution.

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