Mean square slope in SWAN and WAVEWATCH III®; buoy response functions; and limitations of ST1 physics in SWAN

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June 27 2017

Acknowledgements
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Support
This work is supported by the Office of Naval Research via the NRL Core Program. PI: Nancy Baker, NRL-Monterey

Topics covered:

1) We evaluate the ability of the SWAN wave model to predict high frequency wave energy. Thus the focus is on the equilibrium range of the spectral tail, and a parameter which is sensitive to the spectral tail level, m_4, which is proportional to mean square slope (mss).
2) We discuss the suitability of NDBC buoys for evaluation of m_4 and propose a method for calibrating (or checking) the buoy response function.
3) Non-physical impact of swell on windsea growth with ST1/SWAN physics

SWAN hindcast description

- hindcast for the northeast Pacific Ocean, Oct. 25 2015 to Dec. 25 2015.
- SWAN resolution: ~14 km (0.2º ✕ 0.15º), nested in WW3
- WAVEWATCH III® (WW3) resolution: 0.5º
- 3 models evaluated:
  - ➔SWAN with ST1 physics (default)
  - ➔SWAN with ST6 physics
  - ➔WW3 with ST4 physics
- tuning: only simple tuning to remove lowest-order effect of bias in wind forcing as follows:
  - ➔ST1 & ST6: simple factor on winds to eliminate mean bias in overall mean wind stress estimates (performed prior to running SWAN, so this is "blindfold" tuning)
  - ➔ST4: β_{max} parameter to eliminate bias in overall mean waveheight (performed using 2 to 4 trial runs with WaveWatch3)

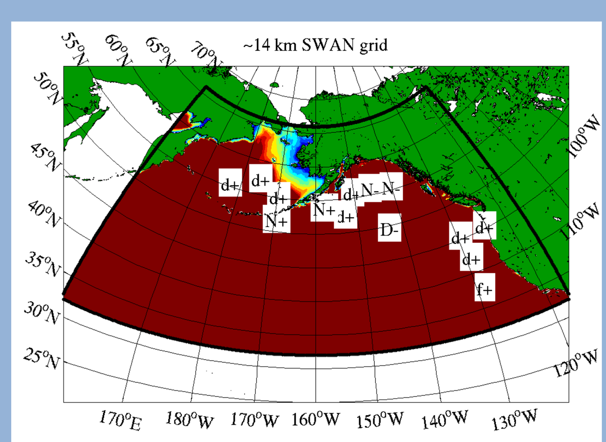
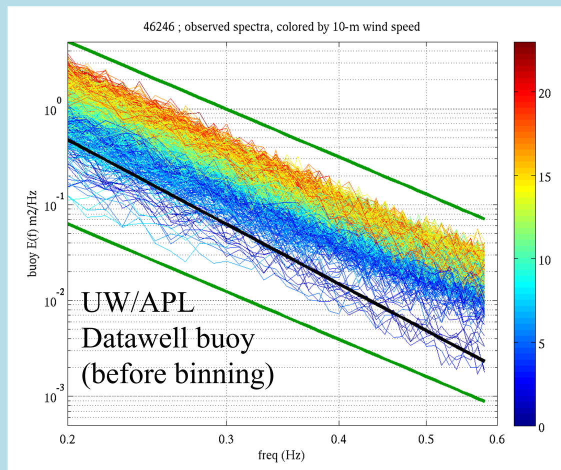
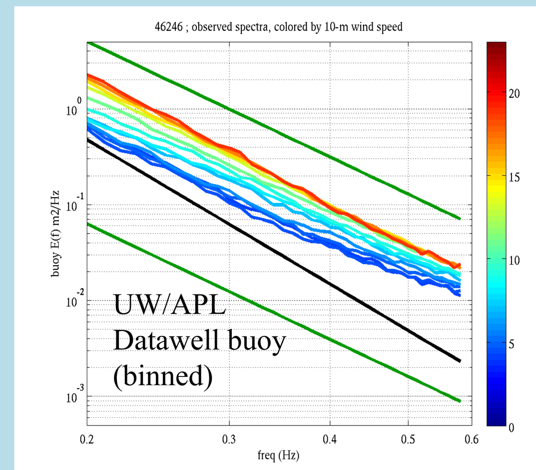
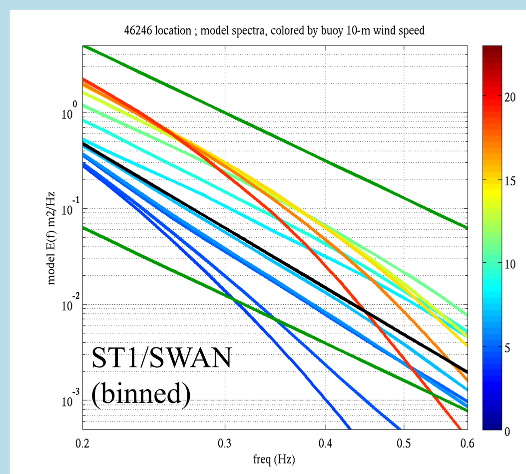


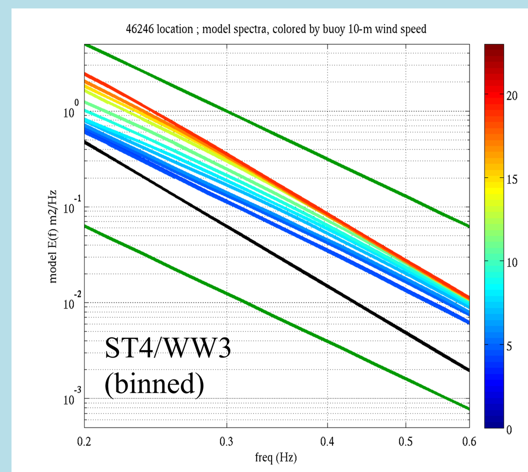
Figure: Thick black line delineates the SWAN grid. Locations of buoys used here are indicated with white rectangles. All are in deep water and all are more than 65 km offshore. "d" = 3-m NDBC discus buoy ; "N" = NDBC Nomad buoy ; "f"=NDBC foam buoy ; "D" = APL/UW Datawell buoy. "+/-" indicates the sign of the bias in m_4 by the ST6 model, if the full range of buoy frequencies is used (e.g. up to 0.485 Hz).

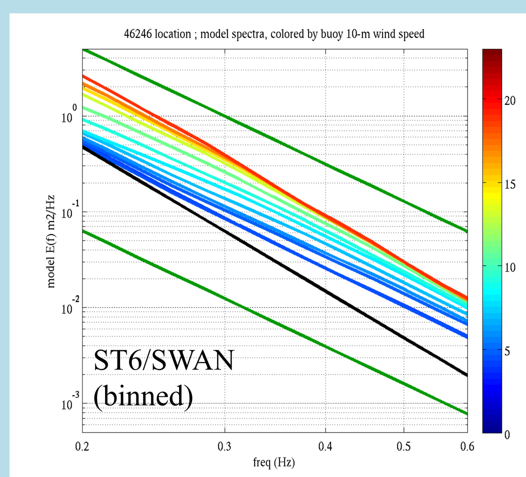
Results: spectral tail











Green lines: f^{-4} slope
Black lines: f^{-5} slope

Conclusions:

- ST4/WW3 and ST6/SWAN capture observed behavior (dependence of tail level on wind speed), though there is some room for minor improvement
- ST1/SWAN has no skill, even in a qualitative sense

NDBC buoys for mean square slope

Here, we repeat the earlier plots, but use one of the NDBC buoys instead: 1) m_4 evaluation of ST6 and 2) spectral tail from buoy. In case of (1), we notice that the model bias is of opposite sign (positive) from the prior comparison using the Datawell buoy (negative)! In case of (2), slope is rather suspect in 0.3 to 0.485 Hz range.

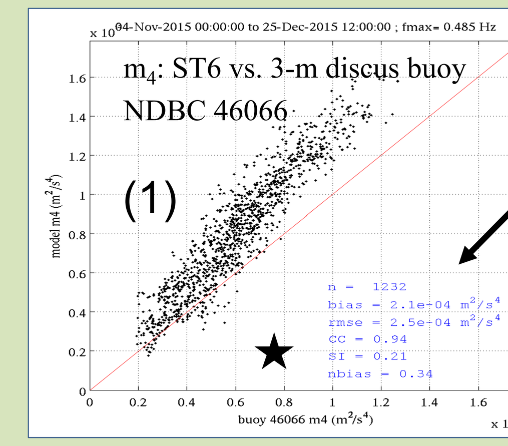
Now, refer to our plot of the buoy locations in the SWAN grid (left side of poster). Note that 8 out of 8 (100%) of the 3-m discus buoys indicate *positive bias* for m_4 of ST6, while the high-quality Datawell buoy shows *negative bias* for m_4 of ST6. Assuming that the Datawell buoy, being a specialized wave buoy, is the *ground truth*, we believe that this is caused by non-optimal response function correction at higher frequencies with the 3-m discus buoys*. Correction used now for 46066 *reduces* high frequency energy (R. Bouchard, NDBC, personal communication), which is counter-intuitive**.

*NDBC buoys have a "Swiss Army Knife" design with meteorological data being the major priority.
**This "correction" (energy reduction) implies that the designer believed that the hull is *over-responsive* to short waves, e.g. due to resonant excitation. We believe this "correction" is incorrect.

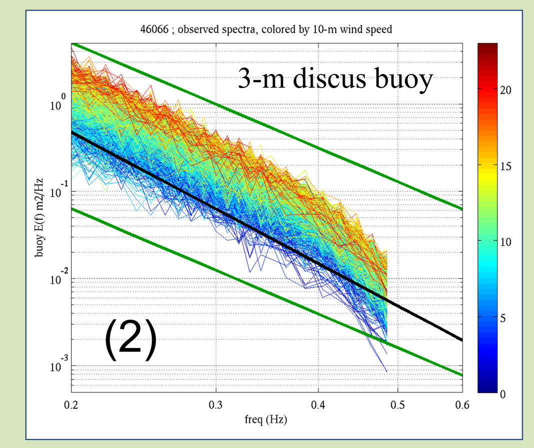
Supporting evidence:

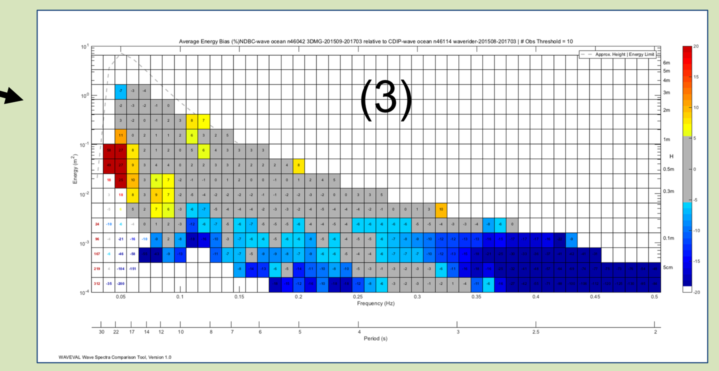
Figure (3) was provided by Bob Jensen (U.S. Army Corps of Engineers). It indicates that the 3-m discus buoy (near Monterey, CA) has negative bias (dark blue color) in higher frequencies (right side of plot).

Conclusion: We should not use data from beyond 0.3 Hz from the 3-m discus buoys for evaluation of models or satellites unless this issue is resolved. Otherwise, we will draw *wrong conclusions* regarding model mss bias (e.g. double bias or wrong sign). In context of this hindcast, we conservatively truncate all (not just 3-m) NDBC buoy data at 0.3 Hz.



Note that bias is positive. Compare other figure marked with ★.





Checking buoy response functions

The above raises an interesting question: can we use the quasi-universal dependence of spectral tail on wind speed (averaged over months) to check or calibrate the buoy response function correction (a.k.a. Response Amplitude Operator, or RAO)?

We believe so.

- accounts for differences in climatological winds from buoy to buoy, and
- is much less expensive than placing two buoys next to each other.

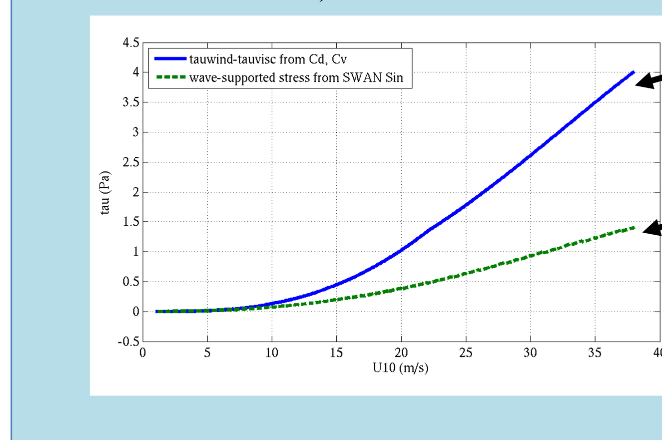
Discussion: problems with ST1/SWAN

It has been shown that

- ST1/SWAN physics provided good skill for waveheight (total energy) (e.g. Ris et al., JGR 1999).
- ST1/SWAN physics, with 2003 update (Rogers et al., JPO 2003)
  - provides good skill for wave period parameters
  - does not have significant non-physical impact of windsea on swell dissipation

The above implies that ST1/SWAN, with the 2003 update is appropriate for operational use. We disagree, for the following reasons:

- ST1/SWAN physics have negligible skill for high frequencies (e.g. 0.25 to 0.50 Hz in Pacific Ocean) and so negligible skill for mean square slope (this poster).
- ST1/SWAN physics use a wind input source function that integrates to unrealistic stress values (see below). This is a crucial shortcoming when coupling (via stresses, or momentum flux) to other models.

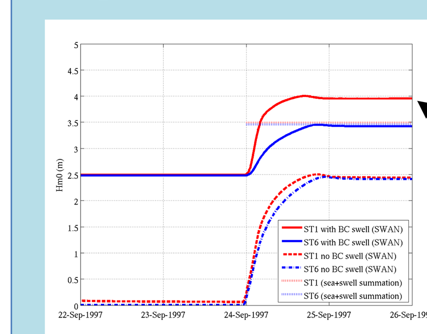


Blue: realistic wind stress (empirical relation)

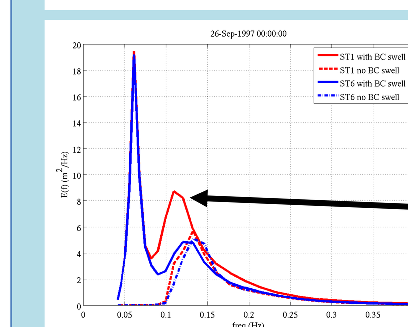
Green: wind stress from ST1/SWAN

Not shown: ST6/SWAN stresses match empirical relation, by design.

- ST1/SWAN physics still exhibit a non-physical impact of swell on windsea growth, as demonstrated by T.U. Delft publications circa 1999-2001. We demonstrate with new plots here.



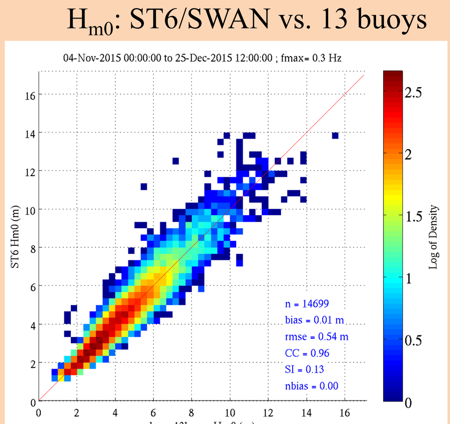
Time series of waveheight. Combined sea+swell: waveheight of 3.5 m is expected. ST6/SWAN (blue) matches this. But with ST1/SWAN (red), the swell causes windsea to grow faster, so waveheight gets up to 4 m. There is no physical reason for this!



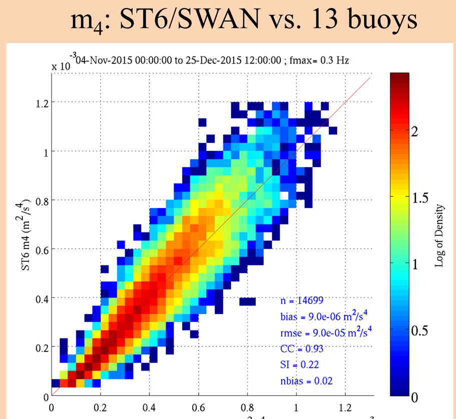
Frequency spectra at end of simulation. ST6/SWAN (blue): windsea peak has similar magnitude with or without swell. But with ST1/SWAN (red), the swell causes windsea peak to gain energy. This is wrong.

Results: bulk parameters

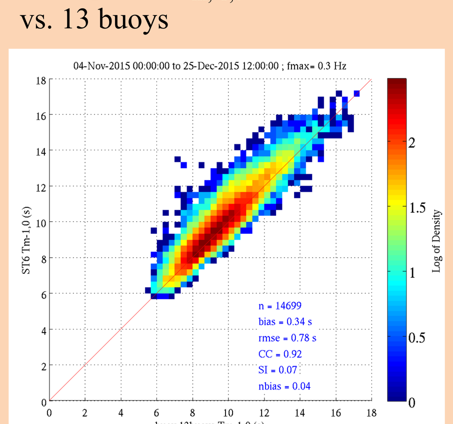
H_{m0}: ST6/SWAN vs. 13 buoys



m_4: ST6/SWAN vs. 13 buoys

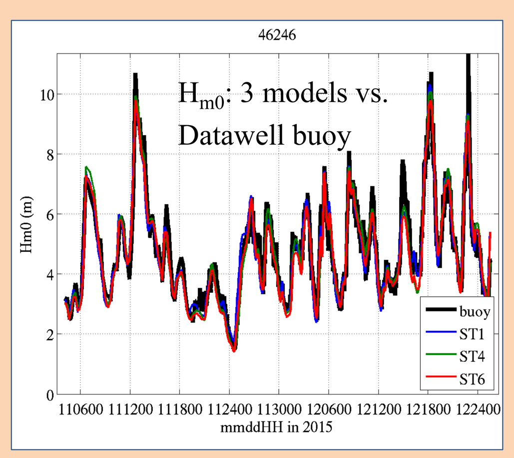


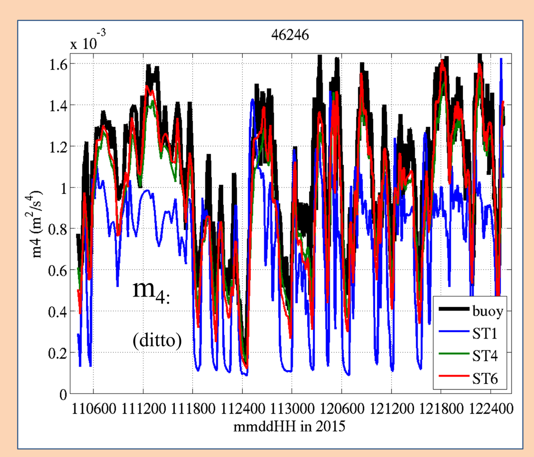
mean period $T_{m,-1,0}$: ST6/SWAN vs. 13 buoys



Above: Scatter plots for ST6 against the 13 NDBC buoys. Due to concerns about data quality, spectra beyond 0.3 Hz are not used (see panel re: NDBC buoys in this poster).

Below: time series vs. APL/UW Datawell buoy (1 buoy)



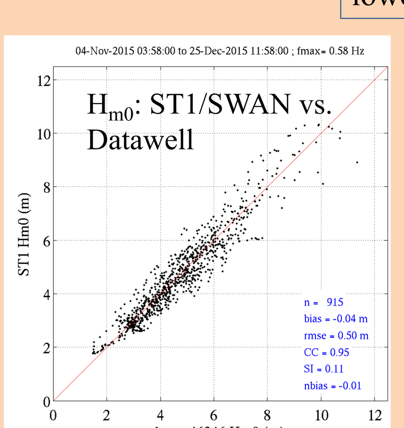


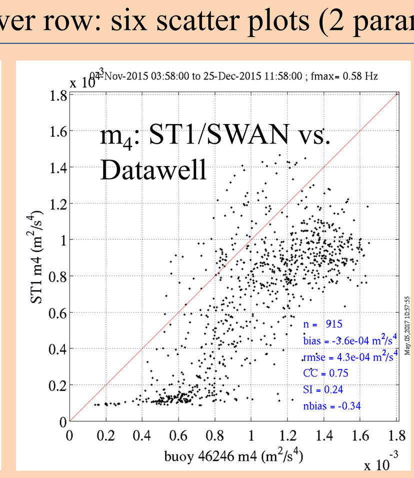
Conclusions:

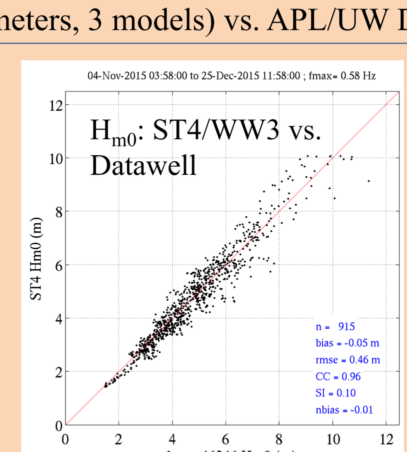
- All three models (ST1, ST4, ST6) demonstrate high skill for traditional parameters such as wave height and mean period.
- ST4/WW3 and ST6/SWAN demonstrate comparable skill for m_4 (moderate to high).
- ST1 has negligible skill for m_4.

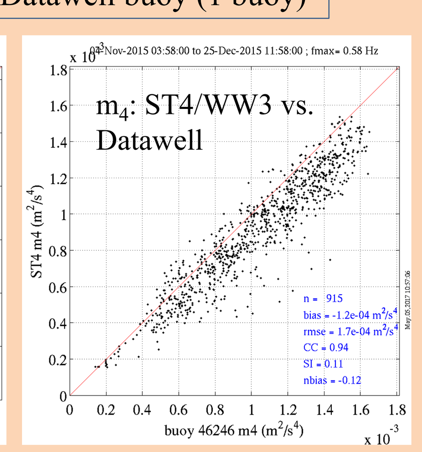
lower row: six scatter plots (2 parameters, 3 models) vs. APL/UW Datawell buoy (1 buoy)

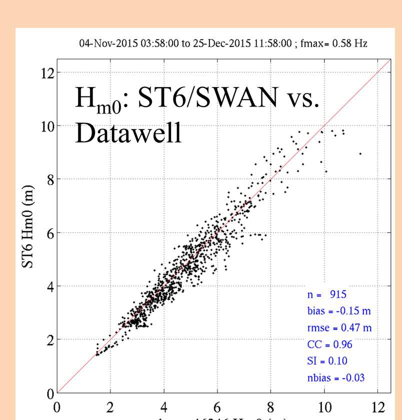
Note that bias is negative. Compare other figure marked with ★.

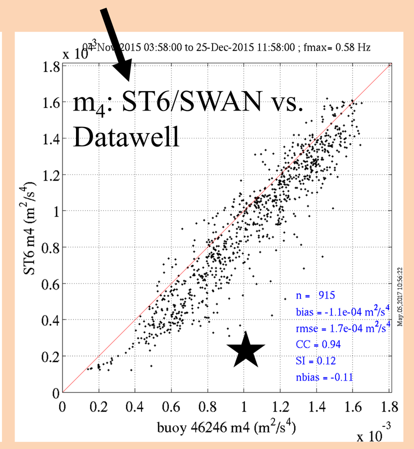












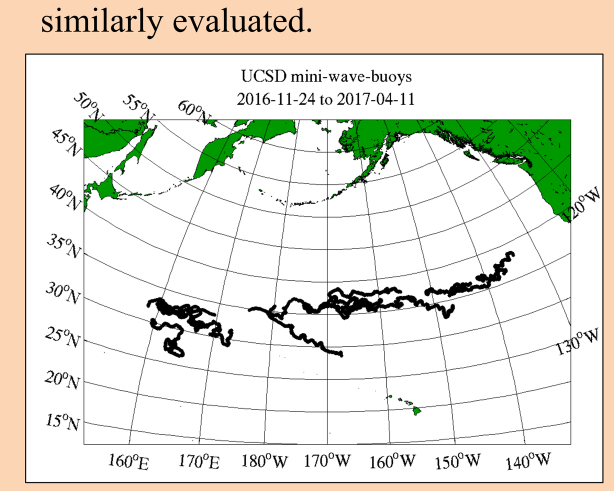
Background and Important References

➤ SWAN: Booij et al. (JGR 1999); maintained by M. Zijlema, G. van Vledder, and others at Delft University.
➤ WW3: WW3 development group (NOAA report, User's Manual, version 5, 2016)
➤ ST1/SWAN (2003): Komen et al. (JPO 1984) with adjustment by Rogers et al. (JPO 2003) (now default in SWAN and used extensively by U.S. Naval Oceanographic Office, among others)
➤ ST4 (2010): Ardhuin et al. (JPO 2010) (WW3 only) (used by most operational centers that have adopted WW3)
➤ ST6/SWAN (2012): Rogers et al. (JTECH 2012). Default in Navy COAMPS (a coupled modeling system). A simple adjustment to the wind input source function was added in SWAN in February 2014, which corrects a positive bias in mss (or m_4), as demonstrated here.
➤ ST6/WW3 (2015): Zieger et al. (OM 2015) (not used here). Stopa et al. (OM 2016) report positive bias in mss (or m_4); this was also a limitation of the old (2010-2013) versions of ST6/SWAN; i.e. we already know how to fix this.

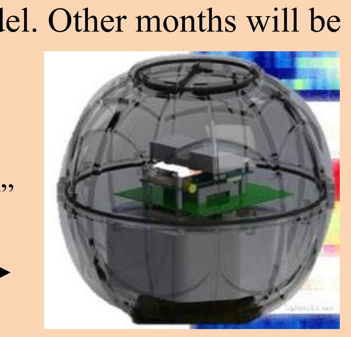
All WW3 and SWAN codes used here are open source and freely available

UCSD buoys

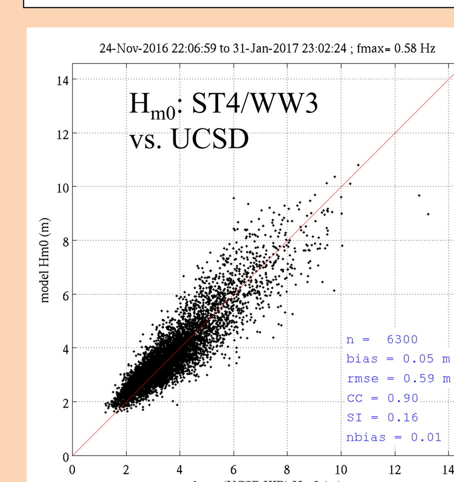
Using data provided by Dr. Eric Terrill (UCSD) from many small wave buoys in the Pacific Ocean, we have started evaluations of parameters such as m_4. Comparisons for Dec. 2016-Jan. 2017 are complete (examples below). The hindcast uses ST4/WW3 and NRL's 3-grid global model. Other months will be similarly evaluated.

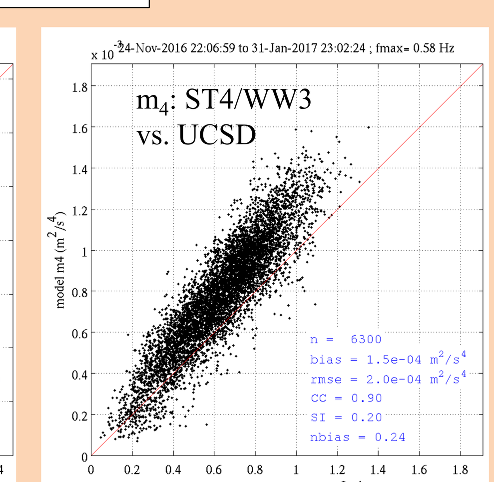


UCSD (Scripps) "miniature wave buoy" (~24 cm).



Drifting buoys in low-latitude Pacific.





Lower panels: Example validation of ST4/WW3. Mean square slope from WW3 is higher than that of the UCSD buoys. Comparison with UW Datawell buoy (not included here) for the same simulation show similar bias in mss.

Subsequent steps

❑ Continue mss evaluations using data provided by Dr. Eric Terrill (UCSD). Evaluate other months. Determine reason for inconsistent mss bias of ST4/WW3: winter 2015/2016 vs. 2016/2017 (biofouling?).

❑ L2 data for mss from the CYGNSS constellation are under development (by U. Michigan, NASA, and others). This will be used to evaluate ST4/WW3.

Further NRL Objective: develop data assimilation procedures for improving winds provided to WW3 as forcing.

Right: CYGNSS, a constellation of eight low-latitude (<=35º) navigation micro-satellites for wind speed and mss.