Kinematic Analysis of Ocean Winds: Past, Present, and Future

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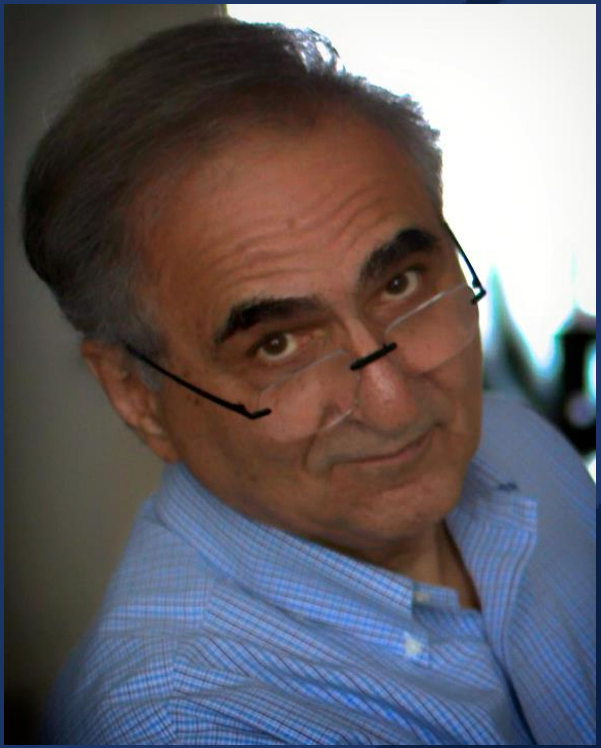
“It’s the winds, stupid!”



Dr. Vincent Cardone
(questioning your wave results)

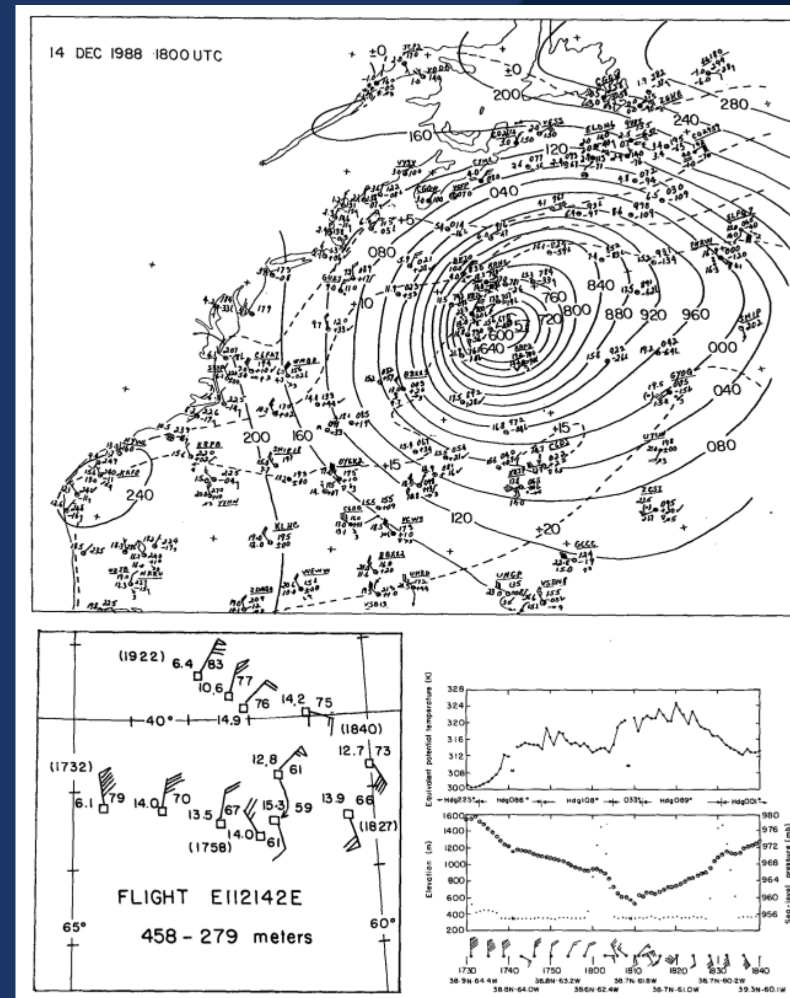
What is Kinematic Analysis?

Kinematic analysis (KA) is the “classic” process of hand-drawing synoptic maps by a trained meteorologist for wind speed and direction.

In KA all available data, corrected for height, averaging period, stability and exposure are plotted at synoptic times and a hand-drawn analysis is performed.

Wind data from models are reviewed but the analysis is largely dependent on the faithful assessment of observations.

KA preserves the time-space evolution of the wind features and particular attention is paid to the continuity of the wind maxima in the storm development.



Detailed wind and pressure analysis performed by Fred Sanders (Weather & Forecasting, 1990)

Effective Neutral Wind

$$U_e(Z) = (U_*/k)\log[Z/Z_o(U_*)]$$

The concept of the "effective neutral wind" was introduced by Dr. Cardone in "Specification of the Wind Distribution in the Marine Boundary Layer for Wave Forecasting" in 1969

Essential for wind analysis and application in ocean response modeling: used to adjust for both height and stability

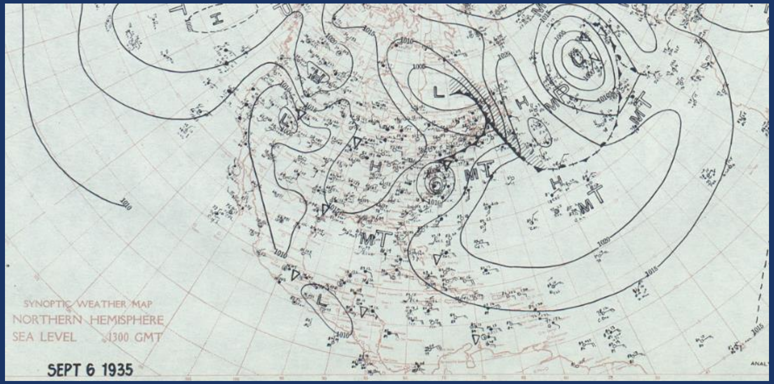
Routinely applied in satellite-derived wind estimates (scatterometers, altimeters, radiometers) and increasing available in reanalysis projects (ERA5 for example)

Stable Conditions Tair > Tsea	Neutral Conditions Tair = Tsea	Unstable Conditions Tair < Tsea
24 knots	19 knots	17 knots
12.4 m/s	9.8 m/s	8.8 m/s

Equivalent wind speeds at 20 meter height for stable, neutral, and unstable conditions

Kinematic Analysis Approach - 1980s/90s

aka "I walked to school up hill both ways, in the snow"!

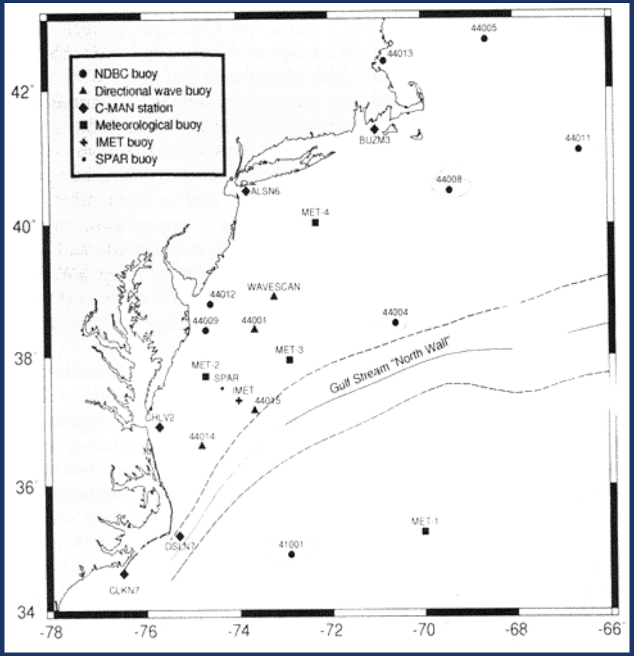


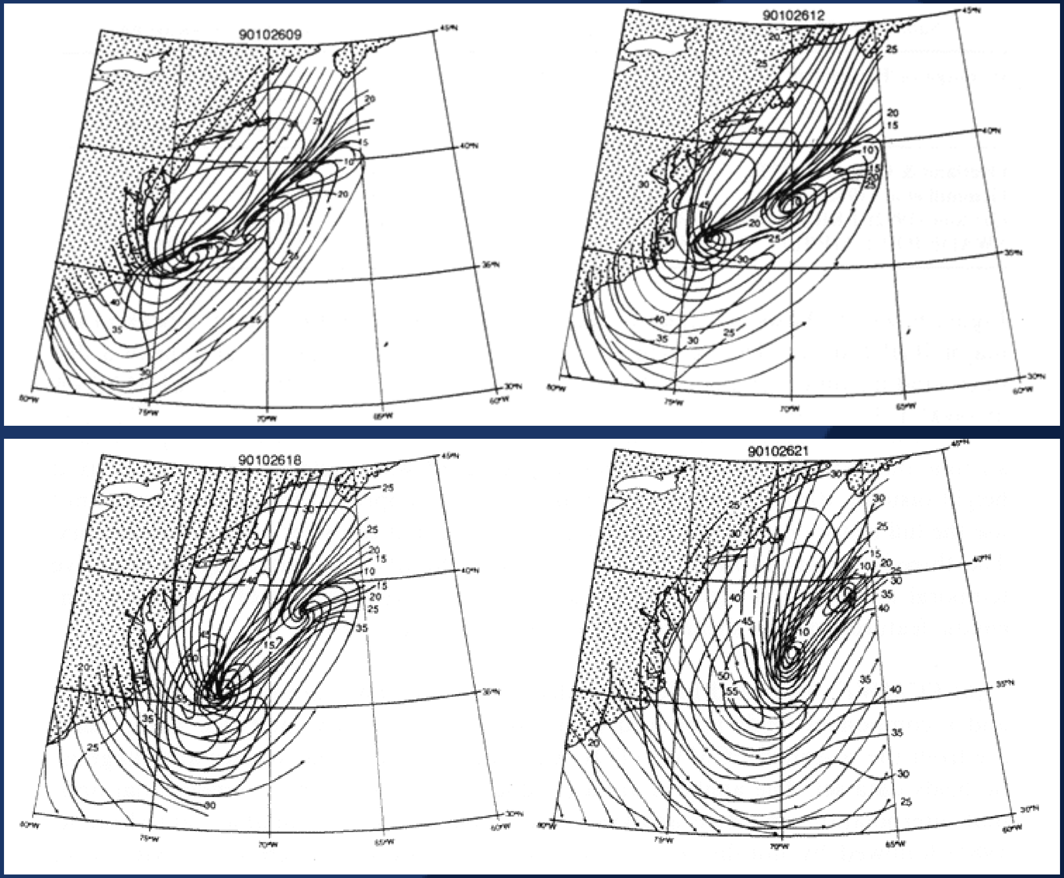
This is the foundation of the hindcast approach which revolutionized the development of ocean data for offshore structure design in the 1980s and early 1990s.

1. Start with surface pressure analysis (6/12/24 hour) typically on microfilm
2. Plot available synoptic observations (originally by hand!) typically obtained on magnetic tape from the National Climatic Data Center (NCDC)
3. Reanalyze surface pressure analysis along with air/sea temperatures
4. Digitize SLP/Tair/Tsea and run a Planetary Boundary Layer (PBL) model to compute the 10 meter surface wind
5. Plot resultant wind field (3 or 6 hourly typically) and available wind observations
6. Perform a kinematic analysis of surface wind speed (isotachs) and direction (streamlines)
7. Digitize wind analysis
8. Run your ocean response model!

Surface Wave Dynamics Experiment (SWADE) - 1990

A kinematic analysis was applied in IOP-1 in late October 1990 to a series of storms offshore the US East Coast. NDBC buoy observations were supplemented with additional moored buoys and research vessel data





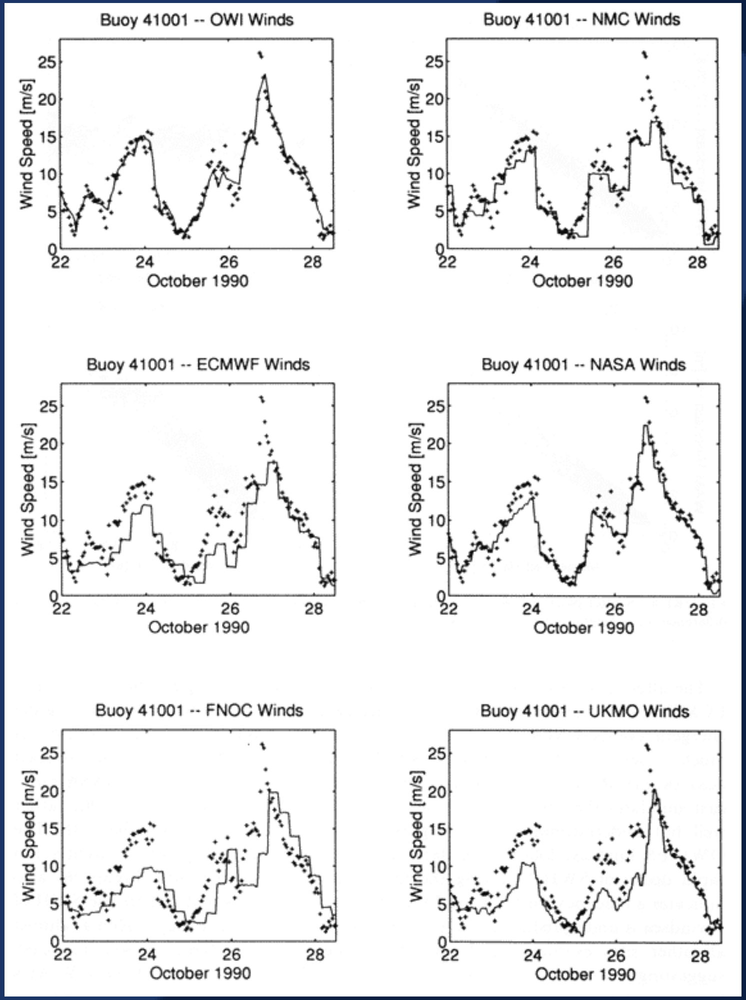
Hand analyzed wind speed (isotachs) and direction (streamlines)

Images from In Search of the True Surface Wind Field in SWADE IOP-1: Ocean Wave Modelling Perspective, Cardone et al. 1995

Surface Wave Dynamics Experiment (SWADE) - 1990

At the time, strong storms posed great difficulty for the operational forecast models at the time. NMC (now NCEP), ECMWF, FNOC (US Navy) and UKMO (now the Metoffice) analysis all depict a weaker variant of the storm at NOAA buoy 41001.

Only the NASA winds, based on a post-real time data assimilation, and the kinematic analysis (OWI) represent the peak winds properly.



Surface Wind Speed Comparison

Images from In Search of the True Surface Wind Field in SWADE IOP-1: Ocean Wave Modelling Perspective, Cardone et al. 1995

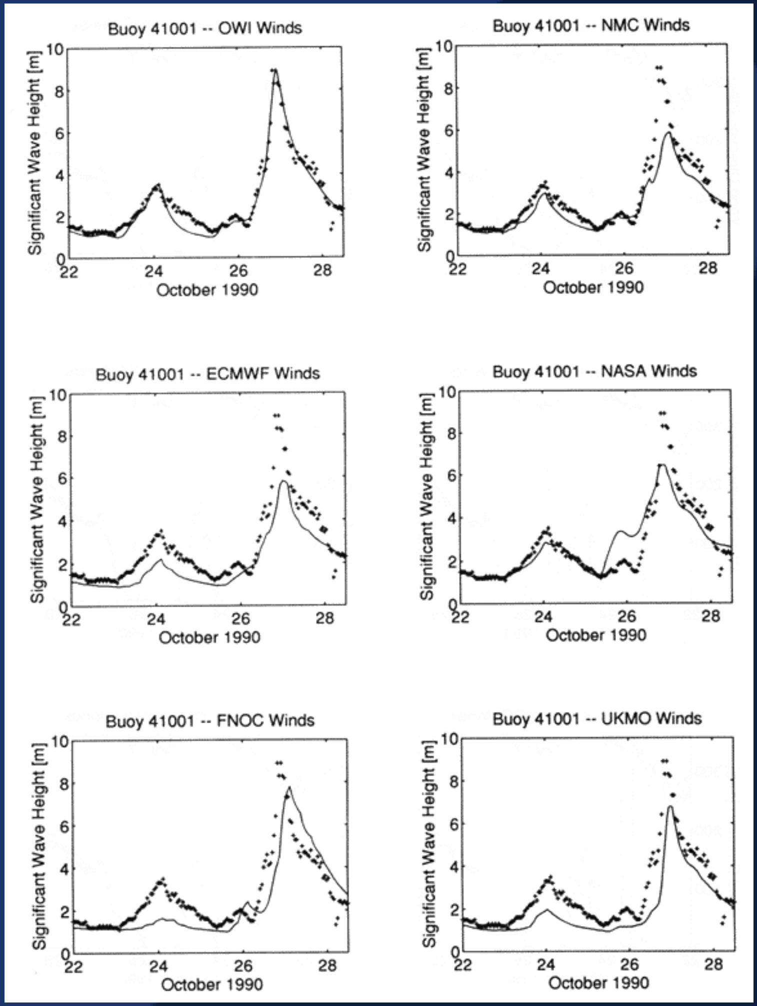
Surface Wave Dynamics Experiment (SWADE) - 1990

Resultant wave comparison when the six wind fields were run through a common WAM Cycle 4 wave model.

All the operational models (NMC, ECMWF, FNOC and UKMO) underestimate the peak and despite the assimilation of buoy winds the NASA resultant waves also underestimate the peak conditions.

Only OWI analysis, which through the process of kinematic analysis tracked and resolved the surface wind features, resulted in a wave hindcast which could resolved the peak wave height.

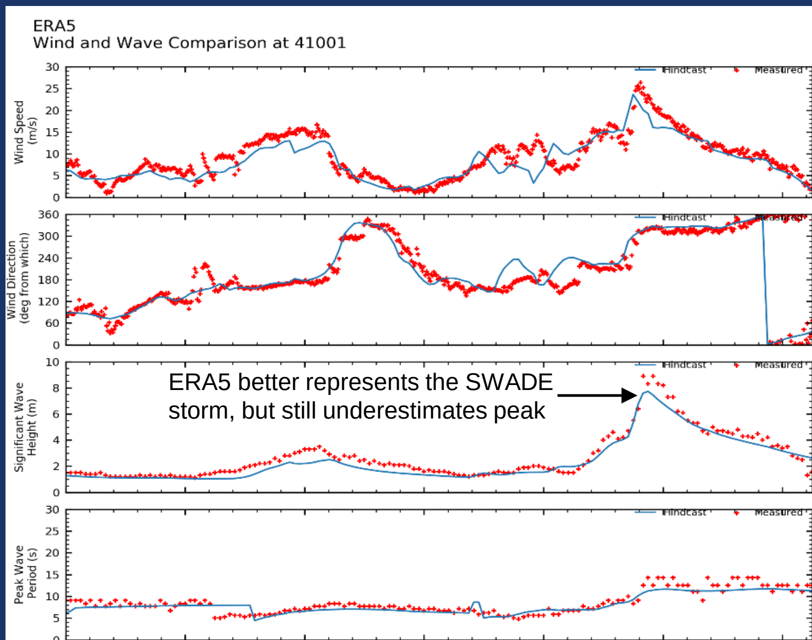
This was a major validation of the 3rd generation WAM model at the time.

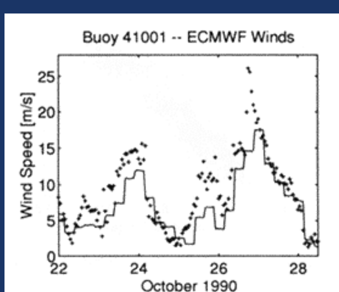


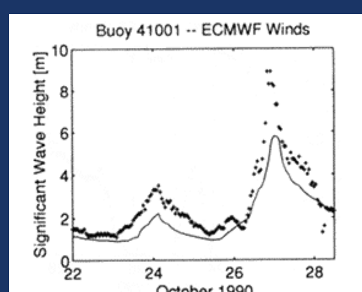
Significant Wave Height Comparison

Images from In Search of the True Surface Wind Field in SWADE IOP-1: Ocean Wave Modelling Perspective, Cardone et al. 1995

Kinematic Analysis Approach - Today



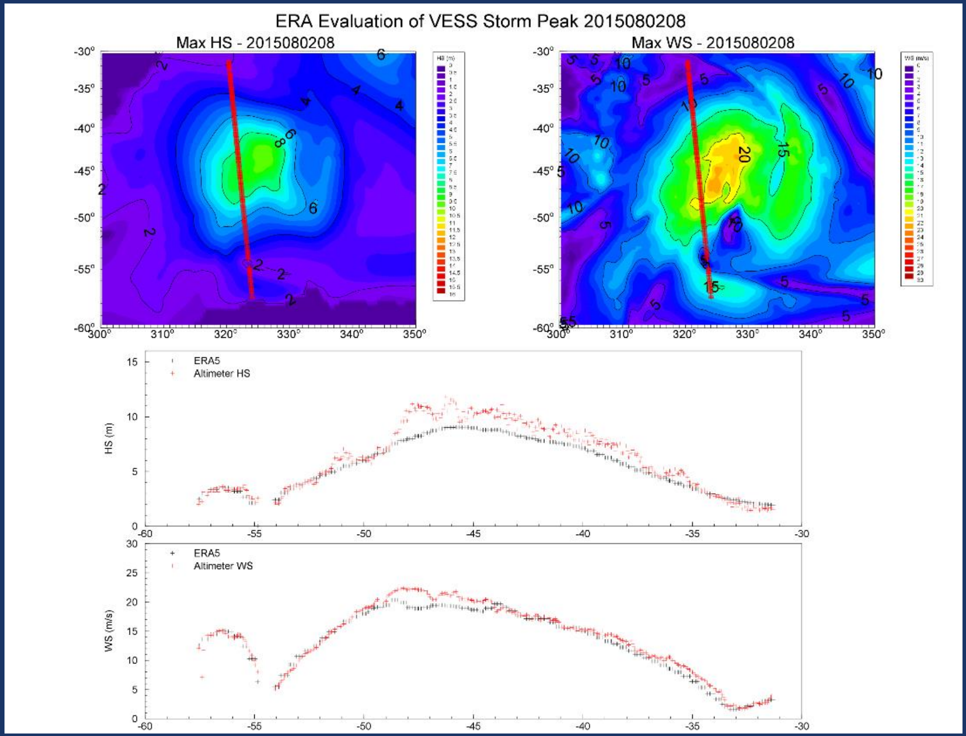




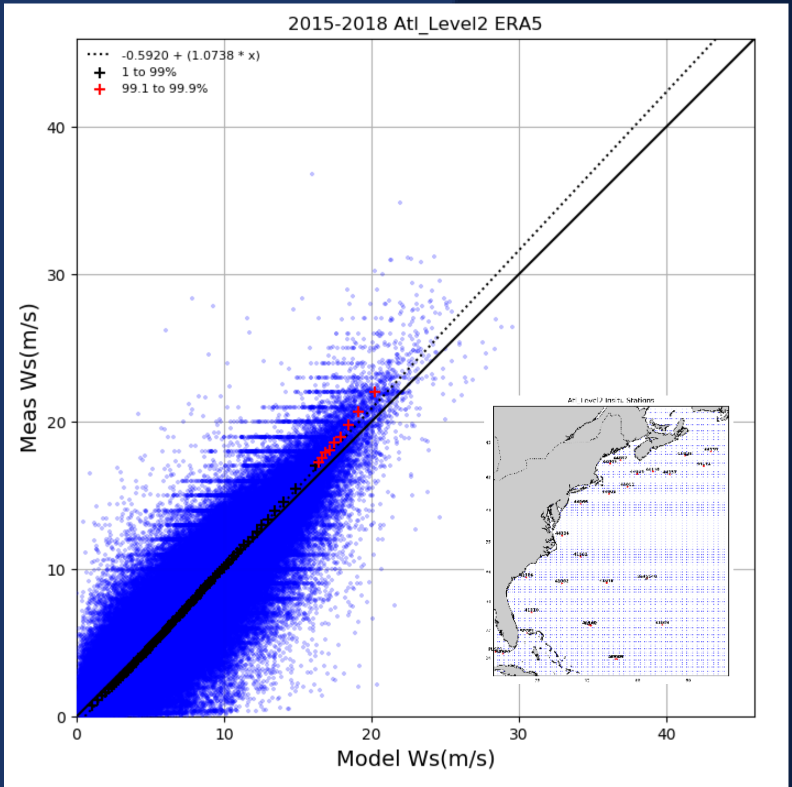
SWADE IOP-1 October storm
ERA5 above, ECMWF from Cardone et al. 1995 below

- Modern atmospheric reanalysis projects (ERA5, CFSR, others) provide a quality starting point
- Satellite based wind and wave datasets provide global coverage, but typically lack temporal coverage to capture full evolution of peak events
- Dynamical downscaling via WRF and other atmospheric models can greatly improve coastal/orographic winds – not as useful for ocean storms
- Graphical workstations speed up the analysis process, but preserve the basic approach

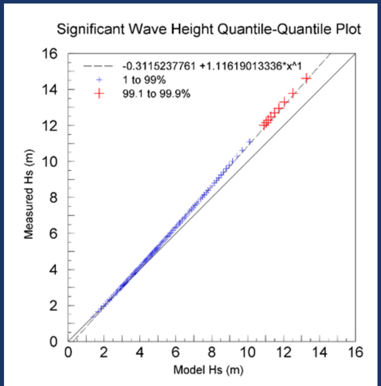
ERA5 Reanalysis in Extra-Tropical Storms



Altimeter pass through a intense extra-tropical storm

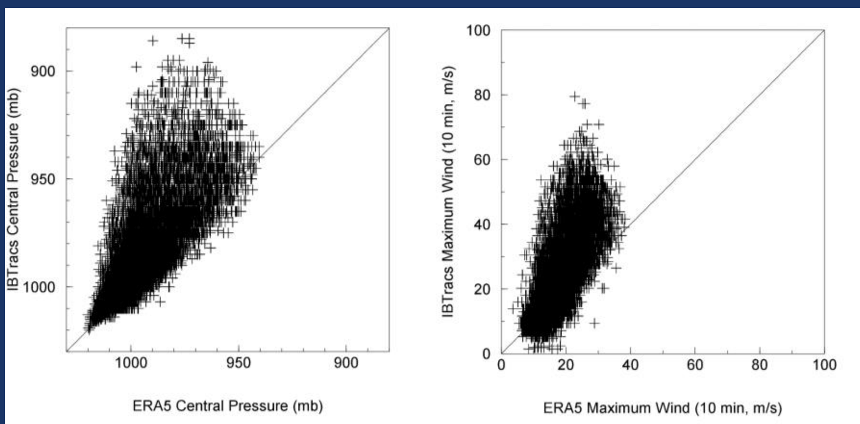


Scatter and quantile-quantile comparison of ERA5 winds (m/s, 10-m neutral) against US East Coast buoy measurements 2015-2018

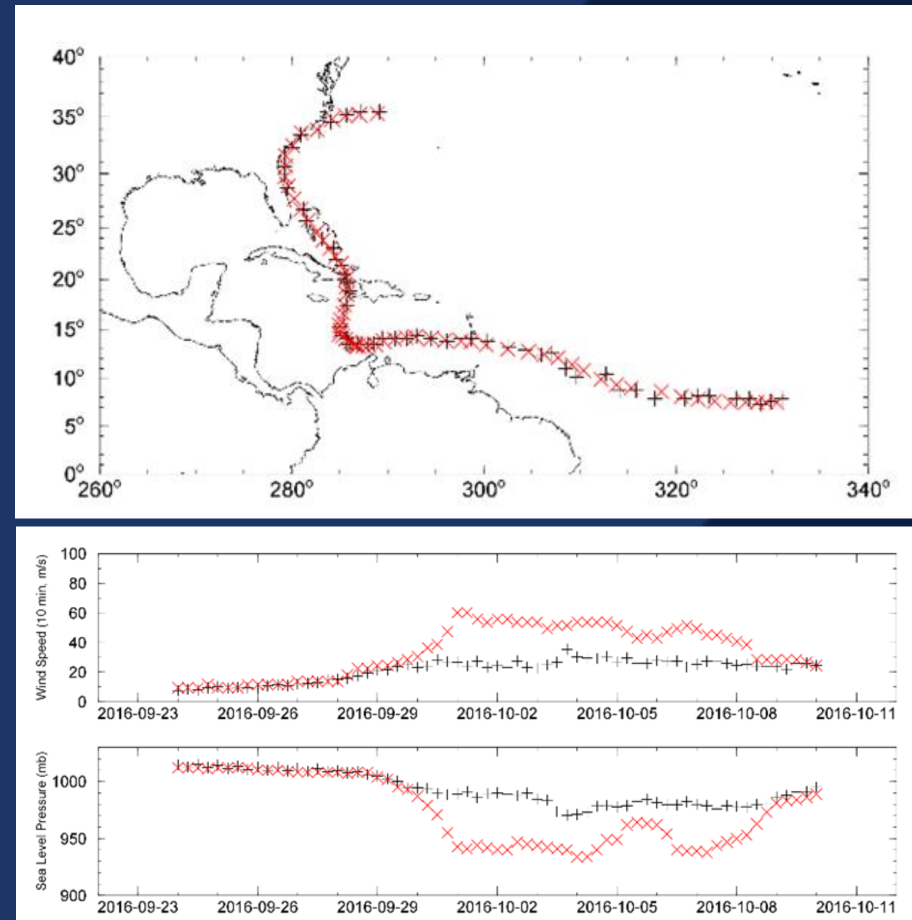


Quantile-quantile significant wave height comparison of ERA5 and combined VESS event (Altimeter Hs > 10m) passes 1991-2018

ERA5 Reanalysis in Tropical Storms



Comparison of IBTracs global tropical cyclone estimates of central pressure and maximum wind vs. ERA5 2010-2016



Comparison of NHC (red) official track and intensity (10-min average winds) in Hurricane Matthew 2016 vs. ERA5 (black)

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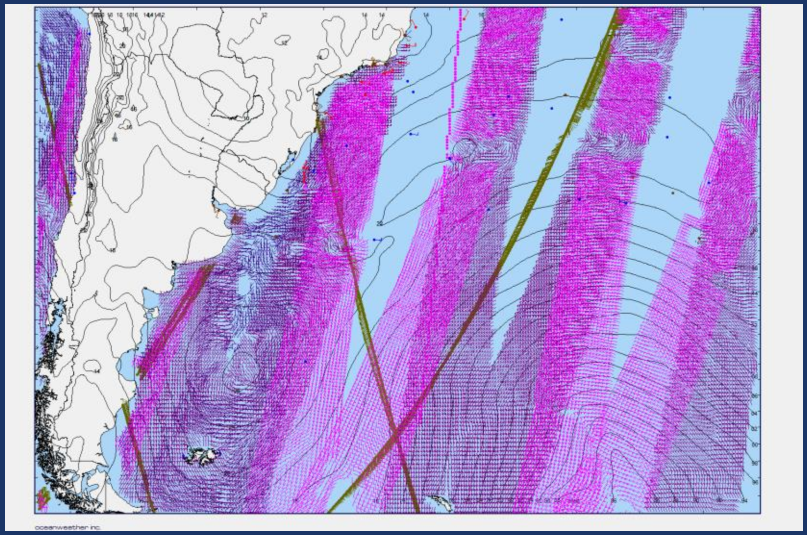
Present Wind Analysis Methodology



Composite plot of wind data from buoys, ships, scatterometers, altimeters, radiometers valid Oct-26-2018 12:00 UTC in the South Atlantic (+/- 1.5 hours)

Start with modern atmospheric reanalysis (ERA5, CFSR, others)

↓

Statistical Downscaling
Assess statistical skill against basin wide satellite measurements

↓

Dynamical Downscaling
Run a mesoscale atmospheric model to include finer coastal effects

↓

Tropical System Analysis
Interactive workstation coupled to PBL Model

↓

Interactive Objective Kinematic Analysis

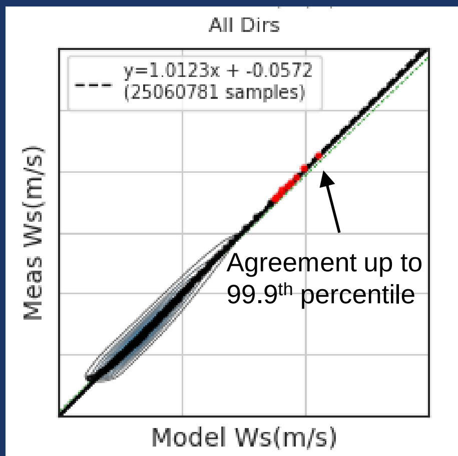
↓

Ocean Response Model

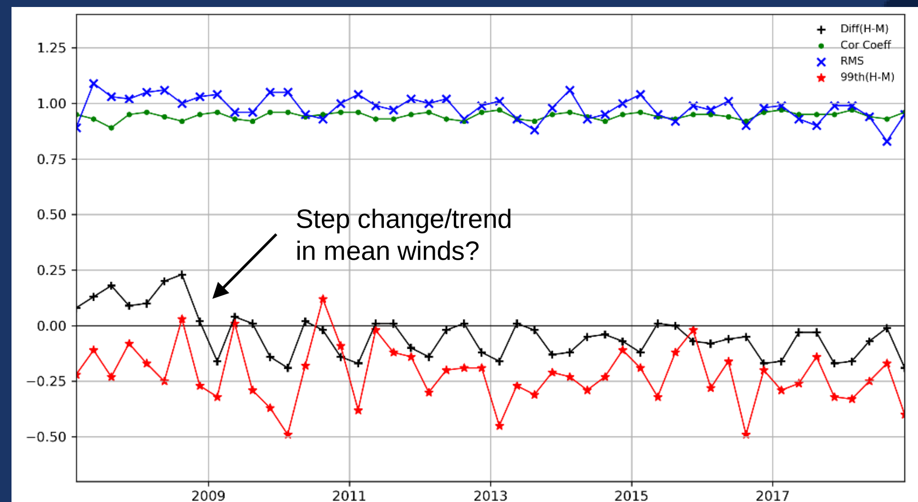
Assessment of Observations

Comparison of ERA5 and satellite winds in North Atlantic - Which would you trust?

KNMI ASCAT



"A"



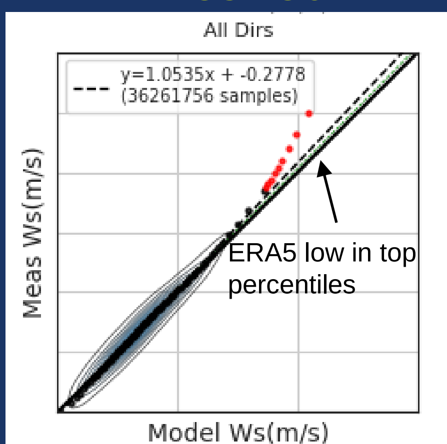
Correlation Coefficient

RMS Error

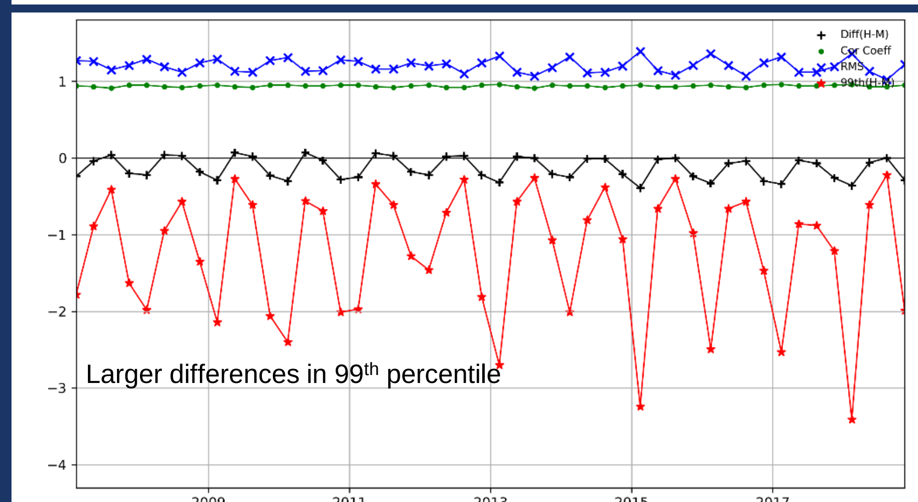
Mean Difference

Difference in 99th Percentile

REMSS ASCAT



"B"



Correlation Coefficient

RMS Error

Mean Difference

Difference in 99th Percentile

Overall Quantile-Quantile Comparison

Seasonal Wind Statistical Comparison 2007-2018

Both comparisons are the ASCAT instrument, but processed by two different agencies – OWI consider REMSS to be more skillful

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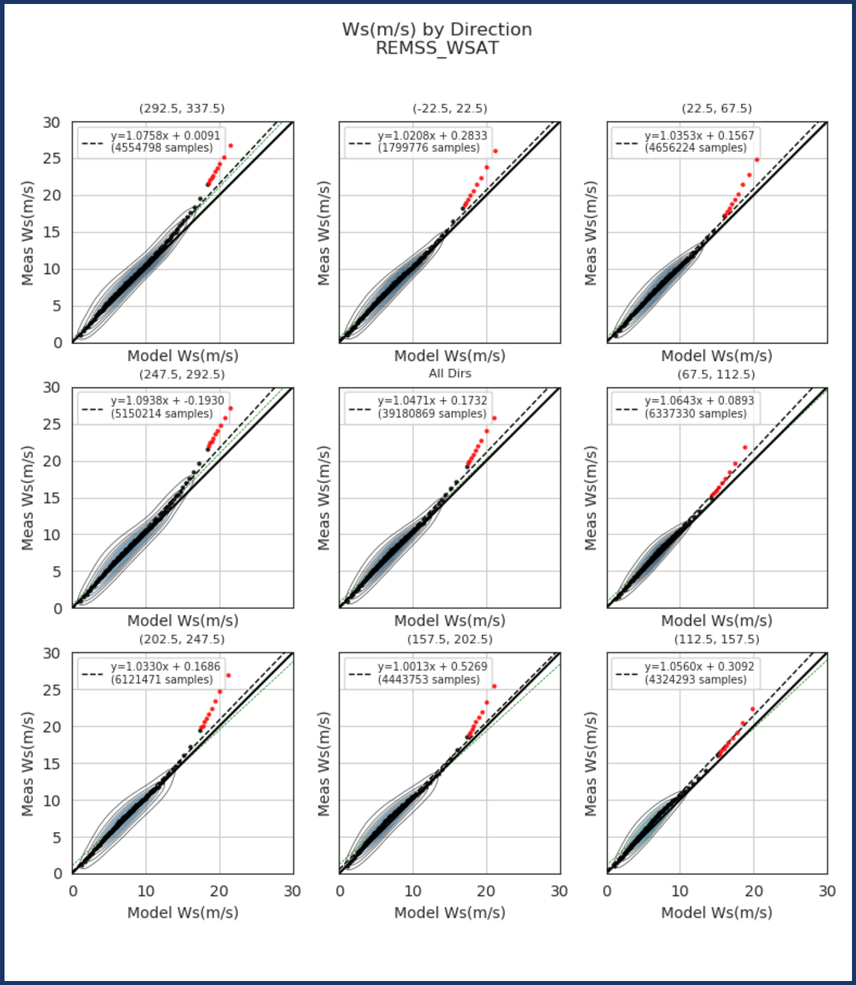
Statistical Downscaling

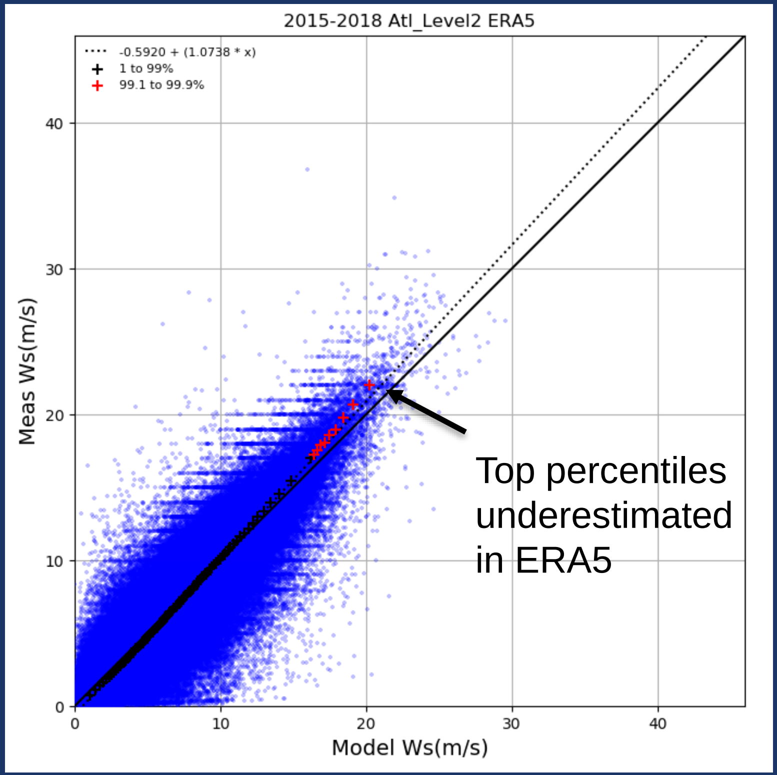


Directional quantile-quantile assessment of Windsat and ERA5 wind speed (m/s) offshore US East Coast

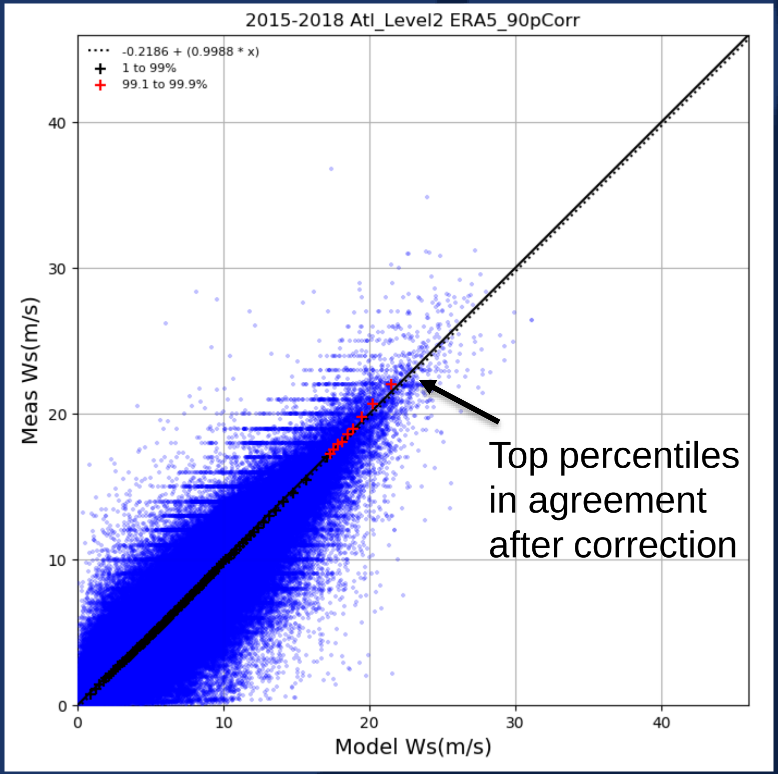
1. Assess available satellite data for evaluation
2. Produce matched pairs of model and satellite measurements
3. Time, space, and wind direction windowing initially set by user
4. Algorithm computes quantile-quantile in directional bins for each grid point – overlap in time/space/direction used to provide enough pairs for a stable fit and ensure continuity from location to location
5. Linear fits determined on monthly/seasonal and directional basis for each location
6. Corrections are applied to entire dataset and assessed via direct comparison with independent data
7. Wind fields pre/post correction run through ocean wave model and resultant wave skill assessed

Statistical Downscaling

ERA5
vs. US East Coast Buoys



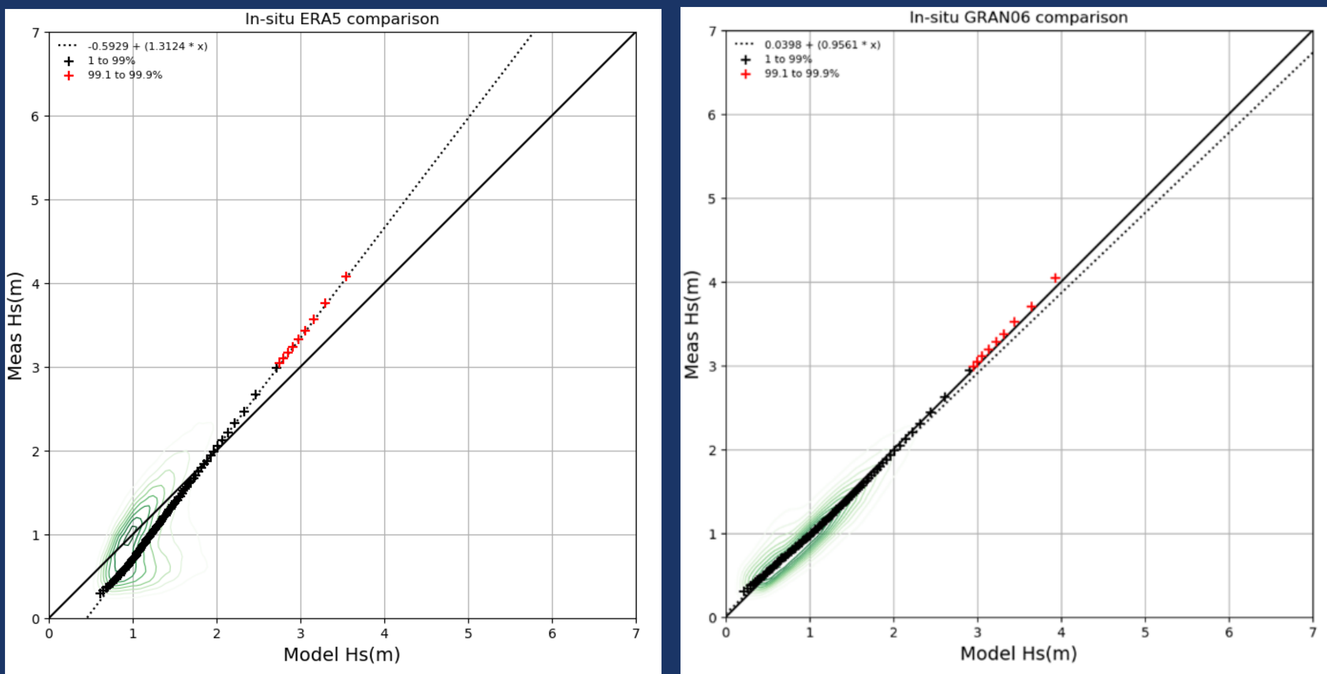
ERA5 with statistical correction
vs. US East Coast Buoys



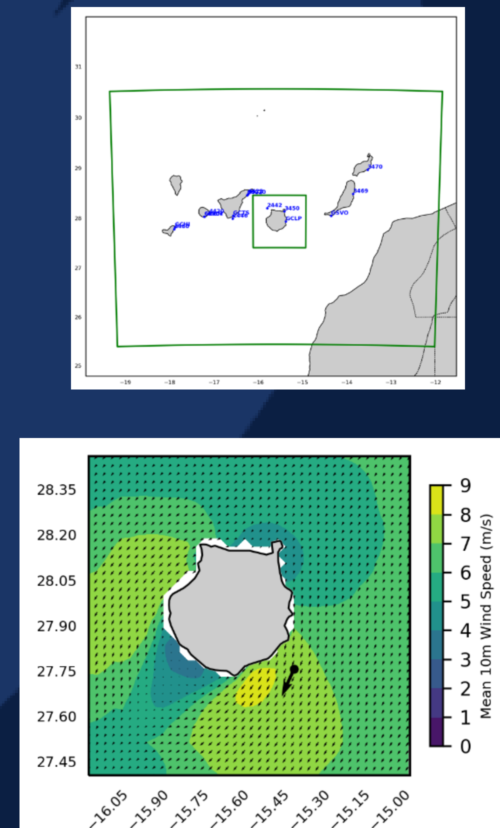
Resulting statistical wind corrections developed using QuikScat and ASCAT scatterometers when compared independently to insitu buoys off the US East Coast

Dynamical Downscaling

Application of mesoscale atmospheric model for coastal orographic features not resolved on global grid



Comparison of significant wave heights from coastal buoys and wave hindcasts driven by ERA5 winds (left) and a 3 km Weather Research and Forecasting (WRF) model (right) in the Canary Islands



WRF 3 km domain surrounding Gran Canaria Island

Tropical Cyclone Analysis

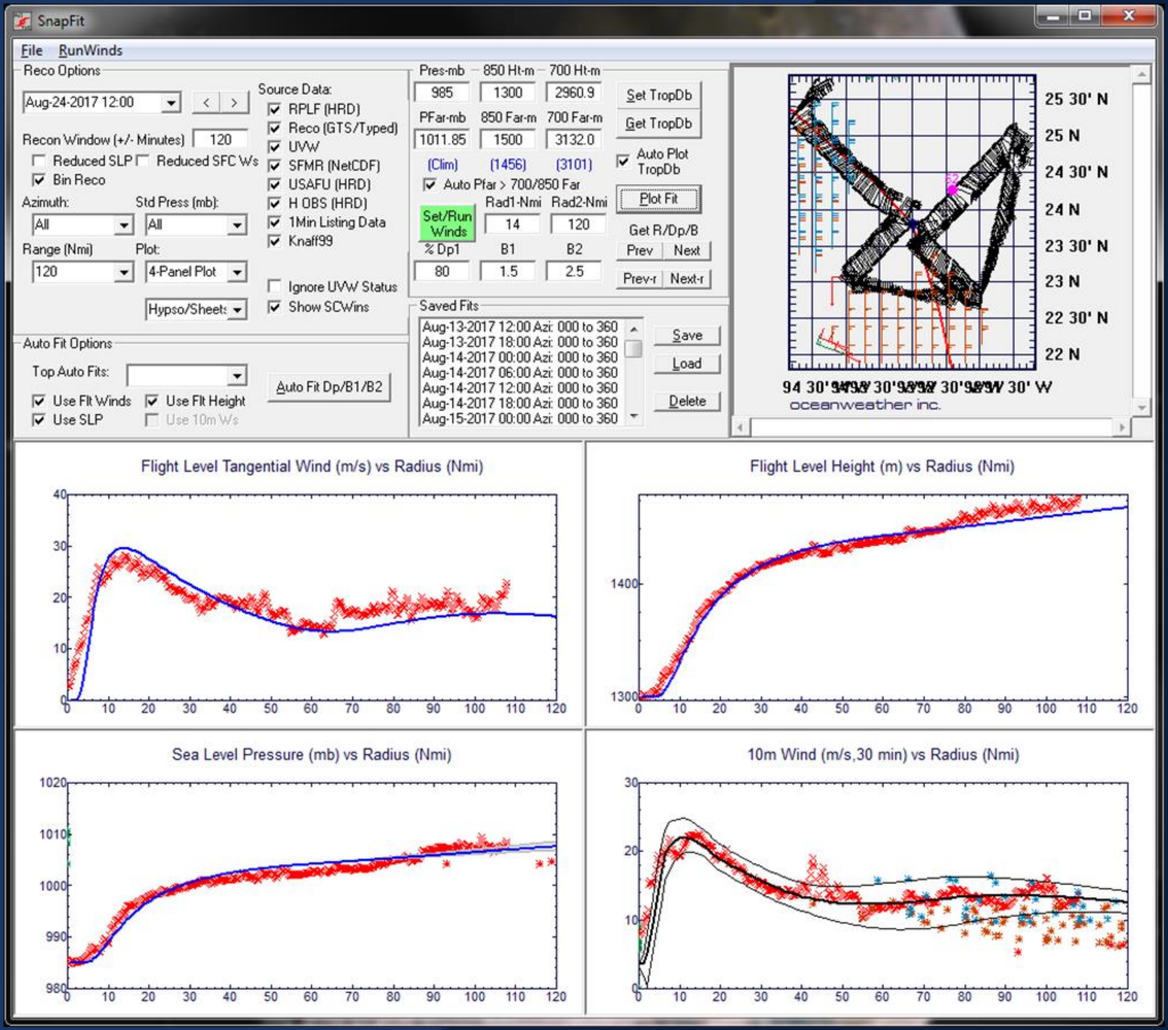
Interactive workstation coupled to tropical PBL model

Pressures described using a “double exponential” Holland profile – 2 radii/B parameters allow for more complicated profile shapes

Analyst able to adjust parameters and see resultant comparisons to measurements

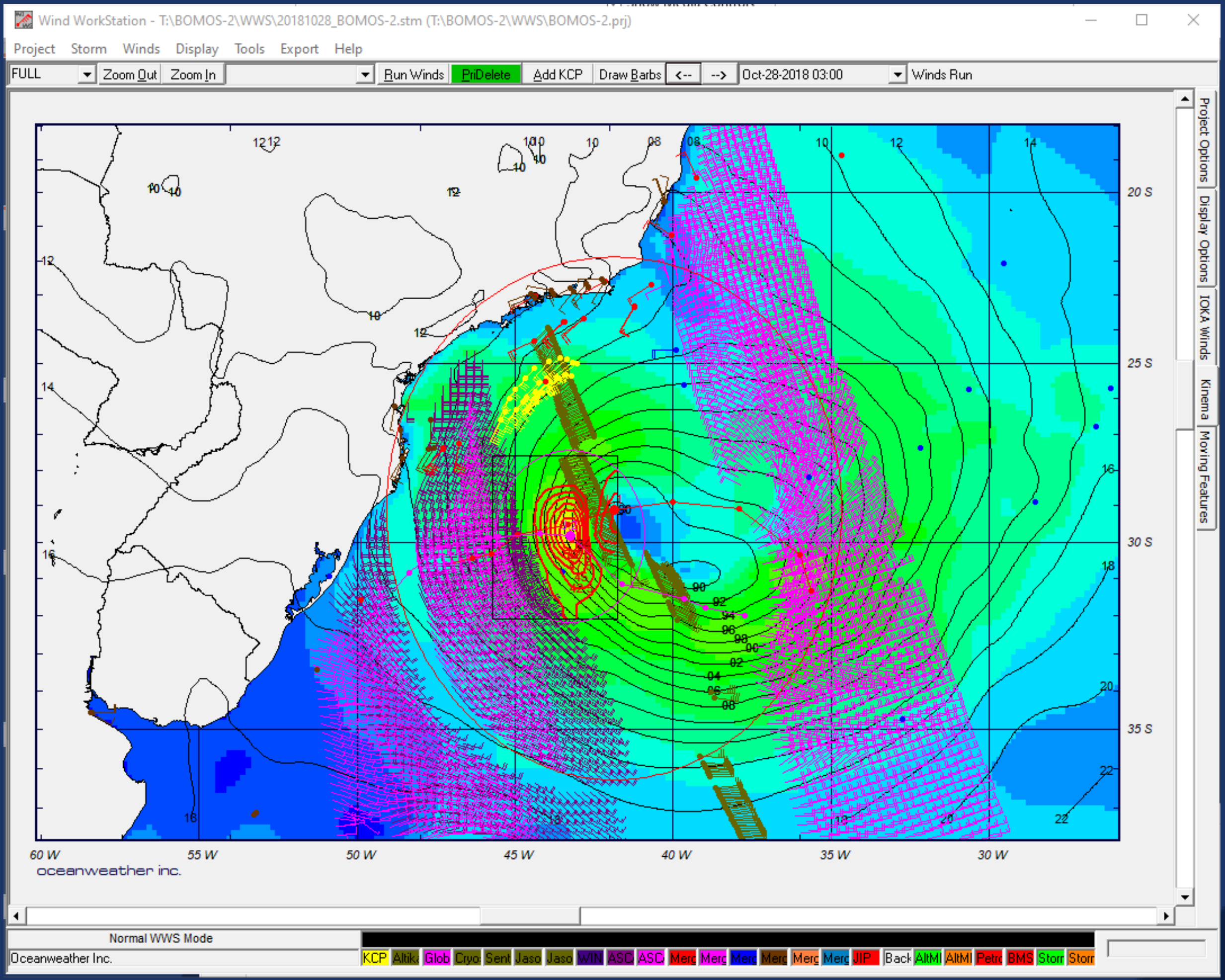
Exports storm-centered wind/pressure fields for blending/overlay

See Wave Workshop Liverpool (2017) presentation for more…



Wind Analysis – Wind WorkStation

Interactive tool for wind analysis



- Displays all wind inputs (models and measurements)
- Individual observations can be selected for inclusion in objective analysis
- Variety of tools for the analysis: kinematic control points, direct draw of isochachs and streamlines, area inflation
- Analysis typically performed 1 or 3 hourly and moving features interpolation applied to preserve maxima on target grids

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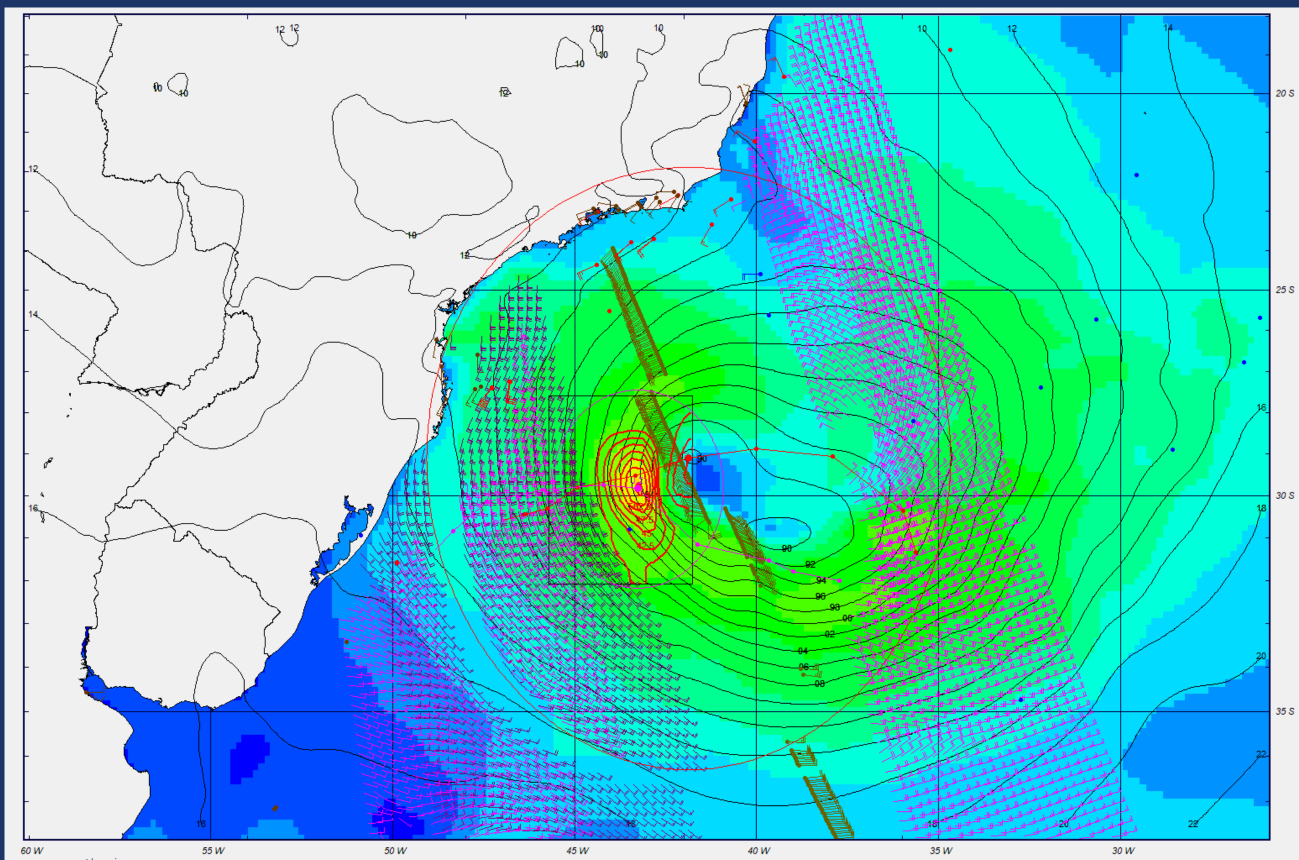
Storm Example

October 2006 Offshore Brazil

Intense extra-tropical cyclone exiting Uruguay/Brazil coastline
Deepened from 1006 mb to 988 mb, 18 mb in 24 hours – explosive cyclogenesis



Storm was well sampled by WINDSAT, ASCAT A/B as well as multiple altimeters

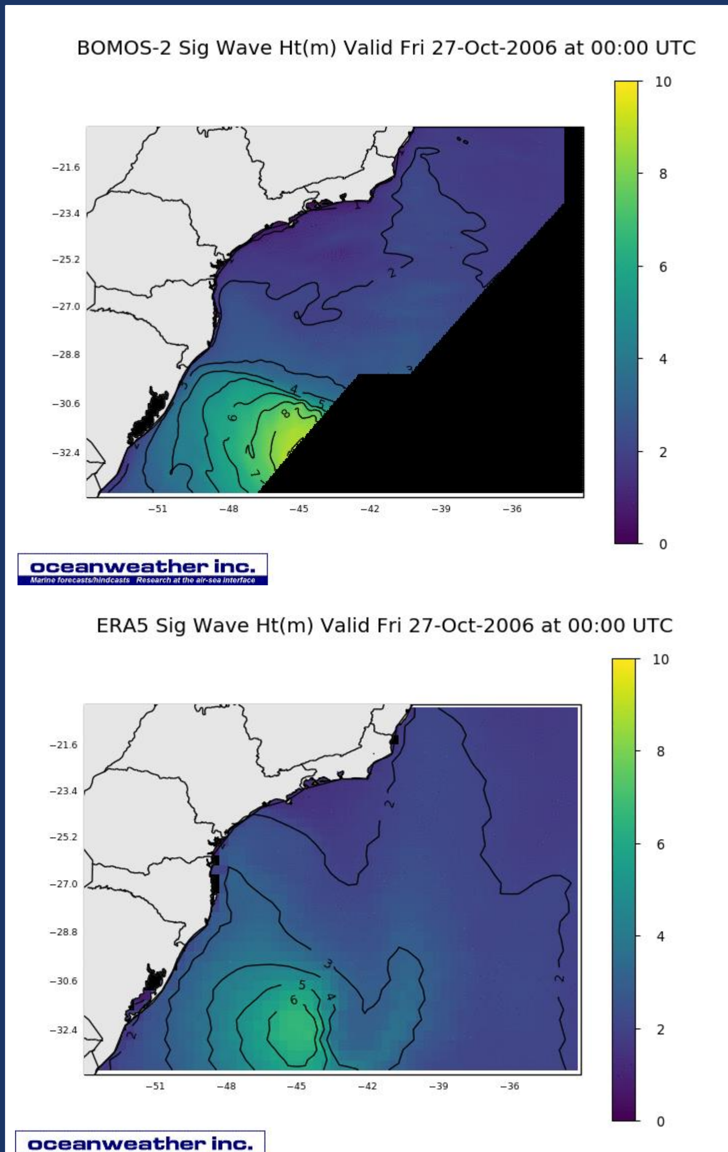
Peak winds in ERA5 were 10-15 knots (5-8 m/s) too low

In this example, continuity analysis from adjacent maps were used to preserve the wind maxima by applying a isotach analysis

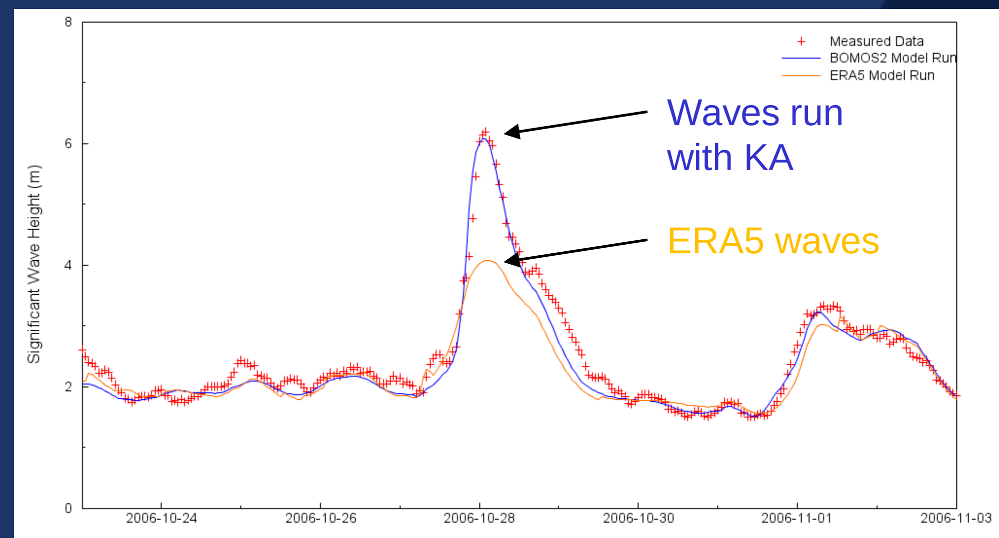
Wind WorkStation display depicting available wind observations and kinematic analysis performed

Storm Example

October 2006 Offshore Brazil

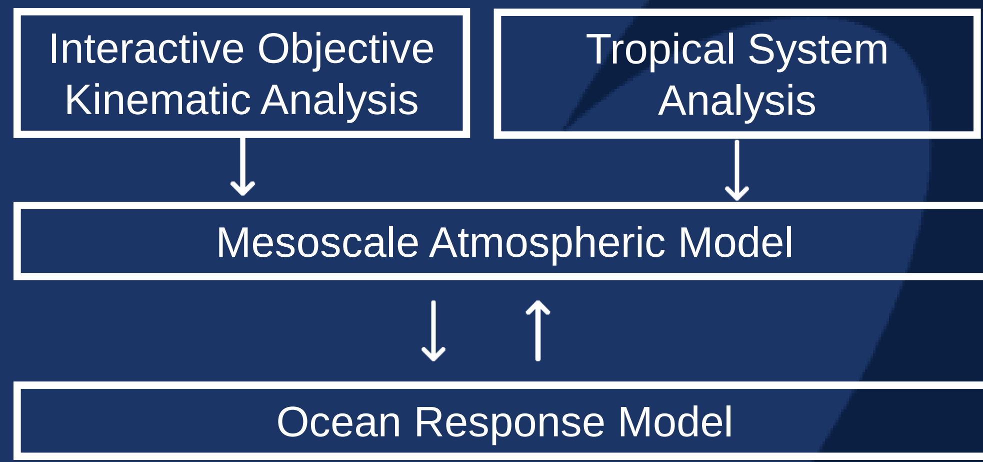


Measured waves from a deep water waverider buoy north of the storm show the impact of kinematically analyzed winds on the resultant waves



Future of Kinematic Analysis

- Kinematic analysis is likely to continue as a useful tool for the analysis and understanding of the top percentile storms
- Coupling of ocean response models requires kinematic analysis and tropical analysis applied as inputs to mesoscale model
- Measurement and modeling of extreme events is often outside the normal range of measurement and model calibration – both require careful scrutiny



~~Machine Learning~~

One more thing…

In the early 1990's, Vince was working on tuning of the OWI's 3rd generation variant of the WAM model. Test cases included both tropical and extra-tropical storms which included detailed tropical modeling and kinematic wind analysis.

When traditional tuning of wave model source terms failed to converge on a single set of factors, Vince theorized that drag coefficient was becoming saturated at high wind speeds and included a drag modification in the model.

A decade later the work of Mark Powell using GPS dropwind sondes in hurricanes and Mark Donelan's wind tank experiments would cement the concept of wind drag saturation and its later inclusion in ocean response models.

In (A-15), the coefficient 28 is subject to a slight variation depending on the representativeness of the drag coefficient. The solution of U_* utilizes the neutral drag law proposed by Wu (1980) and modified in this study for low and high wind speeds. The modified drag law is given by

$$
\begin{aligned}
C_d &= 1.2 \times 10^{-3}, \quad U \leqslant 6.2 \text{ m s}^{-1} \\
&= (0.80 + 0.65U) \times 10^{-3}, \quad 6.2 \text{ m s}^{-1} < U \leqslant 14 \text{ m s}^{-1} \\
&= [(0.80 + 0.065U) - 0.0021(U - 14)^2] \times 10^{-3}, \ 14 \text{ m s}^{-1} < U \leqslant 29.5 \text{ m s}^{-1} \\
&= \{(0.80 + 0.065U) - 0.0021[(U - 14)^2 - (U - 29.5)^2]\} \times 10^{-3}, \\
&\qquad U > 29.5 \text{ m s}^{-1} \quad \text{(A-16)}
\end{aligned}
$$

from Khandekar, Lalbeharry, and Cardone, 1993