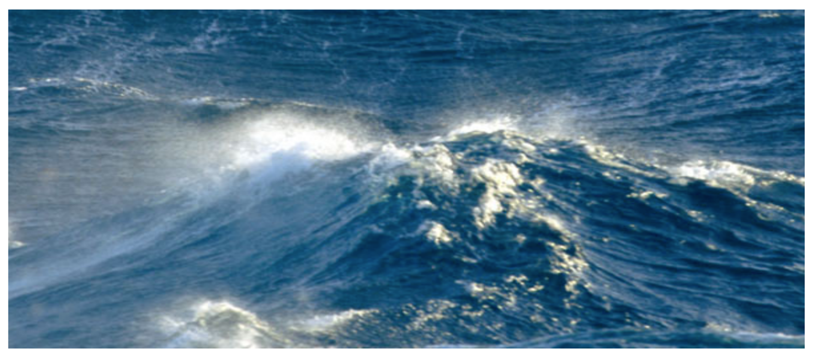
Detection of ocean white-capping by combined use of Jason radiometer and radar datasets alongside global wave model predictions



D. Vandemark[1], H. Feng[1], Y. Quilfen[2], F. Arduin[2], B. Chapron[2]

[1]Ocean Process Analysis Lab ,University of New Hampshire, USA
[2]IFREMER/Centre de Brest, France

University of New Hampshire

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OBJECTIVES:

- **Detect and assess wave-dependence in whitecapping using foam-dependent ocean emissivity data from the Jason satellite radiometers**
- **Support and complement observations using ancillary foam-free measurements of surface wave information from the radar altimeters, wave buoy data, and ocean wave models**

Background: Many field studies have been directed at divining the relationship between near surface wind and wave conditions and the amount of whitecapping and foam that occurs over varied sea states on the global ocean. Motivations for these efforts largely involve the goal to close the energy balance between wind input to waves and the dissipation that occurs to govern observed ocean gravity waves under varied conditions. Breaking waves are central to the dissipation of energy as well as air-sea mass flux and yet the process is ephemeral enough that measuring and modeling of breaking wave processes remains an ongoing topic of research.

Measures that pertain to wave breaking are many and include the probability of breaking, crest length distribution, whitecap fractional coverage, foam thickness, large-scale and smaller scale wave breaking, and active vs. relic or remnant foam traces. The dominant *in situ* approach to determining whitecap coverage has been use of optical systems to document % coverage of whitewater and relate this to other breaking wave statistics under the observed range of field conditions. Despite concerted efforts, the consensus models for predicting whitecap coverage are mostly limited to a single control, that being wind speed (**U**), and a typically cubic or slightly elevated power law. One frequently cited whitecap coverage, (**W**), model is from Monahan and O'Muircheartaigh (1980):

$$\mathbf{W} = 3.84 * e\text{-}06 * \mathbf{U}\text{\^{}}3.41$$

But what is also understood is that there is still a wide range of unexplained scatter in **W** field data at any fixed wind regime. The scatter may be related to the water temperature to some degree, but most results suggest that it is related to changes in the sea state or degree of wave development. In this area, there are some apparent contradictions, where several authors assert that younger underdeveloped seas will have less breaking and foam than more mature seas (Sugihara et al., 2007; Woolf, 2005; Salisbury et al., 2013), while other studies suggest that as seas mature or background waves (swell) intrude, the extent of whitecapping decreases (Lafon et al., 2007; Gemmrich et al., 2008; Sugihara et al., 2007; Kleiss et al., 2010). Recently the work of Salisbury et al. (2013), using off-nadir satellite radiometer data from WINDSAT, attempted to address the issue with mostly inconclusive results. Here we develop an investigation using instead the nadir incidence measurements provided by the Jason radiometers.

Methods

Guiding assumptions

- nadir ocean radiometer emissivity dominated by short-scale waves in absence of foam; and then impacted by foam at and above 18 GHz when wind speed exceeds 5 m/s
- nadir radar backscatter unaffected by foam; responds to both short wave and long wave changes in manner that may differ from emissivity due to foam
- nadir radar dual frequency data can isolate short waves for U > 5-6 m/s (see eq. 4)
- easier to interpret foam in nadir ocean emissivity than off nadir (SSMI, Windsat, AMSR)
- foam depth impacting 18-34 GHz is 1-2 mm so active and passive breaking observed
- literature search suggests fetch-limited or young sea conditions are of interest

Datasets

- Jason-1 Microwave Radiometer (JMR) and Jason-2 Advanced Mic. Radiometer (AMR) brightness temperature data at 18, 23, and 34 GHz
- J-1 and J-2 dual band C and Ku-band radar altimeter radar backscatter
- Hourly NDBC 2D spectral ocean gravity wave measurement buoys
- 3-hourly global ocean wave model estimates from IFREMER-WAVEWATCH 3 including peak and mean wave period, mean square slope of long waves, whitecap coverage

Basic models

a) **ocean surface emissivity at 18, 23 and 34 GHz after atmospheric correction**

$$e_{tot\_freq} = e_{flat\_surface} + e_{waves} + e_{foam} + e_{excess} \quad \textit{where } Tb\_freq = e_{tot\_freq} * SST \qquad (1)$$

$$\text{alternatively,} \quad e_{tot\_freq} = e_{flat\_surface} + e_{rough} + e_{excess} \qquad (2)$$

b) **radar ocean backscatter at 5 (C) and 14 (Ku-band) GHz**

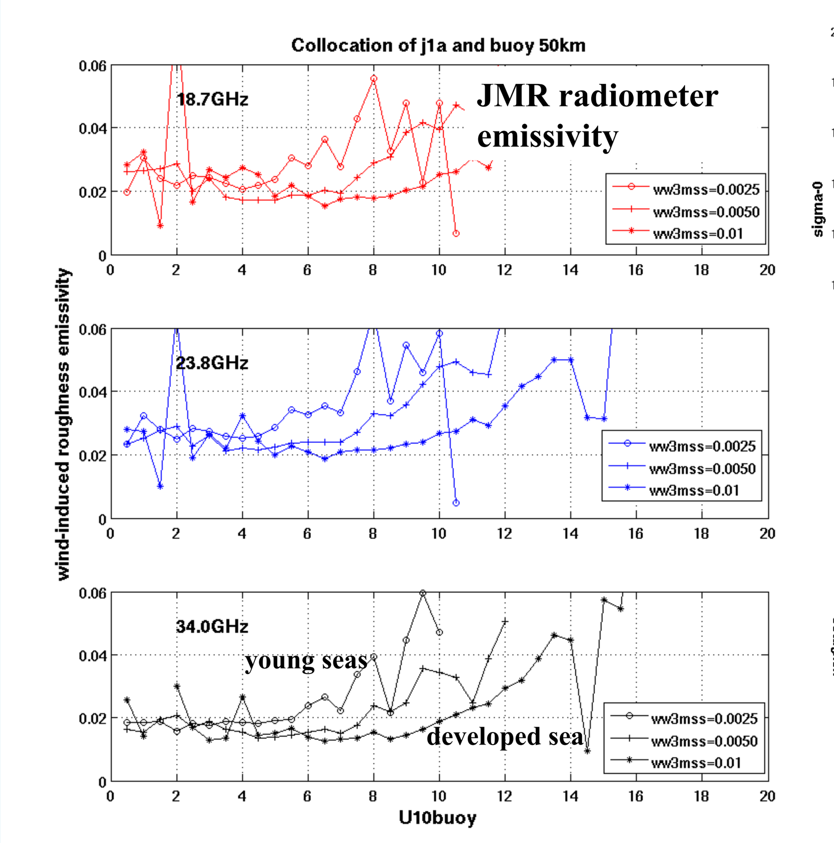
$$\sigma^0_{freq} \sim x / mss_{eff}(U) \quad \textit{where } mss_{eff\_freq}\ (U) \textit{ is total mean square slope} \qquad (3)$$

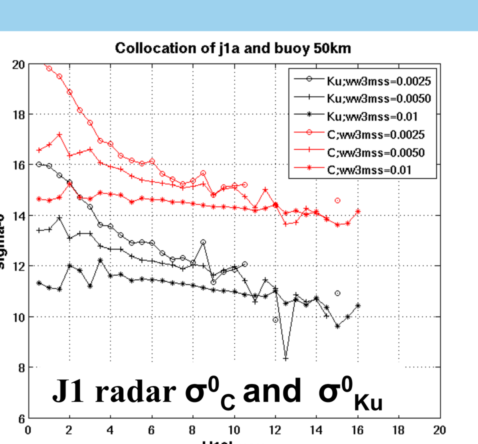
c) **short-wave roughness ~ local wind & breaking for U > 5 m/s**

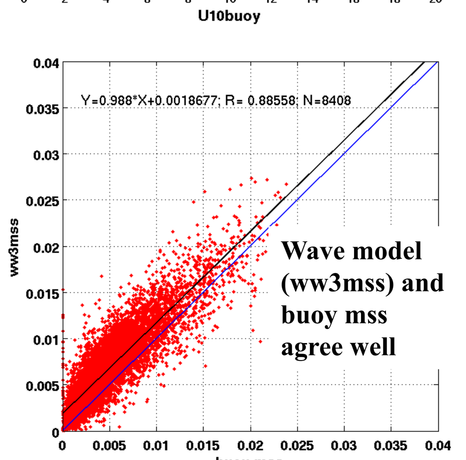
$$\delta\sigma^0_{CKu} \sim [\,(\sigma^0_C / \sigma^0_{Ku}) - 1.0\,] \qquad (4)$$

$$\sim e_{waves} + e_{foam} \cong e_{rough} \text{ for } U > 5$$

Roughness variation with changing waves observed at NDBC buoy sites







Radiometry

- Radiometer emissivity increases as mean square slope of longer waves (wave model mss) decreases
- Radiometer results similar for 18, 23, and 34 GHz
- Increase occurs after 5-6 m/s
- observe a brighter (rougher) ocean for smoother surface, a counterintuitive result **unless it is foam**

Radar

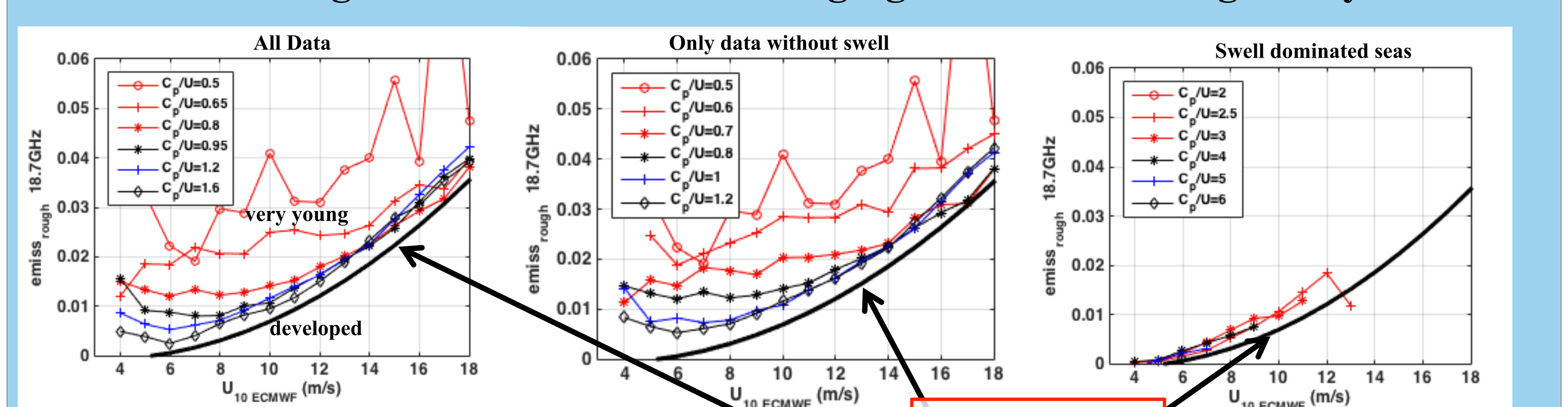
- opposite effect seen in the radar
- σ^0_C and σ^0_{Ku} increase as mean square slope of longer waves (wave model mss) decreases; an expected result indicating smoother surface
- Variation occurs at all wind speeds with greater impact at low winds; i.e. higher impact of longer waves, and not breaking waves or foam effect tied to changes above U = 5 m/s

--- RESULTS NEARLY SAME FOR J1 vs. J2 AND AMR vs. JMR

Variable sea state conditions

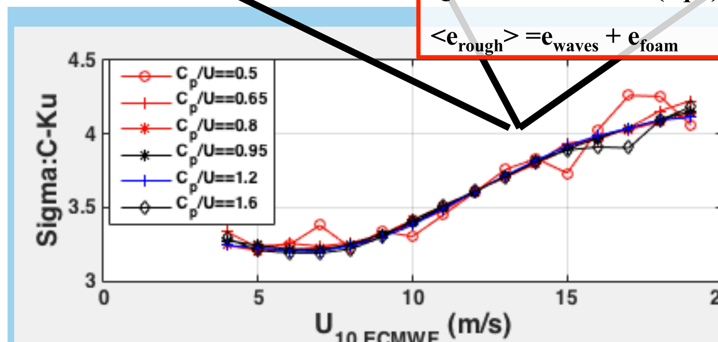
- As a first proxy to evaluate wave state impacts on foam vs. roughness in radar and radiometer data we use the longer wave mean square slope (ww3mss, for waves > 5 m) from either the buoy or wave model. Similar results are seen using either.
- We interpret lower ww3mss at a fixed wind to reflect varied sea state maturity or wave age

Roughness variation with changing waves observed globally



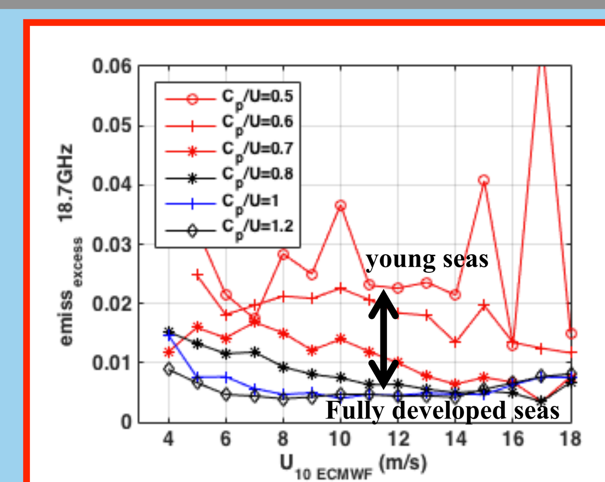
Radiometry

- Radiometer emissivity increases with wind speed with baseline quadratic as per **solid black line** derived from radar (see fig to the right)
- emissivity also decreases at any wind speed as the wave age increases
- Radiometer results similar for 18, 23, and 34 GHz (not shown)
- For very old seas (far right), little sea state variation in emissivity at 18 GHz



Dual-Freq Jason 1 radar

- $\sigma^0_C / \sigma^0_{Ku}$ increases as quadratic wind
- insensitive to wave age variation; MUCH different than for emiss.
- allows quadratic model (**arrows to black line**) for e_{rough} based on the J1 radar data



Key Result

Simple subtraction of baseline e_{rough} as given by empirical model line above and per Eq 2. leaves

e_{excess} ~= f(C_p/U) at U=5 to 15 m/s

This e_{excess} is then foam increase and roughly **ΔW**, approximately linear with C_p/U as per field-based whitecapping studies (see Gemmrich 2008 at left, Lafon et al. 2007; Kleiss and Melville, 2010)

Conclusions, Implications and Next Steps

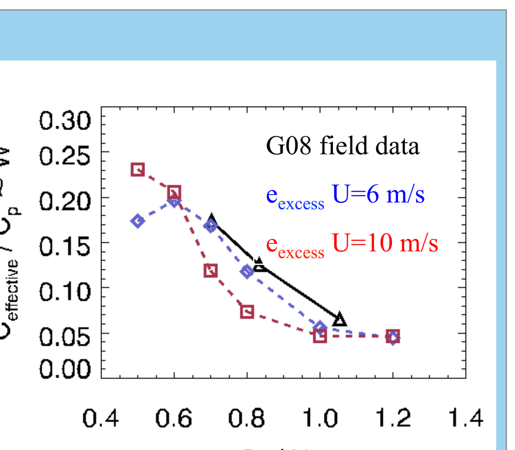
- Little doubt that foam variation due to wave breaking can be isolated in nadir viewing AMR and JMR datasets – a new result?
- Excess foam variation appears to correlate best with decreasing wave age and clearly falls off steeply as the wave field matures towards fully developed (C_p/U ~1.2)
- Results are quite consistent with recent **W** vs. wave age field data
- Observe similar results for 18, 23 and 34 GHz
- Combining results with dual-frequency radar should prove useful to discriminate between surface wave and foam effects (this idea also supported by Ku/Ka radar data from GPM)
- More precise work with 18 and 34 GHz may yield some sense of active vs. passive foam; also dying seas are special case to handle
- Results may lead to refinement of ocean wave model estimation of whitecap coverage (**W**), a satellite method to estimate **W** or variability in **W,** as well as Jason-derived identification and climatologies of young seas and large scale wave breaking
- Will be working to extract & examine the signal near storms and in the off-nadir radiometer datasets such as AMSR and Windsat

Consistent with Gemmrich et al. 2008 Fig 12a

$C_{eff}/C_p = 5.0 * e_{excess}\ (C_p/U)$

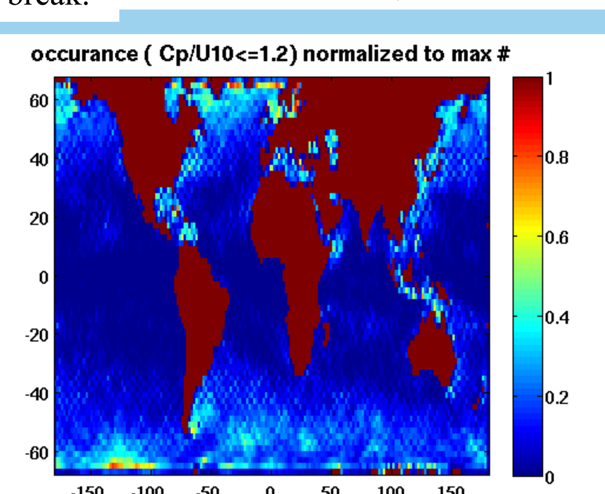
where C_{eff}= effective phase speed of breakers

This increases for young seas; i.e. longer faster waves nearer to T_p break.



Young Sea Distribution

- infrequent globally
- S. Ocean/Arctic
- western edge of basins



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