Air-sea gas exchange fluxes and steady state saturation anomalies at very high wind speeds, as revealed by noble gases

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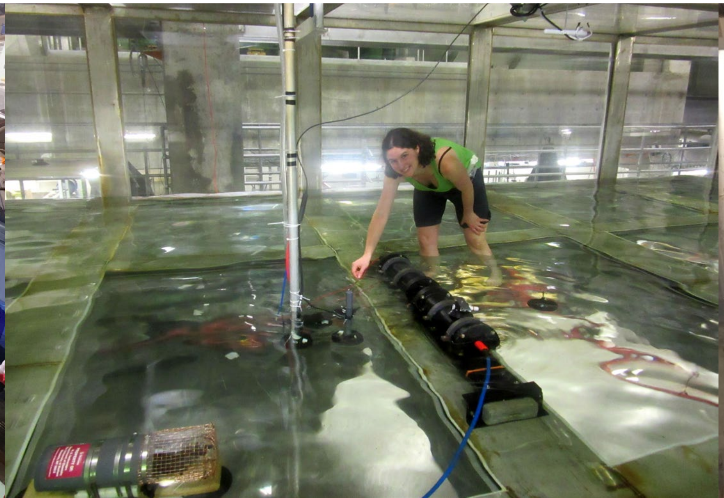

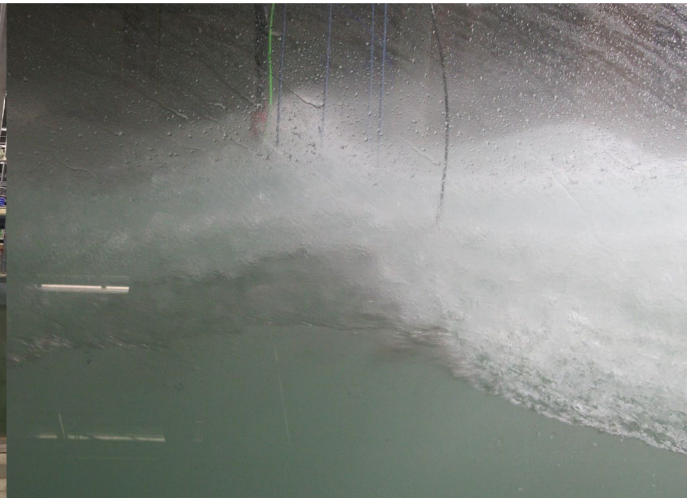

What happens to gas exchange at wind speeds > 35 m s^{-1}?

The famous plots all end – or become highly uncertain – at u 10 > 20 m s-1

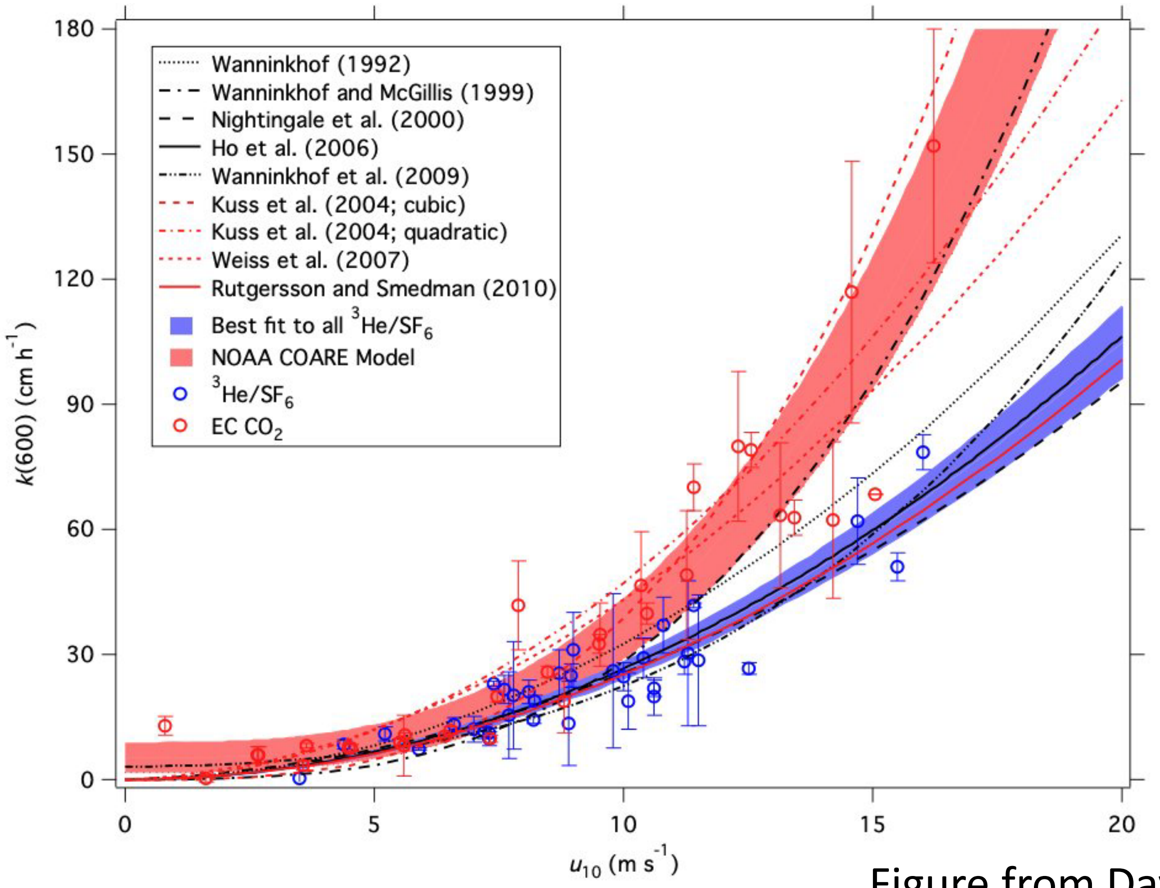

Figure from David Ho

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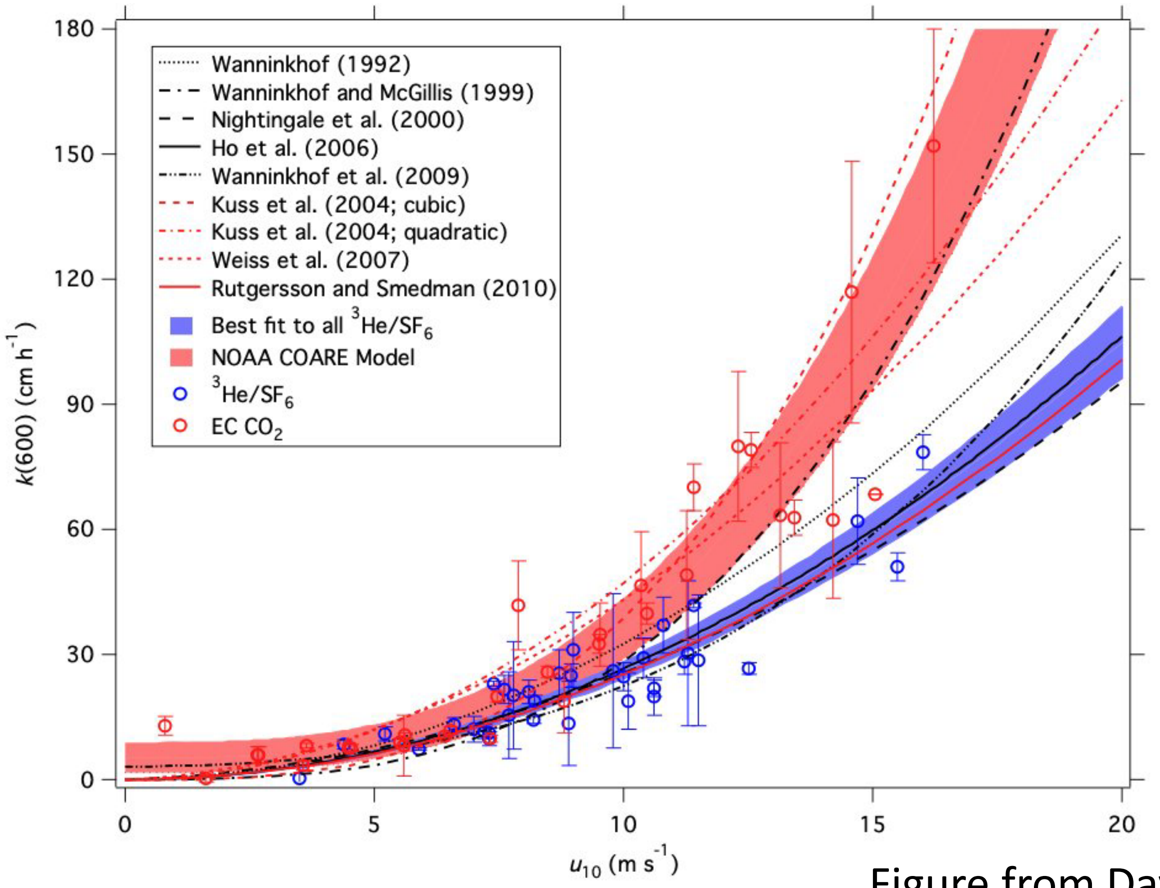
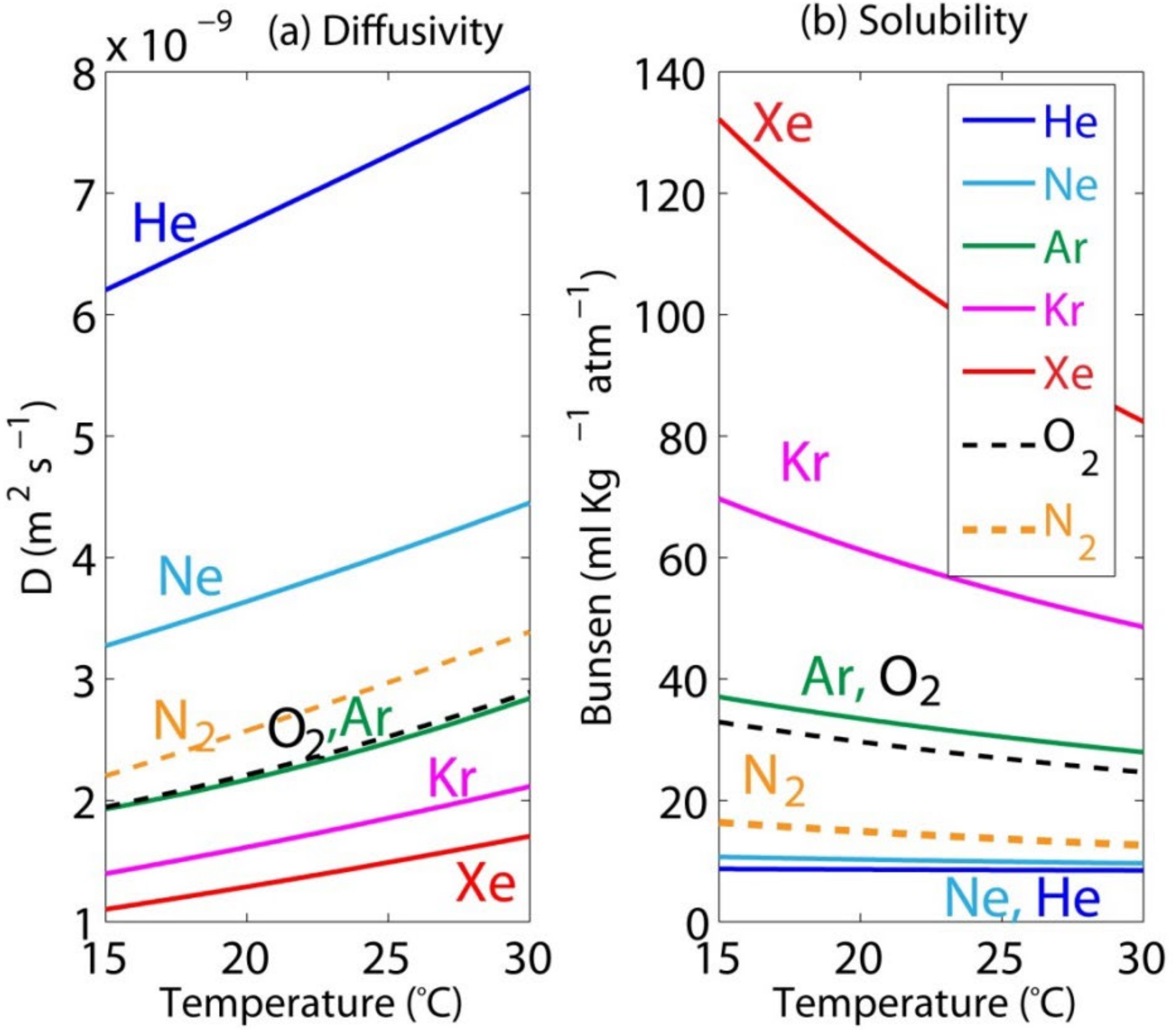


Figure from David Ho

?

Noble gases are powerful tools for studying gas exchange

- Lighter gases (Helium and Ne) sensitive to bubbles
- Heavier gases (Kr and Xe) have temperature dependent solubility
- Ar very similar to oxygen



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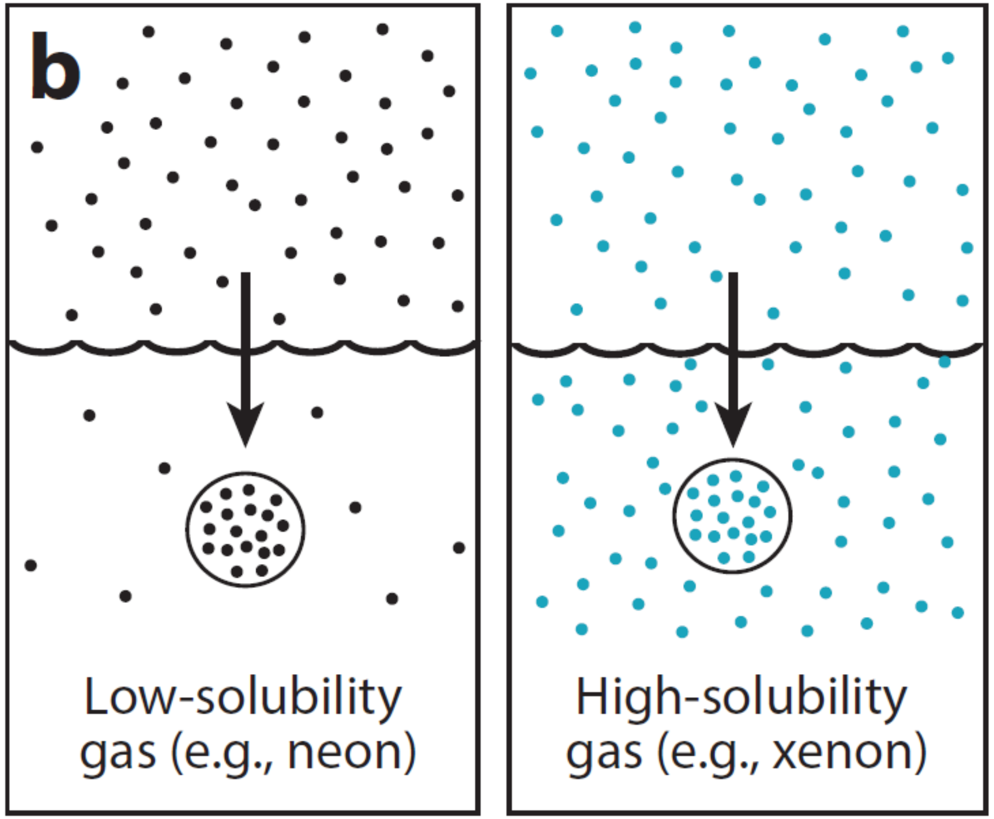
Effect of solubility on bubbles



From Hamme et al. 2018

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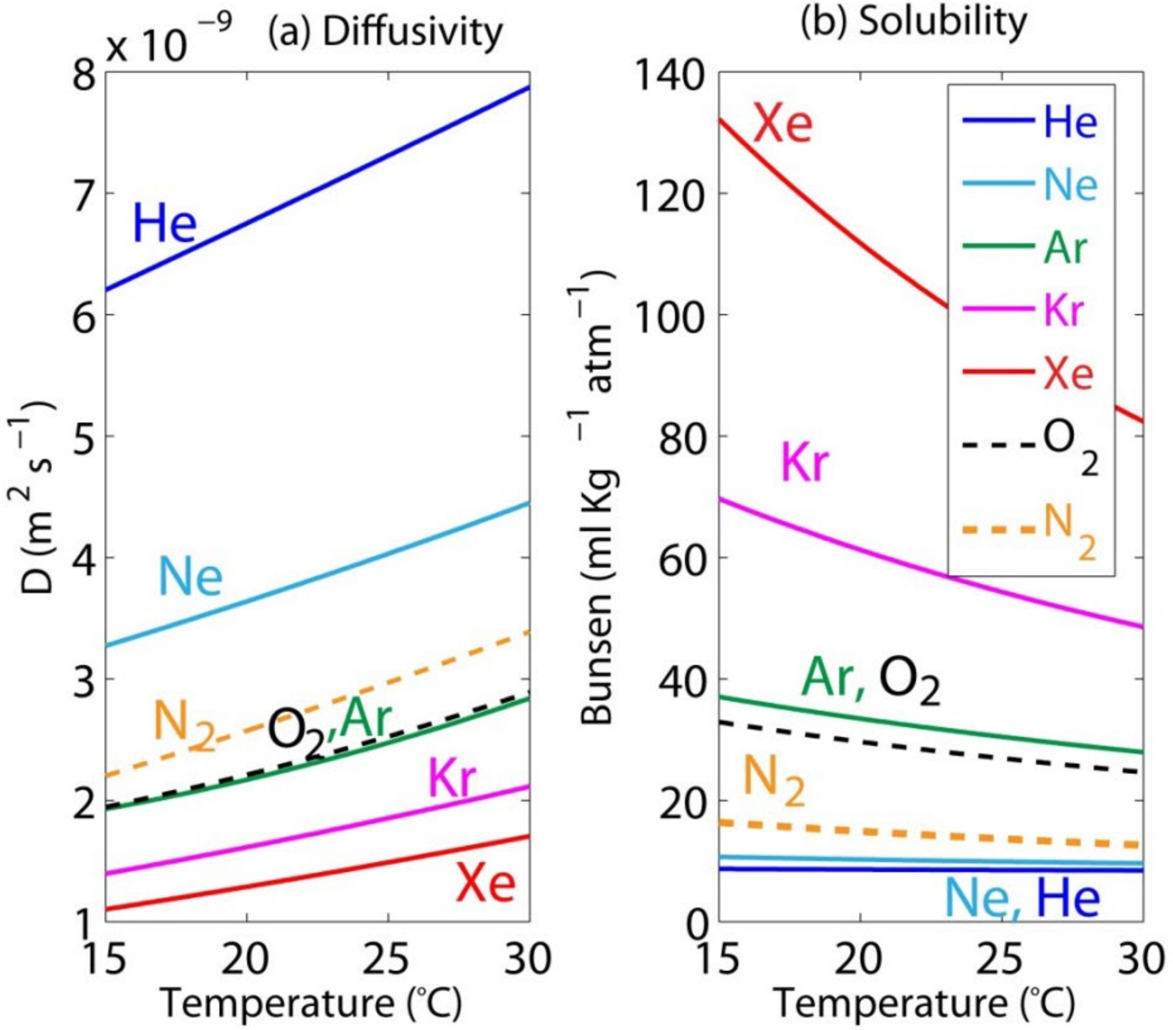
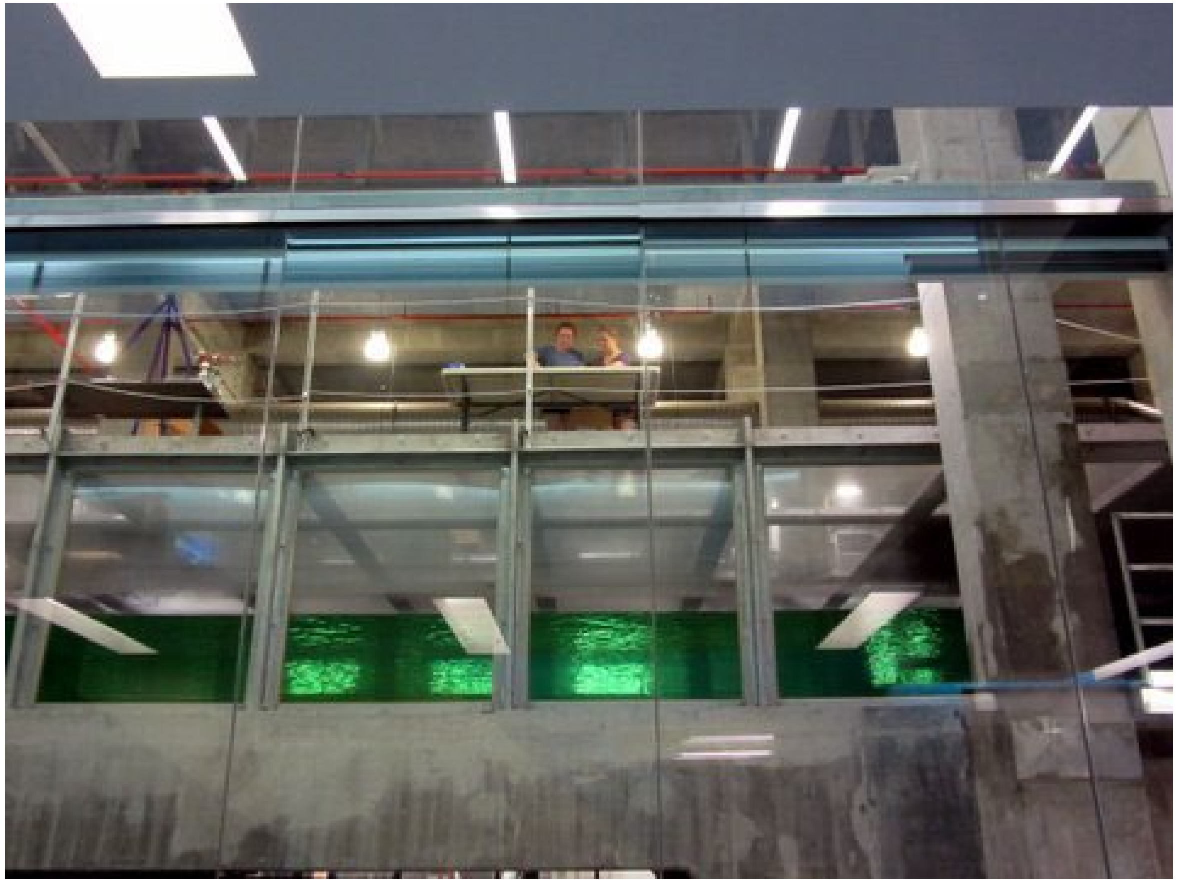


Wind wave tanks enable exploration of very high wind and waves

<u>A few specs</u>
<u>SUSTAIN tank</u>
saltwater
18 x 6 x 2 m
Wave paddles
1460 hp Fan



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- But grain of salt: not true ocean conditions, especially shallow depth

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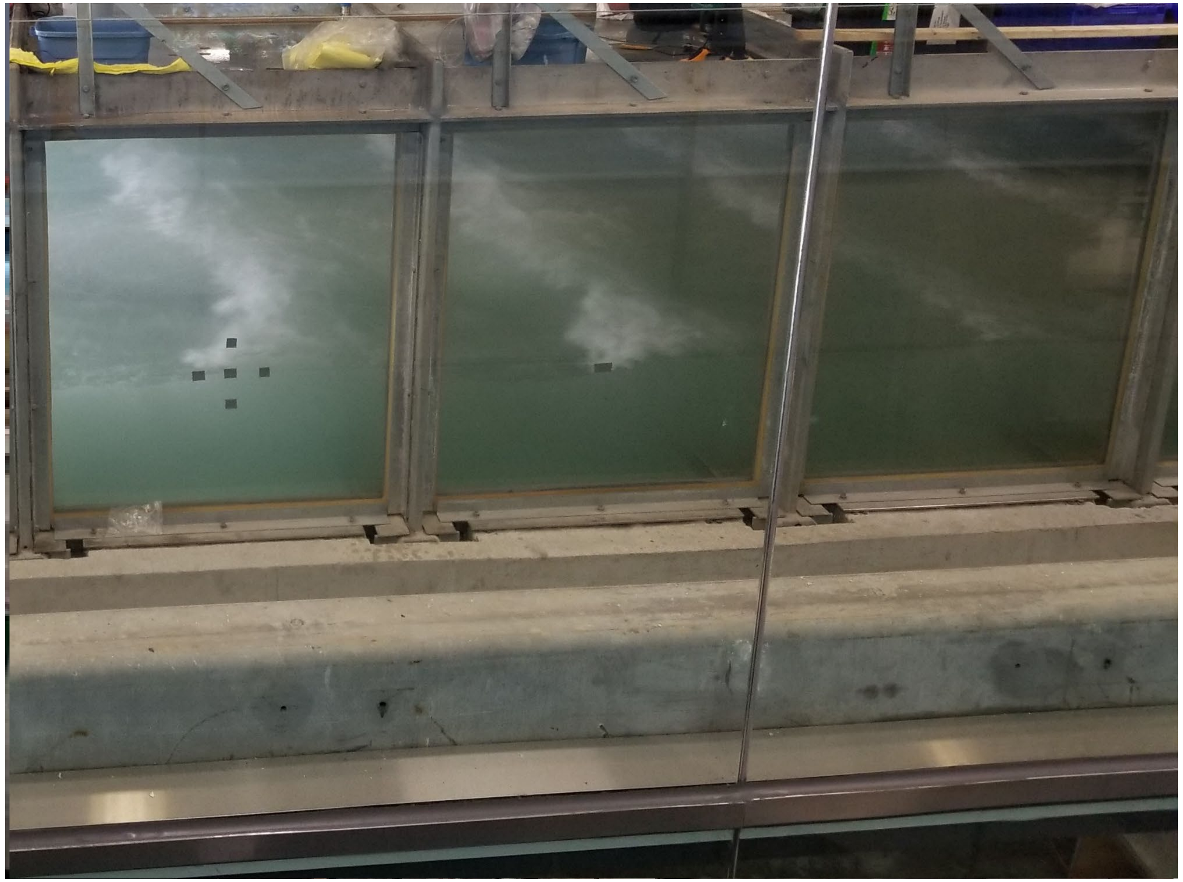
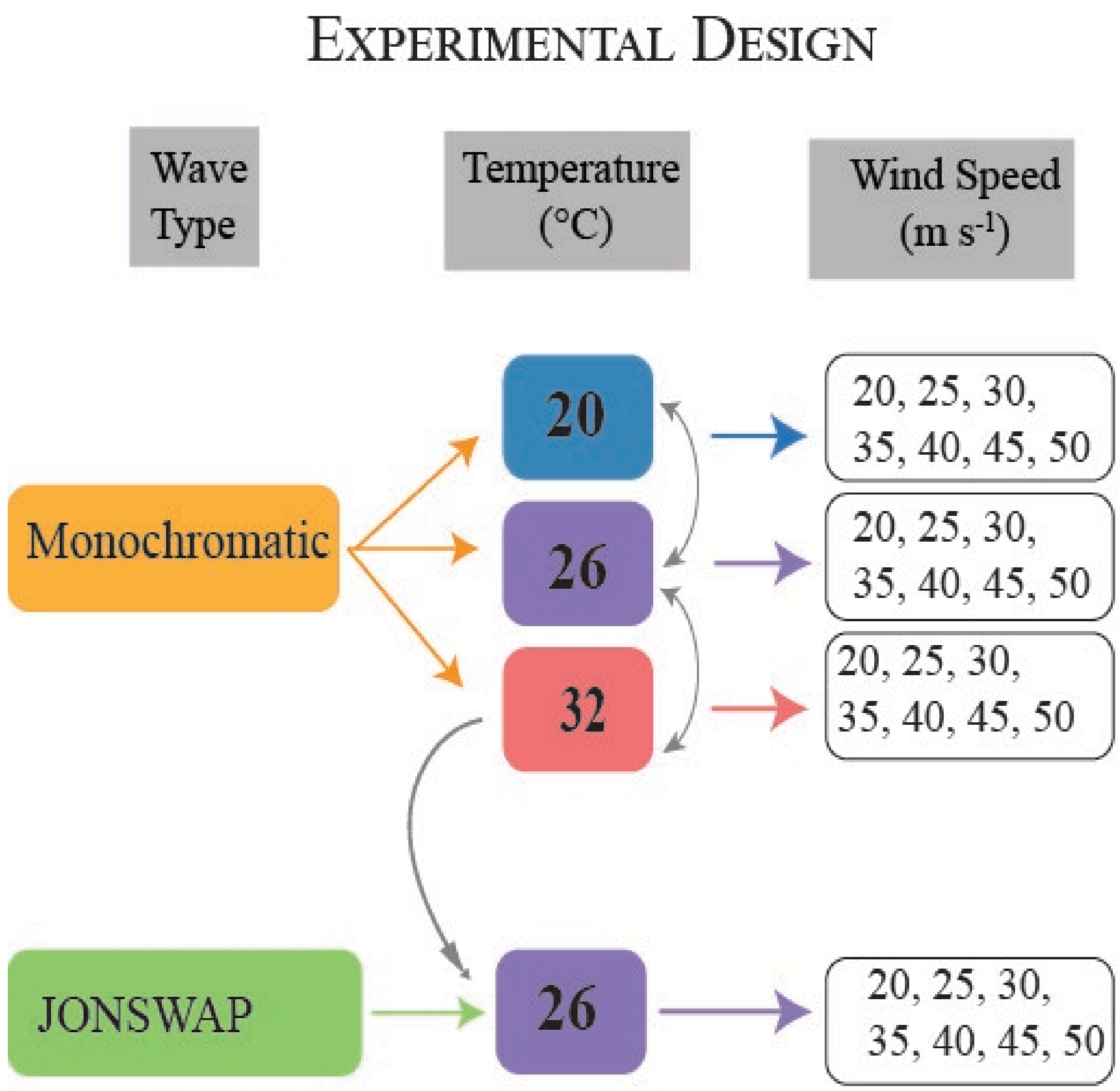


Wave types and water temperatures allowed exploration of additional variables

- Monochromatic: regular wave breaking
- JONSWAP: more realistic, random spectrum



We measured 5 noble gases, bubble properties, wave characteristics, and much more at wind speeds from 20 to 50 m s^{-1} at SUSTAIN

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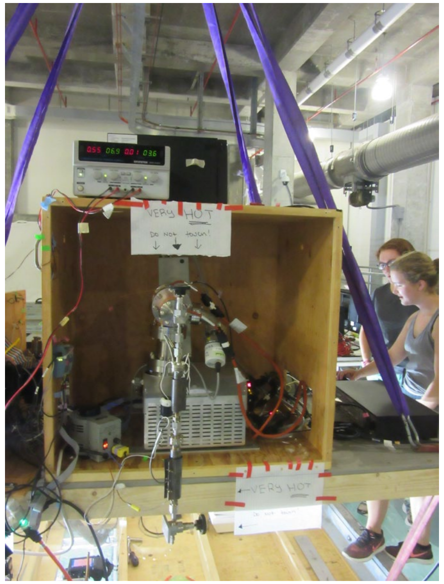

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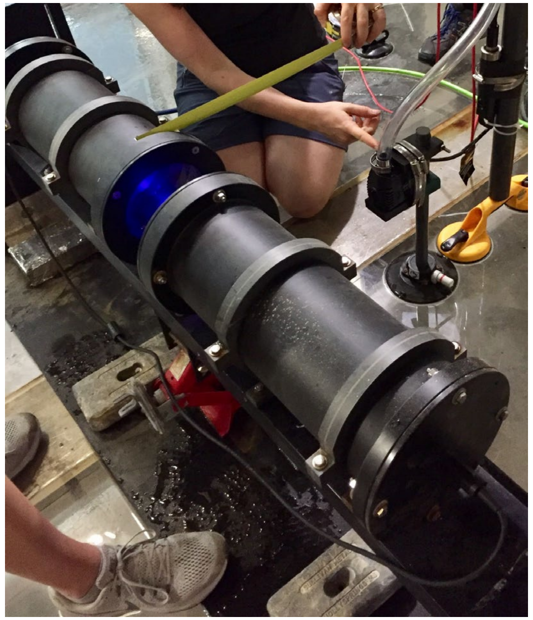

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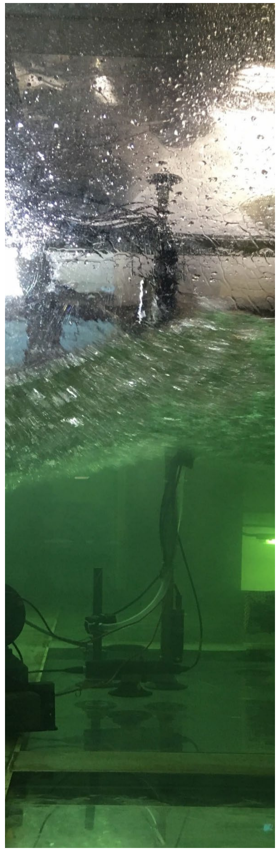
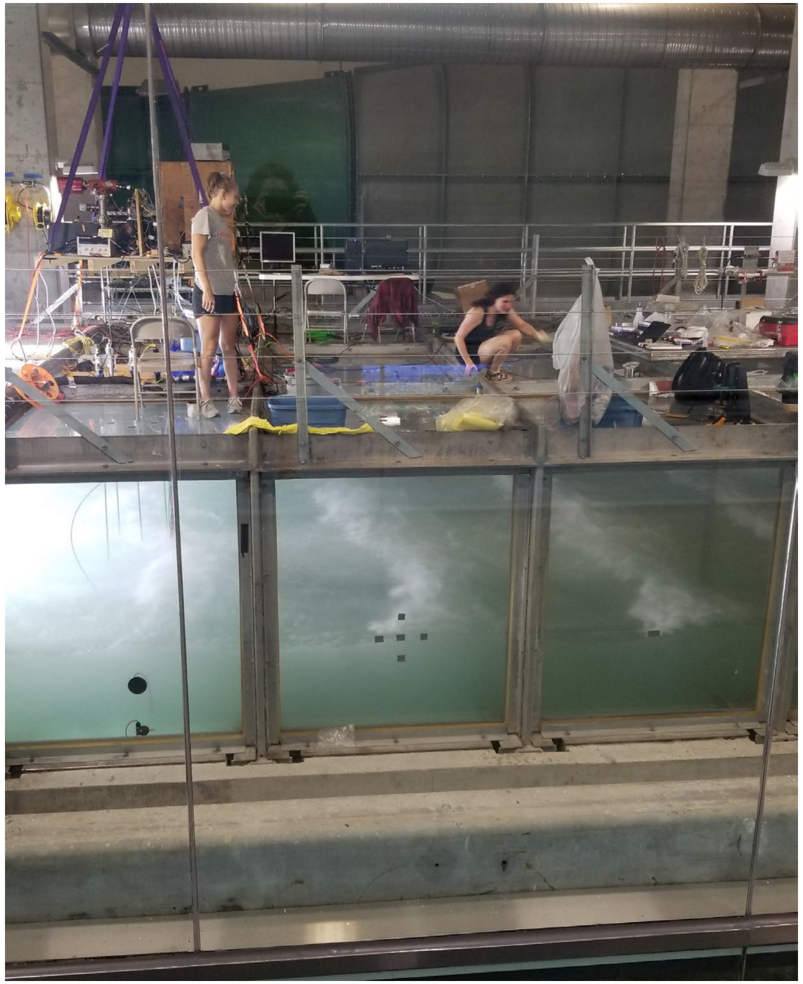
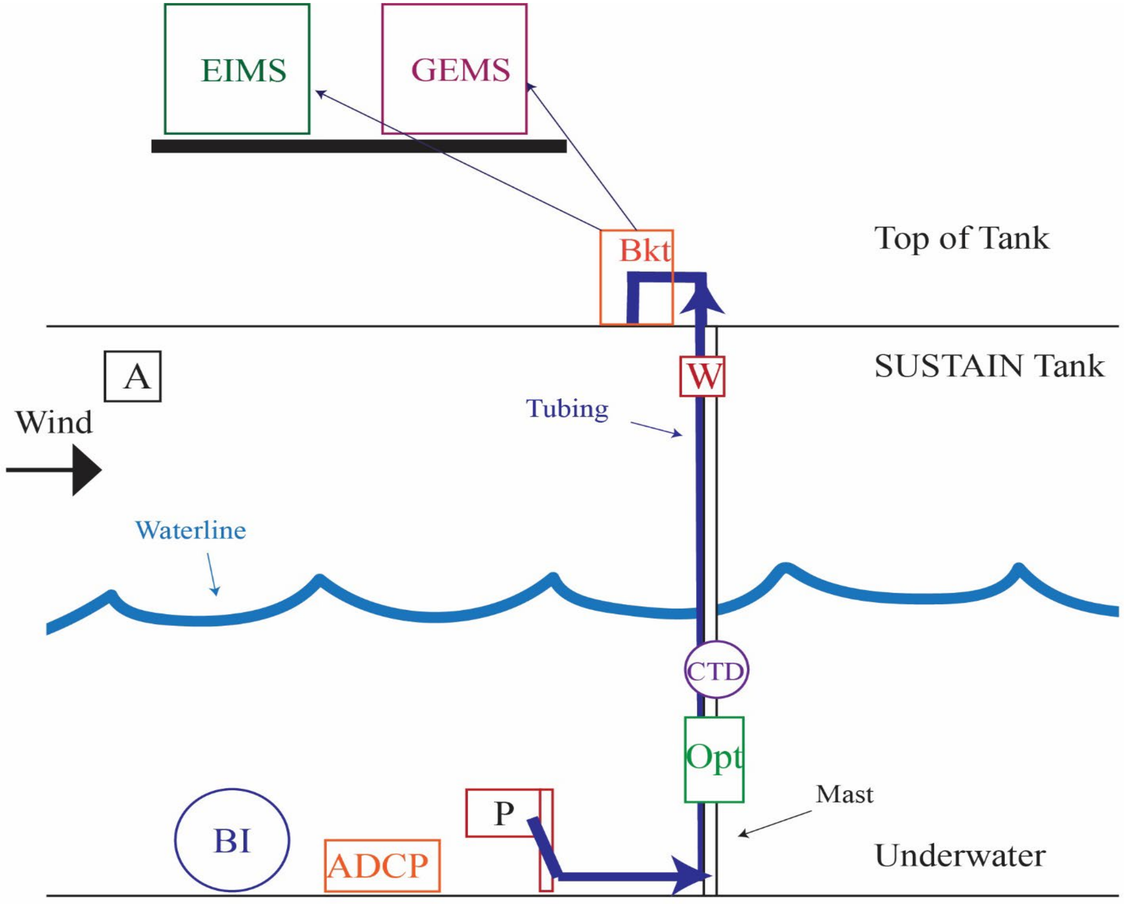
- Discrete noble gas samples from copper tubes
- Continuous noble gas data from portable mass spec.
- Bubble size spectra from bubble imager
- wave height and steepness from 3 wave wires

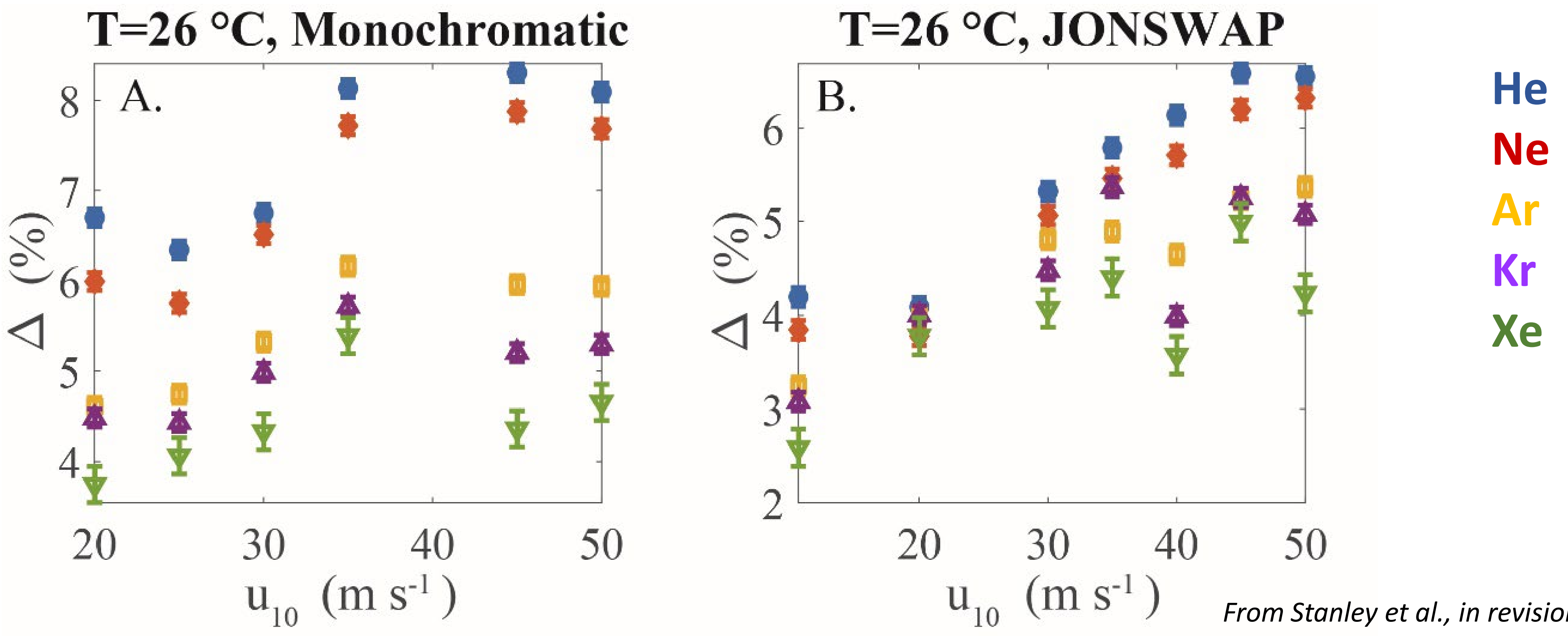


Tank was heavily instrumented!





Steady state gases increase initially and then level off as wind speed continues to increase

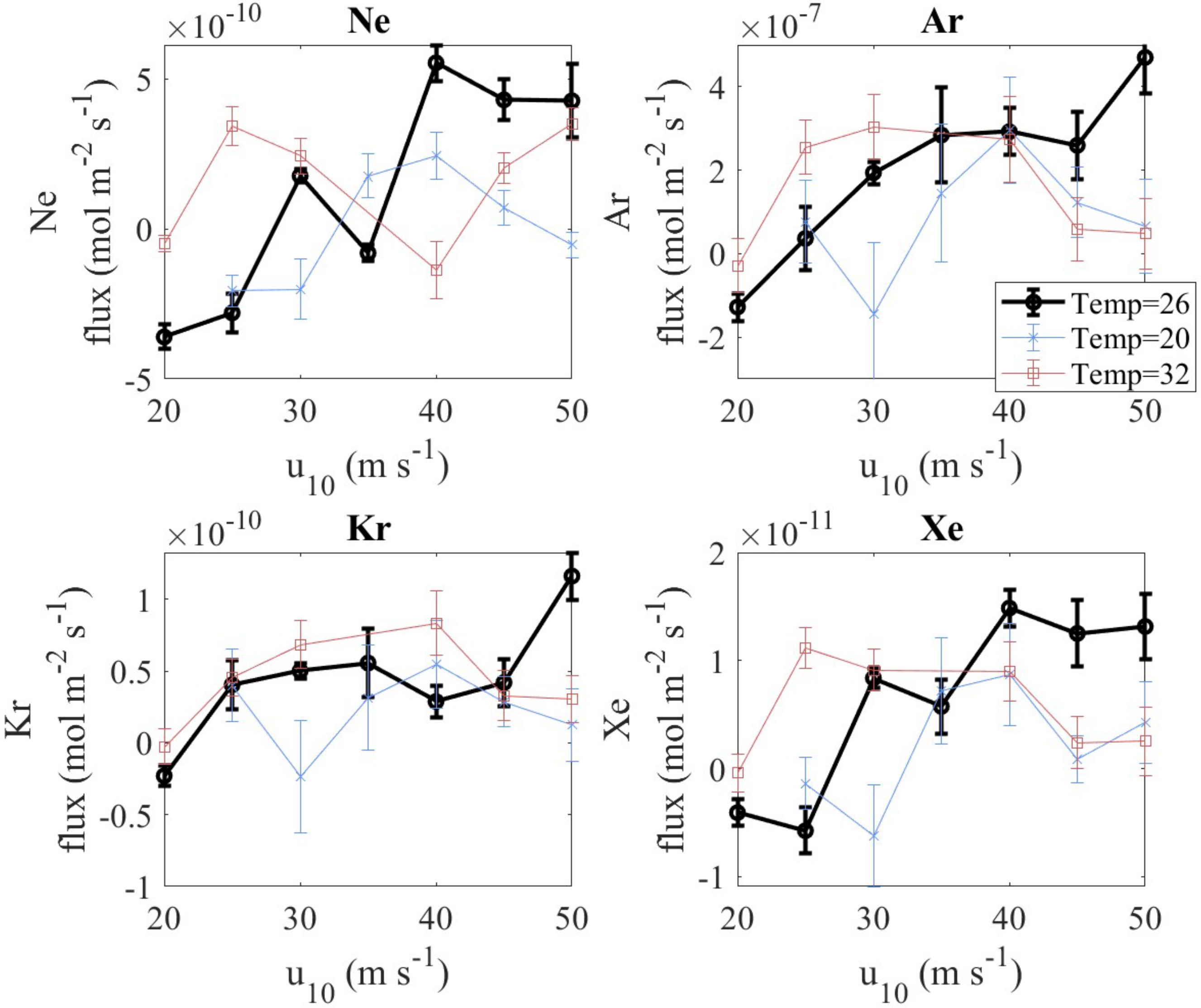


From Stanley et al., in revision JGR Oceans

Δ = steady state saturation anomaly = % supersaturated in quasi-steady state

Gas Fluxes also increase and then level off

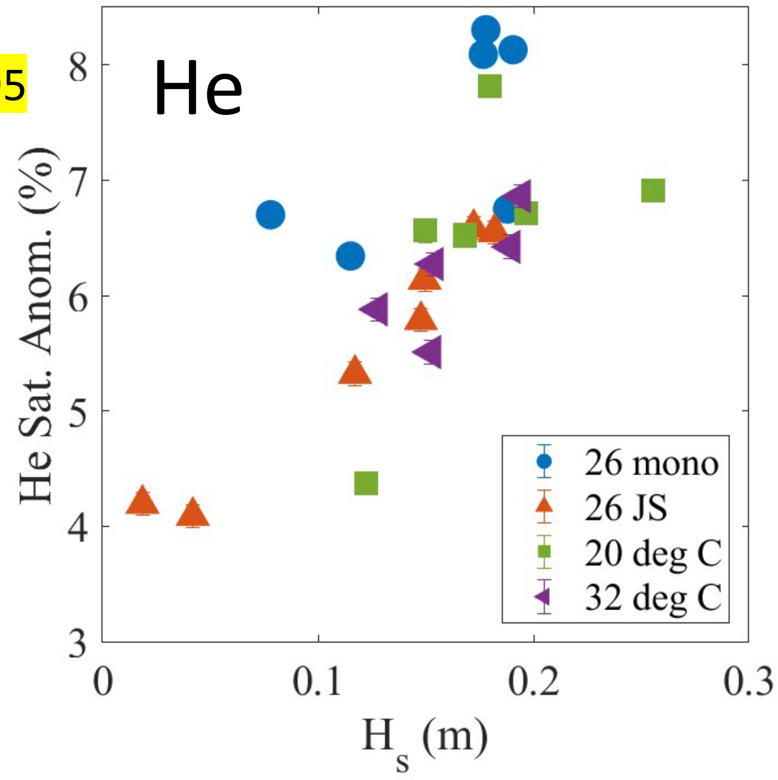
• Fluxes higher errors because of portable mass spectrometer

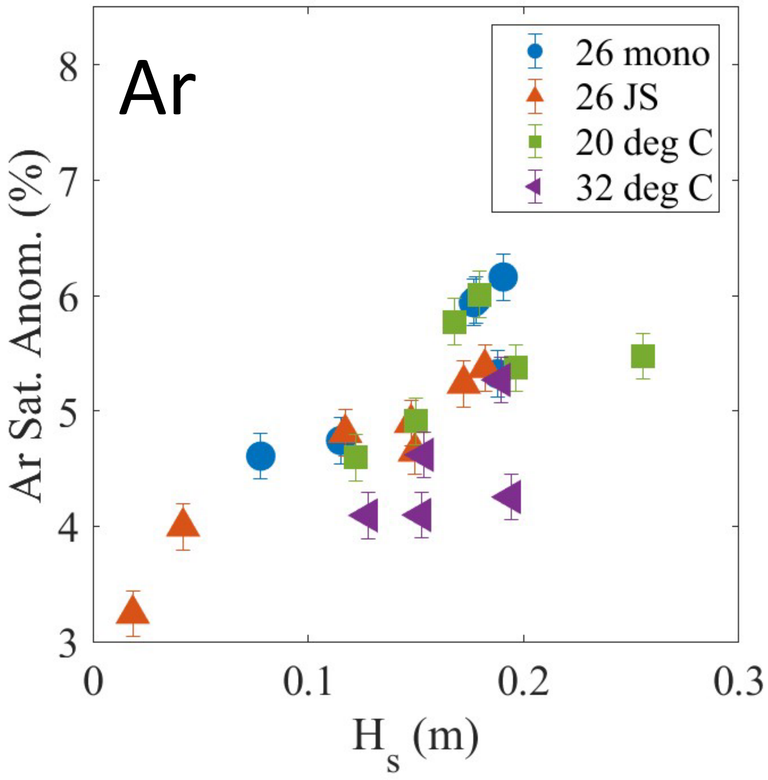


Gases are tightly correlated with wave statistics

Correlations with Significant Wave Height (H_s)

$R^2_{all} = 0.43$
$R^2_{Jonswap} = 0.95$





$R^2_{all} = 0.55$
$R^2_{Jonswap} = 0.90$

From Stanley et al., in revision JGR Oceans

Gases are tightly correlated with wave statistics

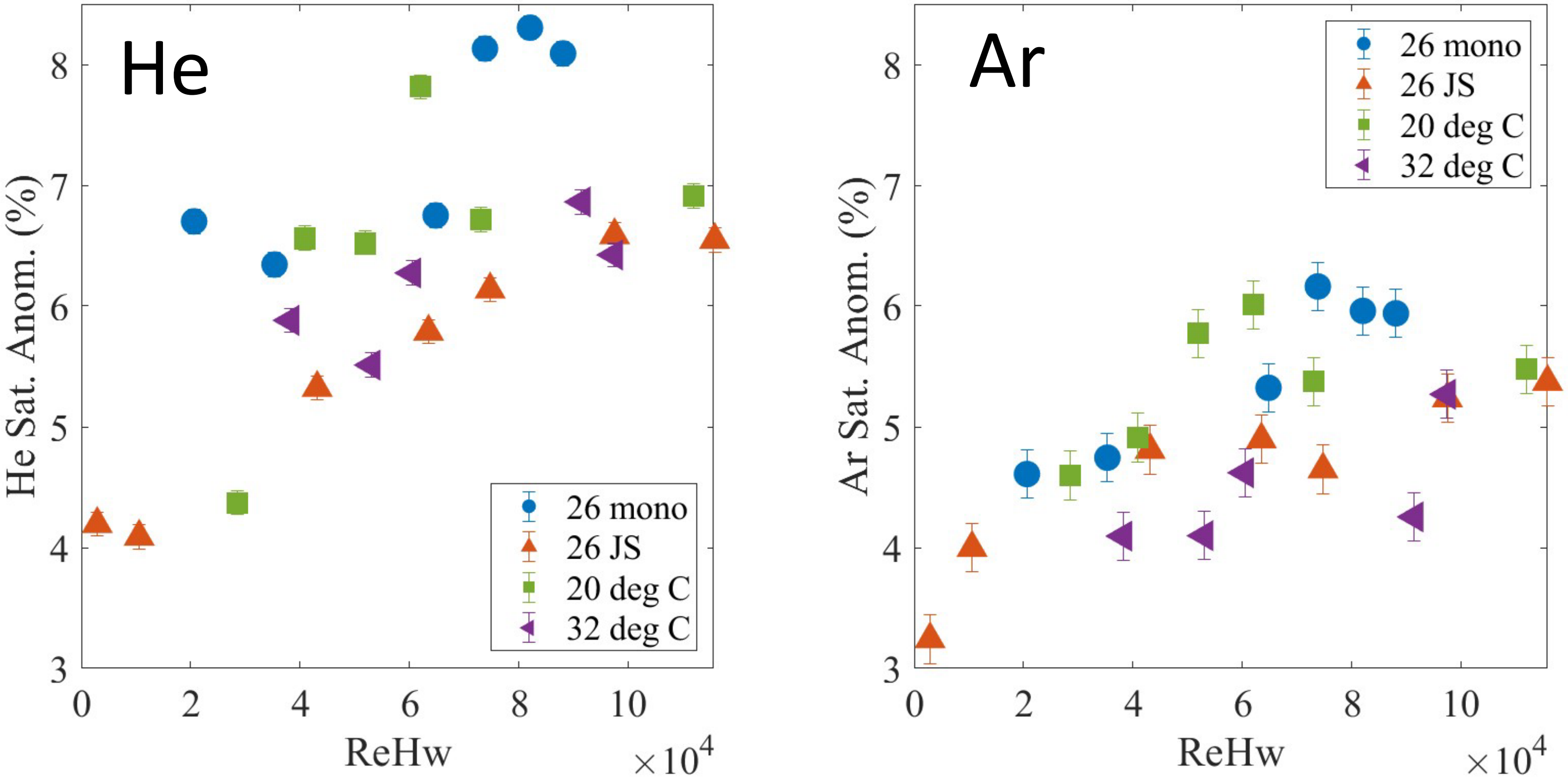
Correlations with Wind-Wave Reynolds Number ReHw = $u_* H_s \upsilon_w^{-1}$

R^2_{all} =0.50

$R^2_{Jonswap}$ = 0.94

R^2_{all} = 0.56

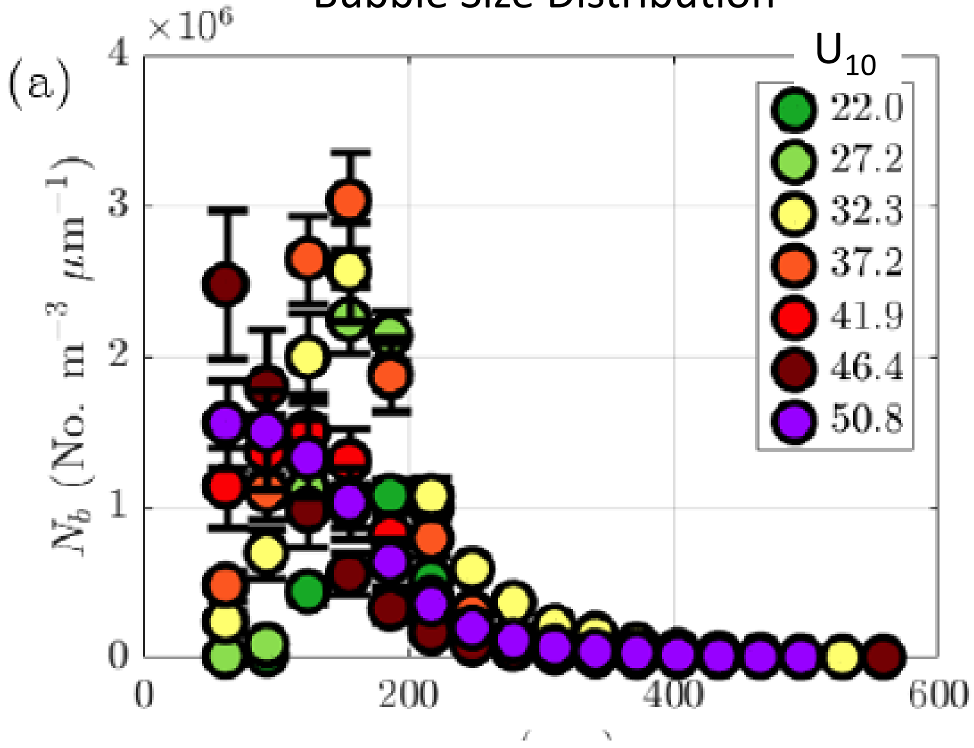
$R^2_{Jonswap}$= 0.79



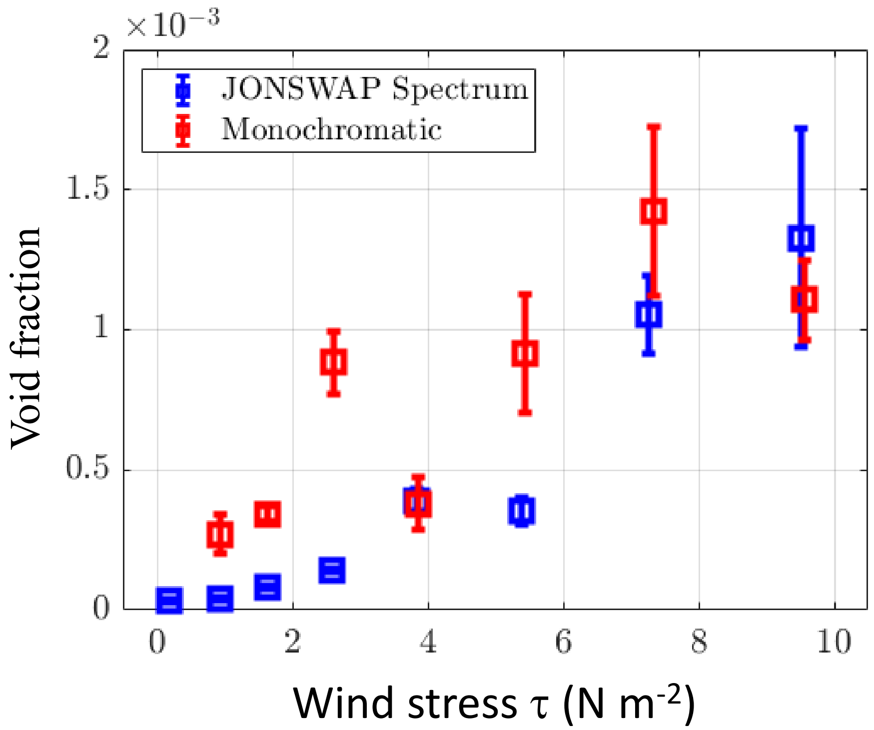
From Stanley et al., in revision JGR Oceans

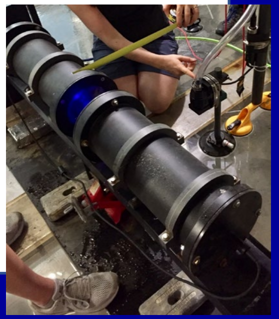
As wind speed increases, a shift to small smaller bubbles and increased bubble volume

Bubble Size Distribution



Bubble Void Fraction



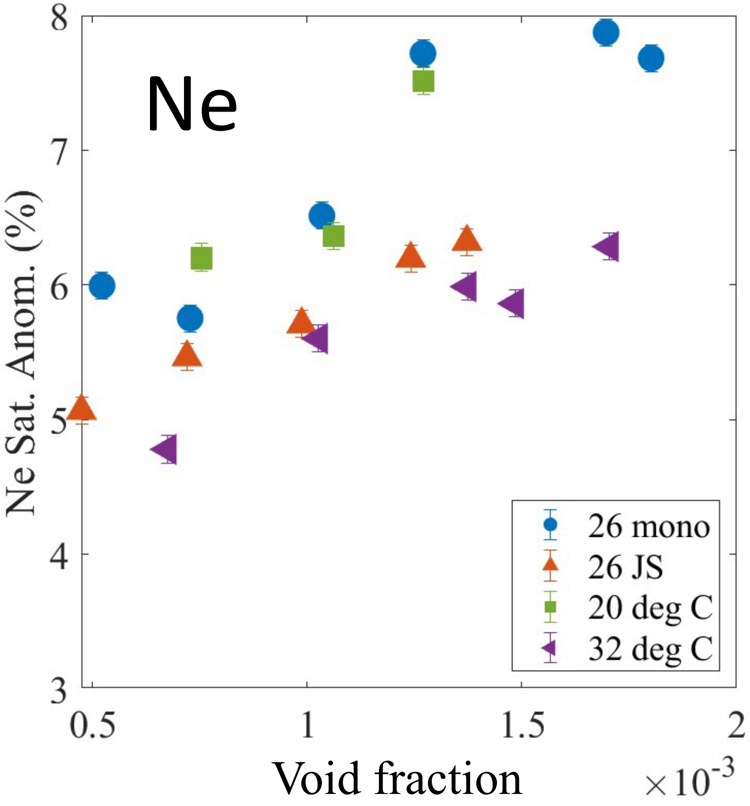


From Smith et al., in revision JPO

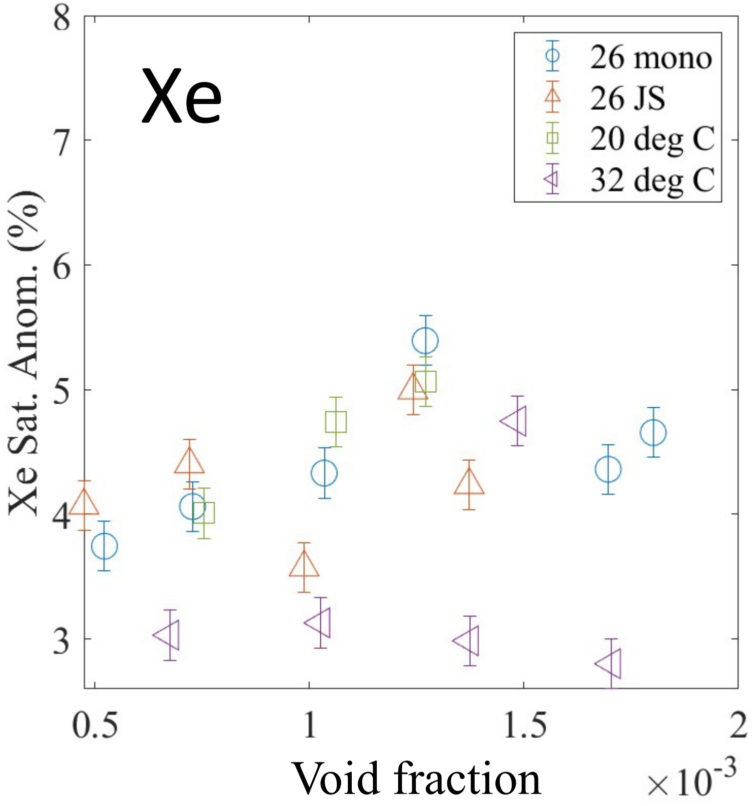
Bubble volume highly correlated with He and Ne

R^2_{all} =0.77
$R^2_{uniform, 26}$ = 0.80
$R^2_{Jonswap}$ = 0.98

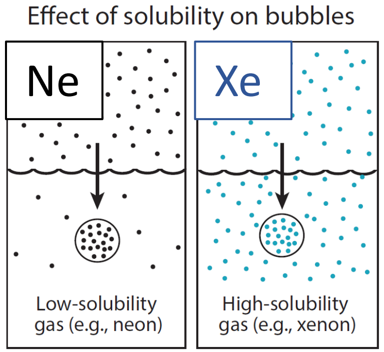
Less soluble gases <u>are</u> very sensitive to bubbles



More soluble gas <u>not</u> very sensitive to bubbles



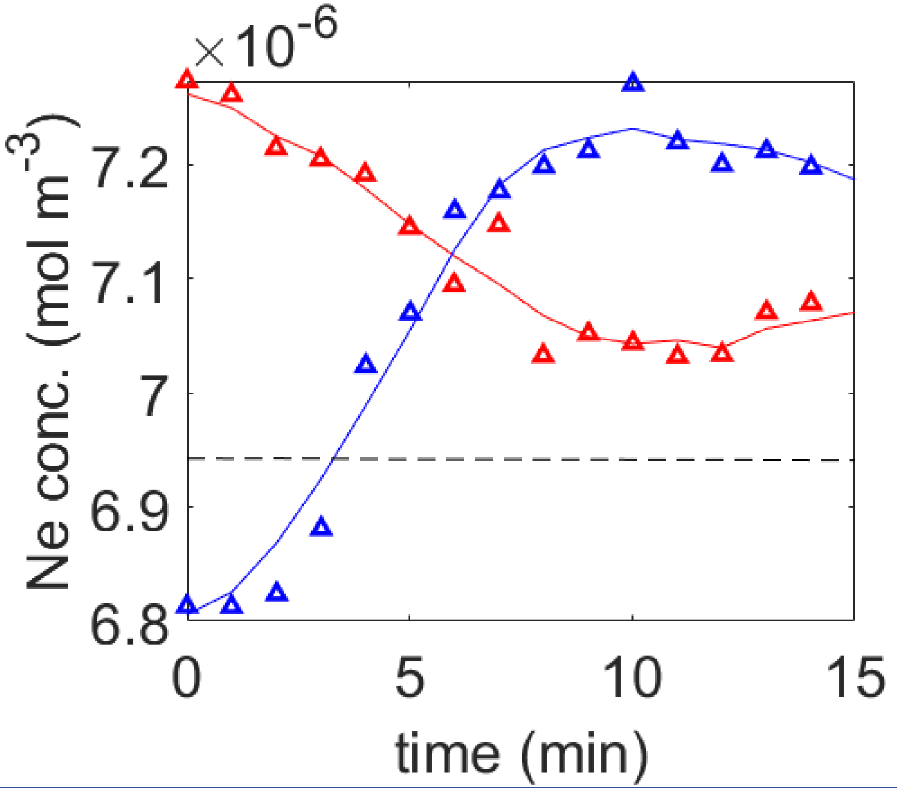
Correlations are not significant



From Stanley et al., in revision JGR Oceans

Asymmetry in action: invasion fluxes are larger than evasion for similar conditions

- Change in temperature used to set up undersaturation or supersaturation, wind speed at 35 m s-1



Invasion: starts undersaturated, Expt #1
Evasion: starts supersaturated, Expt #17

Asymmetry in action: invasion flux is larger than evasion for similar conditions

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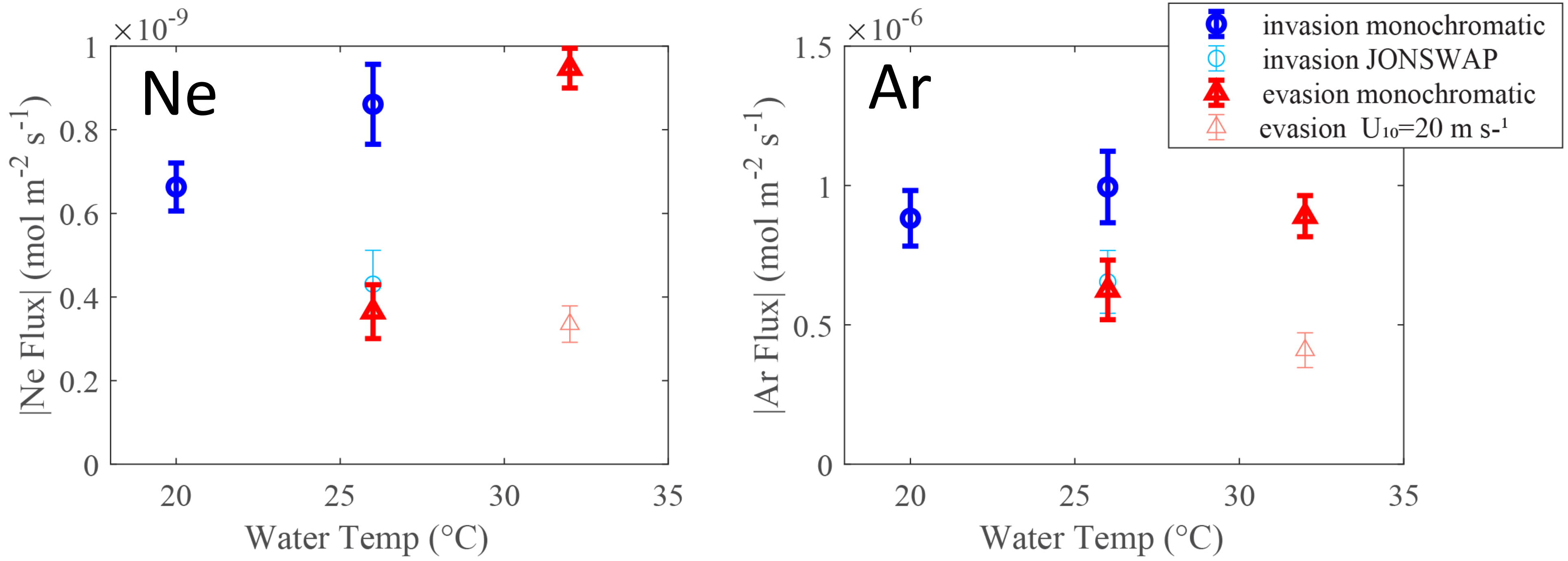


From Stanley et al., in revision JGR Oceans

Conclusions

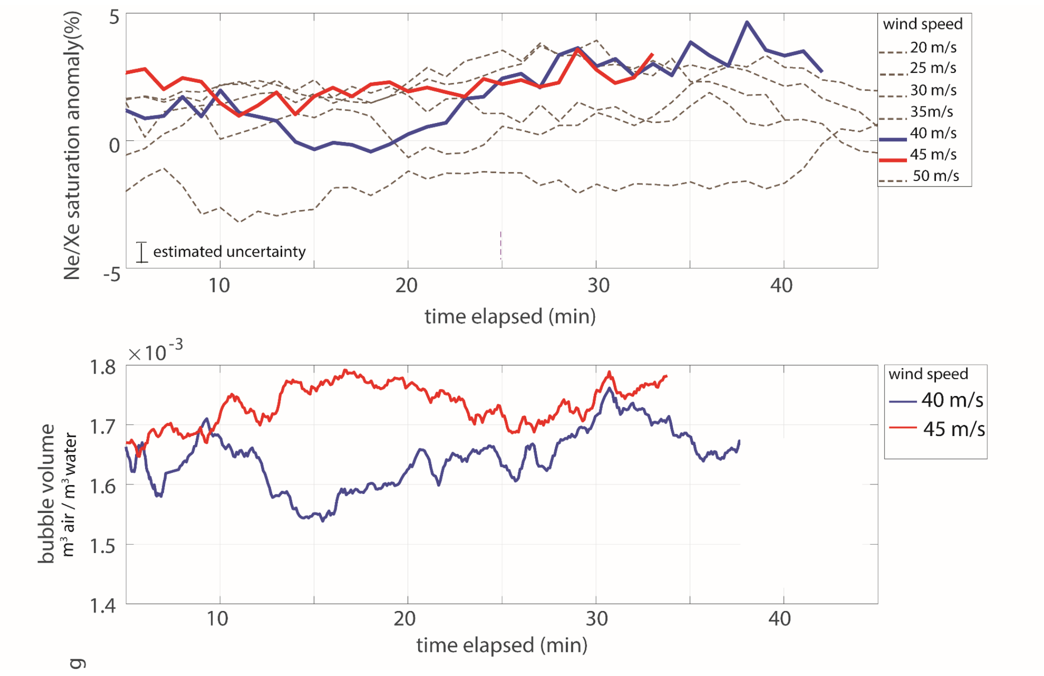
- Air sea fluxes of noble gases initially increase as wind speed increases from 20 m s^{-1} to 35 m s^{-1} but then level off at higher speeds

- Steady state saturation anomalies are more strongly correlated with bubble volume and significant wave height than with wind speed

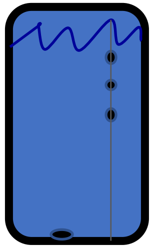
- Invasion fluxes are larger in magnitude than evasion fluxes under similar conditions

Next Steps

- Bubble Model
  - see correspondence between minute by minute bubble distribution and continuous noble gas measurements
  - Constructing 1D model to step forward in time testing some current bubble parameterizations



- Deeper tank? Targeted tank process studies? Field Experiments?



Acknowledgements

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