GULF OF MEXICO RESEARCH INITIATIVE

CARTHE

# Air-sea Gas Exchange and Bio-surfactants: Low and High Wind Speed Extremes

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**in collaboration with**

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*Air-Sea Gas Flux Workshop*

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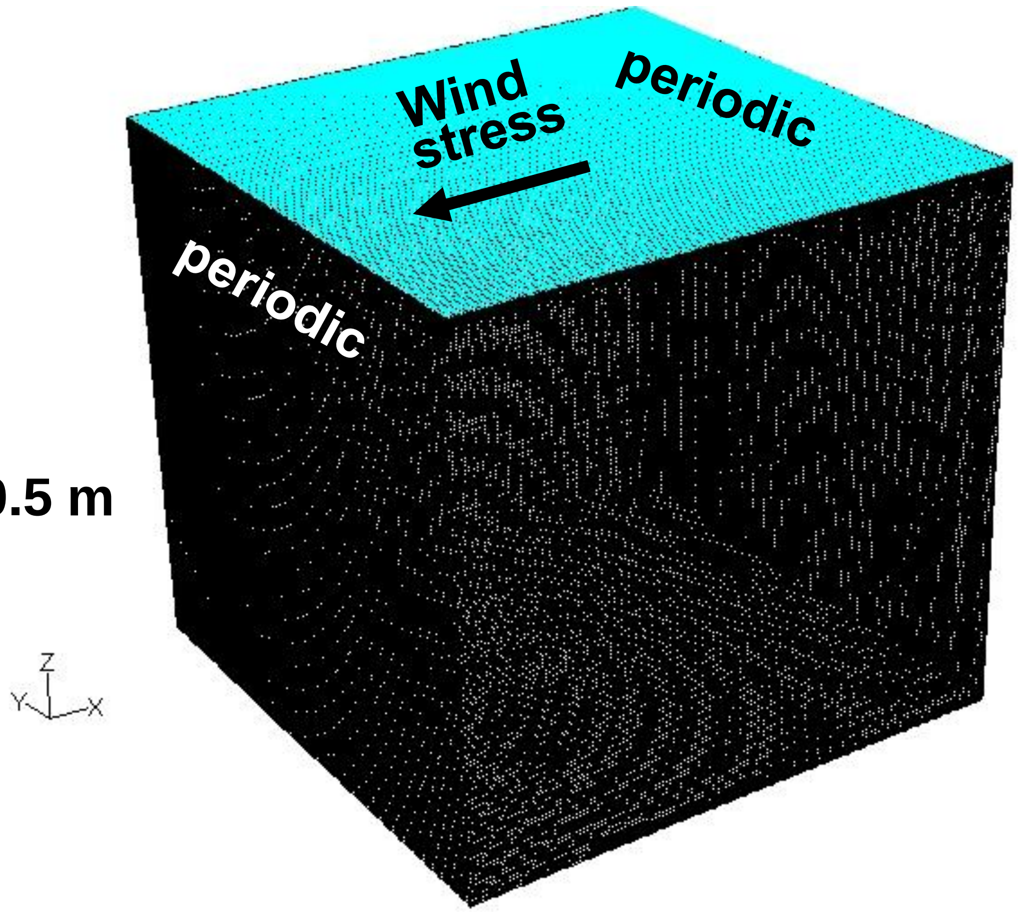
# Outline

1. **Low winds**
   - simulation of surfactant effects with CFD
   - microlayer and surfactant associated bacteria
   - sampling and DNA analysis of bacteria
2. **Strong winds**
   - simulation of air-sea interface with CFD VOF
   - direct disruption of the air-sea interface
   - anticipated effect of surfactants
3. **Conclusions**

# Low Wind: Simulation of Surfactant Effects with Computational Fluid Dynamics (CFD)

| Length, m | Width, m | Height, m | Δx, m | Δy, m | Δz, m | Growth Rate |
|---|---|---|---|---|---|---|
| 0.5 | 0.5 | 0.5 | 0.0025 | 0.0025 | 0.001 | 1.1 |

**0.5 m x 0.5 m x 0.5 m**




Matt et al. (2011)

# Elastic Boundary Condition

**Wind stress** | **Surfactant Marangoni stress** | **Temperature Marangoni stress**

$$\tau_x = \tau_{wind} + \partial\sigma / \partial C \cdot \partial C / \partial x + \partial\sigma / \partial T \cdot \partial T / \partial x$$

$$\tau_y = \partial\sigma / \partial C \cdot \partial C / \partial y + \partial\sigma / \partial T \cdot \partial T / \partial y$$

$\sigma$ – **surface tension**

$C$ – **surfactant concentration**

$T$ – **water surface temperature**

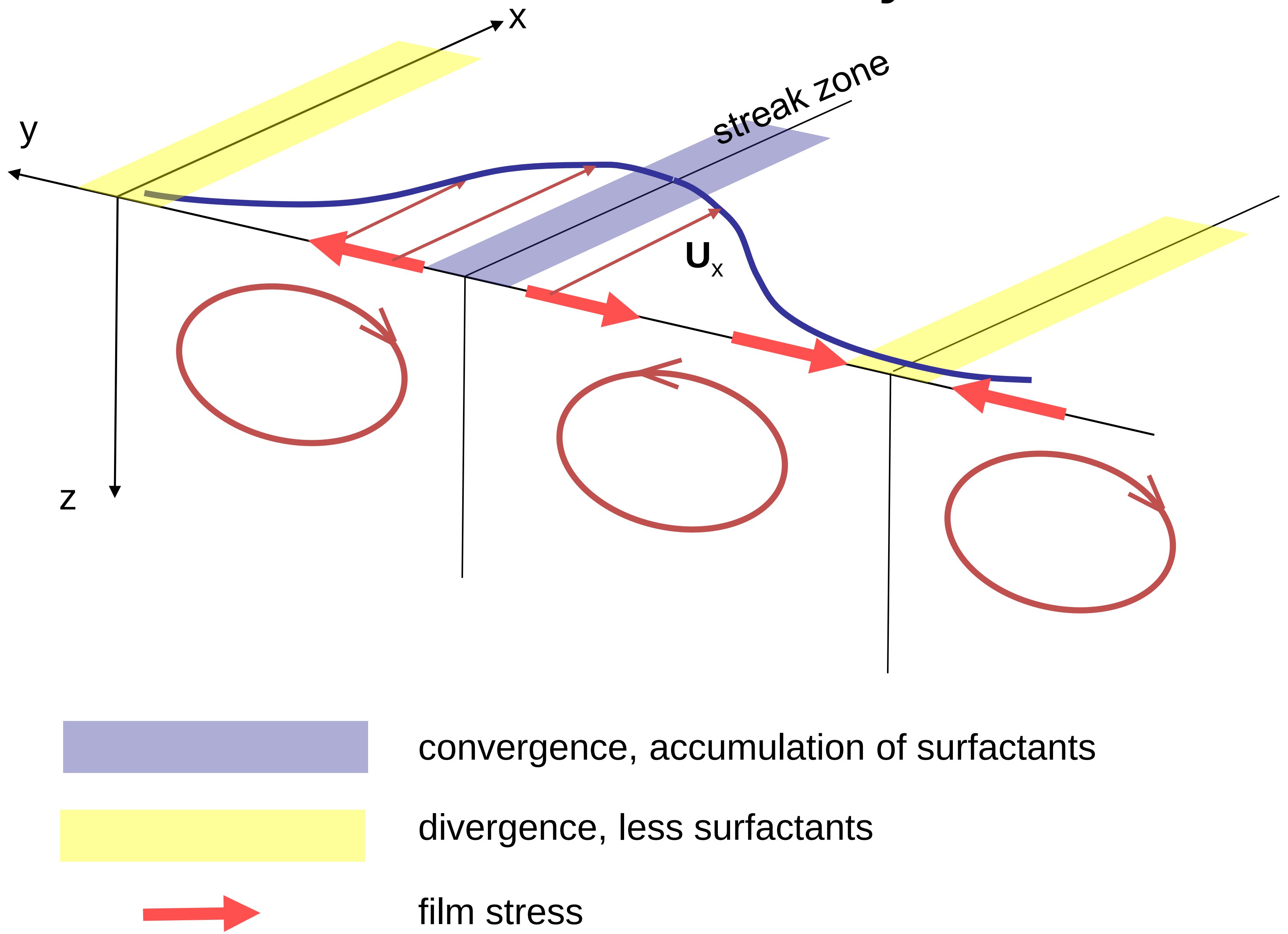
# **No Surfactant** - Top view: U at top (z = 0 cm)

Impossible d'afficher l'image.

# With Surfactant - Top view: U at top (z = 0 cm)

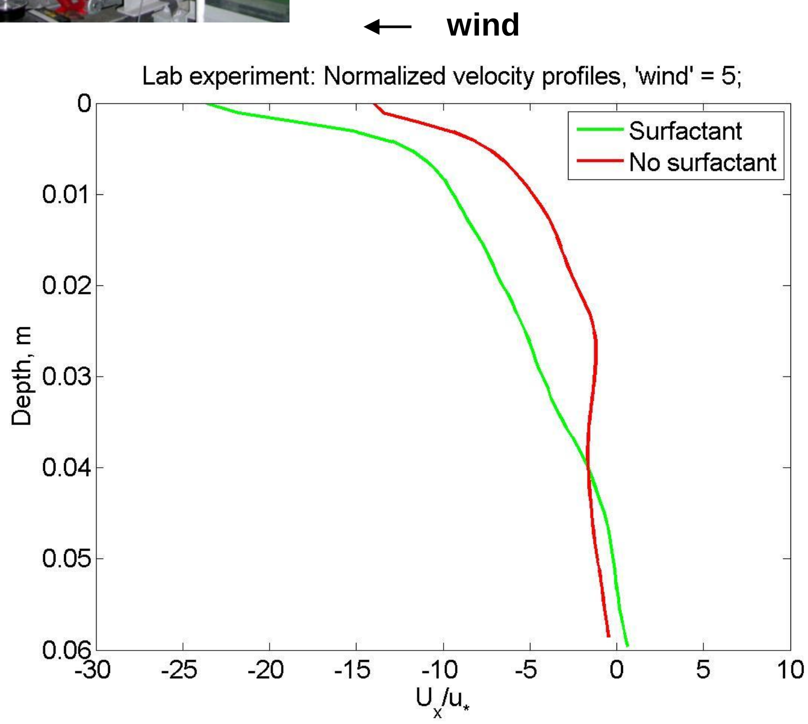
Impossible d'afficher l'image.

# Surfactants suppress coherent streaks and turbulence in the near-surface layer of the ocean

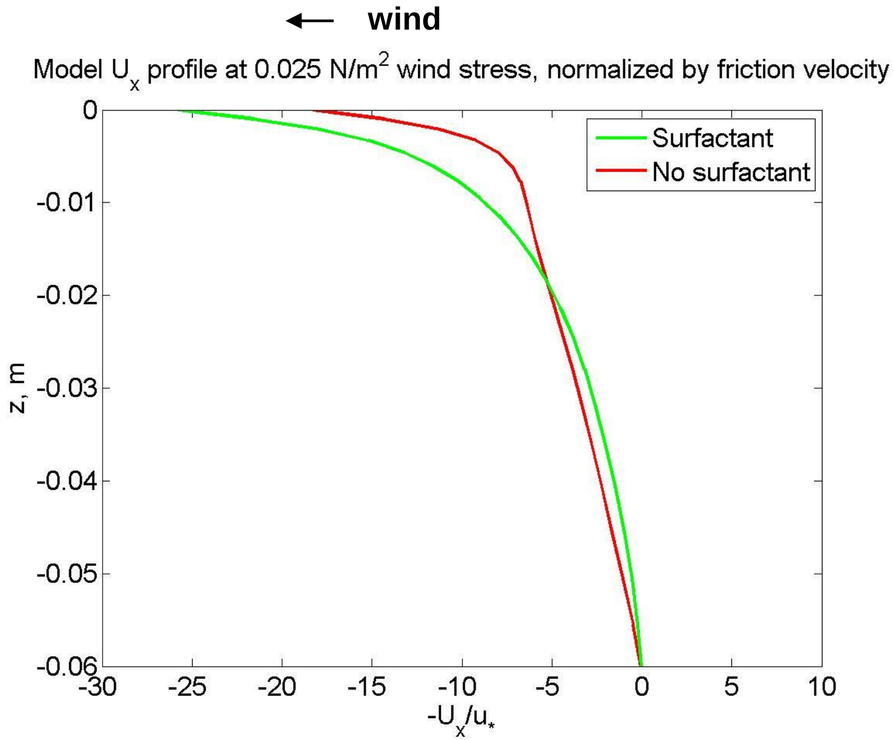


# CFD Model Validation at UM RSMAS ASIST Tank

Soloviev, Matt, Gilman, Hühnerfuss, Haus, Jeong, Savelyev, and Donelan (2011)

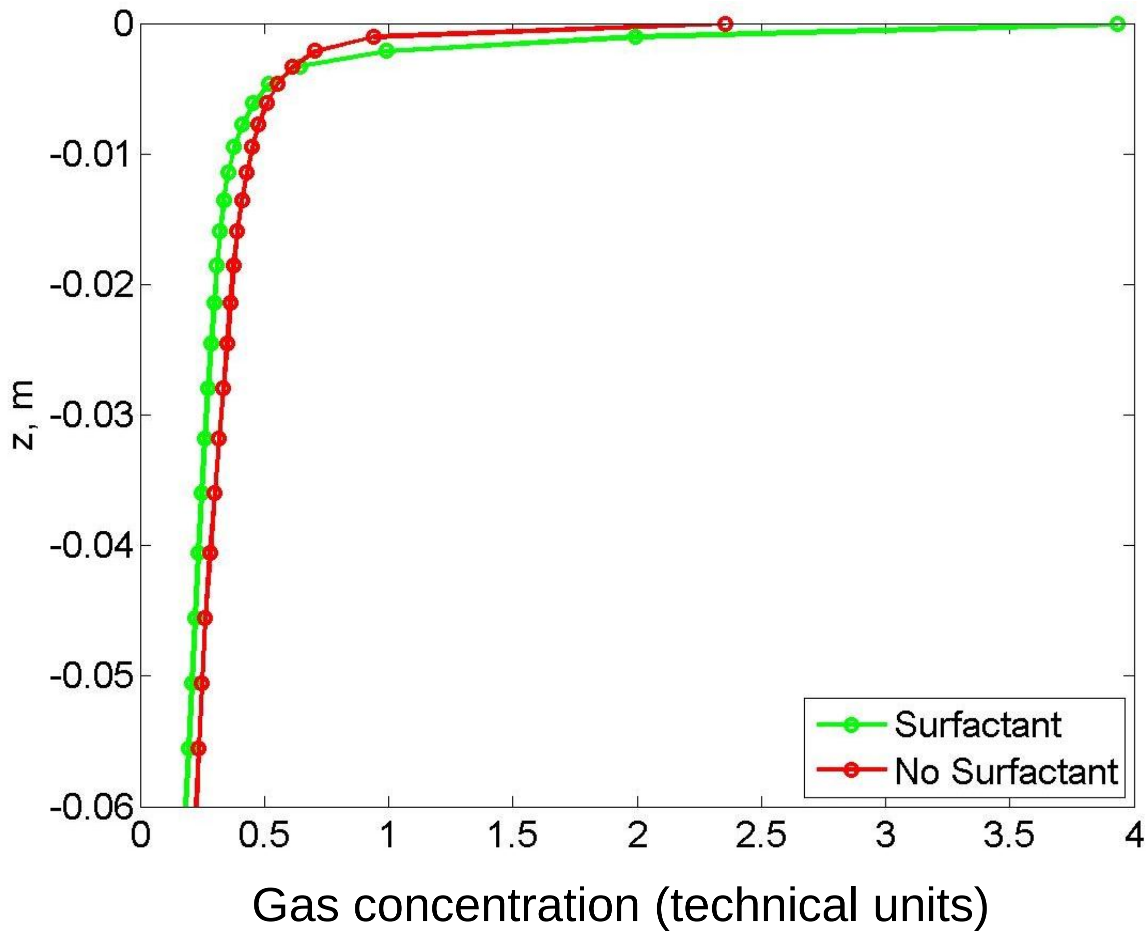



Average velocity profiles (DPIV) from lab experiment at ASIST




Average velocity profiles from CFD *Fluent* with visco-elastic surface boundary condition

# CFD Simulation: Gas Concentration




**CFD model:**

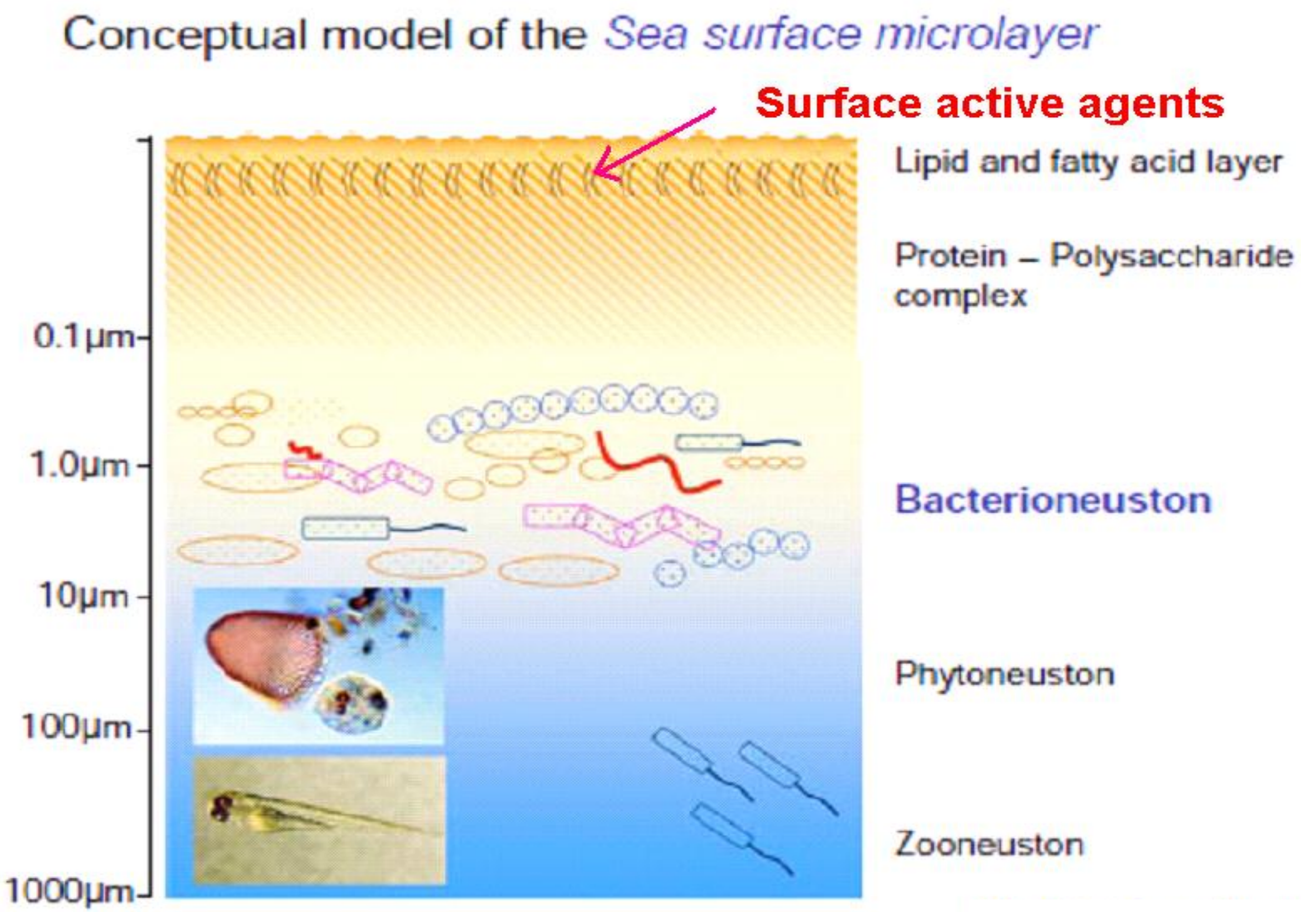
**Nighttime,**

***U*$_{10}$ = 4 ms$^{-1}$**

***Sc* = 10**

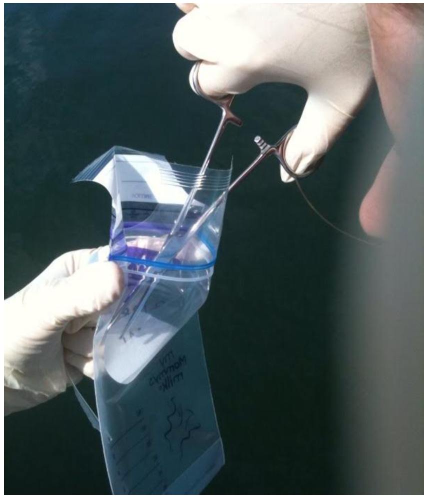
**In the presence of surfactant, gas transfer velocity reduced approximately by a factor of 2**

# Sea Surface Microlayer and Surfactants




Cunliffe et al. (2011)

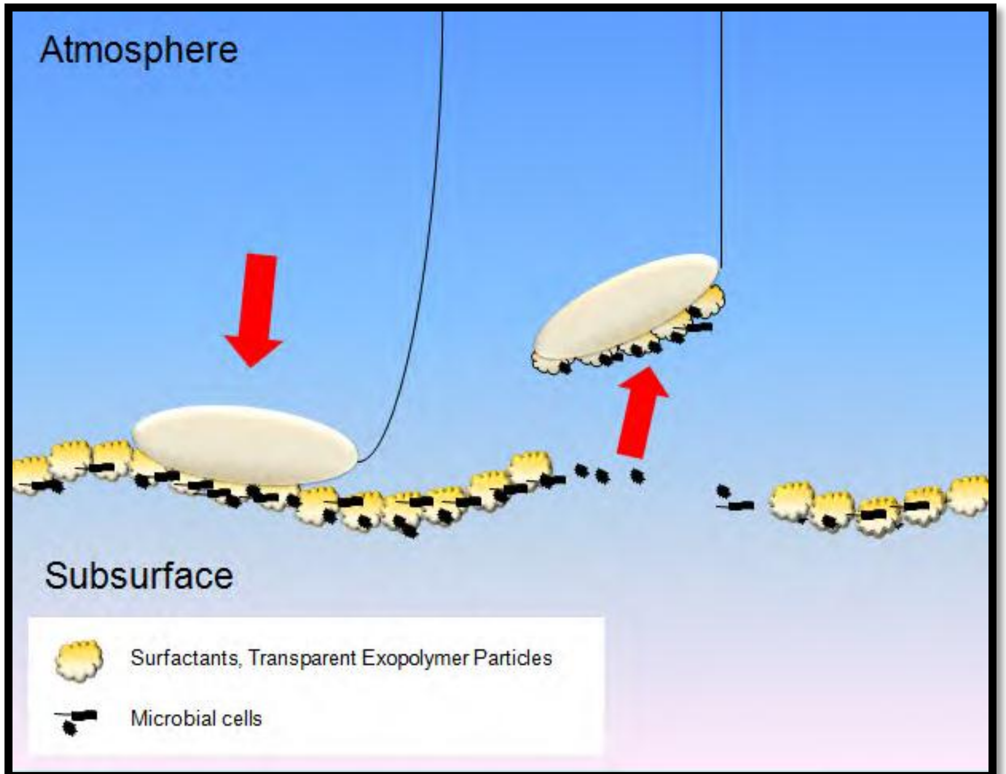
# Sampling of Bacteria in Sea Surface Microlayer



Sampling technique for the sea surface microlayer

Sampling technique for the subsurface water

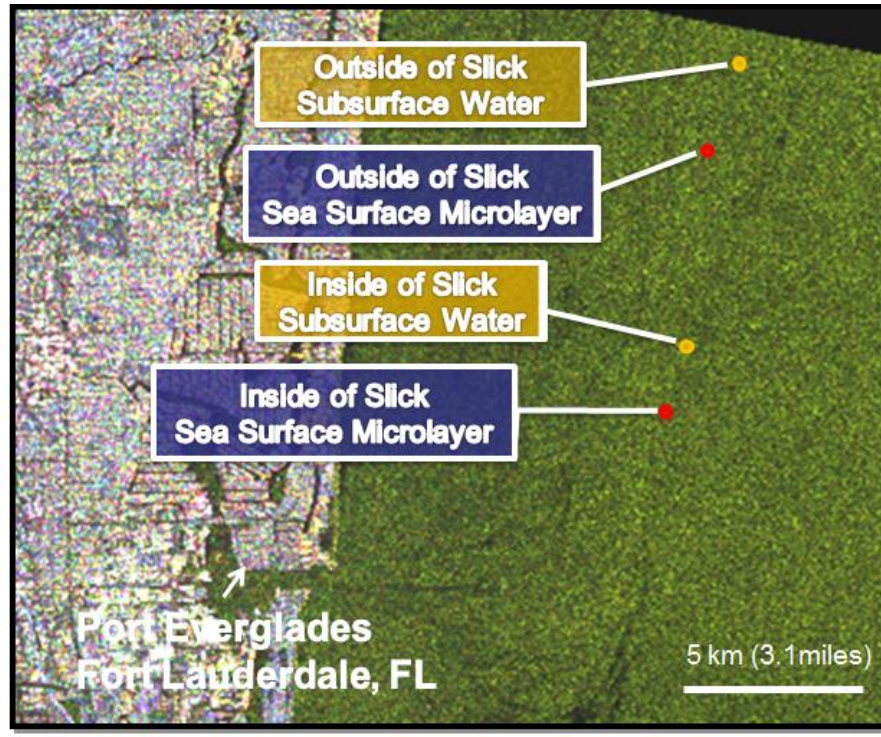
# Sampling of the sea surface microlayer bacteria




Microbial cells in the sea surface microlayer attach to the membrane filter due to surface tension.

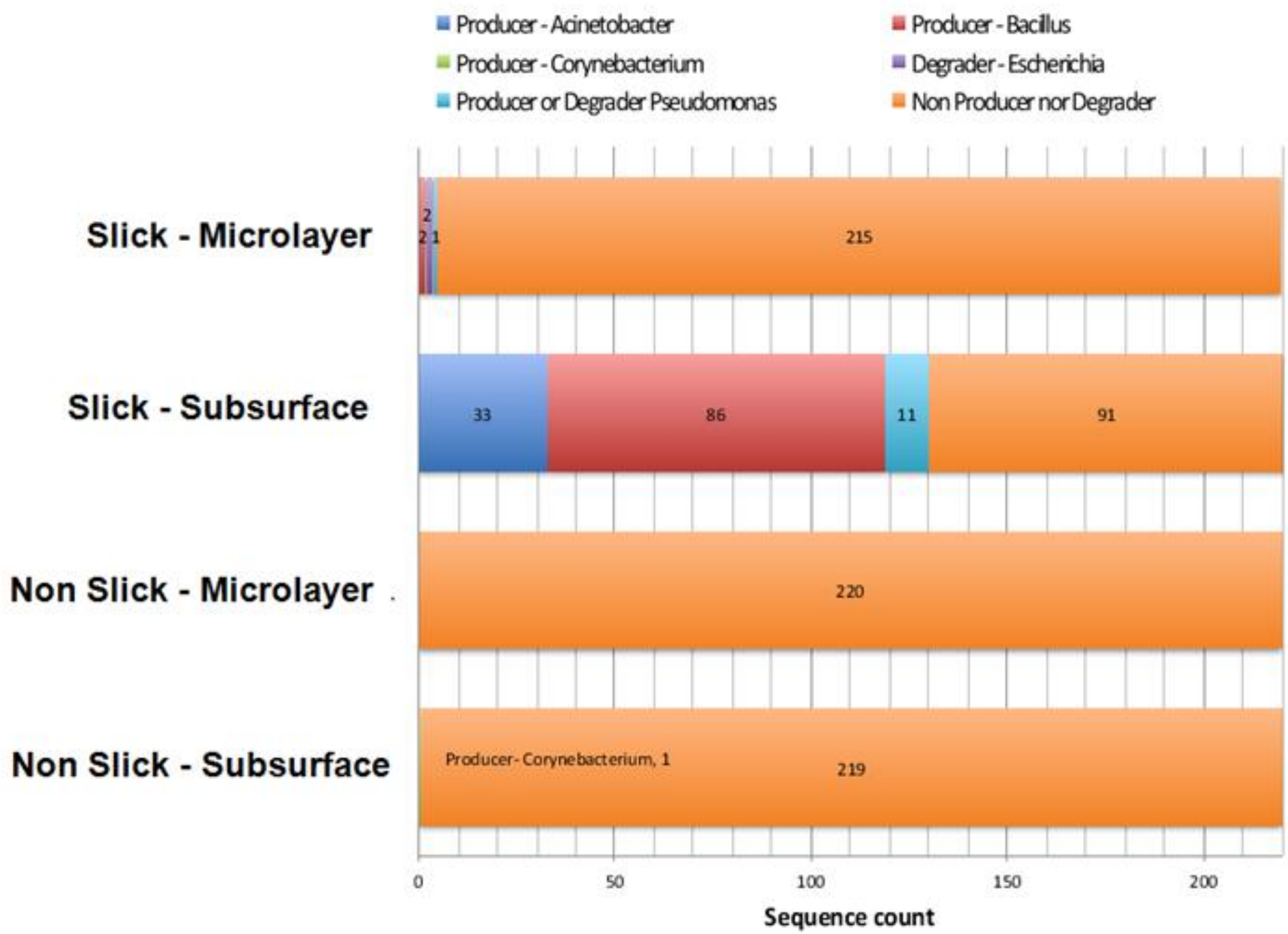
# Sampling in and outside a slick

Photographic image of a slick in the Straits of Florida.




Sampling locations in synthetic aperture radar image (RADSRSAT 2). Courtesy of Will Perrie.

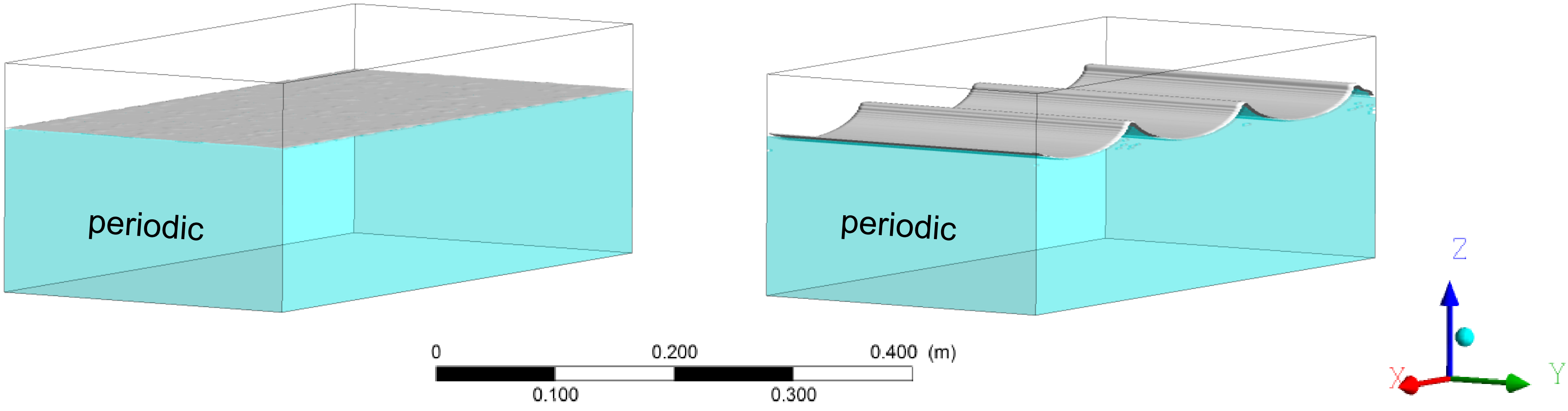
# Surfactant associated bacteria in and outside slick (DNA analysis)




Relative abundance of potential surfactant-associated genera in the sea surface microlayer and subsurface water. Sampling in slick and non-slick areas are shown on the synthetic aperture radar (SAR) image in previous slide. (After Kurata et al., 2013.)

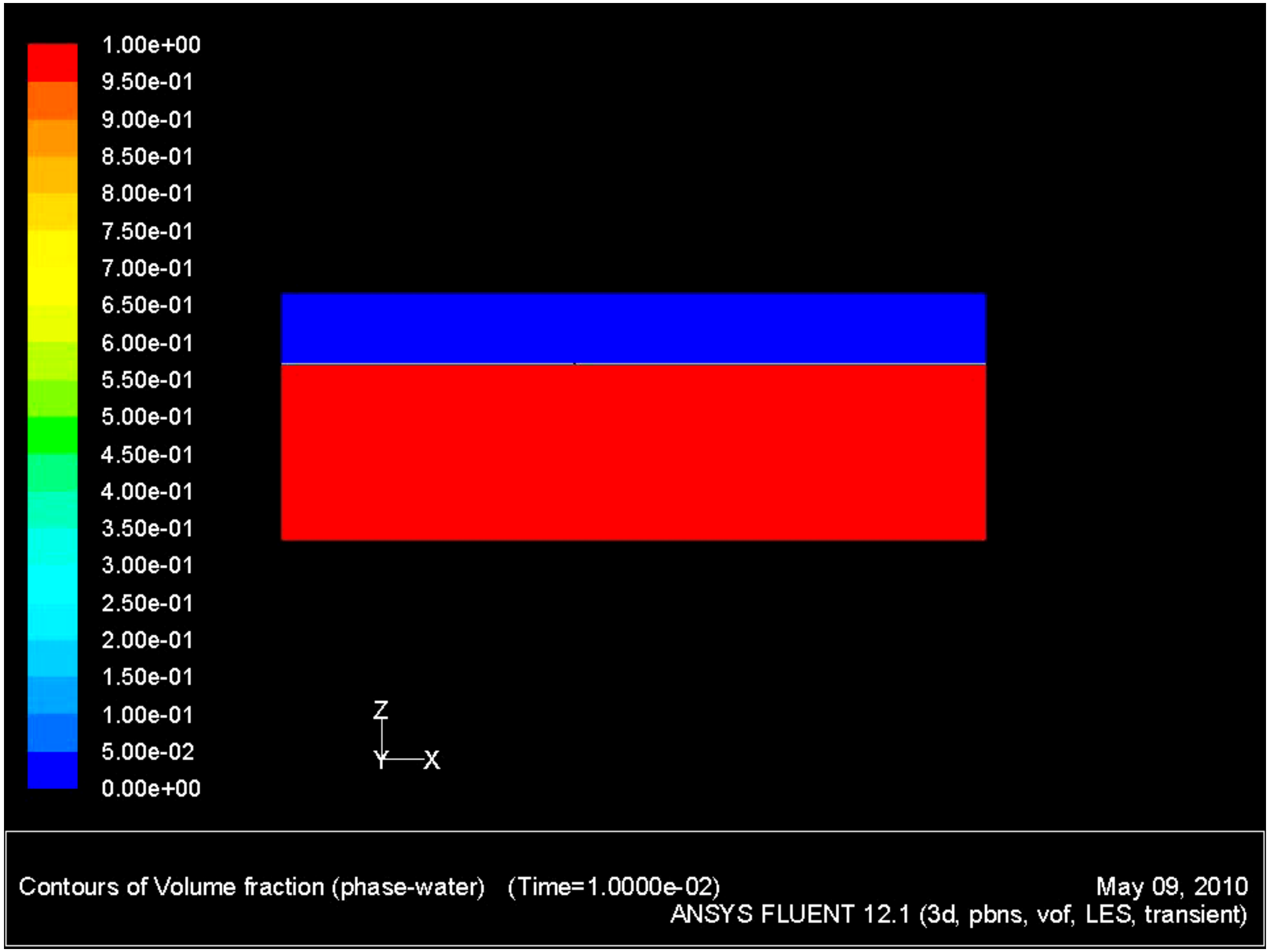
# Numerical Simulations

- In order to demonstrate the possibility of the direct disruption of the air-sea interface under hurricane conditions, we used an idealized 3D VOF-LES model set-up.
- A series of numerical experiments has been conducted using the computational fluid dynamics software ANSYS/Fluent.
- Wind stress was applied at the upper boundary of the air layer, ranging from no wind stress to hurricane force wind stress.



# 3D Simulation of Air-Water Interface in Hurricane Conditions: Volume Fraction –Side View

Wind stress 4 N $m^{-2}$ ($U_{10}$ =40 m/s)

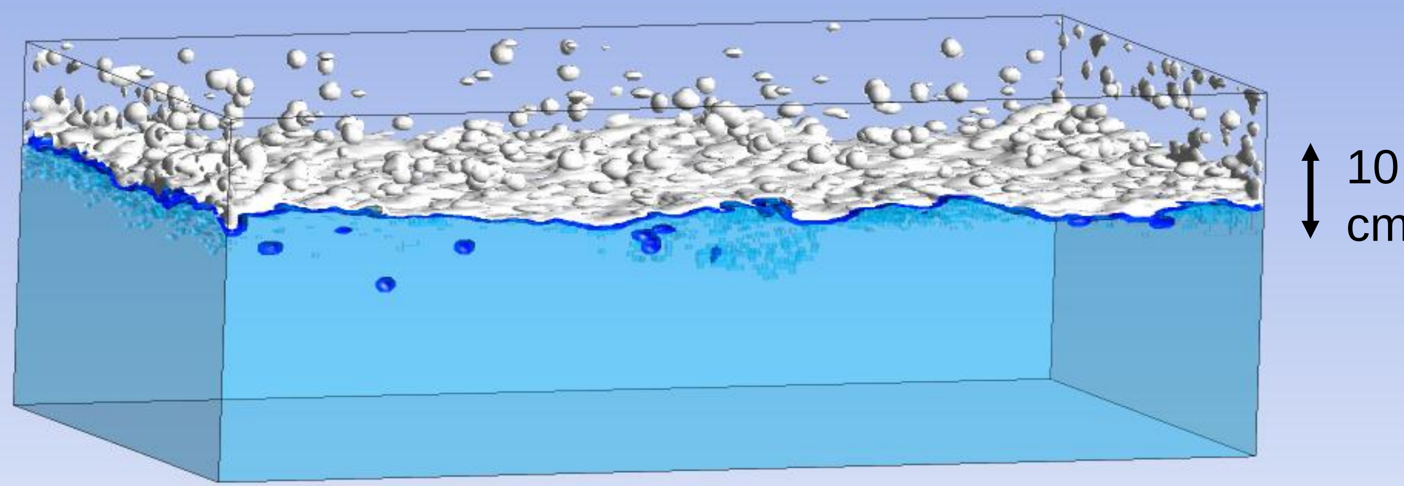



**Fluent: VOF LES WALE. Domain size: 1 m X 0.5 m X 0.3 m**

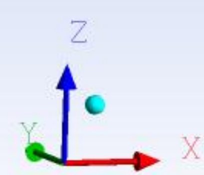
# Air-water interface under hurricane force wind


Wind stress 4 N m$^{-2}$ ($U_{10}$ =50 m/s)

Elapsed time = 2 s

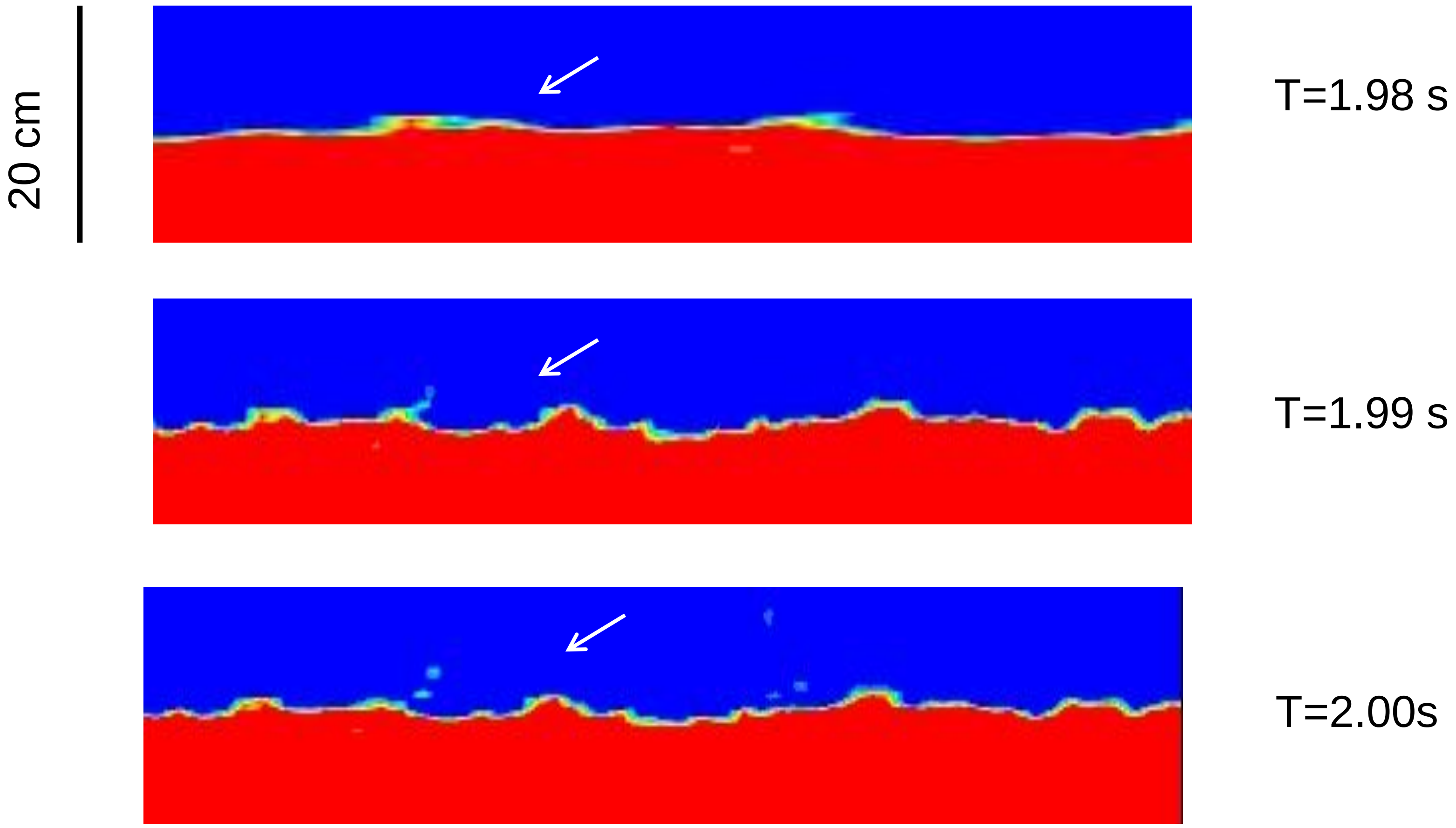



The numerical experiment with an initially flat interface illustrates the possibility of the direct disruption of the air-water interface due to the KH type instability and formation of the two-phase environment under hurricane force winds.



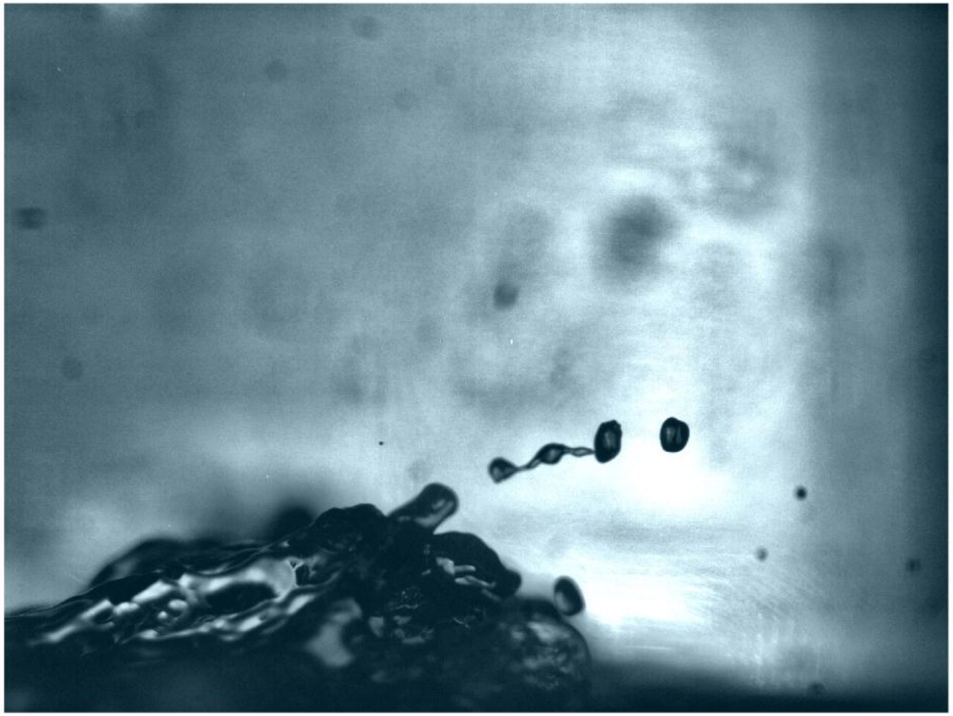

Soloviev, Fujimura, and Matt (JGR, 2012)

# “Projections” from the air-water interface initiate production of large spray particles in strong winds




**VOF-LES model**

# Kelvin-Helmholtz instability is a suitable model for spray generation in strong winds



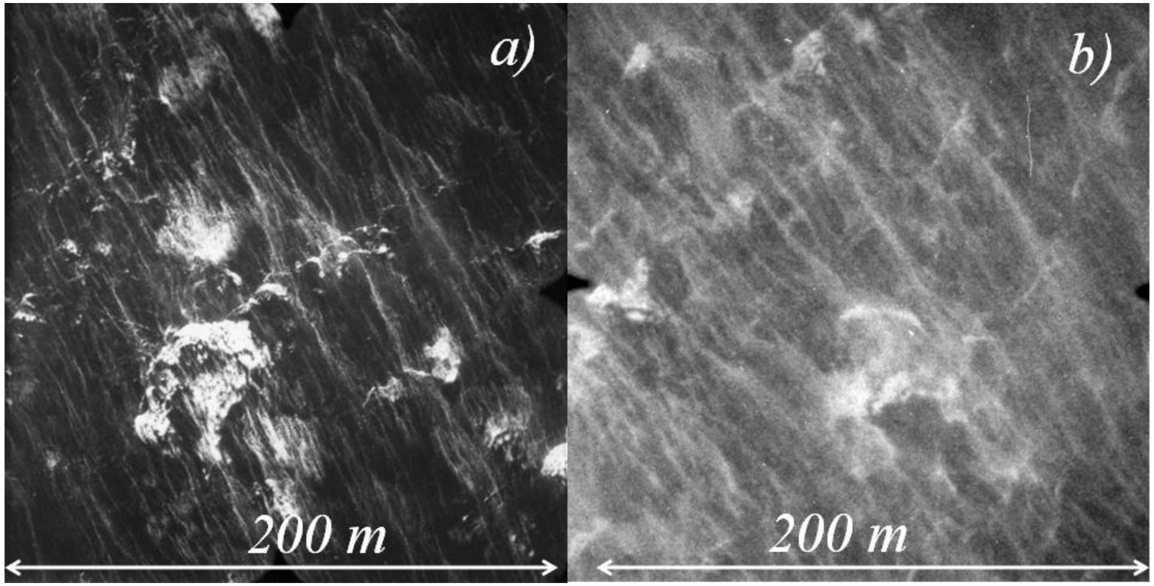
$U_{10}$ = 40 ms$^{-1}$

3 mm

**Large droplets production by breakdown of small "projections"**

Lab experiment at ASIST in collaboration with Brian Haus, Dave Ortiz-Suslow, Nathan Laxague

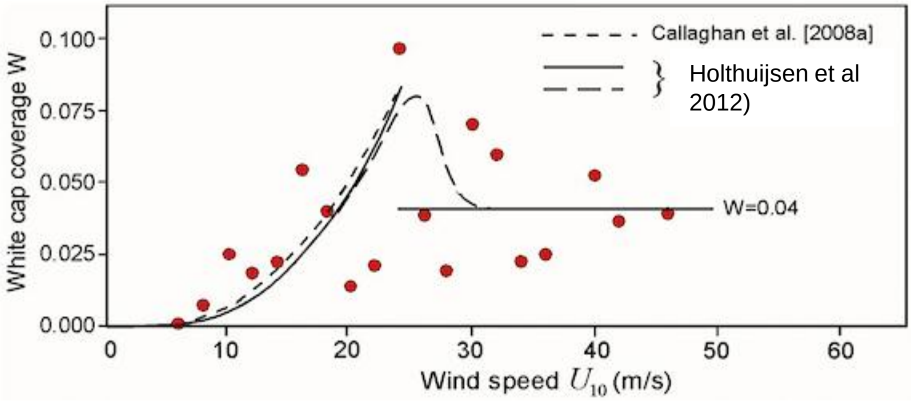
# Foam streaks on the sea surface in hurricane conditions can be a result of KH instability at the air-sea Interface




(a) Wind speed 28 m $s^{-1}$

(b) Wind speed 46 m $s^{-1}$

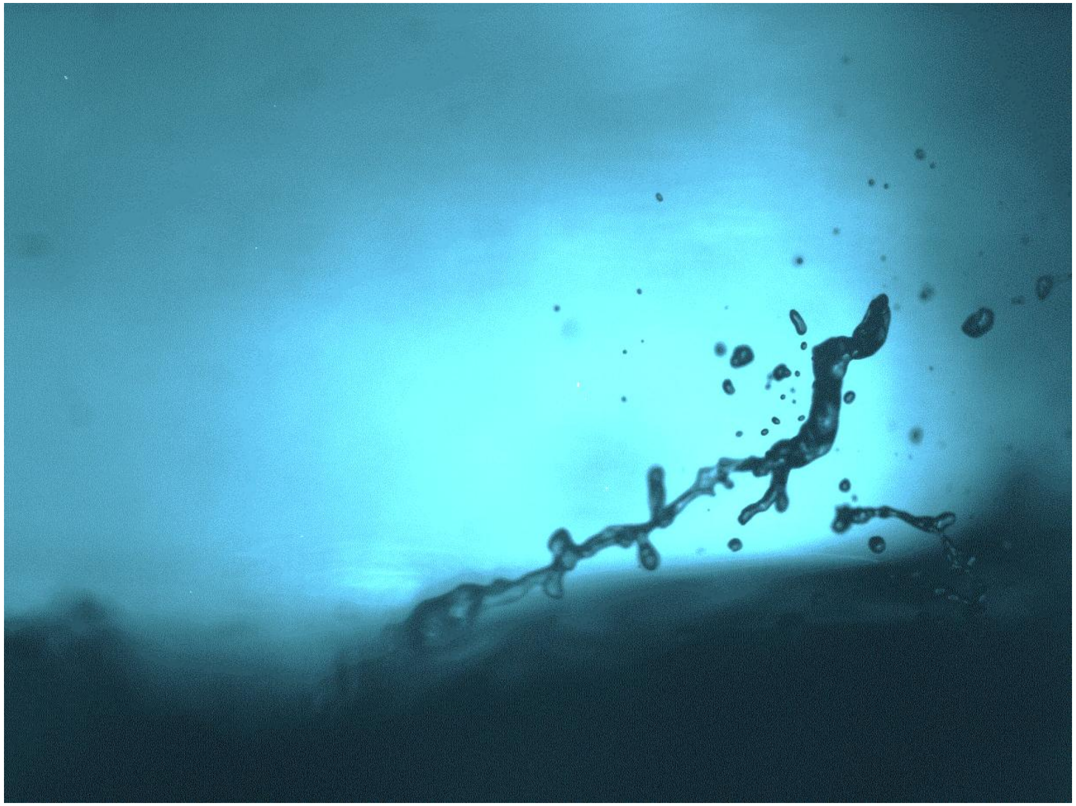
*Black et al.* (2006)




The white cap coverage increases with wind though at very high wind speeds remains at a constant 4% level, while the foam streak coverage increases toward full saturation (Holthuijsen et al. 2012).

# Kelvin-Helmholtz Instability in the Presence of Surfactant

$U_{10}$ = 40 $ms^{-1}$



3 mm

Lab experiment at ASIST in collaboration with Brian Haus, Dave Ortiz-Suslow, Nathan Laxague, and Bryan Hamilton

# Conclusions

- Under low winds, numerical simulations demonstrate significant decrease of the interfacial gas transfer velocity in the presence of surfactant

- Surfactant producing or degrading bacteria can be associated with surfactants. An improved method has been developed for sampling bacterial content of the sea surface microlayer using next generation sequencing (454 FLX GS) analysis

- Surfactants can be an important factor even under very high wind-speed conditions and should eventually be included in parameterizations for production of marine aerosols and air-sea gas exchange

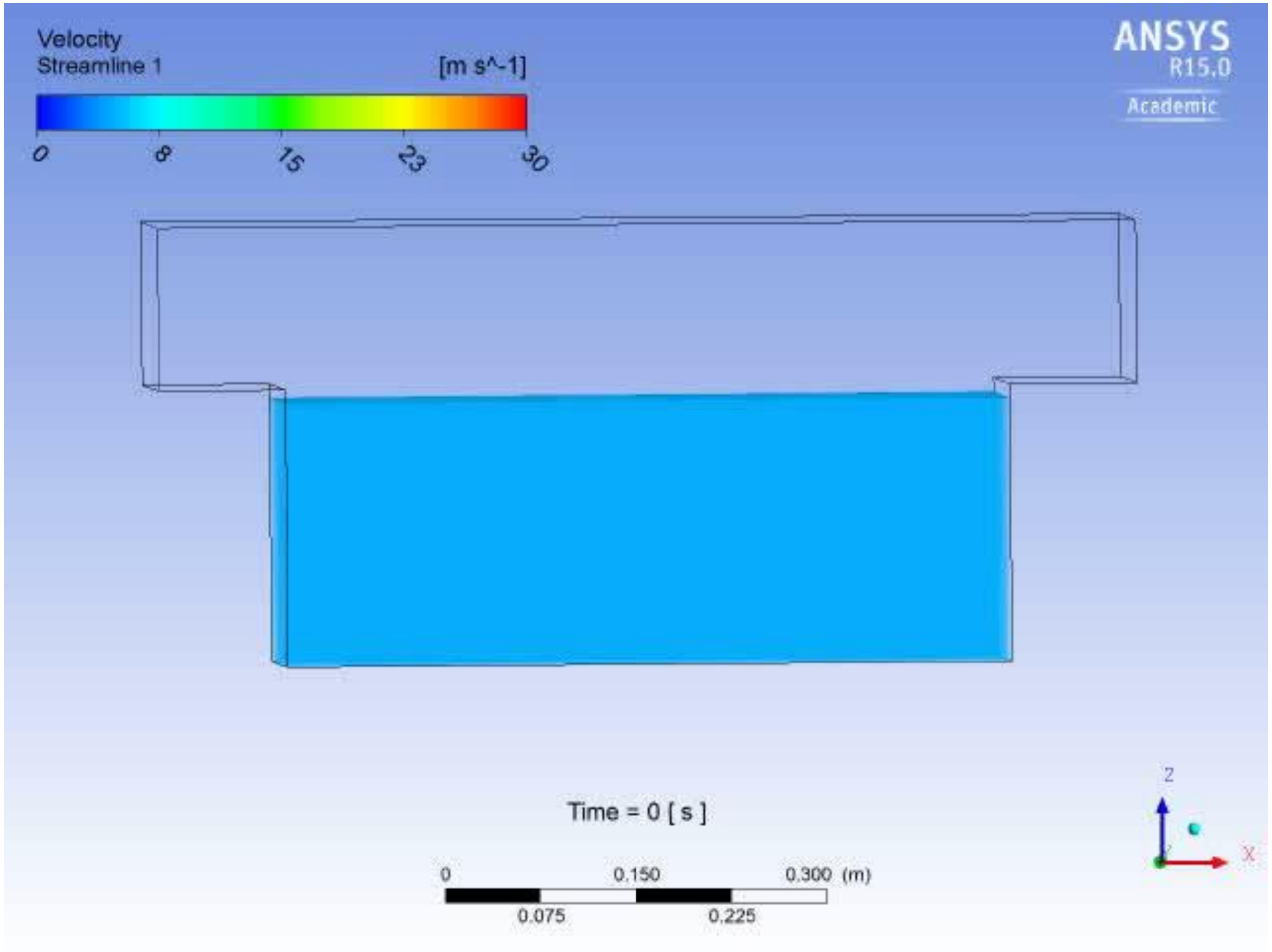
# Acknowledgements

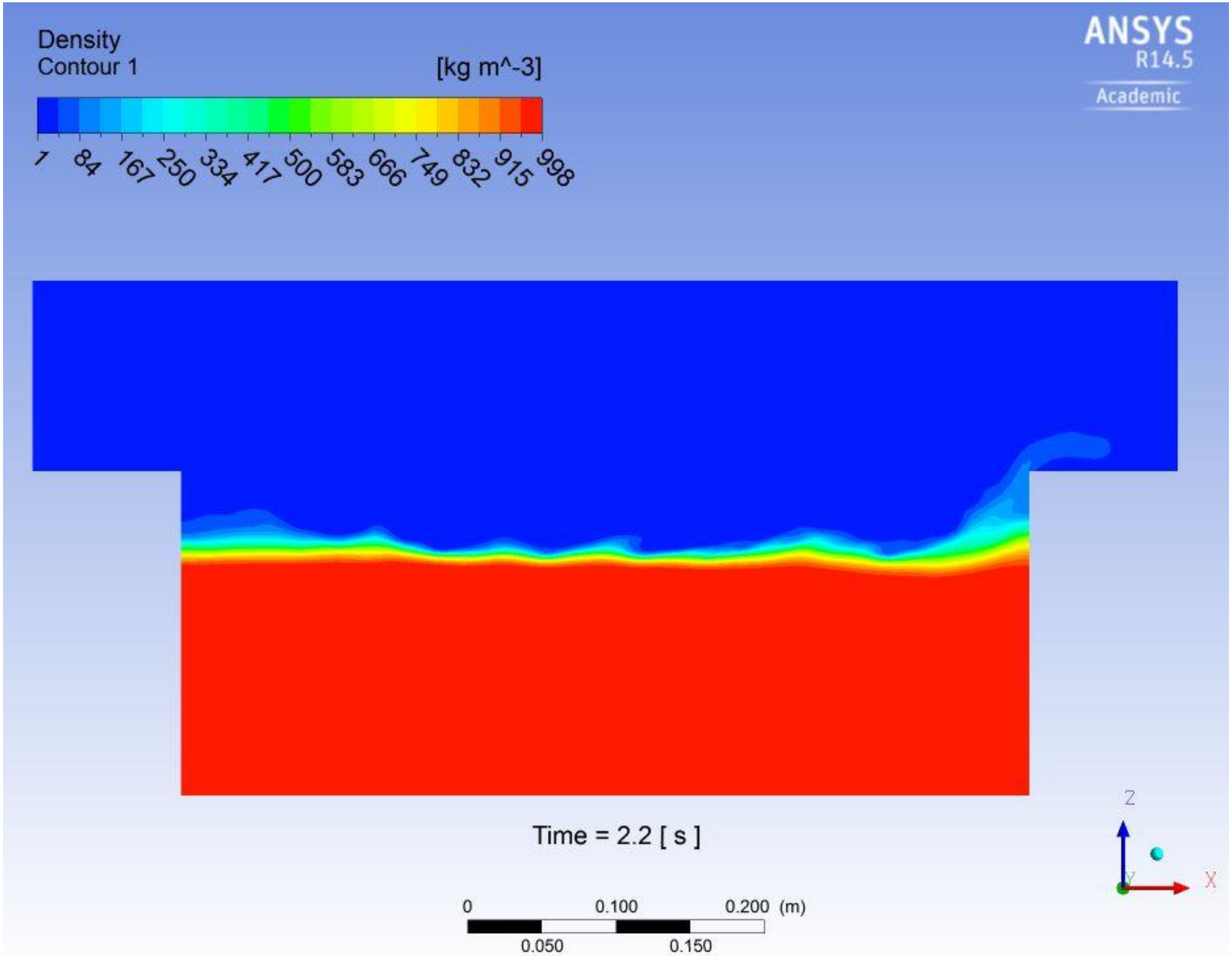
This work has been supported by the NOPP project "Advanced coupled atmosphere-wave-ocean modeling for improving tropical cyclone prediction models" (PIs: Isaac Ginis, URI and Shuyi Chen, UM) and by the Gulf of Mexico Research Initiative (GoMRI) Consortium for Advanced Research on the Transport of Hydrocarbons in the Environment (PI: Tamay Özgökmen, UM).

# Work in Progress

# Model Verification with Lab Data - UM RSMAS ASIST Facility (details in presentation by Prof. Brian Haus)

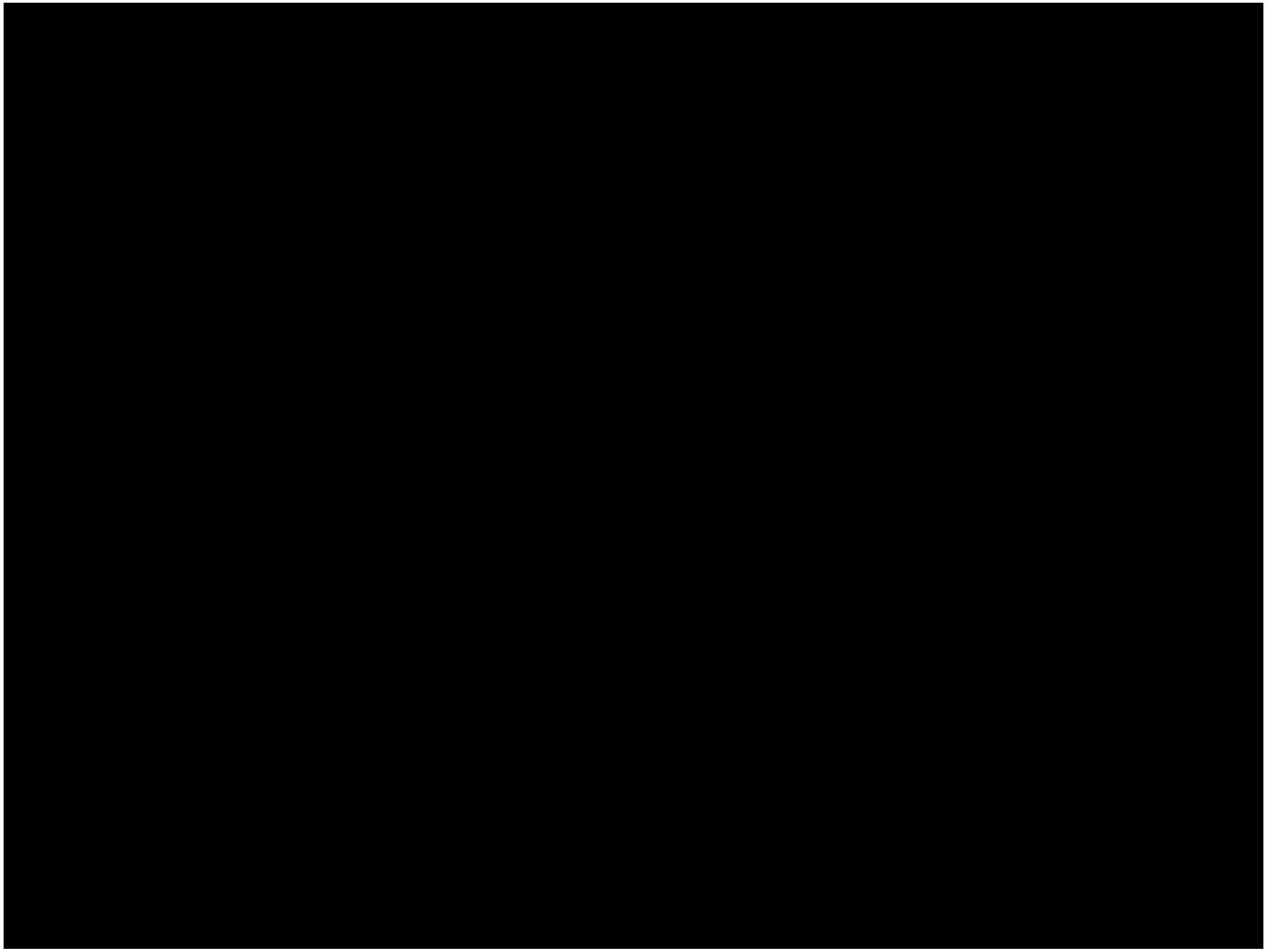
# Air-Water Interface: Numerical Simulation



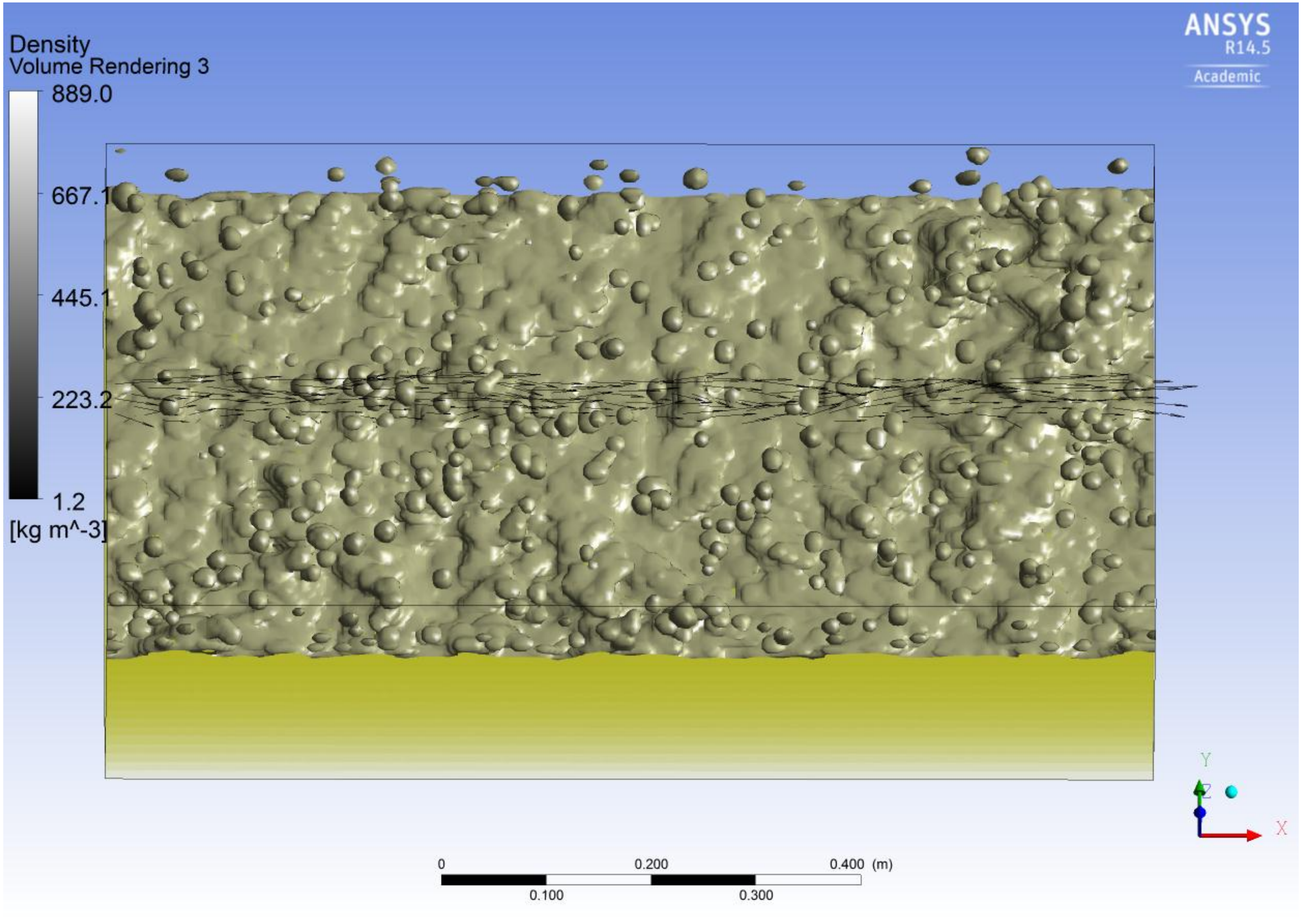


Density
Contour 1
[kg m^-3]
1
84
167
250
334
417
500
583
666
749
832
915
998
ANSYS
R14.5
Academic
Time = 2.2 [ s ]
0
0.100
0.200
(m)
0.050
0.150
Z
Y
X

# Air-Oil Interface: Numerical Simulation

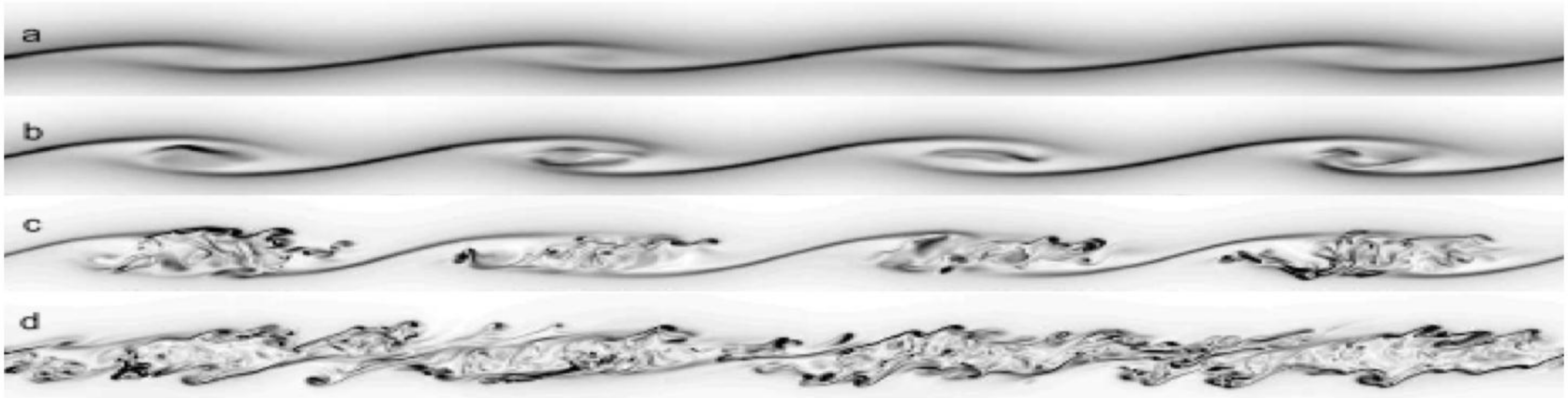


# “Bumps” on the air-oil interface

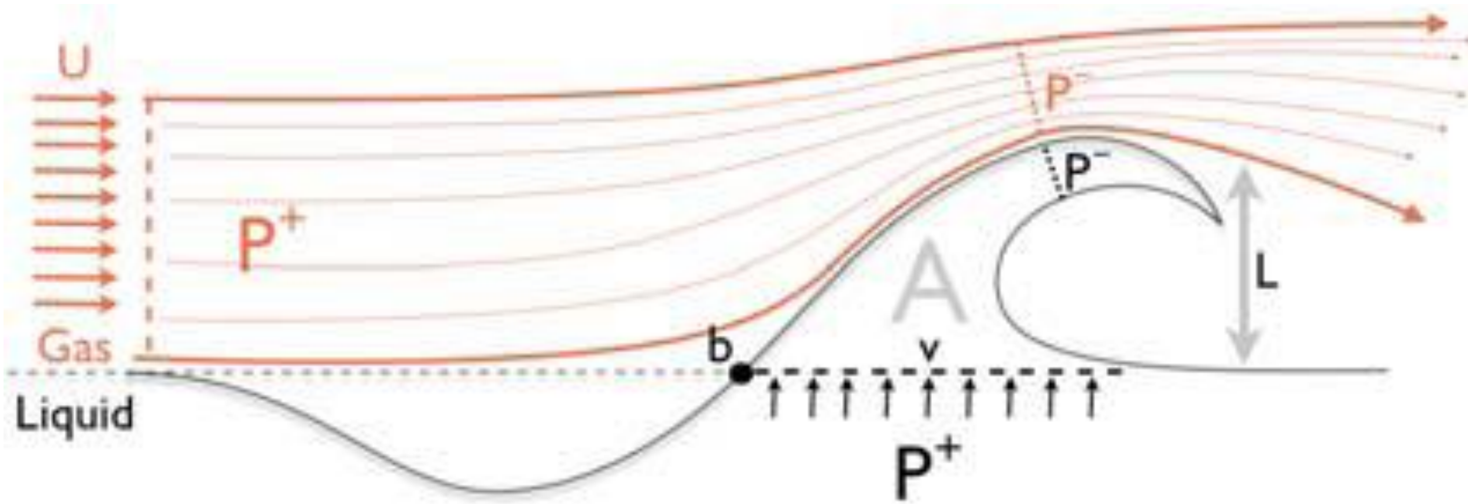


# Strong winds: Direct Disruption of the Air-Sea Interface?

- Air-sea interaction dramatically changes from moderate to very high wind speed conditions (Donelan et al. 2004)
- We pursue the hypothesis that regime of the air-sea interaction under very high wind speeds is associated with direct disruption of the air-sea interface
- The disruption can be realized through the Kelvin-Helmholtz (KH) type shear-layer instability



# Local Perturbation of the KH Instability




$\rho_a$

$\rho_w$

**Hoepffner, Blumenthal, and Zaleski (2011)**

Acceleration of the air stream above a short wave induces a pressure drop:

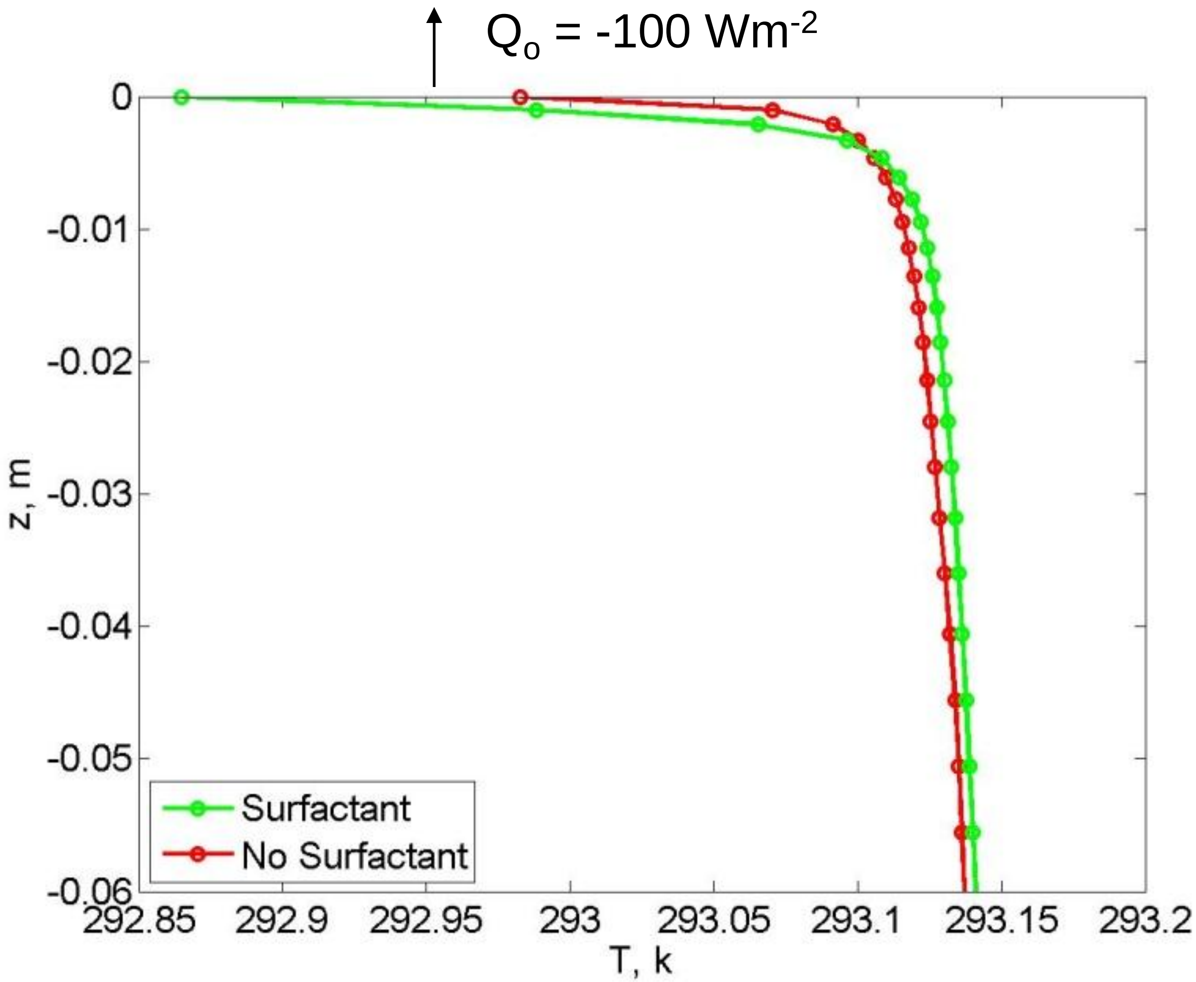
$$\Delta P = P^{+} - P^{-} = \rho_a U^2 k L \, .$$

The instability breaks up the interface if $\Delta P$ exceeds the combined restoring force of gravity and surface tension:

$$\Delta P > (\rho_w g + \sigma_s k^2) L \, ,$$

$\sigma_s$ the surface tension, $k$ the wavelength.

# CFD Simulation: Temperature




**CFD model:**

**Nighttime,**

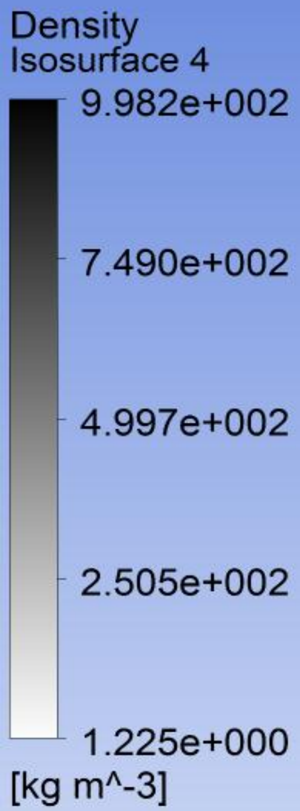
**$U_{10}$ = 4 $ms^{-1}$**

**$Sc$ = 10**

**In the presence of surfactant, $\Delta T$ changed from -0.15 K to -0.3 K**

# Characterization of Microbial DNA

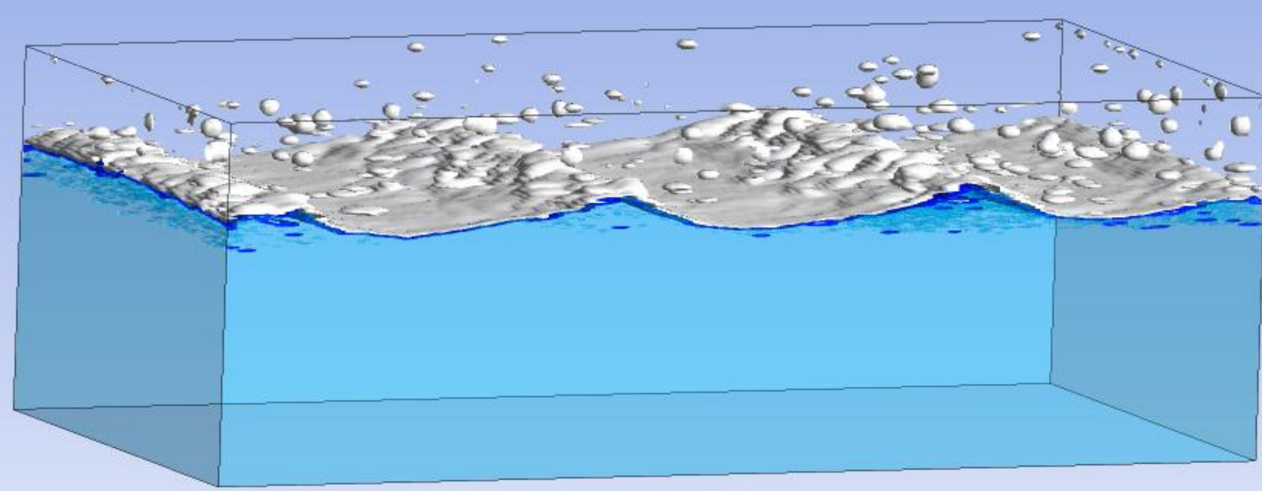
1. Following  Cunliffe, Upstill-Goddard and Murrell (2011), we have implemented DNA analysis for characterizing sea surface bacterioneuston.
2. Genomic DNA of the bacterial samples was extracted directly from the filter membranes (stored in -80$^{o}$C freezer)
3. The 16S ribosomal RNA gene was amplified with universal 16 rRNA primers 27F and1492R (Lane, 1991)
4. Nested PCR was performed using the barcoded universal primers.
5. To obtain statistically robust data sets, next generation sequencing (454 FLX GS) was utilized.
6. Taxonomic composition analysis using the Quantitative Insights Into Microbial Ecology software (QIIME)



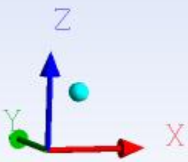

# Air-Water Interface with Imposed Waves Under Hurricane Force Wind

Wind stress 4 N $m^{-2}$

Elapsed time = 0.5 s



The numerical experiment with imposed short wavelets demonstrates the tearing of wave crests, formation of water sheets and spume ejected into the air.




Soloviev, Fujimura, and Matt (JGR, 2012)


*TerraSAR-X*.
Credit DLR.