Chapter 6. High wind speed regime

of

The Near-Surface Layer of the Ocean

Structure, Dynamics and Applications

Soloviev and Lukas

Introduction

- Concept of interface becomes problematic.
- Breaking waves disrupt the air-sea interface producing a two-phase zone — air bubbles in the water and sea spray in the air.
- Two-phase environment eliminates short wind-waves
- Consequences for air-sea drag coefficient.

Introduction

- Sharp interface disappears for longer intervals and over larger areas.

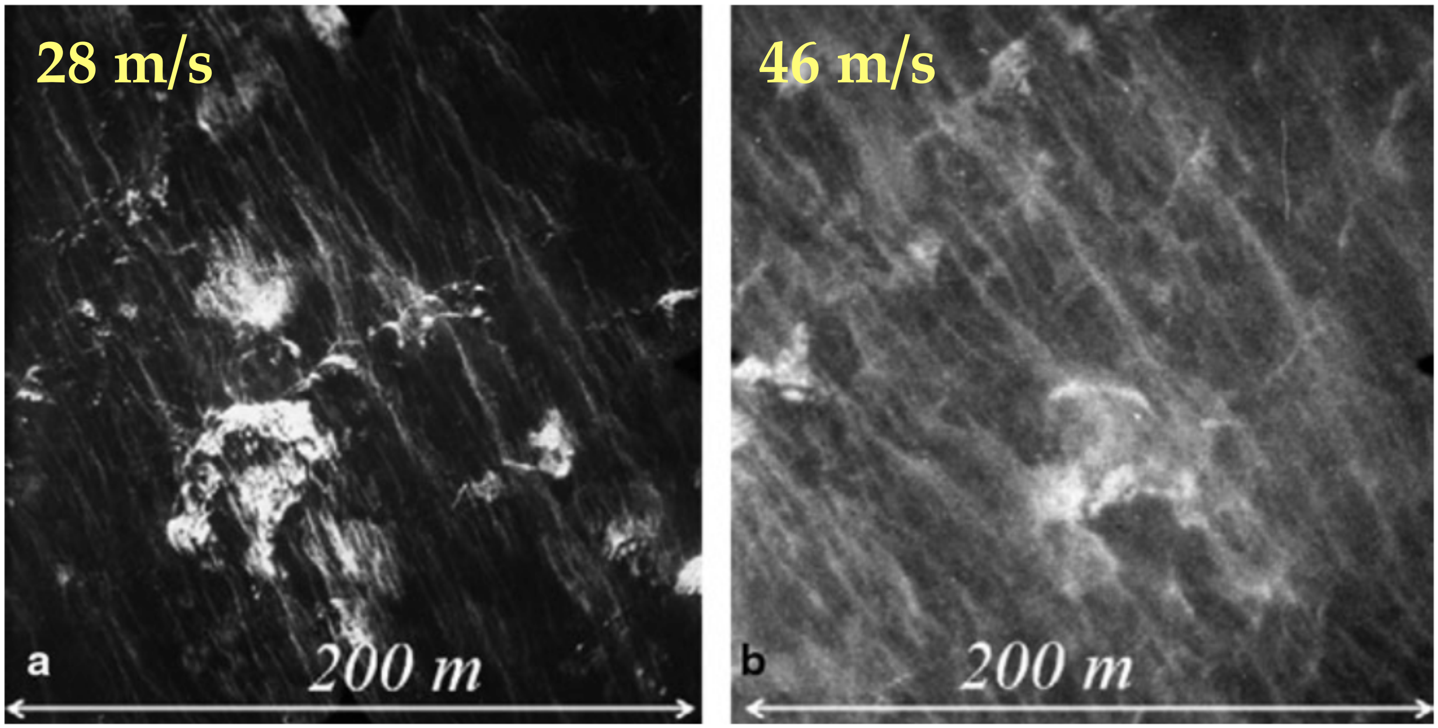


Fig. 6.1 Ocean surface foam streaks observed on photographic images of the sea surface in a hurricane: **a** Wind speed 28 m s^{-1} and **b** wind speed 46 m s^{-1}. After Black et al. (2006)

Air bubbles

- Breaking waves entrain air and create bubble plumes, which a highly transient and localized.
- Fraction of ocean surface covered with wave breakers increases rapidly with windspeed, but does not exceed 10% even on the strong winds.

Life cycle of Air bubbles

Life cycle of wave generated bubbles.

1. Formation
   - Occurs for first 0.1 seconds or less.
2. Injection
   - Plume rapidly descends.
   - Maximum depth penetration.
   - Plume starts at 30^{o}, then tilts to vertical.
3. Rise
   - Mass of bubbles rise towards surface
   - Lasts similar length of time as injection phase

Life cycle of Air bubbles

4. Senescene
    - Plume consists of smaller r<0.2 mm bubbles.
    - Evolves by turbulent diffusion, advection, buoyant degassing, and dissolution.
    - Most observations are of this phase.

- Size-dependent bubble rise velocity mainly determines the residence time of larger bubbles, but the residence time of smaller bubbles may also be affected by the turbulent flow in the near-surface layer.

Bubble rise velocity

- Bubble hydrodynamics depend on bubble size, temperature, and the presence of surfactants.
- Small bubbles (r<0.5mm) are spheroid, larger bubbles are ellipsoid.
- Shape transition depends on temperature and surfactants.

Bubble rise velocity

- Small bubbles are nearly perfect spheres because surface tension dominates over the drag stress that acts upon the rising bubble.
- Surface tension decreases inversely proportional to radius.
- Drag force increases since larger bubbles rise faster and have larger effective cross-sectional area.

Bubble rise velocity

- Larger bubbles can oscillate, in both path and shape, affecting the rise velocity.
- For large bubbles (r>3.5 mm), deformation oscillations are more important, as they result in a reduction of the drag coefficient and thus an increase of rise speed.

Bubble rise velocity

- Surfactants increase drag and decrease rise velocity.
- 0.25mm < r < 10mm bubbles have different hydrodynamics depending the they are “clean” or “dirty” (surfactant covered).
- Observed rise velocities with radii > 0.6mm are close to “clean” bubbles. They rise quickly to the surface and thus do not have sufficient time to collect surfactants.
- Small bubbles are “dirty”, as their surface becomes covered in surfactants almost instantaneously.

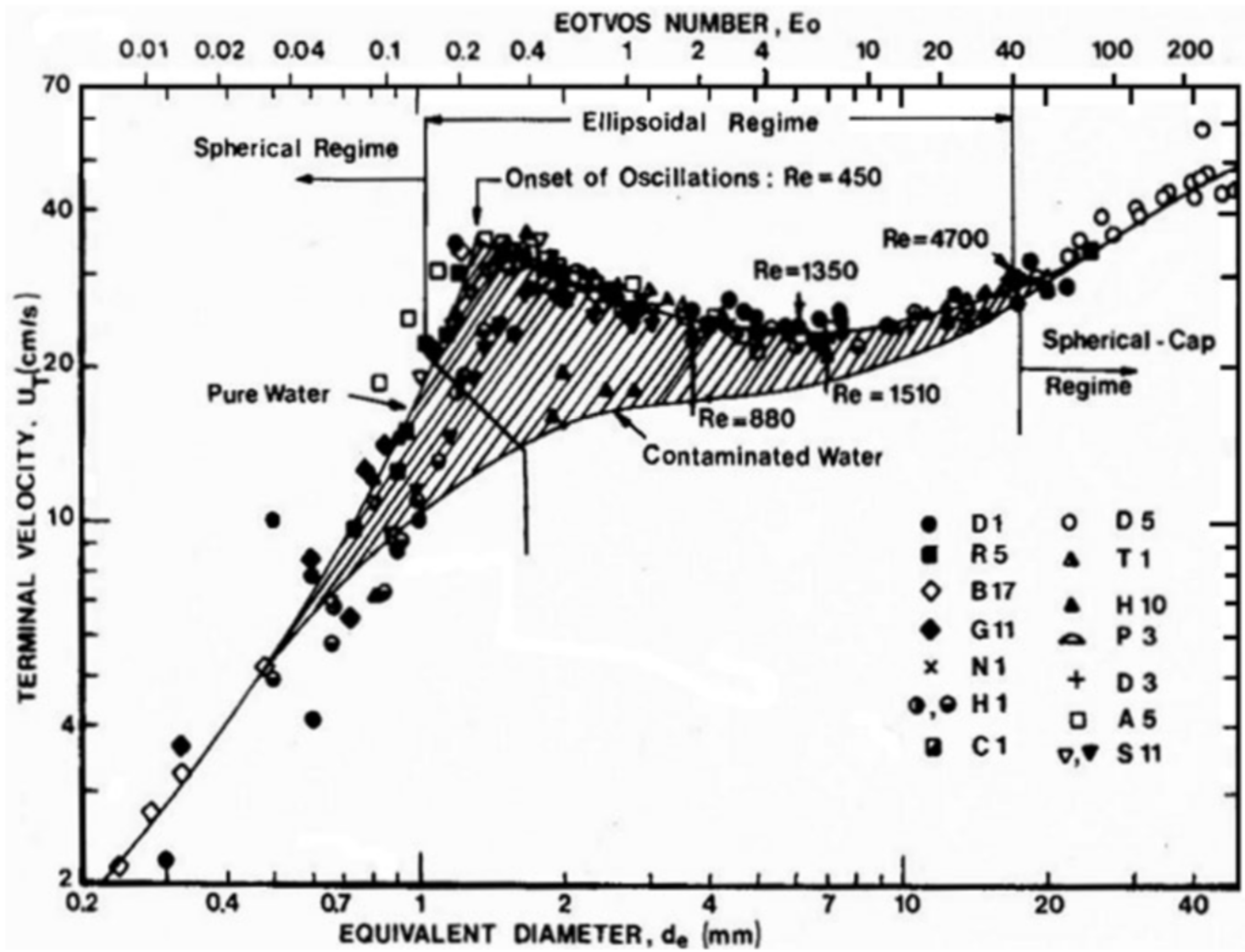


Fig. 6.2 The bubble rise velocity for hydrodynamically clean and dirty bubbles as a function of the bubble size. After Clift et al. (1978)

Bubble rise velocity

- The presence of a persistent air bubble layer near the surface depends on the terminal velocity of bubbles, w, and the root mean square (RMS) vertical turbulence velocity, w_{rms}.
- When $w<w_{rms}$. The bubbles may remain in suspension for a timescale comparable to the average time interval between wave-breaking events.

Bubble size distribution

- Mediates air–sea gas exchanges, production of spray droplets and aerosols, optical properties of the sea surface, generation of ambient noise and sound transmission within the oceans, and scavenging of biological surfactants.
- Measurement techniques
  - Acoustic - common, have trouble with large bubbles or dense clouds.
  - Laser - similar issues
  - Optical - invasive

Bubble size distribution

- Breaking wave inject air directly into wave-stirred layer, as large bubbles.

$TKE_{wave} \gg TKE_{mean}$

$TKE_{wave} > TKE_{mean}$

$TKE_{wave} < TKE_{mean}$

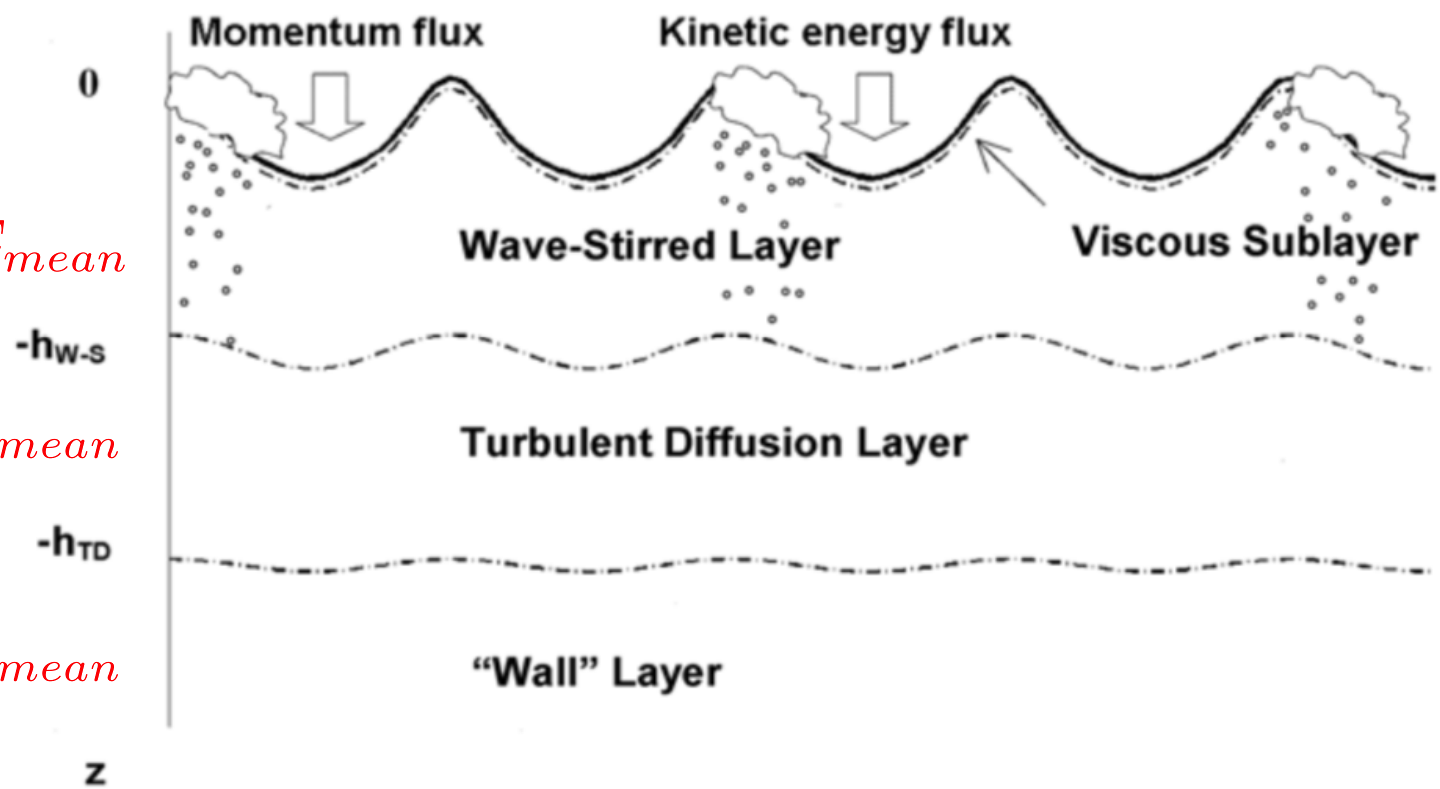
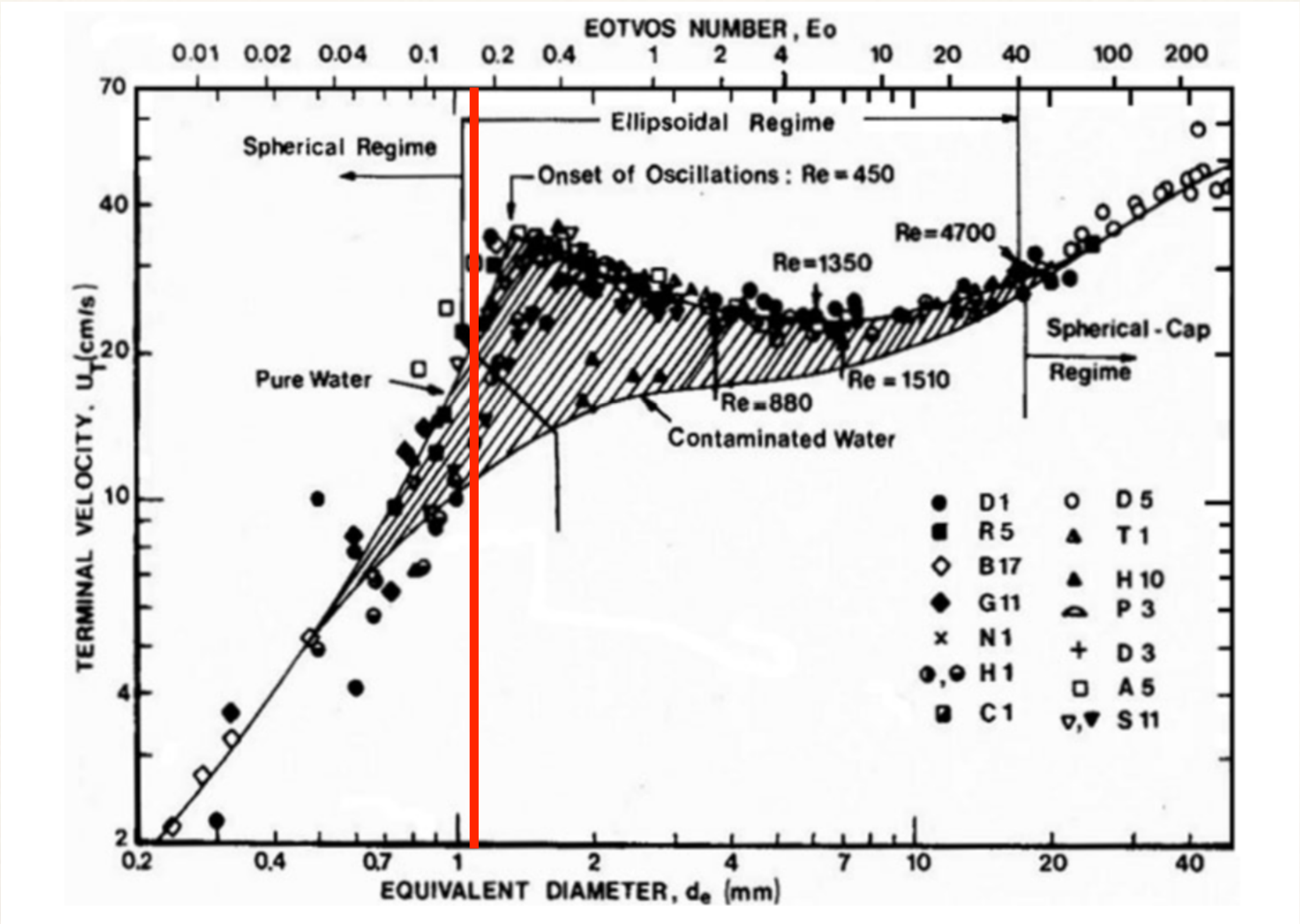


Fig. 3.1 Diagram of the upper ocean turbulent boundary-layer dynamic structures. Here, $h_{W\text{-}S}$ is the wave-stirred layer depth, and h_{TD} is the turbulent diffusion layer depth

Bubble size distribution

- Bubbles with radius *r*>0.7 mm have rising velocities of the order of 0.2 m/s — 0.4 m/s.



Bubble size distribution

- Large bubbles rapidly break into small bubbles.
- Once wave breaker runs out of energy, bubble creation stops.
- Size distribution evolves as larger bubbles leave the area and surface more quickly than smaller ones.

Bubble size distribution

- Bubble fragmentation mechanisms

1. Turbulent fragmentation
    - Dependent on ε, and bubble size
    - Unlike energy cascade minimum bubble size governed by surface tension.

2. Rising-bubble fragmentation including interaction of rising bubbles.

Bubble size distribution

- The density of bubbles, especially of large bubbles, is significantly higher during wave-breaking events.

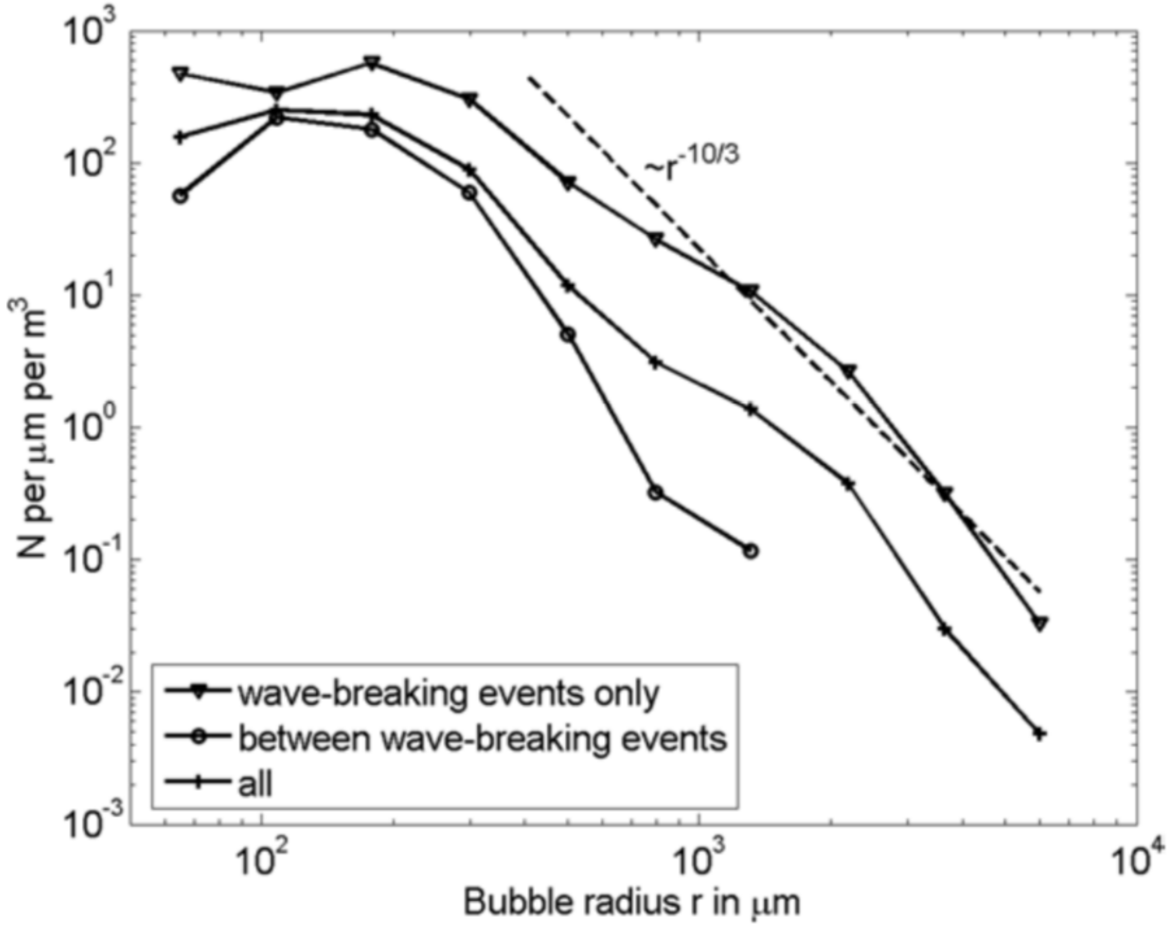
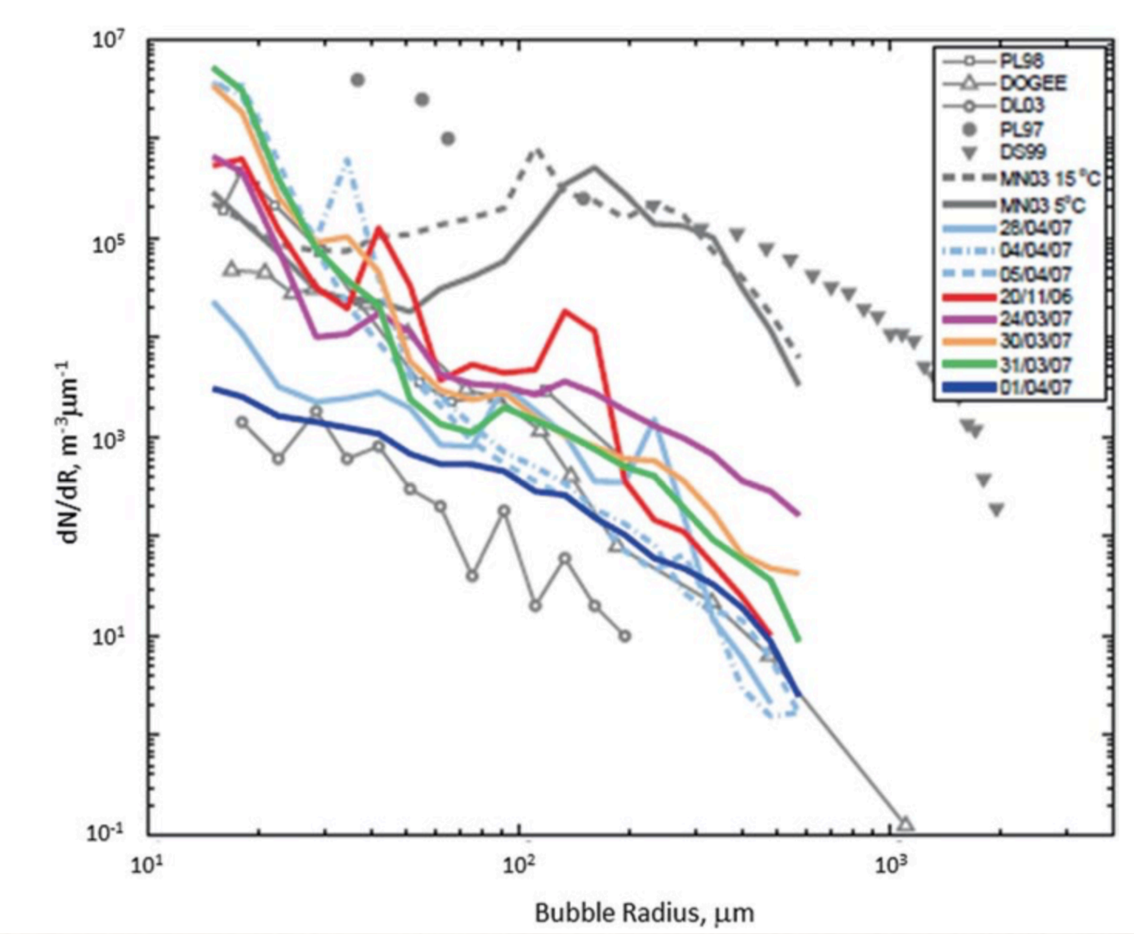


Fig. 6.3 Bubble size distributions at 0.6 m depth including and excluding wave-breaking events (Bowyer 2001). These measurements are taken at 11–13 m s^{-1} wind speed, 2.5 m wave height, and 15–120 km fetch. Reproduced by permission of American Geophysical Union

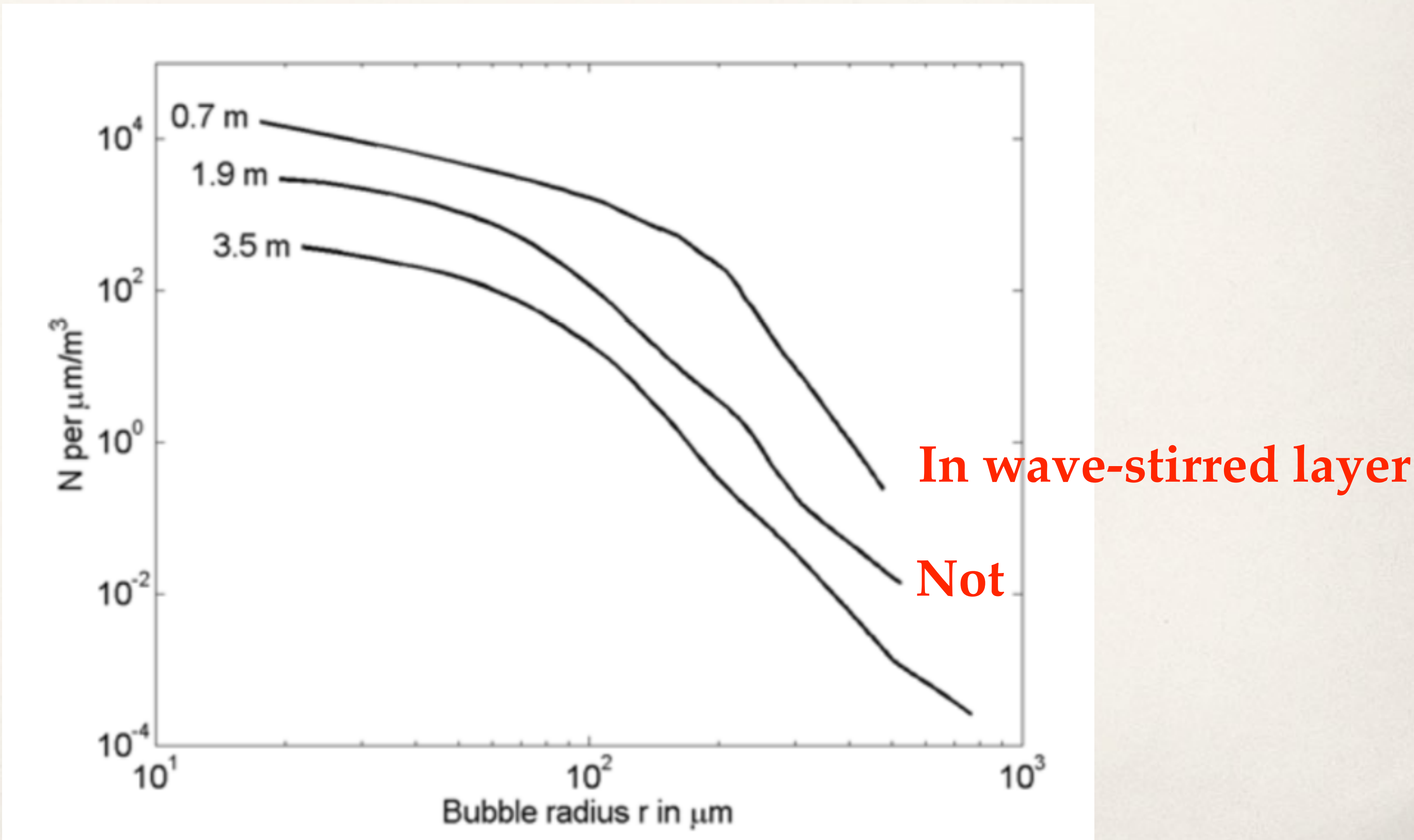
Bubble size distribution

- The laboratory data are neither representative of the surf zone nor of the open ocean. The bimodal distribution of spectra obtained from the laboratory experiment is not observed in any of the surf zone or open ocean.



Bubble size distribution

- Averaged bubble size distributions acquired in the Gulf of Mexico at depths 0.7 m, 1.9 m, and 3.5 m. The bubble density decreases with depth.



Buoyancy effects in bubble plumes

- Can be modeled with similar theory to suspended particles used for dust storms.
- However, near-surface turbulence is generated by wave breaking, rather than mean horizontal shear as in dust storms.

Buoyancy effects in bubble plumes

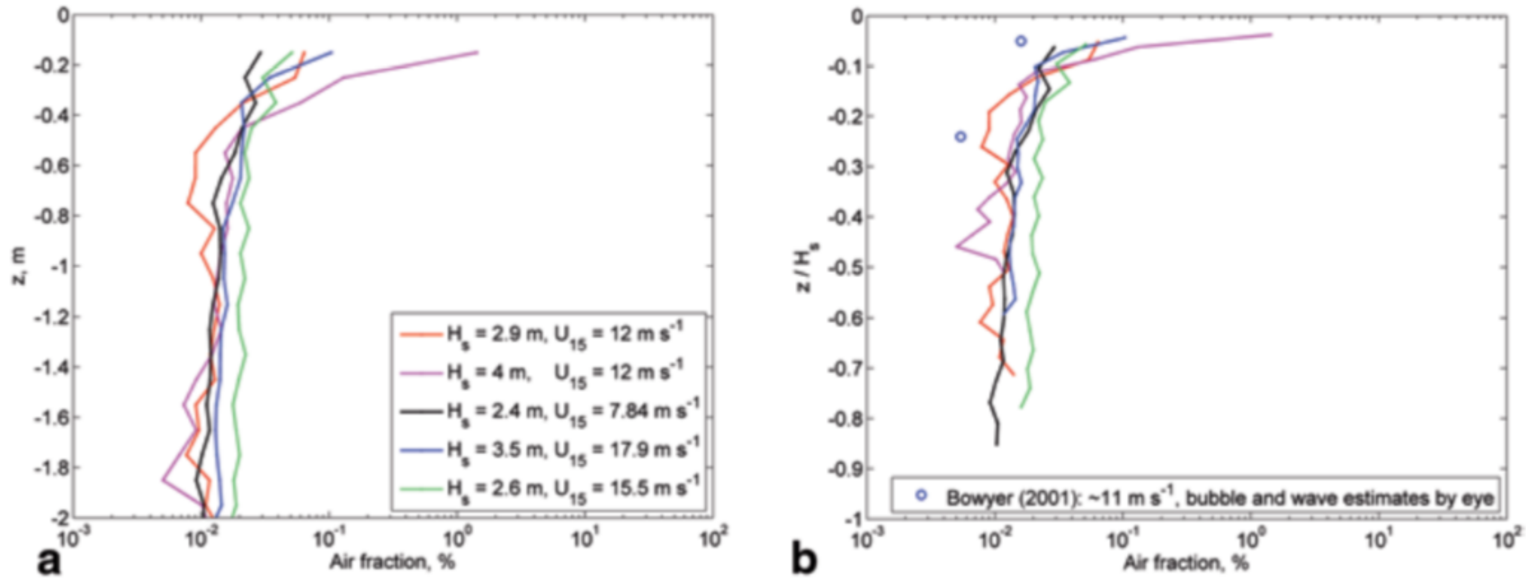


Fig. 6.6 **a** Average vertical air-fraction profiles in the near-surface layer of the ocean obtained by the authors of this monograph with the conductivity sensor installed on the bow of the vessel during the TOGA COARE experiment (more details in Sect. 3.3.5). The wind speed range is from 8 m s^{-1} to 15.5 m s^{-1}. Depth is calculated as distance from the "instantaneous" position of the sea surface. **b** Data from the bow sensor from the upper 1 m of the ocean normalized by significant wave height in comparison with the Bowyer (2001) data (shown as open circles).

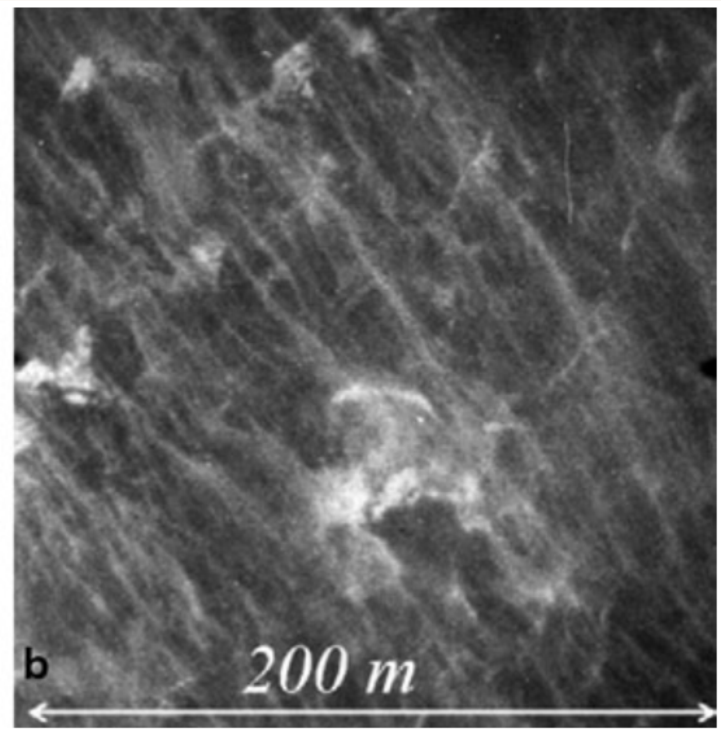
- In terms of buoyancy, a 1 % difference in water density is equivalent to a 30°C temperature difference.

Buoyancy effects in bubble plumes

- Under moderate wind speeds, wave-breaking events last only about 1 s.
- The whitecap area associated with the wave breaker occupies a relatively small fraction of the sea surface.
- The whitecap coverage increases rapidly with wind speed.

Buoyancy effects in bubble plumes

- Whitecap coverage does not exceed 10% even in hurricane conditions.
- Sea state photographs taken during a hurricane show that above U_{10} = 40 m s^{-1}, the sea surface in fact becomes completely covered with the “whiteout” consisting of foam and streaks.



- This suggests that mechanisms other than whitecapping dominate production of the whiteout during hurricanes.

Sea spray aerosols

- Ocean surface layer is a source of *sea spray* and *marine aerosols*.
- About 0.3% of ocean covered with breaking waves.
- Total salt flux to atmosphere is 10^{12} kg / year.
- Important in transfer of heat, moisture, and momentum under high wind speed conditions.
- Composed of seawater enriched with chemical compounds, insoluble organic matter as well as living microorganisms (bacteria, viruses).

Sea spray aerosols

- For small particle sizes, contributions of organic matter to sea spray aerosol in areas with high biological productivity are important.
- This may also be applicable to hydrocarbon dispersion in the form of aerosol particles from oil spills into the atmosphere under strong winds and breaking waves.

Sea spray aerosols

- Small drops are entrained into the turbulent air flow in the marine boundary layer
- Under favorable conditions, completely evaporate producing sea-salt aerosol particles, which are effective cloud condensation nuclei.

Sea spray aerosols

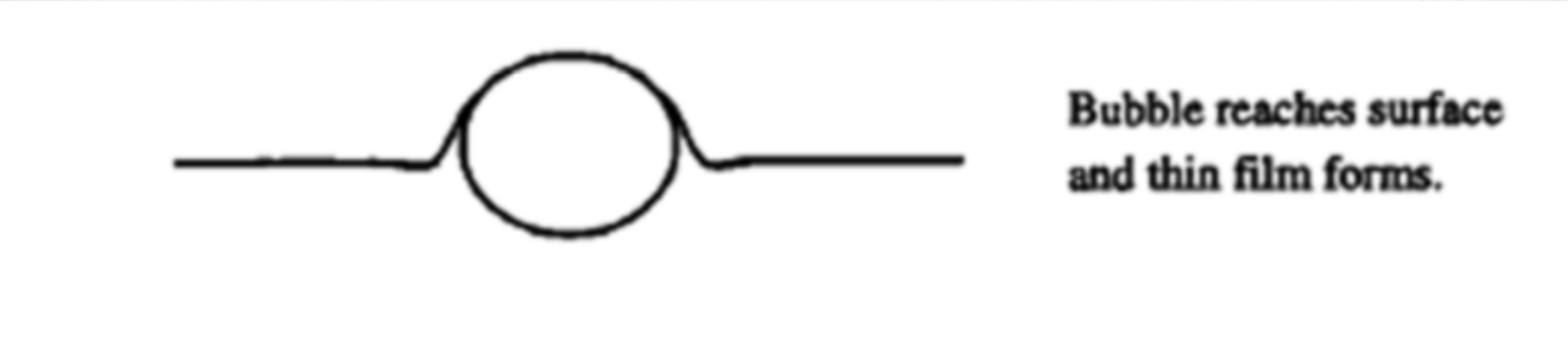
- They affect climate, transfer pollutants from the ocean to the atmosphere.
- Serve as a tracer in the climate record of Arctic and Antarctic snow and ice cores.
- Play a role in corrosion, and cause vegetation stress in coastal regions.

Sea spray aerosols

- Sea-salt particles are an important part of the atmospheric sulfur cycle.
- IPCC estimated the direct and indirect radiative forcing of sulfate aerosols to be in the range –0.2 to –0.8 W m^{-2} and 0 to –1.5 W m^{-2}, respectively. This is comparable in magnitude to the radiative forcing of anthropogenic greenhouse gases.

Sea spray aerosols

- 3 types: film droplets, jet droplets, & spume droplets.
- Bubbles created by breaking waves.
    1. When the bubble rises to the surface a thin film forms;



Sea spray aerosols

- 3 types: film droplets, jet droplets, & spume droplets.
- Bubbles created by breaking waves.

2. The film thins by drainage and ruptures ejecting **film droplets** with radii 0.5 to 5 μm;

Sea spray aerosols

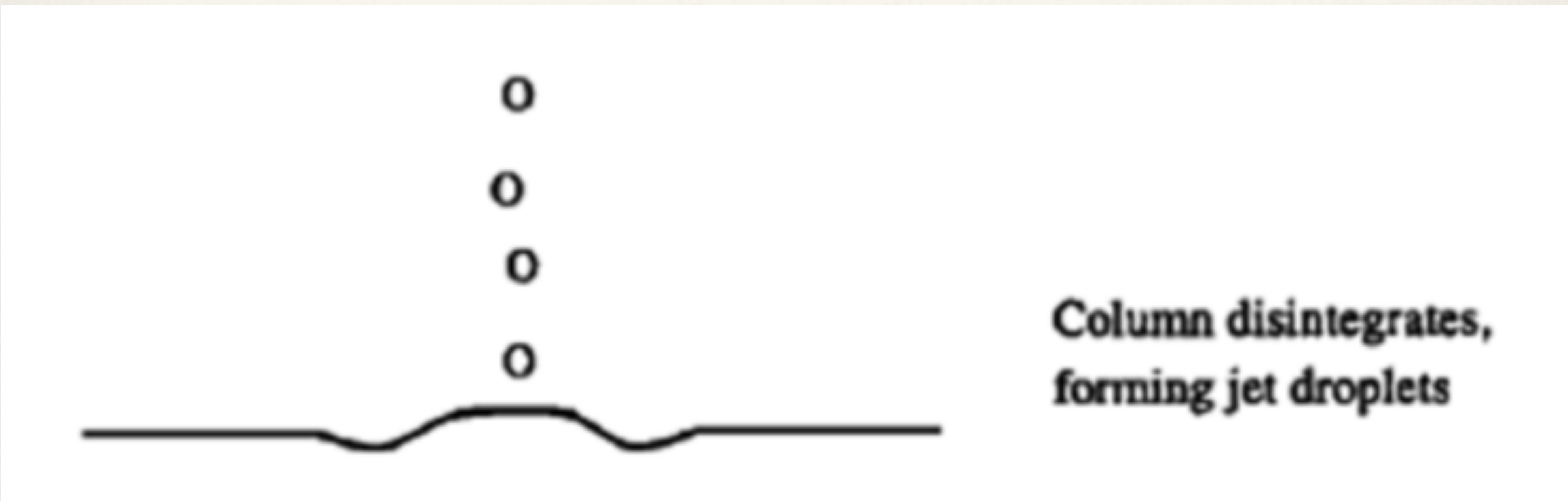
- 3 types: film droplets, jet droplets, & spume droplets.
- Bubbles created by breaking waves.

    3. The collapsing bubble cavity shoots up a jet of water from its bottom.

Sea spray aerosols

- 3 types: film droplets, jet droplets, & spume droplets.
- Bubbles created by breaking waves.

    4. This jet breaks up into a few **jet droplets** with radii typically ranging from 3 to 50 μm.



Sea spray aerosols

- Small bubbles produce only jet drops.
- Bubbles larger than 3.4 mm produce no jet drops

Spume droplets

- **Spume droplets** are by direct “tearing of water” from wave crests at wind speeds higher than about 9 m/s.
- Are the largest spray droplets; minimum radii are generally about 20 μm and there is no definite maximum radius.
- Spume generation is associated with eliminating the clearly defined air–sea interface under high wind speed conditions.

Spume droplets

- Droplets with radii in the range 10–500 μm contribute most to the heat fluxes at high wind speeds.
- The most important mechanism of droplet generation for mediating fluxes under very high wind speed conditions.

Spume droplets

- The dynamics of large droplets is a critical issue in developing the spray generation function for high wind speed conditions.
- After the initial ejection or splashing from the wave crest region these droplets fall quickly and do not diffuse to any significant height above the ocean.
- Can be taken up by the wind gust and fly some distance in the horizontal direction before reentering the ocean surface.

Air-sea exchange

- Spume droplets are particularly important for the fluxes carried sea spray.
- Evaporating spray can cause strong modification of temperature and humidity profiles.
- Feedbacks due to the changes in temperature and humidity are largely poorly understood due to lack of data under high wind conditions.

Air-sea exchange

- Heat and mass exchange of a spray droplet with the air are decoupled.

- The initial droplet temperature equal to the sea surface temperature drops from 28°C to its equilibrium temperature within 1 s, while only 1% of the droplet mass must evaporate for the droplet to reach this equilibrium temperature.
- Remarkably little evaporation occurs until at least 40–50 s after droplet formation.

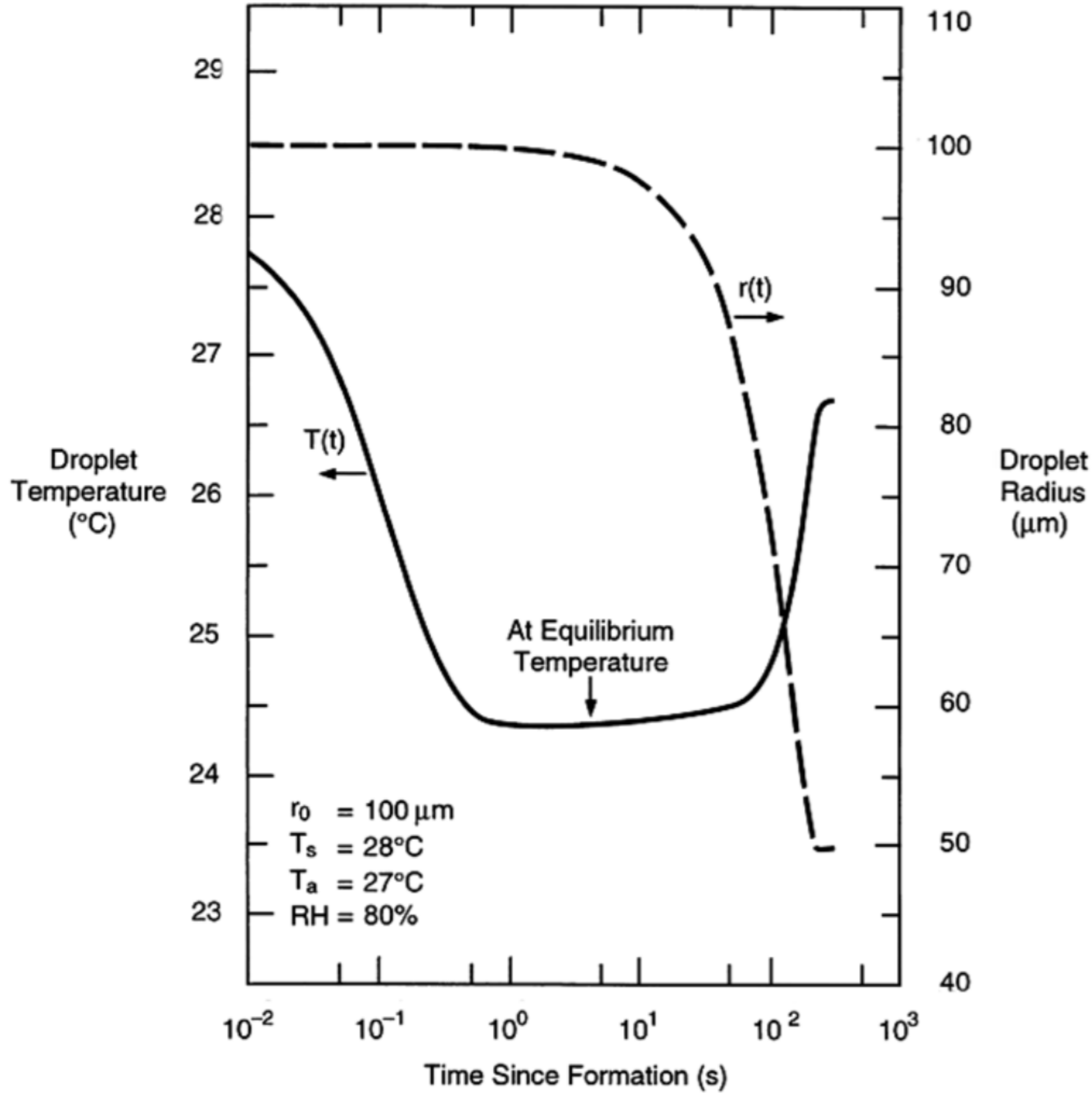


Fig. 6.13 Evolution of temperature and radius of a spray droplet of initial radius $r_0 = 100\ \mu m$, which is ejected from the sea surface at temperature $T_s = 28\,°C$ into the air at temperature $T_a = 27\,°C$ and relative humidity 80 %. The droplet has initial salinity 34 psu, and the barometric pressure is 1,000 mb. After Andreas and Emanuel (2001). Copyright © 2001 American Meteorological Society. Used with permission

Air-sea exchange

- Wind can accelerate spray after it is injected into the atmosphere.
- Extracts momentum from the flow (wind), which is transferred to the ocean when the droplets land.
- Spray droplets with relatively short atmospheric residence time (the re-entrant spray) effectively transfer momentum flux and sensible but not latent heat flux.
- Note that the latent heat flux is usually much larger than the sensible heat flux.

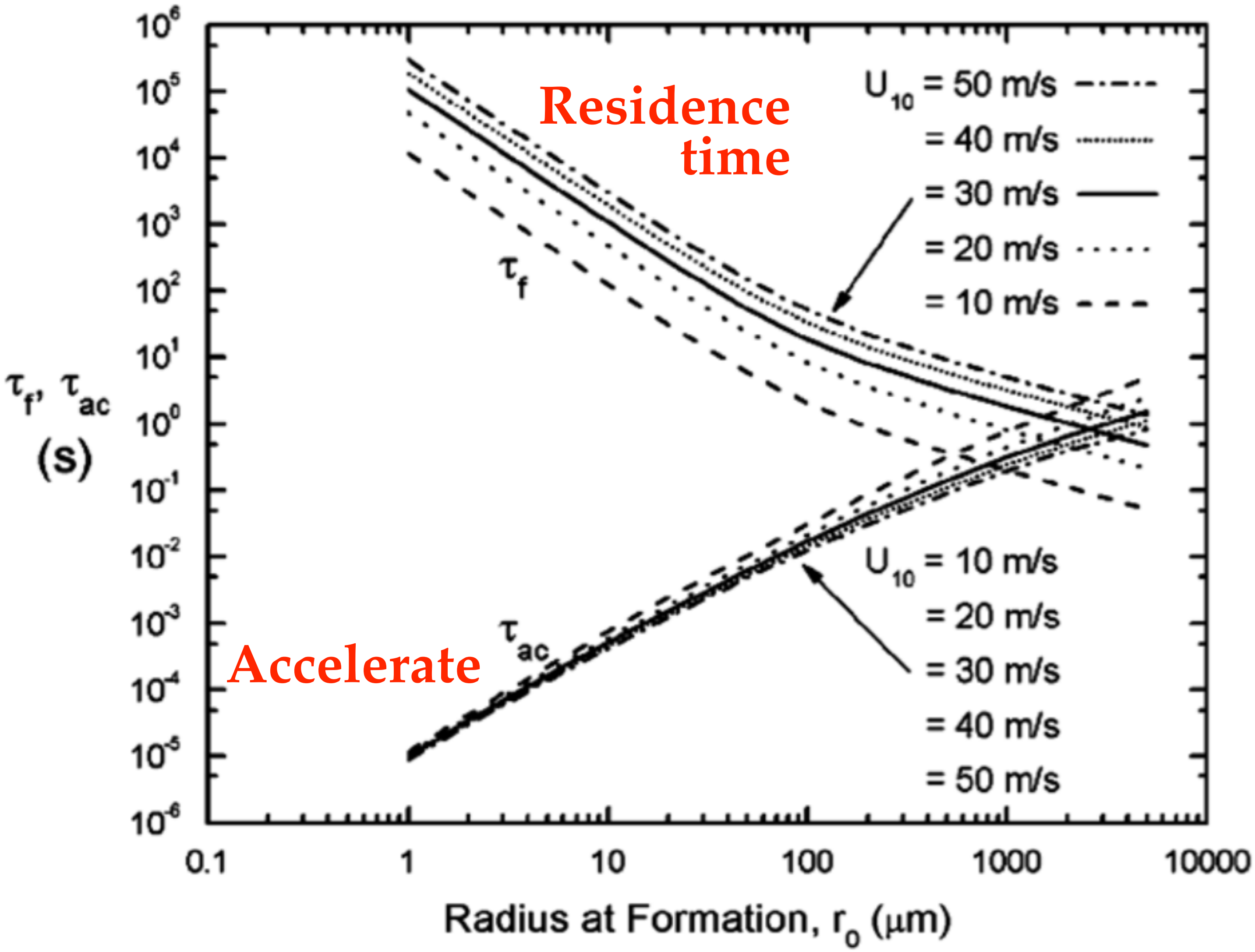


Fig. 6.14 Time τ_{ac} required for sea spray droplets to accelerate to wind speed U_{10}. Here, τ_f is the typical atmospheric residence time for droplets of initial radius r_0 at the indicated wind speed calculated from relation $\tau_f = A_{1/3}/w_t$, where $A_{1/3}$ is the significant wave amplitude determined as $A_{1/3} = 0.015U_{10}^2$ ($A_{1/3}$ is in m and U_{10} is in m s^{-1}). The air temperature is taken as 20 °C, and the barometric pressure as 1,000 hPa. After Andreas (2004). Copyright © 2004 American Meteorological Society. Used with permission

Dynamics

- The spray-saturated atmospheric boundary layer can be represented as a suspension flow, like a dust storm.
- Conceptual model involves a stationary turbulent flow of a dust–gas suspension in semi-infinite region.
- Evaporation is an additional complication over dust storms.

Under hurricane conditions

- Hurricanes take heat energy from the ocean and redeposit some as kinetic energy.
- How effective it is significantly depends on the properties and state of the sea surface.
- At very high wind speeds, the sea surface is dominated by streaks of foam and spray.

Under hurricane conditions

- Whitecap coverage increases with wind, although saturates at about 4%.

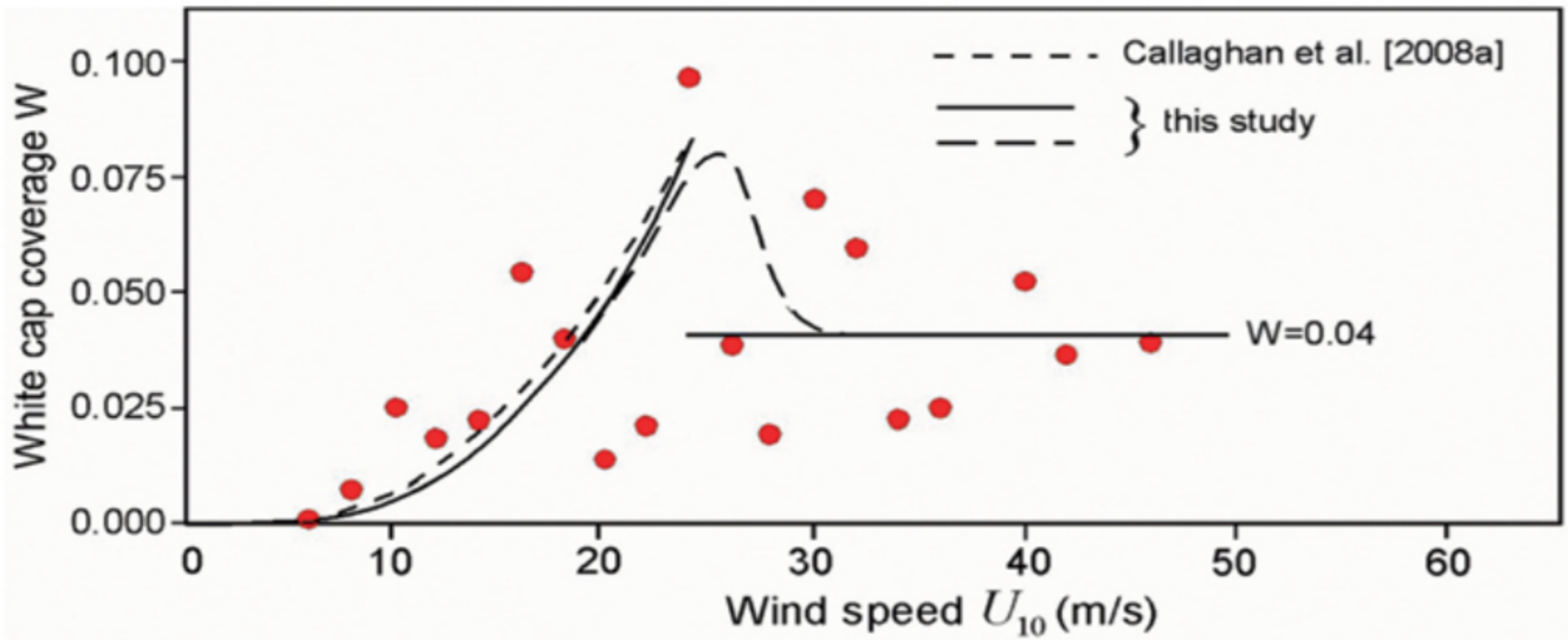


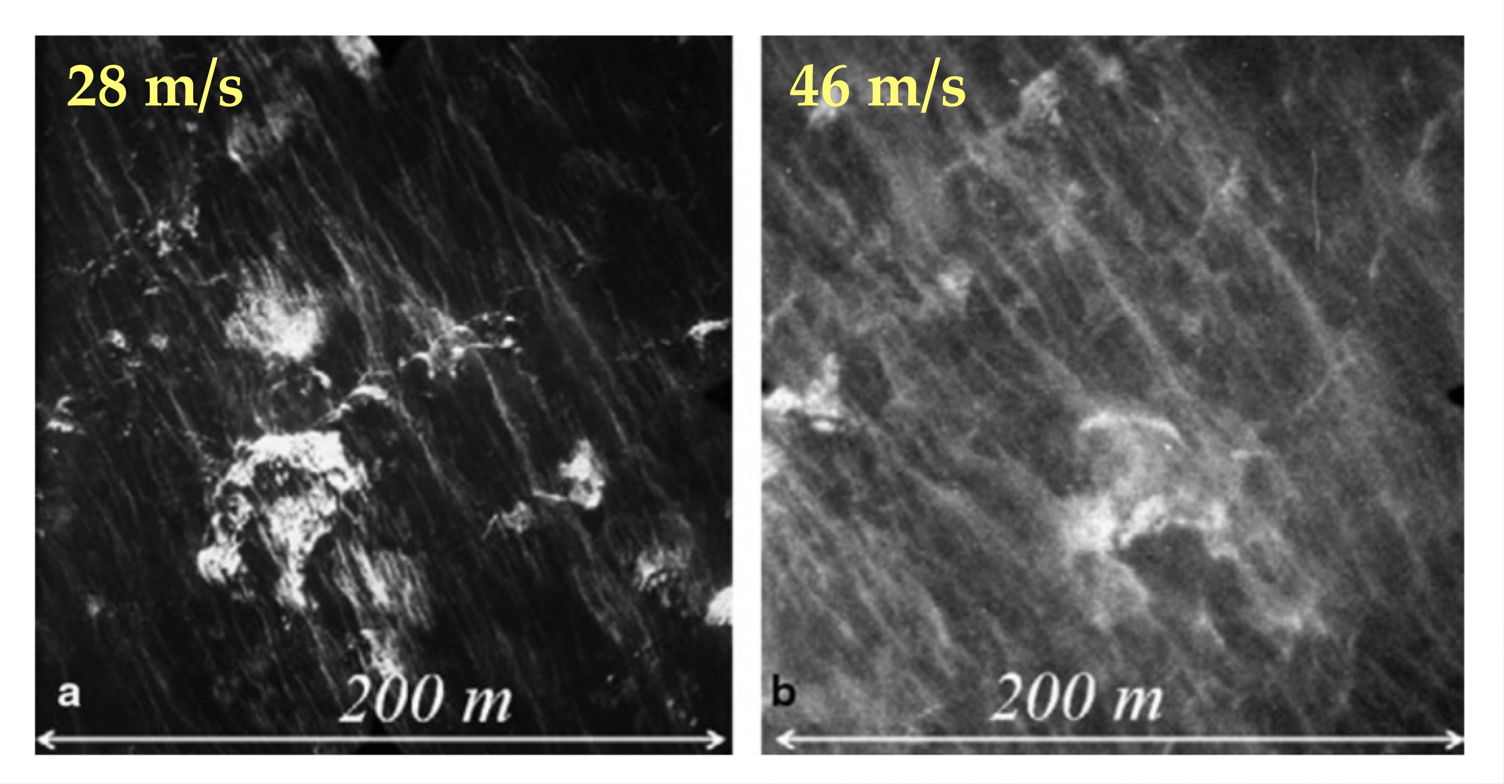
Fig. 6.19 The whitecap coverage obtained from the analysis of photos from low-level reconnaissance flights and approximated with a power law for wind speeds below 24 m s^{-1} and a constant above. A tanh capping with overshoot to a limiting value is shown with long dashes. Adapted from Holthuijsen et al. (2012). Reproduced by permission of American Geophysical Union

Under hurricane conditions

- The traditional assumption was that the whitecap coverage increases to 100 % under hurricane conditions.
- However, the previous studies were limited by 23 m s^{-1} wind speed.

Under hurricane conditions

- At higher wind speeds, the "whiteout" is increasingly dominated by the streaks of foam and spray.
- At wind speeds above 40 m s^{-1}, the streaks merge into a whiteout with complete coverage.



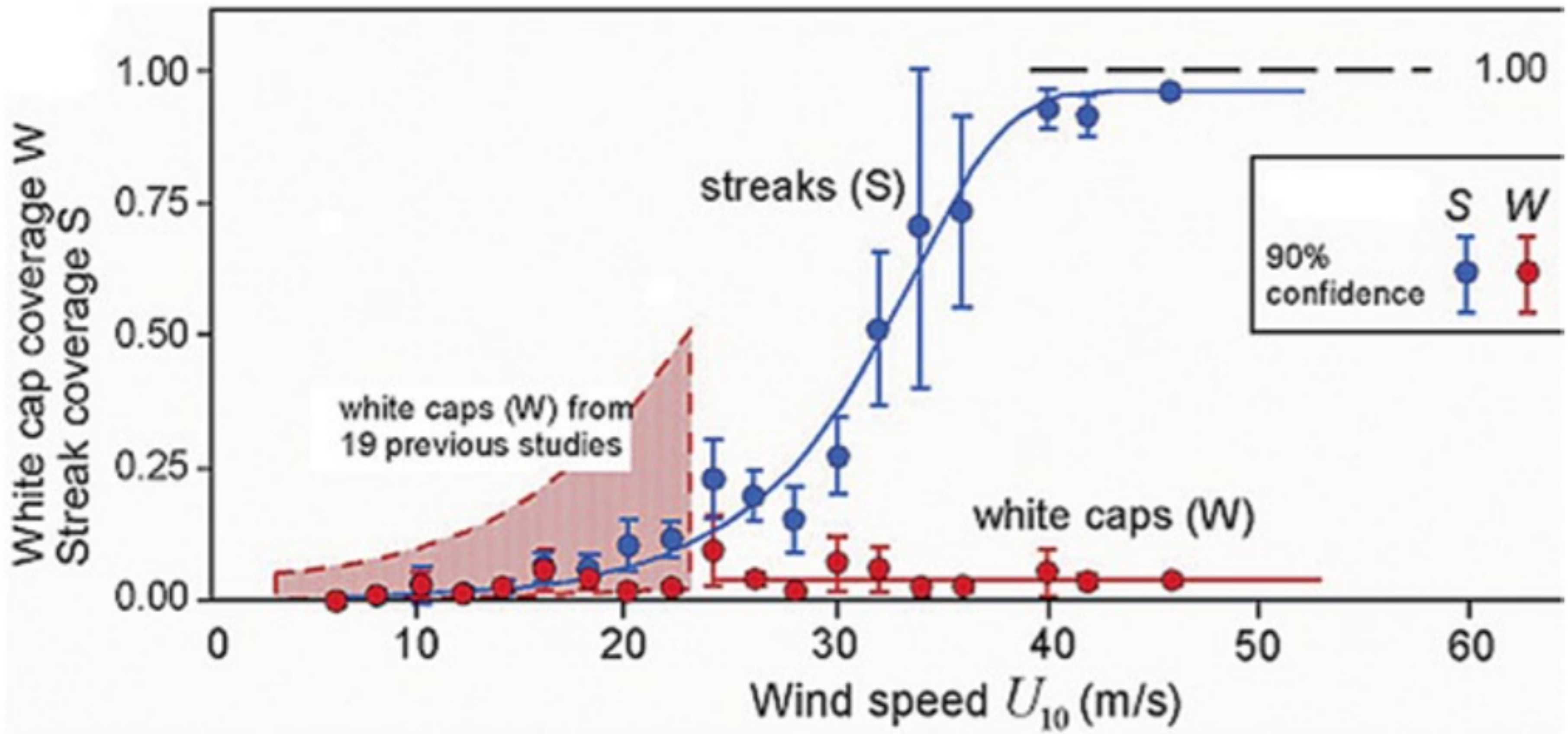


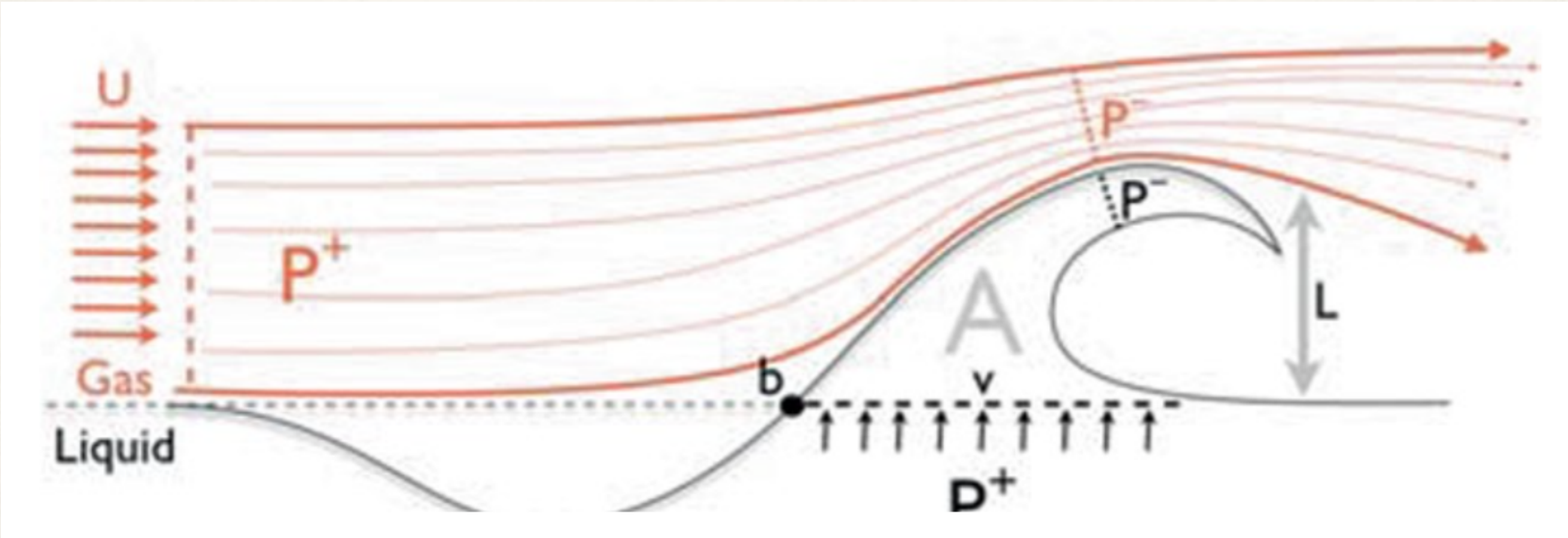
Fig. 6.20 Whitecap coverage W and streak coverage S as a function of wind speed. Blue and red dots represent observations, which are approximated with blue and red lines, respectively. Whitecap coverage W from 19 previous studies compiled by Anguelova and Webster (2006) is represented by shaded area. Adapted from Holthuijsen et al. (2012). Reproduced by permission of American Geophysical Union

Under hurricane conditions

- Whitecapping is not the most effective mechanism for disrupting the air–sea interface under very high speed winds.
- More intense and widespread disruption can be achieved through the KH instability.
- KH instabilities initiate the tearing of short wavelet crests, ejection of spume, and creation of two-phase environment, with subsequent smoothing of the sea surface.

Under hurricane conditions

- Acceleration of the air stream above a short wavelet induces a pressure drop across the air–water interface.
- Pressure drop breaks up the interface if $\Delta P = P^{+} - P^{-}$ exceeds the combined restoring force of gravity and surface tension.



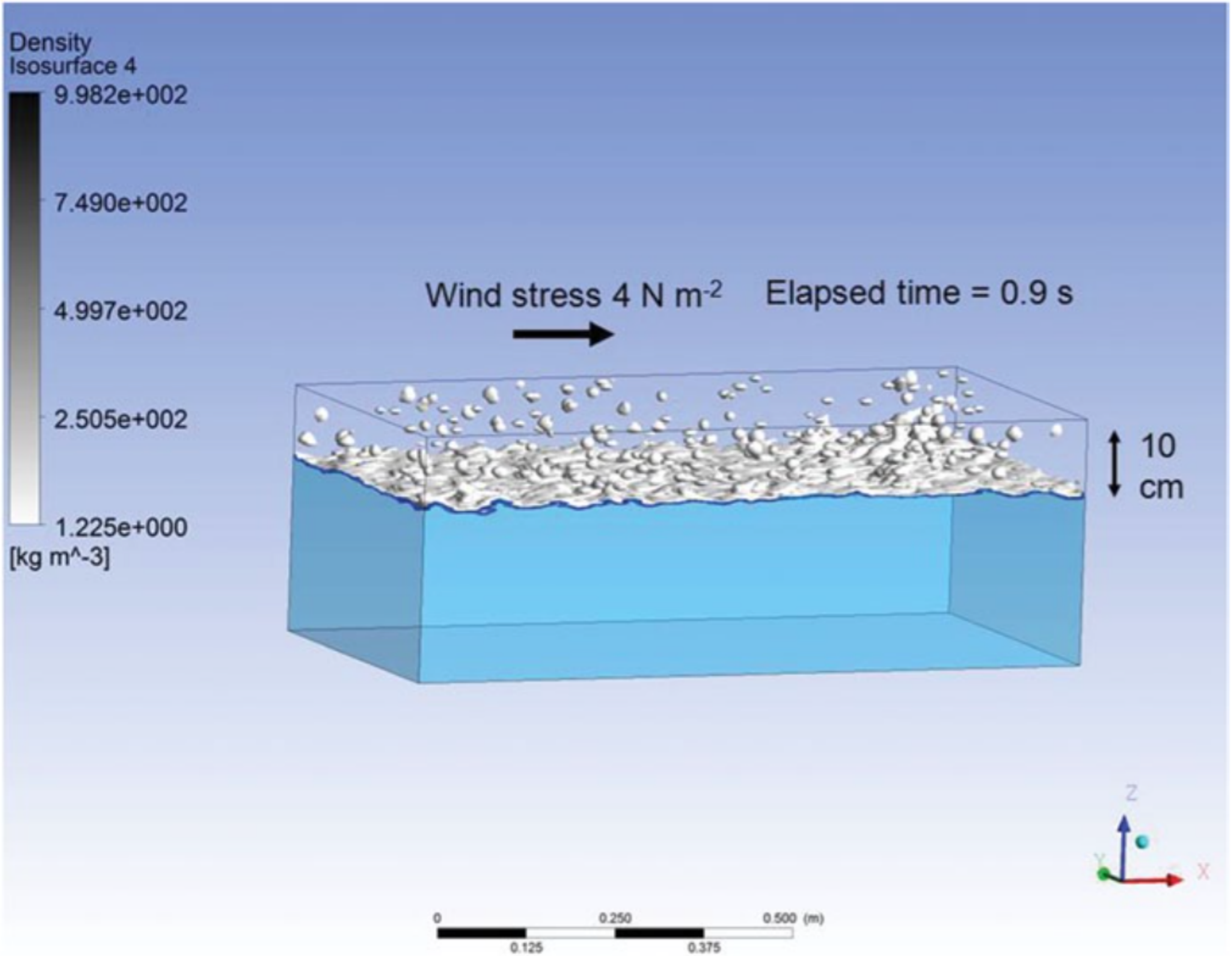


Fig. 6.22 The numerical experiment with an initially flat interface illustrates the possibility of the direct disruption of the air–water interface and formation of the two-phase environment under hurricane force wind. After Soloviev et al. (2012) by permission of John Wiley and Sons

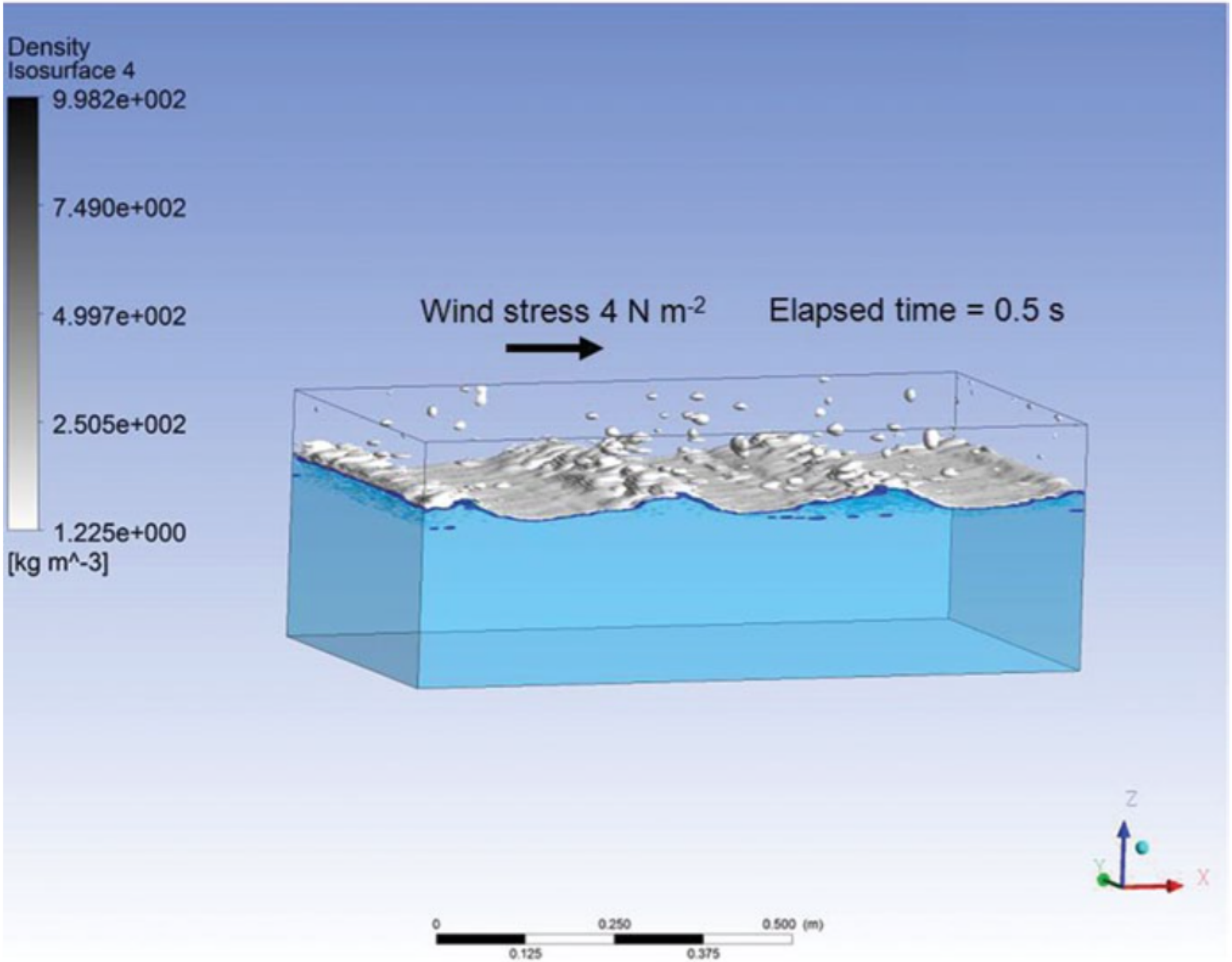


Fig. 6.23 Snapshot from a computational fluid dynamics experiment with imposed short waves demonstrates the tearing of wave crests, formation of water sheets and spume ejection into the air, 0.5 s after hurricane force wind stress is imposed at the top of the air layer. The two-phase mixture (density scale at left) of air and water covers the surface, and individual bubbles and spray droplets are also apparent. The length scale is indicated. After Soloviev et al. (2012) by permission of John Wiley and Sons

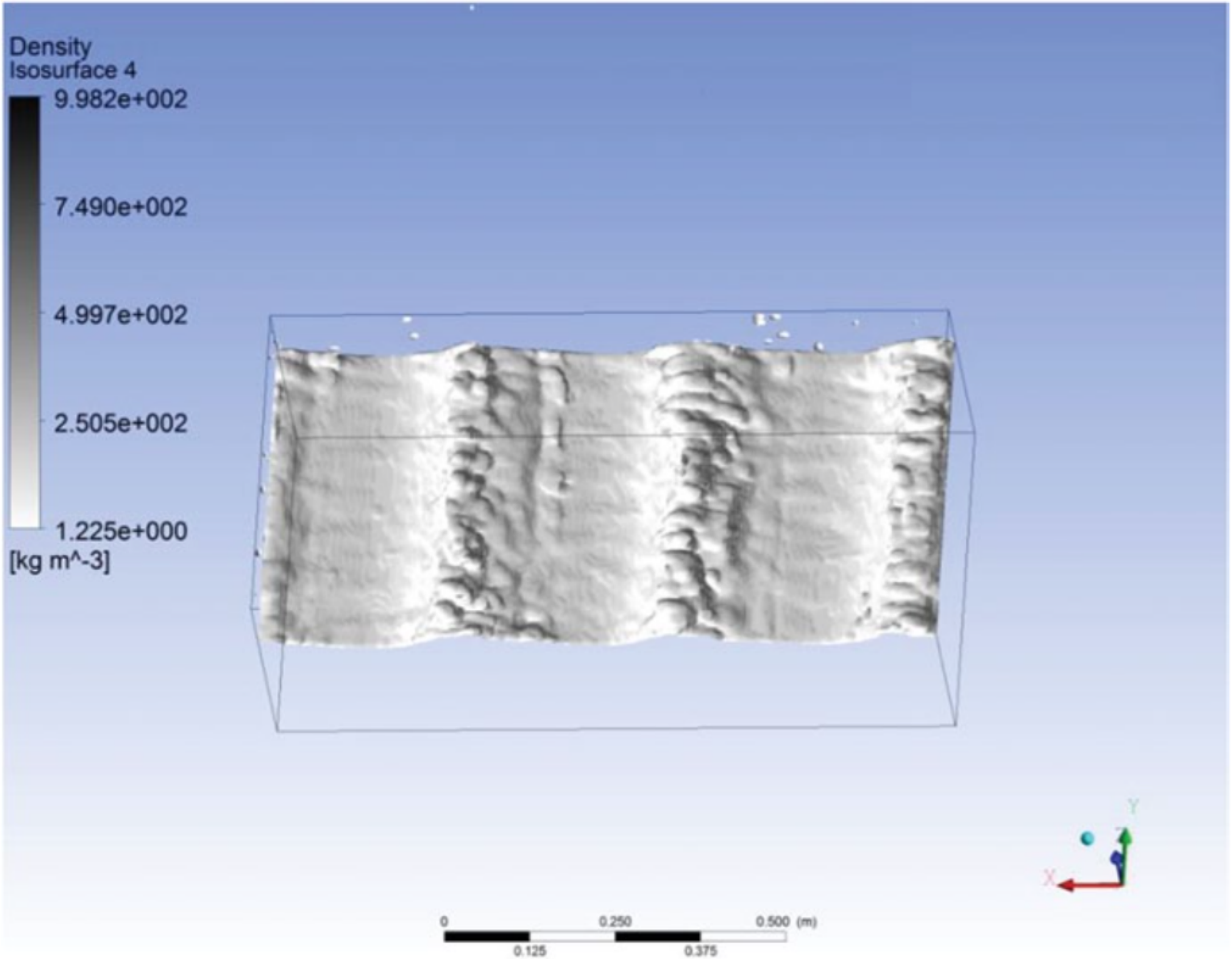


Fig. 6.25 View of the air–water surface shows quasi-periodic structures in the transverse direction along the top of wave crests. After Soloviev et al. (2012) by permission of John Wiley and Sons

Momentum exchange

- Prediction of cyclonic storms needs understanding of physical processes at the air-sea interface.
- Drag coefficient formula of Large and Pond (1981) derived from field measurements, under low and moderate wind speed conditions, gives a linear increase of the drag coefficient with wind.
- There is evidence that this formula does not work in the high wind-speed regime.

Momentum exchange

- There is evidence that this drag formula does not work in the high wind-speed regime.

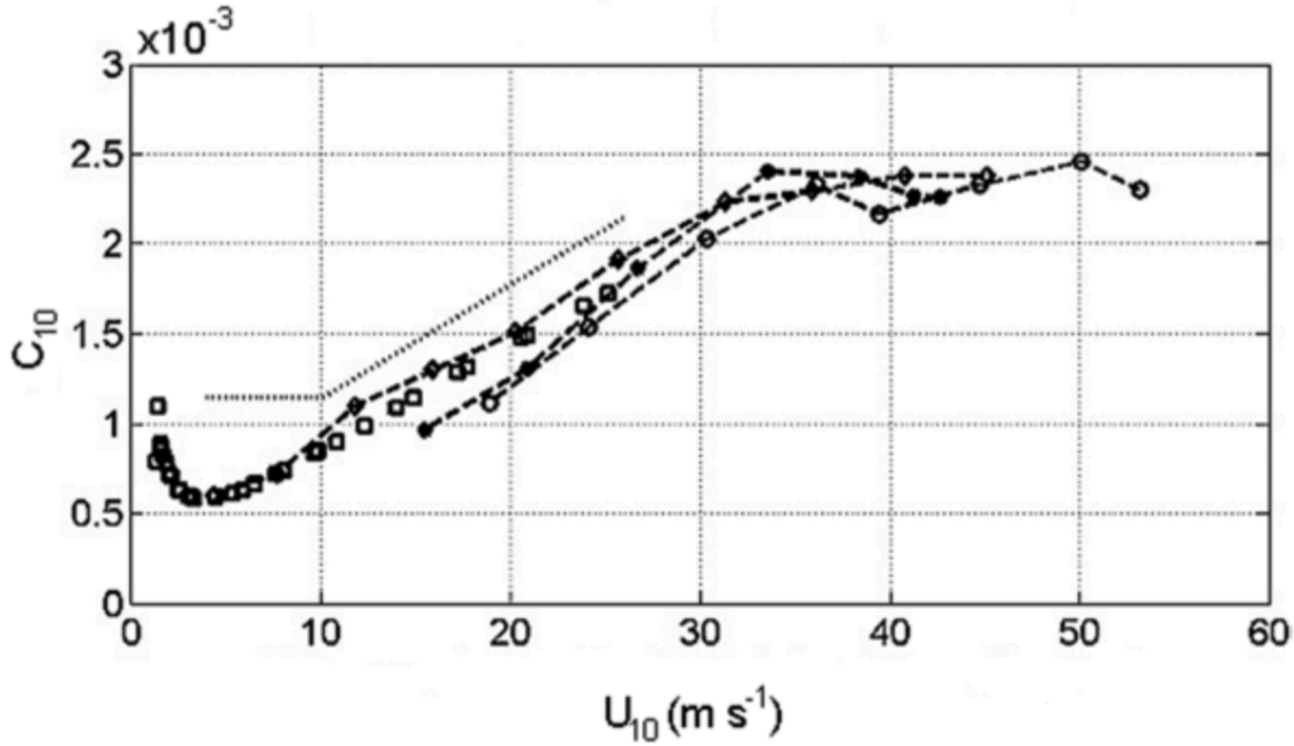


Fig. 6.26 Laboratory tank measurements of the neutral stability drag coefficient C_{10} referred to 10 m height by profile (asterisks), eddy correlation (diamonds), and momentum budget (circles) methods. The squares represent the data obtained in a different tank by Ocampo-Torres et al. (1994). The drag coefficient formula of Large and Pond (1981) derived from field measurements, under relatively low winds, is shown by dots. After Donelan et al. (2004) by permission of American Geophysical Union

Momentum exchange

- There is evidence that this drag formula does not work in the high wind-speed regime.

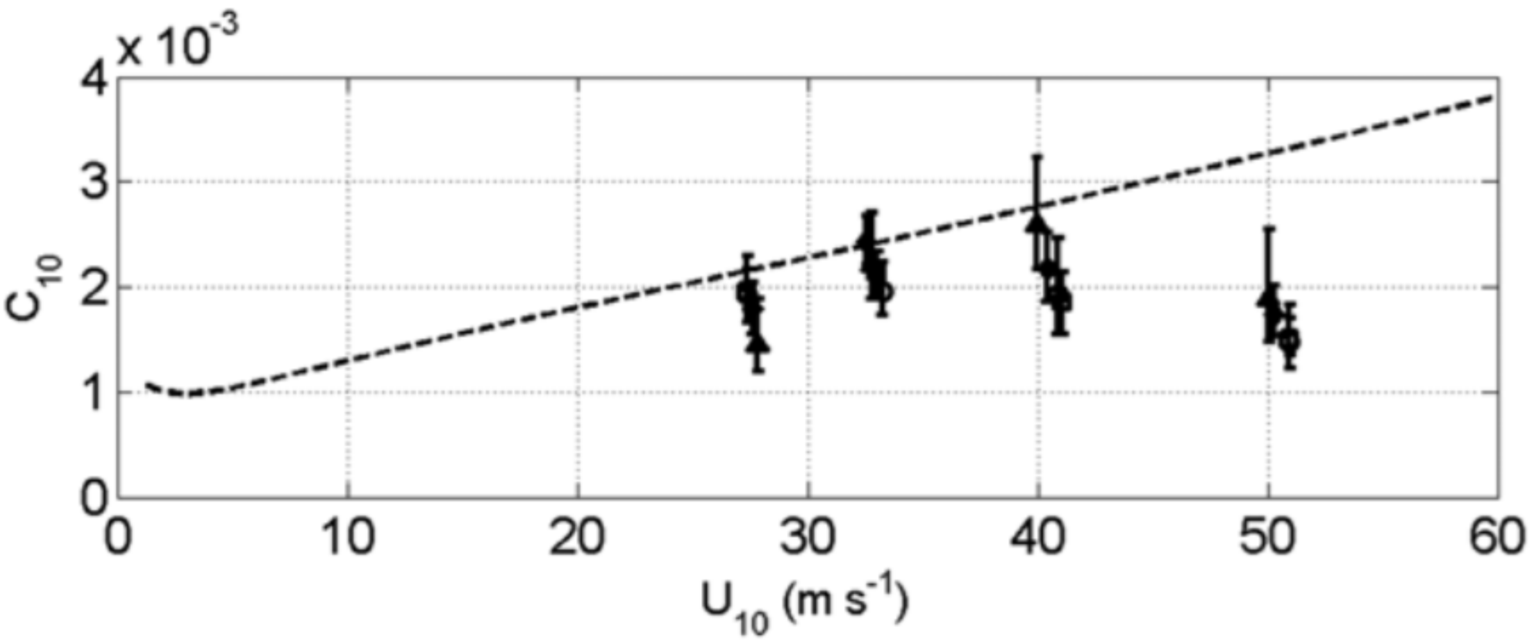


Fig. 6.27 Drag coefficient under high wind speed conditions. Dashed line is the Large and Pond (1981)-type parameterization derived by extrapolating relatively low wind speed measurements. Also shown are the experimental data of Powell et al. (2003) derived from GPS-sonde profiles and the corresponding 95 % confidence limits. Reproduced with permission from Macmillan Publishers Ltd

Momentum exchange

- Why the drop in drag coefficient?
    1. Andreas suggested that when the wind speed reaches about 30 m s^{-1}, the flux of spray droplets is equivalent to a heavy rainfall.

    Rainfall damps some part of short surface waves, which contribute to the surface roughness and thus the drag coefficient.

Momentum exchange

2. Soloviev and Lukas: the developing two-phase environment eliminates a portion of the high wave number wind–wave spectrum, which is responsible for a substantial part of the air–sea drag coefficient, and thus can reduce the drag coefficient in hurricanes conditions.

Under major hurricane conditions (U_{10}>60 m/s), the increasing thickness of the two-phase transition layer may increase of the drag coefficient limiting the maximum wind speed in tropical cyclones.

Hurricanes

- Hurricane track prediction has been steadily improving, while the intensity predictions have shown little or no progress during the last quarter century.
- Tropical cyclone intensity is sensitive to relative strength of enthalpy and momentum fluxes between the ocean and the atmospheric boundary layer in the high wind core of the storm.
- Drag coefficient dependance on wind speed is critical.

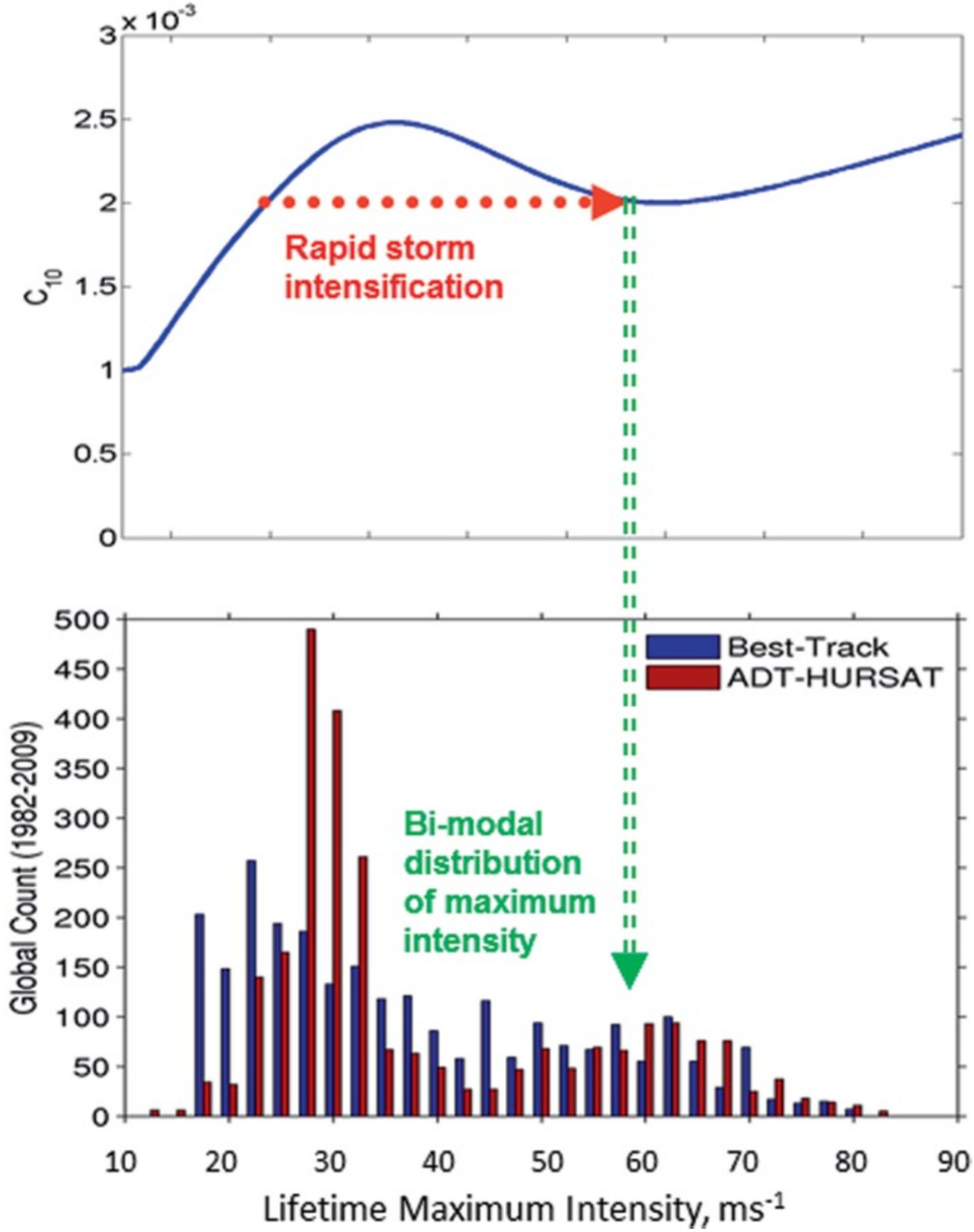


Fig. 6.31 The drag coefficient dependence on wind speed (a) may contribute to the rapid intensification from storms to major tropical cyclone and so may explain the observed (Kossin et al. 2013) bi-modal distribution of tropical cyclone intensity (b). After Soloviev et al. (2013)