The near-surface layer of the ocean

Chapter 2. Sea Surface Microlayer

of

The Near-Surface Layer of the Ocean
Structure, Dynamics and Applications
Soloviev and Lukas

Surface Microlayer

* Top few millimeters.

* Molecular diffusion dominates vertical transport as vertical component of turbulent mixing is suppressed.

* Involved in heat, momentum, and gas transfer.

* Variety of physical, biological, chemical, and photochemical interactions and feedbacks.

Surface Mircolayer

* Dynamics are complicated by surface waves, capillary waves, solar radiation, rain, and surfactants.

* Important for remote sensing.

* Direct ocean measurements are rare. Majority from lab or numerics.
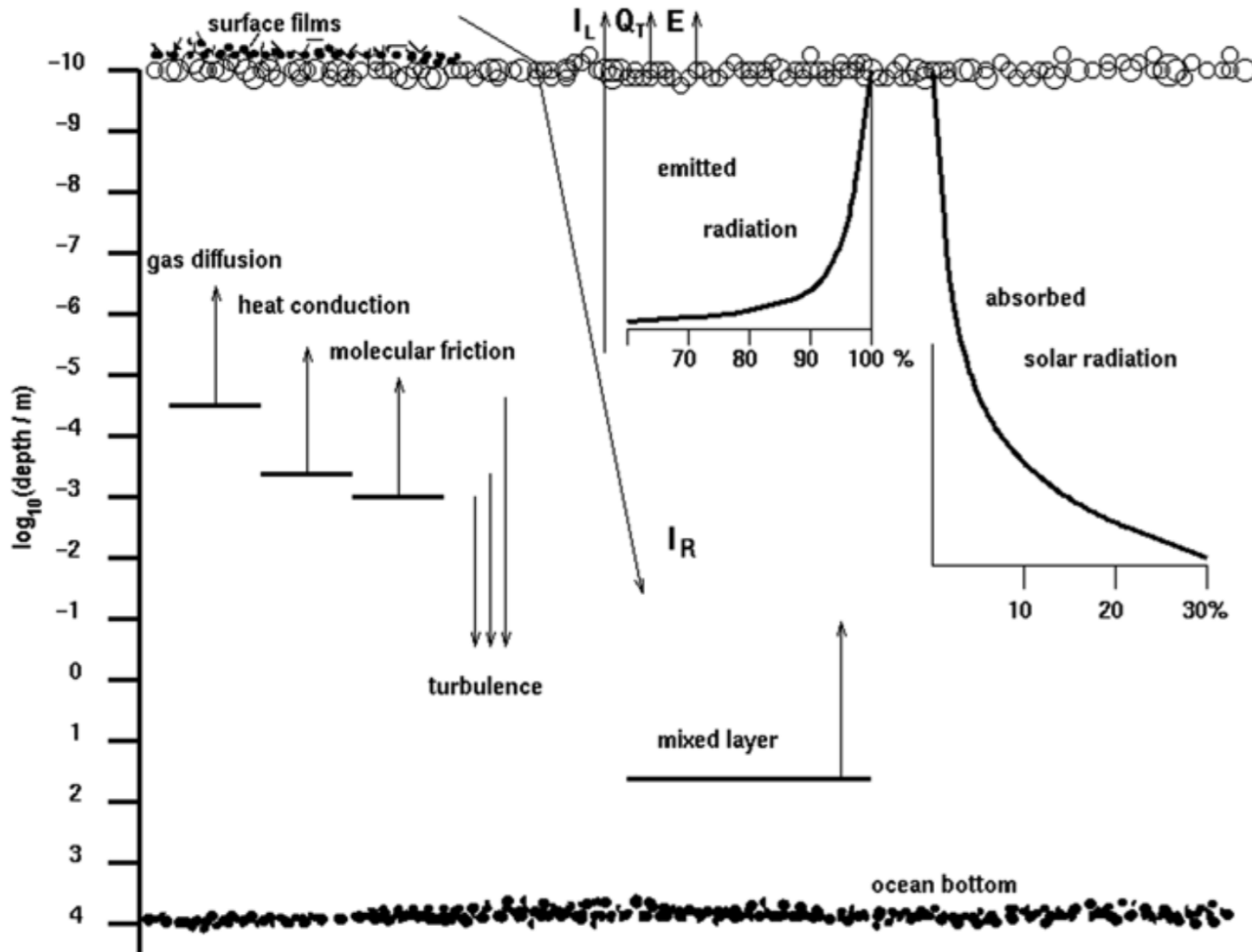
Fig. 2.1 Schematic representation of the vertical structure of physical processes related to the sea surface microlayer. (courtesy of Peter Schlüssel)
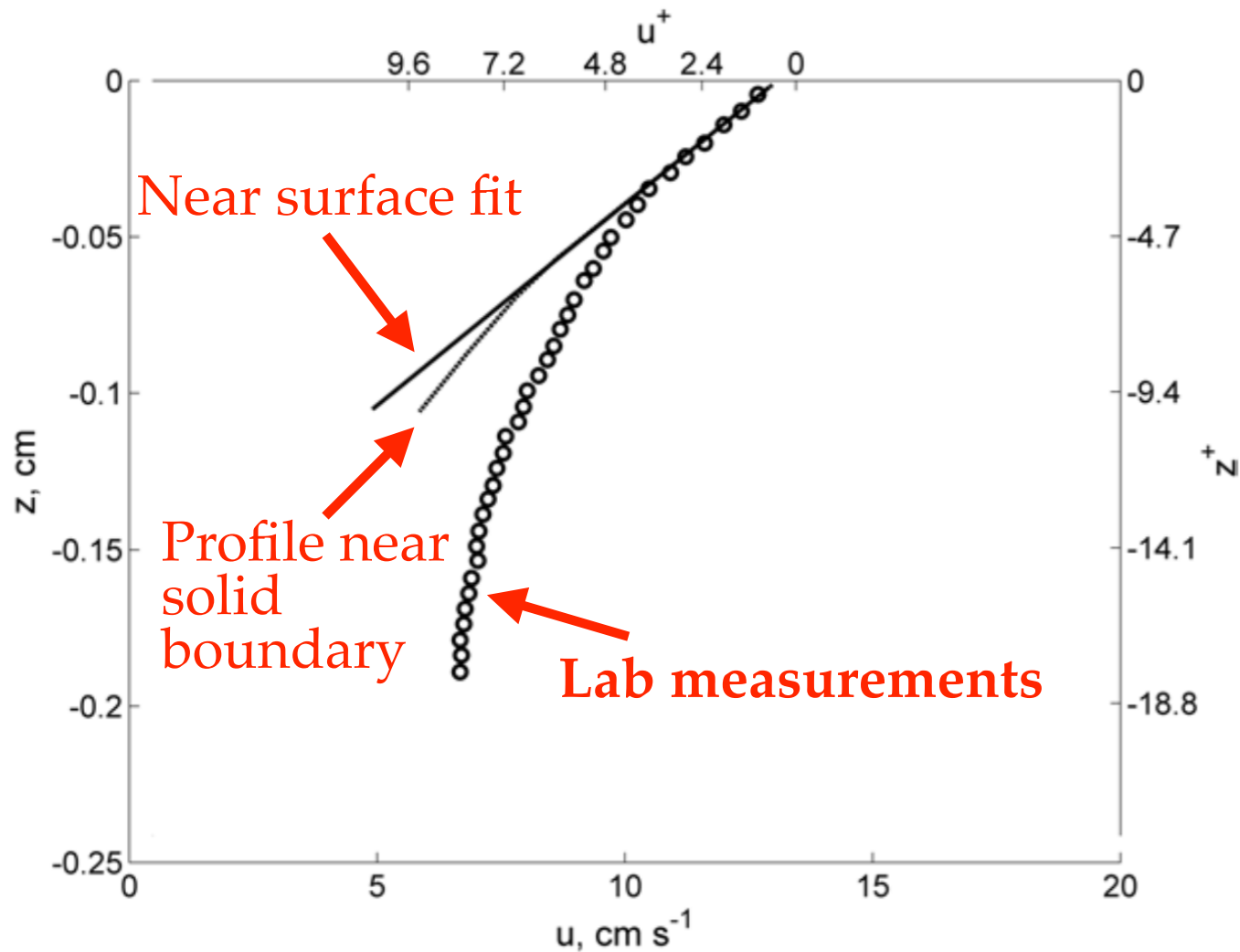
Viscous molecular sublayer

* Develops on both sides of the interface.

* Thickness depends on air-sea interaction regime.

* Typical depths: surface to 1,500 micrometers

$$\eta_v = \left(\frac{\nu^3}{\varepsilon}\right)^{1/4}$$

* Linear near-surface velocity profile, departure from linear fit serves as an indicator of viscous sublayer thickness.

* Approximately half the thickness compared to rigid wall.

Fig. 2.2 Velocity profile below the free water surface measured in a laboratory tank (circles). The straight line fits the near-surface slope, and the curved line follows the mean profile at a solid boundary. The solid boundary dependence is derived from nondimensional values by Kline et al. (1967). The nondimensional coordinates are as follows: $z^+ = zu_*/\nu$ and $u^+ = (u_0 - u)/u_*$, u_* is the friction velocity in water, ν is the molecular kinematic viscosity of water, u is the downwind water velocity, and u_0 is the downwind water velocity at the surface. (After McLeish and Putland 1975)
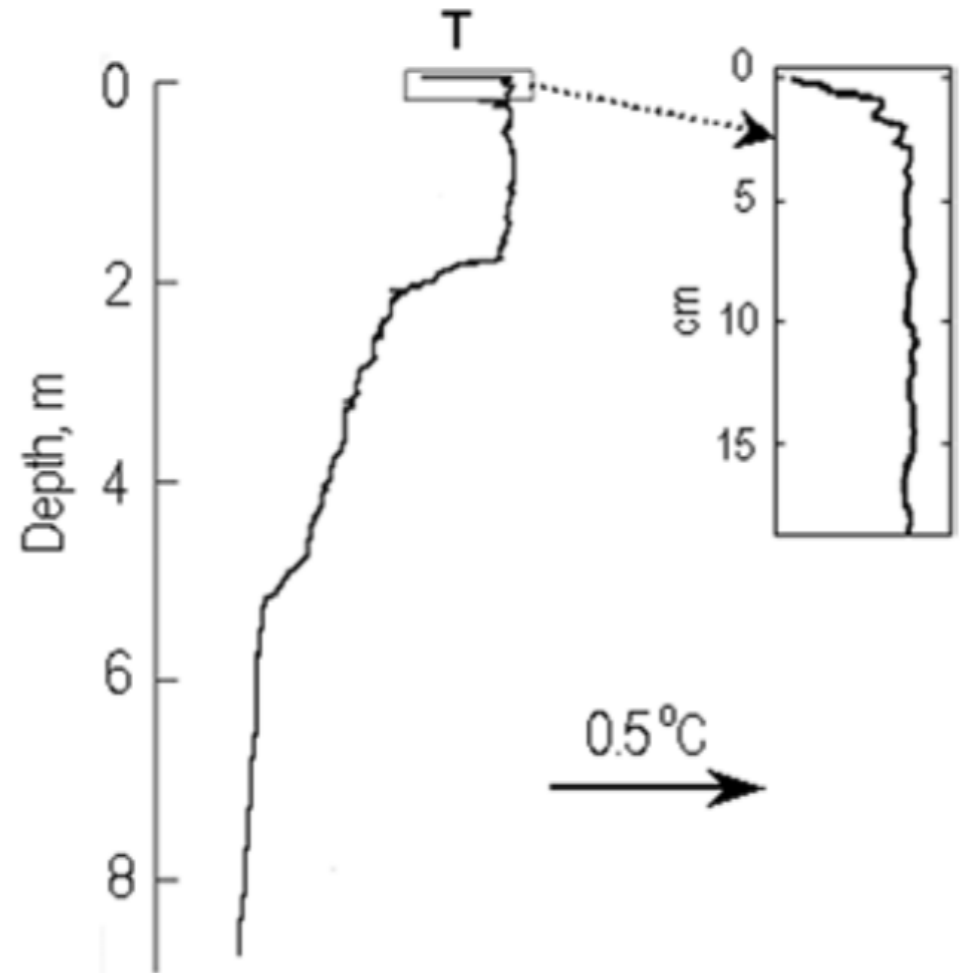
Thermal molecular sublayer

* SST may differ from underlying mixed layer.

* Known as "cool skin", due to absorption of solar radiation may turn into a "warm skin".

* Typical depths: surface to 500 micrometers.

$$\eta_T = \text{Pr}^{-1/2} \left(\frac{\nu^3}{\varepsilon} \right)^{1/4}$$

* A millimeter-thick atmospheric boundary layer, where the vertical transport is dominated by the molecular diffusion.

* The largest temperature difference are in the air rather than water.

Fig. 2.3 An "instantaneous" vertical profile of temperature in the upper ocean taken under low wind speed conditions. (After Soloviev 1992)

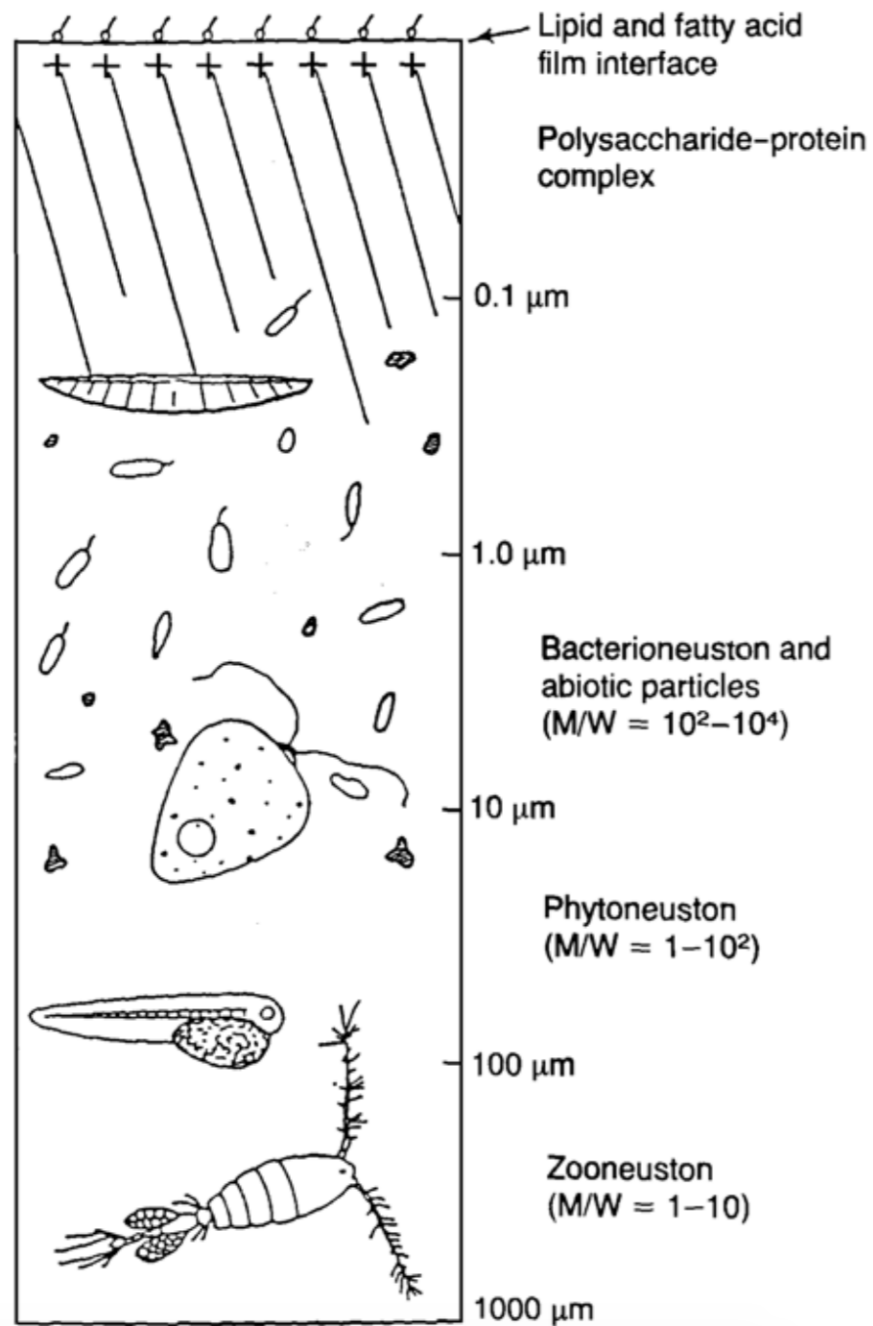$$\Delta T = T_0 - T_b \approx -0.3°C$$

Diffusive molecular sublayers

* Crucial for air-sea gas exchange.

* Practically all the gas concentration difference is in the ocean rather than the atmospheric diffusion sublayer.

* Typical depths: surface to 50 micrometer

$$\eta_D = Sc^{-\frac{1}{2}} \left(\nu^3 / \varepsilon \right)^{\frac{1}{4}}$$

* Schmidt number $\mathrm{Sc} = \nu / D \sim 10^3$, where

  D is the kinematic molecular (mass) diffusion coefficient.

* Salinity transport diffusion sublayer approximately same thickness as the gas diffusion sublayer.

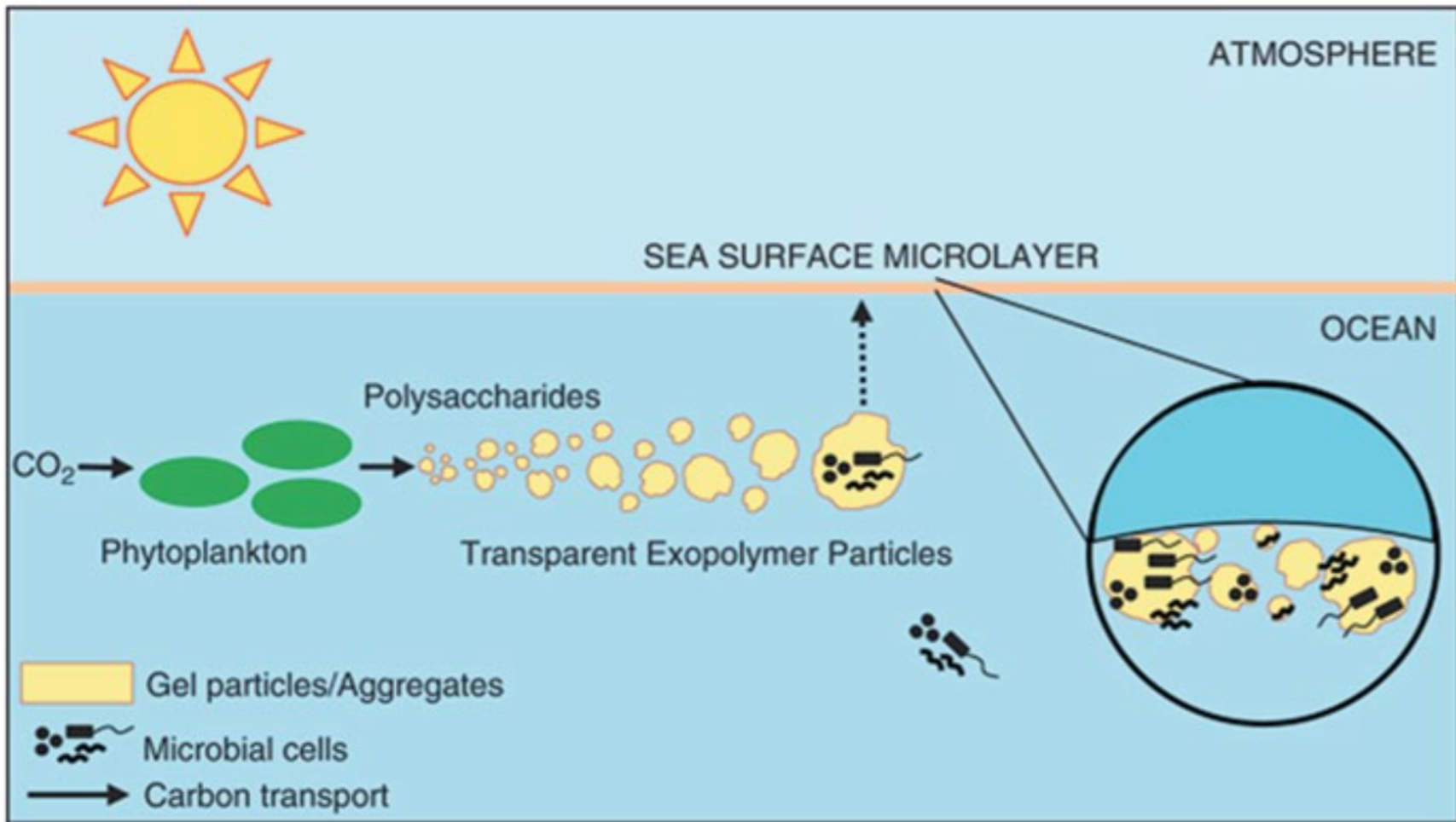* Under evaporative conditions salty skin layer, during rain freshwater skin.

Mircolayer ecosystem

* Highly productive.
* Due to extreme conditions is believed to be where life originated.
* Marine neuston habitat includes eggs and larvae of commercially and ecologically important species.
* Often higher densities than similar organisms in subsurface waters.
* Some neuston remain until turbulence created by breaking waves at winds exceeding 10–15 m s^{-1} disperses them.
*

Fig. 2.4 Conceptual model of the sea surface microlayer ecosystem. M/W = typical microlayer to water concentration ratios based on a number of studies. (Reproduced from Hardy (1982) by permission of Elsevier)

Lipid and fatty acid film interface

Polysaccharide–protein complex

0.1 μm

1.0 μm

Bacterioneuston and abiotic particles (M/W = 10^2–10^4)

10 μm

Phytoneuston (M/W = 1–10^2)

100 μm

Zooneuston (M/W = 1–10)

1000 μm

Fig. 2.5 Conceptual model of the sea surface microlayer based on the Wurl and Holmes (2008) study. The formation of transparent exopolymer particles (TEPs) in the near-surface layer of the ocean is a pervasive process, which is also a significant component of the global carbon cycle. Some TEPs float up to the surface microlayer, forming a gelatinous film. TEPs are readily colonized by microbial cells. (Reproduced from Cunliffe et al. (2009) by permission of John Wiley & Sons Ltd)

Surfactants

* Film: surfactant-influenced surface

* Slick: visibly surfactant-influence surface.

* From multiple sea, land, natural, and anthropogenic sources.

* Dissipate due to microbial, chemical, and photochemical processes and absorption onto particulates.

* Spread out by turbulence, diffusion, transport by bubbles.

* Flow convergences, organized structures, upwelling, and internal waves localize.

Physics of aqueous sublayers

* Subject to disturbances from near-surface turbulence (wave breaking, shear, convection, rising bubbles, spray hitting the sea surface, raindrops, etc.).

* Breaking waves that entrain air and thereby produce whitecaps are the most intense and obvious manifestation of the turbulent disturbance.

* Waves may also break without entraining air: *microscale wave breaking*.

* Capillarity effects and the presence of surface-active materials significantly complicate physics of the free surface.

Convective and shear instabilities

* Molecular sublayers are intermittent in time and space.

* Surface cooling and/or evaporation driven salinity increases result in convection.

* Absorption of solar radiation or rainfall inhibits convection.

* Convection is a process that produces organized structures.
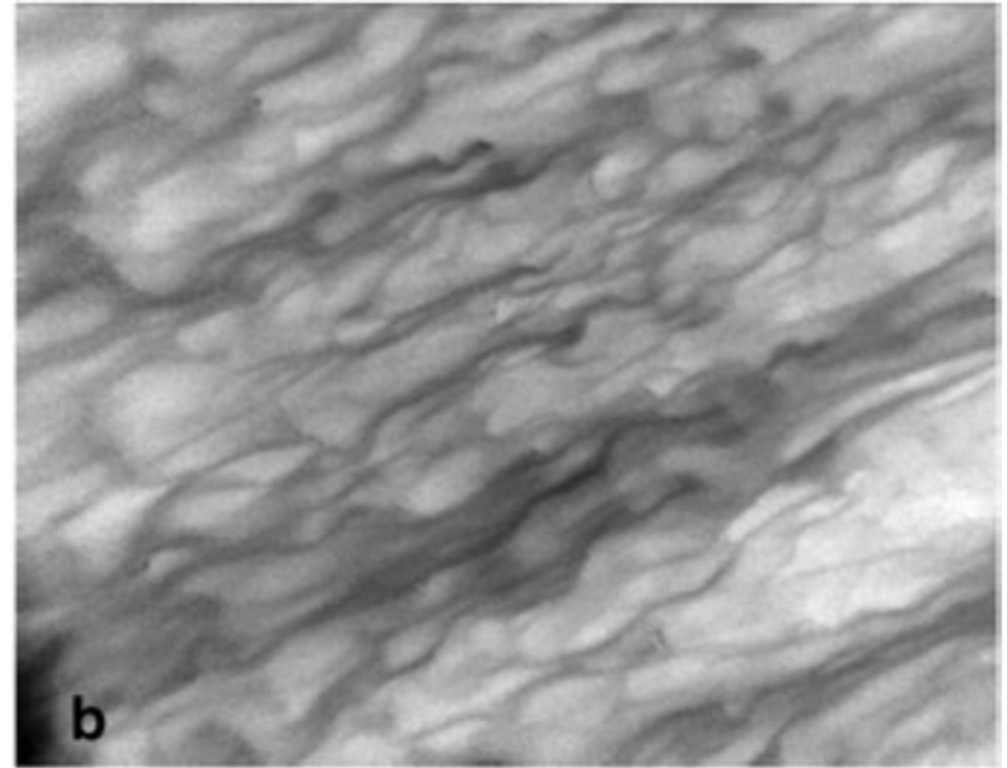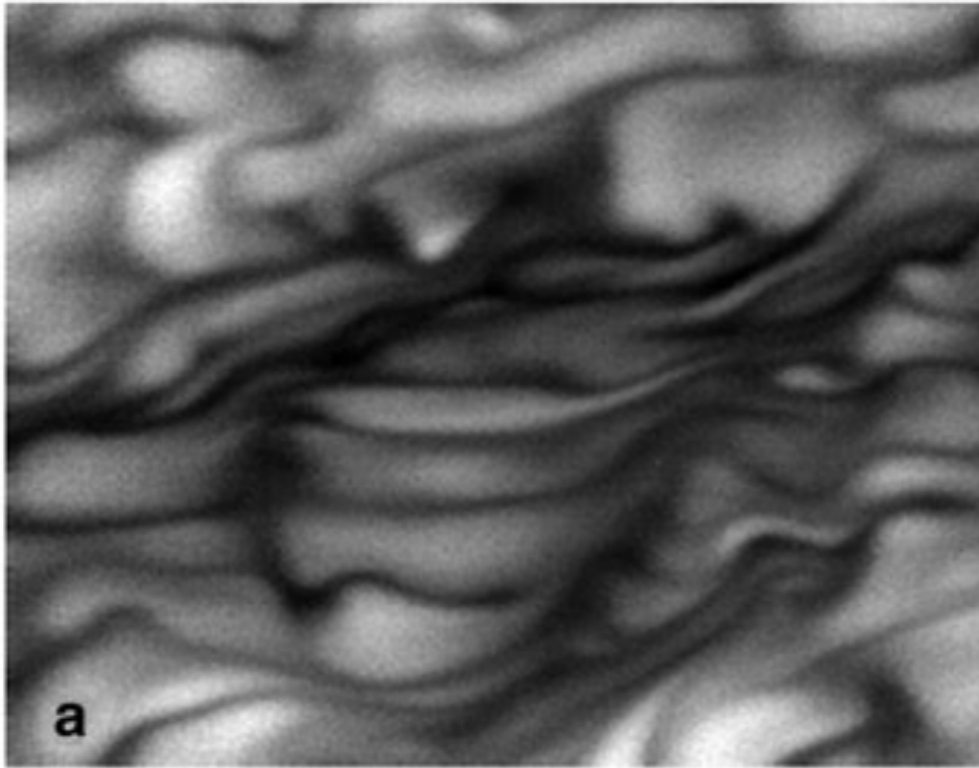
Fig. 2.8 Infrared images of the surface taken in the RSMAS air-sea interaction tank for: **a** light and **b** moderate winds with an imposed air-water temperature difference of 10°C. The water is warmer than the air and light areas are warmer water. (Courtesy of Mark Donelan)

Convective and shear instabilities

* With no solar radiation and precipitation effects
  * Under low wind speeds convective instabilities of thermal sublayer occur.
  * Under moderate to high wind speeds, the molecular sublayers are controlled by wind stress and surface waves.
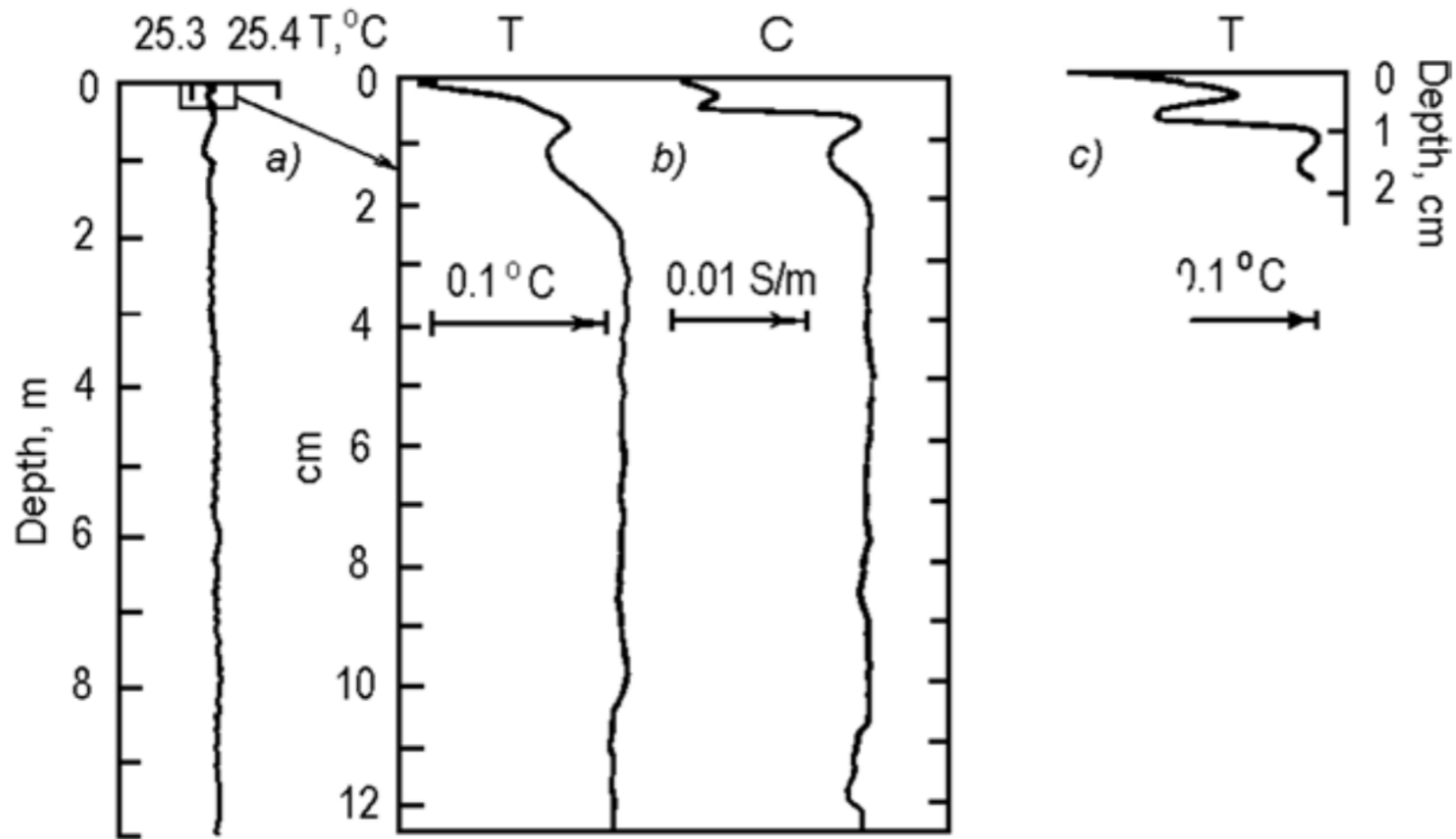
Fig. 2.9 a, b Vertical structure of the near-surface layer of the ocean from measurements with a free-rising profiler in the equatorial Atlantic made at night (02:57 LT) under conditions of low wind speed ($U_{10}=3$ m s^{-1}) and intense cooling of the ocean surface ($Q_0= 170$ W m^{-2}) in comparison **c** with the data from laboratory experiment of Ginzburg et al. (1977). *T* temperature, *C* conductivity of seawater. (Reproduced from Soloviev and Vershinsky (1982) by permission of Elsevier)
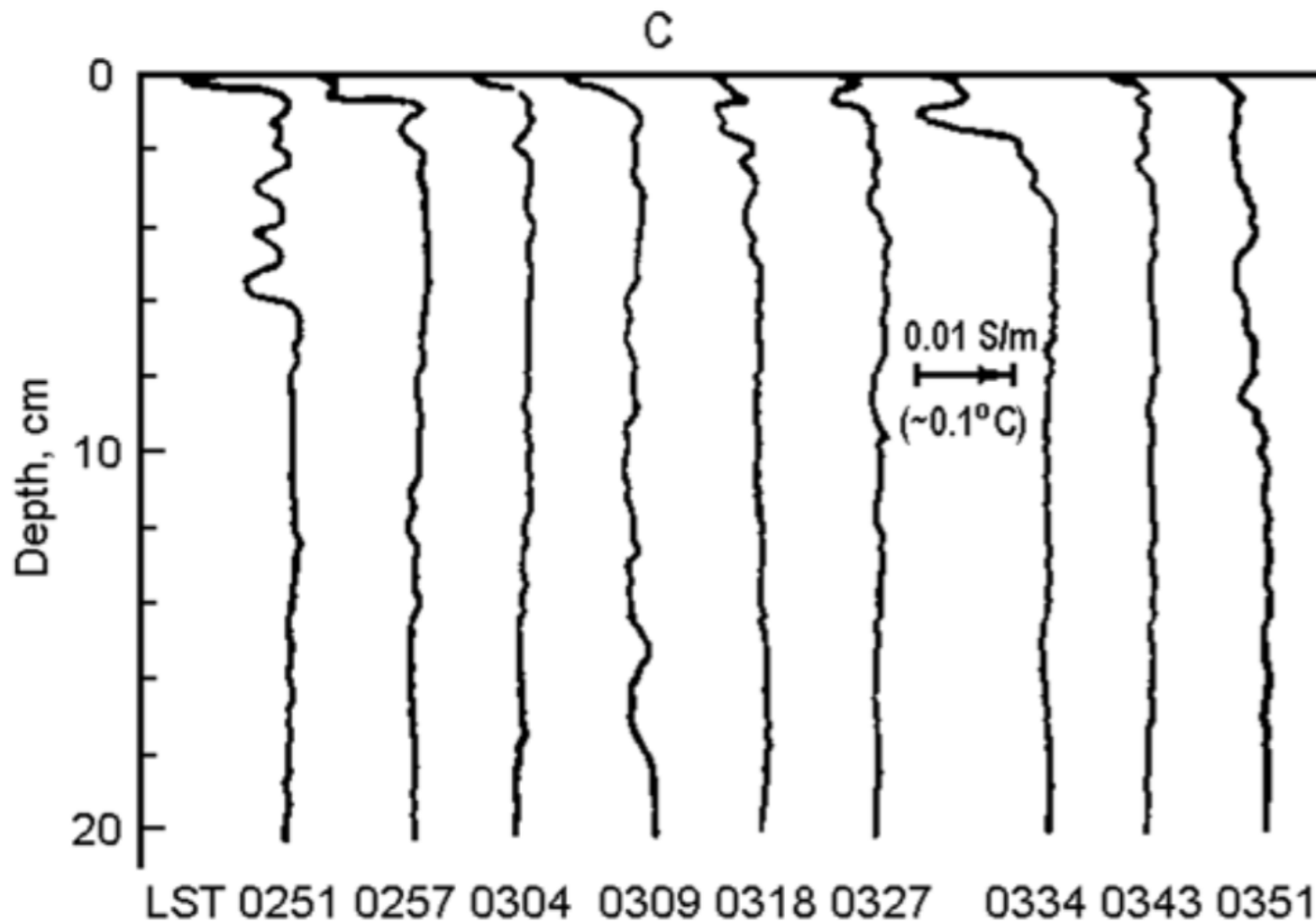
Fig. 2.10 Vertical profiles of conductivity observed during night under convectively unstable conditions near the surface according to measurements in the equatorial Atlantic. The time of observation is marked (LST) under each profile. Wind speed $U_{10} = 3$ m s^{-1}, net surface heat flux $Q_0 = 170$ W m^2. The scale of conductivity is shown in the equivalent temperature units under the assumption of constant salinity. (Reproduced from Soloviev and Vershinsky (1982) by permission of Elsevier)

Convective and shear instabilities

* At large Rayleigh numbers free convection is intermittent in time and space.

* The thermal boundary-layer forms by diffusion, grows until it is thick enough to develop convective instability, and is destroyed by convection, which in turn dies down once the boundary layer is destroyed. Then the cycle begins again.
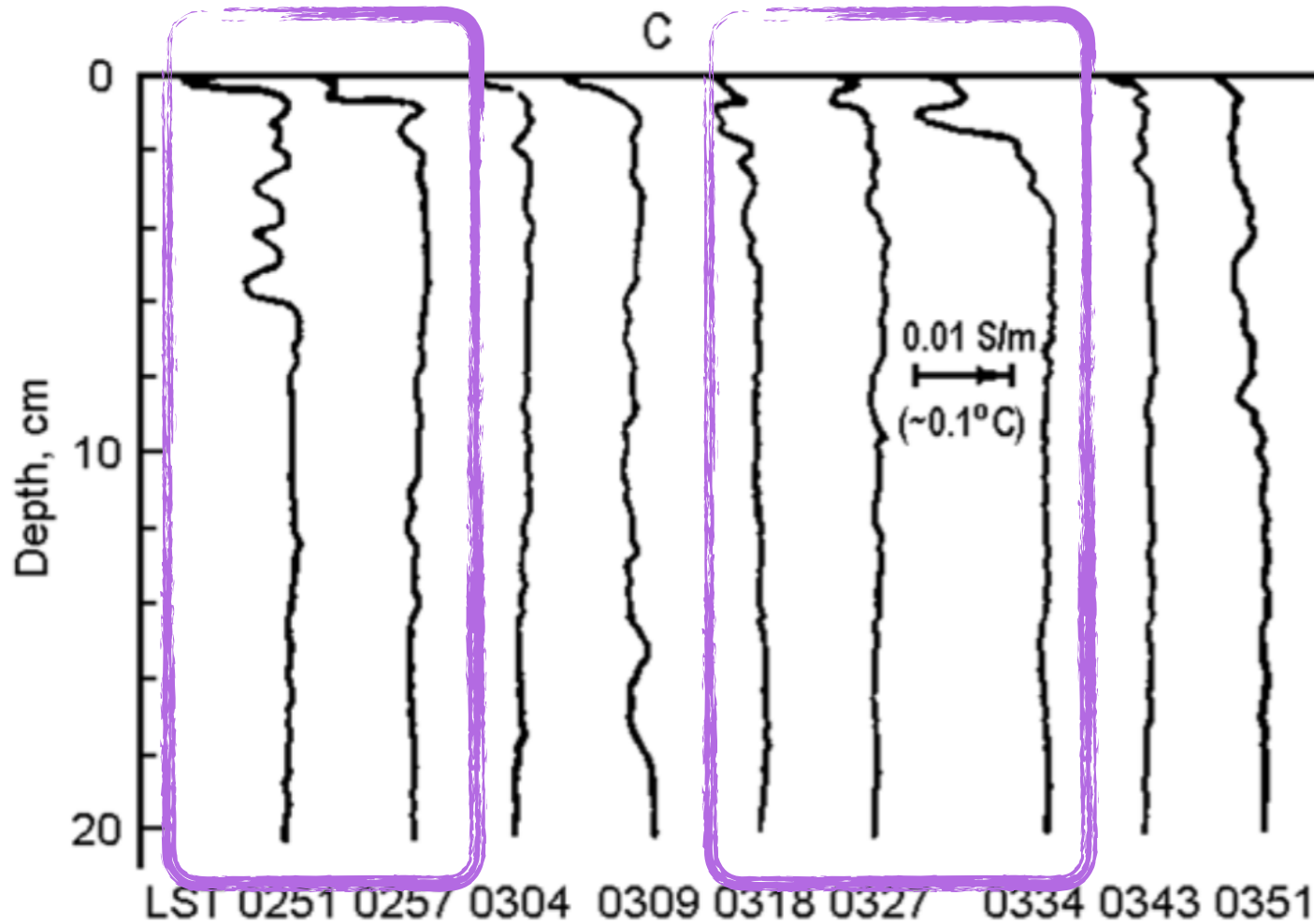
"Can be interpreted as the stage of destruction of the cold surface sublayer by a discrete convective element (thermal)"
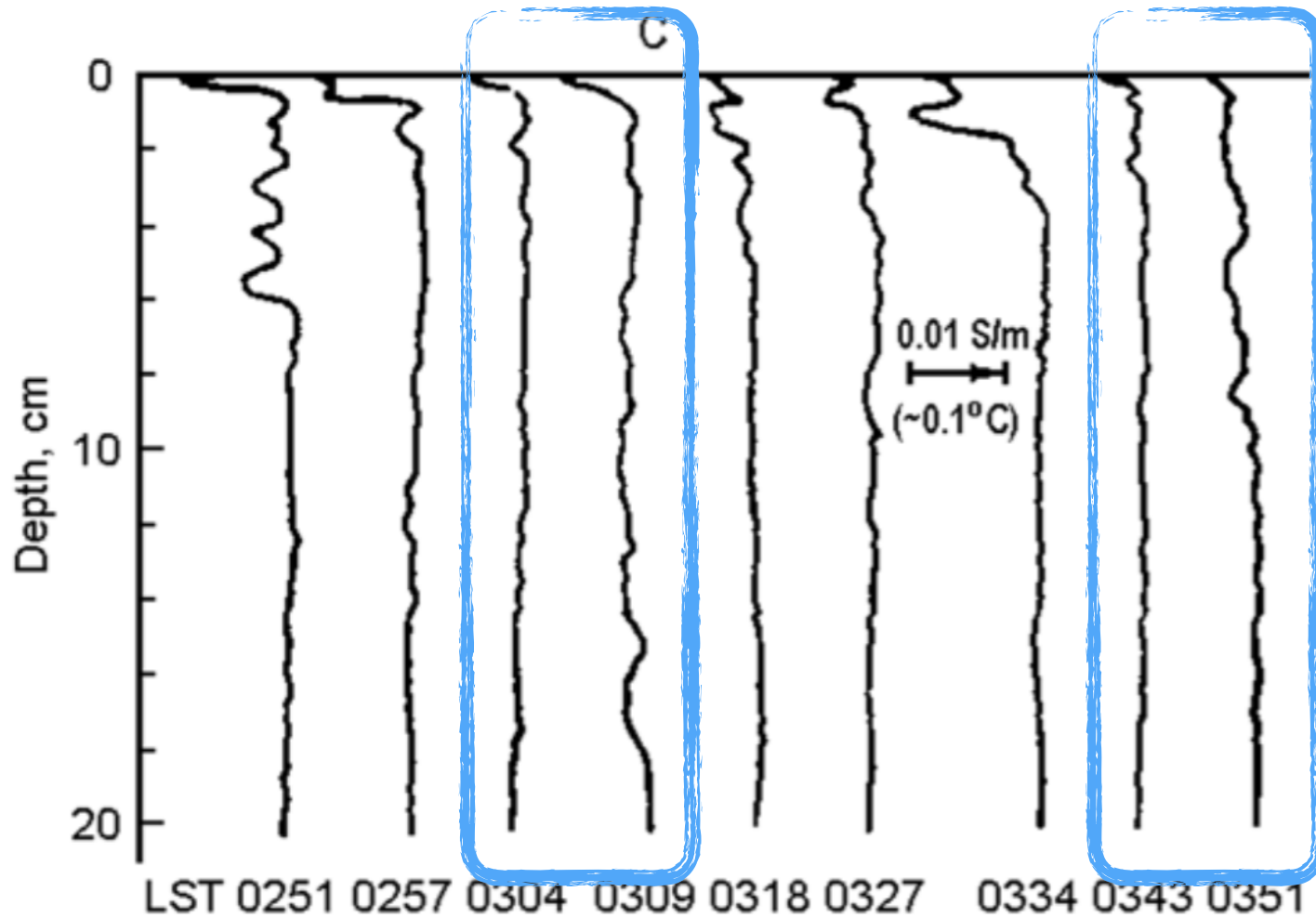
"Can be related to the stage of dissipation of the thermal and beginning of the next cycle by the formation of the unstably stratified thermal sublayer due to the molecular heat diffusion"

Microscale wave breaking

* Typically 0.1 - 1 m in length and a few cm in amplitude.
* Far more wide spread than whitecapping.
* Difficult to identify visually due to lack of air entrainment.
* Produce convergence of flow that leads to intense renewal of surface water.
* Cumulative effect on heat and gas fluxes is significant.

Fig. 2.11 The characteristic feature of a microscale breaking wave is the bore-like crest with parasitic capillary waves riding along the forward face. U wind speed, C_b crest speed of the breaking wavelet (After Longuet-Higgins 1992). Bottom: photograph of a breaking wavelet with a wavelength of roughly 0.1 m (adapted from Jessup et al. 1997). (Reproduced by permission of American Geophysical Union)
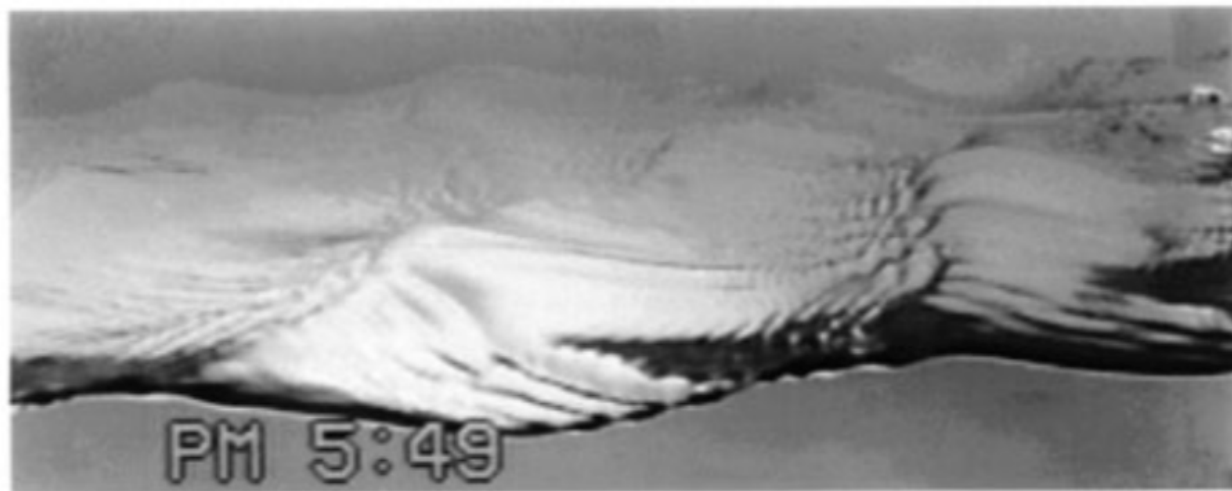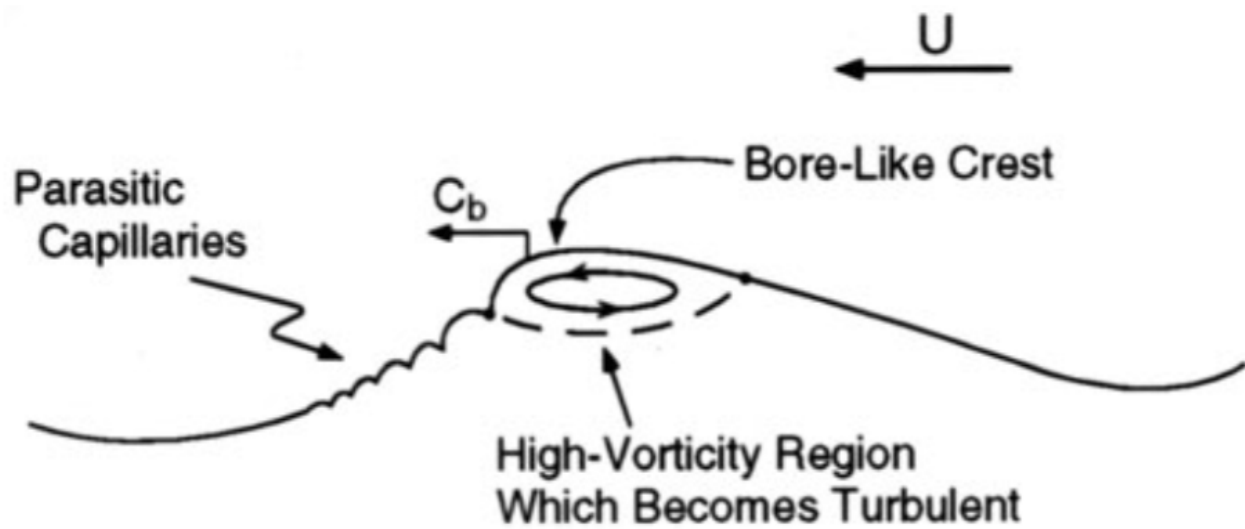
Wave breaking & whitecapping

* Breaking surface waves destroy the molecular sublayers, which reform between breaking events.

* The ratio of tangential wind stress controlling viscous sublayer (τ_t) to the total air-sea momentum flux (τ_0) is

$$\tau_t = \tau_0(1 + Ke/Ke_{cr})^{-1}$$

* Keulegan number, $Ke = u_*^3/(g\nu)$, is a fundamental parameter in the dynamics of free interfaces.

* For $Ke << Ke_{cr}$ interfacial instabilities are suppressed by molecular viscosity.
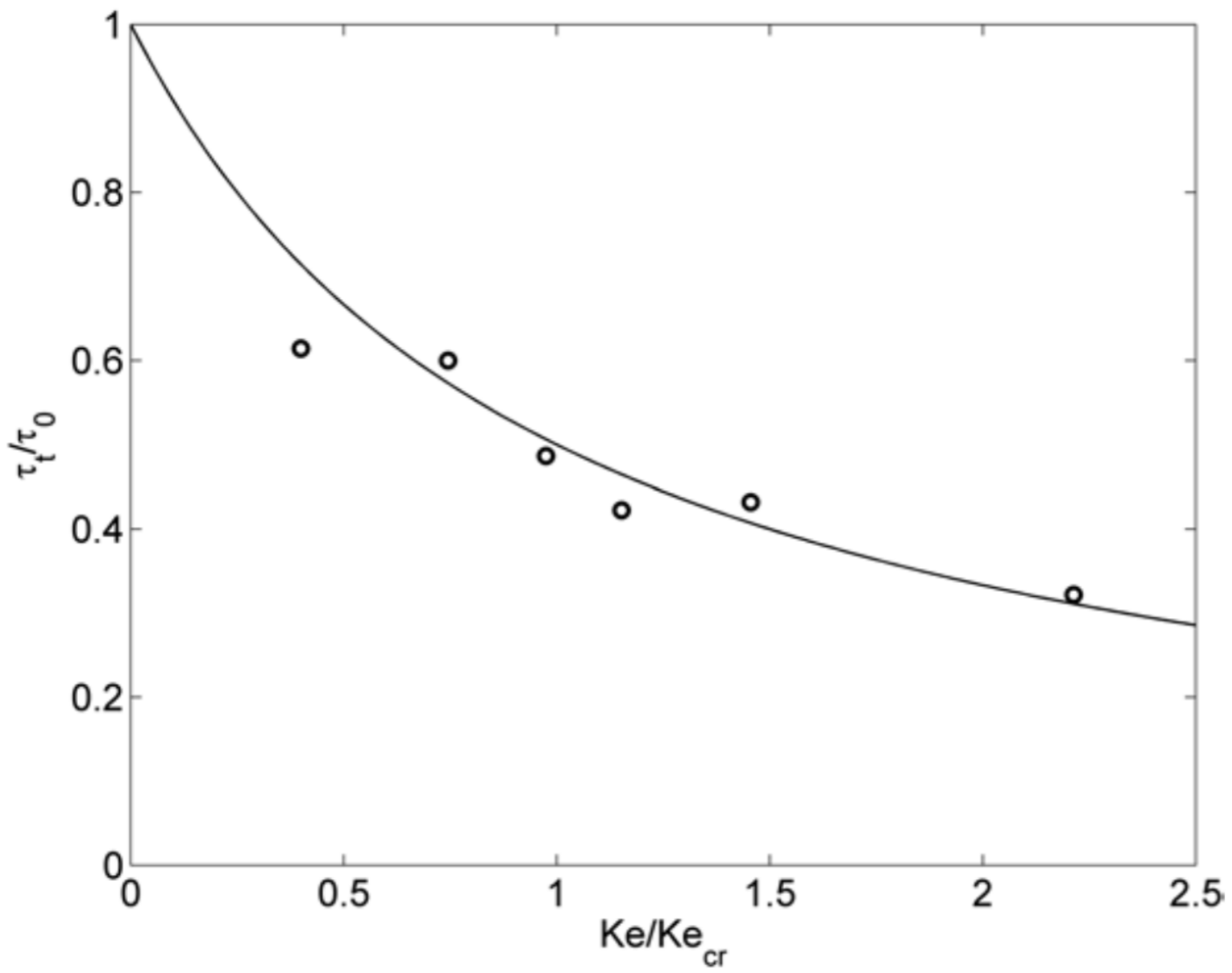
Fig. 2.12 Transformation of the surface wind stress to form drag and whitecapping for high wind speeds. The line is equation (2.8); the circles represent the experiment of Banner and Peirson (1998). (After Soloviev and Schlüssel 1996)

Capillary wave effects

* The presence of capillary waves on the sea surface is a characteristic feature of air–sea interaction. In particular, parasitic capillaries accompany microscale wave breaking, which is one of the principle mechanisms controlling the molecular sub- layers

* There is evidence, mainly from lab studies, the capillary waves have a direct impact on air-sea exchange.

Capillary wave effects

✤ Possible mechanisms include

1. Convergence/divergence of orbital motions disturbs the boundary layer where fluxes are controlled by molecular diffusion.

2. The decay of capillary wave trains delivers horizontal momentum to the water in patches corresponding to the locations of the wave trains. This patchy driving force can induce turbulent motions.

3. Short gravity waves and capillaries dramatically increase the momentum transferred to the ocean via increased sea surface roughness, thus enhancing near-surface mixing.

Chemical / biological effects

* Complex chemical and photochemical reactions can produce a feedbacks into biological and physical processes.

* elevated levels of intermediate elements can cause a "reaction barrier" to transport of gases.

* Phytoplankton derived POM rises into microlayer.

* Iron is supplied via surface microlayer.

Effects of surface films

* Air–sea exchanges depend on film properties, especially under low wind-speed conditions.

* Surface tension can be reduced by up to 60 % due to surface films.

* The presence of surface films on the ocean is one of the factors leading to uncertainty in the existing air–sea exchange parameterizations.

* Breaking waves and flow convergences substantially erode the surface films above wind speeds of 5–6 m s^{-1}.
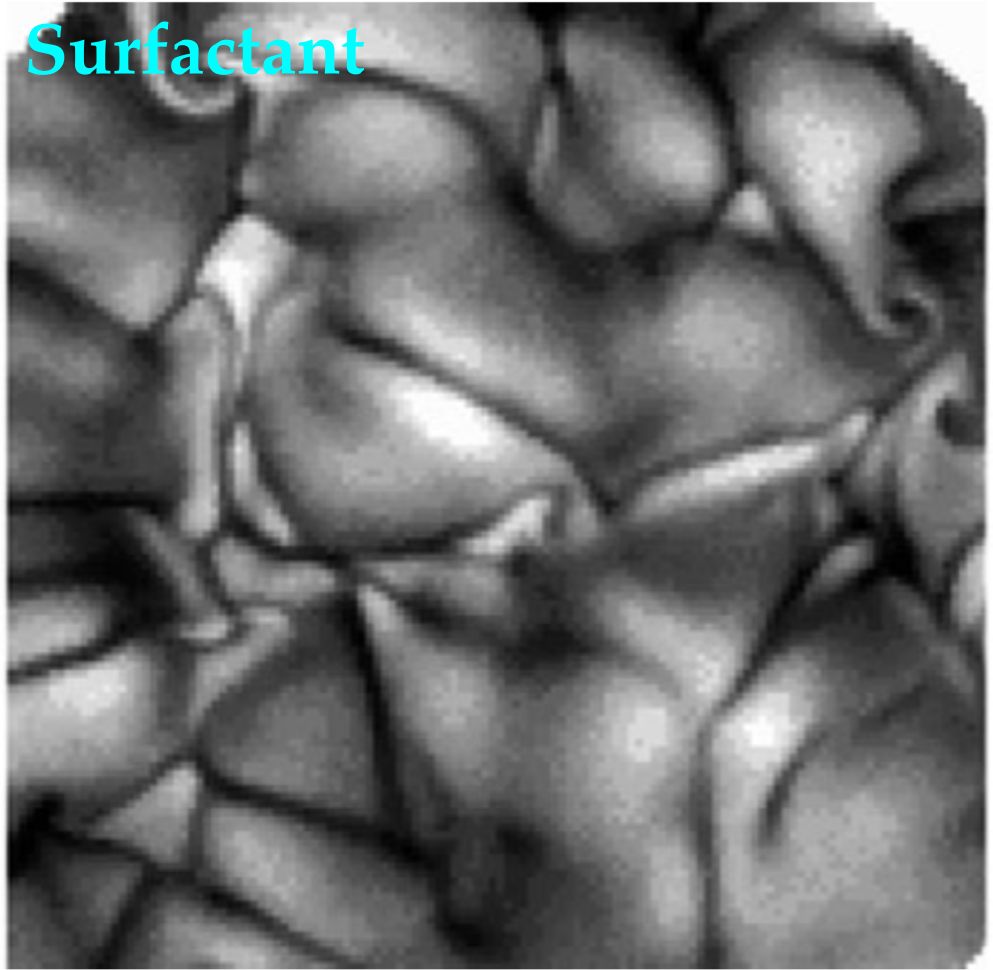
* Surface films are also fragmented by rain.

Effects of surface films

* Can modify SST by affecting dynamics of thermal sublayer.

* The spatial scale of the convective structures dramatically changes when surfactant is present on the water surface compared to a clean surface.

* The surfactant film inhibits very fine structures and emphasizes larger scale motions.
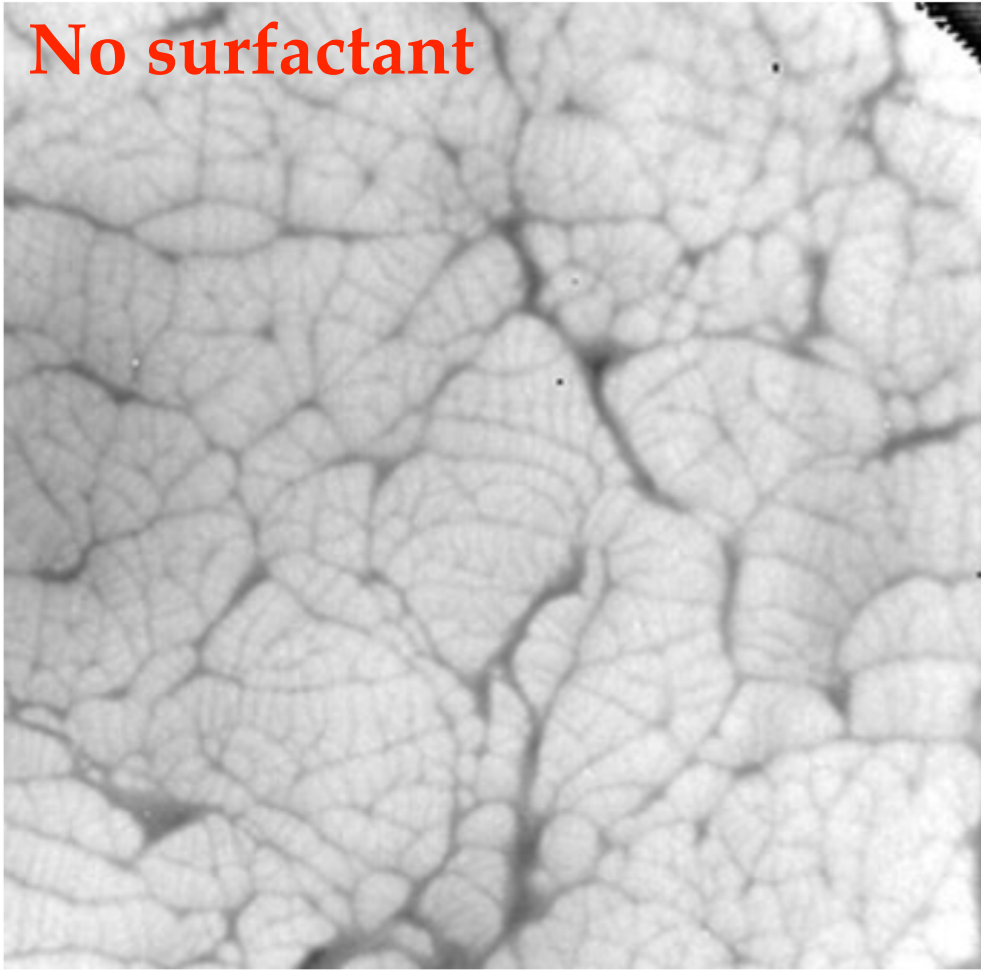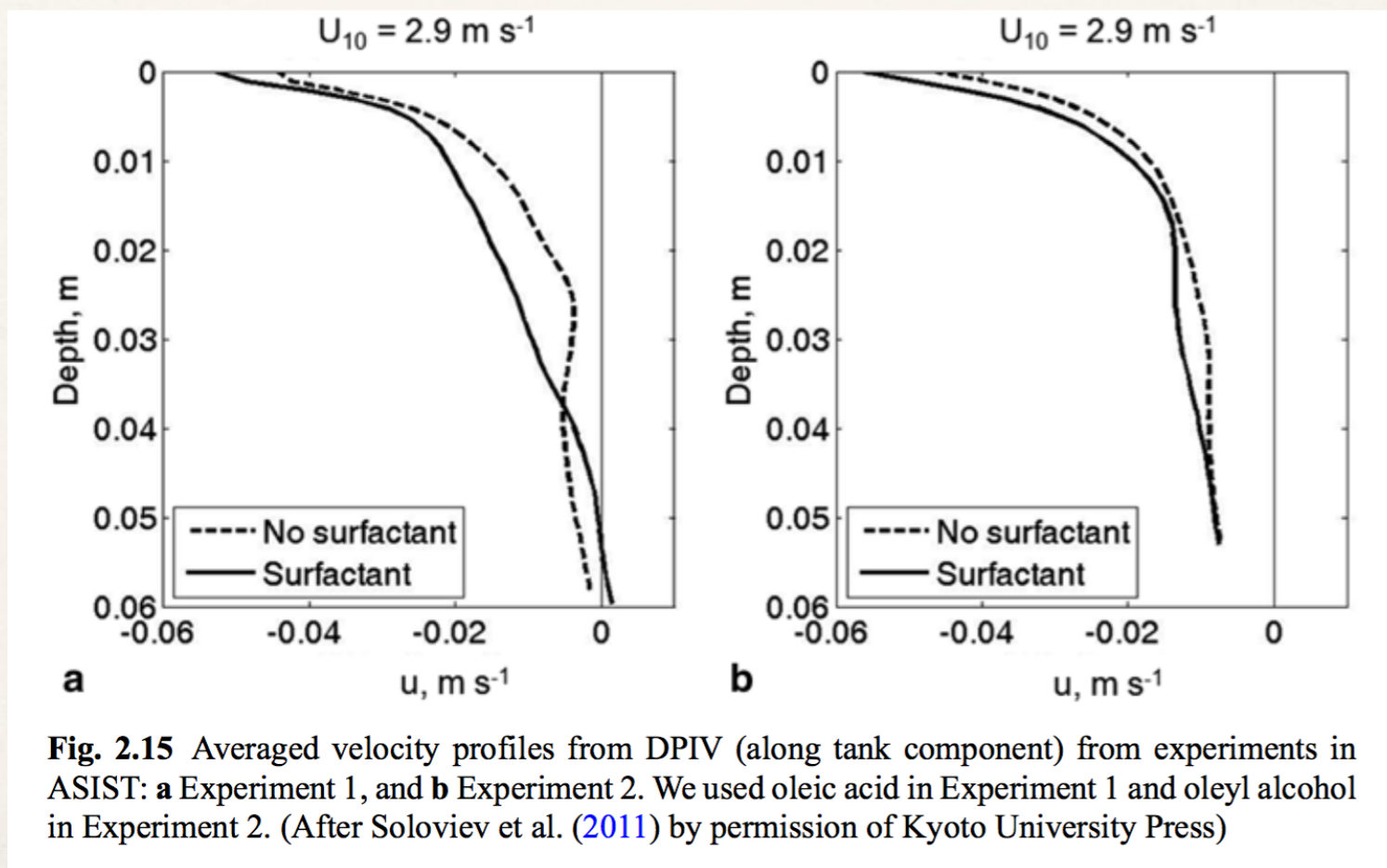
Fig. 2.13 Infrared images of sea temperature under convective conditions for clean (left subplot) and surfactant covered (right subplot) surface for a heat flux of 407 W m^{-2}. The mean temperature is subtracted in the images so that white represents temperatures above the mean and black represents temperatures below the mean. The dynamic range of the image is approximately 1 K. (Reused with permission from Flack et al. 2001 AIP)
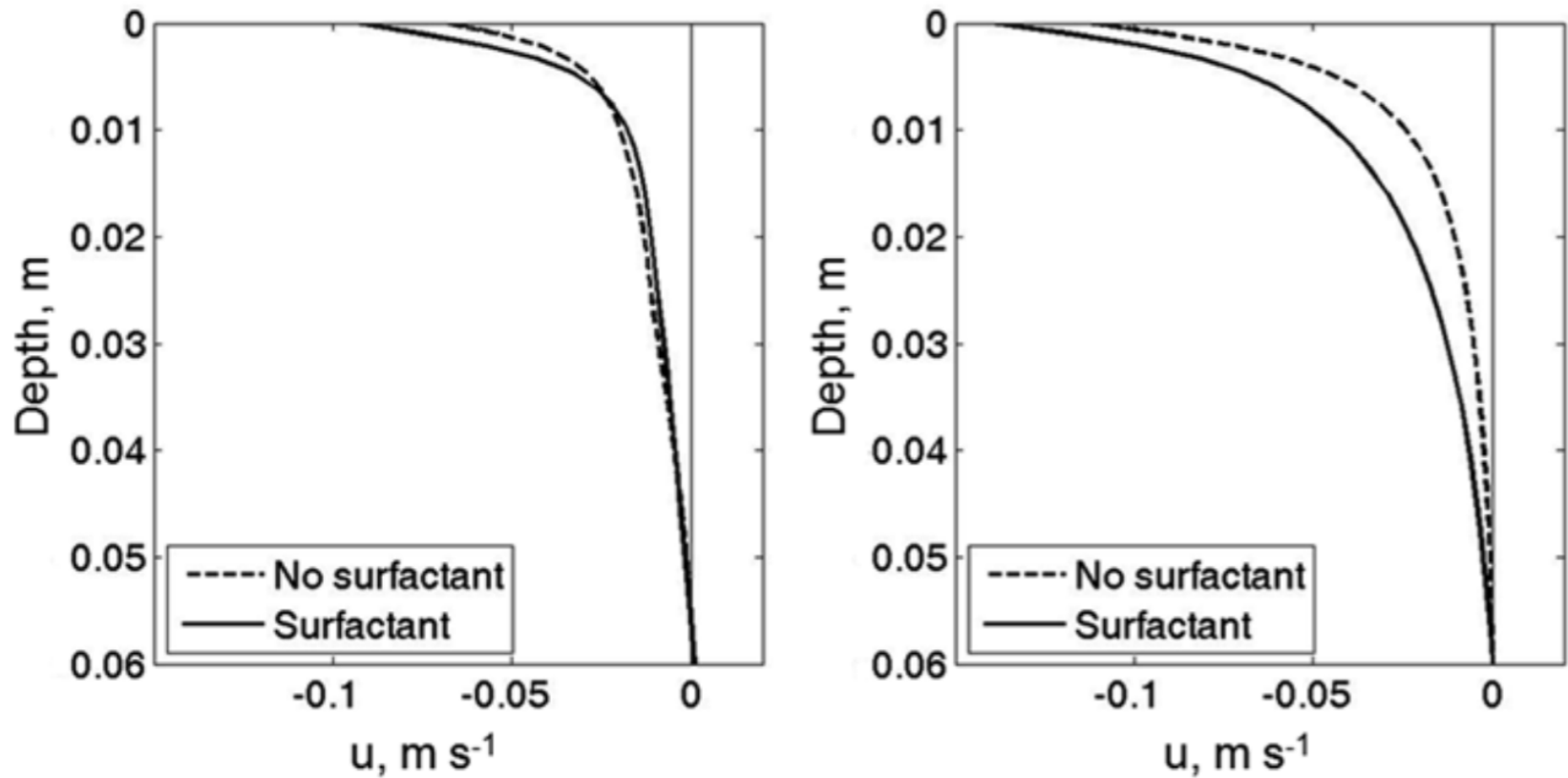
Effects of surface films

* Surfactant increases surface drift velocity by approximately 25%. Equivalent to waterside drag coefficient reduction of 36%.

Lab experiment

Fig. 2.15 Averaged velocity profiles from DPIV (along tank component) from experiments in ASIST: **a** Experiment 1, and **b** Experiment 2. We used oleic acid in Experiment 1 and oleyl alcohol in Experiment 2. (After Soloviev et al. (2011) by permission of Kyoto University Press)

Fig. 2.17 Along tank velocity (u) referenced to $z = -0.06$ m (CFD model). (left) Large eddy simulation wall-adaptive local eddy viscosity model (LES-WALE), (right) detached eddy simulation (DES) model with realizable k-ε. Note increase of the surface drift velocity in the presence of surfactant. (After Soloviev et al. (2011) by permission of Kyoto University Press)
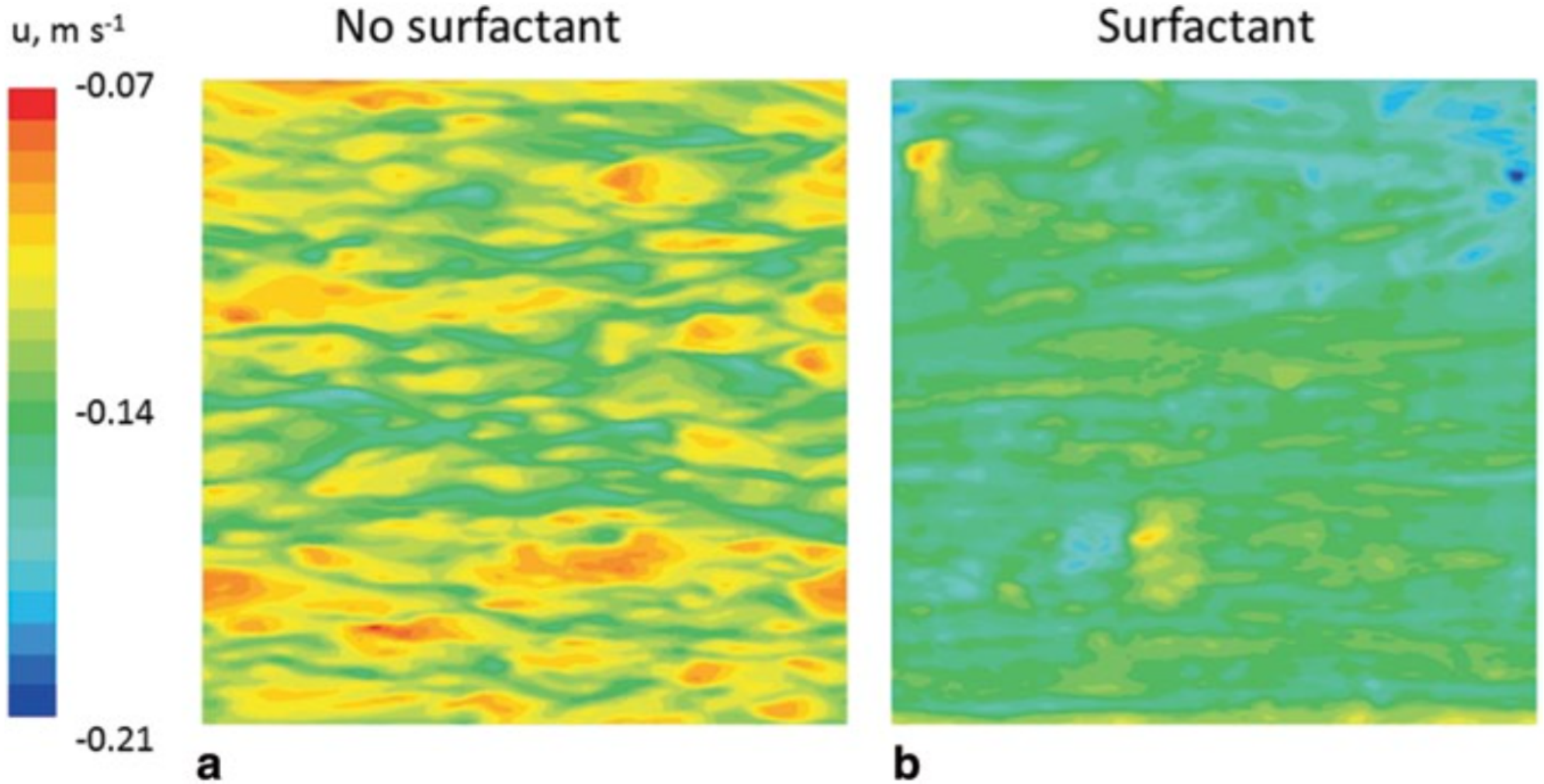
Fig. 2.16 Top view of along tank velocity without **a** and with **b** elastic boundary condition simulating surfactant effect. (After Matt et al. (2011) by permission of Kyoto University Press)

Red colors are slower velocities
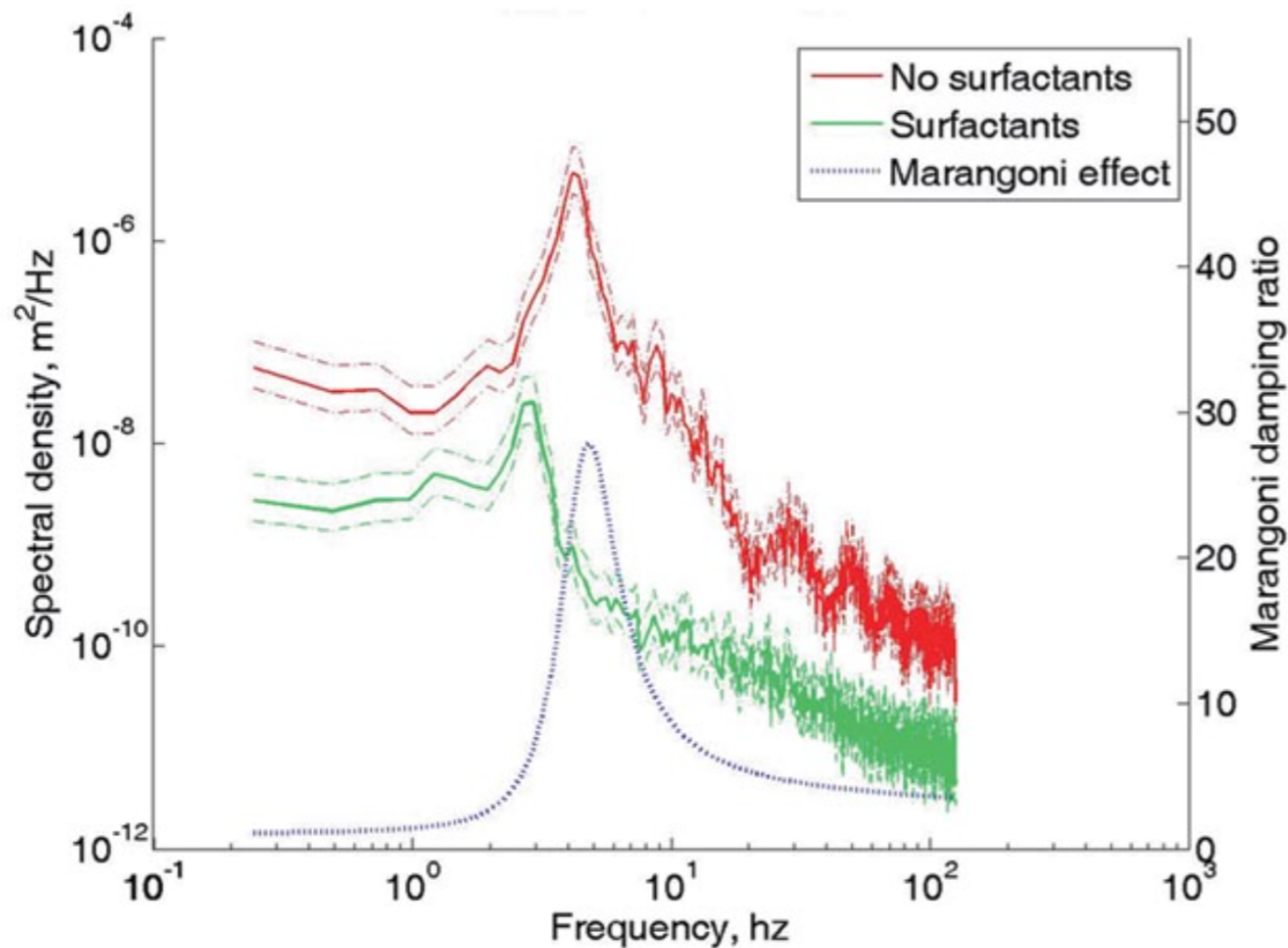
Fig. 2.14 Wind wave spectra of clean water surface (red) and in the presence of oleyl alcohol surface film (green)—measurements in ASIST facility of UM RSMAS. The 95 % confidence interval is shown by the dash-dot lines. The wind speed recalculated to a 10 m height was approximately $U_{10} = 7$ m/s. The dotted line represented the curve (ordinate on the right-hand side) for Marangoni wave theory for oleyl alcohol (eqs. 1–4 in Hühnerfuss 1987). After Soloviev et al. (2011) by permission of Kyoto University Press

The increase in the surface drift velocity observed in the presence of surfactants results in the suppression of turbulent velocity fluctuations and coherent structures due to the dilatational viscoelasticity of the monomolecular surface film
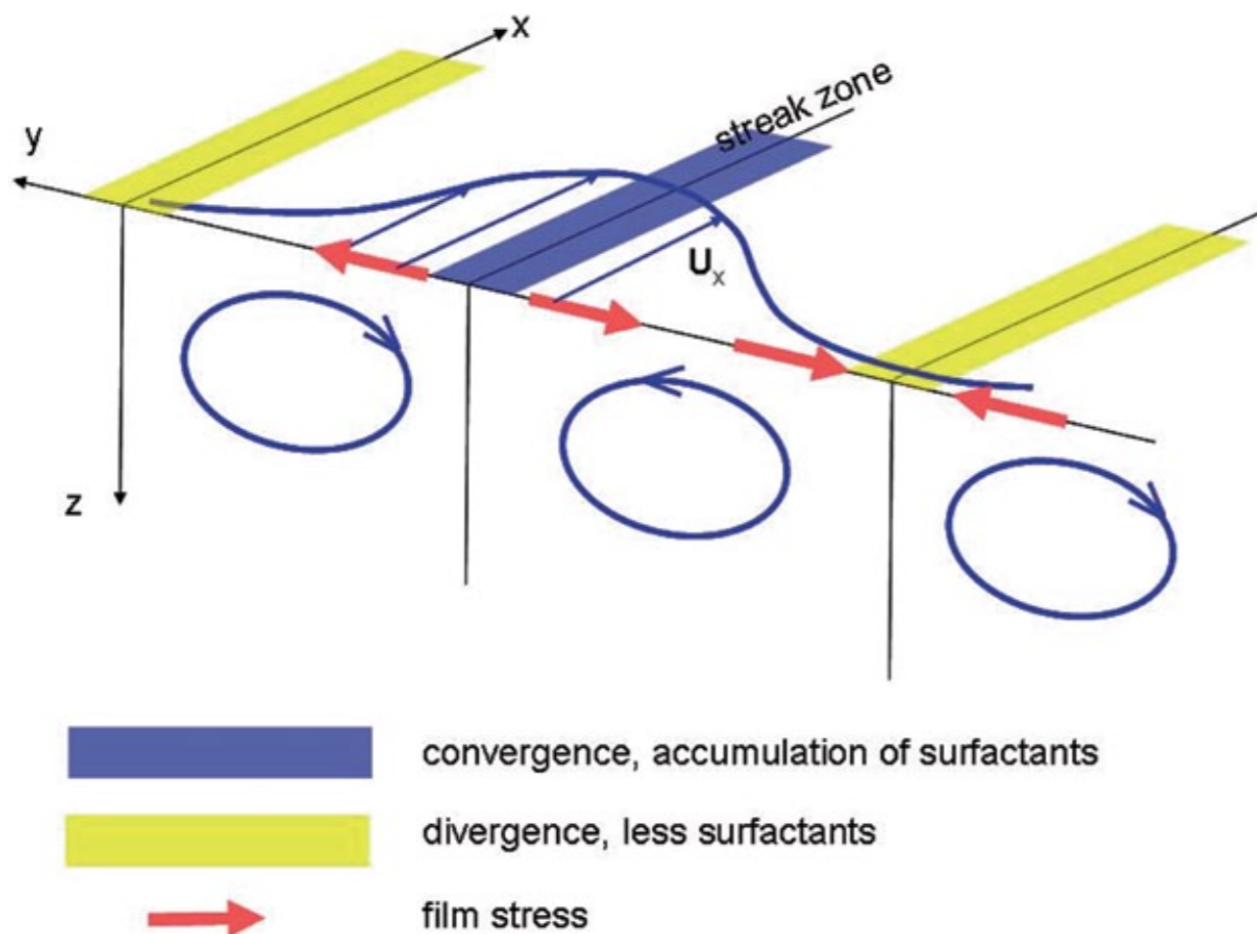
Fig. 2.18 Schematic representation of the effect of surfactants on near-surface circulation. (After Soloviev et al. (2011) by permission of Kyoto University Press)
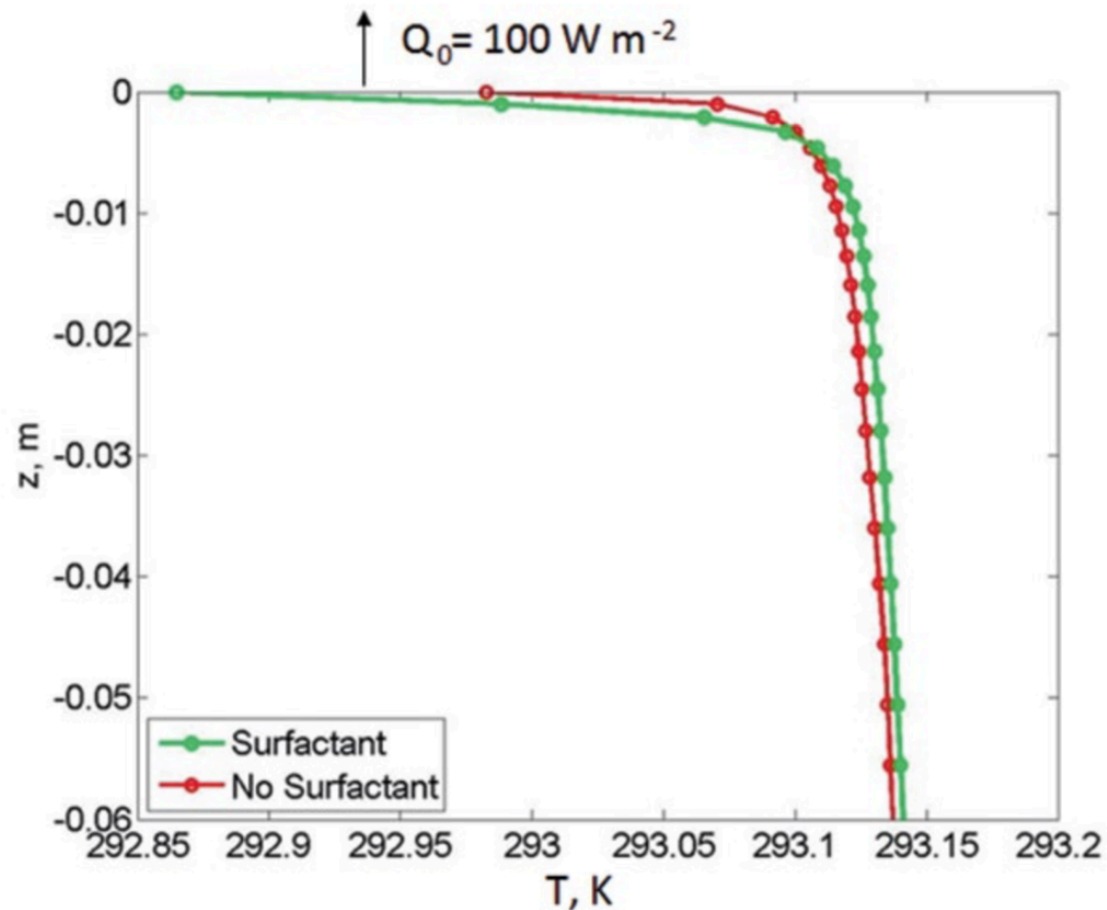
Effects of surface films

The removal of surface films by convection, rain, near-surface shear, and breaking waves affects hydrodynamic processes at the air–sea interface, especially the capillary wave field, which substantially determines the surface roughness and thus air–sea exchanges. This process has a dual effect on the gravity-capillary wave field: It damps waves due to increased turbulence, and it enhances waves due to fragmentation and dissipation of surface films.

Effects of surface films

During nighttime, the temperature difference across the cool skin increased approximately by a factor of 2 in the presence of surfactant.

Fig. 2.19 Effect of surfactants on SST during nighttime calculated with CFD model at $U_{10} =$ 4 ms^{-1}. Due to effect of surfactants, temperature difference across the cool skin ΔT changed from -0.15 K to -0.3 K. (After Soloviev et al. 2012)

Effects of surface films

During day-time, under conditions of strong solar radiation and light winds, the presence of surfactants resulted in an increase in the temperature difference across the warm skin by approximately 25%.
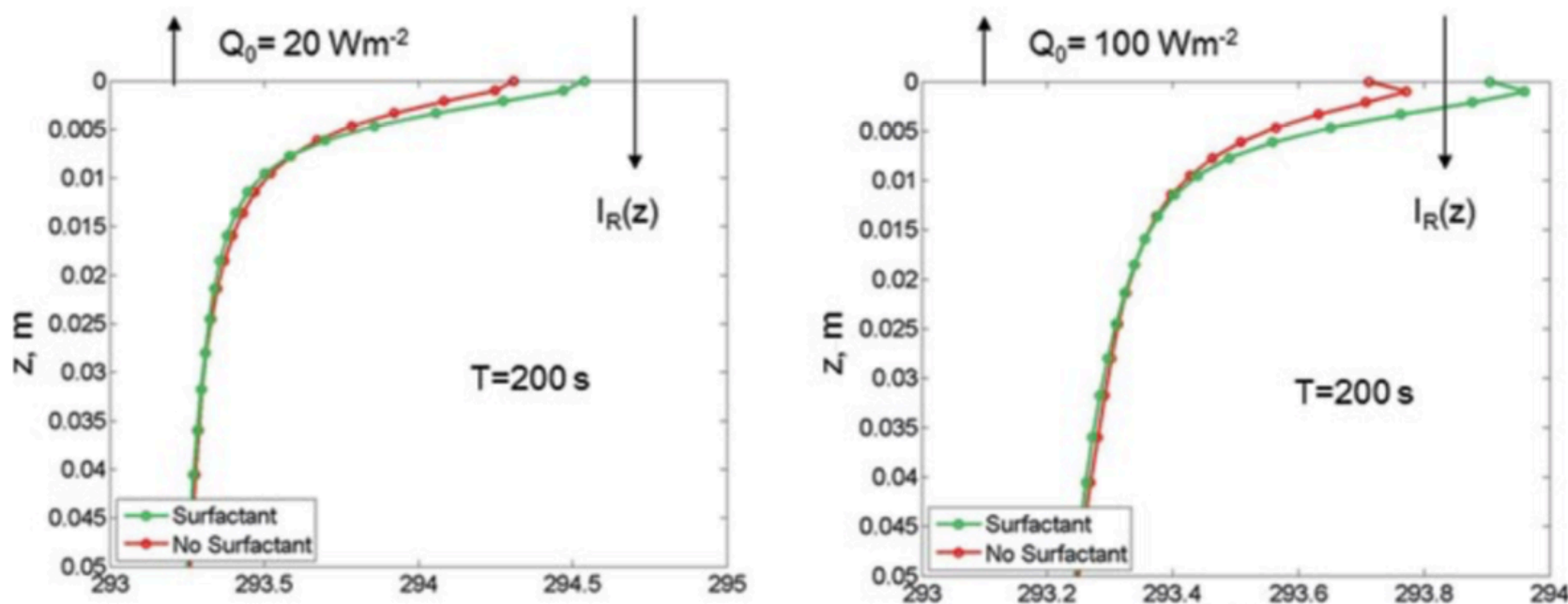
Fig. 2.20 Effect of surfactants on SST during daytime calculated with CFD Model at $U_{10} = 1$ ms^{-1}, $I_R(0) = 1200$ Wm^{-2}. Under strong solar irradiance, "cool skin" turns into a "warm skin". (After Soloviev et al. 2012)

Role of surface heat fluxes
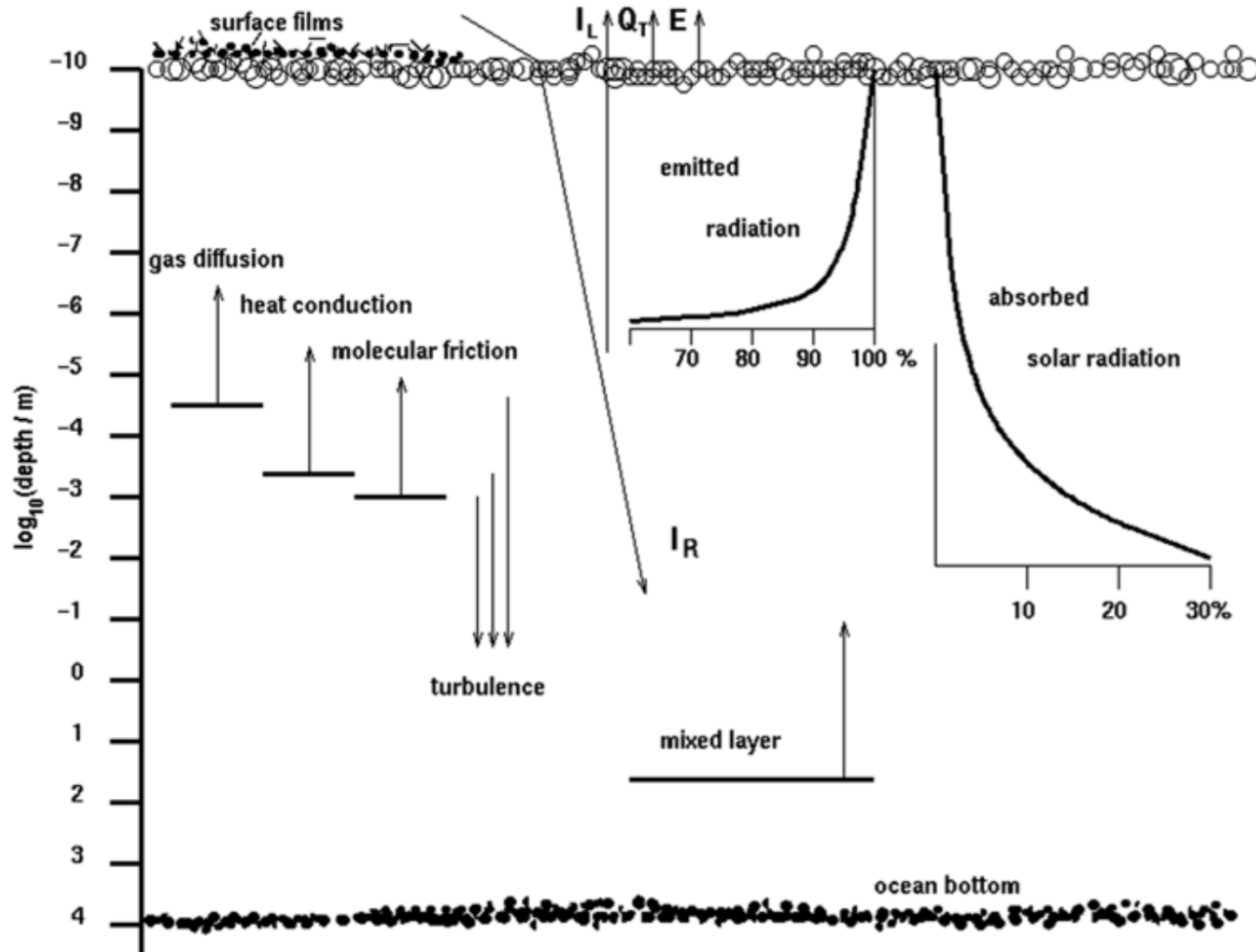
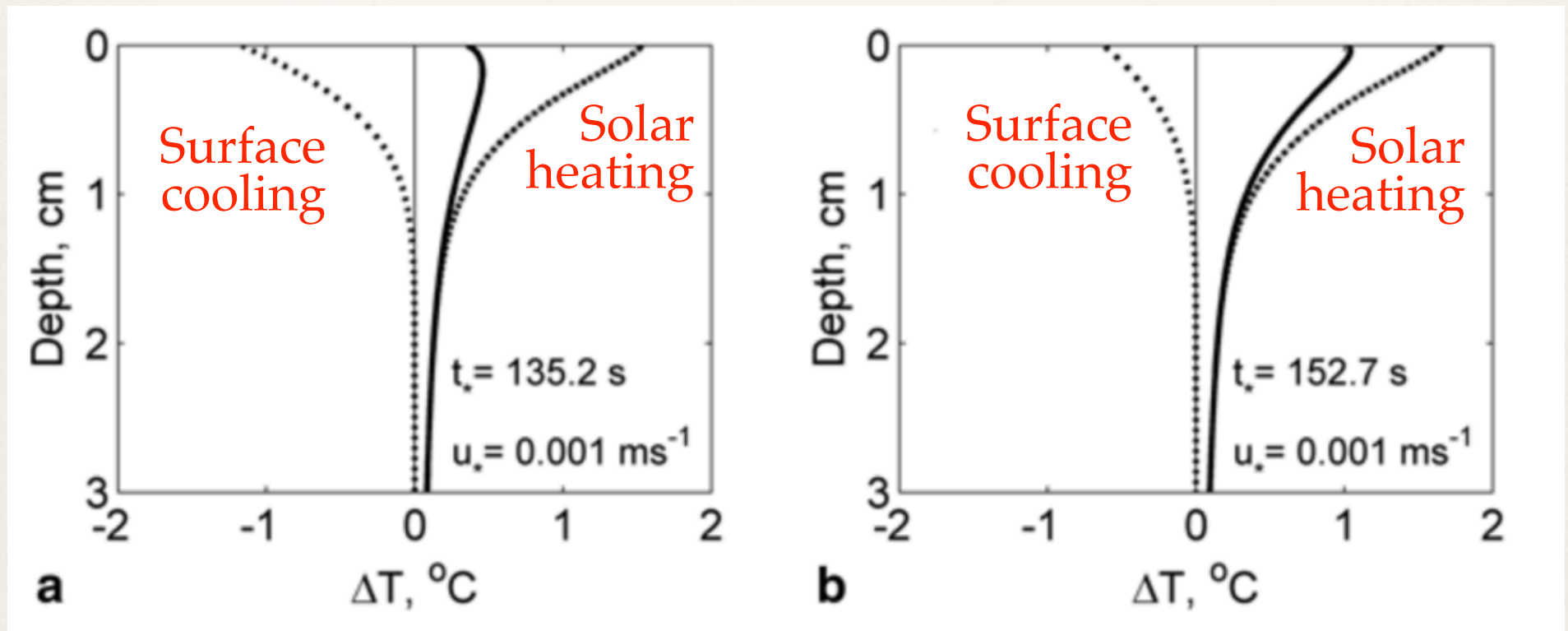Fig. 2.1 Schematic representation of the vertical structure of physical processes related to the sea surface microlayer. (courtesy of Peter Schlüssel)

Role of surface heat fluxes

In a low wind-speed regime, the greatest temperature deviations extend to depths of several centimeters.

$$Q_0 = 140 \text{ W/m}^2$$
$$Q_E = 70 \text{ W/m}^2$$

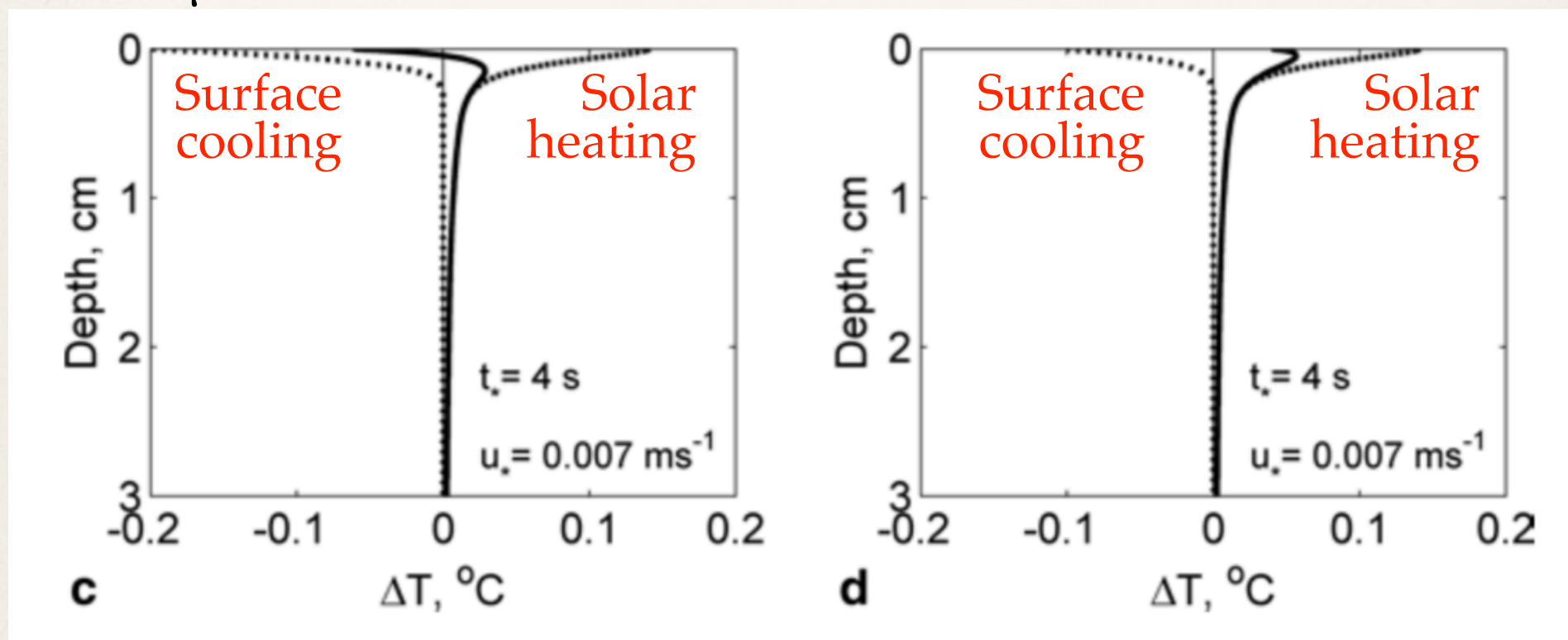$$Q_0 = 70 \text{ W/m}^2$$
$$Q_E = 35 \text{ W/m}^2$$

Role of surface heat fluxes

Higher friction velocities are affected by surface cooling and heating only very close to the interface. The combined effect, $\Delta T(z)$, shows a maximum in a small range of depths between 50 and 150 μm.

$Q_0 = 140 \ \text{W/m}^2$
$Q_E = 70 \ \text{W/m}^2$

$Q_0 = 70 \ \text{W/m}^2$
$Q_E = 35 \ \text{W/m}^2$

Effect of rainfall

✤ Modifies sublayers through effects: additional momentum flux, stabilizing buoyancy flux from air to sea, additional sensible heat flux modification of physical water constants because of temperature and salinity changes, increase in the surface roughness, damping of short gravity waves, excitation of capillary waves at higher wave frequencies, and the surface mixing by droplets.

Effect of rainfall

* During rainfall the raindrops penetrate to tens of centimeters directly affecting the near-surface salinity.

* Rain falling on the sea surface also establishes a haline diffusive molecular sublayer with a salinity gradient. The freshwater skin is only about 50 μm thick.

* Gas solubility depends on salinity. A 1 % decrease in the seawater salinity results in a 0.5 % increase in the CO_2 solubility and 0.1% increase in the O_2 solubility.

Effect of rainfall

1. The freshwater flux due to rain produces a buoyancy flux in the near-surface layer of the ocean, which tends to suppress convection.

2. Raindrop temperatures are usually lower than the SST.

3. Changes in the temperature and salinity due to rain modify physical constants of sea surface water. In particular, the kinematic viscosity increases with decreasing temperature and decreases with decreasing salinity.

Effect of rainfall

4. Rainfall can enhance the surface roughness as much as two orders of magnitude by generation of impact craters, Rayleigh jets, splash drops, and small waves.

5. Raindrops falling into the ocean fragment and partly remove surface films.

6. Raindrops penetrating through the surface disturb wave motions and damp the short gravity waves by reducing the amplitudes at which they break. As a result, small-scale wave breaking intensifies and the surface renewal time period decreases.

Effect of rainfall

7.   Raindrops impact the sea surface and submerge into the ocean, generating additional surface renewals.

8. Raindrops obtain horizontal momentum from the airflow at cloud levels. These raindrops subsequently pass this momentum to the atmospheric boundary layer and to the sea surface, adding to the wind stress that acts on the surface. All the momentum of the drop is transferred to the ocean, as opposed to only a small fraction the air.

Effect of rainfall

9. The freshwater skin coexisting with the cool skin is subject to irreversible thermodynamic processes due to significant local temperature and salinity gradients

1.

Effect of rainfall on freshwater skin

* Freshwater skin is where a salinity flux takes place via molecular diffusion.

* With no rain, evaporation increases salinity and destabilizes the surface water.

* With the part of the rain that does not submerge into the ocean can compensate for the evaporation effect and create a stably stratified freshwater skin.
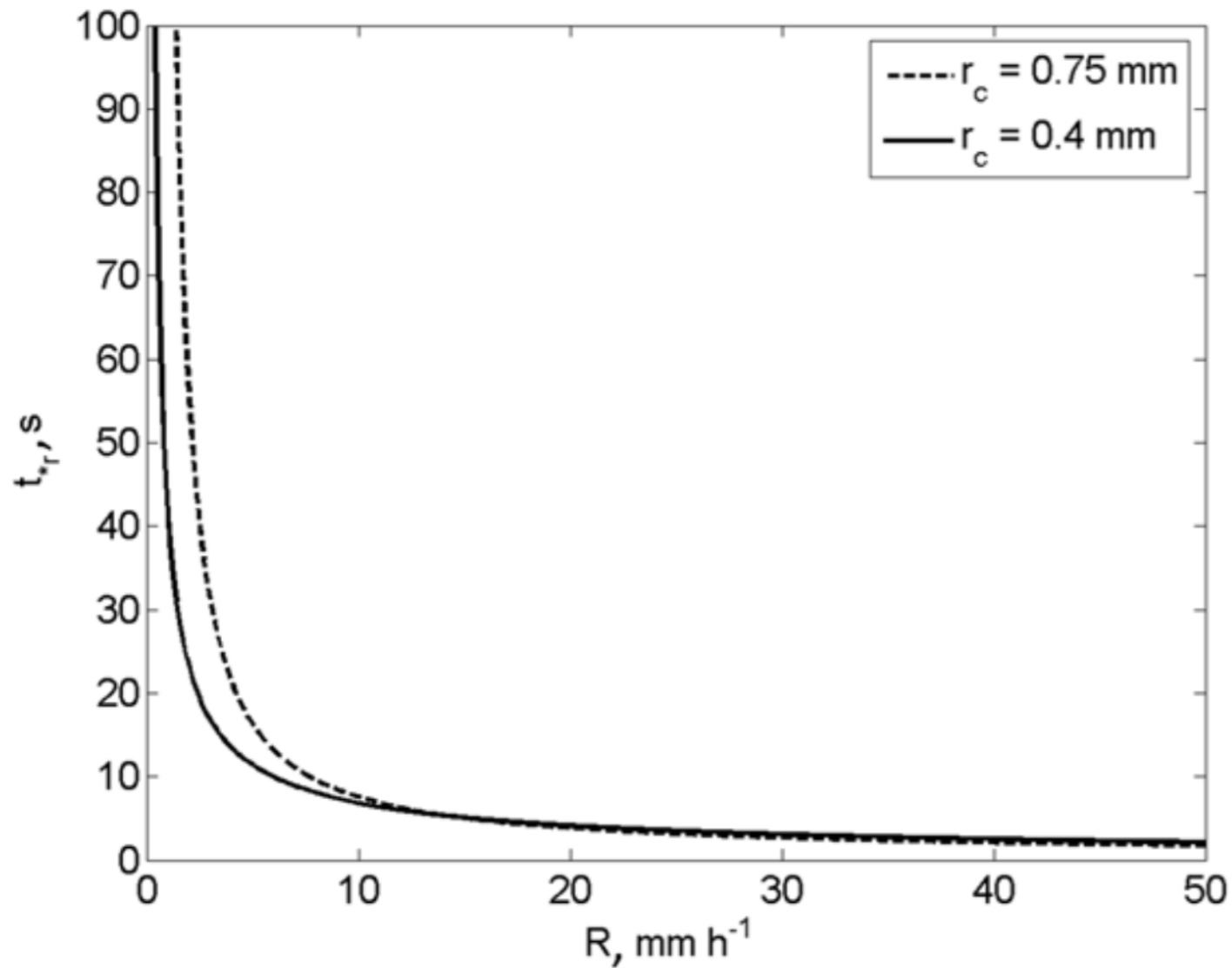
Surface renewal due to rain

* Small do not produce an impact crater on the sea surface, while large drops represent "catastrophic" events.

* Impact crater radius, r_k, is 2 - 4 times drop radius.

* The area subject to microlayer renewal is equal to the area of the impact crater.

Surface renewal due to rain

* The renewal time is defined as the inverse of the impact-flux density. $t_{*r} = 1/F_k$

* Under moderate and heavy rain conditions the renewal time is restricted to very small values, while in light rain the drop of surface salinity remains relatively small.

* For $P > 2$ mm h^{-1}, the rain-induced surface disruptions dominate the renewal process including the surface renewals caused by breaking wavelets or long breaking waves.

Fig. 2.32 Surface renewal time due to rain calculated from (2.117) as a function of rain rate for two critical radii r_c. (After Schlüssel et al. 1997)

Fig. 2.33 Skin cooling by rainfall with a typical rain drop temperature of 5 °C below the sea surface temperature (**a**) and freshwater skin due to rainfall at bulk salinity of $S_w = 35$ psu (**b**), both as a function of rain rate with respect to renewal times determined by the rainfall; the total effects are shown by the solid line, the effects due to drops penetrating into the ocean by the dashed lines and that due to surface heat flux by the dotted lines. (After Schlüessel et al. (1997). Reproduced with permission from Springer Science and Business Media)
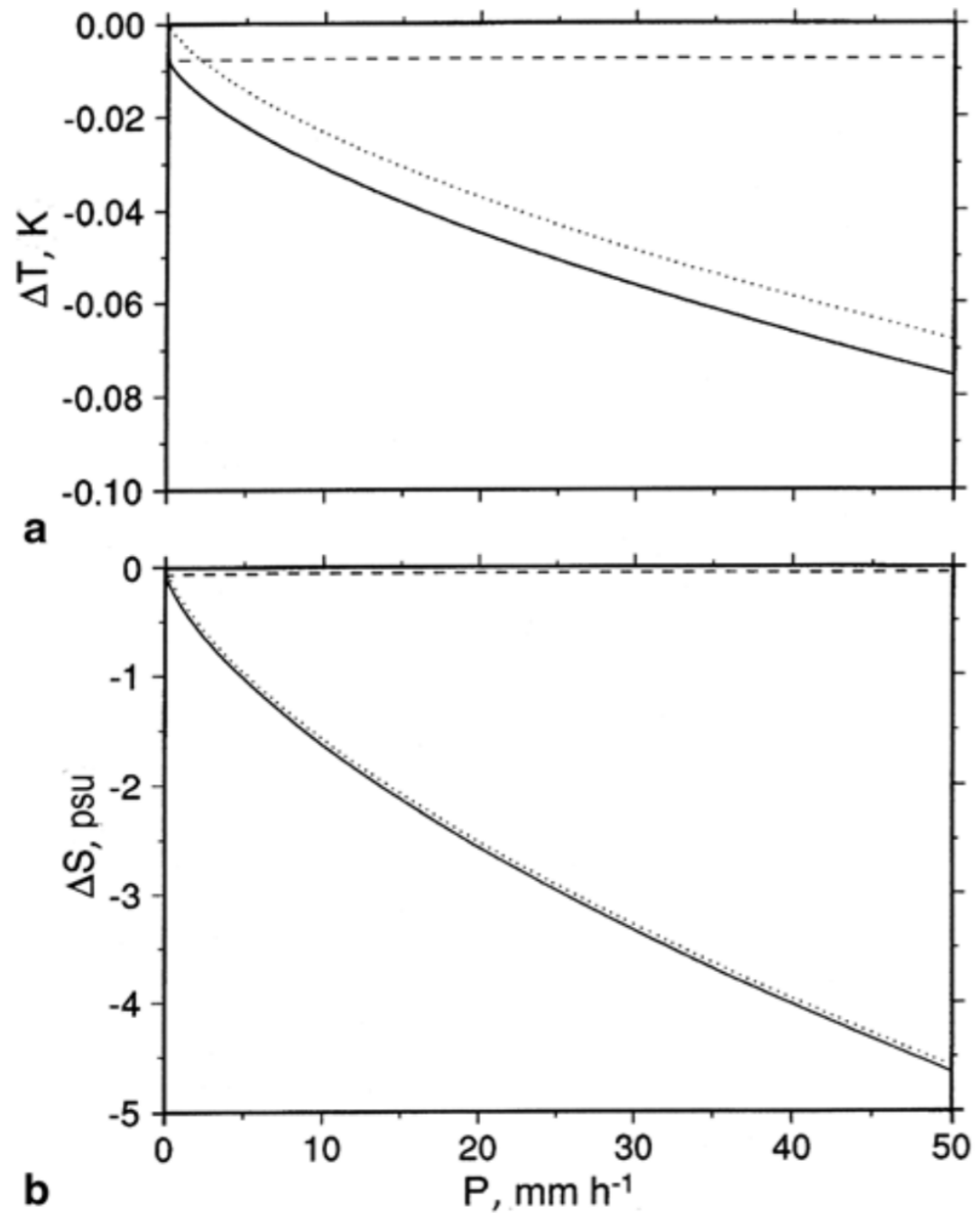
Buoyancy effects

* Even for very low rain rates the buoyancy flux due to freshwater input is stronger than the counterparts due to the thermal convection and evaporative surface salinity increase.
* Below (~ 0.1 mm /h) the buoyancy effect inhibits the additional mixing due to rain.

Effects on sea surface roughness

✤ The roughness elements produced by the rain do not propagate as the wind-induced waves do and therefore resemble fixed obstacles such as roughness elements on land surfaces.

Effects of rain

* Of the various processes, the most important appears to be the rain-induced mixing that leads to enhanced surface renewals and the additional surface and volume cooling by raindrops with temperatures below the SST.