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# Active suppression of buoyancy driven turbulence

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ABSTRACT

The aqueous turbulent layer at the air–sea interface plays an important role in determining interfacial fluxes. Here a method of determining the heat flux at such an interface is explored by simulating the effects of surface heating on the evolution of buoyancy driven turbulence. We find that the turbulence can be almost entirely eliminated when the source is of sufficient strength, depth, and duration. As the fluid cools, it is found to undergo an abrupt transition to turbulence which corresponds to a signature in the surface temperature. A simple one-dimensional conduction model is found to accurately describe the temporal response of the surface temperature during heating and cooling.


## 1. Introduction

Estimates of the flux of greenhouse gases across the air–sea interface are required for global climate predictions [5]. Various means, both theoretical [37,26,27] and experimental [6,17,19,30,11,10], have been used to estimate interfacial fluxes of gases as well as of heat. Since the air–sea interface is subject to both wind shear and buoyancy forces, turbulence is generated at and below the interface. However, the interfacial flux of greenhouse gases is almost entirely controlled by the turbulent water-side interfacial boundary layer. This follows from the fact that the aqueous molecular diffusivities of most greenhouse gases such as carbon dioxide and methane, are generally more than two orders of magnitude smaller than the diffusivity of momentum. Characterizing the nature of this aqueous turbulence is therefore of great significance in estimating interfacial gas flux [26,27,17]. Moreover, interfacial turbulence is involved in determining the thermal characteristics of the sea surface [32,28,31,23,36,35,38,21,14,34,20,13,33]. Estimates of gas flux rely on a variety of models of the water-side turbulence, the most prominent of these being surface renewal models [15,3,7,24]. These theoretical considerations lead to the conclusion that heat flux can be used as a proxy for gas flux [18].

The importance of interfacial turbulence in air–sea exchange processes motivates the present work in which we consider turbulence at a shear-free boundary subject to a cooling outgoing heat flux. If the liquid is initially quiescent, a thermal boundary layer grows downward into the fluid bulk. Once the layer thickness grows to sufficient size, flow instabilities will grow in strength, an effect governed by the Rayleigh number [2,4]. Subsequently, buoyancy driven turbulent convection will appear [9,8,16,22,25,39]. This turbulence generates an upward convective flux of thermal energy which balances downward diffusion, thereby resulting in a statistically steady thermal boundary layer. The emphasis here is to investigate the effect of surface heating on this turbulent surface layer. In an experimental setting, the surface heating can be implemented via a laser as in the 'controlled flux' method [18]. In particular, we are interested in determining the conditions needed to suppress surface turbulence. If this can be achieved, simple conduction models, as opposed to ad hoc surface renewal ones, can used to determine the heat flux. We have explored this possibility here by performing direct numerical simulations of buoyancy driven turbulence subject to surface heating.

## 2. Problem formulation, numerical methods, and scaling

To investigate the effect of surface heating on turbulent buoyant convection driven by a surface heat flux, we have performed a series of direct numerical simulations based upon the following governing equations:

$$\frac{\partial \vec{V}}{\partial t} = \vec{V} \times \vec{\Omega} - \vec{\nabla}\Pi + \nu\nabla^2\vec{V} + \beta g\theta\hat{e}_y, \quad (1)$$

$$\vec{\nabla} \cdot \vec{V} = 0, \quad (2)$$

and

$$\frac{\partial \theta}{\partial t} + \vec{V} \cdot \vec{\nabla}\theta = \alpha\nabla^2\theta + S/\rho c, \quad (3)$$

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**Nomenclature**

| | |
|---|---|
| $c$ | specific heat |
| $\hat{e}_y$ | unit vector in vertical direction |
| $g$ | gravitational acceleration |
| $H(t)$ | Heavyside function |
| $I(t)$ | volumetric surface heat source |
| $k$ | thermal conductivity |
| $L$ | length scale |
| $L_x, L_z$ | horizontal domain lengths |
| $L_y$ | vertical depth |
| $N_s$ | heating strength parameter |
| $N_\delta$ | heating penetration depth parameter |
| $N_\tau$ | heating duration parameter |
| $Pr$ | Prandtl number |
| $Q$ | heat flux |
| $Ra_q$ | flux based Rayleigh number |
| $Ra_T$ | temperature based Rayleigh number |
| $S$ | volumetric heat source |
| $s$ | constant volumetric heat source |
| $T$ | fluid temperature |
| $T_0$ | reference temperature |
| $t$ | time |
| $t^*$ | time scale |
| $u^*$ | velocity scale |
| $\vec{V}$ | velocity |
| $v'$ | fluctuating vertical velocity |
| $x, z$ | horizontal coordinates |
| $y$ | vertical coordinate |

*Greek letters*

| | |
|---|---|
| $\alpha$ | thermal diffusivity |
| $\beta$ | thermal expansion coefficient |
| $\Delta T$ | temperature difference |
| $\delta_{bl}$ | length scale |
| $\delta_p$ | penetration depth of surface heat source |
| $\theta$ | temperature |
| $\theta^*$ | temperature scale |
| $\bar{\theta}$ | horizontal average of surface temperature |
| $\theta'$ | fluctuating temperature |
| $\nu$ | kinematic viscosity |
| $\Pi$ | modified pressure divided by density |
| $\rho$ | density |
| $\tau$ | duration of surface heat source |
| $\Phi$ | strength of surface heat source |
| $\vec{\Omega}$ | vorticity |

which represent conservation of momentum, mass, and thermal energy respectively. Here $\vec{V}$ is the fluid velocity, $\vec{\Omega}$ is the vorticity, $\Pi$ is a modified pressure divided by density, $t$ is time, $\nu$ is the kinematic viscosity, $\beta$ is the coefficient of expansion of the fluid, $g$ is the gravitational acceleration, $\theta = (T - T_0)$, where $T$ is the fluid temperature and $T_0$ is a reference temperature, $\alpha = k/\rho c$ is the thermal diffusivity in which $k$ is the thermal conductivity, $\rho$ is the density, and $c$ is the specific heat, $S$ is a volumetric heat source (W/m$^3$), and $\hat{e}_y$ is a unit vector in the ($y$) vertical direction, opposite to the direction of gravity. These equations represent the standard Boussinesq approximation [25,39]. This system is solved in a computational domain with dimensions $L_x \times L_y \times L_z$, and a grid resolution of $128 \times 129 \times 128$ in the $x$, $y$ and $z$ directions respectively, where $x$ and $z$ are the horizontal coordinates. The domain aspect ratio was $L_x = L_z = 2L_y$ with $L_y = 11.713$ cm. At the top of the domain ($y = 0$) shear free (rigid-lid) conditions are applied to the velocity field, and a spatially and temporally constant outward going heat flux ($Q$) is applied to the thermal field. Shear free conditions are applied at the domain bottom ($y = -L_y$) along with insulation conditions on the thermal field. A fully spectral code is implemented in which Fourier modes are used in the horizontal directions, and Chebyshev modes are employed in y [39]. The volumetric heat source is chosen to be $S(t) = s + I(t)$, where $s$ is a spatially and temporally constant source chosen to exactly compensate for the heat being removed from the surface of the fluid, thereby eliminating temperature drift. The source $I(t)$ is used to model surface heating and is given by $I(t) = \Phi[H(t) - H(t-\tau)]e^{y/\delta_p}$, in which $\Phi$ and $\delta_p$ are the heat source strength and penetration depth respectively, $H(t)$ is the Heavyside function, and $\tau$ is the source duration. The simulations proceed by first applying an outward going heat flux to the fluid surface which generates statistically steady turbulent convection [25,39]. Subsequently, the source $I(t)$ is turned on for a time interval $\tau$.

Aside from the fluid properties, four independent parameters define this flow: $\Phi$ , $\delta_p$, $\tau$, and $Q$. Here we introduce other appropriate scales [1,23,36,25] of length, velocity, time, and temperature given by $\delta_{bl} = \sqrt{2}(\beta g Q/\alpha\nu k)^{-1/4}$, $u^* = (\beta g Q \delta_{bl}/\rho c)^{1/3}$, $t^* = \delta_{bl}/u^*$, and $\theta^* = \sqrt{\pi/2}(\beta g/\alpha\nu)^{-1/4}(Q/k)^{3/4}$. Using these scales to nondimensionalize Eqs. (1)–(3) results in the dimensionless numbers $Ra_q = \beta g Q L_y^4/\alpha\nu k$, a flux based Rayleigh number, $Pr = \nu/\alpha$, the Prandtl number, $N_s = \Phi\delta_p/Q$, a dimensionless source strength, $N_\delta = \delta_p/\delta_{bl}$, a dimensionless source penetration depth, and $N_\tau = \alpha\tau/\delta_{bl}^2$, a dimensionless source duration. The numbers $N_s$, $N_\delta$, and $N_\tau$ can be thought of as representing, the source strength relative to the applied heat flux, the penetration depth relative to the thermal boundary thickness, and the source duration relative to a diffusion time scale.

A series of direct simulations were performed in which $N_\delta$, $N_\tau$, and $Pr$ were fixed ($N_\delta = 4.386$, $N_\tau = 10.992$, $Pr = 7$). This choice of $N_\delta$ and $N_\tau$, each being significantly greater than one, allows for the possibility that the source could have a significant effect on the existing buoyancy driven turbulence. With these parameters fixed, we varied the source strength parameter which was set to $N_s = 20, 10, 5, 2$, and the Rayleigh number, which had values given by $Ra_q = 4.45 \times 10^8$, $8.9 \times 10^8$ and $2.25 \times 10^9$. These Rayleigh numbers correspond to heat flux magnitudes $Q = 100$, 200, and 500 W/m$^2$ for fluid properties corresponding to water at 20 °C.

## 3. Results

In Fig. 1 the temporal response of the horizontal average of the surface temperature, $\bar{\theta}$, is shown for a range of surface heat fluxes and source strengths, keeping all other dimensionless numbers fixed. In each case, once the statistically steady buoyancy driven turbulence is subject to volumetric surface heating, $\bar{\theta}$ is seen to rise (heating phase), followed by a fall (cooling phase) when the source is removed. For the larger source strengths, $N_s = 20, 10, 5$, we observe in most cases a subtle but clearly discernible change in slope ($d\bar{\theta}/dt$) in the surface temperature during the cooling phase. For example, for $N_s = 5$ these 'events' or 'bumps' are evident at $t \sim 110$, 200, and 280, for $Q = 500$, 200, and 100 W/m$^2$, respectively. In the case of the weakest surface heating ($N_s = 2$) the surface temperature rise due to heating is still distinguishable from the random background thermal fluctuations associated with buoyancy induced turbulent motions.

A more detailed view of the thermal response of the surface can be obtained by visualizing the instantaneous temperature fields at