Pergamon

Phys. Chem. Earth, Vol. 23, No. 5-6, pp. 531-535, 1998
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0079-1946/98/$ - see front matter

PII: S0079-1946(98)00066-4

Impact of the Skin Effect on the Near-Surface Temperature Profile

Christoph Zülicke and Eberhard Hagen

Baltic Sea Research Institute, Warnemünde, Germany

Received 25 April 1997; accepted 12 November 1997

Abstract. The near surface temperature profile is described by a combination of theories for the molecular skin layer (Soloviev and Schlüssel, 1994) and the turbulent bulk layer (Monin and Ozmidov, 1985). The formulation presented by Soloviev et al. (1994) describes the temperature difference through the thermal molecular boundary layer, whereas similarity theories is appropriate for the turbulent bulk layers below. A combination of both theories allows for the relation of bulk temperatures at arbitrary depth of the well-mixing near-surface layer to the skin temperature of the infrared layer (10 µm thickness, from where thermal radiation is emitted into the atmosphere). In an example is shown, that for usual night-time conditions (surface heat flux of $Q_0 = 100$ W/m^2, 10-meter wind velocity varying between $U_{10} = 0 ... 25$ m/s), the skin layer forms between 62 ... 88 % of the oceanic temperature signal at 1 m depth. The contributions of the skin to the overall temperature signal are large for strong cooling (free convection) and strong winds (breaking of long surface waves).

1 Introduction

The heat flux through the surface layers of the ocean plays a crucial role for climate and weather. Global application of infrared remote sensing devices to oceanic problems require detailed knowledge of the near surface temperature profile (Schlüssel et al, 1990; van Scoy, 1995). The skin sea surface temperature (skin-SST) is characteristic for the infrared layer (uppermost 10 µm, which are the source of upwelling infrared radiation) - it represents a key parameter for the thermal radiation balance and all atmospheric processes above the ocean. The skin layer just below the surface is characterized by molecular transport processes and is usually less then a millimetre thick. The temperature difference through it is called the "skin effect". It is followed by a bulk region, where turbulent transport processes are realising the transports. We will call this actively mixing surface layer of some meters depth "near surface layer". The fine structure of the near-surface layer must be properly parameterized because usual measurements of bulk-SST are done at various depths (using buoys, buckets, cooling water inlets, CTD and XBT soundings). At the one hand, correct calibration of remotely sensed skin-SST needs adjustment for this reference depth of the bulk-SST. At the other hand, the estimation of the skin-SST from oceanic circulation models or routine observations needs correct parameterizations, too.

In this paper we attempt to develop a depth-dependence into the parameterization of the skin-bulk-SST difference. Hasse (1971) presented in his paper such a depth-dependent parameterization, but in most of the papers related to the skin effect a more or less arbitrary depth for the bulk-SST is chosen. Some investigators use depths in the decimetre range (Hasse, 1970; Grassl, 1976; Schlüssel et al., 1990; Soloviev at al., 1994), measured from little platforms manipulated from the stationary ship. For operational applications, the depth of the cooling water inlet (some 2 - 4 m depth) could be taken, which is recorded continuously. Another reference depth is related to the uppermost grid points in eddy-resolving circulation models - their thickness is in the order of meters. However, to give an idea of the expected effects, we will relate our findings to the depths of 10 cm and 1 m, respectively.

With the construction of the near surface temperature profile we not only cover the regime of wind-forced turbulence, but extend the range of validity to cooling-forced free convection. Such situations are important for night time and autumn seasons, for example. This approach supplements Hasses (1971) findings, which are valid for wind-driven turbulence. We exclude the impact of heating (see Hasse, 1971; Paulson et al., 1981 and Soloviev et al., 1996), leaving this subject to a forthcoming paper.

The approach is as follows: the difference between the skin temperature at the surface (T_0) and the bulk temperature at the depth z (T(z))

$$\Delta T(z) = T(z) - T(0) = \Delta T_{skin} + \Delta T_{bulk}(z) \quad (1)$$

Correspondence to: Christoph Zülicke

is decomposed into a contribution from the skin and the bulk. For both layers, different theories will be used. We consider mean profiles, as they are formed by hourly mean values.

A number of authors introduced parameterisations of the temperature difference between skin and bulk-SST through the molecular layer (ΔT_{skin}), which could be applied to a wide range of conditions. In particular, the surface renewal theory allows for closed expressions for the temperature deviation through the molecular skin of the ocean for calm and medium winds as well as for breaking waves under high winds (Soloviev and Schlüssel, 1994). This theory is briefly referenced in section 2.

However, such theories have a certain shortcoming in a priori assuming the bulk temperature to be homogeneous. This assumption is used for the construction of the skin-bulk-SST difference from observations using a stepwise linear temperature profile (Grassl, 1976), or as a boundary condition for theoretical considerations (Liu et al., 1975). Instead, we use Monin-Obukhov similarity theory (Monin and Ozmidov, 1985) to derive depth-dependent temperature profiles in the layers below ($\Delta T_{bulk}(z)$, section 3). It is shown, that already at 10 cm depth there are systematic contributions from the bulk, which should not be neglected.

A brief summary is given in section 4.

2 Surface Renewal in the Skin Layer

The skin layer is characterized by molecular transport processes. It extends form the surface of the water (z=0) into some depth ($z=-\delta_*$). In this section we summarise some mean properties of the heat conduction from the Soloviev and Schlüssel (1994) paper.

The mean temperature difference through the skin layer is

$$\Delta T_{skin} = \Delta T_* = T_* - T_1 \qquad (2)$$

where $T_1 = T(z=-\delta_*)$ is the bulk temperature at skin depth δ_*. The surface-renewal theory assumes below the skin layer a uniform temperature: The molecular scales in the skin are much smaller then the turbulent scales in the bulk.

The driving forces constitute depth-constant fluxes of momentum and heat. They read friction velocity u_{*0} and upwelling surface heat flux $Q_0 = L_0+H_0+R_{LW,0}$. The latter sums up the heat losses by evaporated latent heat (L_0), sensible heat (H_0) and long-wave (thermal) radiation ($R_{LW,0}$) of the ocean. Lateron, the abbreviation $q_0=Q_0/(c_p\rho)$ will be used. In Soloviev and Schlüssel (1994) the skin-bulk-SST difference is parameterized as

$$\Delta T_* = \Lambda_0 \Pr^{1/2} \frac{q_0}{u_{*0}} \frac{(1+Ke/Ke_{cr})^{1/2}}{(1+Rf_0/Rf_{cr})^{1/4}} \qquad (3\text{-}1)$$

Here, a number of dimensionless parameters has been used: the surface Richardson number $Rf_0=\alpha g\nu q_0/u_{*0}^4$, the Keulegan number $Ke = u_{*0}^3/(g\nu)$ and the Prandtl number $Pr=\nu/\kappa$; the remaining constants are $Rf_{cr}=1.5\ 10^{-4}$, $Ke_{cr} = 0.18$ and $\Lambda_0 = 13.3$. For later use we quote here some check values for pressure p = 0 Pa, salinity S = 35 PSU and temperature T = 20 °C from Landolt and Boernstein (1989): kinematic viscosity $\nu = 1.05\ 10^{-6}\ m^2/s$, acceleration due to gravity $g = 9.81\ m/s^2$, specific heat capacity $c_p = 4015$ Ws/(kgK), density $\rho = 1025\ kg/m^3$, thermal expansion coefficient $\alpha = 2.6\ 10^{-4}$ 1/K. With the kinematic conductivity $\kappa = 1.49\ 10^{-7}\ m^2/s$ we have a Prandtl number of Pr = 7.

The depth of the skin layer is estimated from the assumption of a linear temperature profile

$$\delta_* = \kappa \frac{\Delta T_*}{q_0} = \frac{\Lambda_0}{\Pr^{1/2}} \frac{\nu}{u_{*0}} \frac{(1+Ke/Ke_{cr})^{1/2}}{(1+Rf_0/Rf_{cr})^{1/4}} \qquad (3\text{-}2)$$

The functional behaviour of the temperature difference (Eq. (3-1)) is shown in Fig. 1. The range of validity is including calm winds (free convection, lower gray region) and breaking long gravity waves (above 10 m/s wind speed, upper gray region). It is interesting to note, that the skin-bulk-SST difference has a certain minimum value under moderate cooling and wind conditions (see Fig. 2). To quantify this statement, let us investigate the wind-dependence of the skin-bulk-SST difference. For this purpose we calculate

$$\frac{\partial \Delta T_*}{\partial u_{*0}} = 0 \qquad (4)$$

The resulting polynomial of fourth order is solved up to first order in the heat flux. We obtain for a heat flux of $Q_0 = 100\ W/m^2$ (resp. $q_0=2.43\ 10^{-5}$ Km/s)

$$u_{*min} \approx (2Ke_{cr} g \nu)^{1/3} - \frac{\alpha q_0}{Rf_{cr} Ke_{cr}} = 0.0152\ m/s \qquad (5)$$

This corresponds to a 10-meter wind velocity of $u_{10} = 12.3$ m/s, if the atmosphere is neutrally stratified (using the bulk formula $\rho u_{*0}^2 = C_{Da} \rho_a u_{10}$ with the neutral drag coefficient $C_{Da} = 1.3\ 10^{-3}$ and the air density $\rho_a = 1.203\ kg/m^3$). In this situation, the wind is most effectively acting on the surface gravity waves and the skin effect is minimal.

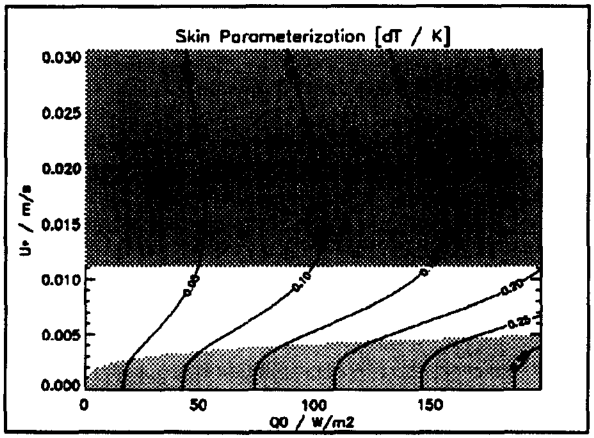

Fig. 1. Contour plot of skin-bulk temperature deviation ΔT_* (Eq. 3) (ordinate: friction velocity U_{*0}; abscissa: heat flux Q_0, contour levels of 0.05 K). Filled background indicates the forcing regime: light gray in the lower part for free convection, dark gray in the upper part for breaking waves).

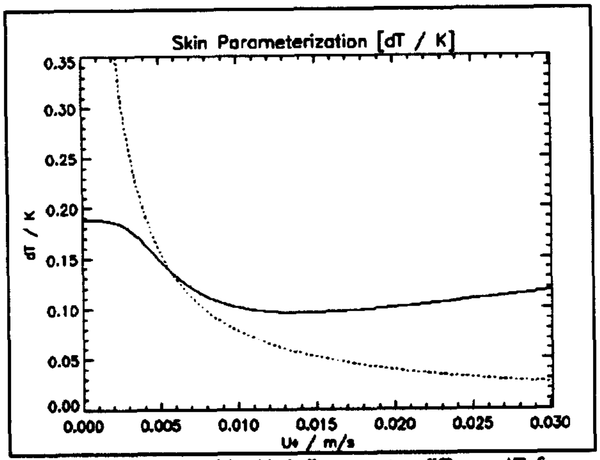

Fig. 2. Wind-dependence of the skin-bulk temperature difference ΔT_* for fixed heat flux and varying winds (solid line). The dotted line represents the Saunders, 1967, approximation (set $Rf_{cr} \to \infty$ and $Ke_{cr} \to \infty$; Eq. (3-1)).

3 Stationary Turbulence in the Bulk Layer

From the viewpoint of similarity theory, the molecular sublayer must be parameterized in a suitable manner to match the turbulent region. The molecular sublayer can be characterised by its thickness δ (i.e. where the molecular region matches the turbulent region) or the so-called roughness length z_0 (adjusting the turbulent profile to a finite value). These numbers are not the same, but are closely related to each other (see Chriss and Caldwell, 1984). Actually, the treatment of the molecular sublayer of the oceanic boundary layer is still subject of intense investigations. Whereas for the atmospheric boundary layer the impact of roughness, in particular of waves, is quite clear (see Kagan B.A., 1995, for an comprehensive overview - chapters 3.3 and 3.4), the analogue in the ocean is less well understood (Craig and Banner, 1994). Operational parameterizations are not available yet.

Using the findings for the skin layer we continue the temperature profile into the bulk of the water. In particular, the bulk temperature T_1 of the calculations above will be identified with the temperature at the boundary of the turbulent layer. For the bulk layer just below, we adopt results from the Monin-Obukhov similarity theory (Monin and Ozmidov, 1985). The depth range of applicatibity is characterized by the constancy of vertical fluxes, statistically stationarity and horizontal homogeneity of turbulence. These conditions may be expected in the well-mixed surface layer of the ocean.

By the direct matching of the molecular with the turbulent region we skipped the treatment of a transition region for three reasons:

(i) to stay with more clear and feasible analytical formulations.

(ii) not to introduce speculative transition layer ansatzes, which should be valid for different stratifications.

(iii) to be correct for the reference depth, which are important for practical applications. In particular the depths of 10 cm resp. 1 m are 100 resp. 1000 times larger then the skin thickness. Hence, the details of the profile in the transition region (if smooth or abrupt) turn out to be rather unimportant.

3.1 General Formulation

To continue with the formulation of the heat transfer in the bulk, we adopt the following values for the boundary of the turbulent layer:

$$z_1 = -\delta_* \qquad (6\text{-}1)$$

$$T_1 = T(z_1) \qquad (6\text{-}2)$$

For the calculation of the temperature profile we adopt the following formula

$$\Delta T_{bulk}(z) = \int_{z_1}^{z} dz' q_0 \frac{1}{k u_{*0} z'} \varphi_T(-\frac{z'}{L}) \qquad (6\text{-}3)$$

We have used here the Monin-Obukhov length $L = -u_{*0}^3/(kg\alpha q_0)$ and the van Karman constant k=0.4. For a general formulation, we use the following form of the universal function

$$\varphi_T(\zeta) = \begin{cases} 1 + 5\zeta & : 0.0 \le \zeta \\ (1 - 16\zeta)^{-1/2} & : -1.0 \le \zeta < 0.0 \\ (-29 - 99\zeta)^{-1/3} & : \zeta \le -1.0 \end{cases} \qquad (6\text{-}4)$$

with $\zeta = -z/L$ (Large et al., 1994). The integral (6) can be solved numerically. However, we will continue with analytical expressions for some physically interesting limiting cases.

3.2 Free convection (strong cooling)

In particular, we find for the case of free convection (Q_0 = 100 W/m², U_{*0} = 0 m/s, $Rf_0 = +\infty >> Rf_{cr}$, $Ke = 0 << Ke_{cr}$, Fig. 3).

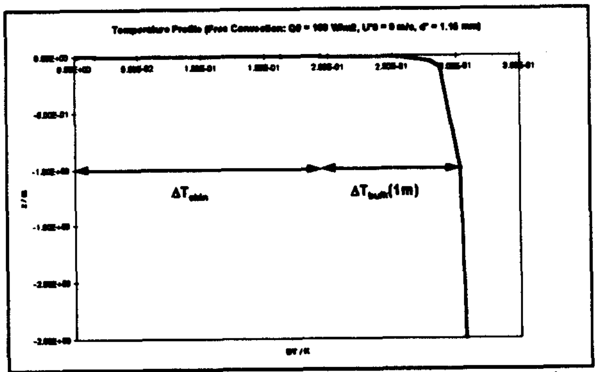

Fig. 3. Depth-dependent skin-bulk temperature difference ΔT(z) for the free convection/ strong cooling case according to Eq. (7) with Q_0 = 100 W/m², U_{*0} = 0.0 m/s, δ_* = 1.15 mm, ΔT_* = 0.19 K. There are indicated the different skin and bulk contributions 1m depth.

For the universal function we use the limit for unstable stratification $\varphi(\zeta \rightarrow -\infty) \rightarrow -99\zeta$ and obtain from Eq.s (3) and (6)

$$\Delta T = \tag{7-1}$$

$$= \frac{\Lambda_0 \mathrm{Pr}^{1/2} \mathrm{Rf_{cr}}^{1/4}}{(\alpha g \nu)^{1/4}} q_0{}^{3/4} + \frac{3(99)^{-1/3}}{k(k\alpha g)^{1/3}} q_0{}^{2/3} \left(\frac{1}{z^{1/3}} - \frac{1}{z_1{}^{1/3}}\right)$$

The thickness of the skin layer in this regime is

$$\delta_* = -z_1 = \Lambda_0 \mathrm{Rf_{cr}}^{1/4} \frac{(\nu\kappa^2)^{1/4}}{(\alpha g)^{1/4}} q_0{}^{-1/4} \tag{7-2}$$

Note, that both contributions are independent from the shear stress and approach a finite temperature difference with a potential law. With increasing depth, the temperature profile becomes asymptotically constant with fixed skin and bulk terms. Both contributions scale with 3/4-power of the heat flux ($Q_0{}^{3/4}$), the asymptotic scaling can be expressed by

$$\Delta T(z) \propto A_1(z)\, Q_0{}^{3/4} \tag{7-3}$$

The skin contribution ΔT_{skin} at 10 cm depth forms 65% of the overall skin-bulk difference ΔT; at 1 m depth they are still 62%.

3.3 Forced convection (moderate winds)

For the case of moderate winds ($Q_0 = 100$ W/m^2, $U_{*0} = 0.01$ m/s resp. $U_{10} = 8.1$ m/s in neutral atmosphere; $\mathrm{Rf}_0 = 6.49\ 10^{-6} << \mathrm{Rf_{cr}}$, $\mathrm{Ke} = 9.72\ 10^{-2} << \mathrm{Ke_{cr}}$, Fig. 4) we find neutral stratification at 1 m depth and use for Eq. (6) $\varphi_T(0.0248 << 1.0) \approx 1.0$. It results the logarithmic profile

$$\Delta T(z) = \Lambda_0 \mathrm{Pr}^{1/2} \frac{q_0}{u_{*0}} + \frac{1}{k} \frac{q_0}{u_{*0}} \ln\left(\frac{z}{z_1}\right) \tag{8-1}$$

with

$$\delta_* = -z_1 = \frac{\Lambda_0}{\mathrm{Pr}^{1/2}} \frac{\nu}{u_{*0}} \tag{8-2}$$

The skin contributions to the temperature difference make, in this case, 73 % at a depth of 10 cm and 65 % at 1 m. In comparison to the case of free convection, the impact of the skin layer on the overall temperature difference has been reduced. The larger the depth, the more dominant becomes the bulk layer and the skin impact can be more and more neglected.

For a neutrally stratified atmosphere, eq. (8-1) could be brought into a similar form as proposed by Hasse (1971):

$$\Delta T(z) \propto C_1(z) \frac{Q_0}{U_{10}} \tag{8-3}$$

The values of C_1 are not directly comparable to Hasse (1971), because he used in his original 1971 paper a dimensionless conductive layer thickness of $\eta=11$. The Soloviev-Schlüssel formula is consistent with Saunder's (1967) constant $\lambda=5$, which has been reproduced in many field experiments (see Soloviev et al. (1995) for intercomparison). However, the advantage in using the new formulation is that the depth-dependence is explicitly given and the atmosphere needs not to be neutrally stratified.

The temperature profile by Eifler (1993) reveals the same SST difference through the conductive sublayer and a similar form of Eq. (8). Actually, he uses another transition-layer model, resulting in a different expression for the reference depth z_1 (application of his eq. (13.b) results in a 5 times larger value as compared with our eq. (6-1)). However, he comes up with a skin impact of 80% at a depth of 1m, which is comparable with our estimate of 65%.

3.4 Breaking Waves (strong winds)

For stormy situations ($Q_0 = 100$ W/m^2, $U_{*0} = 0.03$ m/s resp. $U_{10} = 25$ m/s in neutral atmosphere, $\mathrm{Rf}_0 = 7.16\ 10^{-8} << \mathrm{Rf_{cr}}$, $\mathrm{Ke} = 2.83 >> \mathrm{Ke_{cr}}$, Fig. 5) the skin terms are

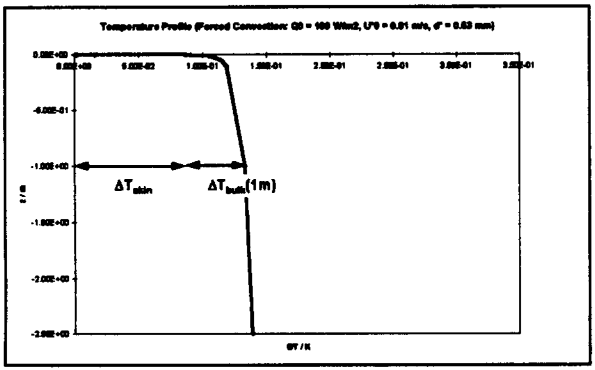

Fig. 4. Depth-dependent skin-bulk temperature difference $\Delta T(z)$ for the forced convection case according to Eq. (8) with $Q_0 = 100$ W/m^2, $U_{*0} = 0.01$ m/s, $\delta_* = 0.53$ mm, $\Delta T_* = 0.09$ K.

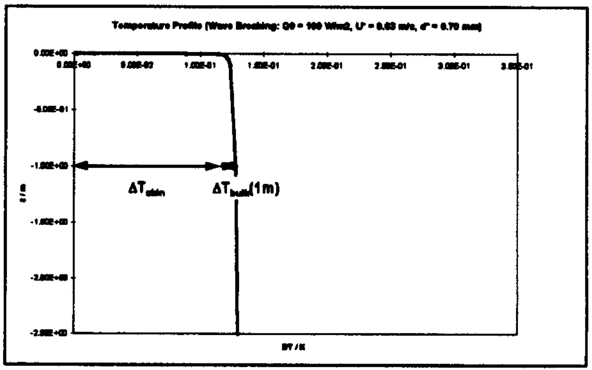

Fig. 5. Depth-dependent skin-bulk temperature difference $\Delta T(z)$ for the free convection case according to Eq. (9) with $Q_0 = 100$ W/m^2, $U_{*0} = 0.03$ m/s, $\delta_* = 0.70$ mm, $\Delta T_* = 0.11$ K.

changing, whereas the form of the bulk expression remains logartithmically (for 1 m depth we find $\varphi_T(0.0008 << 1.0) \approx 1.0$).

$$\Delta T(z) = \frac{\Lambda_0 \, Pr^{1/2}}{Ke_{cr}^{1/2}} \frac{q_0 u_{*0}^{1/2}}{(g\nu)^{1/2}} + \frac{1}{k} \frac{q_0}{u_{*0}} \ln(\frac{z}{z_1}) \qquad (9\text{-}1)$$

with

$$\delta_* = -z_1 = \frac{\Lambda_0}{(Pr\,Ke_{cr})^{1/2}} (\frac{\nu}{g})^{1/2} u_{*0}^{1/2} \qquad (9\text{-}2)$$

Here, 92% of the temperature difference at 10 cm comes from the skin (88% at 1 m). Although the skin temperature difference ΔT_{skin} is quite large, it will be dominated by the bulk contributions ΔT_{bulk} with increasing depth. For small depth it scales with the product of heat flux and square-root wind ($Q_0 * U_{10}^{1/2}$), whereas for larger depth the bulk scaling is more relevant (Q_0 / U_{10}).

$$\Delta T(z) \propto B_0 Q_0 U_{10}^{1/2} + B_1(z) \frac{Q_0}{U_{10}} \qquad (9\text{-}3)$$

Note, that for wind exceeding a critical velocity (see Eq. (5)) the influence of the skin on the temperature is rising.

4 Summary

Based on the surface renewal and similarity theory a consistent picture for the heat flux near the ocean surface was developed. Limiting laws for the cases of neutral and unstable stratification of the water body are presented. It is demonstrated, that below the conductive skin layer (order 1 mm thickness) there are arising significant contributions to the temperature difference. From the analysis of the formulae it is found, that the skin - bulk-SST difference has a certain minimum under favourable wind conditions, if situations with the same heat flux are compared. The impact of the skin layer on the temperature at larger depth is large for the cases of free convection and breaking waves. Another finding underlines, that for the regime of free convection the bulk contribution becomes asymptotically constant for increasing depth.

However, in any situation it is necessary to exactly specify the reference level for the skin-bulk-SST difference. Another conclusion concerns remotely sensed infrared images of SST, which are mostly fitted to bulk-SST in varying depths. Possibly, the use of different depths explains part of the scatter in the related in-situ data. For operational applications, the knowledge of a bulk-SST at a certain depth and the involved fluxes allows for an estimate of the skin-SST, which is relevant for the thermal radiation emitted into the atmosphere and related climatological problems. The particular choice of the bulk-SST could be the engine water inlet (or another routine observation) or the temperature of the uppermost grid point in numerical models.

As a final remark some statements concerning the comparison of the proposed contribution to the field of theory with observational data. The measurements should jointly include meteorological parameters, skin-SST observations (with infrared radiometers) and continuous subsurface profiles of bulk-SST (with uprising dissipation profilers). The latter data would reasonably complete the datasets with turbulent characteristics, such as temperature and shear fluctuations, dissipation rates and others. The collection of such a joint database would certainly require much effort including a number of specific field campaigns. One should bear in mind, that seasonal coverage would be necessary to meet the different stratification regimes. In view of the complexity of the required observations, they should be subject of future investigations.

Acknowledgements. We would like to thank Peter Schlüssel (University of Munich, Germany) and Walter Eifler (Space Applications Institute, Ispra, Italy) for a number of encouraging discussions. The authors acknowledge the critical remarks and questions of the anonymous referees and editor Sergey Gulev (P. Shishov Institute of Oceanology, Moscow, Russia), who helped to considerably improve the paper. This is contribution no. 254 of the Baltic Sea Research Institute, Warnemünde, Germany.

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