JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 86, NO. C7, PAGES 6426–6428, JULY 20, 1981

The Influence of Optical Water Type on the Heating Rate of a Constant Depth Mixed Layer

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A simple heat budget model for a radiation-dominated mixed layer of constant depth is presented. In this model the influence of the vertical irradiance (heat flux) profile is examined by means of the *Jerlov* [1976] optical water type classification. It is shown that the vertical irradiance profile is important in determining the mixed layer heating rate. The heating rate varies greatly as a function of water type, mixed layer depth, and diffusivity beneath the mixed layer, ranging from 0.098°C/day for oceanic water type I with a mixed layer depth of 20 m and diffusivity beneath the mixed layer of 1.0 cm^2 s^{-1} to 0.316°C/day for coastal type 9 with a mixed layer depth of 10 m and zero diffusivity beneath the mixed layer, a variation of more than a factor of 3.

INTRODUCTION

Heat budget considerations are of importance in determining the dynamics of the upper ocean, particularly the surface mixed layer [*Niiler and Kraus,* 1977]. In this paper we address one specific aspect of the heat budget, the influence of the vertical distribution of solar heat flux (irradiance) on the vertical temperature distribution in the upper ocean.

This work does not take into consideration fluctuations in mixed layer thickness. When the wind stress is small, mixed layer thickness is nearly constant [*Denman,* 1973]. When the wind stress is large, all solar energy can be considered as a surface input [*Niiler,* 1975]. The values derived here for heating rates are therefore upper limits except for time periods shorter than a day.

Heat budget models usually employ a scheme in which the vertical profile of the absorption of heat is given by an exponential [*Denman and Miyake,* 1973] or in which the net heat flux is considered to be a surface input [*Bowden,* 1977; *Niiler,* 1975]. The vertical distribution of solar heat flux (irradiance) may intuitively seem unimportant since most solar energy is absorbed in the top few meters and 99% of all solar energy is absorbed in the top 75 m. We will show, however, that the vertical distribution of irradiance can influence the mixed layer heating rate significantly.

In an earlier paper [*Zaneveld and Spinrad,* 1980] we showed that an arctangent model of total solar irradiance penetration best describes the greater than exponential decrease of irradiance near the surface and the exponential decrease at greater depths. The model is given by the equation

$$E(z) = E(0)e^{-K_1 z}[1 - K_2 \tan^{-1}(K_3 z)] \qquad (1)$$

where $E(z)$ is the downward vector irradiance (radiant flux on the upper face of an infinitesimally small element of a surface, divided by the area of that element) and K_1, K_2, and K_3 are parameters determined by the radiation absorption and scattering characteristics of the water mass. The depth (z) is defined positive downward.

Jerlov [1976] described a classification scheme for the total solar irradiance penetration profiles in the ocean, and presented a chart displaying the regional distribution of optical water types. By using Jerlov's classification scheme and (1) it is possible to investigate systematically the influence of irradiance profiles on mixed layer heating. Table 1 shows the coefficients K_1, K_2, and K_3 for the various water types.

We have carried out the calculations of mixed layer heating for two typical surface mixed layer thicknesses (10 and 20 m) and for various diffusivities beneath the mixed layer in the thermocline (0, 0.1, and 1.0 cm^2/s).

For demonstration purposes, we have used the incident heat flux and heat loss values determined by *Bowden* [1977] off northwest Africa. Bowden also showed a simple heat budget model with which we compared our results. More importantly, his measurements were made in the northwest African upwelling region in which there is a juxtaposition of turbid and clear waters. In that case, a large horizontal gradient in heating can have an important effect on the dynamics.

MODEL

Ignoring all horizontal terms, and assuming no vertical advection, the equation controlling the temperature distribution in a water column is

$$\frac{dT}{dt} = \frac{-1}{\rho c_p}\frac{\partial E}{\partial z} + \frac{\partial}{\partial z}\left(A\frac{\partial T}{\partial z}\right) \qquad (2)$$

where T is temperature, z is depth (positive downward), ρ is the density of water, c_p is the specific heat of water, E is the irradiance, and A is the eddy diffusivity for temperature. We do not take into account heat losses from a layer due to backscattering or heat gains by attenuation of upwelling irradiance. These effects counteract each other to some degree. The maximum ratio of upwelling irradiance to downwelling irradiance is 10% for blue light in the clearest oceanic water [*Jerlov,* 1976]. The typical ratio is much less (on the order of 3%), and the effect of ignoring upwelling irradiance is accordingly small.

Equation (2) is a parameterization of the heat conservation equation (it has been assumed that the turbulent heat flux can be modeled by $A\ \partial T/\partial z$) and can be approximated by the following difference equation:

$$T_{t+1,z} = T_{t,z} + \frac{\tau}{H}(E_{t,z-1/2} - E_{t,z+1/2}) + \frac{\tau}{H^2}[A_{t,z+1/2}(T_{t,z+1} - T_{t,z}) + A_{t,z-1/2}(T_{t,z-1} - T_{t,z})] \qquad (3)$$

Paper number 1C0121.
0148-0228/81/001C-0121$01.00

TABLE 1. Parameters of the Arctangent Model of Solar Irradiance Penetration (Equation (1)) for Various Optical Water Types

Water Type	$K_1 (10^{-2}\ cm^{-1})$	K_2	$K_3 (10^{-2}\ cm^{-1})$
I (clearest oceanic)	0.0440	0.3963	4.4547
IA	0.0490	0.3981	4.4236
IB	0.0574	0.4103	4.0725
II	0.0670	0.4158	3.9865
III	0.1250	0.4234	3.7062
1	0.1360	0.4500	3.3772
3	0.2231	0.4495	3.7049
5	0.3541	0.4626	3.6806
7	0.5028	0.4789	3.7150
9 (most turbid coastal)	0.5913	0.5427	3.6026

where τ is the time increment and H is the depth increment for the model. The boundary conditions are that the heat flux across the air-sea interface is equal to the sum (B) of back radiation, conduction to the atmosphere and evaporation. The product of the density, ρ, and the specific heat, C_p, is so close to 1.00 that these terms were dropped in the numerical calculation. This difference equation is known to be stable if $A\ \tau/H^2 \leq \frac{1}{2}$ [*Richtmyer and Morton,* 1967].

PARAMETERS

The values of incident heat flux, Q_s, and heat loss, B, are taken from an example (leg 1) given by *Bowden* [1977]: Q_s = 559 cal cm^{-2} day^{-1} and B = 242 cal cm^{-2} day. The incident flux is applied sinusoidally over a 14-h daylight period, and the heat losses are applied equally over the entire 24-h day. The relative decrease of the irradiance with depth is computed by (1). The parameters K_1, K_2, K_3 are given in Table 1.

The vertical eddy diffusivity is generally reported to be in the range 0.1 – 100 cm^2 s^{-1} [*Ichiye et al,* 1972; *O'Brien and Wroblewski,* 1973]. To produce a surface mixed layer, diffusivities of the order 100 cm^2 s^{-1} were found to be necessary. Diffusivities of 0.1 to 1 cm^2 s^{-1} beneath the surface layer produced gradients often observed in the thermocline. In the case of zero diffusivity below the mixed layer and large diffusivities in the mixed layer (corresponding to the *Bowden* [1977] model) our equation reduces to

$$\frac{dT}{dt} = \frac{Q_s}{\rho c_p D}\{1 - [1 - K_2 \tan^{-1}(K_3 D)] \exp(-K_1 D)\} - \frac{B}{\rho c_p D} \quad (4)$$

which gives daily temperature increased for the mixed layer directly. D is the depth of the mixed layer. A few examples were calculated with zero diffusivity beneath the mixed layer to verify that (4) gives the same results as (3).

DISCUSSION

The average daily heating rates (after 5 days of heating as predicted by the numerical model, equation (3)) for eight water types under two mixed layer thicknesses (10 and 20 m) and diffusivities beneath the mixed layer of 0, 0.1, and 1 cm^2 s^{-1} are given in Table 2. As was previously stated, a diffusivity of 100 cm^2/s was used for the mixed layer. In most of the coastal water types, very little radiant energy passes through even a 10-m mixed layer. The mixed layer loses significant amounts of heat by diffusion through the thermocline, however. In the oceanic water types, as much as 50% of the incident radiation penetrates below shallow pycnoclines. In situations such as coastal upwelling where turbid coastal water types are juxtaposed with clear oceanic types, differential heating rates of as much as 0.2°C/day across a front might be produced especially if the surface mixed layers of the two water types were of different thicknesses. This could have a large effect on the dynamics of the region. If, for example, a front is formed by the boundary of oceanic water type III with a mixed layer depth of 20 m and coastal water type 5 with a mixed layer depth of 10 m, the differential heating rate across the front would be 0.19°C/day. Beam transmission measurement off the Oregon coast [*Kitchen et al.,* 1978; *Zaneveld and Pak,* 1979] indicate that such a front is not at all unlikely. Unfortunately, irradiance measurements were not available to accurately determine water types.

The thermal gradients produced in the models from penetration of irradiance were at most 1°C per 10 m, which are in the same order of the observed gradients presented by *Bowden* [1977]. Bowden's assumption that all solar energy is a surface input is thus adequate for very turbid water. However, if a large temperature gradient can be maintained by other mechanisms (e.g., vertical shear in horizontal advection), diffusion may become extremely important. This situation could be modeled as follows:

$$\frac{dT}{dt} = \frac{Q_s}{\rho c_p D}[1 - (1 - K_2 \tan^{-1}(K_3 D)) \exp(-K_1 D)] - \frac{B}{\rho c_p D} + \frac{GA}{D}$$

where G is the thermal gradient (generally negative) externally maintained in the thermocline. If G were of the order of 1°C/m, then one could ignore the diffusivity term in the case of a 20-m mixed layer of a coastal water type only if $A \ll 0.4$ cm^2/s. For the same 20 m mixed layer with the 0.08°C/m temperature gradient generated by the model after 5 days of heating, we can ignore the diffusivity term if $A \ll 4.6$ cm^2/s. The model parameter 0.1 cm^2 s^{-1} marginally satisfies these requirements as verified by the results in Table 2 for the 20 m mixed layer.

CONCLUSIONS

It is shown that the profile of solar irradiance (heat flux) is important in determining the heating rate of mixed layers in the absence of strong wind-induced mixing. The heating rate of the mixed layer increases with decreasing thickness of the mixed layer and increasing turbidity. At the beginning of a seasonal thermocline formation, the warm surface water will be present in a thin layer. For example, off Peru a shallow (<10 m) mixed layer was observed (K. H. Brink, personal communication, 1980) in which the temperature and thickness fluctuated diurnally. The high temperature in the thin surface mixed layer is conducive to rapid growth of phytoplankton, which in turn increases turbidity and hence the heating rate. This physical/biological feedback loop would contribute to the further progress of a seasonal thermocline. A phytoplankton bloom can rapidly increase the concentration of suspended matter. Each doubling in concentration would approximately double the parameter K_1 in Table 1. It is thus seen that a bloom which doubles phytoplankton in a day could transform a water mass from oceanic type II to coastal

TABLE 2. Heating Rate of the Surface Mixed Layer in °C/day for Various Optical Water Types, Mixed Layer Depths, and Diffusivities Beneath the Mixed Layer

Mixed Layer Depth, m	Diffusivity Beneath Mixed Layer, $cm^2\ s^{-1}$	I	II	III	1	2	5	7	9
10	0	0.178	0.214	0.261	0.272	0.298	0.312	0.316	0.316
10	0.1	0.163	0.196	0.238	0.246	0.268	0.278	0.280	0.280
10	1.0	0.132	0.156	0.184	0.190	0.200	0.204	0.206	0.206
20	0	0.114	0.132	0.150	0.152	0.157	0.158	0.158	0.158
20	0.1	0.110	0.126	0.142	0.144	0.148	0.150	0.150	0.150
20	1.0	0.098	0.111	0.122	0.124	0.126	0.126	0.126	0.126

Diffusivity in mixed layer = 100 cm^2/s.

type 5 in a matter of days, increasing the heating rate by 0.1°C/day. In such a situation as well as in frontal zones where shallow, warm, and turbid layers flow over clearer and colder water masses, it is thus conceivable that the biological processes can affect the dynamics via heating of the surface layer.

In less extreme cases it is still clear that the irradiance profiles should be measured if useful models of the upper ocean are to be constructed. If, for modeling purposes, solar irradiance profiles are required in the absence of measurements, one can use existing maps of oceanic water types such as in *Jerlov* [1976], *Rutsleovskaya and Khalemskiy* [1977], and *Spinrad et al.* [1979] and obtain the profile by means of (1) and Table 1.

Acknowledgments. This research was supported by the Office of Naval Research through contract N00014-79-C-0004 and by the Department of Energy contract DE-AM06-76RL02227.

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(Received July 3, 1980;
revised January 13, 1981;
accepted January 13, 1981.)