SOLAR HEATING OF WATER BODIES AS INFLUENCED BY THEIR INHERENT OPTICAL PROPERTIES

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Abstract. A simple one-dimensional model has been developed for calculating the development of thermal structure in water bodies under specified meteorological conditions, as a function of their inherent optical properties (spectral absorption coefficients, scattering coefficient). Penetration of radiant solar energy is modeled with a previously derived equation relating attenuation of irradiance in narrow wavebands to absorption coefficient, scattering coefficient and solar angle. Evaporative and other heat exchange processes at the surface are taken into account. Vertical heat transfer is calculated by making use of a recently published parameterization of the eddy diffusion coefficient. The calculations show marked changes in thermal structure as absorption and scattering are varied over a range of optical water types from coastal seawater to highly colored and turbid inland water. In general terms, increasing the color and/or turbidity shifts the zone of shortwave energy absorption more toward the surface and leads to warmer but shallower mixed layers.

Introduction

An understanding of the annual cycle of solar heating of water bodies is essential for an understanding of the physical, chemical, and biological processes going on within them. Solar heating influences these processes not only by determining the temperature at which they go on, but also by bringing about thermal stratification, with its associated chemical and biological stratification. Of its great importance, this phenomenon has been extensively studied in marine and inland waters, both by field measurement and by numerical modeling, but no general review of this field will be attempted here. The intention rather is to consider in detail one particular aspect of the solar heating process, namely, the way in which it is affected by the inherent optical properties of the aquatic medium.

Natural waters vary enormously in their optical character. Some oligotrophic oceanic waters are optically equivalent to distilled water, whereas some inland waters in eroding catchments can present the appearance of liquid mud. The values of inherent optical properties, such as the absorption coefficient (a) and the scattering coefficient (b), or apparent optical properties, such as the vertical attenuation coefficient (Kd) for downward irradiance of the photosynthetic waveband (400-700 nm), vary by orders of magnitude amongst the water bodies of the world [Jerlov, 1976; Kirk, 1983]. It seems inherently likely that the extreme variability of penetration of solar radiation in water bodies is accompanied by comparable variability in thermal behavior, but the relationship is not well characterized. The variability, however, should be related mainly to the shortwave (visible) part of the solar flux. The infrared (λ > 700 nm) band, constituting about half the total, is absorbed so strongly by water itself that most of it is converted to heat in the upper half-meter layer, regardless of the optical character of the water.

Klein [1980] carried out numerical modeling of thermocline development for two optical types of oceanic water and predicted a higher sea surface temperature and more stable stratification in the more turbid water. Zaneveld et al. [1981] carried out calculations of the rate of heating in the surface mixed layer of marine waters, ranging in optical character from oceanic type I to coastal type 9 in the Jerlov [1976] classification. For a constant mixed layer depth, the heating rate (in degrees Celsius per day) increased progressively as the transparency of the water decreased. In a 10-m-deep mixed layer the heating rate increased by 56 to 78% (depending on the assumed diffusivity) in proceeding from oceanic water type I to coastal water type 9. Harleman [1982], in his modeling of thermocline development in lakes and reservoirs, found the calculated depth of the upper, wind-mixed, layer to decrease markedly as the assumed extinction coefficient for shortwave radiation increased. H. Kraus and Turner [1967] showed that oceanic thermocline formation predicted a decrease in mixed layer depth with increasing attenuation of the water, as did the model of Simpson and Dickey [1981]. Calculations by Woods et al. [1984] for oceanic waters types I to III (Jerlov classification) showed that the seasonal rate of solar heating below the mixed layer increased as the attenuation by the water decreased.

In addition to these modeling studies, there are some field observations relating thermal behavior of water bodies to their optical properties. Idso and Foster [1974] found, in a highly eutrophic pond, that when an algal bloom developed, with a consequent increased attenuation of solar radiation, the upper layer of the water showed a much greater rise in temperature during the day than it did before the bloom appeared. Zimmerman et al. [1981] compared two nearby lakes in Georgia, one highly colored and the other only moderately colored. The highly colored lake stratified in the summer; the other did not. Schwager (1986) observed, in an eutrophic pond, intense heating in the near-surface waters during periods of high surface turbidity and less intense heating to a greater depth when surface turbidity was lower. Various workers have reported enhanced heating within patches of algal blooms in inland

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Paper number 8D0283.
0148-0227/88/008D-0283$0.50

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In the light of this theoretical and observational evidence, the importance of the optical properties of a water body for its thermal behavior appears clearly established. It therefore follows that in predictive modeling of such behavior the optical aspects should be dealt with in a realistic and accurate manner. Klein [1980] concluded, from the modeling studies referred to earlier, that a precise parameterization of solar radiation penetration is required for a simulation of marine thermal structure.

In the modeling studies described so far, rather approximative treatments of solar penetration have been used, in which the depth variation of total irradiance has been fitted to empirical equations. Such treatments do not readily lend themselves to a systematic study of the consequences of varying the optical properties of the water in a fundamental manner, i.e., varying the inherent optical properties, the absorption coefficient and spectral absorption coefficients. A model which takes account of the inherent optical properties is more flexible and more powerful, since the behavior of any aquatic medium for which the composition and hence the inherent optical properties can be specified can be modeled. Furthermore, the most important optical character, the absorption spectrum (absorption coefficient as a function of wavelength) can, in models of this type, be represented to any desired degree of accuracy.

An example of a modeling procedure of the fundamental type referred to is the Monte Carlo method [Plass and Kattawar, 1972; Gordon et al., 1975; Schreiner, 1984]. In this method the computer follows the fate of a large number of photons, one at a time, passing into an imaginary body of water with specified optical properties. The optical properties determine the probabilities of the various things that can happen to the photons. So, with the use of random numbers and appropriate cumulative frequency distributions, each photon can be followed throughout its lifetime in the water body, and then, from the behavior of all the photons, a complete picture of the underwater radiation field, including radiant energy absorption rate as a function of depth, can be put together. This approach has recently been used in a study of energy collection by a solar pond as a function of its optical properties [Kirk, 1987].

A disadvantage of the Monte Carlo procedure is that it is rather slow, typically requiring several hours to follow the fates of 10^9 photons. On the basis of a series of Monte Carlo studies, however, by systematically varying the optical properties and the solar altitude, a widely applicable analytical relationship has been found [Kirk, 1984a] which makes it possible to carry out such calculations more simply, but which reproduces the Monte Carlo results with a high degree of accuracy. It is expressed in the form

\[ K_d(z) = 1 \left[ a^2 + (0.425 \mu_o - 0.19)ab \right]^4 \]  

where \( K_d(z) \) is the average value of the vertical attention coefficient (\( K_d \)) for downward irradiance in the euphotic zone (the layer in which irradiance diminishes to 1%) of the subsurface value) for monochromatic light incident on the surface at an angle such that the cosine of the photons (to the vertical) is \( \mu_o \) after refraction at the surface: \( a \) is the absorption coefficient for that waveband, and \( b \) is the scattering coefficient, both with units m^-1. \( K_d \) characterizes the rate of the approximately exponential attenuation of downward irradiance \( (E_d) \) with depth \( z \) (meters, measured from the surface downwards) in accordance with

\[ E_d(z) = E_d(0)e^{-K_dz} \]  

This calculation procedure can be applied to the whole solar flux by dividing this up into a set of narrow wavebands and applying (1) and (2) to each of these in turn. A program has been written which makes it possible to calculate the penetration of solar radiation very simply and quickly on a microcomputer, with an accuracy comparable to that obtained by complete Monte Carlo simulation of the process.

Although the Monte Carlo model, or its speedier derivative, can accurately calculate the localized rate of conversion of radiant energy to heat as a function of depth in water bodies of varying optical type, this is not sufficient to characterize the thermal behavior of the water body. Transfer of sensible heat within the water body, and various heat exchange processes at the surface must also be taken into account. This paper describes a study in which, for waters of widely ranging optical character, radiant energy transfer calculations carried out with (1) have been combined with calculations of vertical heat transfer carried out with a simple one-dimensional model based on Henderson-Sellers' [1985] parameterization of the eddy diffusion coefficient, together with appropriate parameterization of evaporative and other heat exchange processes at the surface. In this way, the influence of the inherent optical properties on the development of thermal structure has been explored. Although the parameterization of the model are unavoidably approximate, it is believed that these calculations will provide some indication of the likely magnitude of the effects that variation in optical properties will have on thermal behavior of real-world water bodies.

The Model

In general terms, what the model does is to calculate one-dimensional heat transfer within the water body for a series of 1-min time intervals extending through a total period of 24 hours. Advection is ignored, and edge effects are assumed to be negligible. The prevailing meteorological conditions and the inherent optical properties of the water are specified. The temperature change due to radiant energy absorption in each of a series of layers of water is calculated for a given 1-min time interval. Using calculated values of eddy diffusivity and surface heat exchange, the vertical transfer of sensible heat between the layers in that time interval is determined, and the resultant temperature changes are calculated and combined with those due to absorption of radiation. The temperature profile is adjusted appropriately, calculation continues.
for the next time interval, and so on. Details of the calculation steps are outlined below.

**Initial Conditions**

Each run corresponds to 24 hours, comprising twelve 2-hour periods, with the first of these beginning on the hour just before dawn e.g., if period is 0700-0900. The initial depth profile of water is specified in terms of the temperatures of each of 20 successive layers of water, from the surface down to the bottom layer. It is assumed that the water below the bottom layer has the same temperature as the bottom layer. An appropriate layer thickness is chosen.

**Meteorological Factors**

The date and the latitude to which the simulation is to apply are entered. Declination is calculated using a Fourier series which expresses declination as a function of date [Spencer, 1971]. The day length and times of sunrise and sunset are calculated from the declination and latitude [Kirk, 1983]. Values of maximum and minimum air temperatures during the 24-hour period are selected, usually on the basis of published meteorological data for the location in question. As an approximate model of diurnal temperature variation, it is assumed that air temperature starts with its minimum value at dawn, rises sinusoidally to the maximum value at 1400, and, after falling in a similar manner to the minimum value, remains at that value until the end of the 24-hour period. Air temperature is calculated for the midpoint of each 2-hour period and is assumed to remain constant throughout that period. Diurnal temperature variation is of course more complex than this, but I believe this simple model to be sufficiently realistic for our present purposes.

A value of noon solar irradiance (W m⁻²) appropriate for the latitude and date is chosen. It is assumed that the sky remains clear and that solar irradiance varies in a sinusoidal manner during the day [Monteith, 1973], rising from zero at dawn to the maximum value at noon, and then down to zero again at sunset. Solar irradiance is calculated for the middle of each 2-hour period and is assumed to remain constant throughout that period.

Values of barometric pressure and vapor pressure of the air (in millibars) are entered and are assumed to be constant throughout the 24-hour period. Values of wind speed (m s⁻¹) for each of the twelve 2-hour periods are specified.

**Optical Factors**

The values of the inherent optical properties of the aquatic medium (the absorption coefficients at a series of wavelengths over the range 325-2325 nm and the scattering coefficient) are specified for each run in accordance with the optical character of the water being studied. The absorption coefficients for pure water for nineteen 50-nm wavebands covering the range 325-1275 nm, taken from the literature [Smith and Baker, 1981; Palmer and Williams, 1976], are incorporated into the program. The very high absorption of the remaining infrared band (1275-2325 nm) is approximated by an absorption coefficient of 1000 m⁻¹. The set of absorption coefficients due to the combined contributions of dissolved and particulate humic color, phytoplankton, other than water itself, for the ten 50-nm wavebands extending from 325 to 825 nm are entered, and automatically added to the corresponding absorption coefficients for pure water. The actual values of these absorption coefficients, of course, depends on just what assumptions are made about the composition of the water.

So far as the dissolved yellow humic substances are concerned, it is convenient to take advantage of the fact that the absorption spectrum conforms quite closely to the equation

\[ a(\lambda) = a_0(\lambda) \exp \left[-S(\lambda - \lambda_0)\right] \]  

where \( \lambda_0 \) is a particular wavelength (440 nm is suitable) at which the absorption coefficient can be specified, and \( S \) is a coefficient whose value varies in different types of water from 0.010 to 0.020 but is commonly about 0.014 [Bricaud et al, 1981]. The absorption coefficient at 440 nm due to dissolved yellow color ("gilvin", "gelbstoff") we shall indicate by \( a_{440} \). Thus it is sufficient to choose a suitable value of \( a_{440} \), perhaps using collected literature data [Kirk, 1983] as a guide and to give \( S \) the value 0.014, and the required set of absorption coefficients for the series of wavebands centered on 350, 400, 450 nm etc. can be calculated. Figure 1 shows the absorption spectrum calculated in this way of yellow humic color at concentrations corresponding to \( a_{440} = 1.0 \) m⁻¹ and 0.1 m⁻¹ together with the absorption spectrum of pure water.

Particulate humic color has a rather similar absorption spectrum to the soluble material and so for modeling purposes can be lumped in with it. Phytoplankton have a very different spectrum. Specific absorption coefficients obtained on natural populations, such as those reported by Morel and Prieur [1977], combined with an appropriate assumption about concentration, will generate the necessary set of absorption coefficients.

At wavelengths in the infrared above 825 nm, absorption by water itself is so intense that the contribution of other components of the medium can be neglected.

For each run the value of the scattering coefficient of the medium is specified. There is evidence that the value of \( b \) varies approximately inversely with wavelength [Morel, 1973]. Accordingly, in these simulations the assigned value of the scattering coefficient is assumed to apply at 800 nm (approximately the median wavelength in the spectral distribution of incident solar energy), and values for each of the other wavebands are calculated assuming the inverse dependence on wavelength.

The Monte Carlo calculations from which (1) was derived assumed that the water had a normalized volume scattering function (angular distribution of scattering) identical to that measured by Petzold [1972] for San Diego harbor water. This volume scattering function, which we may reasonably consider to be applicable to most natural waters, is therefore implicitly assumed to apply in the present calculations.
Absorption of Solar Radiant Energy

While any desired spectral distribution could be used, it is assumed in the present calculations that the incident solar radiation has the same spectral distribution as that measured by Bird et al. [1982] for the total solar flux at Bedford, Massachusetts (air mass 1.07, atmospheric turbidity -0.21). Relative irradiance values for all 20 wavebands are incorporated in the program. Although the chosen spectral distribution is that for global irradiance, to simplify the calculation it is assumed that all the light is in the direct solar beam (under clear skies, ~85% of solar radiation is direct). Possible changes in spectral distribution during the day are not considered.

For each 2-hour period the solar altitude at the midpoint is calculated from the time, the latitude and the declination, and it is assumed to apply to the whole of that period. As noted previously, solar irradiance for that 2-hour period is calculated from the assumed midday value, assuming sinusoidal variation during the day. The angle of the refracted beam below the surface is calculated from Snell's law, assuming a refractive index for water of 1.333, and is in turn used to calculate $\mu_0$, the cosine of the photons. The fraction of the incident solar flux lost by reflection at the surface is obtained from the Fresnel equation, any decrease in reflection associated with wind ruffling of the surface [Austin, 1974] being neglected. The downward irradiance just below the surface is distributed among the 20 wavebands, in accordance with the spectral distribution of the incident solar radiation.

Within any water body there is, as a consequence of upward scattering, an upwelling flux as well as a downwelling flux of photons, and, at least in the more highly scattering waters, this should be taken account in heating calculations. From Monte Carlo calculations the empirical relationship

$$R(\theta) = (0.975 - 0.629 \mu_0) b_0 / a$$  \hspace{1cm} (4)$$

has been obtained [Kirk, 1984a], where $R(\theta)$ is the irradiance reflectance (ratio of upward to downward irradiance) just below the surface, and $b_0$ is the backscattering coefficient ($b_0 = 0.019 b$ for typical natural waters). Irradiance reflectance just below the surface is calculated for each waveband using (4). About half the upwelling light flux just beneath the surface is reflected downward again at the water/air interface [Austin, 1974]. Accordingly, in these calculations the incident downward irradiance just below the surface in each waveband is increased by an amount corresponding to downward reflection of half of the upwelling flux.

Because of the changing angular distribution, reflectance increases with depth [Kirk, 1977]. As an approximate allowance for this effect, it is assumed that irradiance reflectance at any greater depth is 20% higher than that just below the surface: this is a minor correction, for which great accuracy is not required.

For each waveband, using (1) together with the value of $\mu_0$ and the appropriate values of absorption coefficient and scattering coefficient, the corresponding value of $K_d$ is calculated. Using (2) and the subsurface irradiance in each waveband, the downward irradiance values at a series of depths corresponding to the lower surfaces of the successive layers of water defined earlier are calculated. Each value of downward irradiance is multiplied by the irradiance reflectance to give the upward irradiance, $E_u$, which is then subtracted from the downward irradiance to give the net downward irradiance, $E$, in each waveband at each depth. At each depth the net downward irradiance in all wavebands is summed to give total net downward irradiance at that
depth. For any layer, e.g., the ith layer, the rate of radiant solar energy absorption per unit area, \( Q_s(i) \), is equal to the net downward irradiance at its upper surface minus the net downward irradiance at its lower surface. The consequent increase in temperature of the ith layer in time interval \( \Delta t \) (sec) is given by

\[
\Delta T_a(i) = 10^{-3} \frac{Q_s(i) \Delta t}{\Delta z \rho c_p}
\]

where \( \Delta z \) is the thickness of the layer (m), \( \rho \) is the density of water (kg m\(^{-3}\)) and \( c_p \) is the specific heat of water, here assumed to be 4.18 kJ kg\(^{-1}\) °C\(^{-1}\).

### Heat Exchange Between Surface Layer and Atmosphere

The flux of long-wave radiation onto the water surface from the atmosphere is obtained from Swinbank's [1963] equation

\[
Q_a = 5.31 \times 10^{-13} T_a^6 \text{ W m}^{-2}
\]

where \( T_a \) is air temperature (at screen height) in degrees Kelvin. It is assumed that 6.6% of this diffuse radiation is lost by reflection at the surface [Jerlov, 1976] and that the remainder is completely absorbed within the surface layer.

The water surface is considered to act as a blackbody radiator, with a rate of emission of energy to the atmosphere given by

\[
Q_b = 5.67 \times 10^{-8} T_w^4 \text{ W m}^{-2}
\]

where \( T_w \) is the water surface temperature (in degrees Kelvin).

The rate of evaporative heat loss from the water surface is calculated using the empirical relationship of Rohwer [1931], (as cited by Meinzel [1942]), which on conversion to metric units is expressed as

\[
Q_e = 16.3 \times (1.465 - 0.000549 B)(0.44 + 0.264 W)(e_w - e_a) \text{ W m}^{-2}
\]

where \( W \) is the wind speed in m s\(^{-1}\), \( B \) is atmospheric pressure, \( e_w \) is the saturated vapor pressure of water at the temperature of the water surface, and \( e_a \) is the water vapor pressure in the air (at screen height) above the water surface, all these pressures being in millibars. The saturated vapor pressure of the water is calculated from the Glanz and Orlob [1973] equation (as cited by Henderson-Sellers [1986]):

\[
e_w = 2.1718 \times 10^8 \exp\left[-4157/(T_w-33.91)\right] \text{ mbar}
\]

Sensible heat loss, \( Q_s \), from the surface to the atmosphere is obtained by multiplying the evaporative heat loss by the Bowen [1926] ratio,

\[
R_B = \frac{0.00060526 B(T_w-T_a)}{e_w-e_a}
\]

The net rate of heat energy uptake by the surface layer, resulting from the combined effects of solar energy absorption and these various surface heat exchange processes, is

\[
Q_n = Q_s(i) + Q_a - Q_b - Q_e - Q_c
\]

and the consequent change in temperature of this layer in time interval \( \Delta t \) (in seconds) is given by

\[
\Delta T_s(i) = 10^{-3} \frac{Q_n \Delta t}{10^3 \Delta z \rho c_p}
\]

### Vertical Heat Transfer

Once the water body has ceased to be isothermal, i.e., as soon as absorption of solar radiation has established a variation of water temperature with depth, then there must be vertical transfer of heat from the warmer to the cooler regions. It is assumed that, except when wind speed is zero, this transfer takes place by eddy diffusion and that the rate of change of temperature, \( T \), at depth \( z \) due to this diffusion is given by

\[
\frac{\partial T}{\partial t} = \frac{\delta}{\delta z}\left[A(t,z)\frac{\partial T}{\partial z}\right]
\]

where \( A(t,z) \) is the kinematic eddy diffusivity for temperature applicable at that time at depth \( z \). The change in temperature of the ith layer in time interval \( \Delta t \) due to vertical heat transfer is given by

\[
\Delta T_{d}(i) = \Delta t \left[A(t,z_{i-1})(T_{i-1}-T_{i}) - A(t,z_{i})(T_{i}-T_{i+1})\right]
\]

where the ith layer is that between \( z_{i-1} \) (above) and \( z_i \) (below).

Eddy diffusivity as a function of depth is calculated using [Henderson-Sellers, 1985; equation (42)]

\[
A(t,z) = u_s z \exp(-k*z)
\]

where \( k* \) is von Karman's constant (here assumed to have a value of 0.4); \( u_s* \) is the friction velocity at the surface and is related to wind speed, \( U \), by

\[
u_s* = 1.2 \times 10^{-3} U
\]

where \( k^* \) is the Ekman velocity profile parameter in the expression for friction velocity \( (u^*) \) as a function of depth,

\[
u = \frac{u_s* \exp(-k^* z)}{\nu 1.84}
\]

\( P_0 \) is the neutral value of the turbulent Prandtl
Richardson number at depth $z$, and is given by

$$R_i = -1 + (1 + 40X) \frac{X}{20}$$

(19)

where

$$X = \frac{N^2 \rho z^2}{u_b^2 \exp(-2kz)}$$

(20)

and

$$N^2 = \frac{g(\theta \rho)}{\rho}$$

(21)

where $g$ is the acceleration due to gravity ($9.81 \text{ m s}^{-2}$) and $\rho$ is the density of the water at depth $z$. Density (of fresh water) is obtained from temperature, using the formula of Heggen [1983]

$$\rho = 1000 - 0.0195491T^{-2771.68}$$

(22)

For a detailed justification of this parameterization of eddy diffusivity, the paper by Henderson-Sellers [1985] should be consulted.

For calculation of vertical heat transfer during each time interval $\Delta t$, the values of eddy diffusivity, $A(t, z, \rho)$, used for the series of depths are determined on the basis of the temperature (and hence density) profile existing at the beginning of that time interval. For those periods in which wind speed is assumed to be zero, eddy diffusivity is also assumed to be zero, and vertical heat transfer is assumed to take place by molecular diffusion, with a kinematic molecular diffusivity value of $1.435 \times 10^{-5} \text{ m}^2 \text{s}^{-1}$.

Temperature Profile

Within each 2-hour period the depth profile of temperature is calculated at intervals of 1 min. The temperature change, $\Delta T_a(i)$, of each of the 20 water layers due to absorption of solar radiation, together in the case of the surface layer with surface heat exchange processes, during the 1-min interval is calculated on the basis of the temperature profile arrived at in this way is deemed to correspond to a stable water column. The temperature profile arrived at in this way is deemed to correspond to a stable water column. The temperature profile arrived at in this way is deemed to correspond to a stable water column.

$$\Delta T(i) = \Delta T_a(i) + \Delta T_d(i)$$

(23)

and the new temperature of each layer, i.e., the new depth profile of temperature, is calculated.

At night and during part of the day (early morning, late afternoon) heat losses from the surface layer, especially those due to back-radiation and evaporation, can exceed heat gains, so that there is surface cooling. As a consequence, the surface water can become cooler and therefore denser than the water beneath. It is assumed here that the resultant instability is overcome by penetrative convection, i.e., by sinking and mixing of the cold water with the water below. The effect of mixing the upper layer uniformly first with the second layer, then with the second and third layers, then with the second, third, and fourth layers, and so on, is calculated until it is determined to what level mixing must be carried out to ensure that the water below is just cooler than the mixed water mass above. The temperature profile arrived at in this way is deemed to correspond to a stable water column. The temperature profile arrived at in this way is deemed to correspond to a stable water column. The temperature profile arrived at in this way is deemed to correspond to a stable water column.

Calculations

A BASIC computer program, TEMPRO, has been written with which this sequence of calculations can be carried out on a desk computer. Given the latitude and longitude of the location, the radiation and evaporation, can exceed heat gains, where this latter condition corresponds to wind speeds of 0, 1, 2, 4, 4, 2, 1, 0, 0, 0, 0 m s$^{-1}$, respectively, in the sequence of the twelve 2-hour periods making up the 24-hour period. Given that the simulation for October 21 begins at 0500, "moderately windy" corresponds to wind existing from 0900 to 2100, rising to a peak of 4 m s$^{-1}$ between 1300 and 1700.

In every case the water was assumed to be isothermal, at 12° C, at the start of simulation (0000) on October 21, where development of thermal structure during a sequence of consecutive days was followed, the temperature profile at the start of each 24-hour period was that established at the end of the previous 24-hour period.

The absorption properties of the water were varied by varying the concentration of yellow humic color (gilvin); absorption coefficients in ten 50-nm wavebands (covering 325-825 nm) due to components other than water, and the wind speed in each of the twelve 2-hour periods, the computer calculates the new temperature profile established at the end of each of the twelve 2-hour periods. On an inexpensive, 280-based personal computer, the calculation takes about 5 hours, but much shorter computation times could be achieved on a more sophisticated machine.

The calculations presented here have been carried out for a location at 35°S (the latitude of Canberra, Australia), for October 21, or for a series of days beginning with that date, for sunny conditions with a solar irradiance at noon of 1022 W m$^{-2}$ [Spencer, 1978], a minimum air temperature of 7°C and a maximum of 21°C, and a barometric pressure of 1000 and 10 mbar vapor pressure. Conditions for the 24 hours have been assumed to be entirely windless or moderately windy, where this latter condition corresponds to wind speeds of 0, 1, 2, 4, 4, 2, 1, 0, 0, 0, 0 m s$^{-1}$, respectively, in the sequence of the twelve 2-hour periods making up the 24-hour period. Given that the simulation for October 21 begins at 0500, "moderately windy" corresponds to wind existing from 0900 to 2100, rising to a peak of 4 m s$^{-1}$ between 1300 and 1700.

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Kirk: Solar Heating and Optical Water Type 10,903

Fig. 2. Development of thermal structure during a 24-hour period. The water body is of either high ($g_{440} = 3.0 \text{ m}^{-1}$, continuous line) or low ($g_{440} = 0.25 \text{ m}^{-1}$, broken line) color, and it is under either still (upper curves) or moderately windy (lower curves) conditions (see text for details). The scattering coefficient is $2.0 \text{ m}^{-1}$.

from $2.0 \text{ m}^{-1}$, typical of the more turbid coastal, and less turbid inland, waters, to $12.0 \text{ m}^{-1}$, characteristic of moderately turbid inland waters.

Results

Figure 2 shows the temperature profiles which develop during the day in initially isothermal waters with low ($g_{440} = 0.25 \text{ m}^{-1}$) or high ($g_{440} = 3.0 \text{ m}^{-1}$) color, and under still, or moderately windy, conditions. In both optical water types, in the absence of wind, the upper region of the water is at its warmest at about 1700, the temperature being highest at the surface and decreasing approximately exponentially with depth. The surface temperature at 1700 is higher in the more intensely colored water; 22.7°C compared to 19.6°C in the less-colored water. At night, surface cooling occurs, leading to penetrative convection and consequent mixing of the surface layers: by 0500 a uniform temperature of 13.4°C in the less-colored and 14.7°C in the more-colored water has been established down to a depth of 0.6-1.0 m.

Under the moderate wind regime described in the previous section, the greatly increased downward heat transport resulting from the initiation of eddy diffusion leads to the uniform mixing of heat within an upper layer during the day, i.e., to thermal stratification, this being first established between 1300 and 1500. The upper, isothermal layer, extending down to 0.6 m, at 1500 has a temperature of 15.1°C in the low-color and of 16.7°C in the high-color water. Below the upper, mixed layer, temperature decreases in the usual sigmoidal manner leveling off at approximately the original temperature of the water body in the deeper water. During the night, surface cooling and penetrative convection bring about a deepening of the isothermal upper layer to 0.8-1.0 m, with a temperature at 0500 of 13.3°C in the less-colored and 14.1°C in the more-colored water.

In Figure 3, for the moderate wind regime the temperature of the mixed surface layer in the afternoon (1500), and toward the end of the following nighttime period (0500), is plotted as a function of the concentration of dissolved color in the water. Also plotted is the heating rate of the upper 1-m layer of the water, calculated from the increase in the average temperature of that layer between 0500 October 21 and 0500 October 22. The heating rate increases from 1.30 to 2.08°C/24 hours, as $g_{440}$ increases from 0.25 to $3.0 \text{ m}^{-1}$.

The rate of accumulation of heat by the whole water body does not of course increase in like manner, since essentially all the solar photons are absorbed somewhere in the water column, whatever the optical properties of the water. What increasing the concentration of dissolved color does is to increase the proportion of incoming photons which are absorbed near the surface rather than at greater depth. Figure 4 shows the rate of solar energy absorption at midday as a function of depth in the low- and the high-colored water it can be seen that the rate of

![Fig. 3. Effect of varying the concentration of dissolved color on heating of upper region of water column. The concentration of gilvin (soluble yellow humic color) is specified in terms of $g_{440}$, and the scattering coefficient is $2.0 \text{ m}^{-1}$.

Simulation is for the period from 0500 on October 21 to 0500 on October 22, under the moderate wind regime, for a water body initially isothermal at 12°C. The temperatures of the upper mixed layer at 1500 on October 21 and 0500 on October 22, are plotted (solid lines). The corresponding heating rates of the upper 1-m layer of water, in degrees Celsius per 24 hours are also plotted (dashed line).]
energy absorption is greater in the high-colored water down to 1.0 m and greater in the low-colored water at depths beyond this. The temperature profiles in Figure 2 in fact cross over at about this depth, the deeper layers being slightly warmer in the less-colored water.

The effects of increasing the turbidity (i.e., scattering) of the water, while keeping the color (i.e., absorption) constant, are slightly more complicated. The irradiance reflectance at all depths increases as a consequence of the increased ratio of scattering to absorption, the value just below the surface being given by (4). About half of the upwelling photons just below the surface are reflected downward again at the water/air interface, but the rest escape through it. Thus in highly turbid inland waters, for which \( R(0) \) values as high as 10-20% for the whole solar waveband may frequently occur, as much as 5-10% of the incoming solar energy may be lost by scattering from below the surface back into the atmosphere. For most marine waters the amount of solar energy lost in this way is likely to be less than 1%. In the case of the inland waters, increasing the turbidity relative to the color (i.e., the scattering relative to the absorption), while it may slightly reduce the total intake of radiant energy, tends nevertheless to increase daytime surface temperature by causing more of the energy to be trapped near the surface. This is because increased scattering makes the light more diffuse, and thus increases the average pathlength the photons must follow in traversing a certain depth, and so increases the probability of their being captured by one of the absorbing components of the medium. Figure 5 shows the depth profile of temperature at 1500 within the upper 1.0-m layer in water bodies with a high level of color (\( g_{440} = 0.0 \text{ m}^{-1} \)) and two levels of scattering - \( b = 2.0 \text{ m}^{-1} \) and \( b = 12.0 \text{ m}^{-1} \). The more turbid water is warmer in the surface layer but cooler below.

All of the simulations described so far have been for water bodies which were isothermal, at 12°C, at the beginning of the 24-hour period. This is a realistic supposition for a water body in a temperate region in the spring. Typically, however, in water bodies above a certain minimum depth, long-term stratification eventually becomes established in spring and lasts through to the autumn, so it is therefore of interest to study what happens on a daily basis to a water body in which stratification is allowed to persist from day to day. Figure 6 shows the temperature profiles at 0500 and 1700 on days 1, 3, and 7 in a 7-day sequence, for a water body initially isothermal at 12°C. The temperature profile at the beginning of each 24-hour period was assumed to be that established at the end of the previous
Fig. 6. Development of thermal structure over 7-day period, under moderate wind regime with high ($\varepsilon_{a440} = 3.0 \text{ m}^{-1}$, solid line) or low ($\varepsilon_{a440} = 0.25 \text{ m}^{-1}$, dashed line) color. The water is initially isothermal at $12^\circ$C, at 0500 October 21. Here $b = 2.0 \text{ m}^{-1}$.

24-hour period. At 1700 on day 7, the temperature of the mixed surface layer was $18.3^\circ$C in the water with low color and $20.6^\circ$C in the water with high color.

Mixing by nighttime penetrative convection extends down to 1.5-2.0 m after a week, under the specified meteorological conditions. The average heating rate of the upper 1.5-m layer of water, calculated from the increase in the average temperature of that layer between 0500 October 21 and 0500 on October 28, was 0.69°C day in the water with $\varepsilon_{a440} = 0.25 \text{ m}^{-1}$ and 0.89°C in the water with $\varepsilon_{a440} = 3.0 \text{ m}^{-1}$. After penetrative convection at night has deepened the upper mixed layer and, in effect, pushed the thermocline downward, solar heating during the following day can establish a new additional thermocline within this upper layer. This can be seen in both optical types of water (Figure 6) but is particularly evident in the more highly absorbing water. Multiple thermoclines are quite common in real lakes. Figure 7 shows a temperature profile with two well-defined thermoclines (for January 23 (southern hemisphere summer)) in an Australian impoundment (Burrinjuck Dam, New South Wales), which in fact had a $\varepsilon_{a440}$ value at the time, in the region of 3.0 m⁻¹. Figure 7 also shows the temperature profile of this water body on a still day about a month later (February 27): the marked warming of the surface layer that takes place in the absence of wind mixing is clearly evident.

Some inland waters absorb and scatter light much more strongly than the water types we have considered so far. For comparison purposes it is of interest to consider the thermal behavior of extremely turbid and colored water. On November 21, 1984, optical measurements were carried out on the water of Lake Ginninderra, Canberra, which, at the time, was particularly turbid and brown as a consequence of erosion from construction sites in its catchment. The absorption coefficient at 440 nm due to particulate color was 14.33 m⁻¹ and that due to dissolved color was 3.13 m⁻¹. The scattering coefficient was 32.0 m⁻¹. Figure 8 shows the calculated development of thermal structure during a 24-hour period for an initially isothermal water body with the optical properties measured for Lake Ginninderra on this occasion. The temperature profiles for our standard low color/low-turbidity water ($\varepsilon_{a440} = 0.25 \text{ m}^{-1}$, $b = 2.0 \text{ m}^{-1}$) are included for comparison purposes. By 1700 the mixed surface layer reached a temperature of $18.5^\circ$C in the "Lake Ginninderra" water, but only $15.1^\circ$C in the low-color/low-turbidity water. However, the temperature profiles cross over, with more heat penetration to greater depths in the latter water.

**Discussion**

The calculations presented here show that variation in the inherent optical properties of water bodies, in the range commonly encountered among inland waters, does significantly influence their thermal behavior and so must be taken into account in any attempts to understand such behavior. It might, however, have been expected that the effects of modifying the optical properties would have been even greater than those calculated in this study. For example, it might be thought that a twelvefold increase in dissolved color (an increase in $\varepsilon_{a440}$ from 0.25 to 3.0 m⁻¹) would bring about even more drastic changes in the thermal behavior of the water than those shown in Figure 2. The reason it does not is that water itself absorbs very strongly in the infrared.

Fig. 7. Thermal structure in Burrinjuck Dam, New South Wales, Australia, on two dates in the summer of 1974.
Fig. 8. Calculated development of thermal structure during a 24-hour period for a turbid, highly colored water body with optical properties similar to those of L. Ginninderra, Australian Capital Territory Australia, on November 21, 1984 (see text for details), shown by a solid line. Curves for a low-color/turbidity water (g_{440} = 0.25 m^{-1}, b = 2.0 m^{-1}) are included for comparison (dashed line).

region. About half the incident solar flux is in the infrared, and consequently, at least half of the incident solar radiation is absorbed in the upper 0.5 m, regardless of the optical properties of the aquatic medium. Changing the amount of color in the water acts mainly on the penetration of the shorter wavelength solar radiation, i.e. the 350 to 700-nm waveband. Figure 9 shows the calculated spectral distribution of downward irradiance at 0- and 0.5-m depth in the two types of water. In both cases, essentially all of the infrared has disappeared by 0.5 m. The greater rate of energy absorption in the upper layer of the more highly colored water can be seen to be mainly of blue-green (400-550 nm) light.

As we have already noted, changing the optical properties has little effect on the total amount of solar energy absorbed by a water body, but it does influence the depth distribution of energy absorption, with an increase in color and/or turbidity shifting the zone of shortwave energy absorption more toward the surface and allowing less energy through to warm the deeper water. Thus highly colored and turbid waters are likely to end up with a warmer mixed layer, but colder below the thermocline, than clear and colorless waters.

In agreement with Harleman [1982] these calculations also predict a shallower mixed layer in the more highly attenuating waters. After 24 hours of the moderate wind regime, the upper isothermal layer is 1.2 to 1.4-m deep in water with g_{440} = 0.25 m^{-1} and 0.8-0.9 m deep in water with g_{440} = 3.0 m^{-1} (Figure 2).

Fig. 9. Changes in the spectral distribution of downward irradiance with depth in waters with low (g_{440} = 0.25 m^{-1}) or high (g_{440} = 3.0 m^{-1}) color, and scattering coefficient (\(\approx 2.0 m^{-1}\)). Calculations carried out with Monte Carlo program WATER 1 [Kirk, 1988].
Acknowledgement. The radiative transfer model used in these calculations required for its development a coherent, well-defined, theoretical framework with clear conceptual distinctions between the inherent optical properties, truly belonging to the aquatic medium itself, and the apparent optical properties (such as $K_{0}$), which are really local properties of the underwater light field but which it is useful in some contexts to treat as though they are optical properties of the water body. Rudy Preisendorfer played a major role in the development of hydrological optic theory over the last four decades, and the clear distinction between inherent and apparent optical properties [Preisendorfer, 1961] is only one of the important contributions he made. I am happy to take this opportunity to acknowledge how much in my own research I have been influenced by, and have made use of, his seminal contributions to the field. This paper is dedicated to his memory.

References


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(Received October 29, 1987; revised March 29, 1988; accepted April 5, 1988.)