Optical and hydrographic consequences of freshwater run-off during spring phytoplankton growth in a Scottish fjord

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A combination of in situ measurements and radiative transfer modelling were used to study optical conditions in the inner basin of Loch Etive, a Scottish fjord, in March and April 2000. The basin was strongly stratified with three layers separated by marked pycnoclines. The surface layer averaged 5 m in depth and was heavily stained with coloured dissolved organic matter (CDOM) which reduced the euphotic depth to between 7 and 10 m. Approximately 20% of the photosynthetically available radiation (PAR) in the water column was absorbed by phytoplankton, 44% by CDOM and 36% by sea water. Detectable concentrations of the major inorganic nutrients (nitrate, phosphate and silicate) occurred at all depths, but significant phytoplankton populations (averaging 6 mg chlorophyll a m^{-3}) were found only in the reduced-salinity surface layer. The freshwater input therefore acted both as a source of buoyancy which promoted phytoplankton growth near the surface and as an attenuator of visible light which inhibited growth deeper in the water column.

INTRODUCTION

The growth of a nutrient-sufficient phytoplankton population in a stratified water column depends on whether the mixed layer depth or the rate of turbulent diffusion permit the cells to spend an adequate amount of time above the compensation depth (Huisman *et al.*, 1999). In the shelf seas of the north east Atlantic the timing of the spring bloom is often linked to a reduction in the depth of mixing due to thermal stratification (Mann and Lazier, 1996). However, in fjords, estuaries and the edge of melting ice shelves, reductions in the depth of mixing can be brought about by lowered salinity rather than elevated temperature and this enables spring phytoplankton growth to start before solar warming of the surface layer occurs (Tett *et al.*, 1986; Cloern, 1991; Mitchell and Holm-Hansen, 1991). In regions such as the west coast of Scotland, the fresh water run-off is heavily stained with coloured dissolved organic matter (CDOM) which strongly attenuates blue light in the water column (McKee *et al.*, 1999; Bowers *et al.*, 2000). High flows of fresh water are therefore likely to promote stratification by adding buoyancy to the water column while simultaneously reducing underwater light levels by effectively creating a yellow optical filter in the surface layer. Numerical models of sea loch ecosystems (Ross *et al.*, 1993, 1994) have identified the level of photosynthetically available radiation (PAR) as the factor most likely to determine both total primary production and the timing of the spring phytoplankton bloom. The object of this paper is therefore to explore how the light-absorbing and stratifying effects of fresh water run-off interact to determine the exposure of phytoplankton cells to PAR early in the year. The location chosen was Loch Etive, a long narrow fjord situated on the west coast of Scotland (Figure 1) which receives river inflows of between 2.4×10^6 and 3.6×10^7 m^3 day^{-1} into a surface area of 2.9×10^7 m^2 (Edwards and Edelsten, 1977). Most of the fresh water is entrained in a surface layer <10 m deep which is therefore diluted at a rate of 1–10% per day. The inner basin is separated from the rest of the loch by a sill at Bonawe at a depth of around 18 m. Previous studies of Loch Etive found that the main inorganic nutrients (nitrate, phosphate and silicate) were non-limiting except at the peak of phytoplankton blooms (Solórzano and Grantham, 1975) and that primary production was usually dominated by

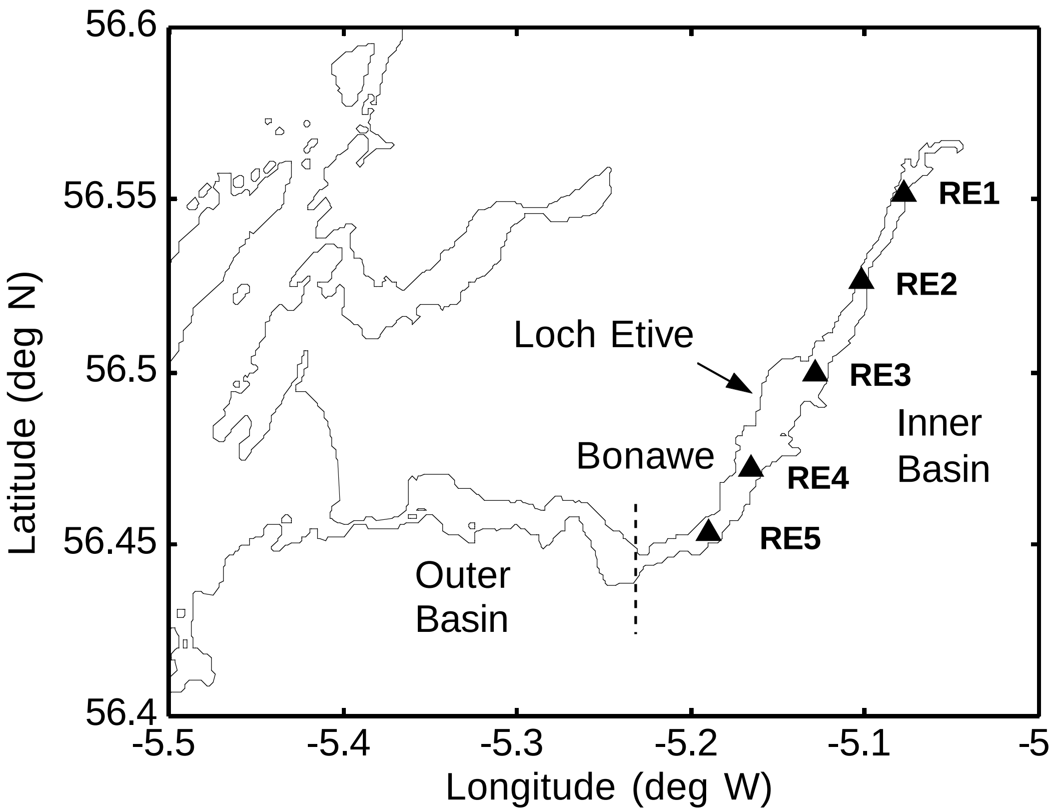

Fig. 1. Map of Loch Etive with station positions indicated. These stations are also used as part of a more comprehensive study of the hydrodynamics and chemistry of Loch Etive by Dunstaffnage Marine Laboratory.

chain-forming diatoms, particularly *Skeletonema costatum* (Wood *et al.*, 1973).

METHOD

Measurements were made in the inner basin of Loch Etive during short cruises on the 30–31st of March and 27–28th April 2000. The situation was broadly similar in both months apart from a significant deepening of the intermediate layer in April. Hydrographic profiles were obtained using a SeaBird SBE 19 CTD system mounted in a rosette sampler with fluorescence, beam transmission and dissolved oxygen sensors attached. Downward irradiance was measured with a Satlantic SPMR free-fall profiling radiometer deployed at least 15 m from the ship. The SPMR detection bands were 10 nm wide and centred at 412, 443, 490, 510, 555, 665 and 700 nm. Periodic checks using a 100 W standard lamp in our laboratory showed no significant drift in the detector sensitivities over the duration of the project, and so the factory calibration figures were applied. In order to derive PAR values from the downward irradiance (E_d) measured *in situ*, it was necessary to assume that the upward irrradiance (E_u) was small enough to be neglected. An approximation to a continuous spectral measurement of E_d was then obtained by linear interpolation between the centre wavelengths of the SPMR channels, and units were converted from W m^{-2} nm^{-1} to μE s^{-1} m^{-2} nm^{-1}. The resulting figures were summed from 400 to 700 nm and divided by 0.8 to compensate for the cosine response of the downward irradiance detector. This procedure differs from the routine supplied by Satlantic for obtaining PAR figures only in the application of the mean cosine correction factor. Its accuracy was checked by running a Hydrolight model for radiative transfer (see below for details) which incorporated typical sea loch inherent optical properties, and comparing the PAR figures calculated by the model with those produced by simulating the SPMR sampling of downward irradiance. PAR estimates obtained from the SPMR E_d bandwidths were within 0.5–1% of the numerically correct values.

Water samples were taken at depths representative of the main hydrographic layers and filtered immediately. CDOM was determined by passing samples through

0.2 μm membrane filters and measuring the absorption of the filtrate at 440 nm (a_{440}) in a laboratory-made 20 cm pathlength cuvette. Chlorophyll *a* plus phaeopigment (referred to simply as chlorophyll in the remainder of the text) was measured by filtering 1 l samples through 25 mm GF/F filters, extracting pigments overnight in ice-cold acetone, and measuring the peak fluorescence emitted from 710 to 730 nm before and after acidification while scanning the excitation source from 660 to 670 nm in 1 nm steps. The measurement procedure was calibrated using solutions of purified chlorophyll *a* (Chl *a*) (Sigma) whose concentrations were determined by spectrophotometry using the equations recommended by Jeffrey *et al.* (Jeffrey *et al.*, 1997). Previous work in Loch Etive and the neighbouring coastal area found reasonable linear correlations between CDOM concentration and salinity and between fluorescence and extractable chlorophyll (Cunningham *et al.*, 2001). Linear regressions on all samples measured in March 2000 produced correlation coefficients of 0.84 for CDOM against salinity and 0.94 for chlorophyll against fluorescence. These linear relationships were used to estimate concentrations of CDOM and chlorophyll from the hydrographic profiles in order to provide input to our optical model at 1 m intervals, a higher spatial resolution than could be achieved by the analysis of water bottle samples. Particulate absorption spectra were measured by the quantitative filter technique, using the spectral decomposition procedure described by Bricaud and Stramski (Bricaud and Stramski, 1990). Dissolved nitrate plus nitrite, phosphate and silicate were determined on GF/F filtered water samples using a Lachat Quikchem 800 flow injection analyser and protocols based on the chemistry of Grasshof (Grasshof, 1976) as described by Ranger (Ranger, 1994).

Radiative transfer modelling

Numerical modelling of the underwater light climate was carried out using version 4.1 of the Hydrolight radiative transfer package (Mobley, 1994). Irradiance values just above the sea surface were calculated by RADTRAN, an atmosphere model supplied with Hydrolight, with appropriate date and time coordinates and realistic percentage cloud cover. The calculated irradiance spectra were

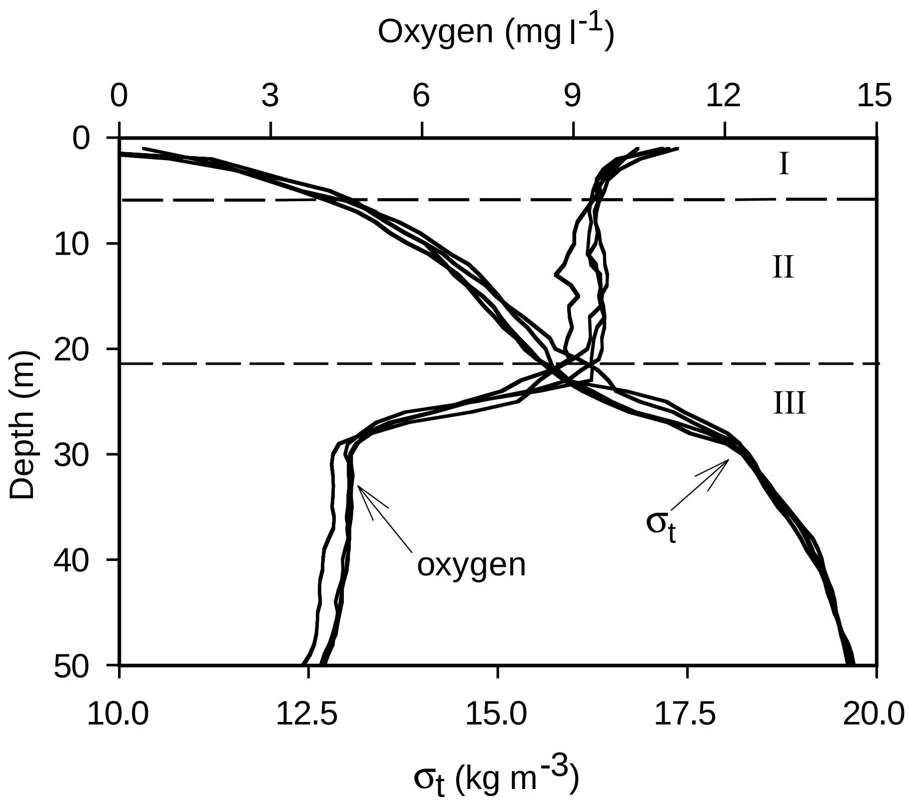

Fig. 2. Water column profiles of density (as σ_t) and dissolved oxygen concentration for four stations in the Loch Etive inner basin in March 2000, indicating the two pycnoclines and three hydrographic layers. Only the upper 50 m is plotted, but in some locations the lower layer extends down to more than 150 m.

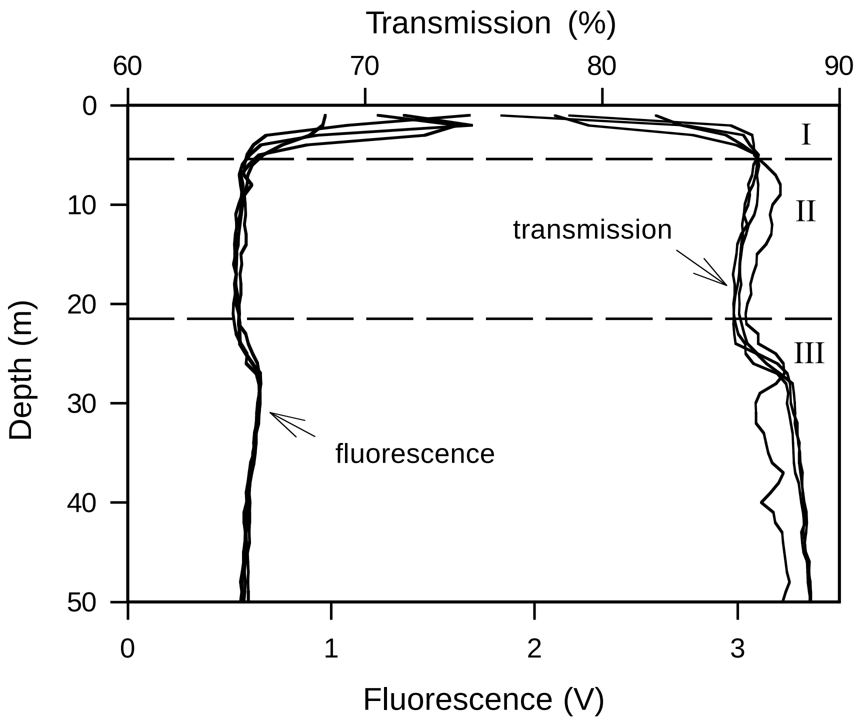

Fig. 3. Profiles of stimulated fluorescence and beam transmission at 660 nm for the stations plotted in Figure 2.

checked by comparison with the output of the Satlantic deck reference radiometer. Absorption coefficients were obtained by scaling specific absorption spectra measured on surface samples by the concentration profiles derived from fluorescence and salinity measurements. Since concentrations of suspended mineral particles are generally low in Loch Etive, scattering was assumed to originate from the phytoplankton component with a scattering coefficient determined by a power law (Loisel and Morel, 1988) and an 'average Petzold' scattering phase function (Mobley, 1994). Inelastic scattering from both CDOM and chlorophyll was taken into account using the default Hydrolight values for spectral quantum efficiencies. The radiative transfer modelling had two main purposes. One was to calculate the partitioning of absorption in the water column between the three optically significant components (water, CDOM and phytoplankton). The second was to investigate the effect of varying concentrations of CDOM and phytoplankton on the depth of the euphotic zone.

RESULTS

Hydrography

Figure 2 shows profiles of density (expressed as σ_t) and dissolved oxygen concentration for the upper 50 m of the four deepest stations in the inner basin in March. The horizontal lines on the profiles mark the approximate limits of a well defined intermediate layer with a lower boundary at ~20 m. The near-vertical slope of the dissolved oxygen curve indicates that this layer was well mixed by tidal flow over the sill at Bonawe. The water overlying the intermediate layer was characterized by strong gradients in density and dissolved oxygen. Below the intermediate layer deep water of higher density and steadily decreasing dissolved oxygen concentration extended to the bottom of the basin. The renewal of deep water in this basin is known to be intermittent (Edwards and Edelsten, 1977) and the low oxygen content and relatively high temperature of the bottom water in spring 2000 suggested that it had not been renewed since the previous summer. The differences in

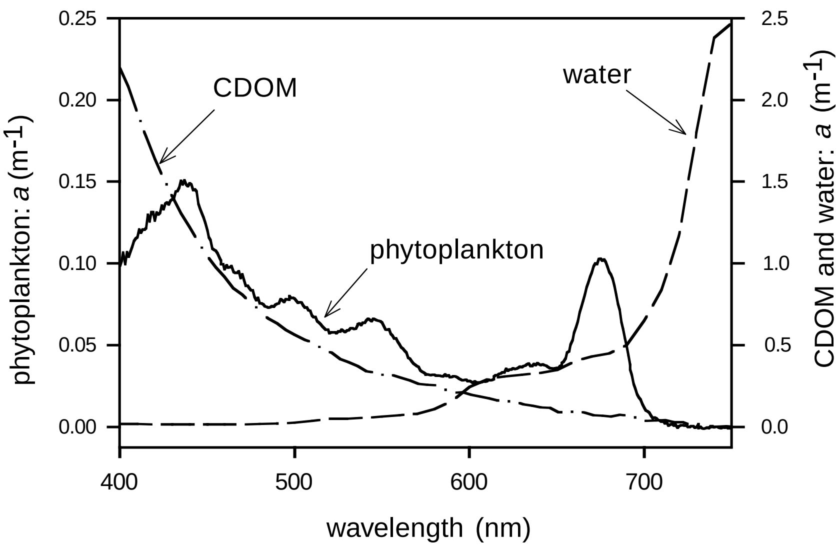

Fig. 4. Absorption spectra for the upper mixed layer in Loch Etive in March 2000. The gelbstoff spectrum was measured on 0.2 μm filtered samples, the phytoplankton spectrum on samples retained on a glass fibre filter, and the water spectrum is plotted from tabulated values.

density observed in the water column were due to lowered salinity rather than to thermal stratification. In March, for example, the surface water had an average salinity of 10 psu while the deepest water reached 27 psu, but the deep layer was actually 5°C warmer than the surface. In April, renewal of the deep water in the upper basin had begun, and the well-mixed intermediate layer extended down to 55 m. However, in spite of unusually high winds the reduced salinity surface layer remained as a well-defined feature of 4–5 m depth. Figure 3 shows profiles of fluorescence and beam transmission for the stations illustrated in Figure 2. The two signals were generally well correlated and the magnitude of both increased sharply in the surface layer where the highest chlorophyll concentrations were found. Two of the March stations showed low ratios of fluorescence to scattering just below the surface, suggesting that even in early spring there was enough light to induce significant quenching of induced fluorescence.

Water composition

Basin-average characteristics of the water column at depths of 2, 10 and 40 m are summarized in Table I. Chlorophyll concentrations in the surface layer were in the range 3.5–8.5 mg m^{-3} in both March and April while CDOM concentrations, measured as a_{440}, varied from 1.2 m^{-1} to 1.4 m^{-1}. The Loch Awe outflow which is the major source of fresh water for Loch Etive had a CDOM (a_{440}) attenuation of 1.86 m^{-1}. Levels of the three major inorganic nutrients appeared to be non-limiting in both

Table I: Typical characteristics of the upper water column in the Etive inner basin in March (M) and April (A) 2000

Depth m	Pigment mg m^{-3}		CDOM A_{440}, m^{-1}		PAR μE m^{-2} s^{-1}		$NO_3 + NO_2$ μmol l^{-1}		SiO_4 μmol l^{-1}		PO_4 μmol l^{-1}	
	M	A	M	A	M	A	M	A	M	A	M	A
2	4.0	9.6	1.0	0.7	56	89	4.8	3.4	9.4	4.1	0.2	0.1
10	0.5	9.4	0.8	0.6	1	2	4.7	4.3	10.2	4.6	0.4	0.1
40	0.7	1.7	0.6	0.6	0	0	5.8	6.5	17.7	10.0	1.1	0.4

Irradiance measured in air around midday was 375 μE m^{-2} s^{-1} in March and 584 μE m^{-2} s^{-1} in April.

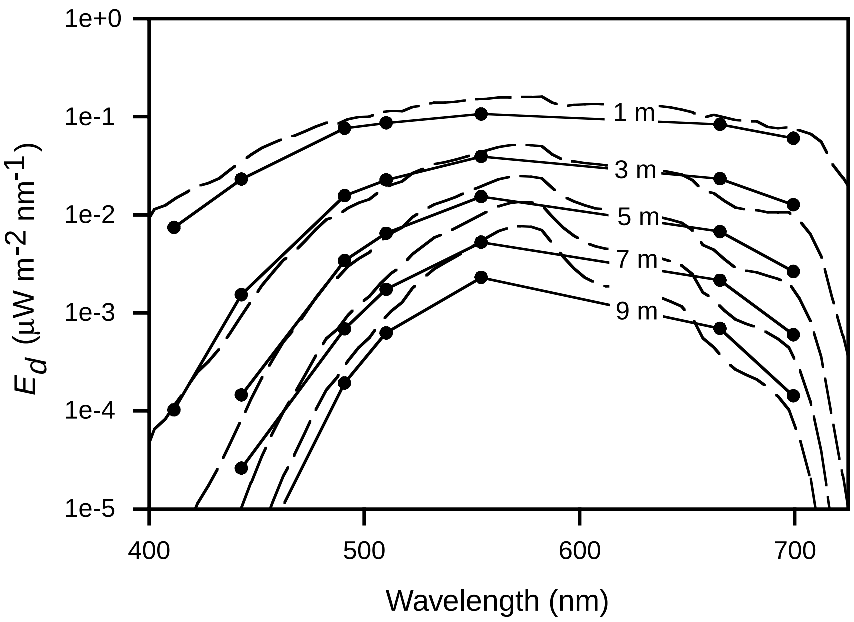

Fig. 5. Downward irradiance spectra for RE4 in March 2000 measured with a 7-waveband profiling radiometer (solid lines and symbols) with the output of the radiative transfer model (broken lines) superimposed.

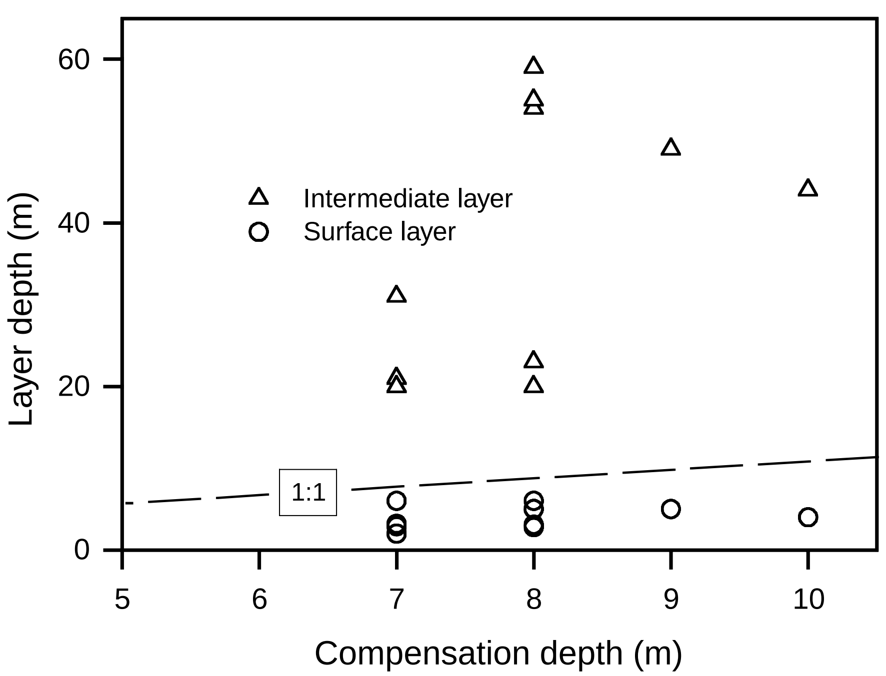

Fig. 6. Lower boundaries of the surface and intermediate hydrographic layers plotted against the compensation depth (taken to be the point at which PAR falls to 1% of its air value) for Loch Etive in March and April 2000. The broken line indicates equality between layer depth and compensation depth.

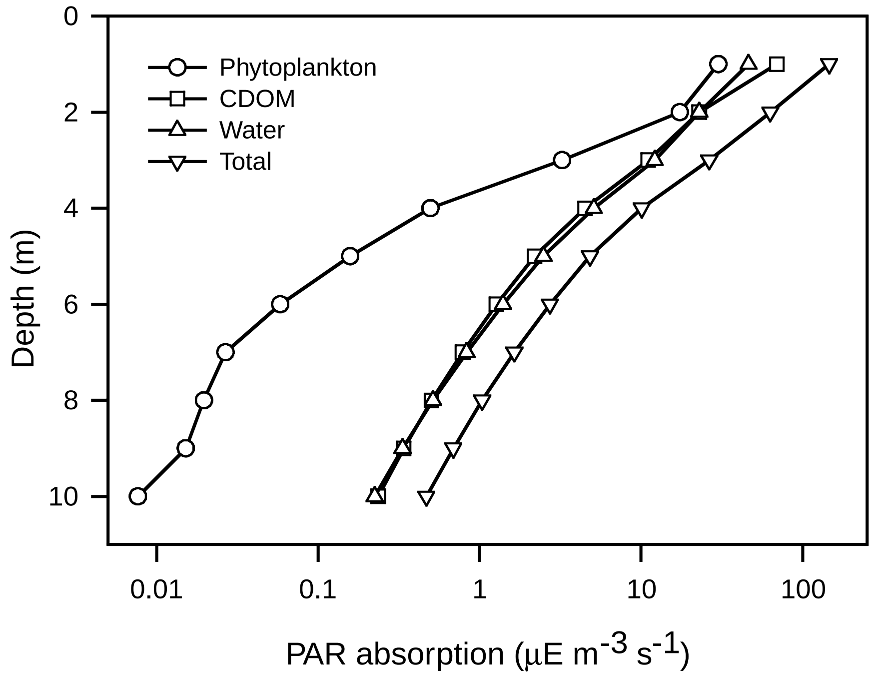

Fig. 7. Calculated profiles of PAR absorption in the upper 10 m of RE4. For this station, PAR fell to 1% of the air value at 7 m.

March and April, but they were lowest in the surface layer and by the end of April phosphate was close to depletion near the surface.

Absorption coefficients

Typical spectral absorption coefficients for the three main optical contributors to PAR attenuation (water, CDOM and phytoplankton) in the surface layer in March are shown in Figure 4. The water spectrum is plotted from values published by Pope and Fry (Pope and Fry, 1997) while the gelbstoff and phytoplankton curves were measured on samples of surface water containing 8 mg m^{-3} Chl *a* plus phaeopigment and 1.4 m^{-1} (a_{440}) gelbstoff. The chlorophyll-specific absorption coefficient (a^*) at 675 nm was therefore 0.034 m^2 mg^{-1}, rather higher than the value of 0.02 m^2 mg^{-1} for oceanic phytoplankton quoted by Morel and Prieur (Morel and Prieur, 1977). The phytoplankton spectrum shows chlorophyll absorption bands in the blue and red regions with well defined subsidiary peaks between 500 and 600 nm and is quite different from that generated by typical diatoms but consistent with an early bloom of cryptophytes or cyanophytes. The 550 nm peak corresponds to the absorption maximum of phycoerythrobilin, while the peak at 500 nm could be due to phycourobilin or to a carotenoid (Jeffrey *et al.*, 1997). Figure 5 illustrates how CDOM-dominated blue absorption and water-dominated red absorption combine to produce the characteristic yellow–brown colouration of reflected and transmitted light in sea lochs, and also indicates the significance of accessory pigment absorption in the wavelength region which has the greatest depth of water penetration.

Irradiance and PAR

Downward irradiance spectra (E_d) measured by the SPMR on March 30th at station RE4 together with the output of the Hydrolight model for this station are illustrated in Figure 5. The model shows generally good agreement with the data, indicating that it can be used as a basis for further calculations of absorption and PAR attenuation. At midday in April, PAR measured 1 m below the surface had a value of 130 μE m^{-2} s^{-1}. Kiefer (Kiefer, 1994) and Kirk (Kirk, 1994) quote values in the range 100–140 μE m^{-2} s^{-1} for the onset of saturation in the photosynthesis–irradiance relationship of typical coastal phytoplankton. The surface layer would therefore appear to be capable of sustaining high photosynthetic rates.

Relative depths of euphotic zone and upper layer

The lower limit of the euphotic zone (the compensation depth) is usually defined as the depth at which PAR falls to 1% of its value just beneath the surface. However in

Loch Etive, the diffuse attenuation coefficient for PAR is typically 0.3–0.4 m^{-1}, and the radiometer would have to be held very close to the surface to obtain accurate subsurface values. This is difficult to achieve in the presence of even modest waves, particularly with a free-fall instrument such as the SPMR. Consequently, we have assumed that the bottom of the euphotic zone can be approximated by the depth at which PAR falls to 1% of the value measured in air by the deck reference radiometer. Examination of the Loch Etive optical model suggests that this approximation is within 1.5 m of that calculated using the subsurface value. The approximate compensation depth obtained in this way also appears to be consistent with physiological criteria. For example, in March around midday 1% of PAR measured in air was 3.8 μE m^{-2} s^{-1}, which is close to the figure of 4 μE m^{-2} s^{-1} quoted by Kirk (Kirk, 1994) for coastal phytoplankton. The position of the lower boundary of the surface and intermediate layers for all stations occupied in March and April is plotted against the measured compensation depth in Figure 6. It can be seen that the surface layer lay entirely above the compensation depth in all cases, while the intermediate layer extended to at least twice the compensation depth. On average, the 1% PAR depth penetrated into the top 16% of the intermediate layer.

Photon partitioning

The contribution of individual components to the absorption of diffuse light in the water column is proportional to their absorption coefficients (Kirk, 1994). It is possible therefore to calculate the fraction of visible photons absorbed by water, CDOM and phytoplankton in a given increment of depth by dividing the total attenuation of scalar irradiance in that increment by the relative absorption coefficients of the three components. The results of this procedure for the radiative transfer calculation for RE4 are illustrated in Figure 7. Integration of the absorption curves down to 10 m indicates that phytoplankton were responsible for 20% of the total absorption of PAR, gelbstoff absorbed 44% and water 36%. This is consistent with the suggestion by Kirk (Kirk, 1994) that phytoplankton in coastal waters capture between 8 and 27% of PAR. However, the percentage figures mask the significance of the reduction in the depth of the euphotic zone for phytoplankton growth in a stratified water column.

The radiative transfer model allows quantitative exploration of the sensitivity of the compensation depth to changes in seawater composition. If the chlorophyll concentration profile of RE4 were preserved but all CDOM was removed from the water column, the compensation depth would increase from 7 to 38 m. On the other hand, if the existing CDOM profile was retained and the chlorophyll removed the compensation depth would only extend down to 11 m. In the event of a major bloom raising phytoplankton concentrations to 40 mg m^{-3} in the surface layer, a realistic value for some sea lochs (Tett *et al.*, 2001), the euphotic depth would be reduced to 2 m.

DISCUSSION

The high flow of fresh water into Loch Etive had a marked influence on both the stratification of the water column and the depth of penetration of visible light. From the point of view of the ecosystem of the inner basin, these two effects combined to strongly limit spring primary production. Light and nutrient levels in the surface layer were sufficient to sustain active phytoplankton growth in early spring, but the short residence time of the surface water meant that most of this production would be exported to the outer basin. Moreover since the surface layer was rarely >5 m deep, phytoplankton held in this layer were unable to benefit from the full euphotic zone. On the other hand the intermediate layer was mixed to well below the compensation depth, so that any entrained phytoplankton cells were light-limited and unable to utilize the plentiful supply of inorganic nutrients in this layer. Variations in the stratification regimes and mixing depths in basins of this type would have interesting consequences for phytoplankton growth, and this topic is worthy of further exploration. However, the single most obvious factor limiting production in Loch Etive was the high CDOM content of the fresh water run-off. Radiative transfer calculations indicate that if CDOM concentrations in the surface layer were reduced to ~0.2 m^{-1} (a_{440}) then the euphotic zone would have extended to the bottom of the intermediate mixed layer in March and conditions would have been favourable for substantial growth of the phytoplankton population.

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