Operational Oceanography. The Challenge for European Co-operation
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The Integrated North Sea Programme (INP)

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We present detailed (hourly sampled) bio-optical and physical data from an extensive (27 months in four years) mooring programme in the central North Sea (Oyster Grounds). The purpose of the programme was a detailed study on the variability of phytoplankton abundance and the, possibly associated, impact of vertical exchange by atmospheric disturbances across the (seasonal) thermocline. After this campaign, we conclude that sophisticated moorings are not yet adequate for long-term, routine oceanographic monitoring purposes, as the instruments generally need too much attendance by regular in-situ calibration and servicing (at least once a month). The data analysis showed that no observational evidence has been found for the spring bloom to enhance the (onset of) stratification or vice versa for the stratification to favour the spring bloom.

Instead, a spring bloom is found before the stratification becomes well established and, prior to that, a subtle dependance of the evolution of the spring bloom has been found on the turbulence intensity in the water column. From a numerical model, in which we used the observations for initiaition and verification, it became clear that the timing of the onset of stratification is critical for the entire growth season. In summer no sub-surface maximum in chlorophyll was observed at our mooring site, because sufficient irradiation reached to the bottom. Despite the strong stratification, a bloom developed after a strong (convective) mixing event in late summer, and another one also prior to that, probably after internal mixing events induced by strong current shear across the pycnocline, although the role of horizontal advection could not be ruled out entirely.

1. THE PROGRAMME

Although the North Sea is claimed to be one of the marine ecosystems most intensively studied ever, detailed descriptions of the seasonal cycle of phytoplankton are limited. Most studies are based on sampling insufficient to resolve even the main features of the annual cycle or on measurements in coastal stations close to marine laboratories and therefore not representative for the offshore environment. Until the end of the eigthies, the technology of oceanographic instrumentation prevented a comprehensive data set from being constructed, because moorable instruments capable of measuring biological parameters were not available.

In July 1991 the Integrated North Sea Programme (INP) was launched to carry out an extensive field study to establish properly the variability of phytoplankton abundance in the central North Sea (water depth ~50 m) covering a full annual cycle. In contrast with shallower parts of the North Sea, which are well-mixed from surface to bottom throughout the year, this part of the North Sea becomes stratified in spring, after a period of sufficient insolation, which lasts through the summer (Figure 1). In this area the water depth exceeds the sum of the depth of a wind and convectively mixed near-surface layer (typically 10-20 m) and that of a tidally mixed near-bottom layer (typically 10-30 m, depending on the current speed).

At the start of the programme, the general idea was that the onset of a phytoplankton bloom in spring will not occur before stratification is established and the surface mixed layer is shallower than the critical optical depth [*1*]. For the open ocean on the other hand, some researchers predicted a spring bloom prior to the onset of stratification [*2*].

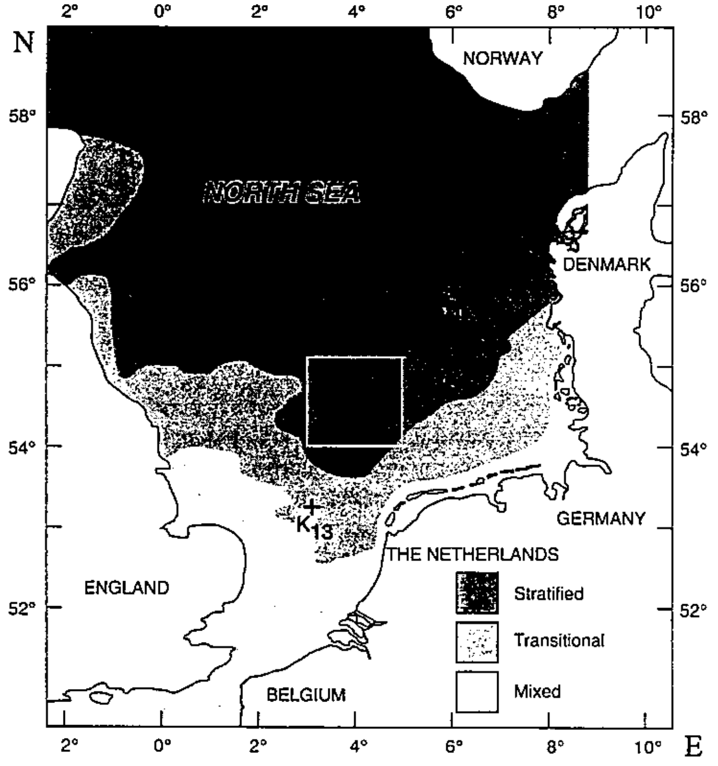

Figure 1. Map of the INP research area (rectangle), the mooring site (•) and the platforms K_{13} and AUK for meteorological data superposed on a general indication of the summer stratification extent.

For the summer one assumed that in the central North Sea the two well-mixed layers are separated by a sharp and thin density jump (pycnocline), which acts as a barrier for vertical exchange of solutes (Figure 2A). As nutrients are to be supplied mainly from the bottom mixed layer, such physical system implies, under the assumption that the critical optical depth is not larger than the local water depth, a bottom mixed layer which is relatively light limited and a surface mixed layer which is relatively nutrient limited. Then, the maximum amount of phytoplankton is to be found not in the photic zone proper, but rather near the pycnocline, i.e. roughly in the middle of the water column.

The main aim of INP was to verify this concept and to study the influence of atmospheric disturbances on the vertical exchange across the pycnocline. It was expected that such diapycnal mixing events and the associated short-term bursts of fluxes of nutrients (and perhaps phytoplankton) between the near-bottom and the near-surface mixed layers would happen irregularly in time, and might have longer-term impact on the pelagic biology, especially the phytoplankton species composition, abundance, productivity and sedimentation.

In addition, further aims of the project were to use newly developed moorable instruments to sample the relevant physical, biological and chemical data over long periods of time (up to a periods of time (up to a year) and at a sufficiently high rate (at least once an hour). This provided a test for future long-term unmanned oceanographic monitoring. Finally, the data should be used to initiate and calibrate a new coupled model for the lower trophic levels in the pelagic system.

2. LOGISTICS AND TECHNOLOGY

The INP mooring site is located in the central North Sea, Oyster Grounds, at 54° 25' N and 04° 02' E, where the waterdepth is about 45 m (Figure 1). The location is well within the region of seasonal (thermal) stratification. The site has been chosen with care to be well away from frontal zones marking the transition between stratified and totally mixed waters. Nevertheless, frontal meandering and the advection of patches of phytoplankton and suspended matter were detected at times during the study, thereby complicating the analysis.

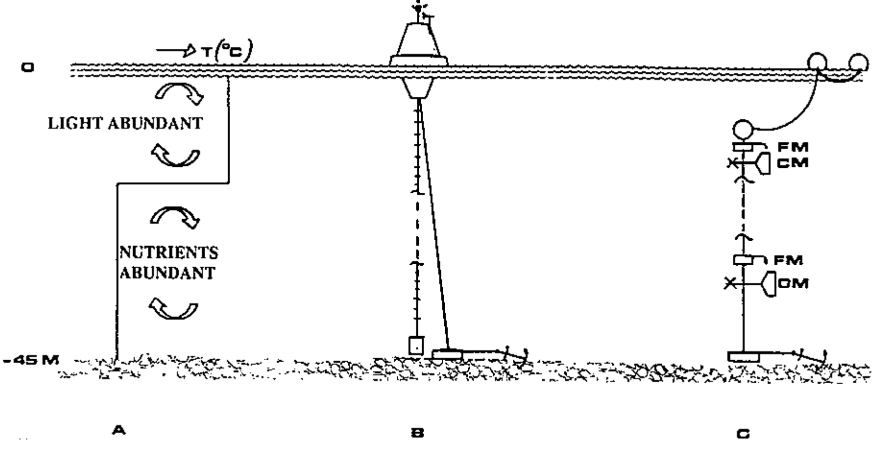

Figure 2. Schematic of the types of mooring used during INP and a sketch of the "classic" two-layer stratification, indicated by the temperature profile as a function of depth in A. B. Surface mooring with meteorological data buoy and thermistor strings. C. general mooring with current meters (CM) and fluorometers (FM).

Sedimentologically, the area may be characterized as a temporal depocentre where sediment may be deposited during periods of calm weather and, especially in winter, erosion prevails during stormy periods [3].

The site has been studied between July 1991 and February 1995, with instruments in place during about 29 months. In 1991 the summer period has been covered, in 1992 the late winter and summer periods, in 1993 the spring period (with bad data return) and from november 1993 onward the site has been occupied for fifteen consecutive months. In 1991 every two weeks, and, lateron, at least once a month the mooring site was visited by the R.V. Pelagia (owned by the Netherlands Institute for Sea Research, NIOZ) or the R.V. Holland (from the Dutch tidal waters divsion, Directorate fpr the North Sea, RWS-DNZ) for instrument servicing and additional sampling for calibration and hydrographic purposes.

Moored self-contained instruments were to sample physical parameters (oceanographical, current, density (temperature), radiation as well as meteorological) and bio-geochemical parameters (chlorophyll-a, nutrients, suspended matter). This data acquisition required some techniques recently developed (especially for bio-optical and acoustic instruments) and technology development (in-situ nutrient auto analyzers). Adopting the two-layer model for the stratified water column, the mooring of two instruments of every type is at minimum, when one instrument is moored in the near-surface layer and the other in the near-bottom mixed layer.

During the full period of the study the water temperature was monitored at every 2 m from surface to bottom using coupled thermistor strings suspended from a surface buoy (Figure 2). All other moorings contained a sub-surface buoy that became moored at a depth of about 10 m to avoid too severe wind-induced current and wave action, typical for the North Sea, thereby omitting the monitoring of the upper 12 m of the water column. From early 1994 onward, after a grant from the Netherlands Organiziation for the advancement of Scientific Research (NWO), the instrumentation became more suitable for the aim of the study as it was supplemented, a.o., by Acoustic Doppler Current Profilers (ADCP) which can sample all three velocity components every 0.5 m between 3 m above the bottom and about 7 m from the surface, a wave-tide recorder, moorable transmissometers, additional fluorometers and in-situ nutrient (NOx) auto analyzers.

The sampling rate varied from once per minute (ADCP) to once per hour (optical instruments), so that a hitherto unachieved detailed set of data was obtained spanning long periods of time. Although relevant biological time scales typically are about one day, and largest forcing is expected on synoptic scales of one to five days, the relatively high sampling rate was needed to resolve (internal) tidal effects. The fast sampling of the ADCP was used in an attempt to estimate directly vertical fluxes of matter and momentum, but due to the problems with this instrument only a limited span of time became covered with good data.

Similarly, the additional development and the many troubles, which needed to be solved during the study, resulted in little good data harvest from the in-situ nutrient auto analyzers. Overall, the loss of data amounted for the moored instruments about 30%, of which some 10% was due to complete mooring and/or instrument loss. Due to bad weather conditions about half of the hydrographic surveys scheduled could not be completed.

The general conclusion after the field study was that such sophisticated moorings are not yet adequate for long-term, routine oceanographic monitoring purposes, as most instruments need too much attendance by regular in-situ calibration and servicing. Instruments measuring physical parameters may remain unattended for a period of a year (thermistor string, ADCP) or three months (current meters, meteorological instruments). Biological parameters can be obtained without servicing and in-situ calibration data for two to four weeks (bio-optical instruments), whereas almost permanent attendance is, still, needed for instruments measuring chemical parameters such as nutrients.

3. MODELLING

A reduced set of daily averaged observations has been invoked to initiate and calibrate a one-dimensional integrated ecosystem model, which was forced with meteorological and current data measured at the INP site. The purpose of the modeling was to further unravel the relevant factors contributing to phytoplankton dynamics during the annual cycle.

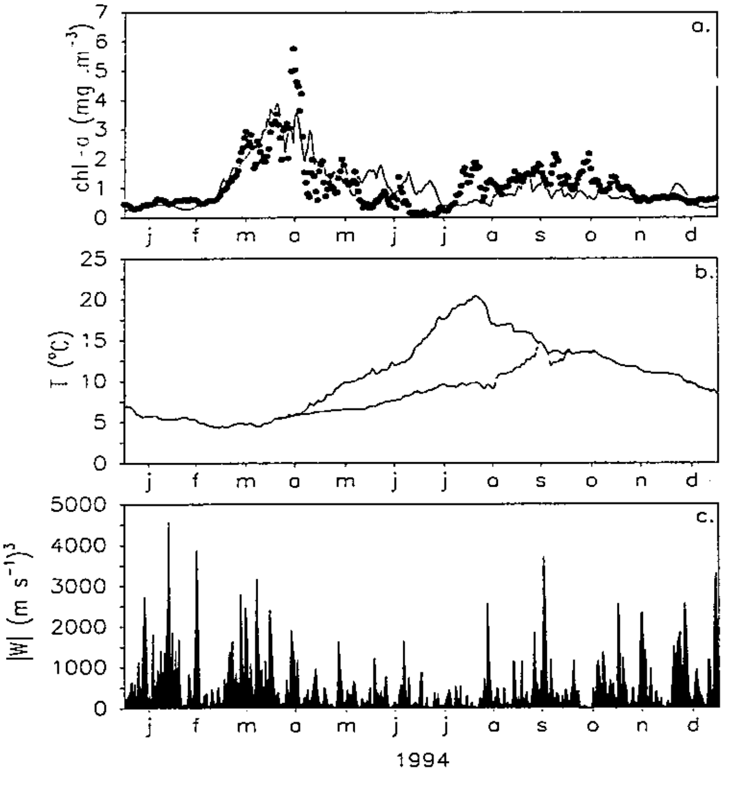

Figure 3. Some of the year long 1994 data. a. chlorophyll at 13 m depth from fluorescence data (dots) and from the numerical model (solid line). b. Temperature measured at 2 m from the surface (solid line) and at 2 m from the bottom (dashed line). c. Wind speed (cubed) measured at AUK.

In the physical submodel a vertically integrated mixed layer model is used in which the exchange between the surface and bottom layers and the (initially non-turbulent) pycnocline is governed by en-/detrainment [*4,5*]. After calibration some background diffusivity had to be invoked for the pycnocline in order to simulate the gradual increase of temperature in the near-bottom mixed layer [*6*]. By its one-dimensional nature, horizontal advection is not accounted for in the model.

The rather sophisticated ecosystem component, which has been based upon the European Regional Seas Ecosystems Models (ERSEM), describes biological and chemical processes in the water column as well as in the sediment and consists of nine functional groups to describe pelagic biology, ranging from bacteria to carnivorous zooplankton [*7*]. The dynamics of chemical variables like nutrients are fully coupled to the biologically driven processes. Early diagenetic transformations and fluxes of organic matter and nutrients in the sediment and across the sediment-water interface are included explicitly.

4. RESULTS

The 1994 yearlong series of near-surface chlorophyll-a (chl-a), as extracted from fluorescence observations is shown in Figure 3, along with the variation with time of the thermal stratification and the wind speed (cubed). The familiar two phytoplankton blooms per year are seen, one in spring and the other in late summer/early autumn. The spring bloom develops before stratification becomes established, and the summer bloom clearly starts out while the water column is still strongly stratified and no strong wind events occur. Observed and modelled winter chl-a levels of 0.5 ± 0.1 mg m^{-3} are above background level (0.1 mg m^{-3}).

Detailed data analysis, fuelled by the numerical model results, shows that indeed the spring bloom disappears from the near-surface layer as soon as the stratification becomes solidly established. It shows, however, also a dependence of the chl-a distribution on the turbulence intensity in the water column prior to stable stratification, as is inversely inferred from, short-lived, weakly stratified periods during which the near-surface values of chl-a decrease at the expense of increasing near-bottom values (Figure 4).

The spring bloom starts around the beginning of March, as soon as light penetrates 10-15 m deep. The bloom comprises basically relatively heavy plankton species, *i.e.* mainly diatoms, as is inferred from the negligible phase differences between stratification rate and the rate of chl-a variation with time. The full use of available nutrients and the extent of the bloom in this time of the year thus depend on subtle variations in time between short periods of stratification, when diatoms and suspended matter sink to the bottom and the water column becomes clearer, and short periods of mixing, by which diatoms are brought back into the photic zone. Details are given in [*8*].

No observational evidence has been found for the spring bloom to enhance the (onset of) stratification, which seems typical for the open ocean. No evidence has also been found for the opposite situation, in which the stratification favours the spring bloom, which seems typical for shallow seas like the central North Sea. The analysis does show that the turbulence intensity critically influences the growth and that the spring bloom declines as soon as the stratification becomes well established (Figure 4). As a curious result, one could use phytoplankton as an indicator for the turbulence intensity in the water column.

The numerical model further showed the important role of the background light extinction in the water and the implications of the timing of the onset of the stratification, not just for the spring bloom, but also for the plankton growth in the rest of the year. It became clear that variations in this timing have major consequences for the production and the succession of the different plankton species and the structure of the pelagic food web during the entire growth season. A different timing of the onset of stratification implies a different ratio of the main phytoplankton species (e.g. diatoms vs flagellates) developing during spring and, accordingly, a different amount of sedimenting diatoms and thus differences in the availability of nutrients in the mixed layers.

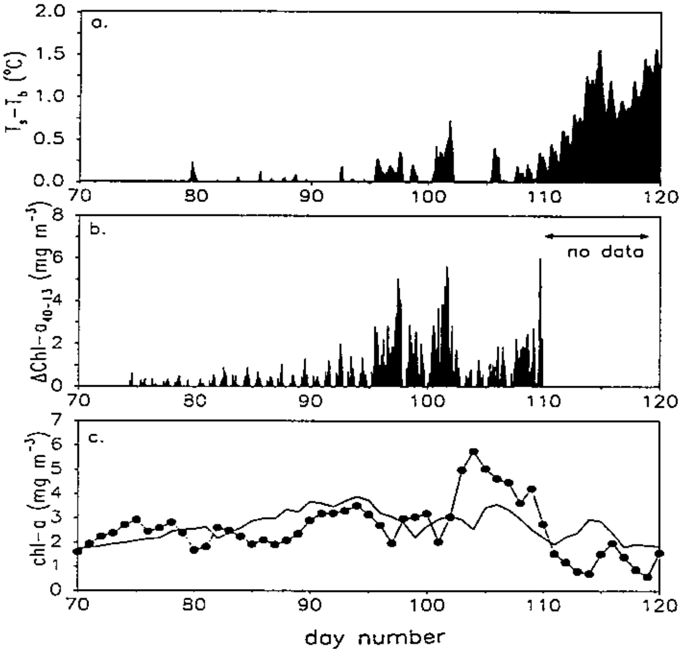

Figure 4. Spring 1994. a. Hourly averaged observed water temperature difference between 2 and 43 m depth. b. Hourly averaged observed chl-a difference between 40 and 13 m depth. c. Daily averaged chl-a at 13 m as observed (dots/line) and modelled (solid line).

Temperature observations made in 1994 show a multiply layered water column over most of the summer suggesting limited nutrient input from the near-bottom mixed layer, and yet, a summer bloom initiation during that period (Figure 5). This may have been due to horizontal advection as the hydrographic survey at the time showed strong frontal activity. On the other hand, from the ADCP data it became clear that the stability of the water column in terms of Richardson number frequently became critical during that period, due to strong current shear across the pycnocline induced by indirect atmospheric effects, i.e.

inertial oscillations. Some support for exchange across the pycnocline, though statistically barely significant, was provided by the observations of periods of enhanced vertical matter fluxes as directly estimated from the ADCP data.

The early summer bloom was not confirmed by the numerical model, which simulated only a late summer bloom some three weeks later, when after a strong wind event the multiple layers reduced to a sharp and thin pycnocline and the classic two-layer system became established (Figure 5c). This discrepancy between model and observations is explained by the

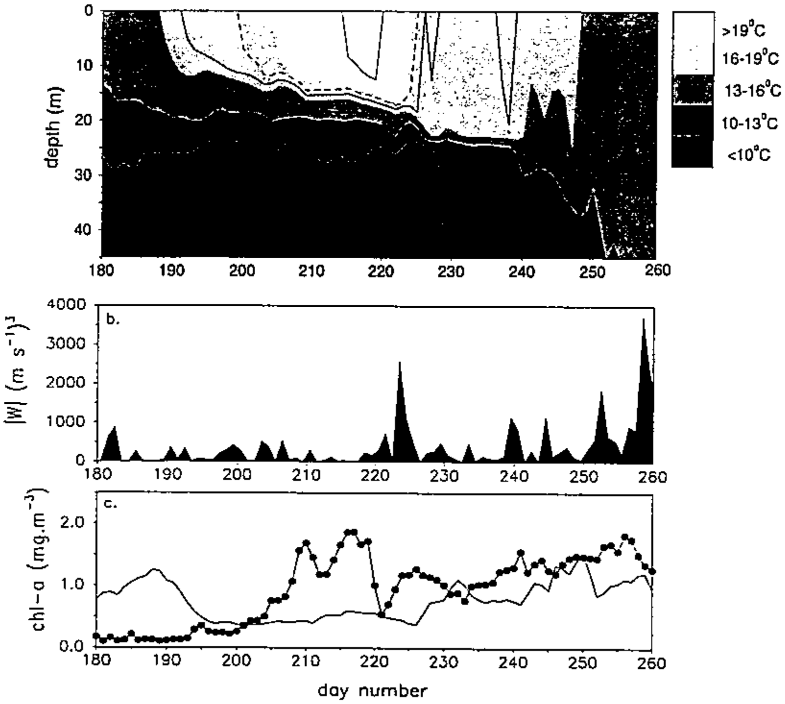

Figure 5. Summer 1994. a. Daily averaged isotherms, as inferred from temperature data, and drawn every 1 °C between 9 °C and 20 °C. b. Wind speed (cubed) measured at AUK. c. Chl-a at 13 m from observations (dots) and the model (thick solid line).

lack of the physical mechanism causing increased vertical mixing in the model, and possibly, by the role of horizontal advection. Nonetheless, from both the model and the observations atmospherically induced exchange has been inferred across the pycnocline during late summer. The development of the late summer bloom is more strongly governed by convective mixing rather than wind mixing, as has been found after examination of the 1991 and 1992 observations.

From the 1994 observations it was also concluded that light is not limiting phytoplankton production in the near-bottom layer during summer. At the INP location no, or just weak, sub-surface maxima in chl-a content are found near the pycnocline. Prior to the onset of the late summer bloom, the highest concentrations of chl-a are found evenly distributed over the entire near-bottom mixed layer. This has been supported by the outcome of the numerical model (Figure 6).

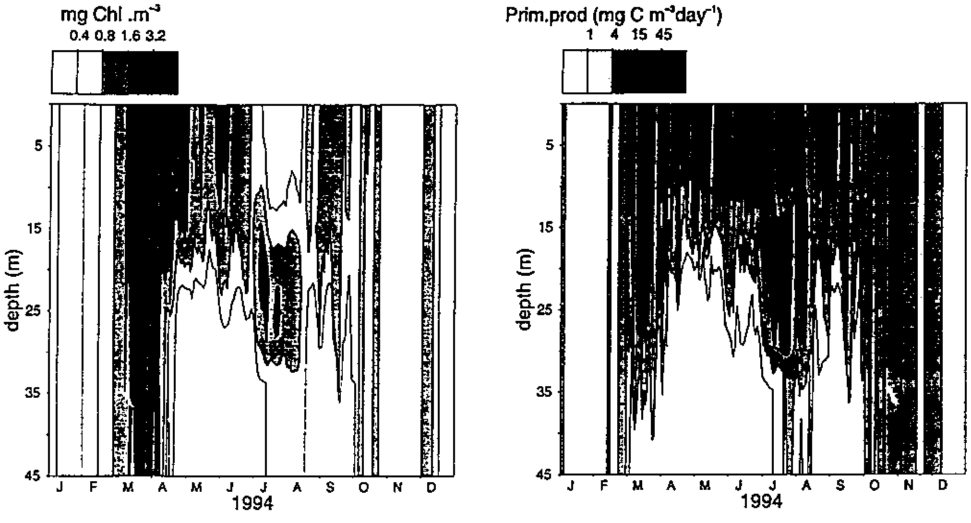

Figure 6. a. Simulated vertical distribution of chl-a in 1994. Note that only during spring a sub-surface chl-a maximum is found. b. Simulated vertical distribution of primary production in 1994, which shows a maximum near the pycnocline during summer.

5. CONCLUSIONS

- Sophisticated moorings are not yet adequate for long-term, routine oceanographic monitoring purposes, as the instruments generally need too much attendance by regular in-situ calibration and servicing.
- No observational evidence has been found for the spring bloom to enhance the (onset of) stratification or vice versa for the stratification to favour the spring bloom. Instead, a spring bloom is found before the stratification becomes well established and, prior to that, a subtle dependance of the evolution of the spring bloom has been found on the turbulence intensity in the water column. The timing of the onset of stratification is critical for the entire growth season.
- In summer no sub-surface maximum in chl-a was observed at INP, because sufficient irradiation reached to the bottom. Despite the strong stratification, a bloom developed after a strong (convective) mixing event in late summer, and another one also prior to that, probably after internal mixing events induced by strong current shear across the pycnocline, although the role of horizontal advection could not be ruled out entirely.

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