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# Whipped and Mixed Warm Clouds in the Deep Sea

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**Abstract** Turbulence is indispensable to redistribute nutrients for all life forms larger than microbial, on land and in the ocean. Yet, the development of deep-sea turbulence was not studied in three dimensions to date. As a disproportionate laboratory, an array of nearly 3,000 high-resolution temperature sensors had been installed for three years on the flat 2,500-m deep bottom of the Mediterranean Sea. The time series from the half-cubic hectometer mooring-array allows for the creation of unique movies of deep-sea water motions. Although temperature differences are typically 0.001°C, variable convection-turbulence is observed as expected from geothermal heating through the flat seafloor. During about 40% of the time, an additional turbulence, 3 times stronger in magnitude, is observed from slantwise advected warmer waters to pass in turbulent clouds. Besides turbulent clouds and seafloor heating, movies also reveal weakly turbulent interfacial-wave breakdown that commonly occurs in the open ocean far away from boundaries.

**Plain Language Summary** Without deep-sea turbulence, life as we know it would not exist. Developments of deep-sea turbulent motions were studied using a three-dimensional array of nearly 3,000 high-resolution temperature sensors. The array was installed on the flat 2,500-m deep bottom of the Mediterranean Sea for three years. The temperature data allow for the creation of unique movies of deep-sea water motions. The movies show 0.0001°C temperature differences in "flames" of up to 100-m tall due to geothermal heating through the seafloor. During about 40% of the time, 3 times stronger turbulence is carried by warmer-water clouds from above and sideways. Besides turbulent clouds and seafloor heating, movies also reveal 3–10 times weaker small internal-wave breaking that commonly occurs in the open ocean far away from boundaries.

## 1. Introduction

Below the wind-agitated sea surface, the sea waters are not quiescent but also constantly in motion. These ocean-interior motions occur on a wide variety of scales, from several hundred kilometres large-scale circulations via tens of kilometres "mesoscale" eddies to tens of meters turbulent overturns that eventually lose their energy at millimeter scales. One of the major contributors to ocean-interior motions are internal waves, which are largely driven by stable vertical density stratification of generally warm, fresh waters above cooler, saltier waters. In contrast to waves at the ocean surface, internal waves propagate in three dimensions (3D) including into the deep ocean (LeBlond & Mysak, 1978). Major sources of internal waves are tides and (near) inertial motions. The latter are remainders from the passage of atmospheric disturbances, deflected by the Earth's rotation. Commonly, freely propagating internal waves can exist between the inertial frequency and the buoyancy frequency, which is related to the stratification. Internal waves transfer their energy to irreversible turbulence when they deform and break. Deep-sea turbulence is mostly generated by internal-wave breaking at steep seafloor topography (Eriksen, 1982; Thorpe, 1987).

Turbulence is of high interest as it is an enabling factor for life for the spread of oxygen and nutrients. However, precise development of turbulence in 3D is difficult to study, one reason being that it extends over many orders of magnitude. In the deep sea, turbulence is commonly studied using instrumentation attached to a single line that is lowered from a ship or moored at the seafloor, thereby limiting the observations to 1D.

In this paper, year-long observations are presented from a custom-made, 45-line mooring-array with densely spaced high-resolution temperature "T"-sensors to monitor nearly half-a-million cubic meters of deep-sea waters. The array was deployed in the Western Mediterranean at a flat seafloor of 2,458-m water depth, in the vicinity of the under-water cubic kilometer neutrino telescope KM3NeT/ORCA off France (Adrián-Martinez et al., 2016). Tidal energy is low in this part of the Mediterranean, but alpine winds regularly induce near-inertial waves. These internal waves can combine with mesoscale eddies along with a distinct all-year round boundary waterflow,
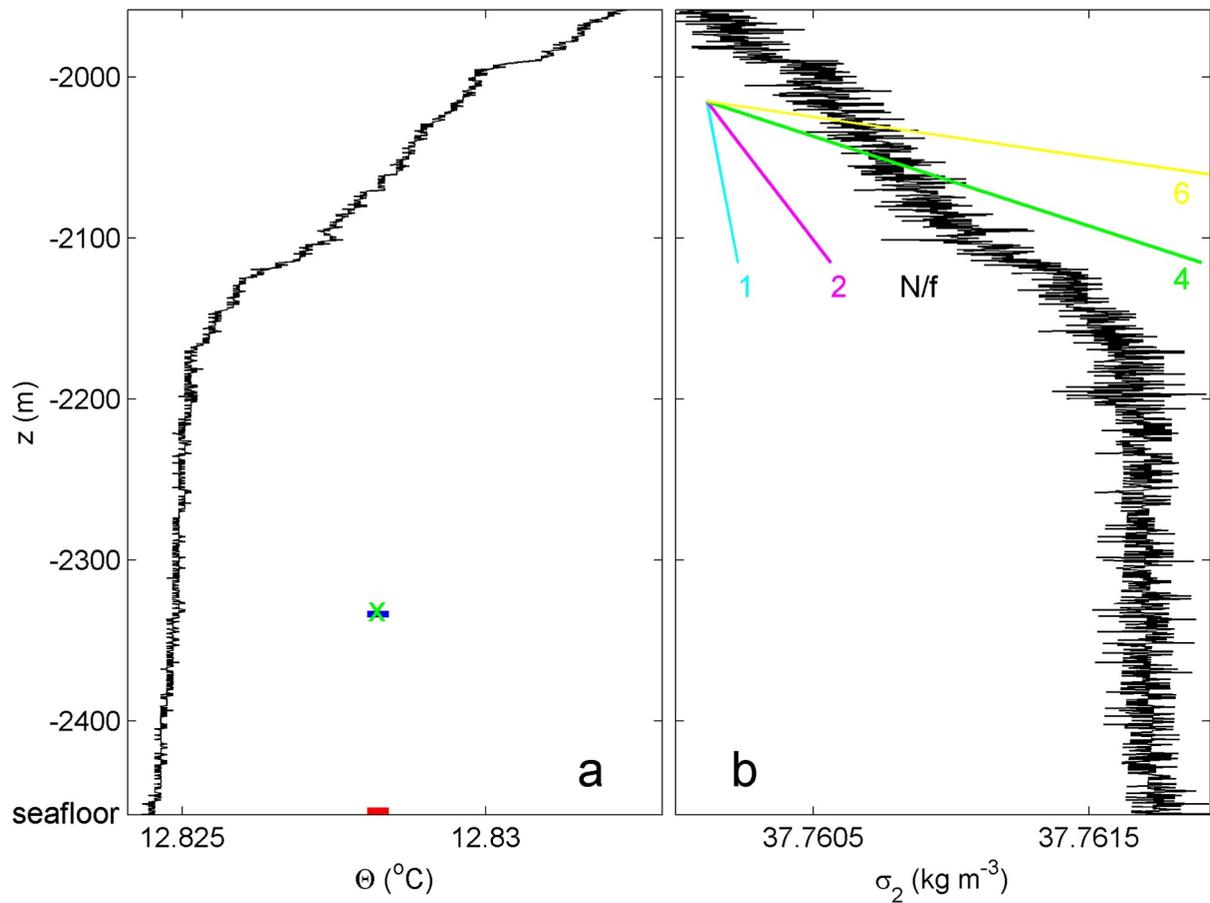
**Figure 1.** Lower 500 m of single shipborne Conductivity Temperature Depth profile measured within height $h = 0.5$ m above seafloor, about 1 km from the large-ring mooring site during the deployment cruise in 2020. Small color bars in panel (a) indicate heights of uppermost (blue) and lowest (red) T-sensors in a mooring line, and the green cross the height of current meters. (a) Conservative Temperature (IOC et al., 2010). (b) Density anomaly $-1,000$ kg m$^{-3}$ referenced to a pressure level of $2 \times 10^7$ N m$^{-2}$. The color lines refer to slopes of different levels of 100-m vertical density stratification, and indicate the ratio of "$N$" buoyancy over "$f$" inertial frequency.

stronger in winter (Crepon et al., 1982; Gascard, 1978; Taupier-Letage & Millot, 1986; Testor & Gascard, 2006). Of the expected vertical transport processes in the area, deep dense-water formation due to the potentially highly turbulent sinking of unstable cool surface waters is known to occur, but is rare at decadal scales (Mertens & Schott, 1998). Thus far, it has never been observed directly (Thorpe, 2005). However, eddies (Testor & Gascard, 2006) and near-inertial and high-frequency nonlinear internal waves (van Haren et al., 2014) that generate turbulence upon breaking may transport heat downward. This heat transport from above may mask turbulent geothermal heating (GH) through the seafloor from below. Previous shipborne observations have suggested that GH generates about twice as energetic turbulence than internal-wave breaking for the entire Northwestern Mediterranean (Ferron et al., 2017).

Materials and methods are in Supporting Information S1. Data from the 3D mooring-array allow for two major advancements in the study of turbulence: (a) Statistics of nearly 3,000 independent T-sensors improve calculations of turbulence quantities and spectral information. This enhances understanding of coupling between turbulent motions and sources like internal waves and eddies. (b) Movies, created from the four-dimensional data enable studies of the development of various turbulence sources.

## 2. Results

In Figure 1 the lower 500 m above the seafloor are shown of a standard oceanographic single CTD vertical ($z$) profile. It demonstrates a correspondence between Conservative Temperature (IOC et al., 2010), henceforth
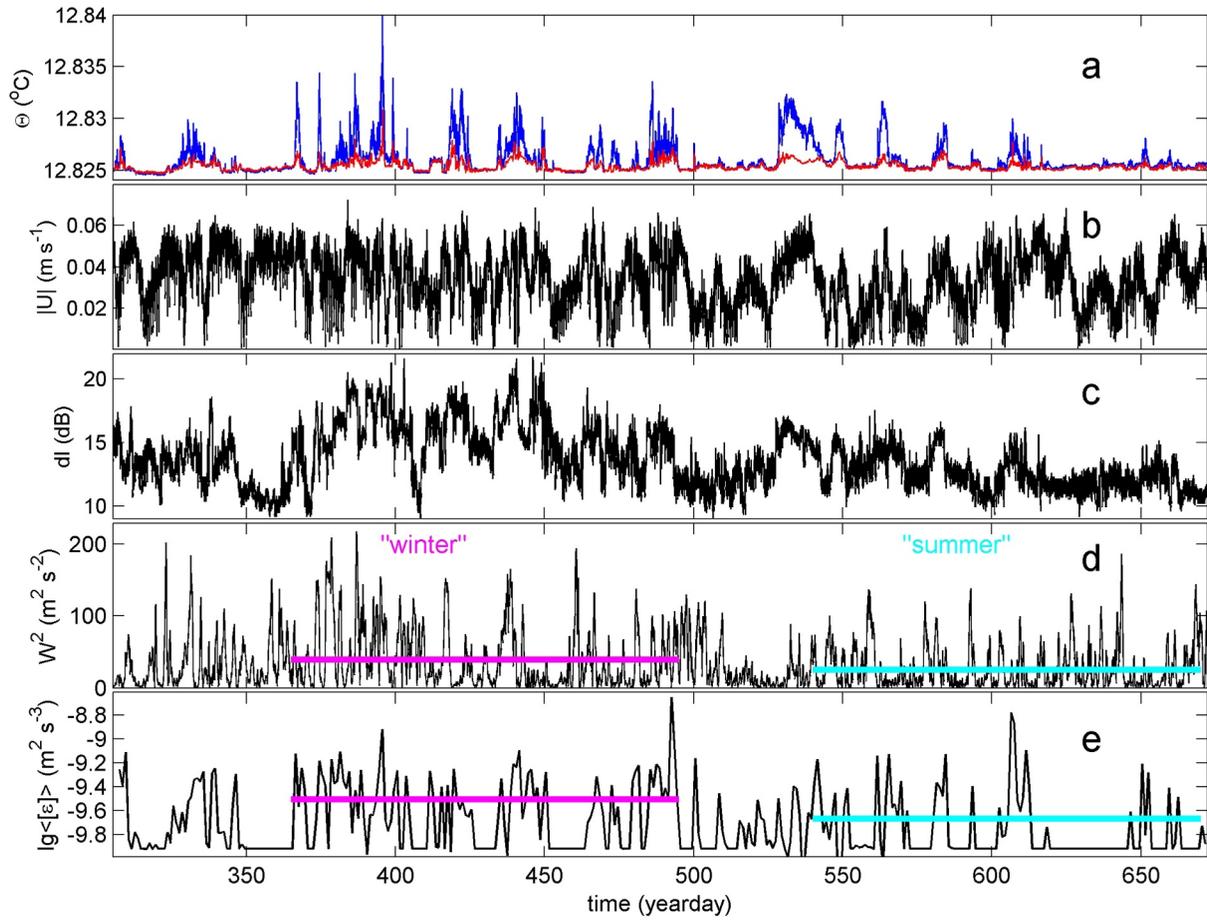
**Figure 2.** Yearlong time series, mainly from data measured at the large-ring mooring. Time in days since beginning of 2020. (a) Detrended Conservative Temperature from lowest (red; $h = 1$ m above seafloor) and uppermost (blue; $h = 125$ m) T-sensors of line 24, sub-sampled at once per 10 s. (b) Hourly averaged waterflow speed at $h = 126$ m. (c) Relative acoustic amplitude measured at $h = 126$ m. (d) Wind-load measured at island-station Porquerolles, about 20 km north of the mooring site. The magenta and cyan bars indicate average values over 130 days. (e) Logarithm of daily, 124-m vertically, and 45-line averages of turbulence dissipation rate inferred from T-sensor data. During periods of near-homogeneous conditions, values are fixed at the mean value due to dominant geothermal heat flux.

"temperature" for short, and density variations. The relationship between variations in temperature ($\Theta$, Figure 1a) and density anomaly referenced to 1,000 kg m$^{-3}$ at a pressure of $2 \times 10^7$ N m$^{-2}$ ($\sigma_2$, Figure 1b) is found $\delta\sigma_2/\delta\Theta = -0.25 \pm 0.01$ kg m$^{-3}$°C$^{-1}$ over the stratified waters at $z > -2,200$ m.

In these waters around $z = -2,050$ m, the large-100-m scale buoyancy frequency amounts to $N \approx 2f$, where $f$ denotes the local inertial frequency (Figure 1b). In the lower 250 m above seafloor, $N \approx (0.5–1)f$. As a result, the frequency range of freely propagating internal waves is about half the size of those in more stratified waters above. Over 1–10 m small vertical scales, larger $N \geq 4f$ can be found, for example, $z = -2,110$ and $-1,980$ m in Figure 1. Such 1–10 m thin, stratified layers are occasionally also found at greater depths, as is best seen in Figure 1a rather than in the noisier profile of Figure 1b. Thin layers can carry interfacial waves. Thus, a considerable variation is seen in vertical stratification, but the situation is not stable in time as may be suggested from the CTD profile.

First-year time series of the data are shown in Figure 2. Short periods of increasing temperature are frequently observed. As these data are from a single line, the direction of motion cannot be established. For this, a comparison with data from multiple lines has to be made. From a single line temperature differences can be observed of up to 0.015°C above background values for the uppermost T-sensors at $h = 125$ m above seafloor and smaller values below (Figure 2a). Such relatively warm stratified-water (SW) conditions alternate in time with near-homogeneous (NH) conditions of hardly any temperature difference over the 124-m T-sensor range. Also at the lowest T-sensor, periods of NH are generally found to be cooler than SW, with an occurrence in time of about

40% and 60% for SW and NH, respectively. Cool, substantially negatively stratified, unstable periods are not observed. The stratification variation contrasts with the near-bottom CTD-profile. Stratification increase either occurs via lowering warmer waters about 400 m vertically or advecting them horizontally. Internal waves and eddies are thought primary drivers of such motions that, combined, may lead to convection-turbulence that is slanted to the vertical (Marshall & Schott, 1999; Straneo et al., 2002), for example, by deflection due to the horizontal component of the Coriolis force.

Comparing the temperature time series with those of waterflow speed (Figure 2b) shows that the relatively warm SW seem to be related with the dominant 0.05-m s$^{-1}$ amplitude variations occurring with about 20-day periodicity. These relatively broadband (not shown) quasi-periodic waterflow-speed variations are considered to be related to the dynamically unstable meandering Northern boundary Current and associated mesoscale eddies (Crepon et al., 1982). Although the waterflow is generally strongest near the surface, it can still be measured at great depths. Spatial flow varies over only 50 m horizontally. Peak variations are associated in half the cases in their absolute value with SW (not shown). These flow differences represent smaller than sub-mesoscale vorticity and/or divergence. The SW in temperature also correlates in-phase with the relative acoustic amplitude (Figure 2c), which reflects the amount of suspended particles and zooplankton, and by a delay of about 5 days with the near-local wind speed (Figure 2d), as established from lag-correlation analysis. The wind-speed squared (wind-load) is observed to be 20% higher than the average value in winter, while 13% lower than the average value in summer.

This seasonal variation in wind-load is reflected in 124-m vertically, 45-line horizontally, and daily averaged deep-sea turbulence dissipation rates (Figure 2e), which are about 25% higher than the year-long average value in winter and 14% lower than the average value in summer. The seasonal variation in wind-load also reflects that turbulence dissipation rates are generally larger under SW than under NH conditions, on average by a factor of 3.5 (Figure 2e). NH are dominated by buoyancy-driven GH-fluxes through the seafloor that provide average turbulence dissipation rate of $\varepsilon_{GH} = 1.2 \times 10^{-10}$ m$^2$ s$^{-3}$ in the area. SW are dominated by internal-wave breaking driven by sub-mesoscale and near-inertial motions.

To compare SW-turbulence values with those possibly generated by deep dense-water formation a proxy is used from observed nighttime near-surface cooling (Brainerd & Gregg, 1995). To match SW-turbulence values, deep dense water should reach the ~2,500-m deep seafloor during a period of about 2.5 months once every 8 years, or during 9 days every year, which is not observed.

The observed average turbulence dissipation rate over the year of $2.4 \pm 0.2 \times 10^{-10}$ m$^2$ s$^{-3}$ from the tide-deprived deep Western Mediterranean site is a factor 3–10 larger than found in the tide-dominated open ocean well away from boundaries (de Lavergne et al., 2020; Yasuda et al., 2021). The standard deviation reflects the variation between the 45 lines. Environmental variations with time provide a larger spread of values and result in a larger apparent standard deviation for single-line values.

One of the aims of the mooring-array was to enable investigations of deep-sea turbulence via short movies (Figure 3; movies in: van Haren & KM3NeT Collaboration, 2025a). Six examples are presented, three categorized as SW and three as NH. Several characteristics including mean waterflows are given in Table 1. In each movie, progress with time is visualized by a white line moving in a time-depth panel from line 24. This panel is above the cube of flashing T-sensors. For the cube, the fixed viewpoint is lifted up near the east-southeasterly corner. All T-sensors are visible in this view, but one needs to capture the perspective of 3D-interpretation in the 2D-projected cube. Waterflow measurements are only made at $h = 126$ m, which is just above the top of the cube.

In Figure 3a a common SW period is shown, with typical vertical temperature difference and turbulence dissipation rate (Table 1). The movie has a calm start for $t < 307.66$ with gentle short-"wave" temperature variations crossing the lines near their top. The smaller than 1 hour periodicity is too short for freely propagating internal waves, and the motions are in the turbulence range mainly. Relatively warm waters are seen to enter from above plunging about 100 m down and reaching the seafloor. They briefly generate relatively strong turbulence. The warm waters are replaced by a turbulent cold front near the seafloor coming from the northeast with trailing slow internal waves near the local buoyancy frequency and small-scale turbulence jitter. To capture motion-directions, repeated playing and rewinding of the movie is helpful.

In Figure 3b characteristics of NH are shown with a one order of magnitude smaller temperature range than in Figure 3a. Putting the deep-sea motions in perspective: hypothetical particles advected by this flow cross the cube
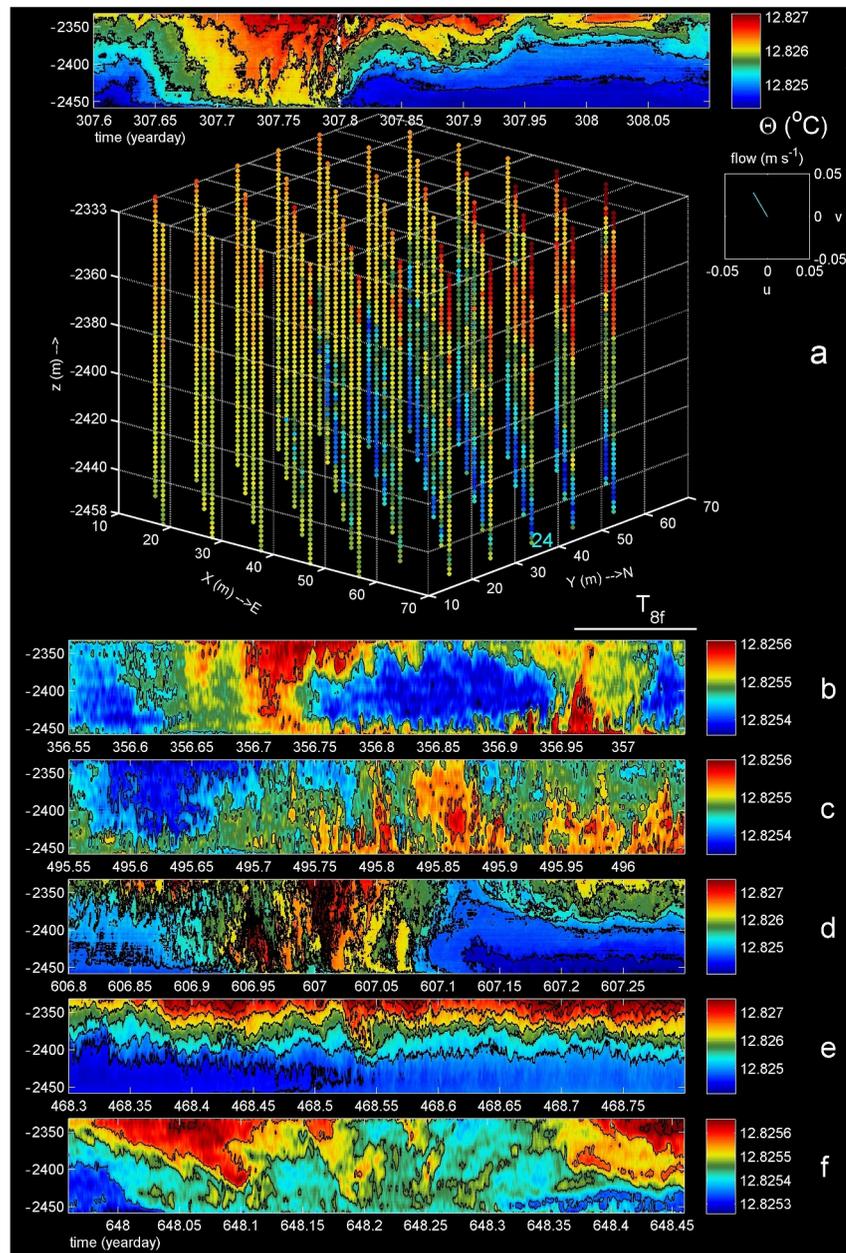
**Figure 3.** Six quasi-3D movies from about 2800 T-sensors in nearly 0.5 hm$^3$ mooring-array. As indicated in (a) only, each sensor is represented by a small filled circle, of which the color indicates a temperature in the scale above. In the movies, above the cube, which is vertically depressed by about a factor of 2, a white time-line progresses in a half-day/124-m time/depth image from line 24 on the east side of the cube. The 72-s movies are accelerated by a factor of 600 with respect to real-time. Environmental characteristics are given in Table 1. (a) Full image of a movie. Example of stratified-water (SW) conditions. Upper-panel black contours are drawn at 0.0004°C intervals. (b) Time-depth image only of example of near-homogeneous (NH) conditions including mostly small suppressed geothermal-heating (GH) plumes. Contour interval is 0.0001°C. The white bar on top indicates the period of the overall maximum 2-m small-scale buoyancy period. (c) As (b), but for NH including large GH plumes. Contour interval is 0.00005°C. (d) As (b), but for strongly turbulent SW. Contour interval is 0.0004°C. (e) As (b), but for SW interfacial internal-wave turbulent overturns above suppressed GH. Contour interval is 0.0005°C. (f) As (b), but for double-inertial frequency waves and warm-water deposits under NH. Contour interval is 0.0001°C.

in about 0.014 days, which is 2 s in movie time. Similar to the developments displayed in Figure 3a also here a calm start is observed, this time with a mid-depth turbulent cloud, which is replaced by a warming from above across the T-sensor range. In contrast to the developments shown in Figure 3a, the cold-water replacement enters

**Table 1**
*General Characteristics Are Given for Half-Day Periods of Figure 3, as Indicated by Their Panel and Start Day*

| Figure 3 | Start day | Cond. | $\varepsilon$ (m$^2$ s$^{-3}$) | $\Delta\Theta$ (°C) | $|U|$ (m s$^{-1}$) | Dir. |
|---|---|---|---|---|---|---|
| a | 307.6 | SW | $3.8 \pm 0.6 \times 10^{-10}$ | 0.003 | 0.03 | NNW |
| b | 356.55 | NH | $1.4 \pm 0.2 \times 10^{-10}$ | 0.00025 | 0.05 | ENE |
| c | 495.55 | NH | $1.1 \pm 0.2 \times 10^{-10}$ | 0.00025 | 0.05 | WNW |
| d | 606.8 | SW | $4.0 \pm 0.3 \times 10^{-9}$ | 0.0035 | 0.005 | SSE |
| e | 468.3 | SW | $1.0 \pm 0.1 \times 10^{-10}$ | 0.003 | 0.01 | SE |
| f | 647.96 | NH | $9 \pm 1 \times 10^{-11}$ | 0.0004 | 0.03 | ESE |

*Note.* The 45-line, 124-m, and half-day mean turbulence dissipation rate values $\varepsilon$ are given besides the full temperature range $\Delta\Theta$. Half-day mean waterflow speed $|U|$ and direction (oceanographic convention) are provided from measurements at $h = 126$ m above seafloor. Two environmental conditions are defined: SW = stratified-water, NH = near-homogenous, and may include geothermal heat GH. The categories are distinguished by the equivalent of 124-m, half-day mean $N = 0.65f$.

at mid-height. Above and below small-scale warming motions occur. Near the top, a slow wavy-like turbulence pattern is seen. Near the seafloor GH's horizontal scales are small and differences are seen per line. This is similar to the boiling in a pot that is uniformly heated from below, but for which the fluid responds with varying positions of small-scale bubble lines designating the upgoing motions (especially after day 356.9). The 9.5-m horizontal separation between lines is at least two orders of magnitude smaller than reported underground geological vents that feed the heating from below (Kunath et al., 2021). Despite the considerable mean waterflow near the top, most small-scale motions near the seafloor are found to be strictly vertical, and vertically suppressed presumably by weakly stratified waters above. Toward the end of this movie, GH flares up at the upper T-sensors and leaves turbulent clouds behind that are advected by the waterflow out of the cube.

The NH example shown in Figure 3c displays more large-scale GH, which frequently varies in height and in intensity. Some heated water and turbulent clouds are advected with the mean flow across the cube, for example, around day 495.73. Advection seems to occur at some distance, about $h > 30$ m, from the seafloor. As in Figure 3b, most convection-turbulence motions are found vertically varying with time, and between neighboring lines.

In Figure 3d one of the most turbulent SW periods is seen, between days 606.9 and 607.1. It is one order of magnitude more turbulent than the average. Initially, warm water comes from above with fast waves of turbulent motions. The motions have quasi-periodicities that are tenfold larger than the maximum small-scale buoyancy period. They unlikely represent freely propagating internal waves. They are followed by fast moving turbulent clouds from the side mostly from the northeast, with apparent fast half turn and slanting from above/sideways of warm waters into the cube around day 606.97. Near the seafloor cooler water comes from the west-northwest. The second half of the movie shows calmer internal waves, with the largest one having a periodicity commensurate with maximum small-scale buoyancy frequency, but remaining turbulently jittering with higher frequent quasi-periodic overturn motions. In the blue, a two-arm front passes over the seafloor in south-southwesterly direction between days 607.12 and 607.15.

In Figure 3e interfacial-wave turbulence of various scales and in various propagation directions is demonstrated. The position of the interface of relatively strong stratification in a thin layer varies with time about 50 m vertically. The horizontal extension of the array is large enough to resolve the amplitudes of the motion. Across interfaces, the 2-m-small-scale buoyancy frequency reaches a maximum of $N_s = 6f$. Thus, freely propagating internal waves have shortest measurable periods of about 3 hr (1.3 times the bar in Figure 3b). No information is available about possible smaller-scale buoyancy frequencies, because of the 2-m interval between T-sensors. Faster fluctuating turbulent motions are pumping the interface up and down at about 10-m scales in counter-phase between neighboring lines, best visible in the cyan-colored layer, for example, between 468.4 and 468.45. Just after the start of the movie at day 468.35 a cyan cloud is transported to the west, thereby forcing the interface up generating a wavy motion (best seen in the time-depth plot for line 24). The apparent up- and down-going standing wave motions represent transitions to turbulent overturns under sufficient shear for growth of instabilities (Bogdanov et al., 2023). These transitions are reminiscent of the process of parametric instability in which primary, freely propagating waves disintegrate into mode-2 oscillations of much shorter length scale. Mode-2 oscillations are
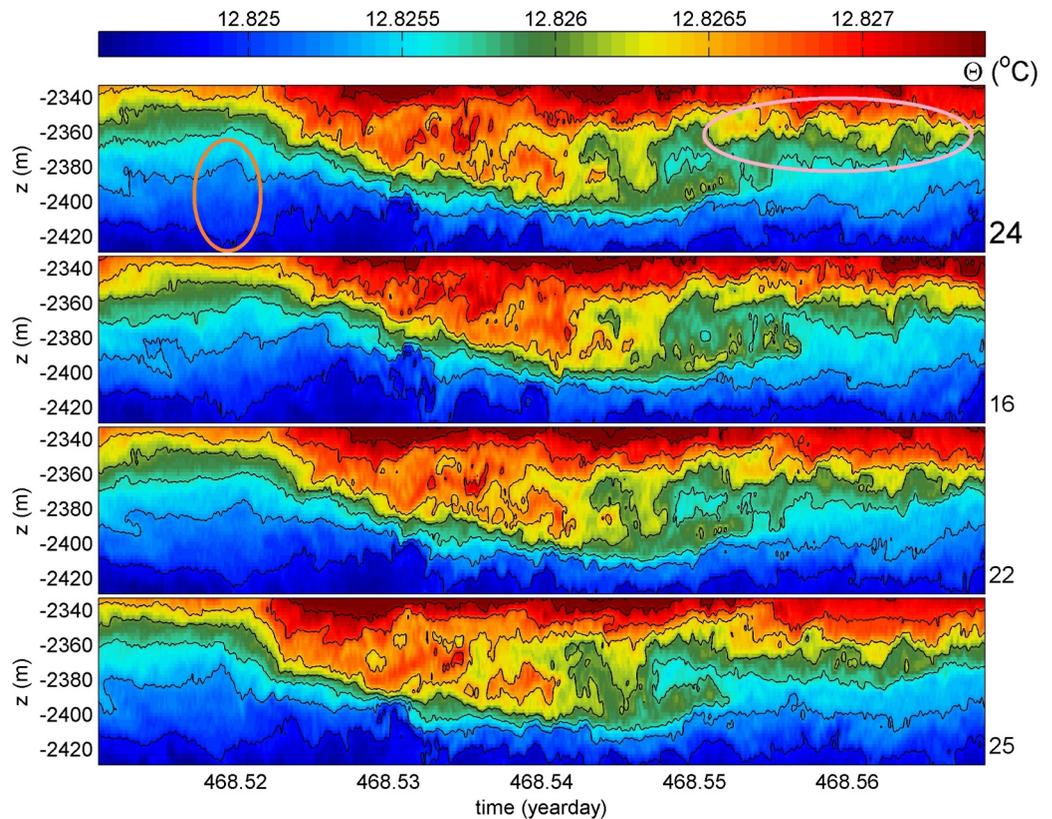
**Figure 4.** Time-depth enlargement of one large overturn from the movie in Figure 3e, for reference line 24 and its three neighbors. Throughout the images widening and shrinking is observed of black isotherms, which are drawn at fixed intervals of 0.0004°C. The observations evidence deep-sea turbulence generation via the process of parametric instability. Not only is the large breaker in the middle differently developing at different lines, but also the isotherm widening at all scales throughout the panel, for example, in the ellipses (see text for explanation).

distinguished by counter-moving isotherms. Such a transition process has been shown theoretically and in a laboratory model (Davis & Acrivos, 1967). In the present deep-sea data, the scale of the standing waves exceeds 10 m, as neighboring lines consistently show out-of-phase motions in time in all directions, with widening and shrinking in color bands in the vertical. This can better be seen in the enlargement of reference-line 24 and its three neighbors, for example, in the purple and orange ellipses around a single large overturn of Figure 4. This mechanism of turbulence generation is observed at many different time and length scales. The mean turbulence dissipation rate of such interior internal-wave breaking amounts to $3 \pm 1 \times 10^{-11}$ m$^2$ s$^{-3}$, which is equivalent to open-ocean turbulence measurements (Yasuda et al., 2021) and one order of magnitude smaller than average slantwise warming. During the second half of the movie, GH becomes apparent near the seafloor, but is not well visible with the used color-coding.

In Figure 3f NH is presented that is not clearly dominated by GH. Via warming from above, regular gentle turbulence is spread over the lower 100 m above the seafloor. The movie seems in slow-motion compared to the previous movies, but it has the same speed. The main variation in temperature has a period of about 0.35 days, which is half the inertial period. Turbulent overturns of different sizes are visible, clouds of warmer water are deposited at the seafloor, move partially up, and disperse out of the cube. While in the time-depth panel on the top slanted spurs of relatively warm water are visible, these are seen in the movie to go up or down, as well as become advected out of the cube. They represent local turbulent overturns with scales O(10) m.

## 3. Discussion and Conclusions

The large-ring mooring provides observational insight in 3D and time development of deep-sea turbulence in an area where stratification is generally weak. Besides improved statistics of spectral information, to be investigated

in near-future, and of turbulence dissipation rate, the large-ring mooring covers a reasonable range of sizes to distinguish internal-wave and geothermal-heat induced turbulence development as inferred from half-day real-time-compressed movies. This information cannot be obtained by common 1D oceanographic observations, or in 2D. Thus, the large-ring mooring provides sufficiently new insights, potentially also at other ocean areas in the future. The 9.5-m horizontal and 2-m vertical scales seem adequate for the purpose. However, for resolution of entire internal-tidal excursion lengths of about 1 km in the deep sea a larger set-up is required. To turn the mooring in a cabled observatory requires a new design and construction of T-sensors.

Unfortunately, the 20-month-long records do not register the sinking of unstable cool waters, which may be rare at the mooring site close to the continental slope. Instead of sinking of cool water, the T-sensor data show a dominance of warm-water pushes from above and sideways and, when stratification is negligible, GH-induced convection-turbulence. GH can only be detected when internal-wave action from above is low. GH's water response is found to vary strongly in height, from O(10) to O(100) m, with equivalent horizontal sizes so that small-scale response is different even between neighboring lines. Waters heated from below are advected horizontally when they reach at least 30 m above seafloor. GH's mean dissipation rate (van Haren, 2025a) matches the local average mean heat flux of 0.11 W m$^{-2}$ determined from geophysics measurements (Pasquale et al., 1996) and which are considered important for deep-sea circulation (Adcroft et al., 2001; Ferron et al., 2017; Park et al., 2013). Besides GH, three more processes of turbulence generation are distinguished.

The case of warm-water input from above conceptualizes as a stably stratified condition, which is previously thought to suppress turbulence. However, it is inferred that such a case can provide about 3.5 times larger average turbulence in the deep sea than GH, which contrasts with previous findings (Feron et al., 2017) for the entire Northwestern Mediterranean and is closer to their Ligurian-Sea data. The large turbulence is not representing deep dense-water formation, because it is observed year-round and because associated intensification of waterflow speed is not observed. As warming occurs sufficiently often, about 40% of time versus 60% for NH conditions, it dominates the turbulence generation at the mooring site. It is about one order of magnitude more energetic than average open-ocean turbulence away from boundaries as inferred from low-noise-profiler data (e.g., Yasuda et al., 2021). Occasional tenfold more energetic turbulence than average is observed generated by internal-wave motions with amplitudes exceeding the 124-m range of observations, and resulting in turbulent clouds that are advected through the mooring-array. Thus SW conditions generate considerably more turbulent mixing in the deep sea over a flat seafloor than hitherto thought, which is important for organisms living there.

Processes of relatively weak turbulence 10 times smaller than the SW-average are found in two different cases. In the case of near-homogeneous waters, turbulence is seen to deposit warm-water blobs at the seafloor that subsequently rise again from the seafloor as in convection. In the case of relatively strong, compared to the large-scale average, thin-layer stratification, propagating primary internal waves are seen to parametrically generate short-scale mode-2 standing wave motions of 10-m horizontal scales that break locally. Such interfacial internal-wave instabilities were observed to occur in laboratory models and shallow seas (Bogdanov et al., 2023; Davis & Acrivos, 1967). However, they occur also in the generally weakly stratified deep sea where interfaces of local strong stratification are expected to be rare. Considering their observed mean turbulence value, this mechanism may explain the weak open-ocean turbulence away from boundaries.

A coupling with variations on a seasonal scale is suggested between SW-conditions including associated turbulence and wind-load. The 2,500-m deep-sea response trails the surface by about 1 week. The pathway of energy transfer from an atmospheric disturbance passage is via formation of mesoscale, sub-mesoscale eddies and internal wave motions. In the area, anticyclonic eddies live longest, typically 1 year (Testor & Gascard, 2006). Such eddies trap near-inertial motions (Kunze, 1985). These lead to transfer of warmer water to approach the seafloor, breaking waves and subsequent turbulence generation, most likely via slantwise convection (Marshall & Schott, 1999; Straneo et al., 2002). As convection occurs in up- and down-going plumes, the slantwise deflection in the direction of the Earth rotation vector results in local apparent minimum large-scale buoyancy frequency of $N_{\min} \approx 2f$ (van Haren, 2008), as observed. A transfer from 1000-km atmosphere scale, to near-surface 100 and 10-km eddies, and sea-interior 1-km inertial-wave scale leads via strong nonlinear interactions to deep-sea 100-m and smaller-scale internal waves and, eventually, convection-turbulence overturning. The observed turbulence mechanisms locally mix suspended matter, oxygen and replenishes food for different life forms. This seems to be completely sufficient to maintain the food supply, as for this year no local deep dense water formation had been observed.

## Appendix A: Authors of the KM3NeT Collaboration

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## Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

## Data Availability Statement

Current meter and CTD data are available from van Haren (2025b). Data to Figures 2–4 are available from van Haren and KM3NeT Collaboration (2025b). Movies to Figure 3 are available in: van Haren and KM3NeT Collaboration (2025a). Atmospheric data are retrieved from https://content.meteoblue.com/en/business-solutions/weather-apis/dataset-api.

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