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Technical note: Spectral slopes in a deep, weakly stratified ocean and coupling between sub-mesoscale motion and small-scale mechanisms

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Abstract. Large, basin-wide ocean circulations are complex non-linear dynamical systems. They include small-scale physical processes such as transport by sub-mesoscale eddies and turbulence-generating breaking of internal waves. To date, however, knowledge is lacking on the precise interactions between the different processes. In this note, a potential contributor to the interactions is investigated using spectra from deep-sea-moored observations. In weakly stratified waters, continuous spectral slopes are observed that extend from sub-mesoscales across the internal wave band to the turbulence range. In the latter, the governing slope can be distinctly different from the inertial subrange of shear turbulence and is described as the buoyancy subrange of convection turbulence. At sub-inertial frequencies, the slope's extension describes either quasi-gyroscopic waves or sub-mesoscale eddies. Such cross-spectral correspondence suggests a potential feedback mechanism stabilizing large-scale ocean circulations.

1 Introduction

The extent of anthropogenic influence on Earth's climate warrants studies of the ocean as a major player. Large, basin-wide ocean circulations are important for transporting properties like heat, carbon, and nutrients. Schematically, the Atlantic Meridional Overturning Circulation (AMOC) is depicted as transporting heat from the Equator to the poles near the surface and carbon in the abyssal return (e.g. Aldama-Campino et al., 2023). It includes physical processes like deep dense-water formation in the polar region. Recent mathematical and numerical modelling such as that based on varying single parameters like sea surface temperature (e.g. Ditlevsen and Ditlevsen, 2023) and freshwater influx (e.g. van Westen et al., 2024) suggests a potential future collapse of the AMOC. It is argued that this may have consequences for the northwestern European climate.

Whilst the modelling might be robust mathematically, it lacks physical processes of the drivers of the AMOC and observational evidence thereof. This will have consequences for the feedback mechanisms at work in the non-linear dynamical system of ocean circulation. As has been reviewed for AMOC numerical models (Gent, 2018), important feedback mechanisms include vertical turbulent mixing, sub-mesoscale gyre eddy transport, and coupling with the atmosphere. Here we elaborate on the importance of turbulence induced by internal-wave breaking, possible coupling with sub-mesoscale eddies (e.g. Chunchuzov et al., 2021), and stability variations in vertical density stratification for such feedback by reviewing insights from recent modelling and deep-sea observations. In particular, as an example of the complexity of dynamical system interactions, the core of ocean motions is spectrally investigated, focusing on most energetic mesoscale, internal wave, and turbulence scales for deep weakly stratified waters.

In contrast to the atmosphere, the ocean is not an effective heat engine (Wunsch and Ferrari, 2004), despite its heat transportation. As a result, the AMOC is not predominantly buoyancy-driven via push by deep dense-water formation near the poles (Marshall and Schott, 1999; Marotzke and Scott, 1999), which notably occurs in sporadic pulses rather than continuously. Instead, the AMOC is mainly wind-steered (e.g. Liu et al., 2024) and tide-driven, with turbulent

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mixing by internal-wave breaking and possible associated upwelling close to the boundaries (Ferrari et al., 2016; McDougall and Ferrari, 2017), which is considered an important physics process of pull that dominates over push by a heat engine. Winds near the ocean surface and tides via interaction with the seafloor topography deeper down contribute about equally to generating internal waves that are found everywhere in the ocean interior. Such waves break predominantly at ubiquitous underwater seamounts and continental slopes.

Without turbulent mixing, the AMOC would be confined to a 100 m near-surface layer and the deep ocean would be a stagnant pool of cold water (Munk and Wunsch, 1998). This is not the case, however, and the solar heat is mixed from the surface downward so that the ocean is stably stratified in density all the way into its deepest trenches, as has been shown in hydrographic deep-ocean observations (Taira et al., 2005; van Haren et al., 2021a). Although turbulent mixing by internal-wave breaking in the ocean interior is insufficient by at least a factor of 2 for maintaining the vertical density stratification (e.g. Gregg, 1989, Polzin et al., 1997), such breaking along ocean boundaries has been suggested to be more than sufficient (Munk, 1966; Polzin et al., 1997). Large internal-wave breaking especially is expected to occur above steeply sloping topography (Eriksen, 1982; Thorpe, 1987; Sarkar and Scotti, 2017). Because there are more and larger seamounts than mountains on land, equally abundant sloping seafloors lead to abundant turbulent mixing, as has been charted from recent observations and the modelling results summarized below.

As recent observations (van Haren and Dijkstra, 2021; van Haren et al., 2024) demonstrate that breaking waves can lead to considerable buoyancy-driven convection turbulence, this note seeks further understanding of a little-studied deep-sea complex process and its potential interaction with submesoscale motions. The sub-inertial range of sub-mesoscale motions has rarely been a subject of oceanographic spectral observations. Knowledge about such small-scale processes and their interactions may be vital for understanding potential feedback mechanisms affecting the stability of large-scale ocean circulations.

2 Recent internal-wave-breaking results

Detailed observations and numerical modeling have revealed the extent of internal tide-breaking processes above the ocean topography (van Haren and Gostiaux, 2012; Winters, 2015; Wynne-Cattanach et al., 2024). Using high-resolution observations (e.g. van Haren and Gostiaux, 2012), internal tide breaking above steep deep-sea slopes is observed to generate a spring-neap-average turbulent vertical diffusivity value of about $3 \times 10^{-3}\,\mathrm{m^2\,s^{-1}}$. This value is twice that theoretically required to yield upwelling in a thin layer above a sloping topography (McDougall and Ferrari, 2017). Such quantification of turbulent mixing shows that it occurs with typical tidal-period-average values that are more than 100 times larger over super-critical slopes than open-ocean values. A super-critical seafloor slope is steeper than the slope of internal wave characteristics. While ocean-wide tides energetically dominate internal waves, not all seafloor slopes are super-critical for these waves. In contrast, nearly all seafloor slopes are super-critical for at least one component of secondary energetic near-inertial waves, which are generated via geostrophic adjustment following the passage or collapse of a disturbance such as fronts or atmospheric storms on the rotating Earth. Under common stratification, near-inertial waves are at the lowest frequency of freely propagating internal waves. The highest-frequency propagating internal waves, near the buoyancy frequency, experience nearly vertical walls as super-critical seafloor slopes.

Within a tidal, or near-inertial, period, turbulence peaks in bursts of durations shorter than half an hour when highly non-linear internal waves propagate as internal bores up a super-critical slope, once or twice a tidal cycle. The breaking of bores leads primarily to convection and buoyancy-driven turbulence rather than frictional shear turbulence over the sloping seafloor and occurs in a wide variety of deep-sea and deep-ocean locations (e.g. van Haren et al., 2013; van Haren et al., 2024). Between bores, the turbulent mixing varies by 1 order of magnitude in intensity, with effects extending about 100 m vertically and several kilometres horizontally from the seafloor. Intermittently occurring in a given position of the sloping seafloor and with about 10 % varying in arrival time, the turbulence is generated internally by the tide for about 60 % (Wunsch and Ferrari, 2004) and by winds for about 40 % in a stratified ocean environment. The turbulent bores also re-suspend sediment and thereby replenish nutrients away from the seafloor (Hosegood et al., 2004), which is important for deep-sea life. Enhanced turbulent mixing above sloping boundaries has a demonstrated effect on the outcome of ocean general circulation models (e.g. Scott and Marotzke, 2002), with predicted subtle effects on upwelling near the seafloor (Ferrari et al., 2016).

The complexities of turbulence generation, mixing, and restratification are still subjects of deep-ocean research. While shear-induced turbulence has been studied relatively well in the stratified ocean, deviations such as convection turbulence are little observed, with recent exceptions (van Haren and Dijkstra, 2021; van Haren et al., 2024). Convection turbulence is dominant in the atmosphere, especially during daytime, and has also been observed in the near-surface ocean during nighttime (e.g. Brainerd and Gregg, 1995), but it has never been quantitatively and directly observed in deep dense-water formation zones (Thorpe, 2005) and above geothermal vents. Lagrangian float measurements yielded average vertical heat flux estimates due to convection reaching down to 1000 m from the surface in the Labrador Sea (Steffen and D'Asaro, 2002). It would be challenging to set up an experiment in which such floats are equipped with microstructure instrumentation and to be able to measure convection turbulence from the surface down to the deep seafloor.

Deep dense-water formation occurs not only in the polar seas, but also occasionally in the at least 10 °C warmer Mediterranean (Gascard, 1978), with an important contribution of atmospheric exchange due to orographically generated winds affecting the pre-conditioning by cooling and drying of near-surface waters. Similarly, internal waves occur in oceans and in the Mediterranean under stratification conditions that vary by at least 1 order of magnitude in time and space, but tides are relatively weak in the Mediterranean, and yet the turbulent diapycnal mixing sufficient for maintenance of deep-sea stratification and therefore driving of the overturning circulation is generated via breaking above the topography of near-inertial motions (van Haren et al., 2013). Further complications are expected from interactions between internal waves with sub-mesoscale eddies and the potential consequences of varying the intensity thereof, e.g. on seasonal scales.

3 Mediterranean observations as an example proxy for ocean conditions

In many physical oceanographic aspects of heat and salt budgets, large-scale water-flow circulation, strong boundary flow, eddies at sub-mesoscales, and near-inertial motions including gyroscopic waves and internal wave turbulence, the Mediterranean Sea can be considered a sample for the state of the much larger oceans (e.g. Gascard, 1973; Crepon et al., 1982; Garrett, 1994; Milllot, 1999; van Haren and Millot, 2004; Testor and Gascard, 2006). Like in the oceans, the Mediterranean seafloor reaches great depths and can be rugged with steep slopes in places, including continental slopes incised by deep canyons.

In the north-western Mediterranean, vertical density stratification varies markedly with the seasons and years, with relatively large near-surface values in summer and relatively low values in winter. The proximity of extensive mountain ranges on land generates highly variable winds that can cool and dry surface waters. In winter in weaker stratified waters, this may lead to unstable conditions of buoyancy-driven convection in an exchange of dense water down and less dense waters up. Like in the polar regions, such exchange can be observed daily in the upper 10 m from the sea surface, regularly down to a few hundred metres from the surface and seldom once every 5–8 years (e.g. Rhein, 1995; Mertens and Schott, 1998), down to the abyssal seafloor at about 2500 m. In contrast, horizontal density gradients are associated with forcing of a dynamically unstable boundary current and eddies at multiple 1–100 km sub-mesoscales (e.g. Crepon et al., 1982; Testor and Gascard, 2006). These eddy motions may push relatively warm waters down, thereby increasing the weak stratification in the deep sea.

In summer, atmospheric disturbances are less intense, near-surface stratification is large due to solar heating, and eddy activity associated with some continental boundary flows is weaker (Albérola et al., 1995). This opens up the possibility of detection of near-inertial wave dominance in kinetic energy. In relatively strong stratification, gravity-driven parts of near-inertial waves generate the largest vertical current difference shears that destabilize stratification due to their relatively short vertical length scale, not only in the Mediterranean, but also as observed in the Atlantic Ocean (van Haren, 2007). This destabilization may lead to small 10 m vertical-scale layering of near-homogeneous waters throughout the seas and oceans. On larger, 100 m vertical scales, near-homogeneous waters occur in deep waters of the Mediterranean as well as North Atlantic basins like the Bay of Biscay and the Canary Basin. In near-homogeneous water layers with weak stratification, gyroscopic, Earth-rotation-driven parts of near-inertial waves dominate and result in a 0.1–1 km diameter smaller than sub-mesoscale tubes of slantwise rather than vertical convection (Emanuel, 1994; Marshall and Schott, 1999; van Haren and Millot, 2004). Hence, one may expect frequency spectra of non-tidal-dominated data from instruments moored in the Mediterranean to reveal convection and thus deep transport under winter and summer conditions.

It is noted that ocean spectra, such as frequency spectra of kinetic energy and scalar quantities like temperature from data registered by moored instrumentation, may show peaks such as at narrowband tidal frequencies and, in a broader band, inertial frequencies, but they lack gaps. This lack of spectral gaps potentially couples motions at sub-inertial waves to inertial-buoyancy internal waves, with super-buoyancy turbulence frequency ranges. However, it is unclear how such coupling may work as some motions represent two-dimensional (2D) eddies, some linear waves, some non-linear waves, some anisotropic, quasi 3D, and stratified turbulence, and some isotropic 3D turbulence. This is investigated by renewed spectral analysis below, using, in analogy, slopes typical for investigating energy cascades in turbulence research.

4 Uncommon slopes in revisited spectra

Kinetic energy (KE) spectra from historic moored current meter observations down to mid-depth $z = -1100$ m in the Ligurian Sea under upper-sea strongly stratified "summer" and weakly stratified "winter" conditions surely lack gaps (Fig. 1). Year-round at $z = -1100$ m, the buoyancy frequency N, reflecting the square root of vertical density stratification, is small at $N \sim O(f)$, with f denoting the inertial frequency involving Earth rotation. This narrows the local internal wave band, while, especially in winter, sub-mesoscale activity is large in the area, and, occasionally, the few moored current meter temperature records show inver-

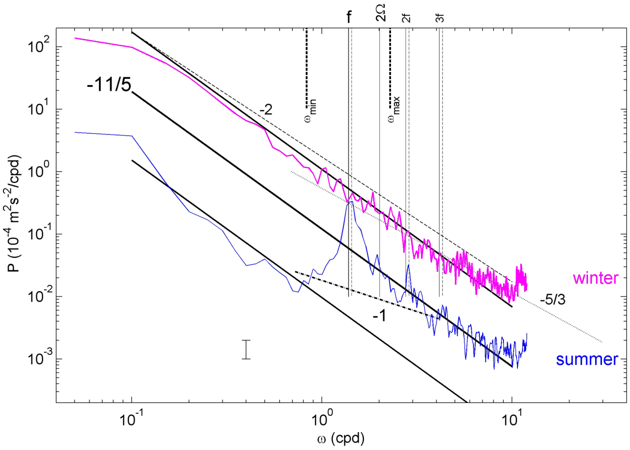

Figure 1. Moderately smoothed (20 degrees of freedom, DOF) kinetic energy (KE) spectra over 100 d of data from a 3600 s Aanderaa mechanical current meter moored in 1981/1982 at $z = -1100$ m, well above the continental slope of the Ligurian Sea at 43°28.32′ N, 7°46.10′ E and 2250 m water depth. For details on these data, see van Haren and Millot (2003). The two spectra are not offset deliberately from each other. "Noise" also contains other signals near the Nyquist frequency. The "summer" (blue) spectrum is an average from data between days 190 and 290 (in 1981), and the "winter" (magenta) spectrum originated between days 375 and 475 (adding + 365 for days in 1982). Several frequencies are indicated, including inertial frequency f, Earth rotation Ω, and inertio-gravity wave bounds [$\omega_{\min} \leq f$, $\omega_{\max} \geq N$, 2Ω] for buoyancy frequency $N = f$. The dashed lines indicate harmonics of 1.04f. Four spectral slopes ω^{p} are indicated by their exponent: $p = -11/5$ (solid slope in the log–log plot) for Bolgiano–Obukhov (BO) scaling reflecting the buoyancy subrange of convection turbulence (e.g. Pawar and Arakeri, 2016), $p = -5/3$ (dotted slope) for Kolmogorov–Obukhov (KO) scaling reflecting the equilibrium inertial subrange for dominant shear-induced turbulence (Kolmogorov 1941; Obukhov, 1949), $p = -1$ (dash-dotted slope) for intermittency of self-organized criticality (Schuster, 1984; Bak et al., 1987), and $p = -2$ (dashed slope) for internal wave scaling (Garrett and Munk, 1972) or fine-structured contamination (Phillips, 1971; Reid, 1971).

sions (van Haren and Millot, 2003). Although these hourly sampled data barely resolve the turbulence ranges at frequencies $\omega > N$, the internal wave continuum was suggested to scale like ω^{p}, with, in a log–log plot, a spectral slope $p = -2.2 \pm 0.4$, independent of location and season albeit with different KE (power) levels.

Within the uncertainty range, several possible explanations can be given for the observed spectral slope. Freely propagating internal gravity waves have been fitted to $p = -2 \pm 0.5$, but only for $f \ll \omega \ll N$ (Garrett and Munk, 1972). Considering that the data in Fig. 1 are from a site where, locally, $N = (3 \pm 2) f$ irrespective of the season (van Haren and Millot, 2003), alternative explanations have been sought for observed spectral slopes at sub-inertial frequencies 0.2 cpd $< \omega < f$. Cpd is short for "cycles per day". An obvious candidate is the fine-structured contamination of step functions passing sensors, which gives a theoretical value of $p = -2$ (Phillips, 1971; Reid, 1971). For their winter data, van Haren and Millot (2003) attributed such a slope to intense mesoscale activity, because of the continuation of the slope to $\omega = 5$ cpd before rolling off near the Nyquist frequency. However, they did not elaborate. Below, the data in Fig. 1 are re-analysed from the perspective of convection turbulence.

Theoretical considerations of non-zero-mean flow convection turbulence suggest spectral scalings in the buoyancy subrange of $p = -11/5 = -2.2$ for KE and $p = -7/5$ for an active scalar quantity. This BO scaling follows the atmospheric and theoretical works of Bolgiano (1959) and Obukhov (1959). The scaling was set up for a stably stratified atmospheric environment for the anisotropic part in which turbulent kinetic energy is partially converted into potential energy, leading to turbulent convection. Later works extended BO scaling to purely buoyancy-driven turbulence, e.g. for Rayleigh–Bénard convection (Lohse and Xia, 2010) and Rayleigh–Taylor instabilities (Poujade, 2006; Celani et al., 2006).

Laboratory experiments on such gravitationally driven convection are inconclusive regarding BO scaling. On the one hand, this scaling is confirmed for both KE and temperature in the experiments of Ashkenazi and Steinberg (1999), while on the other hand it is only confirmed for scalars by Pawar and Arakeri (2016), who found a slope of $p = -5/3$ for KE. The $p = -5/3$ slope suggests dominance of shear-induced turbulence of the inertial subrange for the equilibrium isotropic turbulence cascade in the KO scaling (Kolmogorov, 1941; Obukhov, 1949) but should also be found in spectra of scalars that are passive in this range. While Liot et al. (2016) show KO scaling in their model, which may have to do with their Lagrangian data as proper transfer brings the data closer to BO scaling, Poujade (2006) and Celani et al. (2006) show clear BO scaling in their models. This suggests that particular conditions do affect the dominance of shear or convection turbulence. It is noted that BO scaling is also simply considered a significant deviation from KO scaling, which is more commonly observed in stratified shear flows.

Obviously, scalars cannot be passive and active at the same time and in the same space. This discrepancy between types of scaling between scalars and KE may be because the laboratory experiments of Pawar and Arakeri (2016) were in zero mean flow. Also, under sufficiently stable conditions without shear, no inertial subrange is expected (Bolgiano, 1959). However, the spectral extent of BO scaling is largely unknown, but it is more generally found adjacent to the higher-frequency inertial subrange. While KO scaling is based on a forward cascade of energy, the direction of energy cascade is inconclusive for BO scaling and may be partially forward and partially backward, at least as reasoned for pure buoyancy-driven convection turbulence (Lohse and Xia, 2010). Probably, directions of cascade change with locality in the flow depend on the scale, which would also imply that KO and BO scaling cannot be found at the same site.

Revisiting data from non-zero mean flow and a weakly stratified deep sea in Fig. 1 demonstrates the possibility of a fit of $p = -11/5$ outside near-inertial harmonic peaks. In winter, such a fit is observed consistently through the entire range of $0.2 < \omega < 5$ cpd. In traditional terms, this frequency range covers the transition from mesoscale $\omega < f$, via internal wave $f < \omega < N$, to turbulence $\omega > N$ motions. In summer, the $p = -11/5$ slope is found at two different KE levels for bands $0.2 < \omega < \omega_{\mathrm{min}}$ and $2\Omega < \omega < 5$ cpd at sub- and super-IGW (inertio-gravity-wave) frequencies, respectively. Here, $\omega_{\mathrm{min}} \leq f$ denotes the minimum frequency bound for IGW (LeBlond and Mysak, 1978) and Ω Earth's rotational frequency. The maximum IGW frequency is denoted by $\omega_{\mathrm{max}} \geq 2\Omega$, N. ω_{min} and ω_{max} are functions of N, latitude ϕ, and the direction of wave propagation (LeBlond and Mysak, 1978; Gerkema et al., 2008),

$$\omega_{\mathrm{max}}, \omega_{\mathrm{min}} = (A \pm (A^2 - B^2)^{1/2})^{1/2}/\sqrt{2}, \tag{1}$$

in which $A = N^2 + f^2 + f_{\mathrm{s}}^2$, $B = 2fN$, and $f_{\mathrm{s}} = f_{\mathrm{h}} \sin\alpha$, with α the angle to ϕ. For $f_{\mathrm{s}} = 0$ or $N \gg 2\Omega$, the traditional bounds $[f, N]$ are retrieved from Eq. (1). The plotted IGW bounds $[\omega_{\mathrm{min}}\omega_{\mathrm{max}}]$ are for weakly stratified, near-homogeneous layers in which $N = f$. This weak stratification would lead to an impossible wave solution with the traditional approximation, but Eq. (1) allows wave propagation, albeit horizontally for one component (e.g. Gerkema et al., 2008).

The bridge between the KE levels at sub- and super-IGW is formed by the finitely broad near-inertial peak. The base of this peak is proposed to slope like $p = -1$, reaching super-IGW BO scaling at about $\omega \approx 4$ cpd $\approx N$. Such a $p = -1$ slope has been observed for the KE spectral continuum in $[f\,N]$ from the deep Bay of Biscay and the north-eastern Atlantic Ocean (van Haren et al., 2002). Theoretically, this slope represents spectral scaling of the intermittency of a weakly chaotic non-linear system (Schuster, 1984), i.e. 3D dynamical systems that evolve into self-organized critical structures of states which are minimally stable (Bak et al., 1987). Such a spectral bridge, or hump, is expected for turbulence in unstable stratification, as has been illustrated using atmospheric observations (Lin, 1969). This is attributed to the flow field absorbing energy from the scalar temperature field as potential energy is converted into kinetic energy. It is not clear to what extent near-inertial internal waves contribute in a similar way to the spectral redistribution of energy in our oceanographic data. As the observations from the central Ligurian Sea show similar results, the hump is unlikely to be associated with seafloor slopes matching the slopes of near-inertial internal wave rays.

These spectral observations suggest a dominance of convection cascades from sub-mesoscales via IGW to, probably because unresolved, turbulence scales under high-energy winter conditions, as they show a continuous slope across their frequency ranges. Such a cascade is also suggested under quieter summer conditions, when, however, it is masked by IGW, which leads to a cascade at $\omega > \omega_{\mathrm{min}}$. The sub-inertial range of apparent BO scaling especially seems out of the turbulence range, unless waters are near-homogeneous in $N \to 0$, i.e. $\omega_{\mathrm{min}} \to 0$ from Eq. (1). This would extend not only IGW, notably gyroscopic waves, but also turbulence, probably in the form of slantwise convection, to the sub-mesoscale range.

For the mesoscale range, the observations in Fig. 1 are supported by numerical modelling results that have suggested eddy KE as having a broad range of spectral slopes in the range $-3 < p < -5/3$ (Storer et al., 2022) and by satellite altimetry observations that indicated, after noise correction and transfer to KE, a best fit of $p = -2.28$ (Xu and Fu, 2012). No mention was made of BO scaling, but the correspondence seems evident.

The KE in Fig. 1 is at least 1 order of magnitude larger in winter than in summer. A near-inertial peak, if it exists, will be part of the spectral continuum during the former. The winter observations suggest a continuous spread of sub-mesoscale energy across the IGW band, including inertial motions and into the turbulence range. In winter, near-surface stratification is considerably weaker than in summer, so that local atmospherically generated near-inertial motions will be smaller. It is noted that the signals near the Nyquist frequency contain not only instrumental white noise but also unresolved turbulence motions, which are also larger in winter than in summer.

Inspired by western Mediterranean observations, Saint-Guily (1972) proposed from theoretical work that winter-time inertial KE is spread over a broad featureless band, like quasi-gyroscopic waves that may be present between IGW bounds (see Eq. 1 for $N \sim f$; LeBlond and Mysak, 1978; Gerkema et al., 2008). However, observations from the year-round upper-layer-stratified central western Mediterranean demonstrate that, also in deep homogeneous $N = 0$ waters, a near-inertial peak can be observed in KE spectra (van Haren and Millot, 2004). This may be attributed to a year-round source of atmospherically generated inertial waves that are the only internal waves that can propagate without attenuation from well-stratified to near-homogeneous layers and vice versa (van Haren, 2023b).

Based on limited spectral observations, Gascard (1973) suggested generation of 12 h stability waves close to the buoyancy frequency of very weak stratification briefly forcing dense-water formation, thereby implicitly suggesting a link between internal waves and sub-mesoscale eddies. As such eddies have estimated a relative vorticity of $|\zeta| = f/2$ in the western Mediterranean (Testor and Gascard, 2006), this addition to the planetary vorticity (f) automatically widens the effective near-inertial band $0.5f < f_{\mathrm{eff}} < 1.5f$, of which the bounds are close to the IGW bounds for $N = 0.8f$. The properties can include a modification of near-inertial frequency (Perkins, 1976) and trapping with downward propagation of near-inertial waves in anticyclonic eddies (Kunze, 1985; Voet et al., 2024). Such frequency modification may add to local physics of inertial-wave caustics due to latitudinal variation (LeBlond and Mysak, 1978), which however can only lead to a change in f of up to 15 % in the Mediterranean. Although found to be limited to the rather flat KE spectral dip in the immediate half-order-of-magnitude sub-inertial frequency band, standing vortical modes, i.e. low-frequency non-propagating motions, of the vertical length scale < 10 m are suggested to be as energetic as internal waves (Polzin et al., 2003). Alternatively, it has been suggested for North Atlantic observations that vortical modes may interact with internal waves, affecting internal-wave shear peaks over O(10) m vertical scales at IGW frequencies in a band with limits determined by weak stratification as in $N = f$ (van Haren, 2007).

For a hypothetical $\omega_{\min} = 0.2$ cpd at which the observed spectral slope changes away from $p = -11/5$ (Fig. 1), one would require $N = 0.21 f$, which is almost unmeasurable and non-existent for any prolonged period, even in the deep north-western Mediterranean, to the knowledge of the authors. However, this may reflect the $\omega_{\min}$ computed using $f_{\text{eff}} = 0.5 f$ and $N = f_{\text{eff}}$, noting that such conditions can only apply for part of the record. If so, this would reflect a direct coupling between sub-mesoscale and IGW motions with slantwise convection (Marshall and Schott, 1999; van Haren and Millot, 2004; Gerkema et al., 2008). $p = -11/5$ is significantly distinguishable from -2 over a frequency range of nearly 2 orders of magnitude and from $-5/3$ over a range of just over half an order of magnitude (Fig. 1). The roll-off to noise (slope 0) for $\omega > 5$ cpd may partially be seen as following a slope of $p = -5/3$ before 0. The roll-off around 0.1 cpd suggests an unresolved broad mesoscale peak value between 0.01 and 0.1 cpd. While these 1980s moored current meter data barely resolved the turbulence part of the KE spectrum and thus also not the $p = -5/3$ inertial subrange slope, their temperature sensors were too poor to simultaneously verify any spectral scaling for scalars.

About 40 years later, high-resolution and high-precision moored temperature sensor T data provided an opportunity to verify scalar spectral scaling of turbulence energetic motions in the area. These T data showed occasional warming of the deep north-western Mediterranean seafloor (Fig. 2a), which, after comparison with data from higher up, appeared to be coming from above or slanted sideways under relatively stratified conditions and from general non-vent geothermal heating from below (van Haren, 2023a). The data were collected during mid-autumn, when near-surface waters were stratified well and no cold, dense-water production through convection was observed. Locally near the seafloor, the broad 2 d warming around day 308 is most stratified, whilst during other periods waters are only weakly stratified, including the quasi-inertial variations between days 316 and 322. These weakly stratified near-inertial or near-buoyancy (as $N \approx f$) temperature variations may show slantwise quasi-gyroscopic near-inertial waves, which can have a large vertical component (LeBlond and Mysak, 1978), as opposed to more common near-horizontal near-inertial waves in strongly stratified waters that are barely noticeable in temperature records.

The 18 d average spectrum of the 2 s sampled data resolves sub-mesoscales poorly but shows, near the seafloor, a well-resolved slope of $p = -1.4 \pm 0.025$ in the large range $0.5 < \omega < 6000$ cpd, across the IGW band and well into the turbulence band (Fig. 2b). No transition to a $-5/3$ slope is observed before roll-off to noise, but this does not exclude an inertial subrange at higher frequencies hidden under white noise, although shear will be limited so close to the seafloor. The observed $p = -7/5$ slope is found to be significantly different from $p = -2$ and $-5/3$ over the indicated frequency range of 4 orders of magnitude and over the range $100 < \omega < 10^4$ cpd, thereby representing convection turbulence. Over a frequency range of half an order of magnitude, the slope error is about ± 0.1. While not greatly resolved, the range $\omega_{\max} < \omega < 10$ cpd falls off more steeply at roughly $p = -2$ and the range $10 < \omega < 100$ cpd shows a reduced variance that may partially be characterized by intermittency ($p = -1$; Schuster, 1984) albeit not yet explained. Here, it is observed to bridge between $p = -2$ and the super-IGW BO scaling $p = -7/5$. This would be a further observation of a marginal ocean state in the -1 scaling in KE spectra (Fig. 1 and van Haren et al., 2002) and the continuum of the band $[f\ N]$ in open-ocean T spectra (van Haren and Gostiaux, 2009).

About 140 m above the seafloor, a less precise older-type T sensor demonstrates $p = -7/5$ between a reduced range of about $10 < \omega < 1000$ cpd, with a suggestion for $p = -5/3$ around 10 cpd. This indicates that convection can still dominate over a shear extending O(100 m) above the seafloor, as has been shown in more detail for certain periods (van Haren, 2023c).

Whilst more extended work with longer datasets and more T sensors is to be done, the extended continuous spectral slope from these high-resolution temperature observations suggests a direct coupling between sub-mesoscale motions and IGW motions comprising internal gravity and gyroscopic waves and convection turbulence. The temperature spectra also show consistency with the limited KE spectra of Fig. 1 from roughly the same area, and both indicate a dominance of non-isotropic, stratified turbulence convection between the sub-mesoscales and the largest turbulent overturning scales in extended BO scaling, suggesting cross-spectral coupling. The discrepancy in KE spectra in the laboratory experiments of Pawar and Arakeri (2016) may be due to the difference in the settings. In a non-zero-mean flow turbulence convection experiment near the gas–liquid critical point, BO scaling was observed for both KE and temperature (Ashkenazi and Steinberg, 1999). We recall that our deep-sea conditions are non-zero-mean flow, weak tides, very-high bulk Reynolds numbers O(10^5) given the large scales, and vary-

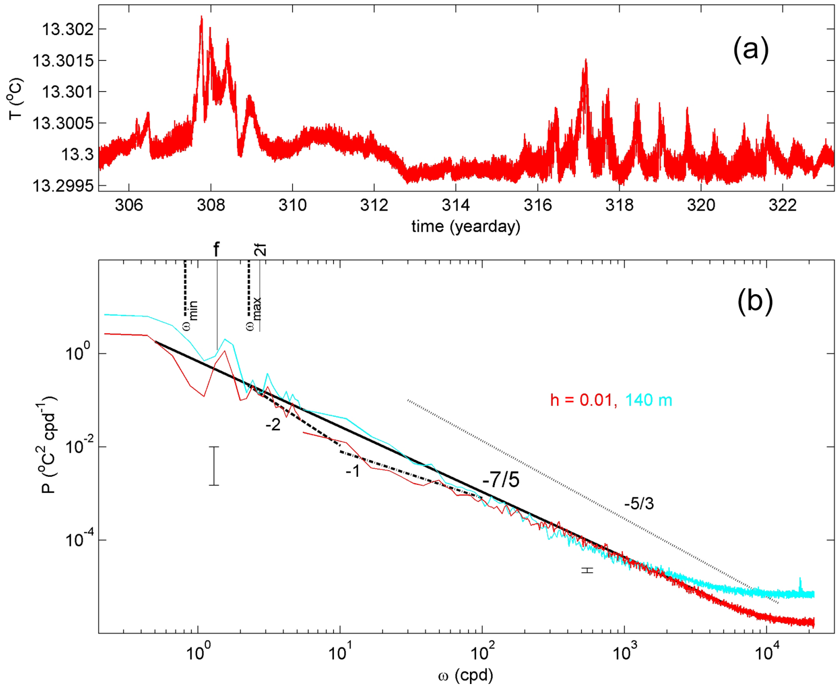

Figure 2. Eighteen days of high-resolution 2 s sampled temperature T data from a NIOZ T sensor that fell off a mooring line in 2020 and lay 0.01 m above a flat seafloor about 10 km south of the foot of the continental slope at 42°49.50′ N, 6°11.78′ E and 2458 m water depth, about 100 km WSW from the site in Fig. 1. For details on these data, see van Haren (2023a). **(a)** Time series of 18 d of raw temperature data. **(b)** Temperature variance spectrum that is stitched together using two spectra with different smoothings. Weakly smoothed (10 DOF; $\omega < 5$ cpd) and strongly smoothed (250 DOF; $\omega > 5$ cpd) spectra of the data are shown in panel **(a)**, with bars showing the respective 95 % confidence limits. For comparison, a spectrum is shown in cyan from data of a less precise T sensor at a drag-parachute line stuck at 140 m above the seafloor. The frequency and spectral slope indications are as in Fig. 1, while $-7/5$ (solid slope) indicates the BO scaling of an active scalar (e.g. Pawar and Arakeri, 2016). Note the different axis ranges compared with Fig. 1.

ing non-zero vertical density stratification, and our example spectra did not clearly resolve the KO scaling.

This 18 d T-sensor dataset demonstrates dominant deviations from the inertial subrange over several orders of magnitude of the frequency range. The mesoscale-IGW turbulence motions transport and locally mix warm waters with cooler surroundings outside a period of buoyancy-driven dense-water formation, which is thought to bring cooler waters downward during short periods of time.

5 How robust is the system of ocean circulation and stratification?

Any variation in the non-linear system of ocean circulation may encounter several complex feedback mechanisms of which the effects are not yet fully understood for the present-day ocean. Although stable density stratification hampers vertical exchange by turbulent mixing, it does not block it. While stratification supports internal waves and their destabilizing shear, turbulent mixing during a particular phase of a wave may decrease or destroy it locally in time and space. However, a subsequent internal wave phase will re-stratify the mixed patch, thereby maintaining its own support of sta-

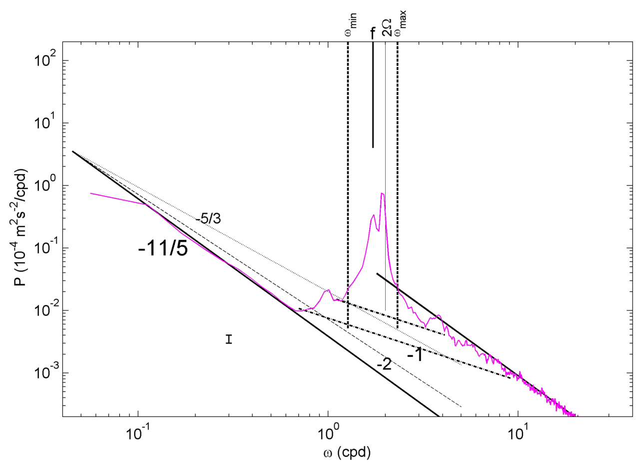

Figure 3. Like Fig. 1 with the same axis ranges but for strongly smoothed (50 DOF) KE spectra averaged over 400 d of data from a 600 s Valeport mechanical current meter moored at $z = -1000$ m over the Mid-Atlantic Ridge at 58°59.67′ N, 33°56.12′ W and 2540 m water depth in 2003/2004, within the project discussed in van Haren (2007). The small bar shows the 95 % confidence interval.

ble stratification. Such a feedback system may be at work, e.g. when the ocean absorbs more heat.

Increased sea surface temperature may lead to increased vertical density stratification, which may lead to less turbulent exchange as vertical overturning is suppressed. However, it will also lead to more internal waves through the extension of the spectral band to higher frequencies, with the potential for increased interaction, non-linearity, and turbulence-generating wave breaking. In particular, internal waves can propagate deep into the ocean interior away from their sources, and they can cause enhanced turbulent mixing elsewhere (e.g. Alford, 2003).

Limited observations have thus far not provided evidence of an inverse correspondence between changes in turbulent mixing and changes in temperature across the near-surface photic zone along a longitudinal section of the north-eastern Atlantic Ocean (van Haren et al., 2021b). This lack of correspondence suggests a feedback mechanism at work mediating potential physical environmental changes so that global warming may not affect vertical turbulent fluxes of heat and therefore also of e.g. carbon.

One such feedback mechanism may be convection turbulence induced by internal waves and sub-mesoscale eddies. Renewed analysis of year-long moored current meter data from the Irminger Sea in the North Atlantic Ocean demonstrates a significant $p = -11/5$ spectral slope at sub- and super-inertial frequencies (Fig. 3). As was outlined in van Haren (2007), the area showed an IGW band (Eq. 1) for $N = f$, with dominant sub-inertial shear at small 8 m vertical scales despite the dominant internal tidal KE. The correspondence to the Mediterranean data of Fig. 1 is striking, including the change in KE of 1 order of magnitude between sub- and super-IGW $p = -11/5$ slopes with similar $p = -1$ bridges albeit with uncertain crossing levels and similar heights of near-inertial peaks despite the tidal peak in Fig. 3.

Moored deep-water observations (e.g. van Haren and Dijkstra, 2021; van Haren et al., 2024) have demonstrated BO scaling at internal-wave-turbulence frequencies lower than the Ozmidov frequency, the largest scale at which isotropic 3D turbulent overturns can exist in a stratified environment. This is similar to stratified turbulence with low Froude numbers at horizontal scales of O(10–100) m exceeding the Ozmidov scale that includes non-linear internal waves (Riley and Lindborg, 2008; Falder et al., 2016; Chini et al., 2022). Horizontal wavenumber k_h spectra are presented, arguing that a scaling of $k_\mathrm{h}^{-5/3}$ in fact reflects stratified turbulence outside the inertial subrange of isotropic 3D turbulence. However, visual inspection also shows BO scaling in several figures of Riley and Lindborg (2008). As the internal wave–turbulence range is associated with vertical Froude numbers O(1), stratified turbulence has been associated with marginal stability in numerical modelling (Chini et al., 2022). Previously, marginal stability was described in the context of non-linear flows (Abarbanel et al., 1984) and e.g. in explanation of stratified North Sea observations (van Haren et al., 1999).

While few ocean observations have thus far been presented of BO scaling in comparison with KO scaling, perhaps also because of the lack of precision of standard oceanographic instrumentation, coupling has not been established between convection and stratified small-scale turbulence with mesoscale motions. Likewise, complicating factors include spectral interruption by internal waves. However, internal-wave trapping by mesoscale eddies has been described well (e.g. Kunze, 1985; Voet et al., 2024) and thus provides an obvious coupling between these motions. It is expected that such coupling will lead to strong non-linearity of the internal waves that in turn leads to turbulent mixing produced by wave breaking. Although such turbulent mixing is smaller than that induced by internal-wave breaking above a sloping topography, such coupling may be an important factor in downward transport of near-inertial energy that eventually breaks elsewhere, e.g. over topography.

As demonstrated using Mediterranean observations, not only convectively unstable cooler and/or saltier waters potentially lead to downward motions from the surface. Sub-mesoscale eddies and near-inertial waves can also push stratified waters into the deep sea. Such a downward push can be fast to transport materials from the surface to a 2500 m seafloor in a day (van Haren et al., 2006) and is of the same order of magnitude as attributed to dense-water convection (Schott et al., 1996). It can also be more turbulent compared to shear-induced motions in the stratified ocean interior, whereby turbulence reaches the seafloor according to a few observations of the abyssal Pacific (van Haren, 2020) and the alpine freshwater Lake Garda (van Haren and Dijkstra, 2021). Further extended observational evidence is urgently needed, preferably resolving much larger scales.

Although the anthropogenic influence on Earth's climate is certain, the impact on the ocean circulation is not fully known because we lack sufficient observational information on the relevant processes that cannot be modelled properly yet. Therefore, we should be cautious in making predictions (e.g. Ditlevsen and Ditlevsen, 2023; van Westen et al., 2024) about the future ocean circulation based on single parameters like ocean surface temperature or freshwater flux that are uncertain proxies. Because no observational (van Haren et al., 2021b), modelling (Little et al., 2020), or palaeo-proxy validation (Cisneros et al., 2019) physics evidence exists that sea surface temperature is a solid estimator of AMOC strength variations, other properties like vertical density gradients (stratification) and turbulence intensity may be considered. Small-scale physical processes such as transport by sub-mesoscale eddies and turbulence-generating breaking of internal waves that are not incorporated into these models will alter such parameters and thereby statistical analyses. This may lead to feedback mechanisms on property gradients such as density stratification so that large-scale ocean circulations like the AMOC may not collapse.

Variability of the ocean in space and time is a key to its dynamics, but it is unclear how robust such variations can be, e.g. whether shifting sites for deep dense-water formation (Gou et al., 2024) may be part of the same system. Observational evidence verifying numerical simulation outcomes, not only predictions but also present-day ones, of the ocean state is needed. Observations are also required to demonstrate variability in relevant physics processes for model implementation. Besides eddies and coupling with the atmosphere (e.g. Gent, 2018), numerical models of complex nonlinear ocean circulation should contain internal-wave turbulence with appropriate space and time dependency. The importance of internal-wave breaking leading to boundary mixing above a sloping topography in general ocean circulation models has been acknowledged in various ways (Scott and Marotzke, 2002; Ferrari et al., 2016).

As for the ocean circulation in the horizontal plane near its surface with the most impact on humans, wind will remain the main driver. As long as Earth's rotation does not alter the direction, wind will maintain its general course (Wunsch, 2004). The atmosphere remains the key player in the global heat transport across the mid-latitudes rather than the ocean. Simultaneously, the importance of processes like stratification and turbulent mixing induced by e.g. internal-wave breaking with or without sub-mesoscale coupling cannot be underestimated for life near the ocean surface or in the deep ocean, because this would come to a halt without such processes.

Data availability. No new data were created or analysed in this study: re-plotted and re-analysed data were presented in van Haren and Millot (2003) and van Haren (2007, 2023a). They are available from the author upon reasonable request.

Competing interests. The author has declared that there are no competing interests.

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