

# Evidence of High Vertical Wave-Number Behavior in a Continuously Stratified Reservoir: Boadella, Spain

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**Abstract:** High vertical wave-number modes clearly dominate the internal wave field during the stratification period in Boadella reservoir in northeast Spain. In this period, the extraction of hypolimnetic water, due to summer irrigation, brought the surface level down by 6 m in one month and the epilimnetic water progressively occupied the whole water column. The temperature profile, with the exception of a few meters at the surface layer, presented an almost constant temperature gradient of about 0.7°C/m. The period of the main vertical mode is 24 h with an amplitude of around 1 m. Thermistor chain records and meteorological data allow us to deduce that this mode is, at least, a third vertical mode forced by the wind, which normally has a typical periodicity of 24 h. However, when the wind changes direction from south to north, the circulation cells developed due to this forced nonstationary oscillation are destroyed. When this occurs, the Bulk Richardson number is  $Ri_b \sim 1$ . Similar vertical structures as a response to wind forcing should be expected in similar systems, although this has not been reported in the literature.

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## Introduction

Although internal seiching in lakes and reservoirs has been widely discussed (Imberger and Patterson 1990; Imberger 1994; Straskraba and Gnauck 1985), and high vertical modes are usually assumed that can be excited, they have scarcely been reported. General agreement exists that thick metalimnions enhance the excitation of second vertical modes (Stevens and Imberger 1996) and that they are associated with wind forcing (Wiegand and Chanberlain 1987; Münnich et al. 1992). However, wind resonance is not a necessary condition for second vertical modes, as Roget et al. (1997) reported. Vertical modes larger than the second are even more uncommon in the literature, with a few exceptions (LaZerte 1980; Antenucci et al. 2000). This might be because the study of the internal modes has usually focused on the thermocline depth. Also, due to the superposition of different modes, higher vertical modes can be erroneously interpreted as second modes. In this paper, we present a clear picture of a sustained high vertical mode in response to the wind in Boadella reservoir, using temperature data recorded during the irrigation season, when the reservoir was continuously stratified.

Sustained internal low-speed oscillations is a widely studied topic, in both lakes and oceans (Rippeth et al. 2001; Lorke et al. 2002). This is because of their relationship to the distribution of living organisms and also to the resuspension of particles and nutrients, which contribute to the generation of bottom boundary layers (Pierson and Weyhenmeyer 1994). In the case of the Boadella reservoir, a particle boundary layer is also developed every year, with maximum values for particle concentration at the end of the summer (Casamitjana et al. 2001, 2002).

Boadella reservoir (Fig. 1) is located in the northeast of Spain in the eastern pre-Pyrenees (42° 20' 15" N, 2° 21' 07" E). Its full elevation is 160 m ASL (above sea level) and its base is at 106 m ASL. It has a maximum capacity of 62 Hm<sup>3</sup> and a maximum surface area of 364 Ha. Water inflows occur through two main tributaries: the Muga and the Arnera (Fig. 1). It has been estimated that the Muga contributes 65% of the total inflow budget, while the Arnera contributes approximately 35%. Outflow levels are located at 154 m (spillway), 127, 118, and 116 m ASL. A certain percentage of the outflow water is returned to the river as "ecological flow." The remaining outflow water is used to supply drinking water to the town of Figueres and other small towns downstream, and to sustain a hydroelectric plant. After leaving the plant, this water is used to irrigate fields. The outflow water given over to irrigation is highest in summer. For example, in the summer of 2000, 61% of the total withdrawn water was used for this purpose. This water was withdrawn through the deepest outlet, i.e., the one situated at 116 m ASL.

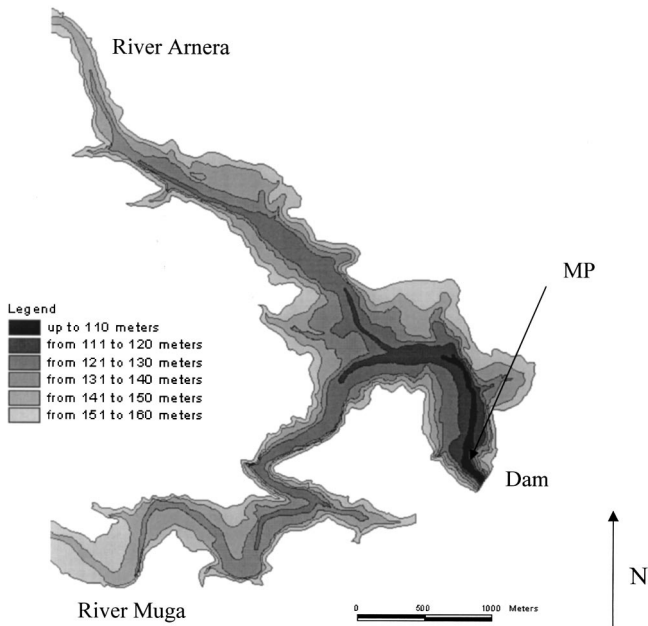
The thermal evolution of the reservoir depends mainly on interannual rain variability (which is high in the Mediterranean climate), and on management policy. In fact, the start of the irrigation season, in summer, marks a change in the stratification process initiated in early spring. Due to the extraction of the hypolimnetic water, the warm, oxygenated, and phosphorous depleted epilimnetic water gradually occupies the whole reservoir

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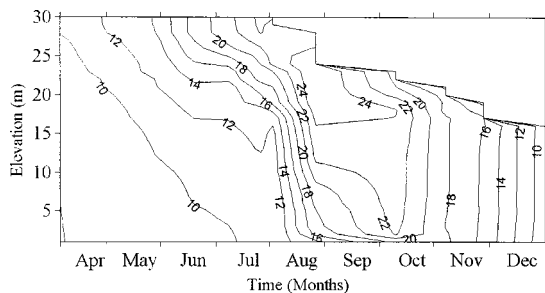
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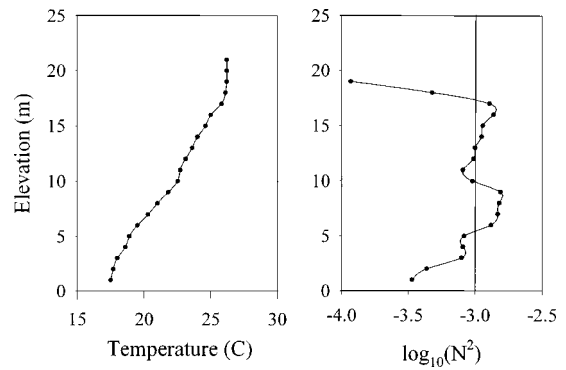
**Fig. 1.** Bathymetric map of Boadella reservoir showing the location of the measurement station (MP). Contour intervals, in meters, refer to height above sea level.

with no seasonal thermocline and a continuously thermal stratified water column (Fig. 2). At the beginning of summer, the isotherms begin to descend at a rate of about 1 m per day. At the end of summer the whole water column is weakly stratified and the annual overturn process is nearly completed.

The data analyzed in this report was recorded from the 6th to the 30th of July 1998, when the surface level dropped from 28 to 22 m (Fig. 2). During this period, the stratification gradient was nearly constant (about  $0.7^{\circ}\text{C}/\text{m}$ ). The temperature data was recorded by a Thermistor string every 10 min at 2, 3, 4, 8, 10, 11, 12, 13, 14, 15, and 16 m above the bottom, at a station located 300 m from the dam wall (Fig. 1). Unfortunately, the continuous measurements do not cover the whole water column. Fig. 3 shows the temperature and the logarithm of the stratification frequency ( $\log_{10} N^2$ ) from a profile of the whole water column, which was recorded on July 27, 1998. The isotherms represented in Fig. 2 show that the stratification frequency profile should be expected to be similar for the other days of the period, as is confirmed with the continuous data in the last 16 m.



**Fig. 2.** Thermal structure of Boadella reservoir from March 3 to December 3, 1998. Lines show the isotherms, in  $^{\circ}\text{C}$ , computed from data recorded every 20 days, at the station shown in Fig. 1.

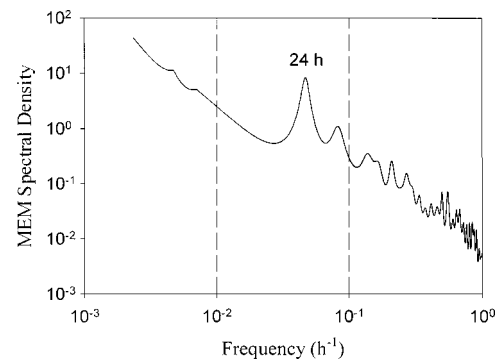


**Fig. 3.** Temperature and stratification frequency ( $\log_{10} N^2$ ) profiles on July 27, 1998

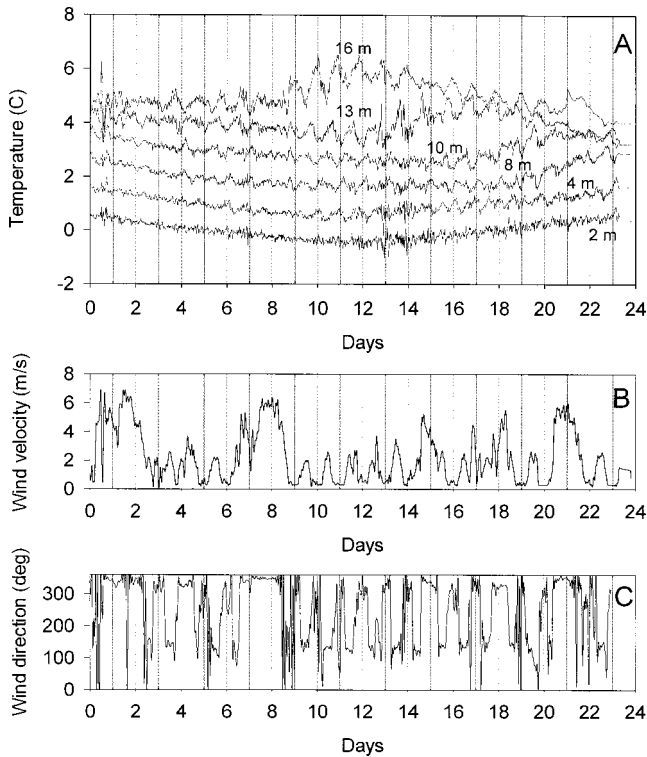
### Analysis of Forced Wave Field

Wave analysis from temperature data at a fixed position is usually carried out after computing the depth location of the isotherms. However, in this case, due to the significant descent of the isotherms through the water column during the period under study, the data series of the depth position of the isotherms was very short, and none of them covered the whole period. Because of this, although wave amplitude was obtained from the isotherms' location, the mode analysis is mainly presented from temperature data recorded at a fixed depth. Because the mean temperature gradient of the lower 18 m of the water column was relatively constant within the studied period, the spectral decomposition of the internal wave field does not present any significant shift in the frequency of the main oscillations. The maximum entropy spectral analysis of the  $17^{\circ}\text{C}$  isotherm, which covers most of the period under study, is presented in Fig. 4. As observed, high energy peaks are found at different frequencies from  $4.1 \times 10^{-2} \text{ h}^{-1}$  to  $5.0 \times 10^{-1} \text{ h}^{-1}$ , i.e., within a period range from about 24 to 2 h; the highest energy peak corresponds to that of 24 h (Fig. 4).

Fig. 5(a) shows the temperature data recorded at depths of 2, 4, 8, 10, 13, and 16 m from the bottom, after performing a linear detrend and vertically shifting the zero. In spite of the superposition of different modes, the mode of 24 h dominates and can be seen to oscillate completely out of phase between 16 and 10 m, and also between 10 and 4 m. This indicates the excitation of a third vertical mode. However, considering that data from the



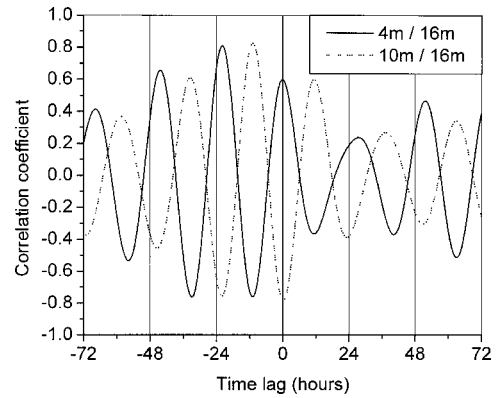
**Fig. 4.** Maximum entropy method spectral density of the  $17^{\circ}\text{C}$  isotherm, from the 8th to 26th of July 1998. Parameters used in the maximum entropy method were  $N=2,549$ ,  $m=180$ , the measuring frequency being  $0.1667 \text{ h}^{-1}$ .



**Fig. 5.** Water temperature and wind data from the 6th to 30th of July 1998. Grid lines correspond to zero hours (solar time) every day. (a) Temperature variations recorded every 10 min at 2, 4, 8, 10, 13, and 16 m from the bottom, at the measuring point (see Fig. 1), (b) wind velocity, and (c) wind direction.

upper part of the stratified water column was not available, even a higher vertical mode may also have been excited. Wind data were recorded every hour at Cabanes station, located 15 km from the reservoir [Figs. 5(b and c)]. It can be seen that the wind pattern is highly regular due the daily southeasterly wind (sea breeze), which blows at about  $140^\circ$  southeast, with a mean maximum velocity of about 3 m/s. When the sea breeze is not present, the wind blows from the north, usually at velocities lower than 1 m/s. However, there are certain episodes where the velocity of the north wind reaches 6 m/s and is maintained throughout the day. This is observed on days 1, 2, 7, and 21. A high correlation between the 24-h oscillations observed in Fig. 5(a) and the wind pattern is seen when Figs. 5(a, b and c) are compared. More precisely, the maximum velocities of the southeasterly wind, which normally occur in the middle of the day, correspond to the minimum temperatures at 16 m. This can be observed on days 9 to 13 (note that the grid lines of Fig. 5 correspond to 0:00 hours of every day). However, during the days that the north wind predominates, the 24-h oscillation is somewhat dampened (see, for instance, days 1, 8, and 21).

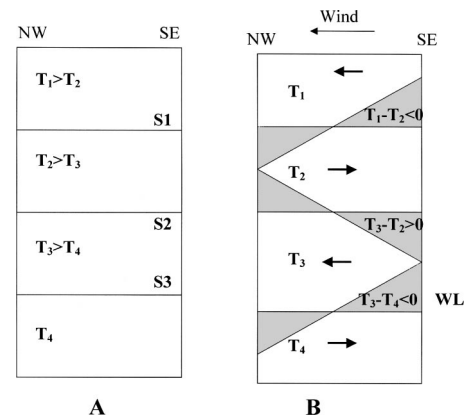
To better illustrate the existence of higher vertical mode, Fig. 6 shows the normalized cross-correlation function (Orfanidis 1996) between the temperature at 16 and 4 m, and again at 16 and 10 m after bandpass-filtering. To be more precise, a third order Butterworth filter was used, and the corresponding band period ranged from 16 to 30 h. As can be seen, both correlation functions present periodic fluctuations of 24 h and they are completely out of phase. At a time lag of zero hours, the correlation between the temperatures at the deepest points (continuous line) is maximum and the correlation between the medium and shallowest points



**Fig. 6.** Normalized correlation functions computed from temperature data recorded every 10 min, at 4, 10, and 16 m above bottom

(dotted line) is minimum, as expected for a third vertical mode. Further, an angle-shift of  $\pi$  rad between the two correlation functions is constant for all time lags.

The phenomenology described above is schematized in Fig. 7 where the reservoir, which is continuously stratified, is presented as a four-layer system with mean layer temperatures decreasing downwards. In Fig. 7(a), where the system is represented in the stable situation,  $S1$ ,  $S2$ , and  $S3$  stand for measuring points at different depths and at different layers. In Fig. 7(b) the system is represented under the effect of the wind. As can be seen in Fig. 5(b), the wind begins to blow during the morning, reaches its maximum intensity at about noon, and calms down again in the evening (e.g., see day 10). As a consequence, at the end of the day, water has been dragged along the fetch direction forcing the isotherms to tilt, as shown in Fig. 7(b). Because of this, the temperature at station  $S1$  decreases (from  $T1$  to  $T2 < T1$ ), while at station  $S2$  it increases (from  $T3$  to  $T2 > T3$ ) and at station  $S3$  it decreases (from  $T3$  to  $T4 < T3$ ). This behavior can be directly observed in Fig. 5(a) from the temperature data recorded at 16, 10, and 4 m. The amplitude of the oscillation can be estimated as follows. As the measuring point MP is close to one extreme of the



**Fig. 7.** Scheme of third vertical mode. (a) Four-layer system in equilibrium.  $S1$ ,  $S2$ , and  $S3$  represent measuring stations located at different depths.  $T1$ ,  $T2$ ,  $T3$ , and  $T4$  stand for temperature of each layer, increasing upwards. (b) Tilting of interfaces after third mode was excited. Differences of temperature indicated at measuring stations show variation of temperature within one quarter of oscillation period. At stations  $S1$  and  $S3$ , temperature decreases, while at station  $S2$  it increases. Withdrawal level schematizes water withdrawal level.

fetch direction (Fig. 1) and assuming, as in Fig. 7, that this high vertical mode corresponds to a first longitudinal, the maximum amplitude of the oscillation is expected to be only slightly larger than it is in the measuring point. By assuming temperature amplitudes of  $\sim 1.5^\circ\text{C}$  [Fig. 5(a)], as the mean temperature gradient is  $0.7^\circ\text{C}/\text{m}$ , an amplitude of  $\sim 2\text{ m}$  can be predicted.

It is instructive to compare our results with those obtained by Koseff and Street (1985). These writers conducted various experiments to study the circulation patterns in a stratified lid-driven cavity flow. The typical flow structure they observed consisted of a primary circulation cell and a number of secondary cells. The number of secondary circulation cells was related to the Bulk Richardson number,

$$Ri_b = g(\Delta\rho/\rho)D/U_b^2 \quad (1)$$

where  $g$  = gravity acceleration;  $\Delta\rho$  = density difference between the top and the bottom of the cavity;  $\rho$  = reference density;  $D$  = cavity depth; and  $U_b$  = speed of the lid. When  $Ri_b \gg 1$ , at least two secondary circulation cells are present in addition to the primary cell. When  $Ri_b \sim 1$ , a primary circulation cell dominates the flow. When  $Ri_b \ll 1$ , the mixed layer eventually penetrates to the lower boundary of the cavity and the circulation is very similar to the isothermal flow. We can estimate  $Ri_b$  for the case of the Boadella reservoir during the period under study, by using the values of  $\Delta\rho/\rho = 1.6 \cdot 10^{-3}$ , corresponding to a difference between the surface and the bottom layer of approximately  $8^\circ\text{C}$  and  $D = 25\text{ m}$  (Fig. 2). For the  $U_b$  value, in the reservoir, we can use the value of the mixed layer velocity  $U$  calculated by using the simple momentum balance

$$d/dt(hU) = u_*^2 \quad (2)$$

where  $h$  = mixed layer depth;  $u_* = (\rho_A/\rho C_D)^{1/2}U_w$  = shear velocity;  $\rho_A$  = air density;  $C_D = 1.3 \cdot 10^{-3}$  = bulk aerodynamic coefficient; and  $U_w$  = wind velocity. Eq. (2) has been shown to be true for the first quarter wave period of the internal wave, provided that the upper mixed layer ( $h \sim 3\text{ m}$  in our case) is much thinner than the other layers (Monismith 1985). Integration of Eq. (2) leads to  $U = u_*^2 t/h$ . We assume that the maximum value of  $U$  is reached when  $t = 6\text{ h}$ , i.e., at the quarter of a wave period, and we use this value in Eq. (1). With all the previous assumptions, when  $U_w = 3\text{ m/s}$ , i.e., a typical wind velocity of the southeasterly wind [Fig. 5(b)],  $Ri_b = 40 \gg 1$ , and therefore the presence of higher vertical modes should be expected. When  $U_w = 7\text{ m/s}$ , i.e., a typical velocity of the northern wind [Fig. 5(b)] then  $Ri_b = 1.3$  and the response of the system in terms of high vertical wave-number structures is no longer seen, according to the Bulk Richardson criteria. However, the relative contribution of wind intensity and wind direction in the destruction of the layered system should be evaluated in further research.

It is important to point out that the tilting of the interfaces associated with the main oscillation mode of the Boadella reservoir may affect the quality of the withdrawn water. In the studied period, water was withdrawn during the mornings from the deepest outlet (see Fig. 7). In September, at the end of the stratification period, there is an accumulation of particles at the bottom of the reservoir forming a particle boundary layer (Casamitjana et al. 2002). The distribution of particles is formed by dead cells of diatoms and green algae, which have sedimented from the surface layers, and also by a mixture of aggregates of inorganic particles, colonies of phytoplankton, zooplankton detritus, etc. If water withdrawal were changed by 12 h, the quality of the water would probably change. During the first half of the day, the slope of the

interfaces is as shown in Fig. 7. Therefore, water withdrawn comes from the bottom layers. However, after 12 h, when the slopes are reversed, water would be withdrawn from the upper layers. Detailed analysis of the daily variation of the water quality parameters near the dam are needed in order to verify if changing the time of water withdrawal would improve water quality.

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