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Rheological properties of natural waters with regard to plankton thin layers. Part 2. A model of pycnocline thickness modified by exopolymeric substances.

by

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Abstract

We model how phytoplankton exopolymeric substances (EPS) may change pycnocline thickness δz through control by Richardson number *Ri*. Shear stress τ_{forced} is imposed across the pycnocline, giving a shear rate $\delta u/\delta z$, where δu is cross-pycnocline velocity difference, modulated by viscosity η. In natural waters viscosity is composed of two components. The first is Newtonian, perfectly dispersed viscosity due to water and salts. The second is non-Newtonian, and depends on phytoplankton abundance raised to an exponent between +1.0 and +1.5. It is also generally shear-thinning, depending on $(\delta u/\delta z)^P$, where P is negative. In suspensions of microbial aggregates viscosity depends also on $(\text{length scale})^d$. Published measurements of EPS rheology in a culture of *Karenia mikimotoi* are input. These measurements were made at 0.5 mm, so they can be scaled to $\delta u/\delta z$ if d is known for this EPS over the appropriate range of length scales. The model shows that $\delta u/\delta z$ is very sensitive to d. At values of d < -0.2 or -0.3, however, high concentrations of *K. mikimotoi* (<31 million $^{L-1}$) have no significant effect on δz at ambient values (>1 cm). Future investigations of pycnocline dynamics should include measurements of rheological properties, and particularly d.

KEYWORDS: Rheology, phytoplankton, pycnocline, thin layer, exopolymeric substance, biogeochemistry

1. *Introduction*

A companion paper (Jenkinson, submitted to this volume) reviews the state-of-the-art of the rheology and rheometry of natural waters. Thin layers (TLs) of dense phytoplankton often occur associated with density discontinuities, or pycnoclines, in coastal seas (Bjørnsen et al., 1993; Dekshenieks, 2001; Alldredge et al., 2002, GEOHAB, 2008), oceans and lakes. Since dense phytoplankon is often associated with increased viscosity as well as elasticity of the seawater or lake water (Jenkinson, submitted to this volume, and references therein), the question arises whether the phytoplankton in such TLs may alter pycnocline characteristics through the rheological affects of their secreted extracellular polymeric substances (EPS). We begin this investigation by modeling the possible effects of increased viscosity on pycnocline thickness. Published values are used for the viscosity and elasticity of seawater (Jenkinson, 1993b; Jenkinson and Biddanda, 1995) and phytoplankton cultures (Jenkinson, 1986, 1993a). Recent findings that the effects of length scale on rheological properties of heterogeneous suspensions of microbial flocs can be modeled using a power law (Jenkinson and Wyatt, 2008) are applied to a natural-water situation for the first time The aim of using this model is to help identify appropriate targets for future research on TL and pycnocline dynamics.

In this paper, the model is presented, some results for seemingly appropriate values of pycnocline parameters, and densities of the harmful algal bloom (HAB) dinoflagellate *Karenia mikimotoi*, that occurs widespread, often forming TLs in relation to pycnoclines (Bjørnsen et al., 1993). Rheological measurements in cultures and seawater have been measured at a length scale only of 0.5 mm, and it is shown that whether rheological effects can modify the values of pycnocline thickness that actually occur, will depend critically on the length scale exponent *d*. Since this model has so far no field data with which to validate it, we then discuss appropriate targets for future investigation.

2. *Model setup and examples*

The aim of this model is not to predict the dynamics of thin layers or pycnoclines. It is to suggest how thin layers or pycnoclines may be sensitive to modification by algal EPS, particularly those of *Karenia mikimotoi*.

We build the model with a standard set of parameters, ready to change each parameter separately for numerical experiments (Table 1). This is a 1-D 3-layer equilibrium model of a pycnocline (Fig. 1) in which Richardson number Ri determines the thickness.

There are three layers: an upper and a lower mixed layer, with a stratified pycnocline between them. The mixed layers are turbulent, with a turbulent eddy viscosity A_z of 10^{-1} to 10^{2} Pa.s in the vertical plane (Massel, 1999), several orders of magnitude greater than the viscosity in the pycnocline, that comprises only molecular viscosity η. There exists a difference in density $\delta\rho$ between the upper and the lower mixed layers, which we vary around a standard value of 1 kg.m^{-3}, and this produces a uniform vertical gradient $\delta\rho/\delta z$ in the pycnocline, where δz is the thickness of the pycnocline. The mean density of the water ρ is all layers is set to 10^{3} kg.m^{-3}, and we ignore the 0.1% or so variation induced by $\delta\rho$.

Initially we consider the pycnocline without phytoplankton or its associated EPS. Eddies in this layer are damped by the stratification, so the only resistance to shearing is that due to molecular viscosity due to water and salt, η_W that is set at 10^{-3} Pa.s. Because of the large difference between the viscosity in the mixed layers A_z, shearing is neglected in the mixed layers, and assumed to take place only in the pycnocline. Vertical shear rate in the pycnocline,

$$\dot{\gamma} = \tau / \eta_W \qquad [\mathrm{s}^{-1}] \qquad (1)$$

The velocity difference between the top and base of the pycnocline,

$$\partial u = \partial z.\dot{\gamma} \qquad [\mathrm{m.s}^{-1}] \qquad (2)$$

Pycnocline stability is governed by the Richardson number (Mann and Lazier, 2006),

$$Ri = \frac{g\,{}^{\delta\rho}\!/\!_{\delta z}}{\rho({}^{\delta u}\!/\!_{\delta z})^2} \qquad [\text{dimensionless}] \ (3)$$

where g is the acceleration due to gravity.

When Ri becomes < 0.25, turbulence is generated within the pycnocline, which entrains water in from one or both mixed layers, thus increasing its thickness (Mann and Lazier, 2006). In this equilibrium model, we fix a critical Richardson number $Ricr$ at 0.25. Substituting $Ricr$ for Ri in (3) and rearranging,

$$\delta z = Ricr.\rho \frac{(\delta u)^2}{g.\delta\rho} \qquad [\mathrm{m}] \qquad (4)$$

Turbulent energy dissipation rate ε in the oceans varies typically from 10^{-6} to 10^{-9} m^{2}.s^{-3} (Mann and Lazier, 2006). Assuming a value for η of 10^{-3} Pa.s, this gives a corresponding value for $\dot{\gamma}$ of 1 to 0.03 s^{-1}, corresponding to a value of shear stress τ of 10^{-3} to 3×10^{-5} Pa.

Now we add phytoplankton and its associated EPS, in this case *K. mikimotoi* (syn.: *Gyrodinium aureolum*). Jenkinson (1993a) measured the rheological properties of a culture of 4.4 cells.µL^{-1} of *K. mikimotoi* over a range of $\dot{\gamma}$ from 0.0021 to 8 s^{-1}. His results are reproduced in Fig 2. From measurements of Jenkinson's Fig.1, it may be deduced that the excess viscosity (due to EPS) varied with $\dot{\gamma}$ thus,

$$\eta = \eta_W + \eta_E \qquad \text{[Pa.s]} \quad (5)$$

$$\eta_E = 1.27\text{x}10^{-4}.\,\dot{\gamma}^{\,-0.75} + 3.16\text{x}10^{-4}.\,\dot{\gamma}^{\,-0.18} \qquad \text{[Pa.s]} \quad (6)$$

Like viscosity, shear stress can be similarly decomposed into the Newtonian part due to water and salts and an excess part due to EPS. So from (1),

$$\tau_W = \eta_W \,.\, \dot{\gamma}\ , \quad \tau_E = \eta_E \,.\, \dot{\gamma}\ , \quad \tau = \eta \,.\, \dot{\gamma} \qquad \text{[Pa]} \quad (7)$$

Multiplying both sides of (6) by $\dot{\gamma}$ gives the excess shear stress for this culture

$$\tau_E = 1.27\text{x}10^{-4}.\,\dot{\gamma}^{\,+0.25} + 3.16\text{x}10^{-4}.\,\dot{\gamma}^{\,+0.82} \qquad \text{[Pa]} \quad (8)$$

Excess viscosity is generally proportional to a power of the concentration of the causative agent, whether this is a dissolved polymer (Ross-Murphy and Shatwell, 1993) or phytoplankton. For phytoplankton, Jenkinson and Biddanda (1995) found the power to be about 1.3. We assume the same power-law relationship between τ_E and *K. mikimotoi* concentration *Km*,

$$\tau_E = (1.27\text{x}10^{-4})\,.\,(Km\,/\,4.4)^{1.3}.\,\dot{\gamma}^{\,+0.25} + (3.16\text{x}10^{-4})\,.\,(Km\,/\,4.4)^{1.3}.\,\dot{\gamma}^{\,+0.82}) \qquad \text{[Pa]} \quad (9)$$

that simplifies to

$$\tau_E = 1.85\text{x}10^{-5}.Km^{1.3}.\ \dot{\gamma}^{\,+0.25} + 4.6\text{x}10^{-5}.Km^{1.3}.\ \dot{\gamma}^{\,+0.82} \qquad \text{[Pa]} \quad (10)$$

Spinosa and Lotito (2003) investigated the yield stress, or resistance to flow just enough to stop flow τ_y in sewage sludge in tubes of different diameters. Their data show that, for different sludge concentrations,

$$\tau_y \sim L^d \qquad \text{[Pa]} \quad (11)$$

where *L* is length scale, in this case tube diameter, and *d* is an exponent in this particular case close to -2. The particular value of *d* might be related to the fractal dimension of the aggregates' shape, size distribution, or both. Like sewage sludge aggregates, marine aggregates and transparent exopolymeric particles (TEP) are quasi-fractally hierarchical organic aggregates rich in EPS (Mari and Kiørboe, 1996).

However, in places where the rheologically active polymer in the sea is more diffuse, then *d* is likely closer to zero, but the effect of length scale on seawater rheological properties has not yet been investigated. The rheological data in Jenkinson (1993a) were all obtained using Couette flow with a measuring gap of 0.5 mm. Therefore to model the effect of *d* (for simplicity assumed to be the same over all values of $\dot{\gamma}$) on excess viscosity, we take the appropriate *in situ* length scale to be δz, applying a "correction" relative to the value of *L* equal to $(\delta z/L)^d$ thus:

$$\tau_E = (1.85\text{x}10^{-5}.Km^{1.3}.\ \dot{\gamma}^{+0.25} + 4.6\text{x}10^{-5}.Km^{1.3}.\ \dot{\gamma}^{+0.82}).(\delta z/L)^d \qquad [\text{Pa.s}] \quad (12)$$

We take the appropriate value of $\dot{\gamma}$ to be the shear rate vertically through the pycnocline, ($\delta u/\delta z$), so that

$$\tau_E = (1.85\text{x}10^{-5}.Km^{1.3}.\ (\delta u/\delta z)^{+0.25} + 4.6\text{x}10^{-5}.Km^{1.3}.\ (\delta u/\delta z)^{+0.82}).(\delta z/L)^d \qquad [\text{Pa.s}] \quad (13)$$

τ_E thus depends on *Km*, $\delta u/\delta z$, δz and *d*. The resistance to shearing by the water phase (water + salt),

$$\tau_W = \eta_W\ .\ (\delta u/\delta z) \qquad [\text{Pa}] \quad (14)$$

where η_W is independent of both shear rate and length scale and is assumed to be 0.001 Pa.s. We have taken respective values for $\delta\rho$ and ρ to be 1 and 1000 kg.m^{-3}. Combining (5) and (14),

$$\tau = \tau_W + \tau_E \qquad [\text{Pa}] \quad (15)$$

To run the model, let us first consider an example of no plankton (Km = 0 cells.µL^{-1}) and a forced shear stress across the pycnocline τ_{forced} = 0.0001 Pa. Here the value of *d* makes no difference to the outcome. The computation proceeds in two steps.

In step 1, values are put in for a forced shear stress τ_{forced} and a value is guessed for δz .We solve for $\tau = \tau_{forced}$ and read off the corresponding value for pycnocline shear rate $\delta u/\delta z$ = (Fig. 3a).

In step 2, δz is now calculated in two ways, firstly from (2), using a range of values for δu, and secondly from (4) (where δz is called δzz), using the same range of values for δu. Here when $\delta z = \delta zz$, δz is read off as well as a new value for δu. (Fig. 3b). As confirmation, *Ri*, calculated from (3), equals *Ricr* always at the same value of δu as when $\delta z = \delta zz$. In the present case, τ equals τ_W since in the absence of phytoplankton and EPS, τ_E is zero

Iteration now proceeds by repeating step 1, putting in the value of δz obtained in step 2, and so on, until the values remain unchanged. In this case δz = 4.0 m, δu = 0.4 m.s^{-1}, $\dot{\gamma}$, or $\delta u/\delta z$, = 0.1 s^{-1}, $\eta = \eta_W = 10^{-3}$ Pa.s, and the buoyancy frequency $N^2 = 2.5 \times 10^{-3}$ rad.s^{-1}.

Now let us add phytoplankton EPS to the model with Km = 4.4 cells.µL^{-1} and $d = 0$ (rheological properties independent of length scale) and, as before, τ_{forced} = 0.0001 Pa. The results are shown in Fig. 3c, d. In Fig. 3c. While the contributions, τ_{Hi}, $\tau_{Lo,}$ τ_E, τ_W and τ_{are} each shown, the co-ordinate of τ-$\dot{\gamma}$ is retained for input to step 2. After iteration, this simulation with phytoplankton EPS gives δz = 50.0 m, δu = 1.43 m.s^{-1}, $\dot{\gamma}$, or $\delta u/\delta z$, = 0.029 s^{-1}, $\eta = 3.5 \times 10^{-3}$ Pa.s, and $N^2 = 2.0 \times 10^{-4}$ rad.s^{-1}.

The code is available at http://assoc.orange.fr/acro/TL/SupInfo.html .

3. Results

In our model pycnocline, the Richardson number *Ri* controls its thickness. With no extra viscosity from phytoplankton EPS, Fig. 4a illustrates that δz shows a linear relationship with $\delta\rho$, and is proportional to the square of τ_{forced}.

At our standard value for τ_{forced} of 0.0001 Pa, and -0.2 for *d*, Fig. 4b shows how *K. mikimotoi* concentration *Km* progressively increases δz, by over 3 times when *Km* = 10 cells μL^{-1}. The two lower curves, for *Km* = 0.1 and 0.316 cells μL^{-1}, cannot be distinguished, and even the curve for *Km* = 1 cell μL^{-1} is barely distinguishable. The relative effect is higher at lower values of τ_{forced}. (Supplementary Table 1 http://assoc.orange.fr/acro/TL/091011SupTab1.xls). Fig. 4b also shows that the effect of *Km* on δz decreases as δz itself increases, This is because the negative value of *d* lessens the functional value of viscosity η as pycnocline thickness increases

Fig. 4c shows the effect of *d* on relationship between δz and $\delta\rho$, in relation to that when *Km* =0. When *Km* is the standard value 4.4 cells μL^{-1} and *d* is zero, and over the range of length scales of interest here, the EPS would be perfectly dispersed. (Water and its viscosity η_W are also perfectly dispersed). Such perfect dispersion of EPS would give thickening independent of length scale, and this is why the curve for *d* = 0 is parallel to that for *Km* = 0. For negative values of *d*, in contrast, as δz increases, η_E decreases, so the curves tend down towards that for *Km* = 0.

4. Discussion

There have recently appeared complaints of models that show "failure to fail", for instance in plankton trophic models (Franks, 2009), while in the field of rheology, Woodcock (2009) bemoans, "computer modeling with many-parameter models is neither 'theory' nor 'experiment'. Moreover, it's not research, it[']s 'animation'!". The present model, in contrast, aims to suggest which parameters are critical to pycnocline dimensions, and under which conditions, and which are not. Our aim is not to animate, but to help focus the attention of future research.

Previous work (Jenkinson 1986, 1993b) modeled, and attempted to predict, the effect of the shear-thinning exponent of phytoplankton EPS on isotropic turbulence. As explained by Jenkinson (submitted to this volume), however, a 10-fold increase in Newtonian viscosity (sucrose solution) imposed for calibration of those experiments did not significantly change the size of turbulent eddies, possibly because the 3-L container constrained a harmonic system of eddies (Jenkinson 2004b).

Later work (Jenkinson et al., 2007; Jenkinson and Wyatt, 2008) pointed out that data presented by Spinosa and Lotito (2003) indicated that the yield stress in suspensions of microbial flocs is strongly length-scale-dependent. This implies that EPS thickening in natural waters is likely to depend not only on the shear-thinning exponent of the polymers *P*, but also on the length-scale exponent *d* and, of course, the EPS abundance and type.

P has already been measured in the sea (Jenkinson 1993b, Jenkinson and Biddanda, 1995) and in phytoplankton cultures (Jenkinson, 1986, 1993a) as mentioned above, while the effect of *P* on isotropic turbulence has also been modeled (Jenkinson, 1986, 1993b, 2004a). The present model, therefore, has kept *P* constant and investigates the effects of changing *d* and the concentration *Km* of a *K. mikimotoi* bloom, whose rheological properties correspond to a culture measured by Jenkinson (1993a) at a known length scale. Comparison of Fig. 4b to Fig. 4c shows that for an imposed shear stress τ_{forced}, changing *d* from 0 to -0.2 changes pycnocline thickness δz by a factor of 10 or more, while a hefty bloom with *Km* of 10 million cells L^{-1}, and *d* = -0.2, increases δz only ~5 times more than with no phytoplankton.

It is important to note that for values of *d* of -0.4 or more negative, the effect of blooms on pycnocline thickness is practically negligible at realistic values of δz, say 1 cm or more, even for blooms of high concentration. To understand whether EPS thickening may be affecting δz *in situ*, effort should be given to measuring *d* in different blooms and cultures. As mentioned, a value for *d* of 0 corresponds to a perfectly dispersed polymer solution, so by changing the flocculation parameters of its EPS, a bloom organism may have the potential to radically change its local environment over a wide range of scales. Simple changes in molecular properties may thus be under strong, and perhaps competing, evolutionary pressures related to niche engineering by bloom species (Jenkinson and Wyatt, 1992; 1995, 2008; Wyatt and Ribera d'Alcalà, 2006). Marine snow and TEP (Alldredge et al., 2002) are common in pycnoclines, and probably form an important component in the allometric floc-size continuum, thus probably influencing *d*.

In aquatic systems, biological and physico-chemical processes, such as diffusion, mixing and encounter, are governed by water deformation, so viscosity and elasticity need to be measured and known at the scales of each process under consideration. Measurement over a range of scales will furthermore allow *d* to be determined, and to be extrapolated, with caution, to other length scales. Associated with such measurements of physical properties, an intense research effort is needed to visualise water movement, together with videos of flocculation and break-up of EPS flocs, turbulence, and organism trajectories in 3D over appropriate ranges of length, time and shear stress. *In situ* observations and measurements should be the aim, and laboratory work only a step on the way towards it.

Finally, this is a proviso concerning the use of the Richardson number in modeling pycnoclines. Dekshenieks et al (2001) measured Richardson number *Ri* on many occasions in a pycnocline in a shallow fjord, and their Figs 4f and 7h show that while a tight lower bound of 0.25 to 0.23 existed for *Ri*, no upper bound was apparent. Since *Ri* is linearly related to δz, a lower bound thus exists similarly for δz but no upper bound. Previously Oakey and Elliott (1982) had worked in Shelf waters off Nova Scotia. Rather similarly to Dekshenieks et al., they found high *Ri*, averaging ~10, in mixed water below 20 m, but values of $R < 0.25$ in the upper 10 m, where active turbulent events, thought to reduce stratification and hence *Ri*, were frequently observed. This implies that the lower limit of *Ri* is fairly tightly controlled by turbulence, but that erosion of the pycnocline at high *Ri* is only a weak mechanism, so other causality for thick pycnoclines, such as their history, may be more important. *In* the present model, *Ri* is determined only indirectly by viscosity, through δz and δu. In the past, the critical value of *Ri* has been determined empirically, without explicitly taking viscosity into account, so we do not know quantitatively the mechanisms behind the control by *Ri*. It is important to know, and would be interesting to investigate, whether viscosity has a *direct* effect on *Ri*, since if it does, η should appear explicitly in (3), corresponding to the way in that case η would be controlling δz.

5. Conclusions

In natural waters, viscosity consists of the sum of two components. Newtonian, perfectly dispersed viscosity is contributed by the water and salts. Non-Newtonian viscosity is contributed mainly by dissolved and flocculated exopolymeric substances (EPS), related to shear rate by a mainly negative exponent *P*, as well as to the plankton concentration raised to the power of another exponent, roughly between +1 and +1.5. Based on work done on other microbe-rich suspensions, EPS viscosity is probably related to length scale by a third, negative exponent *d*, but this has not yet been investigated for natural waters.

Based on published values of how viscosity relates to shear rate in a culture of a *Karenia mikimotoi* culture, we modeled how blooms of *K. mikimotoi* at different concentrations and for different values of *d* would affect pycnocline characteristics. It was found that providing *d* is not more negative than about -0.2 or -0.3, the phytoplankton could affect pycnocline thickness several-fold, but below this value of *d*, even high concentrations of the plankton would have no significant effect. This kind of model thus points out the most critical parameters important for further investigations. In the present case, investigation if *d*, and secondarily *P*, is required, as well as concentration dependence for different species of phytoplankton.

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Legends

Figure 1.-D 3-layer equilibrium model of a pycnocline in which the thickness is determined by Richardson number *Ri*.

Figure 2. Rheological properties of a culture of 4.4 cells.µL^{-1} of *Karenia mikimotoi* (syn: *Gyrodinium* cf. *aureolum*). Excess viscosity η_E and elastic modulus G' are plotted against shear rate. G' was found between 10% and 50% of excess viscous modulus, $G''_E = \eta_E \, . \, \dot{\gamma}$. (Slightly redrawn from Jenkinson, 1993a.)

Figure 3. Examples of output from model. a) For Km = 0 cells.µL^{-1}, $\tau_{forced} = 10^{-4}$ Pa, τ and τ_W (with τ_{forced}) vs. $\dot{\gamma}$ (marked as *γdot*). Since $\tau = \tau_W$ the two lines are superimposed. After iteration, the values of τ and $\dot{\gamma}$ are read off. b) As for a), but solution of δz and Ri as functions of δu. c) As for a) but with Km = 4.4 cells.µL^{-1}, $\tau_{forced} = 10^{-4}$ Pa and $d = 0$. τ_{Hi} (dotted line), τ_{Lo} (dashed line), τ_E (dash-dotted line), τ (upward curving thin continuous line), τ_W (straight thin continuous line) and τ_{forced} (horizontal line) vs. $\dot{\gamma}$ (as *γdot*). d) as for b) but with the same inputs as c).

Figure 4. Some examples of model output of pycnocline thickness δz plotted against density difference across the pycnocline. Standard values of parameters (Table 2) are used except where stated to be otherwise a) No phytoplankton. Values of shear stress across pycnocline τ_{forced} from lower to upper curves: 0.001, 0.000316, 0.0001, 0.0000316, 0.00001 Pa. b) *K. mikimotoi* concentrations, Km from lower to upper curves 0.1, 0.316, 1, 3.16, 10 cells µL^{-1}; The curves for Km equal to 0.1 and 0.316 cannot be distinguished, and serve also to illustrate the case for no phytoplankton. c) Different values of the exponent d defining the relationship between viscosity and length scale. For the lowest curve, the case is given for Km =0, and for the other curves, the standard value of Km 4.4 cells µL^{-1} is used, with d values of -0.1, -0.2, -0.3, -0.4. Note the different vertical scales on the graphs, and that the lowest curve of Figs b and c corresponds to the middle one of Fig a.

Fig 1

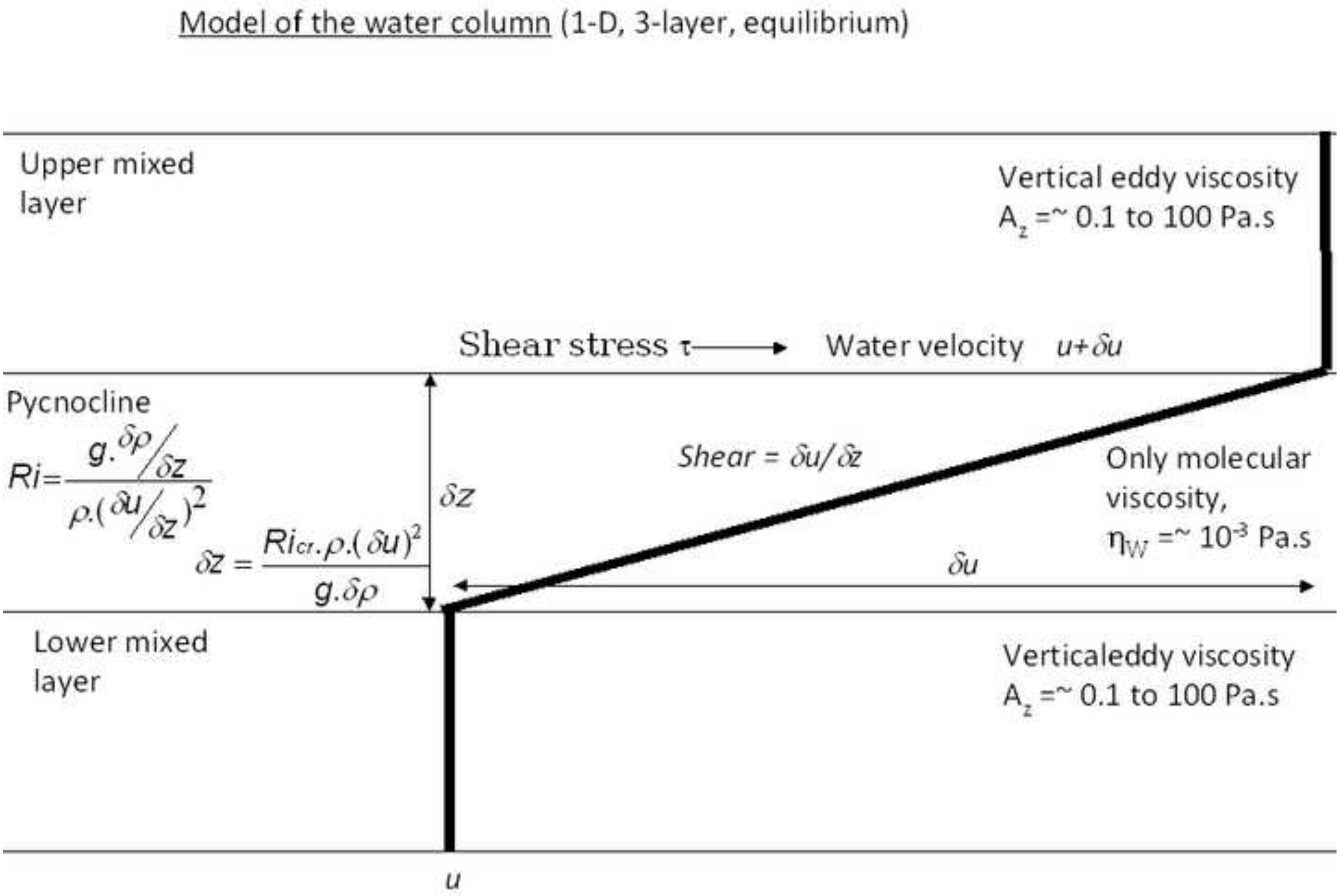

Model of the water column (1-D, 3-layer, equilibrium)
Upper mixed layer
Vertical eddy viscosity
A_z =~ 0.1 to 100 Pa.s
Shear stress τ
Water velocity $u+\delta u$
Pycnocline
$Ri = \frac{g.\delta\rho/\delta z}{\rho.(\delta u/\delta z)^2}$
$\delta z = \frac{Ri_{cr}.\rho.(\delta u)^2}{g.\delta\rho}$
δz
Shear = $\delta u/\delta z$
Only molecular viscosity,
η_W =~ 10^{-3} Pa.s
δu
Lower mixed layer
Verticaleddy viscosity
A_z =~ 0.1 to 100 Pa.s
u

Fig 2

Click here to download high resolution image

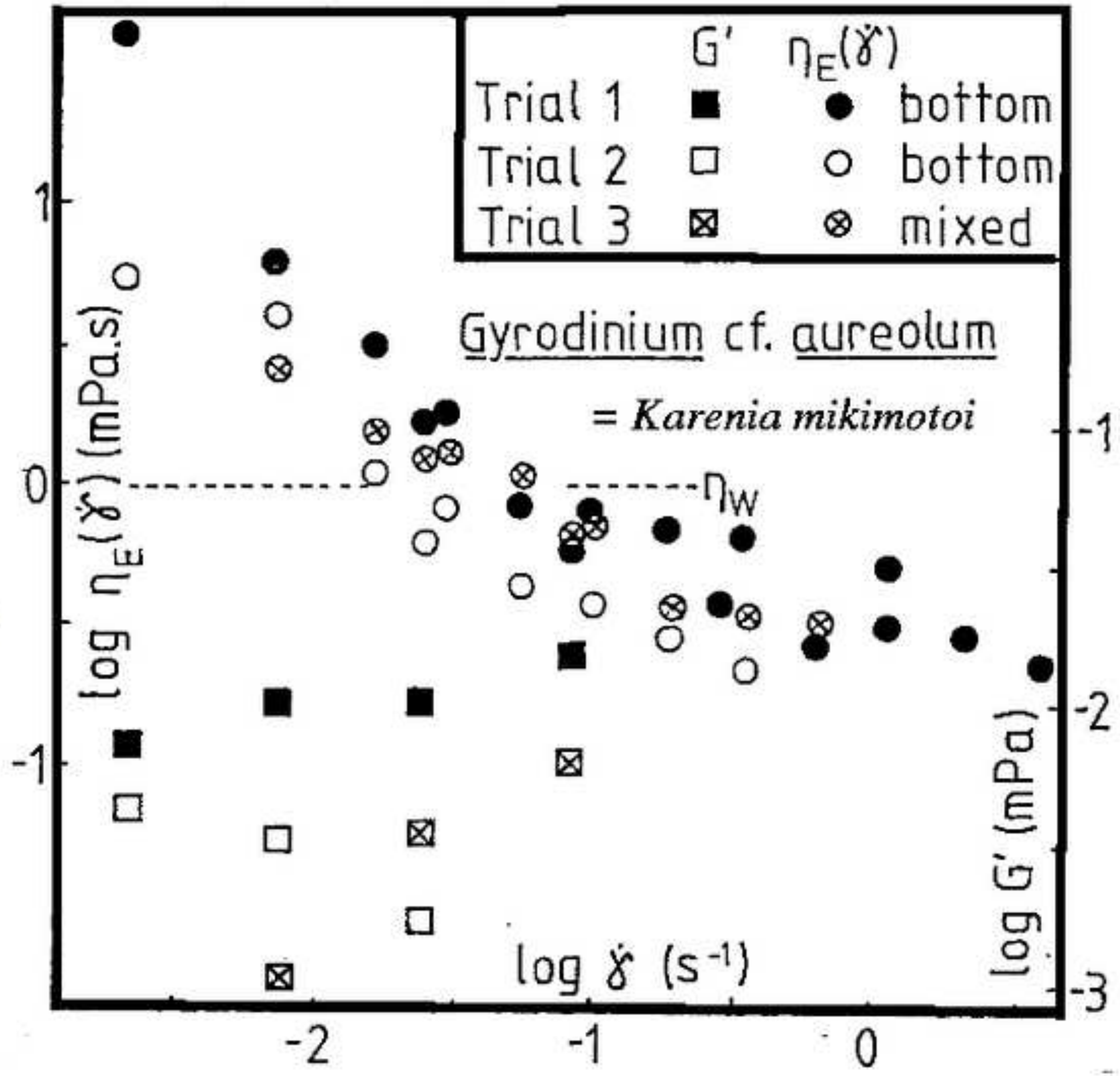


Fig 3

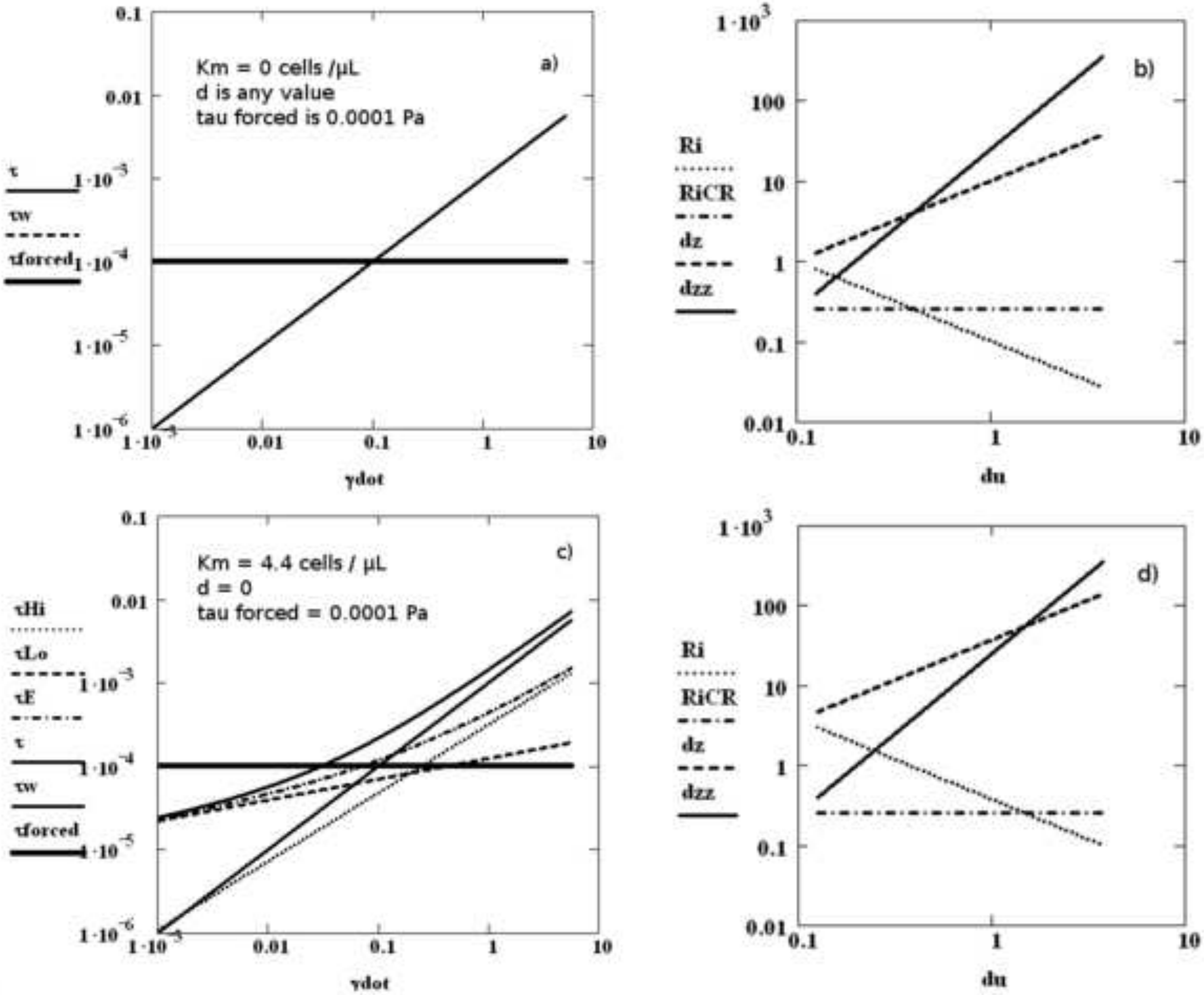
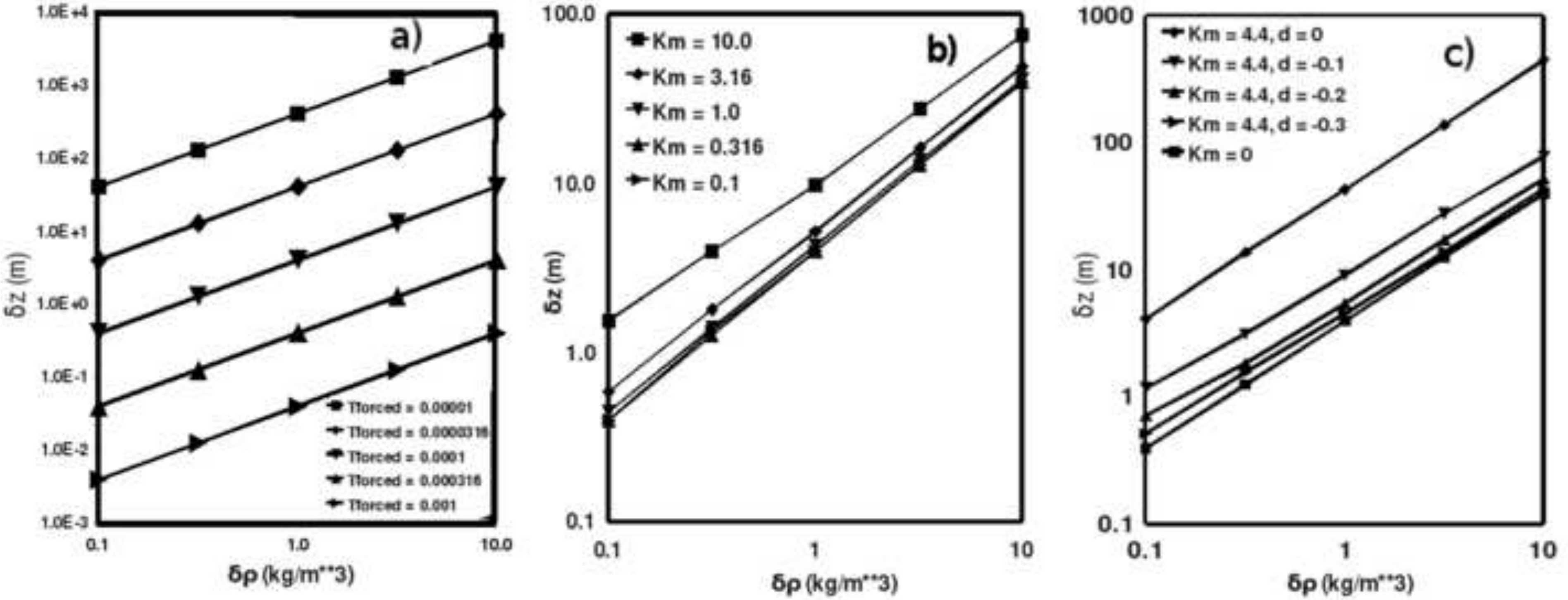

Km = 0 cells /μL
d is any value
tau forced is 0.0001 Pa
a)
τ
τw
τforced
0.1
0.01
1·10⁻³
1·10⁻⁴
1·10⁻⁵
1·10⁻⁶
1·10⁻³
0.01
0.1
1
10
γdot
b)
Ri
RiCR
dz
dzz
1·10³
100
10
1
0.1
0.01
0.1
1
10
du
Km = 4.4 cells / μL
d = 0
tau forced = 0.0001 Pa
c)
τHi
τLo
τE
τ
τw
τforced
0.1
0.01
1·10⁻³
1·10⁻⁴
1·10⁻⁵
1·10⁻⁶
1·10⁻³
0.01
0.1
1
10
γdot
d)
Ri
RiCR
dz
dzz
1·10³
100
10
1
0.1
0.01
0.1
1
10
du

Fig 4


a)
1.0E+4
1.0E+3
1.0E+2
1.0E+1
1.0E+0
1.0E-1
1.0E-2
1.0E-3
δz (m)
0.1
1.0
10.0
δρ (kg/m**3)
Tforced = 0.00001
Tforced = 0.0000316
Tforced = 0.0001
Tforced = 0.000316
Tforced = 0.001
b)
100.0
10.0
1.0
0.1
δz (m)
0.1
1
10
δρ (kg/m**3)
Km = 10.0
Km = 3.16
Km = 1.0
Km = 0.316
Km = 0.1
c)
1000
100
10
1
0.1
δz (m)
0.1
1
10
δρ (kg/m**3)
Km = 4.4, d = 0
Km = 4.4, d = -0.1
Km = 4.4, d = -0.2
Km = 4.4, d = -0.3
Km = 0