Dynamics of biogenic gas bubbles in peat: Potential effects on water storage and peat deformation

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[1] Dynamics of biogenic bubbles in peat soils were studied at a field site in southern Québec, Canada. The maximum gas content measured in this study varied spatially with a maximum seasonal increase in volumetric gas content of 0.15. The size of changes in total gas content of a 1 m deep profile was comparable to the seasonal water storage change. Changes in bubble volume in the saturated zone alter the water table level and, consequently, the water content in the unsaturated zone and the apparent water budget. In highly compressible soils (and floating root mats), buoyancy forces from bubbles also cause relations between the surface and the water table to change. These effects cannot be omitted in modeling the hydrology of peatlands. Our results indicate a great spatial variability of trapped bubbles. Using pressure transducers sealed to the surface, we found pressure deviations indicating small areas closed off by bubbles clogging the pores. The hydrological influence of these areas may be considerable as they may restrict or deflect water flows. Open pipe piezometers did not show these pressure deviations, possibly because the closed zones were too small to influence the head in pipes or because of less amount of gas close to the pipe screen.

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1. Introduction

[2] In peat soils, the production of CH_4, H_2S and CO_2 from decomposing peat is often greater than the amount that is oxidized [*Whalen and Reeburgh*, 1990] and/or transported away by diffusion. Consequently, the concentrations of these gases increase beyond their equilibrium solubility in pore water [*Dinel et al.*, 1988; *Brown et al.*, 1989; *Buttler et al.*, 1991], and gas bubbles form. Many studies in recent time have found abundance of methane gas bubbles in deeper peat [*Dinel et al.*, 1988; *Brown et al.*, 1989; *Romanowicz et al.*, 1993, 1995], but bubbles are likely also abundant in shallow peat layers since anaerobic biological activity is greatest just below the water table [*Brown et al.*, 1989; *Sundh et al.*, 1992]. Calculations based on measured pressure responses at 1–3 m depth in a Minnesota bog estimated volumetric content of trapped gas to be 0.09–0.13 [*Rosenberry et al.*, 2003]. In the laboratory, anaerobic incubations of peat samples have generated gas content increases of 0.05–0.12 [*Beckwith and Baird*, 2001; *Baird and Waldron*, 2003] and even up to 0.30 [*Reynolds et al.*, 1992] of total volume. Seasonal variations of peat gas volumes may also be expected with larger volumes during summer because of greater biological activity and less gas solubility [*Slabaugh and Parsons*, 1976].

[3] The presence of gas bubbles in saturated peat has implications for peatland hydrology. Changes in bubble volume in the saturated zone can be expected to alter the water table level and consequently the water content in the unsaturated zone and the apparent water budget. The presence of gas bubbles also induces buoyancy forces that may play an important role in peat, which is highly compressible [*Price*, 2003] and especially in certain parts of some peatlands where the surface layers are more or less floating [*Hogg and Wein*, 1988; *Fechner-Levy and Hemond*, 1996]. Water table fluctuation caused by atmospheric pressure variation may also be expected [*Peck*, 1960; *Rosenberry et al.*, 2003], since gas is about 10^4 times more compressible than water. The implications for microclimate and ecohydrology can be very large since the water table in peatlands has a small range of fluctuation [*Ingram*, 1983] and the gradients in soil wetness are very sharp [*Roulet et al.*, 1998].

[4] Entrapped gas bubbles decrease peat hydraulic conductivity [*Mathur and Levesque*, 1985; *Buttler et al.*, 1991; *Reynolds et al.*, 1992; *Beckwith and Baird*, 2001; *Baird and Waldron*, 2003] and systems of blocked pores can further trap locally produced peat gas, creating overpressured zones within the peat [*Romanowicz et al.*, 1995; *Rosenberry et al.*, 2003; *Kellner et al.*, 2004]. Since peat is generally very elastic, overpressure zones may cause variations in peat volume [*Glaser et al.*, 2004].

[5] Despite this little attention has been paid to the possible effects of anaerobic peat gas on peat hydrology. Moreover, no direct field measurements of volumetric gas

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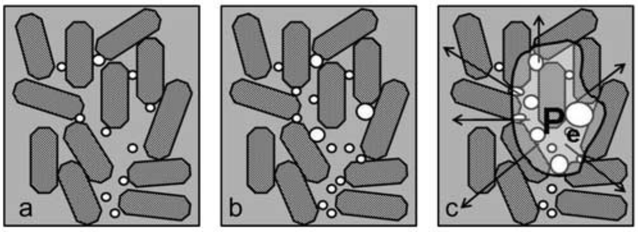

Figure 1. Conceptual model of bubble entrapment. (a) Bubbles get stuck in cavities and to pore walls by adhesion forces. (b) There they accumulate and grow, in such an extent that (c) they may restrict the movement of both water and gas and closed zones or layers may develop. Such confining layers may further trap locally produced peat gas, creating overpressured zones within the peat (P_e).

content have been published to date. The objective of this study therefore is to use field measurements to reveal the seasonal variation and distribution of gas volumes and hydraulic pressure within a 1 m deep saturated peat soil and to examine the effect of gas bubble dynamics on peatland water storage terms and peat volumes. We begin with a short review on processes of entrapped bubbles.

2. Processes of Entrapped Bubbles

[6] We may assume that present or newly formed bubbles normally are attached to, or suspended between, pore walls as long as their buoyancy force or water flux forces do not cause them to move (Figure 1a). If the bubble diameters are smaller than the pore size, they respond to pressure changes as if they were bubbles in free water. The variation of volume is described by Henry's law and the ideal gas law. Henry's law is given by

$$C = \frac{\alpha_{bu}}{RT} P_g \quad (1)$$

where C is the concentration of dissolved gas (moles m^{-3}), P_g is the partial pressure of the gas (Pa), R is universal gas constant (8.314 J m^{-1} K^{-1}), T is temperature (K) and α_{bu} is the Bunsen coefficient for gas solubility (m^3 gas at 273.16 K and 101.3 kPa, per m^3 water) [*Wiesenburg and Guinasso*, 1979]. There is a variation of α_{bu} with temperature such that gases are more soluble at lower temperatures [*Slabaugh and Parsons*, 1976]. The ideal gas law states:

$$P_g V_g = M\ R\ T \quad (2)$$

where V_g is gas volume (m^3) and M is moles of gas molecules.

[7] Consequently, temperature variation causes a seasonal change in bubble(s) volume. During summer, we would expect bubble development to increase (at least in upper layers) with increased temperature and biological activity. Shifts in pressure caused by changes in water table or atmospheric pressure, would cause short-term variations to be superimposed on the seasonal trend. The size of water table variation relative to the pressure change, the barometric efficiency (BE) is related to the gas content in the profile [*Peck*, 1960].

[8] If the bubbles grow and/or coalesce such that their sizes approach pore diameters, they get trapped (Figure 1b). Trapped bubbles block water flow, thus affecting hydraulic conductivity [e.g., *Faybishenko*, 1995] and pore-water pressure distribution [*Gardescu*, 1930; *Wyckoff and Botset*, 1936]. Although no detailed description over how bubbles are distributed has yet been accomplished, many studies suggest that the likelihood of bubbles getting trapped is greater in zones of denser peat and where obstacles such as branches or root tufts occur [*Romanowicz et al.*, 1995; *Rosenberry et al.*, 2003; *Glaser et al.*, 2004; *Kellner et al.*, 2004].

[9] Trapped gas may lead to the development of confining zones, delimited by pore-clogging bubbles. These zones may further entrap locally produced peat gas, which may create a notably higher pressure than in adjacent soil (Figure 1c) [*Romanowicz et al.*, 1995; *Rosenberry et al.*, 2003; *Kellner et al.*, 2004]. Gas eruptions from overpressured zones occur at some threshold of pressure difference across the blocking bubbles [*Kellner et al.*, 2004] by either (or a combination of) pore enlargement [*Johnson et al.*, 2002] or by pushing out bubbles through a pore [*Gardescu*, 1930]. Sudden changes in hydrostatic pressure or peat stress may trigger gas releases [*Strack et al.*, 2005].

3. Methods

3.1. Site

[10] Data were collected at a poor, open fen site (46°40′N 71°10′W) close to the village of St Charles de Bellechasse, Québec. The study area is a 3 hectare unharvested remnant in a patterned fen peatland subjected to drainage and peat cutting over the last 10 years. Small (<2 m) trees (*Larix* spp. and *Betula* spp.) occur sporadically. On ridges there are patches of low ericaceous shrubs whereas grasses and sedges sparsely cover lawns and shallow pool areas. The instrumentation was located at *Sphagnum* lawns, encircling ~150 m^2 pools in three closely situated subsites. Description of the lawn peat is given in Table 1; the mineral content is very low through the profiles, and the pool bottoms were covered by peat mud debris. One site has been drained for eight years, hereafter called "drained" (site D). Another site, called "experimental" (site E), was drained on day (day of year) 161 in early June 2002 by digging a shallow drain from the pool to the drainage network (for a related experiment, not reported here). The third site was an undrained subsite called "control" (site C).

[11] The peat thickness was approximately 80 cm at the drained site, 100 cm at the experimental site before drainage (average decrease in total thickness at the drainage was 7.5 cm) and about 120 cm at the control site. The moss layer is dominated by *Sphagnum papillosum*, *S. magellanicum,* and *S. majus*. Dominating vascular plants are *Rhynchospora alba* and *Carex* spp.

3.2. Measurements

[12] Field measurements were made from early May to late September 2002 and 2003. Water table was monitored continuously with recording wells combined with manual measurements every week. Entrapped gas volume was determined by continuously monitoring the change in

Table 1. Determined Peat Properties, von Post Degree of Decomposition, and Dry Bulk Density ρ_b in Profiles at the Three Different Subsites in the Study

	Site C		Site D		Site E	
Depth, cm	Degree of Decompositon	ρ_b, g cm^{-3}	Degree of Decompositon	ρ_b, g cm^{-3}	Degree of Decompositon	ρ_b, g cm^{-3}
10	2	0.05	5	0.10	1	0.08
25	3	0.08	6	0.17	2	0.14
40	4	0.09	9	0.15	3	0.22
60	4	0.12	9	0.22	-	-

volumetric water content between 25 and 115 cm depth at lawn areas using Campbell Scientific CS615 moisture probes (Campbell Scientific Inc., Logan, Utah, USA). The probes were 30 cm in length and were centered at depths 25, 40, 60, 85, and 100 cm below the surface. Probes were inserted horizontally at 25 cm and vertically at all other depths. The representative soil volume measured by the probes was determined in the laboratory to have a cylindrical shape around the probes with a radius of 5 cm. This type of sensor uses time domain measurement methods that are sensitive to dielectric number (ε), although the method used to determine ε is different from traditional TDR (time domain reflectometry) technique [*Bilskie*, 1997].

[13] Using a mixing model expression [*Birchak et al.*, 1974], the volumetric water content θ (m^3 m^{-3}) for each probe was expressed as

$$\theta = \frac{\varepsilon_r^{\vartheta} - (1-\eta)\varepsilon_m^{\vartheta} - \eta\varepsilon_a^{\vartheta}}{\varepsilon_w(T)^{\vartheta} - \varepsilon_a^{\vartheta}} \tag{3}$$

where ε_r represents the measured dielectric number (dimensionless) while subscripts m, a and w denote the dielectric number for the peat, air, and water respectively, T is temperature, η is porosity of the soil (m^3 m^{-3}), determined from bulk density values (Table 1), and ϑ is a parameter (dimensionless) expressing the direction of layering of the soil, estimated to be 0.35 [*Kellner and Lundin*, 2001].

[14] The probes were calibrated in the laboratory for variations in both water contents and temperatures (2°–25°C). The variation among different sensors in the calibration and the spatial variation of actual porosity were causing a probable error in absolute values of ±0.05. However, uncertainty in the slope of the calibration function was much less. In this paper, we therefore put the emphasis on the measured changes in gas content (water content) of which the estimated uncertainty was ±0.01 (of total volume) within the measured water content range. Changes in gas content as estimated from measured soil moisture were corrected to account for vertical compression and swelling of the peat matrix. This was monitored using elevation sensor rods [*Price*, 2003] inserted at depths of 20, 30, 50, 70, 85, 100 and 130 cm, thereby monitoring layer thickness at the same depths as the sensors. The elevation rods extended above soil surface and they were monitored 2–3 times per week by viewing the position of the rods against a stable datum. The change in volumetric gas content, γ (m^3 m^{-3}), was calculated as

$$\Delta\gamma = (\eta - \eta_0) - (\theta - \theta_0) \tag{4}$$

where θ is measured volumetric water content (m^3 m^{-3}) and η is porosity (m^3 m^{-3}), estimated as

$$\eta = 1 - {(1-\eta_0)}\Big/{L/L_0} \tag{5}$$

where L is layer thickness (m) and subscripts 0 denote the initial values for the season. It should also be mentioned that some gas may have escaped at the time of insertion of the probes, so the original gas content at the beginning of the seasons may have been underestimated.

[15] The seasonal development of total bubble volume per unit area, $\Delta\Gamma$ (m^3 m^{-2}), integrated from water table (WT) down to the total depth of the peat deposit (z_0) is calculated as

$$\Delta\Gamma = \int_{z_0}^{WT} \Delta\gamma dz \tag{6}$$

$\Delta\Gamma$ is hereafter referred to as "specific volume," expressed in mm since this unit is convenient for comparisons with the water budget terms.

[16] Pore-water pressure was automatically recorded with nonvented pressure transducers (KPSI 173, Pressure Systems Inc., Hampton, Virginia, USA) buried in the peat at depths of 25, 40, 60, 85 and 100 cm at the lawn, with approximately 25 cm horizontal distance between sensors. The insertion cavities were sealed with peat mud for the first 10 cm and then with a 10 cm bentonite plug to deter preferential flows of gas and water. The bentonite plug was not considered to influence on the peat chemistry except right at the contact surfaces between the bentonite and the peat, where diffusion exchange may occur. The transducers were later recalibrated in the laboratory; no sign of drift was found. Pressure was also monitored manually at the same depths with 2.5 cm i.d. (nonsealed) piezometer pipes, with 10–20 cm screen length. All hydraulic head measurements were adjusted to account for the vertical displacement of the instruments caused by peat vertical compression and swelling. The displacement was estimated from that of the elevation sensor rods. Air pressure (P_a) was recorded continuously with a barometer (Vaisala PTB210, Vaisala Oyj, Helsinki, Finland).

[17] The effect of the atmospheric pressure on water table elevation was characterized with BE, the ratio between the size of water table (WT, cm) variation and the change in atmospheric pressure P_a (cm water), according to [*Freeze and Cherry*, 1979], as

$$\mathrm{BE} = -\partial \mathrm{WT}/\partial P_a. \tag{7}$$

Barometric efficiency was calculated for two rain-free periods, one in early summer and one in late summer, each

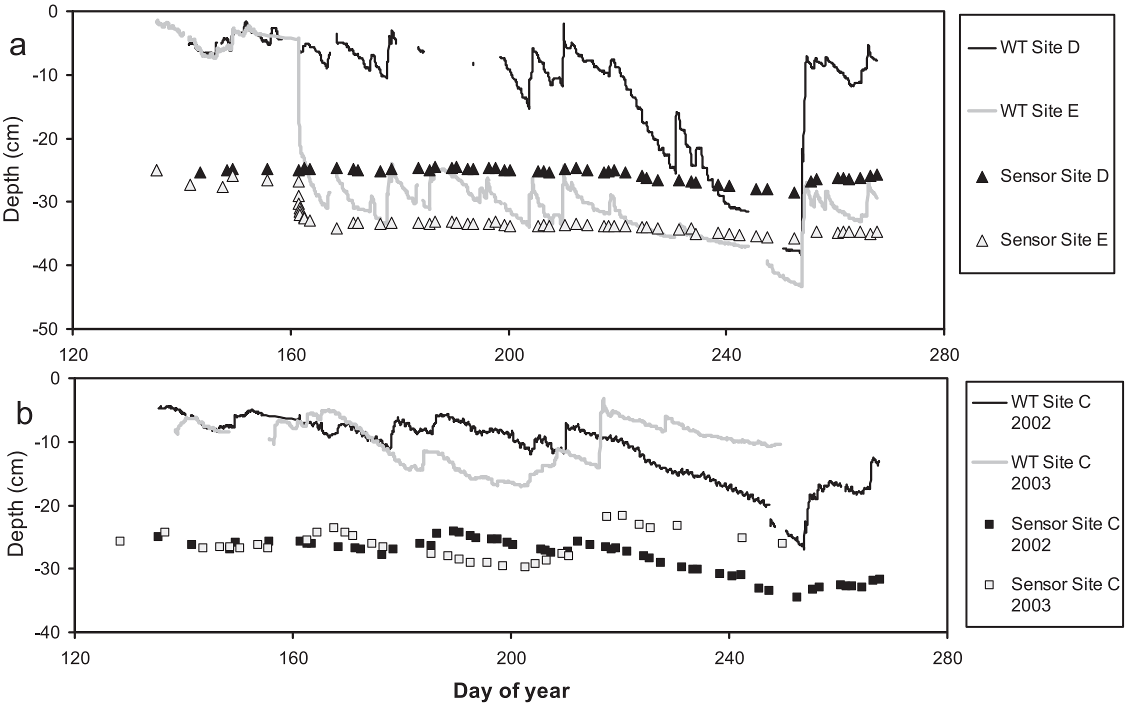

Figure 2. Variation of water tables and levels of moisture sensors installed at 25 cm depth (a) at sites D and E and (b) at site C.

year. This was done by comparing water table and hydraulic head data with atmospheric pressure variation, by linear regression. Before the comparisons the data were detrended by subtracting the total subperiod trend, i.e., the effects of drying.

[18] Rainfall was measured with a tipping bucket rain gauge, and evapotranspiration was measured with lysimeters (5 in a transect at site E and 3 at site D) by weighing 2 times per week. The lysimeters (740 cm^2 surface area, 25 cm deep) consisted of plastic buckets, filled with peat monoliths and perforated through their bases while a second bucket below captured the drainage water so as to prevent undue moisture buildup [*Van Seters and Price*, 2001]. All lysimeters were sunk level to the surface and, when applicable, water tables in the lysimeters were kept at the same level as in adjacent soil. Runoff was measured at sites D and E by collecting water at drainage pipe outlets at least once per day when flow was occurring.

4. Results

[19] In 2002 the precipitation (P) in period May–July (310 mm) was close to long-term averages (see Environment Canada, Canadian climate normals 1971–2000, available at http://www.climate.weatheroffice.ec.gc.ca/climate_normals). August to early September was very dry with only 16 mm of rain, followed by heavy rains with intermittent dry periods later in September. Evapotranspiration (E) averaged 4.2 mm day^{-1} during June and July, 2.8 mm day^{-1} in August and 1.5 mm day^{-1} in September. In 2003 it was a little dryer for the period May–July (P = 210 mm) but wetter in August (P = 150 mm) with two heavy rainstorms. Evapotranspiration was similar with 4.3 mm day^{-1} in June and 3.6 mm day^{-1} in July. Infrequent lysimeter measurements in late summer of 2003 were considered unreliable. However, average net radiation differed by less than 3% between the two years during both August and September (unpublished data) and therefore E was assumed to be similar to 2002 values during this period. Measured runoff at site D and E was normally below 0.1 mm day^{-1} except during and after periods of heavy rain. The runoff from site C could not be measured but, based on results from other studies [e.g., *Nicholson et al.*, 1989], was considered to be smaller than at the other two sites.

[20] The artificial drainage at the experimental site on day 161 lowered the water table there by approximately 20 cm. Otherwise, the water tables responded according to the weather conditions with relatively small variation in 2002 until the beginning of August, after which the water table declined to maximum depths of 43, 38 and 27 cm at the experimental, drained and control sites, respectively (Figure 2). In comparison, the maximum depth at the control site in 2003 reached 17 cm, in mid-July.

[21] All the moisture probes were at all times below water table, except for the 25 cm probes at the experimental (E25) and drained (D25) sites between day 235 and 253 in 2002 (Figure 2). Peats with dry bulk densities greater than 0.1 g cm^{-3} normally have a capillary fringe greater than 5 cm [*Boelter*, 1968]. Since the peat at the monitored depths had a higher bulk density (Table 1), it was assumed that all changes in gas content were considered to be due variations in bubble volumes, except for D25 and E25 between days 235 and 253 in 2002.

4.1. Gas Volumes

[22] The moisture-probe-measured gas volume (γ) started to increase from day 150 to day 160 in 2002 and from about day 140 in 2003. In year 2002 the 25 cm layer at site E (E25) actually had a drop in γ on day 147 after which γ

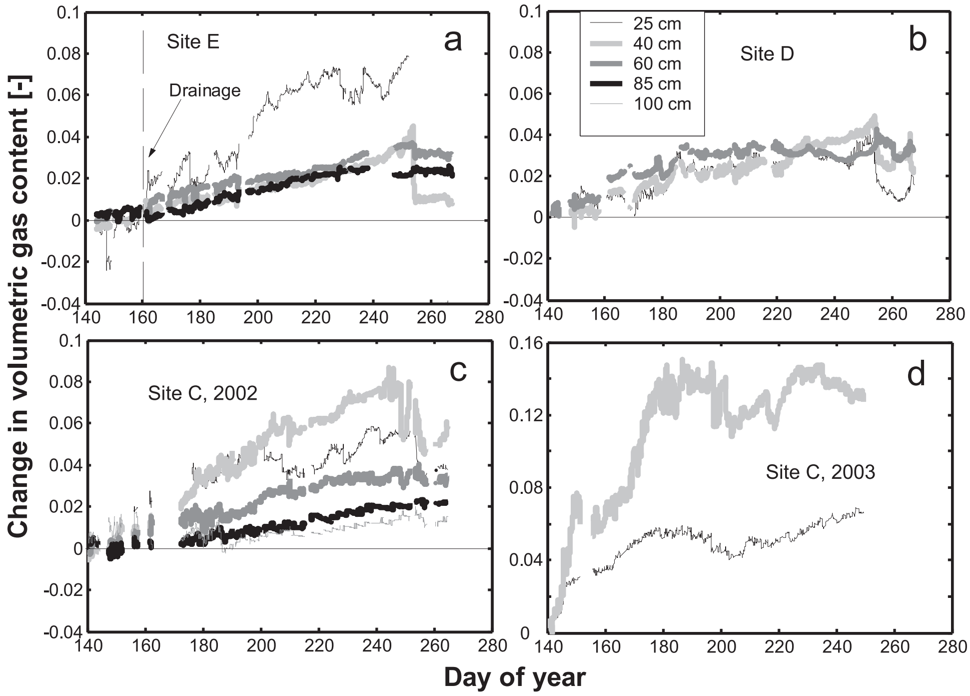

Figure 3. Change in volumetric gas content since the seasonal start of measurements at (a) site E, (b) site D, and site C (c) in year 2002 and (d) in year 2003. Dashed line in Figure 3a denotes the day of drainage (day 161).

stayed at a low level just one day before it resumed at a fairly high rate to earlier gas content. Furthermore there were some peculiar changes in γ at site E in connection with the artificial drainage at day 161 (Figure 3a). The gas content decreased slightly at 40 and 60 cm depths (E40 and E60), while a noticeable increase occurred at E25. At E25 there was a general increase of γ during most of the season but short-term changes with sudden drops and rises were occurring as well as some diurnal variations. These patterns for E25 were not correlated to water table levels. Both the magnitude and the pattern of gas volume variation were different among the different sites (Figure 3). The maximum volumetric gas content increase throughout the site D profile, as well as in deeper layers of all profiles, was about 0.04. However, at 25 and 40 cm in site C (C25 and C40) and at E25, the gas accumulated, giving maximum increases of 0.06, 0.08 and 0.08, respectively. The trend of increasing gas volume at C25 leveled off about day 200, whereas at E25 and E40 it continued to increase until the end of the long dry period at day 253. The storm on day 253–254 coincided with a decrease in the gas volume at most of the measured locations. A seasonal increase of γ was also clear in year 2003 at 25 and 40 cm in the site C profile, $\Delta\gamma$ reaching a maximum of 0.15 at 40 cm depth (Figure 3d). The day-to-day variation of γ was great and there were frequent drops in gas volume indicating events of ebullition or other gas bubble dynamics. No gas volume change was observed at any of the big storm events in 2003. The moisture probe at 60 cm depth at site C did not work in 2003.

[23] Given the uncertainties in absolute values of gas volumes, the estimated maximum volumetric gas contents retained at 25 and 40 cm depths were around 0.15 at site C and E, and 0.10 at site D (Table 2). The lower layers at site C generated consistently smaller gas volumes whereas trends of variation with depth were weaker at the other sites (Table 2).

[24] At site C $\Delta\Gamma$ reached maximums corresponding to 40 and 47 mm for the 2002 and 2003 field seasons, comparable to $P - E$, the net sum of precipitation minus evapotranspiration (Figure 4).

4.2. Pressure Dynamics

[25] Hydraulic head at all piezometer pipes deviated little (between −3 and +1 cm water) from the water table at each site, suggesting the vertical gradients were small throughout the measurement period. In contrast, the pressure transducers recorded large differences in hydraulic head during certain times. The data from pressure transducers present two different but related and often coexistent effects (Figure 5). The first effect was a measured buildup of excess pressure p_e (p_e = hydraulic head − water table level). The typical pattern of the excess pressures was a gradual buildup followed by a sharp drop. For some sensors, a threshold value of p_e seemed to control when the releases occurred. This threshold value was often only valid during certain periods. For example the threshold for C60 was first varying in year 2003, but was kept at 10 cm after day 188, whereas C40 only had shorter periods with distinct threshold in the same year (Figure 5). Maximum p_e varied among the layers from less than 10 to more than 50 cm water (Table 3). The rate of rise in p_e varied considerably over time at all sensors, with maximum rates exceeding 10 cm water day^{-1} (Table 3). The magnitude in drops of p_e varied greatly and was not correlated with the magnitude of p_e nor to the time p_e had existed before the drop. The initial formation of p_e occurred at most sensors, but not all, at times when atmospheric pressure dropped

Table 2. Estimated Initial and Maximum Gas Contents for All Sites in 2002 and for Control Site in 2003[a]

Depth, cm	Control			Experimental			Drained		
	Initial	Maximum	Change	Initial	Maximum	Change	Initial	Maximum	Change
25	0.08 (0.02)	0.14 (0.08)	0.06 (0.06)	0.07	0.15	0.08	0.04	0.08	0.04
40	0.02 (0.02)	0.10 (0.16)	0.08 (0.14)	0.01	0.05	0.04	0.05	0.10	0.05
60	0.02	0.06	0.04	0.03	0.07	0.04	0	0.04	0.04
85	0.015	0.04	0.025	0.085	0.11	0.025	n.a.	n.a.	n.a.
100	0.04	0.06	0.02	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.

[a]Control site values for 2003 are given in parentheses. Note that the standard error for measured values is ±0.05, whereas it is less than ±0.01 for the changes at each location.

after periods of high pressure. Releases in pressure or in gas volumes occurred often at various sensors during the same day, but there was no sign of that a p_e release at one sensor had any immediate effect on adjacent pressure transducers or moisture probes. The second effect was manifested in p_e varying as a mirror reflection of the atmospheric pressure variation (Figure 5). In contrast to the sharp drops in p_e, gradual decreases of p_e were generally associated with increases in atmospheric pressure. This effect occurred as the absolute pressures at the sensors did not fully follow changes in atmospheric pressure. For example if an increase in atmospheric pressure of 10 cm water occurred (while water table was still) at the same time as the absolute pressure monitored by a sensor in soil only increased 5 cm water, p_e would decrease by 5 cm water. Thus the variation of ambient soil water pressure (caused by variation in water table or in atmospheric pressure) was highly damped at some locations. No general trend in p_e size with depth could be found at site E, but a decreasing p_e with depth was found

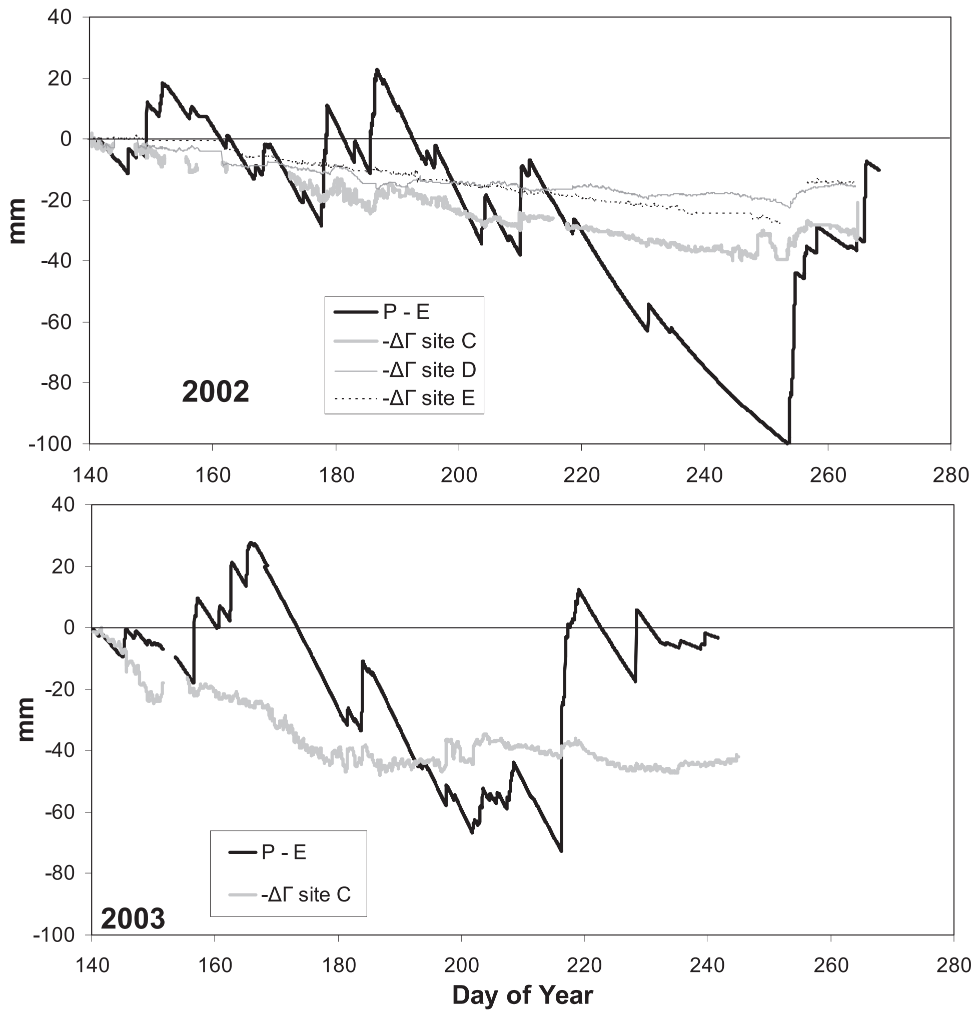

Figure 4. Net sum of precipitation (P) minus evapotranspiration (E) and negative changes of total gas volume per unit area ($-\Delta\Gamma$) since start of measurements in year 2002 and 2003, expressed as millimeters of water equivalents.

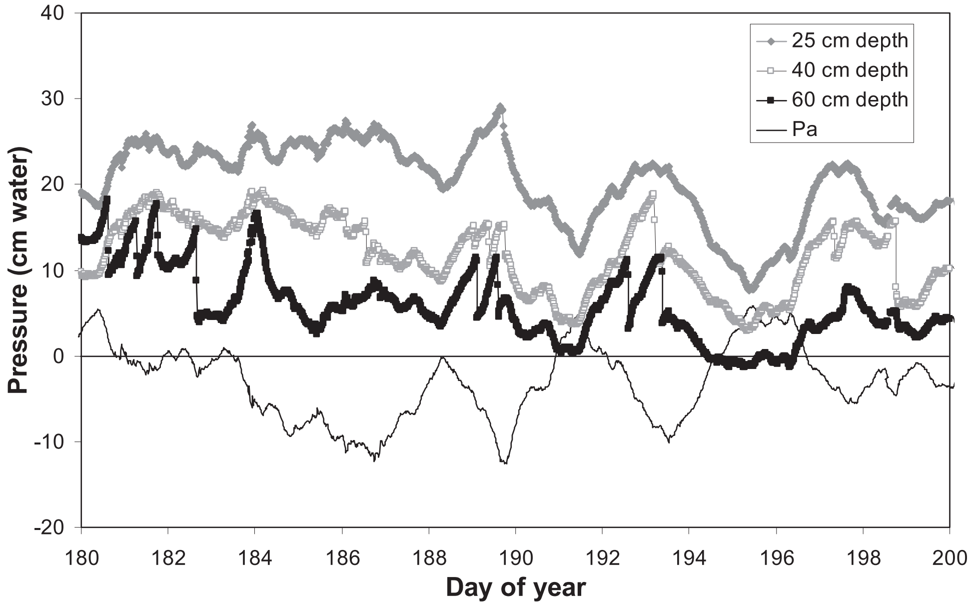

Figure 5. Variation of excess pressure P_e in three levels at site C and deviation of atmospheric pressure P_a from 101.3 kPa (= 1033 cm water) in 2003.

at site C. On the other hand at site D only weak p_e development was monitored in the upper layers by D25 and especially D40, whereas p_e was substantial at D60 (Table 3).

[26] The calculated barometric efficiency BE was rarely notably different from zero for any water table (Table 4). In fact all sites show negative BE values for the early period in 2002. In contrast, many pressure transducers show very high values of BE in late summer, indicating that hydrostatic pressure variation was highly damped at these sensors (Table 4). By comparing the status of adjacent elevation sensor rods before and after sudden changes in p_e at all sensors, we found no signs of any influence on peat volume from the dynamics in p_e.

5. Discussion

5.1. Interpretation of Results

[27] In laboratory incubations, *Reynolds et al.* [1992] measured extraordinarily high gas volume in repacked peat samples, with an initial gas content of γ = 0.10–0.17, increasing to end values of 0.25–0.40. In contrast, *Beckwith and Baird* [2001] had starting values of γ = 0.05–0.10 in undisturbed peat columns, increasing to 0.12–0.19. Simi-

Table 3. Measured Excess Pressure p_e at Different Locations

Sensor	Beginningof p_e or "Decoupling" day	Maximum p_e, cm water	Maximum Rate of p_e Increase, cm water/day	Maximum 1-Hour Drop of p_e, cm water
		2002		
D25	210	22.4	4.3	10.0
D40	195–198	7.6	10[a]	-
D60	187	50.3	6.6	7.5
E25	180	11.4	2.4	5.4
E40	174	20.9	10	12.9
E60	210	22.0	1.9	10.7
E85	177	25.4	3.2	10.9
C25	180	55.1	7.6	20.4
C40	180	28.0	5.5	16.8
C60	-	0	0	0
C85	-	0	0	0
C100	245	12.8	2.7	5.7
		2003		
C25	149	34.8	3.1	2.6
C40	176	25.6	4.9	9.0
C60	149	18.8	7.1	6.6

[a]The p_e increase during one single day.

Table 4. Values of Barometric Efficiency and the Strength of Correlation Between Changes in Barometric Pressure and Hydraulic Head

Sensor	Days 169–174 2002 Barometric Efficiency	Days 169–174 2002 Correlation	Days 236–247 2002 Barometric Efficiency	Days 236–247 2002 Correlation
D WT	−0.031	−0.544[a]	0.000	−0.005
D25	−0.050	−0.563[a]	0.620	0.969[a]
D40	−0.063	−0.708[a]	0.000	0.002
D60	0.005	0.069	0.721	0.998[a]
E WT	−0.22	−0.355[a]	−0.001	−0.148
E25	−0.074	−0.570[a]	0.481	0.926[a]
E40	−0.073	−0.800[a]	0.680	0.987[a]
E60	−0.055	−0.645[a]	0.117	0.961[a]
E85	−0.008	−0.210	0.144	0.973[a]
C WT	−0.040	−0.568[a]	−0.07	−0.209
C25	−0.026	−0.395[a]	0.506	0.980[a]
C40	−0.072	−0.791[a]	−0.024	−0.412[a]
C60	−0.043	−0.707[a]	−0.031	−0.702[a]
C85	−0.049	−0.688[a]	−0.028	−0.775[a]
C100	−0.035	−0.568[a]	0.030	0.742[a]
Sensor	**Day 166–174 2003 Barometric Efficiency**	**Day 166–174 2003 Correlation**	**Days 220–228 2003 Barometric Efficiency**	**Days 220–228 2003 Correlation**
C WT	−0.009	−0.298[a]	−0.006	−0.193
C25	0.784	0.951[a]	0.296	0.721[a]
C40	−0.044	−0.743[a]	0.786	0.976[a]
C60	0.740	0.926[a]	0.128	0.528[a]

[a]Significant at the 0.05 level.

larly, *Baird and Waldron* [2003] measured start values of $\gamma = 0.02–0.07$, increasing to 0.04–0.13. *Beckwith and Baird* [2001] found that warmer temperature caused gas volume to increase more rapidly, but did not affect the end volume because a point of equilibrium was reached whereby the ebullition rate matched the gas production rate. The maximum gas volume that can be retained is probably related to peat structure. The high gas volume reported by *Reynolds et al.* [1992] occurred in repacked peat and was probably not representative of gas retention in undisturbed peat. Furthermore, *Reynolds et al.* [1992] did not calibrate the TDR instrument used to determine gas volume, thus causing uncertainty in the reported values.

[28] The gas volume values we observed in the field compared well with published laboratory studies [e.g., *Beckwith and Baird*, 2001; *Baird and Waldron*, 2003]. Smaller gas volumes typically developed in deeper layers, corresponding to the lower dissolved gas contents at these depths [*Strack et al.*, 2005]. Smaller gas volume growth occurred in the upper layers at site D compared to the other two sites, in accordance with lower concentrations of dissolved gas at this site [*Strack et al.*, 2004]. On the other hand the surface fluxes of CH_4 were similar among the sites [*Strack et al.*, 2004], as was the vegetation cover. However, the peat structure is different at site D where the current vegetation and upper peat have established just recently on a former pool bottom of loose humic matter. Consequently, large parts of the peat in the D profile lack the structure provided by old roots and plants that is characteristic of the other two sites. The absence of this structure at site D may have reduced its capacity to retain bubbles. As such we believe that the strong seasonal variation of methane production in the layers just below the water table causes these seasonal variations of bubble volume and that the structure of the peat determines where and how much gas can be retained. This seasonal production decreases with depth, but seems to be big enough to sustain bubble development at deeper layers. Even if production is greater in upper layers because of more fresh material, deeper layers in the peat are often denser, hence potentially more able to keep large volumes of gas. The greatest volumes of gas found so far have also been at dense layers at more than 2 m depth [*Romanowicz et al.*, 1995; *Rosenberry et al.*, 2003; *Glaser et al.*, 2004].

[29] The observed effects of overpressure and decoupling from hydrostatic pressure changes indicate the existence of closed zones, blocked off by bubbles clogging the pores [*Kellner et al.*, 2004]. The size of these zones cannot be large since sudden changes in pressure at one location did not cause measurable effects on peat layer thickness or on pressure at adjacent sensors. Both the moisture probes and the pressure transducers suggest that there is a great spatial variation in gas volume. This spatial variation can be partly explained by the heterogeneous structure of these ecosystems where patches of sedges occur within *Sphagnum* dominated lawn areas. The heterogeneity supports a spatial variation in peat structure that causes gas bubble entrapment to vary. It may also support a spatial variation of biological activity which creates 'hot spots' where gas production is considerably greater than average [cf. *Rothfuss and Conrad*, 1998].

[30] The barometric efficiencies or water tables were close to zero, and they could not be used to calculate the gas volume using the formula of *Peck* [1960]. One reason could be that the study area is not homogeneous but has a varying microtopography of ridges and pools. Since water in the upper layers of the lawn pool area flows freely back and forth, the pools may help to dampen the water table variation with their greater storativity. We cannot explain the peculiar negative values of BE in the early period of

2002. Intercalibrations with the barometer and the pressure transducers before and after measurements did not reveal any similar deviations.

[31] The absence of p_e or any other indication of closed zones at the open piezometers may be due to the venting of gas through the pipes, or because the closed zones were not large enough to have an influence on the whole screen intake [*Kellner et al.*, 2004]. Another possible cause to the missing closed zone effects can be that the pipes were used for slug tests to determine hydraulic conductivity [*Hvorslev*, 1951] (results not shown here), where 20 cm (≈100 ml) water was inserted in the pipe approximately every second week. The insertions of water could have induced changes in chemical composition of the pore water causing unfavorable conditions for methane production. Alternatively, water insertions could have caused releases (ebullition) of trapped bubbles close to the standpipe by the sudden pressure shifts at the tests, thereby reducing the potential for closed zone formation. In fact recent studies have shown how unusual head recoveries during slug tests can be interpreted in terms of bubble dynamics [*Surridge et al.*, 2005].

5.2. Implications of Gas Bubbles on Water Storage Terms and Peat Volumes

[32] A change in volumetric gas content ($\Delta\gamma$) induces an equal but reverse change in water content ($\Delta\theta$), which in a one-dimensional system brings on a change in water table (WT). The size of the vertical change in the water table level depends on the storativity S,

$$\Delta \mathrm{WT} = \Delta\Gamma / S. \tag{8}$$

The storativity S is expressed as [*Freeze and Cherry*, 1979]

$$S = S_y + bS_s = S_y + b\rho g(\beta_1 + \eta\beta_2), \tag{9}$$

where S_y is specific yield (dimensionless), S_s is specific storage (m^{-1}), b is aquifer thickness below water table (m), ρ is water density (kg m^{-3}), g is acceleration due to free fall (m s^{-2}), β_1 is peat matrix compressibility (Pa^{-1}) and β_2 is fluid compressibility (Pa^{-1}). If there are bubbles in the zone within which the water table fluctuates, S_y will become lower than in totally saturated conditions [*Baird and Waldron*, 2003]. The extent of this effect on S_y is hard to estimate since we are not certain of how the bubbles are distributed in the pores. Rather than making some crude estimate, we simplify the subsequent analysis by assuming that S_y is not affected by bubbles. In the analysis of S_s, we may omit water compressibility since it is very low, 4.4×10^{-7} kPa^{-1} [*Freeze and Cherry*, 1979]. However fluid compressibility is influenced by the gas content, since gas bubbles are compressible. Accordingly, $\eta\beta_2$ corresponds to the change in volumetric gas content with pressure below the water table:

$$\eta\beta_2 \approx \frac{\partial\theta}{\partial P_g} = -\frac{\partial\gamma}{\partial P_g} \tag{10}$$

[33] We assume here that the gas pressure change ∂P_g is the same as the change in hydrostatic pressure, or ∂WT. If we consider a piece of soil with total volume V (m^3), composed by the partial volumes of solids (V_s), gas (V_g) and water (V_w):

$$V = V_s + V_g + V_w = (1-\eta)V + \gamma V + \theta V \tag{11}$$

the gas volume change with pressure change can be given by using Henry's law and the gas law (equations (1) and (2)), assuming $\partial M = -\partial C \times V_w$, and approximating the relative change in V_w to be zero, by

$$\frac{\partial V_g}{\partial P_g} = \frac{-V_g}{P_g} - \alpha_{bu}\frac{V_w}{P_g}, \tag{12}$$

Thus, if we divide by V,

$$\frac{\partial\gamma}{\partial P_g} = \frac{-\gamma}{P_g} - \alpha_{bu}\frac{\theta}{P_g}. \tag{13}$$

With $\gamma = 0.1$, $\theta = 0.85$, $P_g = 106$ kPa (atmosphere pressure + 0.5 m water, in a 1 m thick aquifer) and $\alpha_{bu} = 0.04$ (from *Wiesenburg and Guinasso* [1979] at 15°C) we get

$$\eta\beta_2 \approx -\frac{\partial\gamma}{\partial P_g} = 1.26 \times 10^{-3}\ \mathrm{kPa}^{-1}$$

[34] The same conditions except $\gamma = 0.2$ and $\theta = 0.75$, results in $\partial\gamma/\partial P_g = -2.17 \times 10^{-3}$ kPa^{-1}, whereas changing α_{bu} and P_g within reasonable ranges would only cause a ≈10% change in $\partial\gamma/\partial P_g$. Note that we only use the value of α_{bu} for methane here, although there are also other gases within peat bubbles, which may change this number. Compared with the measured peat compressibility (β_1) of this site (varying between 0.011 kPa^{-1} and 0.090 kPa^{-1} [*Kellner et al.*, 2003]), $\eta\beta_2$ ($\approx -\partial\gamma/\partial P_g$) is at least an order of magnitude less and may be of minor importance for the estimation of S_s. In less compressible peat $\partial\gamma/\partial P_g$ may be relatively more important, and it may be an essential component in situations with thicker peat deposits containing gas. A 4 m thick peat layer with $\beta_1 = 0.01$ kPa^{-1}, $\gamma = 0.1$, $\theta = 0.80$, $P_g = 120$ kPa and $\alpha_{bu} = 0.04$ generates a value of $bS_s = 0.44$, of which the gas term makes up 0.044. This may be compared with average peat profile (0–50 cm) values of S_y, found to vary between 0.06 at cutover sites to 0.14 at natural sites [*Van Seters and Price*, 2002].

[35] Gas bubbles may further influence peat volume, because the bubbles decrease the effective stress (σ'), caused by the weight of the overlying material for a given pressure, by inducing buoyancy forces resulting from the very low density of gas, compared to water. If Δz_u and Δz_s (m) are the thicknesses of the zones above and below the water table respectively, that are situated above a layer at depth $z = \Delta z_u + \Delta z_s$, the effective stress σ' (Pa) at z can be expressed, by using a one-dimensional approach, as

$$\sigma'_z = \left[\left(\rho_p(1-\bar{n}_u) + \rho_w\bar{\theta}_u\right)\right]g\Delta z_u + \left[\left(\rho_p - \rho_w\right)(1-\bar{n}_s) + \left(\rho_g - \rho_w\right)\bar{\gamma}_s\right]g\Delta z_s \tag{14}$$

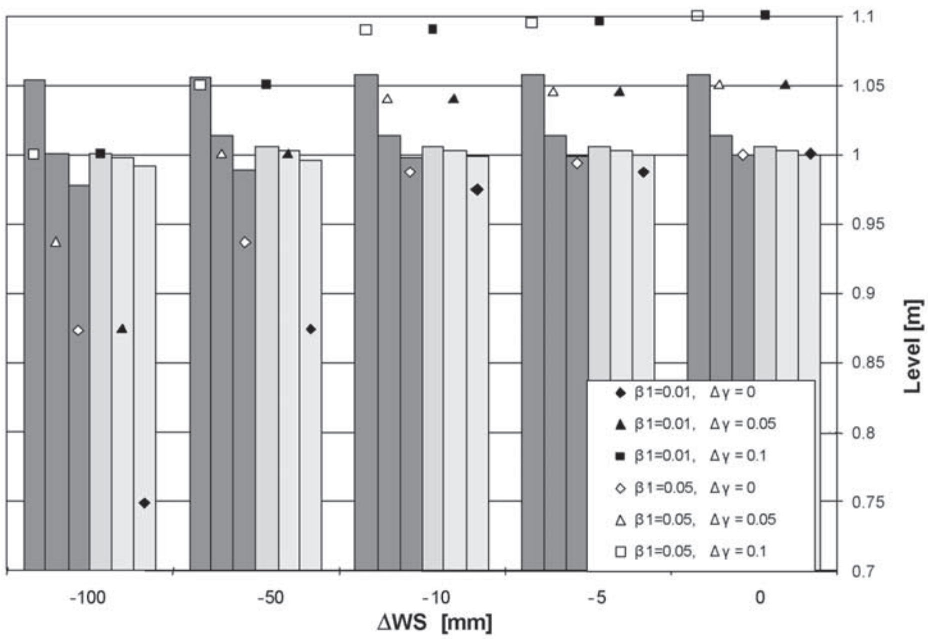

Figure 6. Calculated levels of water table and surface in a 1 m thick peat profile under conditions with different volumetric gas content ($\Delta\gamma$), peat compressibility (β_1), and size of water storage change (ΔWS) from a totally saturated soil. Bars represent surface level (dark for β_1 = 0.05 kPa^{-1} and light for β_1 = 0.01 kPa^{-1}), while symbols represent water table level.

where ρ_p, ρ_w, ρ_g are the densities of peat, water and gas, respectively (kg m^{-3}); g is acceleration due to free fall, $\overline{\eta}$ is average porosity, $\overline{\theta}$ is average water content, $\overline{\gamma}$ is average gas content, and subscripts u and s represent unsaturated and saturated zones, respectively. Note that water pressure in equation 14 is assumed to be only depending on the depth below water table, thus no effects of excess pressure are taken into account.

[36] Since $\rho_w \gg \rho_g$, an increase of gas volume leads to a decrease of effective stress. The size of change in σ' determines the change in peat thickness (L) by the relationship [*Terzaghi*, 1943]

$$\partial L = -L\beta_1\partial\sigma' \tag{15}$$

[37] Thus, in a one-dimensional vertical profile description, as bubble volume growth pushes water out of pores in the saturated zone it will cause an effect of a higher water table by pushing water upward (equation (8)) at the same time as the effect of enlargement of the peat volume (equations (14) and (15)) raises the peat surface, which complicates the estimation of water table level in relation to the surface.

[38] Using equations (8), (9) (assuming $\eta\beta_2$ = 0), (14), and (15), the water table level and surface level were determined for a peat soil profile, 1 m thick, with porosity 0.95. Calculations were made with six different parameter settings. Two different values of soil compressibility were used, β_1 = 0.01 and β_1 = 0.05 kPa^{-1}, in combination with three different gas contents, γ = 0, 0.05 and 0.10. These soil profile parameterizations were then subjected to different scenarios of water storage change (ΔWS) from a totally saturated peat by 0, −5, −10, −50 and −100 mm.

[39] The level of WT depended on the storativity (equation (8)), which itself shifted (S = 1 when WT was above surface, otherwise according to equation (9)). Together with the gas content, the WT level determined the effective stress (equation (14)), thus the peat profile thickness (equation (15)). The results are presented in Figure 6 and described below.

[40] When gas contents were greater than zero, they caused an effect of raising the water table (equation (8)), similarly to an apparent increase in ΔWS. Adding together the values of ΔWS and specific volumes of applied gas (Γ = 50 and 100 mm for γ = 0.05 and 0.10, respectively), the net sum (Γ + ΔWS) became positive for most values of ΔWS. Thus the water table was above surface for most profiles with γ = 0.05 and 0.10.

[41] The lower compressibility, β_1 = 0.01 kPa^{-1}, did not cause any sizeable peat volume change with changes in effective stress (Figure 6). In contrast, the more compressible profiles (β_1 = 0.05 kPa^{-1}), which contained gas, swelled up because of the buoyancy forces of the gas (Figure 6). Also when WT was below ground surface in these profiles, the gas buoyancy sustained a notably greater volume than in the profile with γ = 0 in similar conditions. The high compressibility induced also a greater storativity (equation (9)), which caused less changes in WT compared to the more rigid profiles (Figure 6). To conclude, the main effect by gas volumes in a more rigid soil is a displacement of WT whereas in a more compressible soil the interaction with soil volume changes brings about a damping of WT variation compared to surface level.

[42] As mentioned earlier, possible effects of p_e were not considered in these calculations. However, the peat volume could also be affected by changes in σ' because of p_e

dynamics. With a one-dimensional approach, an overpressure of 10 cm water would cause an expansion of 1% or 5% of the closed zone volume if the compressibility was $\beta_1 = 0.01\ kPa^{-1}$ or $\beta_1 = 0.05\ kPa^{-1}$, respectively [*Kellner et al.*, 2004].

6. Conclusions

[43] Biogenic bubbles in peat soils occupy considerable volumes, which shift during the season as higher temperature increases the biological activity and decreases the solubility of gases. The seasonal increase in gas content measured in this study varied spatially with a maximum increase of 0.15 by volume. The principal cause of the spatial variation of gas accumulation is probably differences in peat structure rather than local rates of gas production. The greatest estimated increase in total specific gas volume of a 1 m deep profile was 47 mm, which was comparable to the seasonal water storage change. Thus displacement of the water table caused by gas volume dynamics may be considerable and a crucial factor for water content estimations for the upper peat. In highly compressible soils (and floating root mats), buoyancy forces caused by bubbles also cause peat volumes to increase, causing relations in surface water table levels to change. Calculations based on the results of this study revealed that these effects are of such a magnitude that they cannot be omitted in modeling the hydrology of peatlands.

[44] The seasonal development of bubble volume also causes a greater amount of bubbles blocking the pores. The trapped bubbles restrict water flow and hence cause a decrease in hydraulic conductivity. Pressure deviation effects suggested that closed zones were developed by trapped bubbles. For many sensors, there was a buildup of pressure followed by sudden release, probably caused by subsequent gas production within these closed zones. The closed zones in this study were probably small and effects of volume change by pressure buildup and release of individual zones were within the uncertainty of the measurements of peat layer thickness. Nevertheless, the influence on hydrology of these closed zones may be considerable as they may more or less totally close off or deflect water flows.

[45] Indications of overpressure zones are seldom found when using nonsealed pipes for hydraulic head measurements. This could be because closed zone volumes are too small to affect the head in the pipes, but we also hypothesize that open piezometer pipes may vent gas from the soil adjacent to the pipe screen. Piezometer pipe slug tests for estimating hydraulic conductivity may also cause ebullition or change the volume and distribution of bubbles.

[46] Many of the results in this study lead to questions and speculations on the processes. A primary concern is the poor characterization of spatial variability, not only of bubbles themselves but also their relations with patterns of biological activity, of peat structure and compressibility.

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