Increased domestic radon exposure caused by permafrost thawing due to global climate change

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INTRODUCTION

Radon is a naturally occurring radioactive gas which accounts for approximately 9% of lung cancer deaths in Europe and 12% in the USA, and is considered to be the most serious environmental carcinogen by the EPA.

The diffusive and advective transport of radon through the soil is controlled by the porosity, fluid saturations, diffusion coefficients and relative permeabilities of the soil. All of these parameters are significantly reduced in the permafrost that makes up one fifth of the Earth's terrestrial surface.

We have carried out a pilot study involving the 2D numerical modelling of radon transport through soil, permafrost and a model unventilated model building.

We find that the presence of the permafrost may act as an effective radon barrier even in the absence of advective transport. For the world average Ra^{226} activity of 40 Bq/kg, the permafrost seems to reduce the domestic radon concentrations by 80 to 90% (5 to 10 Bq/m^3) while leading to an increase in the concentration in the radon behind the barrier by 10 to 15 times (500 to 750 Bq/m^3).

However, when we modelled the thawing of the permafrost that is beginning to occur as a result of global climate change the radon in the building increased transiently by up to 100 times (1000 Bq/m^3) over a timescale of several years before decreasing once again. It is therefore possible that a significant number of people could be exposed to levels of radon in excess of the 200 Bq/m^3 threshold that many countries adopt.

This is particularly worrisome since it is recognized that although radon is known not only to be the most important cause of lung cancer after smoking, it has a much greater impact amongst smokers. This is especially important considering that the prevalence of smoking amongst the tribes of the Canadian Arctic and Greenland are 71% and 79% compared to a rate of 34% for Europe and Central Asia.

METHODS

All modelling was carried out by the finite element solution of linked partial differential equations in 2D as a function of time using FemLab 3.1.

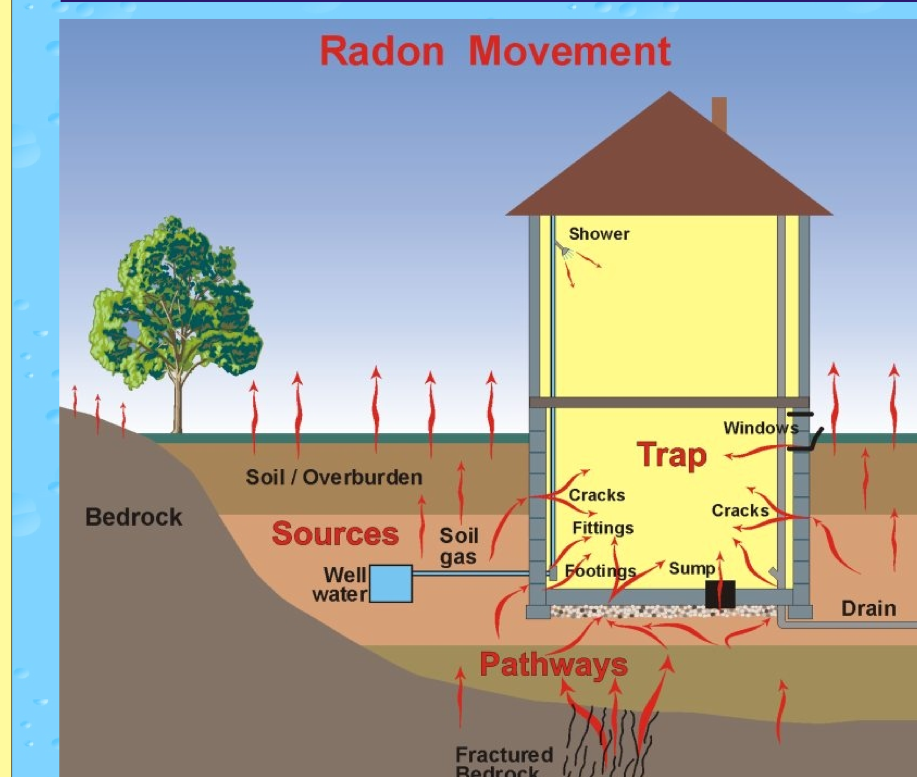
The model is 60 m wide and includes a 45 m depth of soil. The permafrost layer is 13 m thick, beginning 2 m below the surface.

There are four soil domains; (a) soil below the permafrost layer, (b) the permafrost layer, (c) the soil above the permafrost layer on each side of the building. The building is split into three domains, (i) a rectangular basement (4 m high, 18 m wide), which is just below the surface of the soil and penetrates into the permafrost layer, (ii) a rectangular main living space (10 m high, 18 m wide), and (iii) a triangular roof space (5 m high, 18 wide).

A two dimensional mesh is created and refined in all domains of the model. The mesh consists of triangles which are no larger than 2 m in the body of the model, and no larger than 1 m along all boundaries except those where the boundary conditions of insulation and symmetry are applied.

There are over 4000 elements in the final model. The number of elements controls the speed of the final solution. We found that the solutions were reached within several minutes on a standard 3 GHz laboratory PC, and hence retain the described geometry for clarity even though the model is symmetric and could be reduced to half of its size.

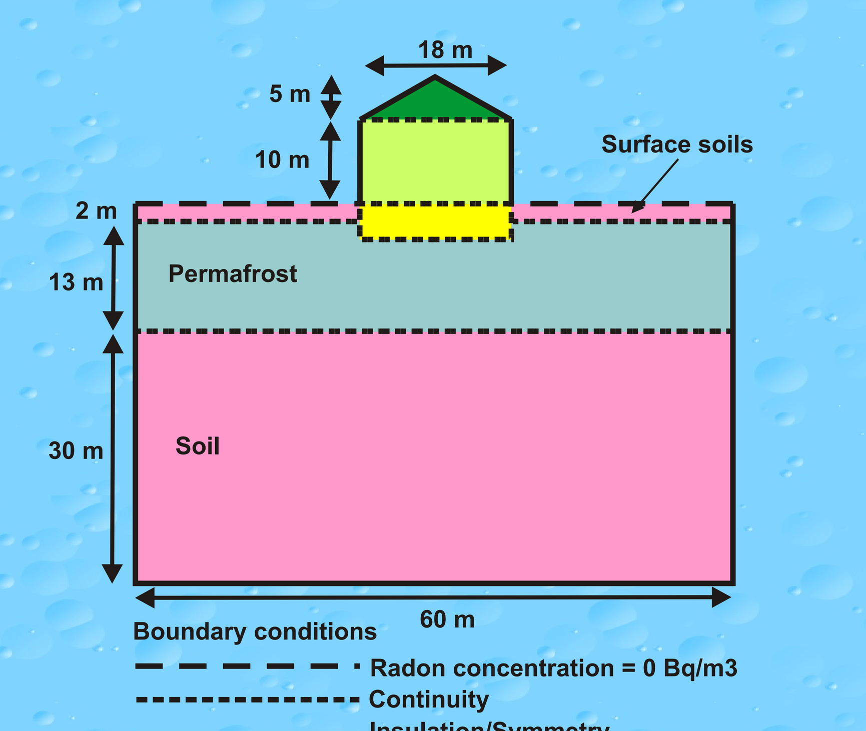
RADON MOVEMENT

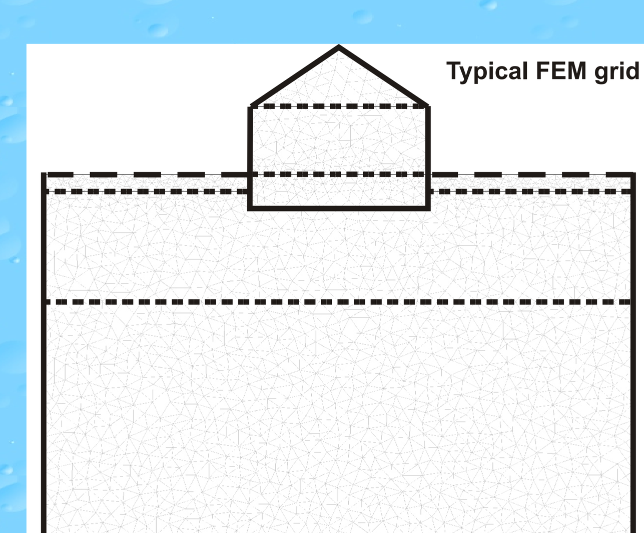


Pathways for movement of radon through rock, soil and dwellings without the layer of permafrost.

The permafrost provides an additional radon barrier.

MODEL GEOMETRY AND BCs





DIFFERENTIAL EQUATIONS

The fundamental differential equations follow from Fick's, Darcy's and Laplaces's equations:

$$\vec{J}_{diff,a} \quad 1 \quad S_w \quad {}_aD_a \quad C_a \qquad \vec{J}_{diff,w} \quad S_w \quad {}_wD_w \quad C_w \qquad \vec{J}_{adv,a} \quad C_a \frac{K_a}{} \quad P \qquad {}^2P \quad 0$$

where J are the bulk fluxes of radon (Bq m^{-2} s^{-1}), the subscripts *adv* and *diff* refer to advection and diffusion respectively, and *a*, *w*, *i* and *s* refer to air, water, ice and solid surfaces, S_w is the water saturation of the pore space (fractional), is the porosity of the soil (fractional), are the tortuosities of the Rn flow (fractional) in each phase, D are the diffusion coefficients of Rn in water and air (m^2 s^{-1}), K_a is the intrinsic permeability to air (m^2), m$_a$ is the dynamic viscosity of air, C are the Rn concentrations in each phase (Bq m^{-3}), and P is the gas pressure (Pa). There is no transport of Rn in the water or ice, and no advective transport in the water (see section below).

Radon is generated within the soil and permafrost at a rate [Bq m^{-3} s^{-1}] = ${}_b$ C^{Ra} where is the sum of the fractional emanation coefficients into the air, water, ice and adsorbed phase (= ${}_{air}$+ ${}_{water}$+ ${}_{ice}$+ ${}_{surface}$), ${}_b$ is the soil bulk density (kg m^{-3}), is the decay constant of radon (s^{-1}) and C^{Ra} is the radium-226 activity per unit dry mass (Bq kg^{-1}).

The mass balance equations for each phase (air, water, ice and solid surfaces, respectively) are given by:

$$(1 \quad S_w \quad S_i) \frac{C_a}{t} \quad 1 \quad S_w \quad S_i \quad {}_aD_a \quad C_a \quad \frac{K_a}{a} \quad P \quad C_a \quad (1 \quad S_w \quad S_i) \quad C_a \quad {}_a \; {}_b \; C^{Ra} \quad {}_{j \; a} T_{aj} \quad T_{ja}$$

$$S_w \frac{C_w}{t} \quad S_w \quad {}_wD_w \quad C_w \quad S_w \quad C_w \quad {}_w \; {}_b \; C^{Ra} \quad {}_{j \; w} T_{wj} \quad T_{jw}$$

$$S_i \frac{C_i}{t} \quad S_i \quad {}_iD_i \quad C_i \quad S_i \quad C_i \quad {}_i \; {}_b \; C^{Ra} \quad {}_{j \; i} T_{wj} \quad T_{jw}$$

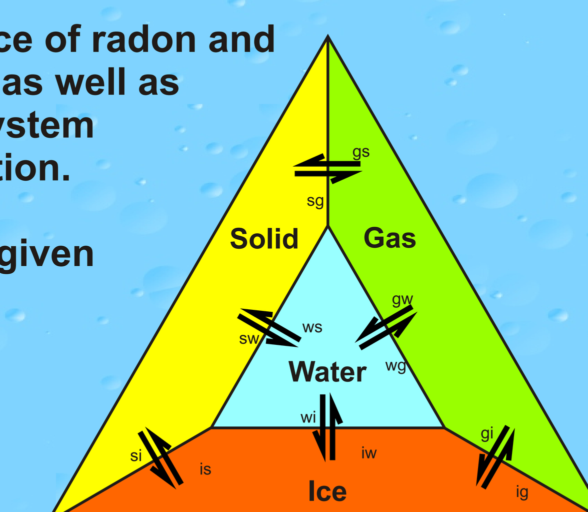
$${}_b \frac{C_s}{t} \quad {}_b \; C_s \quad {}_s \; {}_b \; C^{Ra} \quad {}_{j \; s} T_{sj} \quad T_{js}$$

RADON PARTITIONING

There is a radioactive source of radon and a radioactive loss of radon as well as losses of radon from the system due to diffusion and advection.

The available radon at any given time is partitioned between four phases.

The phases are:
The solid minerals,
Pore gases, Pore waters
and Pore ice



The triangular diagram shows reaction coefficients for the transfer of radon between these phases. The partitioning is important because radon is not as MOBILE in some phases as in others. The differential equations for flow can then be *simplified* to include only the mobile fractions. THUS:

$$\frac{C_a}{t} \quad D \quad C_a \quad \frac{K_a}{a} \quad P \quad C_a \quad C_a$$

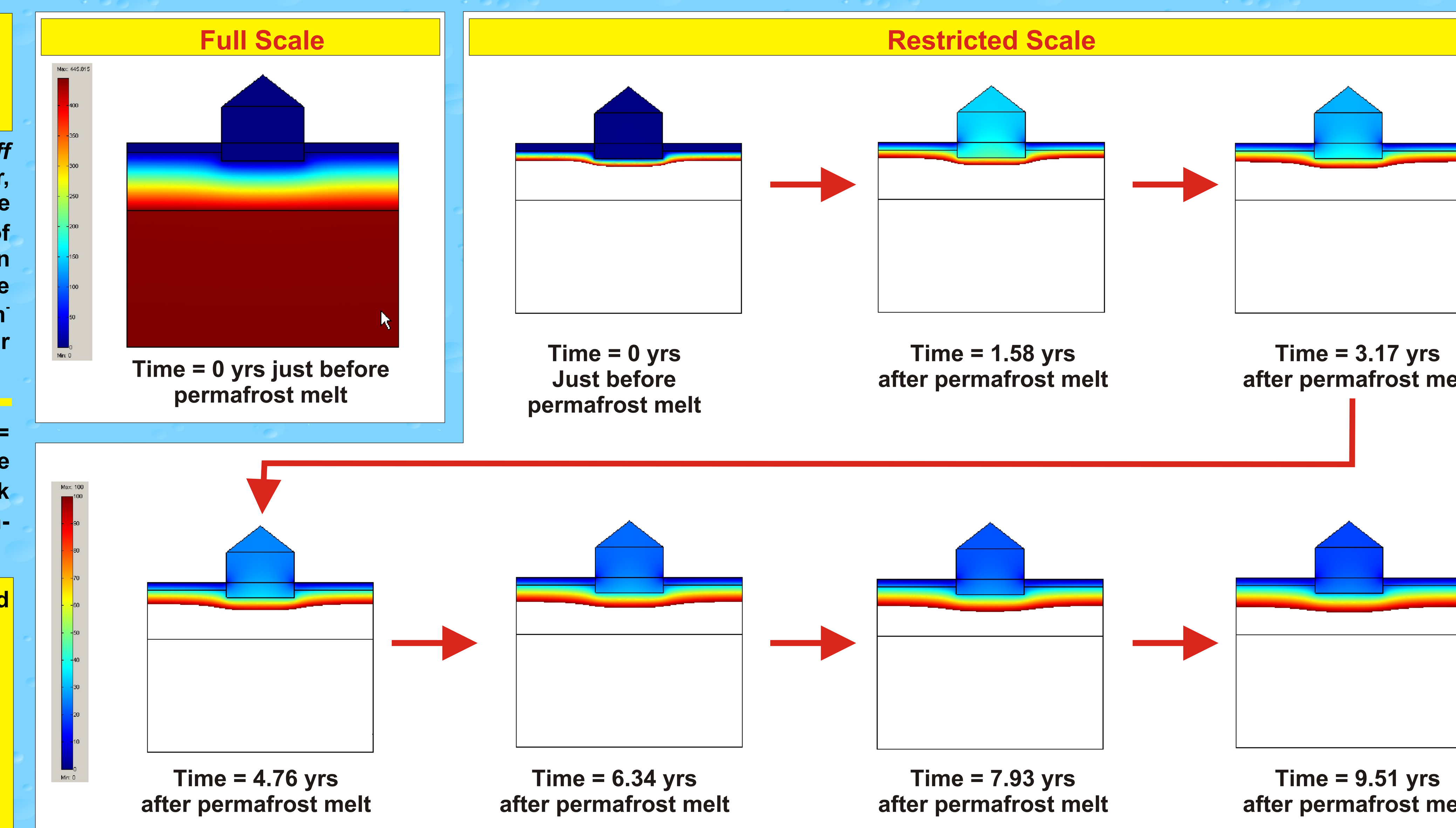
where: $1 \quad S_w \quad S_i \quad S_wL_{aw} \quad S_iL_{ai} \quad {}_bK_{as}$ is the operating porosity

$D \quad 1 \quad S_w \quad S_i \quad {}_aD_a \quad S_w \quad {}_wD_wL_{aw} \quad S_i \quad {}_iD_iL_{ai}$ is effective diffusion coeff.

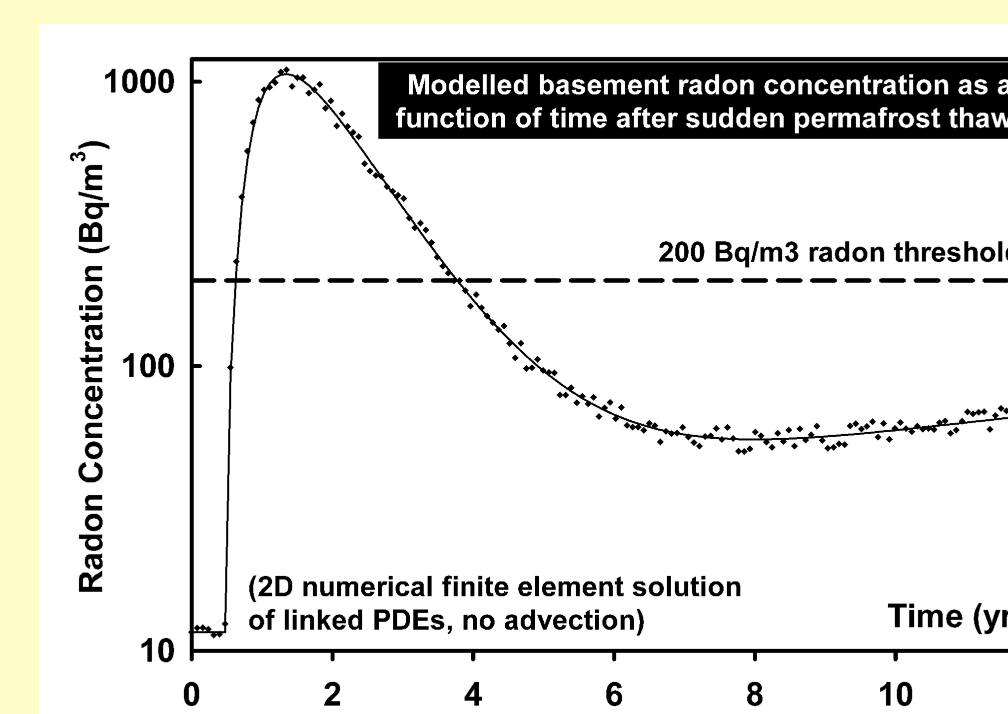
${}_b \quad C_{Ra}$ is the source term

The parameters L_{aw} and L_{ai} are Ostwald coefficients, ${}_j$ are tortuosities, D_j are diffusion coefficients and S_j are phase fractions for each phase.

TIME DEVELOPMENT



IMPLICATIONS FOR RADON EXPOSURE



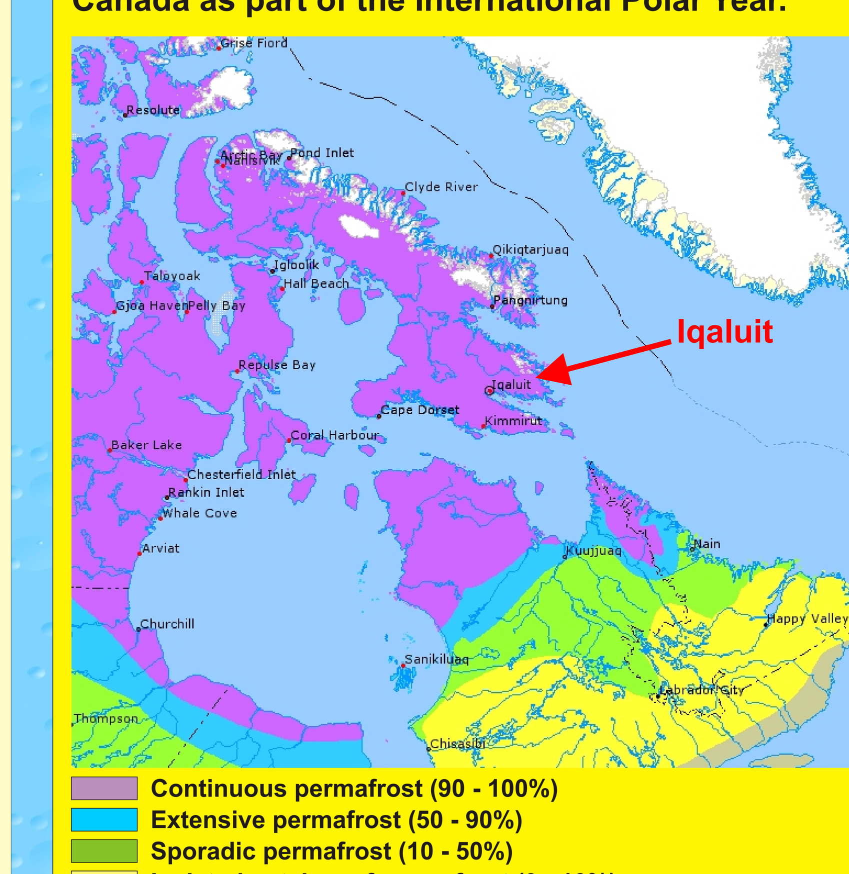
1. The initial level of radon represents that before the permafrost has melted.
2. The permafrost acts as an effective radon barrier.
3. The sudden loss of the permafrost due to melting caused by climate change leads to a 100 fold increase in the exposure to radon within the basement.
4. The radon level remains over the 200 Bq per cubic metre action level for over 3.5 years.
5. The radon level eventually falls to a lower level after more than 6 years.
6. This level is the natural radon level for the area without the protective permafrost barrier.

FUTURE WORK

The main difficulty with this type of modelling is the lack of parameters which characterise radon transport in permafrost.

We have applied for grants to continue the modelling and to carry out field and laboratory work aimed at characterising the transport properties of permafrost more accurately.

The work will be carried out in Iqaluit, northern Canada as part of the International Polar Year.



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