SIMPLIFIED DESCRIPTION OF SNOW IN A GLOBAL MULTIMEDIA FATE MODEL FOR EVALUATING THE INFLUENCE OF CLIMATE CHANGE ON THE GLOBAL FATE OF POPS

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Abstract
Snow and ice play important roles in the fate of persistent organic pollutants at high latitudes. Polar regions are particularly susceptible to climate change, and large changes in terms of snow and ice cover are predicted to occur. Thus our concern is to assess the influence of these changes on the global transport and accumulation of POPs. As most global multimedia fate models do not yet include a description of seasonal snow/ice covers, this study set out to add a simplified description of a seasonal snow cover and ice caps to the global fate model Globo-POP. Water balance equations for annually averaged water fluxes between environmental compartments in 10 climate zones were developed. Seasonal water fluxes accounting for snow hydrology were then calculated according to three seasons based on temperature. In addition, global river discharge data were used to account for major rives flowing between climate zones. The water flux in the revised Globo-POP is a function of temperature and precipitation. Therefore, future climate data over the next 100 years, as predicted by atmosphere-ocean general circulation models, can be directly used as input parameters. This will enable Globo-POP to assess the influence of climate change on the behavior of POPs.

Introduction
Persistent Organic Pollutants (POPs), which have been emitted mostly in the northern temperate regions, are subject to atmospheric long-range transport and accumulation in cold regions at high latitudes and altitudes, where a snow cover is an important environmental compartment influencing the fate of organic chemicals. A permanent snow cover acts as a sink for chemicals, while a seasonal snow cover temporally stores chemicals and delivers them to soils, vegetation, and water bodies during melt.[1] As snow hydrology is expected to be highly affected by a changing climate, our concern is to understand qualitatively and quantitatively the role of snow in the regional and global fate of POPs and in particular to assess the influence of climate change on the polar accumulation of POPs.

We have previously used the Arctic Contamination Potential (ACP), calculated with the zonally averaged global fate and transport model Globo-POP, to assess the accumulation behavior of POPs in the Arctic. A study investigating the sensitivity of ACP to environmental input parameters had indicated that contaminant accumulation in the Arctic is particularly sensitive to changes in latitudinal temperature gradients, sea ice cover and precipitation rates, suggesting that global climate change may significantly impact the accumulation of POPs in the Arctic environment.[2] To prepare the Globo-POP model for the task of exploring the interaction between climate change and global contaminant transport further, we added a description of seasonal snow cover and polar ice-caps.

Materials and Methods
Up to now, only few models of multimedia fate and transport of organic chemicals describe falling snow and a seasonal or permanent snow cover.[1, 3] The challenge of describing snow in multimedia fate models is to strike a balance between the desire for simplicity inherent in such models and the complexity of a metamorphising snow pack as a transient, heterogeneous and highly dynamic system. That challenge is amplified in models of global scale. This study set out to develop an approach that is simpler than earlier approaches[1, 3] but that still captures the essential aspects of a seasonal snow pack's influence on organic contaminant fate and transport. Several steps were required to achieve this. Based on global precipitation and river discharge data, we first derived an annually averaged water balance, which includes all water fluxes between air, forest canopies, soils, snow pack, fresh water, and ocean water in the 10 climate zones of the model. We also account for major rivers crossing the boundaries between climate zones. Seasonally resolved water fluxes that account for the transient nature of the

snowpack were then calculated for three seasons, which are defined based on temperature as in Daly and Wania[1].

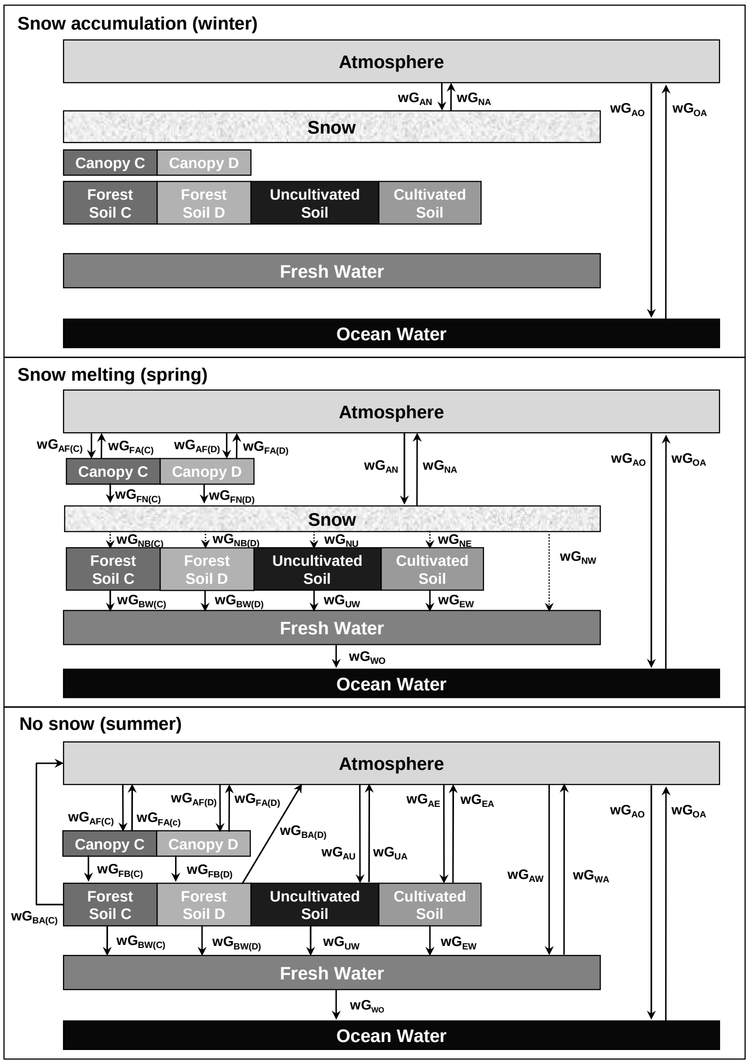

Figure 1. Seasonal water fluxes between the environmental compartments in Globo-POP

Water balance equations

Water fluxes from atmosphere to the surface were calculated by multiplying precipitation rates to the terrestrial environment and to the oceans with the surface areas of the respective compartments. The water fluxes from the surface environments to air were calculated by user-defined evaporation fractions of the total water influx to the compartments. Finally, runoff was calculated to fulfill the water mass balance in each compartment, i.e. the difference between precipitation and evaporation is equal to runoff from that compartment. More details can be found in elsewhere.[4]

The seasonal description of water fluxes varies with the presence of snow (Figure 1). In winter, only water fluxes between air and snow exist in the terrestrial environment. The water flux from fresh water to ocean in winter was neglected in order to maintain the balance between surface compartments. In winter and spring the snowpack prevents water exchange between air and soils. During snowmelt, air-forest canopy fluxes and runoff from soils to fresh water resume. Snowmelt water and particles are also transferred to soils and fresh water.

Snow hydrology

The area covered by snow (AR_N) was assumed to be the same as the terrestrial surface area and to be constant throughout the snow accumulation and melting seasons, i.e. within one zone there is no partial snow cover. Snow height (*HTN(t)*) is expressed as linear functions of time (*t*, 0 – 365×24 hours) (Figure 2):

If $T < 0℃$ and $0 < t < t_{SM}$ (late winter),
$$HTN(t) = \frac{HTN_{Max}}{frS_A \cdot 365 \cdot 24} \cdot (t - t_{SA} + 365 \cdot 24) \qquad (1)$$

If $T > 0℃$ and $t_{SM} < t < t_{SG}$ (spring),
$$HTN(t) = HTN_{Max} - \frac{HTN_{Max}}{frS_M \cdot 365 \cdot 24} \cdot (t - t_{SM}) \qquad (2)$$

If $T > 0℃$ and $t_{SG} < t < t_{SA}$ (summer),
$$HTN(t) = 0 \qquad (3)$$

If $T < 0℃$ and $t_{SA} < t < 365 \cdot 24$ (early winter),
$$HTN(t) = \frac{HTN_{Max}}{frS_A \cdot 365 \cdot 24} \cdot (t - t_{SA}) \qquad (4)$$

where, t_{SA} is the start time of winter (snow accumulation) in hours, t_{SM} is the start time of spring (snow melting), and t_{SG} is the time when the snow disappears. The default length of spring is 30 days ($t_{SG} = t_{SM} + 30 \cdot 24$). The equation for the maximum snow height (HTN_{Max}) is

$$HTN_{Max} = frS_A \cdot 365 \cdot 24 \cdot \frac{wG_{ANa}}{(VFsweN \cdot AR_N)} \quad (5)$$

where, wG_{ANa} is precipitation to the snow pack in winter and the value of the volume fraction of snow water equivalent (VFsweN) is 0.43. Finally, the snow volume (*VON(t)*) is

$$VON(t) = HTN(t) \cdot VFsweN \cdot AR_N \quad (6)$$

For the Antarctic, the height and volume of snow were assumed constant.

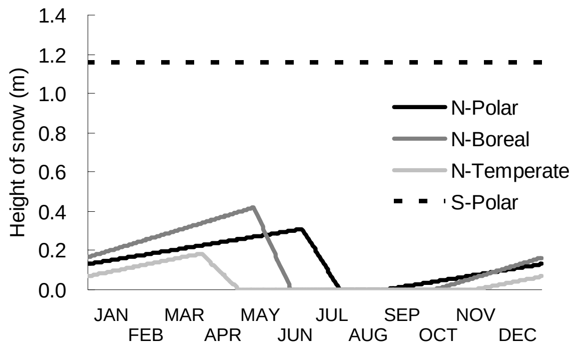

Figure 2. Seasonal changes in snow height calculated by equations 1 to 6 for four climate zones. Longer periods of winter with increasing latitude are apparent. The maximum snow height in the three northernmost climate zones reflects the length of winter and the precipitation rates.

Freshwater fluxes to the Oceans

So far, the Globo-POP model did not properly describe inter-zonal chemical transport by rivers. For example, the Mississippi river, one of the longest rivers in the world, originates in the N-Temperate zone, flows through the N-Subtropic terrestrial zone and then discharges into the N-Tropic Ocean. To account for these river discharge patterns and chemical transport, the global monthly river discharge data set (RivDis 1.1) was used.

The major rivers in the southern hemisphere have one-directional flow to the ocean in the same climate zone. Thus we only considered freshwater fluxes in the northern hemisphere. The boxes and arrows in Figure 3 represent the different fractions of freshwater fluxes. The rivers in the Northern Boreal zone show the most complicated water flows. This indicates that one-directional flow in the same climate zone as described in the previous version of Globo-POP could result in the overestimation of water fluxes and chemical transport to the N-Boreal, N-Temperate, and N-Subtropic oceans.

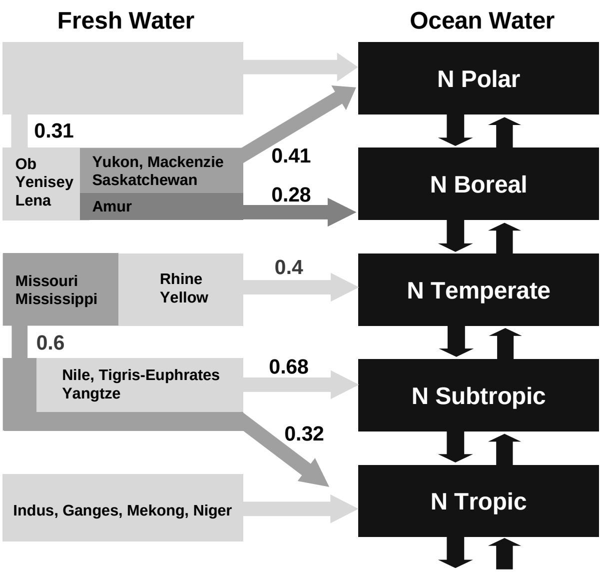

Figure 3. Fractions of freshwater fluxes to the oceans in the northern hemisphere.

Results and Discussion

Total global water fluxes (with arrows indicating the direction of water flow) are presented in Figure 4. There are two types of water flux from fresh water to oceans: one is water flowing in the same climate zones (28,732 km^3/yr), and the other is water flowing between different climate zones (4,038 km^3/yr). The flux of Antarctic water burial (5,835 km^3/yr, indicated with a dashed line) is assumed to be the same as the flux of Antarctic basal melting. Precipitation to the snow pack contributes 17% of the total precipitation to the terrestrial environment, indicating that snow is an important compartment in terms of wet deposition of chemicals in the atmosphere. Owing to its large area, the uncultivated soil receives the largest amount of melt water (41%) and contaminants dissolved in water and associated with organic particles. Forest canopies and forest soils in low-latitude zones are major compartments receiving precipitation. In the mid-latitude and S-Subpolar zones, precipitation to uncultivated soils is dominant. Meanwhile, snow precipitation is significant for mid- and high-latitude zones in the northern hemisphere and for the Antarctic which is assumed to be completely covered by snow year round.

Snow cover and water fluxes in the revised Globo-POP are calculated as a function of the temperature and precipitation data supplied to the model. If supplied with temporally variable climate data, the model will calculate snow coverage and water fluxes that vary from year to year. The modified Globo-POP model thus should be able to evaluate how organic contaminant fate on a global scale may be influenced by a changing climate.

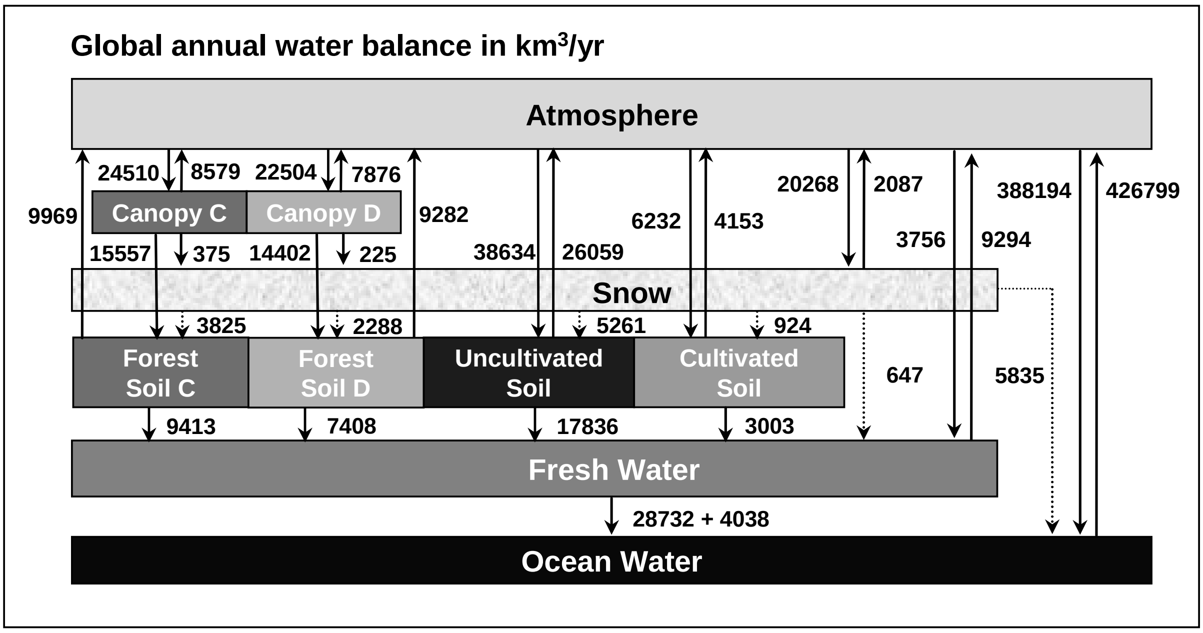

Figure 4. Global annual water flux diagram including all environmental compartments in Globo-POP. A dashed line between snow and ocean water stands for the flux of Antarctic snow burial.

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