WETLAND EXTENT AND METHANE DYNAMICS:
AN OVERVIEW OF THE ESA ALANIS-METHANE PROJECT

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ABSTRACT

The European Space Agency (ESA), as part of its Support to Science Element (STSE), has initiated the *A*tmosphere-*LAN*d *I*nteractions *S*tudy (ALANIS) in collaboration with the Integrated Land Ecosystem-Atmosphere Processes Study (iLEAPS). One of the three themes in ALANIS is considering wetland dynamics and methane emissions (denoted hereinafter ALANIS methane). The ALANIS methane project has a focus on the boreal Eurasia region. The main goal of the project is to produce and use a suite of relevant information derived from Earth Observation (EO) for this domain to validate and improve one of the next generation land-surface models and thus reduce current uncertainties in wetland-related CH_4 emissions. This paper presents an overview of the project, the products and its current status.

1   INTRODUCTION

Over the past two centuries, the concentration of methane (CH_4) in the atmosphere has more than doubled [1] and methane now constitutes 20% of the anthropogenic climate forcing by greenhouse gases [2,3]. The radiative efficiency of CH_4 is about ten times greater than that of carbon dioxide, so increases in methane have a large impact on global climate.

Although the global annual source strength of CH_4 is relatively well constrained, considerable uncertainties exist in the partitioning of sources and their spatial and temporal distribution. Whilst anthropogenic sources are estimated to account for more than 60% of all CH_4 emissions, wetlands are generally accepted as being the largest, but least well quantified, single natural source of CH_4 (ranging from 100-231 Tg yr^{-1}) [4,5]. Emissions of methane from the wetlands and lakes of the Boreal region contribute less than the tropical wetlands to the global wetland methane emissions: Walter et al. [6] calculated that only 25% of the wetlands emissions come from wetlands north of 30˚ N.

Since the late 1970s, there have been significant inter-annual variations in the CH_4 growth rate believed to be due to variability in wetland CH_4 emissions [7,8]. Recently, Bloom et al. [9] and Ringeval et al. [10] used innovative techniques to utilise newly available EO data to correlate methane fluxes with space-based observations. These studies concluded that, although the seasonal cycle is dominated by the tropical wetlands, the northern latitudes dominated the inter-annual variability. The high variability is in part due to the fact that northern wetlands act as net sinks of CO_2 but also as large net sources of

CH$_4$ [11]. The balance depends on climate and hydrology which is highly variable in these regions and due to change significantly in the next century.

The ALANIS methane project has a focus on the boreal Eurasia region. The size and remoteness of boreal Eurasia, however, pose a challenge to quantification of both terrestrial ecosystem processes and their feedbacks to regional and global climate. In the last few years, Earth Observation (EO) data have demonstrated the potential to become a major tool for characterizing the main processes and estimating key variables governing the land-atmosphere interface over the extremely wide and often unreachable northern areas of boreal Eurasia. The main goal of the ALANIS methane project is to produce and use a suite of relevant information derived from Earth Observation (EO) to validate and improve one of the next generation land-surface models and thus reduce current uncertainties in wetland-related CH$_4$ emissions. This paper presents an overview of the project and its current status.

2   LAND SURFACE MODELLING

2.1   Available Models

There are a number of land surface models (LSM) used globally, which share many common features. These include, for example,

- the Joint UK Land Environment Simulator (JULES) model (http://www.jchmr.org/jules)
- Orchidee [part of the French GCM model, http://orchidee.ipsl.jussieu.fr/index.php;
- the US Community Land Model (CLM, and part of the US NCAR climate model, http://www.cgd.ucar.edu/tss/clm/)
- The Lund-Potsdam-Jena Dynamic Global Vegetation Model (LPJ) [http://www.pik-potsdam.de/lpj/lpj_researchvt1.html#furtherinfo]

The first three land surface models (Orchidee, CLM and JULES) are all designed for use within global or regional climate models (GCM or RCM). These land surface models each represent the energy, water and carbon balances of the surface on an hourly basis, which is necessary for accurate calculation of the land-atmosphere fluxes. The LPJ model (and its derivatives such as LPX) is slightly different as it is essentially an off-line model and is not designed to work within an atmosphere model (although components of it have been used as modules to the other land surface models). When run on its own, it runs with a courser time-scale (e.g. monthly) and does not make the same detailed calculations of the energy and water balance. It is generally used to assess the carbon budgets and is regarded as a good model for vegetation dynamics.

The JULES land surface model has been selected for use in this project. JULES is the UK community land surface model.

2.2   The JULES Land Surface Model

JULES is a physically-based model, describing the energy balance of the land surface, soil heat and moisture state, and vegetation and soil carbon stores, amongst other components (see Figure 1). Currently, JULES is driven by only meteorological data, with land cover and soil data specified. The only dynamic aspect of the land surface that can be used as input data is either the Leaf Area Index or the Wetland Fraction. Both of these are optional as the model can be used to predict these.
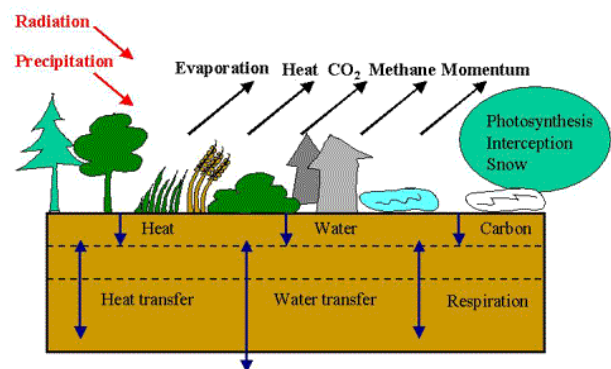

Figure 1: Schematic of the main processes represented in JULES.

The current operational version of JULES has an area of wetland modelled using information on the surface topography and soil

characteristics, following Gedney et al. [12]. In the standard version, CH_4 emissions from wetlands are also modelled following Gedney et al. [12]. The methane production in this model is very simple, dependent on soil moisture and soil temperature. Since the soil carbon modelling was limited, the model was only considered as indicative of the likely methane production.

Recently a more detailed model of soil carbon and nitrogen processes has been added (after Smith et al. [13]). There is a layered representation of methanogenesis and oxidation through the wetland soil profile, while parameterisations of diffusion and ebullition of CH_4 have also been added and tested (following Wania [14]). Further details of the model can be found on the JULES website.

Although designed to be independent of any meteorological or climate model, JULES is the land surface component of HadGEM3, which is a state-of-the-art climate model and the most recent in a line of climate models that have been developed by the Met Office Hadley Centre. HadGEM3 includes a comprehensive atmospheric chemistry and aerosol package, the UK Chemistry Aerosol community model (UKCA [15]). A regional version of HadGEM3 with a horizontal resolution of 0.5° will be used in this project. This regional version can be 'nudged' towards analyses of the atmospheric state to allow simulations in which the synoptic variability is similar to that observed, which greatly facilitates detailed comparison with observed EO time series.

2.3   Model requirements of EO data

The key datasets for boreal wetlands[1] that can be derived from EO data are:

- Land Cover
- Leaf Area Index
- Wetland Extent
- Ground freeze/thaw

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[1]   Some of these will also be useful for modelling of wetlands in tropical and other regions.

- Snow melt

The model will typically be run at 50 km resolution in its offline distributed and regional climate modes. The model requirements for the EO datasets are:

- *Land Cover* needs to be specified in terms of the fractional coverage of the main biomes: needle-leaf trees, broad-leaf trees, grass and shrubs. The land cover map also needs to be pertinent to the years being modelled.

- *Leaf Area Index*: this product needs to be at the 10-day timescale to capture the spring leaf-up as this alters the albedo considerably. The product will need to be split amongst the fractional coverage plant functional types (PFTs) of each grid cell and a spatial resolution of 1 km may be needed.

- *Wetland Extent*: Wetland extent needs to be at the 10 day timescale to capture the rapid spring-time inundation. The data will be used at the 50 km scale within the model, as a fractional cover. The data therefore needs to include all wetland and lake areas. Since some of the wet areas are very small, the EO product may need to be created at a finer scale before being aggregated up for the model.

- *Ground freeze/thaw*: This product will be used to assess key soil thermodynamic parameters. 1-10-day timescale will capture the key dynamic in the soil state. The product is needed at the 50 km spatial scale.

- *Snow melt* is rapid and impacts greatly on the hydrology of the region. A 1-10 day timescale for this product is needed to capture the spring melt event. The product is again needed at the 50 km spatial scale.

Land cover, leaf area index, land surface temperature and soil moisture products are already available. These data will not be developed within the project.

3 ALANIS METHANE PRODUCTS

Following the analysis in Section 2.3, the following EO products will be produced in the ALANIS methane project (see Table 1):

- Wetlands extent and dynamics (regional)
- Wetlands extent and dynamics (local)
- Snowmelt and ground freeze/thaw status
- Atmospheric column CH_4 concentrations

None of the products will have to be developed from scratch; the maturity of the product however varies from e.g. the testing of an implemented concept to adapting an operational procedure to include new sensors and thus enable the extension of the temporal coverage. The development and validation of the products is currently in progress.

3.1 Wetland extent/dynamics (regional)

A multi-sensor method has been used to estimate the wetland extent at large scale from 1993-2004 [16-18]. Detection of inundation primarily relies on the passive microwave land-surface signal from the Special Sensor Microwave/Imager (SSM/I). Relative to non-flooded lands, inundated regions are characterized by low microwave emissivities and high emissivity polarization difference, even under dense canopy. To avoid interference from the atmospheric contribution and modulation by the surface temperature, the microwave emissivities are first calculated from the measured brightness temperatures. Over vegetated areas, the vegetation contribution is estimated with information from coincident ASCAT active microwave. Because the scatterometer is very sensitive to vegetation density [16], it is used to assess vegetation contributions to the SSM/I passive microwave observations. In semiarid regions where bare surfaces and inundation can produce similar SSM/I signatures, Normalized Difference Vegetation Index (NDVI) and reflectance data from the Advanced Very High Resolution Radiometer (AVHRR), rather than scatterometer observations, are used to resolve ambiguities.

The method involves a three step process (i) *pre-processing* of each satellite dataset; (ii) *classification* to merge the three sets of satellite observations using an unsupervised clustering algorithm [19] and (iii) *calculation* of the fractional inundation in all pixels identified as inundated in the preceding step.

In the ALANIS methane project, the algorithm will be adapted (a) to make use of the MetOp ASCAT observations and (b) to produce 10-days estimate. Inundation extents will be created with a 0.25° x 0.25° spatial resolution at the equator (equal area grid). The technique is globally applicable without any tuning for individual environments.

Table 1: Summary of EO products to be produced in ALANIS methane.

Product	Source	Spatial	Temporal
Regional wetland dynamics (fractional water extent)	SSM/I POES-AVHRR MetOp ASCAT	0.25° x 0.25° equal area at the equator	10 day
Local wetland dynamics	ENVISAT ASAR WS	150 m x150 m	10 day Note (a)
Start of snowmelt	MetOp ASCAT	25 km x25 km	one date per year per cell
Ground freeze/thaw	MetOp ASCAT	25 km x25 km	two dates per year per cell
Atmospheric column CH_4 concentrations	ENVISAT Sciamachy	0.5°x 0.5°	Monthly

Note (1) update depending on data availability.

3.2 Wetland extent/dynamics (local)

Inundation patterns will be identified in larger detail based on ENVISAT ASAR Wide Swath data (150 m resolution) [20]. Incoming microwave radiation is typically reflected away from the sensor at calm water surfaces which results in low backscatter in areas with limited vegetation cover. In this study water bodies are classified using a simple threshold method as described in Ref. 21.

The algorithm will be implemented with the use of the SAR Geophysical Retrieval Toolbox (SGRT) developed by the Vienna University of Technology, and the Next ESA SAR Toolbox (NEST), which is developed by ESA. The NEST software features processing in the polar stereographic map projection, which is crucial for high latitude satellite data processing over large regions. Open water surfaces and saturated surfaces are extracted for each acquistion and the inundation history of each 10-day period updated.

3.3 Snow melt and ground freeze/thaw

Inundation is most extensive after snowmelt and is present for a few days to weeks only. Therefore (i) snowmelt timing needs to be precisely identified and (ii) sampling intervals need to be sufficient. The pattern of snowmelt also affects the carbon emissions [22].

The ALANIS methane products will be based on resampled ASCAT level 1b data (~12.5 km spacing) and used to detect the presence of wet snow and the occurrence of ground thaw and freeze-up processes. Parameterization of the detection algorithm is supported by ECMWF ERA-Interim soil temperature data. The intermediate output is a flag for each single measurement for frozen (either snow or snow free), thawing snow cover and unfrozen ground (no snow cover). The information is then used as input for a post-processing step from which the day of year for snow thaw, ground thaw and freeze-up are extracted [23].

3.4 Atmospheric CH$_4$ concentrations

High-quality column-averaged concentrations of CH$_4$ have been derived for the years 2003-2005 using the WFM-DOAS version 1.0 retrieval algorithm [24]. This dataset has recently been extended by IUP-Bremen to 2009 using updates of spectroscopic input parameters and other algorithm improvements to overcome the detector degradation (from late 2005 onwards) [25].

3.5 Test Sites and Product Domain

Three test areas have been selected for the product development and model testing, as shown in Figure 2:

- Western Siberia - North
- Western Siberia – South
- Lower Lena River basin and delta

The areas are all characterized by strong seasonal wetland dynamics but differ regarding climatological factors.

The West Siberian Lowland (WSL) is the largest wetland area of the world more than 2.7×10^6 km^2 [26]. Most of the area is drained by the Ob and Yenisei River. As the Ob basin has only partly permafrost, it has been split up into two parts: North (continuous permafrost) and South (discontinuous to isolated permafrost). This basin contains the largest high latitude peatland area.

The Lena basin is characterized by a continental climate and mostly continuous permafrost. The Lena River Delta (about 29,000 km^2) located at the Laptev Sea coast in north-eastern Siberia is a key region for understanding the basic processes of the dynamic and development of permafrost in the Siberian Arctic. The delta is situated in the zone of continuous permafrost and is characterized by areas of up to 90% ice-rich sediments. The Lena River releases vast quantities of sediment, ice and organic matter during spring floods which rework the existing landscape yearly. These processes occur at the large scale.
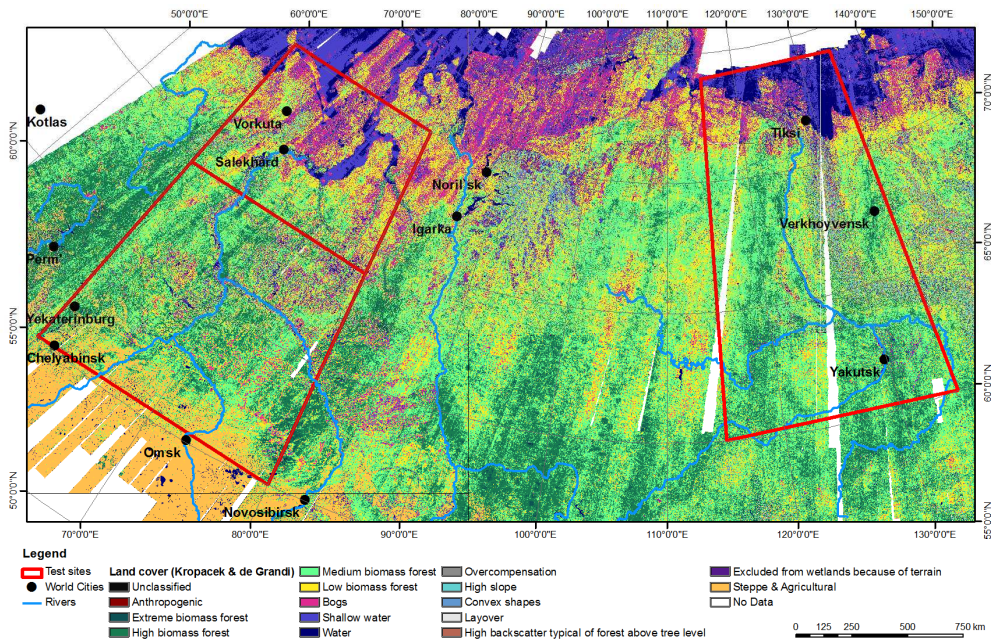
Figure 2: Map of Northern Eurasia overlaid with the domains of the three test case sites.

4 OUTLOOK

4.1 EO products

The main EO deliverable will comprise all the products listed in Table 1 for 2007 and 2008. The spatial coverage will be extended from the three selected test sites (Figure 2) to cover all of Northern Eurasia, north of 50°N and east of (a) 15°E in the northern part of the domain (Note: this include all of Finland but excludes Germany and Poland) and (b) the Russian border in the southern part. The local scale product wetland dynamics product will be limited to regions with flat terrain where inundation can take place.

Figure 3 shows water bodies in the lower Ob basin derived from ASAR WS for the months of June and September 2007. The spring time inundation is very evident.

Figure 4 shows the column-averaged annual mean CH$_4$ concentrations for 2003-2009. Major methane source regions such as paddy fields in China and Russian wetlands can be clearly identified in the global maps. Also shown in Figure 4 is a time series of the global
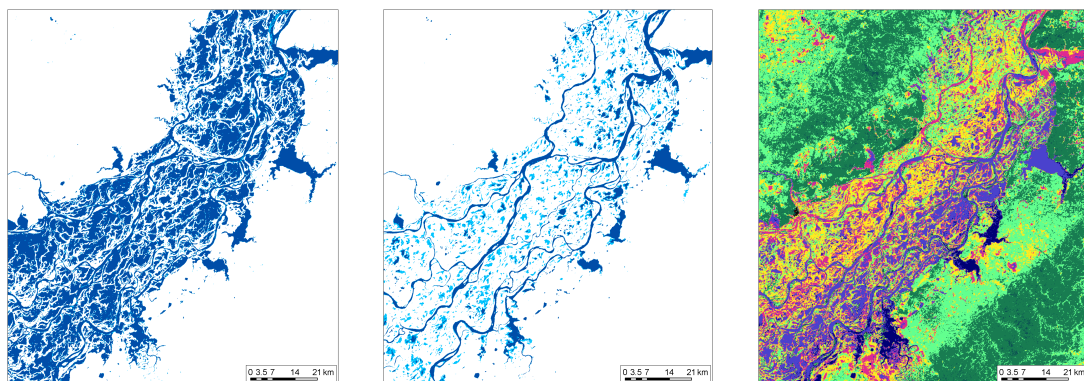

Figure 3: Water bodies in the lower Ob basin derived from ASAR WS (light blue: flooded for <40% of the observations; dark blue: flooded for <40% of the observations) for June 2007 (left-hand panel) and September 2007 (middle panel). The right hand panel shows the GBMF land cover for the same region (JERS, 1996/97 [27]).
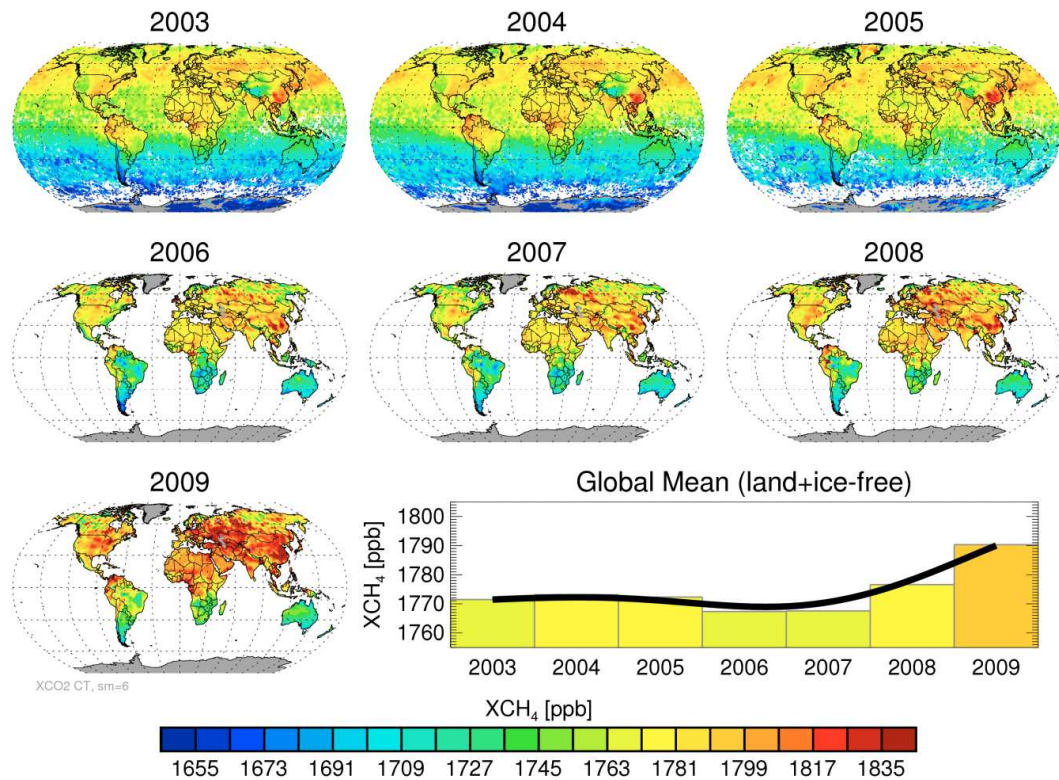
Figure 4: Annual composite averages of quality filtered SCIAMACHY WFMDv2.0 XCH4 retrievals for the years 2003-2009 and corresponding global means. The methane retrievals after 2005 suffer from detector degradation resulting in high noise level and potential biases especially over water. Therefore only data over land are shown for 2006-2009.

column-averaged annual mean CH_4 concentrations. The increase in concentrations that occurred after 2007 is evident.

4.2 JULES Land Surface Modelling

The JULES model will be used in three configurations of increasing complexity:

1. Site specific: The model is run for a single point and calculates the vertical fluxes of water, carbon, methane and energy at sub-diurnal time-steps given the driving meteorological variables of temperature, humidity, windspeed, radiation and precipitation.

2. Offline distributed: The land surface is represented on a grid (regular or irregular) and the driving data vary at the same spatial resolution. The EO data can be used as a driving dataset or as a constraint.

3. Fully-coupled: JULES is integrated as the land surface component in a fully-coupled and interactive regional climate model with atmospheric chemistry.

Model configurations 2 and 3 provide a unique evaluation of the CH_4 fluxes from runs in spatially-distributed mode across boreal Eurasia, using the EO data to define the wetland extent and to constrain key surface parameters that control the surface temperature and snow cover (snowmelt, freeze-thaw).

5 ACKNOWLEDGEMENTS

6 REFERENCES

1. Simpson, I.J., Rowland, F.S., Meinardi, S. & Blake, D.R. (2006). Influence of biomass burning during recent

fluctuations in the slow growth of global tropospheric methane, Geophysical Research Letters, **33**, L22808.

2. IPCC (2007). Climate Change 2007: The Physical Science Basis, Summary for Policymakers; Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. 10th Session of Working Group 1 of the Intergovernmental Panel on Climate Change, IPCC, Paris, France.

3. Frankenberg, C., Meirink, J.F., van Weele, M., Platt, U. & Wagner, T. (2005). Assessing Methane Emissions from Global Space-Borne Observations, Science, **308**, 1010–1014.

4. Wuebbles, D.J. & Hayhoe, K. (2002). Atmospheric methane and global change, Earth Science Reviews, **57**, 177-210.

5. Mikaloff Fletcher, S.E. Tans, P.P., Bruhwiler, L.M., Miller, J.B., & Heimann, M. (2004). CH_4 sources estimated from atmospheric observations of CH_4 and its $^{13}C/^{12}C$ isotopic ratios: 1. Inverse modelling of source processes. Global Biogeochemical Cycles, **18**, GB4004.

6. Walter, B.P., M. Heimann & Matthews, E. (2001). Modeling modern methane emissions from natural wetlands 1. Model description and results. Journal of Geophysical Research, **106**, 34189-34206.

7. Bousquet, P. & 17 others (2006). Contribution of anthropogenic and natural sources to atmospheric methane variability, Nature, **443**, 439-443.

8. Fiore, A.M., Horowitz, L.W., Dlugokencky, E.J. & West, J.J. (2006). Impact of meteorology and emissions on methane trends, 1990-2004, Geophysical Research Letters, L12809.

9. Bloom, A.A., Palmer, P.I., Fraser, A., Reay, D.S. & Frankenberg, C. (2010). Large-scale controls of methanogenesis inferred from methane and gravity spaceborne data. Science, **327**, 322-325

10. Ringeval, B., de Noblet-Ducoudre, N., Ciais, P., Bousquet, P., Prigent, C., Papa, F. & Rossow, W.B. (2010). An attempt to quantify the impact of changes in wetland extent on methane emissions on the seasonal and interannual time scales. Global Biogeochemical Cycles, **24**, GB2003.

11. Friborg, T, Soegaard, H., Christensen, T.R., Lloyd, C.R. & Panikov, N.S. (2003). Siberian wetlands: where a sink is a source, Geophysical Research Letters, **30**, 2129.

12. Gedney, N., Cox, P.M. & Huntingford C. (2004). Climate feedback from wetland methane emissions. Geophysical Research Letters, **31**, L20503.

13. Smith, P. & 20 others (2007). ECOSSE: Estimating Carbon in Organic Soils, Sequestration and Emissions. Report to Scottish Executive, Environment and Rural Affairs Department. Report available from: http://quest.bris.ac.uk/workshops/upland/ECOSSE.pdf.

14. Wania, R. (2007). Modelling northern peatland land surface processes, vegetation dynamics and methane emissions. Ph.D. thesis, Bristol University.

15. Morgenstern, O., Braesicke, P., O'Connor, F.M., Bushell, A.C., Johnson, C.E. & Pyle, J.A. (2009). Evaluation of the new UKCA climate-composition model. Part I. The stratosphere, Geoscientific Model Development, **2**, 43-57.

16. Prigent, C., Matthews, E., Aires, F. & Rossow, W.B. (2001). Remote sensing of global wetland dynamics with multiple satellite data sets, Geophysical Research Letters, **28**, 4631–4634.

17. Prigent, C., Papa, F., Aires, F., Rossow, W.B. & Matthews, E. (2007). Global inundation dynamics inferred from multiple satellite observations, 1993-2000, Journal of Geophysical Research, **112**, D12107.

18. Papa, F., Prigent, C., Jimenez, C., Aires, F. & Rossow, W.B. (2010). Interannual variability of surface water extent at global scale, 1993-2004, Journal of Geophysical Research, **115**, D12111.

19. Kohonen, T. (1984). Self-Organization and Associative Memory, Springer, New York.

20. Bartsch, A., Sabel, D., Schlaffer, S., Naeimi, V., & Wagner, W. (2010). Detection of wetland dynamics with ENVISAT ASAR in support of methane modelling at high latitudes. ESA, iLEAPS, EGU Joint Conference, Earth Observation for Land-Atmosphere Interaction Science.

21. Bartsch, A., Pathe, C., Wagner, W. & Scipal, K. (2008). Detection of permanent open water surfaces in central Siberia with ENVISAT ASAR wide swath data with special emphasis on the estimation of methane fluxes from tundra wetlands. Hydrology Research, **39**, 89–100.

22. Bartsch, A., Kidd, R., Wagner, W. & Bartalis, Z. (2007). Temporal and spatial variability of the beginning and end of daily spring freeze/thaw cycles derived from scatterometer data. Remote Sensing of Environment, **106**, 360-374.

23. Naeimi, V., Paulik, C., Wagner, W. & Bartsch, A. (2010). Freeze/thaw detection in permafrost region with Cband scatterometers. ESA, iLEAPS, EGU Joint Conference: Earth Observation for Land-Atmosphere Interaction Science.

24. Schneising, O., Buchwitz, M., Burrows, J.P., Bovensmann, H., Bergamaschi, P. & Peters, W. (2009). Three years of greenhouse gas column-averaged dry air mole fractions retrieved from satellite - Part 2: Methane, Atmospheric Chemistry and Physics, **9**, 443–465.

25. Schneising, O., Buchwitz, M., Reuter, M., Bovensmann, H., Heymann, J. & Burrows, J.P. (2010). Long-term analysis of carbon dioxide and methane column-averaged mole fractions retrieved from SCIAMACHY, Atmospheric Chemistry and Physics Discussions, submitted.

26. Keddy, P.A. & Fraser, L.H. (2005). Introduction: big is beautiful. In Fraser, L.H., Keddy, P.A. (ed.) The World's Largest Wetlands: Ecology and Conservation, Cambridge University Press, 1-10.

27. Kropacek, J. & De Grandi, G. (2006). Wetlands mapping in Siberia by classification of the GBFM radar mosaic using backscatter and terrain topographic features. In H. Lacoste, editor, Proc. 'GlobWetland: Looking at Wetlands from Space', Frascati, Italy, 19th-20th October 2006 (ESA SP-634, November 2006). ESA Publication Division, 2006.