Water, water everywhere; nor any drop to drink.

Summary

The workshop was held at Sheffield 4th-6th January 2006 and comprised 29 delegates (list submitted separately). The meeting was partly funded by the European Science Foundation (through the Psi-k Network). The balance of the funding came from EPSRC (through a grant GR/S80103/01 "Structural Modelling of the Biological Interface with Materials" headed by one of the organisers (John Harding)).
The format of the workshop was deliberately informal. The programme was divided into eight sessions, each led by a chairman. The chairmen were invited to give a brief introduction to the session and then guide the discussion. For convenience, these people are labelled "speakers" in the participant record. However, the intention of the meeting was that there should not be formal conference presentations. Instead, participants brought powerpoint slides to illustrate the issues they wished to discuss. In the detailed report, those who gave a contribution of this kind are indicated at the end of each session.

The workshop brought together a wide range of people working on water (and problems that involve water) to discuss what the real problems are and what needs to be done to solve them *with specific emphasis on the role of modelling*. A major benefit of the meeting was this bringing together of a wide range of people, both theoreticians and experimentalists, to discuss a range of problems with a common theme. A synopsis of the discussions and conclusions for each session can be found in the detailed report below. A number of specific *scientific challenges* were identified:

- Simulation of the phase diagram of water
- Structure of water at interfaces and surfaces
- Structure of ice surfaces (and reactions at such surfaces)
- Importance of quantum effects (i.e. failure of the classical equations for nuclear motion) for water properties
- Full inclusion of water in biological simulations

These were discussed in depth and as a result of the discussions, it is likely that a number of individual collaborations will be set up. It was agreed that the effect of the meeting had been to constitute a network that should continue to meet. Plans were discussed to enable this (see below).

Also, it was agreed that a topical review on water simulation should be written. Prof. Pat Unwin) has suggested that we raise the matter with the managing editor of *Physical Chemistry Chemical Physics* (whom he knows personally) and this is currently in progress.

Detailed report

Session 1: *Ab initio* methods (leader: Mike Gillan)

The session began with an overview of the successes and failures of density functional theory (DFT) for bulk water; in particular the phase equilibrium and the critical point (essential for experimental comparison at the same reduced state point). The early DFT dynamical simulations [1] (but not in [2]) found that both structure and diffusion coefficients depended strongly on the exchange-correlation functional, a result confirmed by more recent work [3]. The BLYP functional appeared to agree well with experiment (radial distribution functions look respectable, as does the self diffusion coefficient: 1.3×10^{-9} m^2 s^{-1} (BLYP), 2.4×10^{-9} m^2 s^{-1} (expt). Early simulations were too short (few ps compared with 20-30ps used in more recent work). Later work [4] also showed that the fictitious mass used in [1] was too large. Even with much smaller masses however, some coupling between the classical motion of the electronic and ionic degrees of freedom remains. Grossman *et al*. [4a] recently reported that diffusion coefficients calculated by the Car-Parinello method differ from those calculated strictly on the Born-Oppenheimer surface by a factor of two. However, Kuo et al. [4b] did not observe such a difference between Car-Parrinello and Born-Oppenherimer dynamics and found no dependence of the diffusion constant on the fictitious mass (using values of 100, 200, and 300 a.u.). Gibbs ensemble MC calculations [5] show that the vapour-liquid coexistence curve depends strongly on the functional and the basis set. Also very large cutoffs (1200 Ry) were needed to get convergence. Results obtained using the SIESTA code (Emilio Artacho) show that a 20% temperature rescaling is needed to reconcile calculations with experiment. The RPBE functional appears to perform better [6] but this is likely to be due to cancellation of errors. Alfredsson's work shows strong basis-set dependence for water dimer calculations.

The main problem is that various functionals give different answers and it is not known why this is so. Careful calculations on sets of water clusters may help resolve this. Quantum Monte Carlo calculations are needed to investigate the adequacy of the functionals. It is unlikely that failure of the classical equations for atomic motion is relevant. Dispersion terms are not often considered and may be important. We need a *hierarchy* of modelling techniques, within which parameterized models and *ab initio* methods act in concert.
Main contributers: ***Ilja Siepmann, Philip Lindan, Emilio Artacho, Maria Alfredsson***

Session 2: Classical simulations and potentials (leader: Mark Rodger)

Parameterized interaction models for water go back many years. Well-known models include: SPC, TIPnP (n = 3, 4, 5..), AMOEBA, GCPM (Gaussian Charge Polarizable Model). There are over 50 such models [8]. Simple models use unpolarizable point charges on fixed sites in molecule; more sophisticated models are polarizable (dipole moment of H_2O molecule is 50% greater in bulk than in gas). Shell models are sometimes used to include polarizability. All models are valid only over a limited range of thermodynamic states. The problem is finding suitable functional forms to parametrize. Many models have large numbers of parameters. The AMOEBA potential has 304 parameters, all of which might require re-fitting for a mixed system. Complex models are expensive to run; multiple timestep or perturbation methods can be used to speed them up. Models are fitted either to an empirical data set or (increasingly) to a combination where the charge distribution and multipole moments are fitted to quantum calculations and Lennard-Jones parameters to experiment. Gibbs-Duhem methods can be used to optimize and test potentials. We need to find a reasonable compromise between accuracy, transferability and expense. CONDOR pools offer an attractive tool for searching parameter space. A further problem for complex systems is the validity of mixing rules in obtaining potentials and what to do when they fail.
Main contributers: ***Jamshed Anwar, John Finney, Steve Parker, Ilja Siepmann, Dewi Lewis***

Session 3: Ions in solution (leader: Dave Sherman)

Understanding is needed for geological simulations, in particular the properties of metal complexes in solution as a function of temperature and pressure. Major questions surround the mechanisms of formation of hydrothermal ore deposits and the behaviour of metal complexation in high ionic strengths (60 wt% of NaCl) Often geologists use simple Born models of solvation and hope. The lifetime of water molecules in the first hydration shell ranges from 10^{10}sec (Ir^{3+}) to about 10^{-10}sec (Cs^+, Cu^{2+}). Potential-based calculations obtain good local geometries for the first hydration shell. Short residence times can be calculated directly from

integrating over correlation functions; long residence times are obtained using transition state theory. A combination of MIES (**M**etastable **I**mpact **E**lectron **S**pectroscopy), photoelectron spectroscopy can be used to probe the behaviour of ions and metallic atoms in contact with amorphous ice and compared with classical MD simulations. Above about 120K, ice behaves rather like liquid water FOR solvation of alkali halide ions.
Main contributers*: Steve Parker, Volker Kempter, Dewi Lewis.*

Session 4: Ionisable water molecules (leader: Steve Parker)

Many problems involving water are pH dependent. An apparently simple solution is to use fixed concentrations of H_3O^+ and OH^-. This is not satisfactory, firstly because any absorption of these species at a surface changes the solution pH, secondly, the usual size of system used in simulations (a few thousand ions) means that the most important pH conditions cannot be modelled (for example in biological systems, pH is often around six). There are serious difficulties in obtaining reactive water molecules. If partial charges are used, what should the charges of the ions be? If fully charged models are used, the electrostatics needs to be damped. Charge equilibration models need clear rules for the adjustment of the charge. Combined MD/MC calculations (constant pH MD) can be used to obtain sensible structures for the system, but gives up the possibility of understanding the detailed dynamics. Rustad [11] has developed a potential based on the Stillinger-David model; Garafolini [12] has used a damped electrostatic model. Massimo Mella described quantum chemistry calculations to test models. Potentials of the Stillinger type agree with MP2 calculations up to $H^+(H_2O)_6$. Improved semi-empirical methods like PM3 may be a way forward. Also, can cluster calculations of this type be used as a "training set" for deriving new potentials. An allied problem is the simulation of the condensation (and ultimately self-assembly of zeolites (Lewis)). Basic reactions include $Si(OH)_4 + OH^- \rightarrow SiO(OH)_3^- + H_2O$. Reasonable results are obtained for these reactions and the water autolysis reaction $H_3O^+(H_2O)_3 + OH^-(H_2O)_4 \rightarrow (H_2O)_4 + (H_2O)_5$ provided that both a first coordination shell of water and a dielectric representation of the water (COSMO) are used.
Main contributers*: Massimo Mella, Dewi Lewis*

Session 5: Mineral Interfaces (leader: Neal Skipper)

Questions that arise in the simulation of mineral/aqeous interfaces include (i) What are the interfacial ionic species? (ii) How do ions adsorb/desorb? (iii)What is the interfacial water structure? (iv)What is the extent of the aqueous interface? (v) What are the interfacial dynamics/kinetics? (vi)What are the effects of temperature and pressure? (vii) What is the effect of pH? Clay minerals (starting around 1990) have been the subject of a plethora of Monte Carlo and MD simulations using all known brands of water potentials. The water and surface oxygens usually assumed to have the same short-range parameters. Overall, excellent agreement with experiment obtained. Simple models have been used to investigate double layer effects and DFT calculations of speciation are available. Calculations combining these methods are, however, rare. Water on MgO has been studied by a huge range of *ab initio* methods [7] (Hartree-Fock, correlation-corrected Hartree-Fock, DFT, quantum chemistry). RPBE seems to be the functional of choice for water on TiO_2 (Lindan). Alfredsson's MD calculations show strong reconstructions for water absorbed on La_2O_3 (001) surfaces. Can static lattice calculations be of use in these problems or is MD essential?
Main contributors*: Maria Alfredsson, Steve Parker, Mike Gillan, Philip Lindan*

Session 6: Biological systems (leader: Marie-Claire Bellissent-Funel)

Hydration water is found in living cells where it fills cavities and is bound at the surface of protein and membranes. It plays a major role in the stability and function of biological macromolecules. We must consider both the effects of proteins on the structure and dynamics of water and the effects of hydration on the structure, dynamics and function of proteins. At physiological temperatures, internal motions are partly vibrational, partly diffusive, some of which are required for function of proteins. The diffusive motions is of particular interest in the context of the dynamical or "glass transition", which is observed experimentally at ~ 180-220 K. The characterisation of internal diffusion in proteins is complicated by the variety of the motions present, involving groups of atoms undergoing a plethora of continuous or jump-like diffusive dynamics. Dynamic neutron scattering is the most direct probe of diffusive protein dynamics on the ps-ns time scale. However, this technique provide us only with some average information. It is possible to attack this problem and get some detailed information on motions of various parts of protein as well as of hydration water by combining MD simulations (CHARMM force field, TIP3P model potential for water) with neutron results [15]. Other techniques such as NMR, IR, Raman spectroscopies can be associated. MD simulation in native protein environments seem to be the most promising way to achieve progress in this field, in particular to reach the structure and dynamics of water near biological macromolecules. A major problem, particularly with protein folding is that of looking for small differences between a set of large terms. $\Delta G_{folding}$ ~ 20 kcal/mole (Finney); the various contributing terms involved can be well over ten times as great. Hydration cannot be neglected. Experimental neutron scattering measurements on a range of amphiphilic molecules that might serve as simple models for self-assembling systems suggest that popular 'standard' potential functions may often lead to structures that are qualitatively different from those found experimentally, perhaps suggesting problems in handling the balance between different competing interactions (e.g. solute-solute c.f. solute-water. The Solvent-Accessed Surface (SAS) can be obtained [16].

Water is also important for protein-substrate interactions. Walsh discussed the selective adsorption of hexapeptides on titania under aqueous conditions. No model of hydroxylated amorphous titania is currently available so the fully hydroxylated TiO_2 (110) rutile surface as a model surface. A potential due to Predota *et al* [17] was used. Very few tests have been published for AMOEBA (bulk water simulations, small molecule interaction energies). Walsh tested AMOEBA for interactions of the COO^- group in water

Main contributors*: Tiffany Walsh, John Finney, Ilja Siepmann, Carmen Domene, Alex de Vries*

Session 7: Ice (leader: Alain Allouche)

In the interstellar medium, temperatures between 10K and 100K, ice is amorphous. This is however metastable with respect to ice XI, the thermodynamically preferred state. If ordered ice is cooled below 80K, proton order sets in. Amorphous ice is medium-range ordered and can be reasonably well simulated using a proton ordered model. The main reactive sites on its surface are the dangling OH bond (very sensitive infrared mode), the lone-pair dangling oxygen and the four-coordinate oxygen [18]. The dangling OH is indicative to any perturbation on the surface, this can be observed through its vibrational frequency shift. It has been shown that this frequency shift is quadratically related to the electric field variation along the OH bond. It has been shown that the strong ice surface electric field ($7x10^9Vm^{-1}$) polarises layers of absorbed molecules that, in turn, induces a vibrational Stark effect in the OH bond [19]. The electric fields into the ice bulk are also partly responsible for electron trapping. This has been shown by combining MIES/UPS experiments with quantum DFT calculations on metallic sodium ionization in ice [20]. Quantum DFT calculations on dissociation on water ice surface have also been described for some small acids of interstellar or atmospheric interest [21], various DFT and mixed DFT methods were compared. It was shown (V.K.) how spectra [22], obtained with MIES, can be related to the DOS obtained from DFT calculations. The comparison of MIES spectra and the DOS was presented in detail for the interaction of Na atoms with a surfaces of amorphous solid water. The comparison suggests that the Na – induced dissociation of water molecules is initiated by the water – induced delocalization (solvation) of the 3sNa electron.

The complex phase diagram of ice is built from two ideas: each water molecule has two bonds and two hydrogen bonds so the coordination of the oxygens is always tetrahedral; the different possible arrangements of hydrogen bonds mean that structures can be disordered. The calculation of the ice phase diagram is a major challenge for models; calculations [9] using the TIP4P and SCP/E models show that the former is clearly better, but still far from reproducing the topology, let alone the phase boundary positions. Models should also be able to predict the metastable phases and the disordering. Maria Alfredsson presented some calculations on ice VIII using various hybrid functionals. The results show that functionals need to contain significantly more Hartree-Fock character than B3LYP to reproduce the ice structure. Still worse, different properties seem to require different amounts of exact exchange in their functionals. The AMOEBA potential and others can be shown to reproduce most of the water/ice phase diagram remarkably well. However, the ice XI is problematic because proton ordering is not well described by the pair potentials. Ben Slater showed that the deficiency is due to inadequate description of electrostatic multipoles - when terms up to the hexadecapole are included, proton ordering energetics can be reproduced accurately.

Main contributors*: Maria Alfredsson, John Finney, Volker Kempter, Ben Slater*

Session 8: Common challenges; new perspectives (leader: Philip Lindan)

The workshop has underlined the problems that DFT functionals have in describing water. Calculations on simple systems (dimers?) desirable to find out exactly where the functionals are going wrong. The introduction of Quantum Monte Carlo methods is clearly desirable and is under way. We need a better potential for water, preferably incorporating dissociation. The basic problem is that of functional form. Comparison with DFT is not adequate because of the enduring DFT problems; training sets of clusters obtained at MP2-MP4 accuracy are needed. More effort is needed to make quantum and classical calculations work together through embedding strategies. Simulations at interfaces particularly have problems with length and timescales. A number of specific *scientific challenges* were identified:

- The phase diagram of water
- Structure of water at interfaces and surfaces
- Structures of aqueous solutions of ions and molecules
- Structure of ice surfaces (and reactions at such surfaces)
- Importance of quantum effects (i.e. failure of the classical equations for nuclear motion) for water properties
- Full inclusion of water in biological simulations

In all these, the necessity of making explicit connections with experiment was emphasised.

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Results of the meeting and future plans

It was agreed that the meeting had been a highly successful review of the current state of modelling water. The format of the meeting worked well and there was a wide range of contributions from participants as noted above. In particular, the informal nature of the discussion encouraged contributions from younger research workers and also discussion both within and outside the individual sessions. The combination of a wide range of scientific interests with a focus on water enabled participants to identify problems that are common to several areas. A number of collaborations are likely to result from discussions at the meeting.

Particular areas where progress is needed clearly include

- ***The problem of the current choice of functional.*** We need to understand why well-known functionals give different answers for water and how this can be put right. Careful calculations on sets of water clusters may help resolve this. Quantum Monte Carlo calculations are also needed to calibrate systems and work is already in progress to look into this.
- ***Methods for fitting suitable classical potentials.*** The basic problem remains of finding a reasonable compromise between accuracy, transferability and expense. The use of CONDOR pools as a tool for searching parameter space (particularly for complex potentials of the AMOEBA type) was emphasised.
- ***The application of models for ions in solution to geological problems*** was emphasised. Speakers pointed out the crudity of current methods of considering solutions at high concentration in the geological literature and the opportunities that this gave to more accurate simulations.
- ***The need for an accurate model for ionisable water*** was discussed. Many problems in interface chemistry in a wide range of fields are pH dependent and therefore require such a model if progress is to be made. The possibility of using improved PM3 models was canvassed. These issues were also raised in the discussion on mineral interfaces.
- ***The proper inclusion of "hydration water" effects, particularly in proteins.*** Moreover, there remains the computational difficulty of small effects that are the result of the subtraction of large individual terms. This is a particular issue for protein folding.
- ***The simulation of the full phase diagram of water (the various ice phases)*** is both a major challenge in itself and a test-bed for both *ab initio* and potential-based water calculations. The importance for proton ordering of calculating the correct electrostatics was demonstrated.

It was agreed that the meeting formed the basis of a possible network and that action should be taken to ensure that this network should continue to meet. Moreover, a number of possible collaborations emerged during the meeting, and a means of lubricating these should be looked for. Another meeting will be held in about a year's time and possible funding for this meeting has been identified. The organisers of this workshop (Harding and Lindan) have agreed to plan this. Second, it was agreed that an application should be made for a Marie-Curie Research Training Network under Framework 7 when the rules for the new organisation has been announced. In the meantime, the possibility of obtaining funding for a network from the UK Science Research Council (EPSRC) will be investigated.

Professor. Pat Unwin (one of the participants) invited the meeting to submit a review article to *Physical Chemistry Chemical Physics* on the subject of water simulations. We intend to pursue this option. (There is an obvious problem with assigning authorship since such a review (implicitly or explicitly) would consist of contributions from most if not all of the participants. We have discussed this issue in detail with Professor Unwin and the problem is not insuperable. .

APPENDIX

PROGRAMME

4th January

12:00 - 13:30	Lunch	
13:30 - 15:00	SESSION 1:	Developments in Ab initio calculations
	Leader	MIKE GILLAN
15:00 - 15:30	Tea	
15:30 - 17:45	SESSION 2	The state of water potentials: classical simulations
	Leader	MARK RODGER
18:00	Dinner	

5th January

07:30 - 08:45	Breakfast	
9:00 - 10.30	SESSION 3:	Solutions: ions and molecules
	Leader	DAVE SHERMAN
10.30 - 11.00	Tea	
11.00 - 12.00	SESSION 4	Solutions: pH and ionisable water models
	Leader	STEVE PARKER
12:00 -13:30	Lunch	
13:30 - 15:00	SESSION 5	Aqueous mineral interfaces
	Leader	NEAL SKIPPER
15:00 - 15:30	Tea	
15:30 - 17:45	SESSION 6	Biological systems and water
	Leader	MARIE-CLAIRE BELLISSENT-FUNEL
18:00	Dinner	

PROGRAMME

6th January

07:30 - 08:45	Breakfast	
9:00 - 10.30	SESSION 7	Ice
	Leader	ALAIN ALLOUCHE
10.30 - 11.00	Tea	
11.00 - 12.00	SESSION 8	Common challenges and new perspectives
	Leader	PHILIP LINDAN
12:00 -13:30	Lunch	