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The Role of Polarization in a Halogen Bond

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Abstract: A Classical (point charge) self-consistent polarisation model has been used to investigate the role of polarisation in the $CF_3Cl:OH_2$ complex. The polarised electron densities of the component monomers prove to be a good representation of the electron density of the complex, especially for the CF_3Cl. The point charge model over-polarises the water molecule, probably because of the missing exchange repulsion in the classical model calculations.

Introduction

Non-covalent bonding governs intermolecular interactions, which in turn are used by nature and in many technical applications in to effect chemical control of structures and processes. The systematics of chemistry traditionally divide non-covalent interactions into classes such as hydrogen bonding,[1] hydrophobic interactions,[2] van-der-Waals (or dispersion) forces[3] and σ-hole bonding.[4-8] The latter was proposed as a generalisation of halogen bonding,[9] its best known representative, and applies to a variety of "counterintuitive" non-covalent interactions involving second-row and heavier elements of groups IV to VII.The term σ-hole refers to the area of positive molecular electrostatic potential that occurs collinear and opposite to bonds to electronegative elements or groups. Note that. Although the "depth" of the σ-hole may be increased by polarisation, the area of positive MEP usually exits in the unperturbed molecule. Hydrogen- and σ-hole bonding are known to exhibit distinct directional preferences (often for linear linkages), whereas dispersion and hydrophobic interactions have generally been thought to be non-directional. In reality, however, even dispersion and repulsion can display directionality.[10]

The importance of these non-bonded interactions has led to extended interest in the physical effects that underlie them. It has long been clear that the major component of hydrogen bonding must be electrostatic (Coulomb) interactions, but the preference of hydrogen-bonded complexes for linear coordination geometries led to the idea that they involve a significant polar covalent component. This was thought to arise from charge donation by a lone-pair molecular orbital (MO) of the H-bond acceptor to the antibonding σ^*-orbital to the donor hydrogen. Such a polar covalent contribution was believed to be necessary because the electrostatic component was viewed (mistakenly[8,11]) as being isotropic, since the prevailing electrostatic model at that time was based upon net atomic charges, which do not lead to a directional preference. However, the assumption of a significant polar covalent contribution was beset with difficulties from the beginning because σ^*-orbitals involving donor hydrogen atoms are typically very poor acceptors.

Many schemes have been proposed for partitioning calculated interaction energies into components that correspond to chemists' ideas[12] about intermolecular bonding. Depending upon the scheme, such components may include electrostatics, induction or polarization, exchange repulsion, charge transfer, dispersion, orbital interaction,

deformation, etc. A fundamental problem with this approach is that such contributions to interaction energies are not independent of each other; accordingly no partitioning procedure can be physical rigorous.

There are also other problems. Many of these procedures use atom-centred basis functions in partitioning the space between the interacting molecules. Strictly speaking, a molecule (or a complex of molecules) consists of a cloud of indistinguishable electrons moving in the field of a set of (within the Born-Oppenheimer approximation) static nuclei, which are normally considered as point charges. In this picture, there are no atoms or bonds and no borders separating electrons that "belong" to one atom or another. But since we do normally use atom-centred basis sets (atomic orbitals, AOs) for calculations, it is tempting to interpret the occupations and roles of these AOs all too literally in terms of the linear combination of atomic orbitals (LCAO) approximation.[13] This can be very misleading, because physical reality is being ascribed to what is simply a mathematical model.

A practical difficulty is that atom-centred basis sets suffer from basis-set superposition error (BSSE).[14] This mathematical artifact, in which one molecule "borrows" basis functions from another in order to attain a better description of its own electron density, is inextricably associated with atom-centred basis sets and the practice of interpreting their function in MO (or density-functional theory, DFT) calculations according to the LCAO approximation. The conventional way to correct for BSSE is to perform counterpoise calculations,[15,16] in which each component molecule is calculated using the entire basis set of the complex in order to obtain corrected monomer energies. This practice is quite controversial[17] and is certainly not ideal because the "ghost" basis functions of the missing monomer are all formally vacant (in the sense of a population analysis), rather than partly occupied as in the real complex. Thus, partition schemes based on atom-centred basis sets are prone to BSSE-type errors that may not be compensated by counterpoise-type calculations.

A problem that is specific to estimating the polar covalent (charge-transfer) contribution to an interaction energy is that it is either calculated by perturbation theory or is simply defined as what remains after the other terms (e.g. Coulomb, polarization (induction), dispersion etc.) have been evaluated. Stone and Misquitta[18] have pointed out that the perturbation theory approach in its standard form includes Pauli-forbidden interactions that cause overestimation of the charge-transfer energy

by up to an order of magnitude. This is compensated by overestimating the exchange repulsion term, so that the sum of the two represents the charge-transfer contribution and is usually small. Equating the charge-transfer term to the remaining unexplained interaction energy can also lead to errors; if the other terms considered are not complete, then those effects that are not considered correctly will be assigned to the charge-transfer energy. Both techniques can therefore greatly overestimate the charge-transfer term if not used correctly.

There is indeed a difficulty with the very definition of a charge-transfer term. Stone and Misquitta[18] have described the following thought experiment, which makes the problem clear. Imagine that we calculate an intermolecular complex (for the sake of argument, the water dimer) using an atom-centred basis set for just one monomer that is large enough to describe not only its own electron density but also that of the other monomer. This calculation would, at the basis set limit, give the same result as one that used the same atom-centred basis set for both monomers; however it would yield a charge-transfer energy that is by definition zero for all techniques that are based on atom-centred basis sets. It has in fact been observed[19,20] that the charge-transfer contribution in symmetry-adapted perturbation theory (SAPT) decreases at the expense of the induction (polarization) term if the basis set is made larger. Thus, we do not have a unique definition of the charge-transfer (polar covalent) term outside the finite atom-centred basis set picture unless it is simply the remaining interaction energy once all other effects have been considered.

We[21] have pointed out the importance of polarisation (induction) in determining the strength of the Coulomb intermolecular interaction. This is important because polarisation masquerades as a spurious donor-acceptor interaction and is often mistakenly taken to be the latter. The relationship between polarisation and donor-acceptor shifts of electron density has been pointed out many times,[6,9,11,14,20] with perhaps the least compromising formulation of the problem being due to Chen and Martínez: [22] "*charge transfer is an extreme manifestation of polarization*".

Very recently, Misquitta [23] has treated charge-transfer as a tunnelling phenomenon in order to separate it from the induction (polarization) term in Symmetry-Adapted Perturbation theory (SAPT). This Ansatz promises to help clarify the many open questions.

Another method for analysing noncovalent interactions is to compare the electron density of the complex to the sum of those of the monomers in their geometries in the complex. Sometimes this is extended to defining a border between the component monomers with which to divide the electron density into components due to each monomer; however this is not necessarily a part of the analysis. Several questions arise:

1. Are the unperturbed electron densities of the monomers appropriate as reference systems or should pre-polarized monomers (i.e. as they would exist in each other's electric fields) be used?
2. If a border is drawn between the monomers, is it physically justified or arbitrary?
3. Can we even see significant bonding interactions as shifts in electron density and can we assign their cause uniquely to a given effect?

We have advocated using simple point-charge models to isolate the Coulomb effect.[8,23] We now report the use of point-charge models that consist of many (approximately 500,000) small point charges located on a lattice to represent the electron density of one monomer in a complex in order to polarize the other in a realistic manner. This process can be performed in both directions (i.e. monomer 1 is polarized by the point-charge model for monomer 2 and *vice versa*) and can be iterated using the polarized electron densities from the previous cycle until the two point-charge models are self-consistent. In this way, we can quantify polarization effects and examine the differences between unperturbed and polarized monomers in detail. We have used the MP2 electron density in order to avoid the overestimation of electrostatic effects often observed for Hartree-Fock calculations.

We now describe a conceptually simple approach to mutual polarization in the component molecules of a non-covalent complex and its application to a prototype halogen bond; $F_3CCl:OH_2$.

Self-consistent Model Calculations of the Coulomb Energy

The definition of the purely electrostatic (Coulomb) interaction energy is a weak point in many analyses. Simply calculating the Coulomb interaction between the unperturbed monomers is not sufficient since it neglects polarization and leads to significantly underestimated Coulomb contributions, as will be demonstrated below.

The Coulomb interaction can be regarded as a multi-step polarization sequence in which the complementing electrostatic effects of the two monomers on one another must be iterated to self-consistency. The Coulomb interaction energy between the two unperturbed monomers represents an upper bound for the converged Coulomb-plus-polarization (or Coulomb-plus-induction) energy. In each cycle, the monomers polarize each other further in order to minimize the sum of the polarization energies and the Coulomb interaction energy. This self-consistent polarization energy is also calculated in the ALMO approach.[24]

We have used the classical electrostatic embedding technique discussed above in order to investigate these effects. Note that by alternating classical representations of the two monomers, we achieve self-consistency after an adequate number of cycles and at the same time ensure that the effects considered are purely electrostatic. The calculations were performed with Gaussian09 using an in-house program that constructs a lattice of point charges that represent one of the monomers from the Gaussian cube file (one point charge per voxel in the cube file). This array of charges is used to polarize the other monomer. The process is repeated by alternating the monomer that is treated classically until the monomer energies are converged. The results of such a calculation for $F_3CCl:OH_2$ at the restricted Hartree-Fock (RHF) and MP2[25-30] levels using the aug-cc-pVTZ basis set[31-33] are summarized in Table 1.

Table 1. Results of the self-consistent classical polarization calculations described above for the halogen-bonded complex of CF_3Cl with water. E_{dimer} and $E_{Coulomb}$ are given in kcal mol^{-1}. Zero-point vibrational energies are not included. For definitions of E_{dimer} and $E_{Coulomb}$ see the table footnotes[A] For the dimer, E_{dimer} is defined as the total optimized energy of the dimer minus the energies of the monomers for cycle 0.

	Total Energy (a.u)					$E_{Coulomb}$[B]
	RHF		MP2			
	E_{Total} (a.u.)	E_{dimer}[A]	E_{Total} (a.u.)	E_{dimer}[A]		
Dimer	-871.90052	-1.01	-873.29286	-2.22		-4.67
Cycle No.	RHF			MP2		
	CF$_3$Cl		H$_2$O		CF$_3$Cl		H$_2$O		
	E_{Total} (a.u.)	E_{dimer}[A]	E_{Total} (a.u.)	E_{dimer}[A]	E_{Total} (a.u.)	E_{dimer}[A]	E_{Total} (a.u.)	E_{dimer}[A]	
0	-795.83864	0.0	-76.06027	0.0	-796.96033	0.0	-76.32899	0.0	
1	-795.84348	-3.04	-76.06915	-5.58	-796.96504	-2.95	-76.33801	-5.66	-8.15
2	-795.84740	-5.50	-76.06951	-5.80	-796.96893	-5.39	-76.33895	-6.25	-8.40
3	-795.84757	-5.61	-76.07031	-6.30	-796.96910	-5.50	-76.33912	-6.36	-8.44
4	-795.84761	-5.63	-76.07032	-6.31	-796.96914	-5.53	-76.33914	-6.37	-8.45
5	-795.84762	-5.63	-76.07032	-6.31	-796.96914	-5.53	-76.33914	-6.37	-8.45

The calculations converge to 10^{-5} Hartrees in the total energy within five cycles of mutual polarization. We have also observed this behaviour for other systems such as the water dimer. $E_{Coulomb}$ only serves as a guide to the magnitude of the dimerization energy as the point-charge model cannot reproduce the shielding of the real electron density and also because the exchange repulsion is completely missing in the point-charge calculations. The interaction energy between the water charge array and CF_3Cl at convergence (-5.63 and -5.53 kcal mol^{-1} at HF and MP2, respectively) and between the CF_3Cl charge array and water (-6.31 and -6.37 kcal mol^{-1}) are similar but not identical because in each case the polarization energy of the molecule represented by the point-charge array is missing from the total interaction energy, in addition to the exchange repulsion.

Figure 1 shows the shifts in electron density between the unperturbed and the polarized CF_3Cl and water molecules, treated separately.
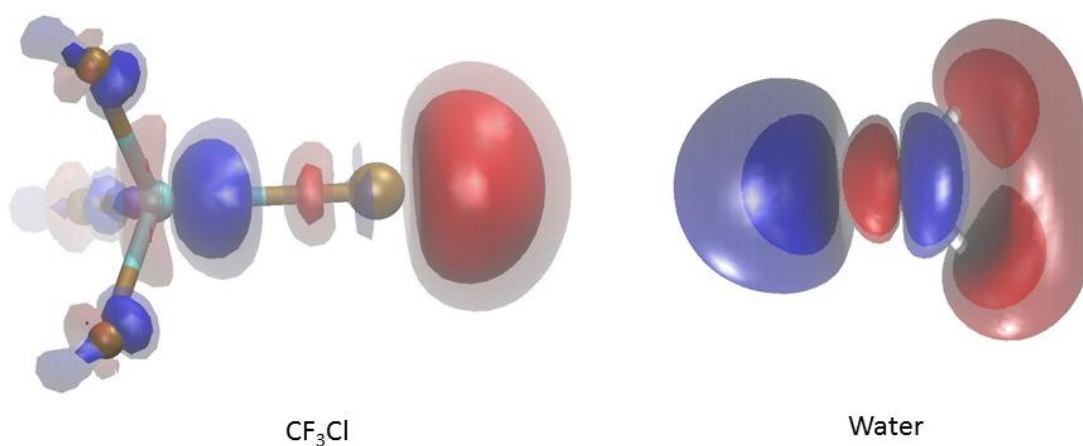

CF$_3$Cl   Water

Figure 1. The shift in MP2/aug-cc-pVTZ electron density caused by the mutual polarization to self-consistency within the point-charge model. The surfaces correspond to density differences of ±0.001 (opaque) and ±0.0005 (transparent|) electrons $Bohr^{-3}$. Blue indicates increased electron density in the polarized monomers, red decreased. The two monomers are calculated separately and the two molecules are positioned relative to one another in the Figure roughly as they occur in the dimer.

The polarization of CF_3Cl is much as expected; electron density is shifted away from the chlorine towards the CF_3 group. Note that this polarization could be (mistakenly) viewed as the changes that would be expected from donation into a σ^*_{CCl} orbital, which it is not because the monomers are being treated separately (and therefore the σ^*_{CCl} orbital is not present in the calculation). The area that corresponds to the σ-hole[4,14] is very strongly and specifically depleted by the polarization. This is exactly the picture suggested for hydrogen bonding[23] and underlines the importance of polarization in determining the strength of non-covalent interactions.

The polarization pattern for water can also be understood easily. Two effects can be seen. The first is that the n-lone pair (the symmetry of the complex is C_{2v}) is polarized towards the CF_3Cl and the second is the polarization of the O-H bond towards the oxygen. Once again, this is the effect emphasized earlier.[23] In terms of orbital models, these polarization effects can be regarded as mixing of the occupied n-lone pair and symmetrical σ_{OH} with the virtual symmetrical σ^*_{OH}, as shown in Figure 2.
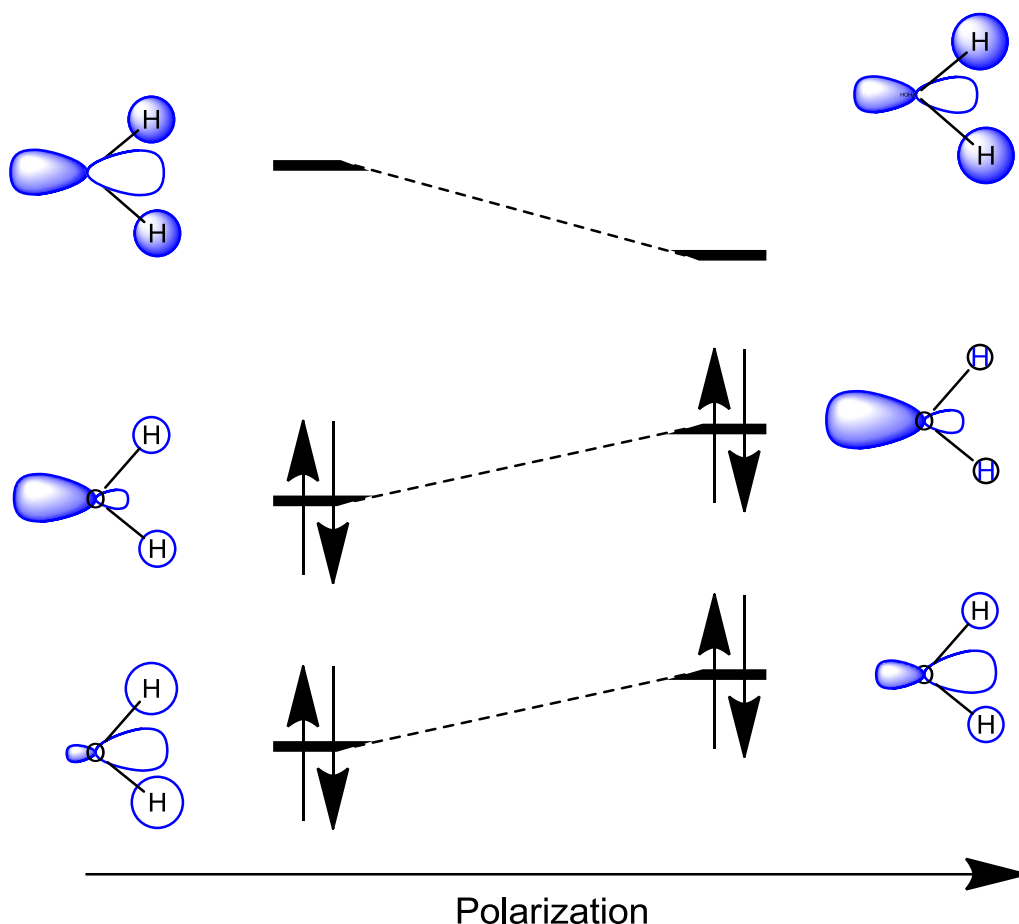
Figure 2. Schematic diagram of the polarization of the two occupied and one virtual B_1 molecular orbitals (σ_{OH}, n and σ^*_{OH}) on forming the $CF_3Cl:OH_2$ complex.

Figure 3 shows the electron density difference diagram obtained by subtracting the electron densities of the unperturbed monomers from that of the complex. No surprisingly, it exhibits a strong similarity to the sum of the two plots shown in Figure 1. Thus, using the unperturbed monomers as reference electron densities, as is often done, largely provides a picture of the mutual polarization of the monomers. This has also been demonstrated for other halogen-bonded complexes.[34] We therefore conclude, as we have pointed out previously,[11] that analysis techniques based on the electron densities of the unpolarized monomers are not appropriate unless they take polarization into account explicitly, as is the case with the ALMO approach[12] or Stone and Misquitta's analysis.[20]
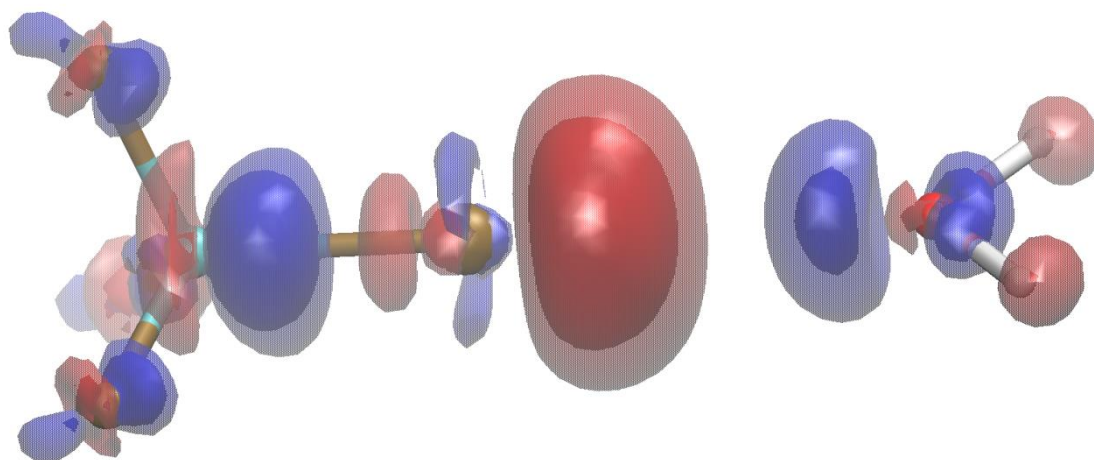
Figure 3. The shift in MP2/aug-cc-pVTZ electron density observed for the $CF_3Cl:OH_2$ complex using the unperturbed monomers as the reference electron density. The surfaces correspond to density differences of ±0.001 (opaque) and ±0.0005 (transparent) electrons Bohr$^{-3.}$ Blue indicates increased electron density in the complex, red decreased.

Figure 4 shows the same plot as Figure 3 with the exception that the reference electron densities used for the monomers are now those taken from the self-consistent polarization calculations. The fact that the density differences of the CF_3Cl moiety are so very minor indicates that its electron density corresponds very closely to that of the polarized monomer. The small transparent blue isosurfaces ($\Delta\rho$ = 0.0005 a.u.) indicate a slight shifting of charge from the water toward the CF_3Cl. We could in principal integrate over the CF_3Cl electron density to quantify this effect but have not done so because (a) the precision of a numerical integration is likely not to be adequate for this purpose and (b) we would have to draw an arbitrary border between the two monomers.

The electron-density difference for the water is more interesting. Firstly, it does not obviously indicate charge-transfer (which must be equal and opposite to any found for the CF_3Cl), but also shows that the self-consistent polarization calculations have over-polarized the water moiety compared to its situation in the real dimer. This observation may be a consequence of our neglect of exchange repulsion, which would lead to higher electron density between the monomers. There are several other possible reasons for this effect, the most trivial of which is simply BSSE, which

is present in the dimer calculation but not for the polarized monomer. This is, however, unlikely because the major increase in electron density on dimer formation is around the hydrogen atoms, which are farthest from the closest CF_3Cl atom. The more likely reason for the observed over-polarization in the self-consistent polarization calculations is the missing Pauli repulsion in the point-charge model used. This would result in the effect shown in Figure 4. It is, however, not observed for the more diffuse chlorine atom of CF_3Cl.
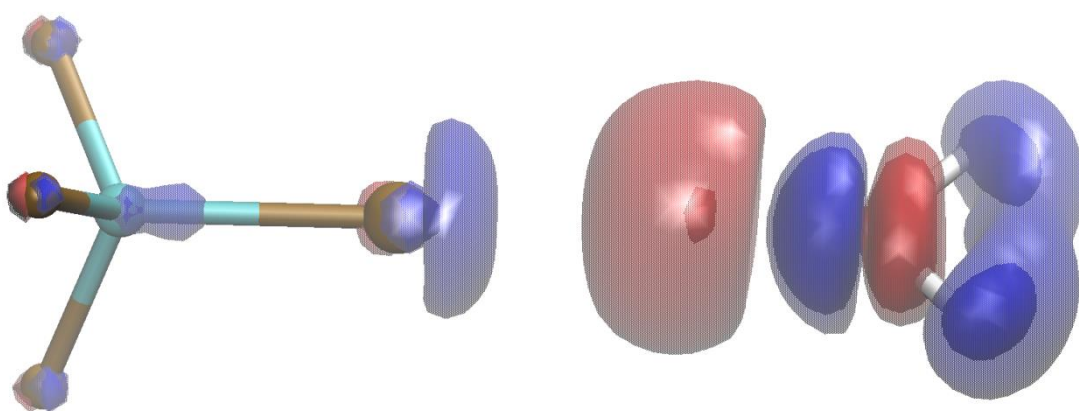

Figure 4. The shift in MP2/aug-cc-pVTZ electron density observed for the $CF_3Cl:OH_2$ complex using the polarized monomers as the reference electron density. The surfaces correspond to density differences of ±0.001 (opaque) and ±0.0005 (transparent). Blue surfaces indicate increased electron density in the complex, red decreased.

We have often discussed σ-hole interactions in terms of the molecular electrostatic potential (MEP). It is therefore instructive to observe the changes in the MEP at the isodensity surfaces of the two monomers caused by the mutual polarization. Figure 5 shows these changes for CF_3Cl and water. They are largely as expected. The σ-hole on the chlorine atom of CF_3Cl becomes ca. 5 kcal mol^{-1} more positive than in the unperturbed molecule and the area around the n-lone pair of the oxygen atom in water more negative by about the same amount. These changes are significant because the strength of the σ-hole bonding correlates linearly with the extremes of the MEP at these positions.[9]
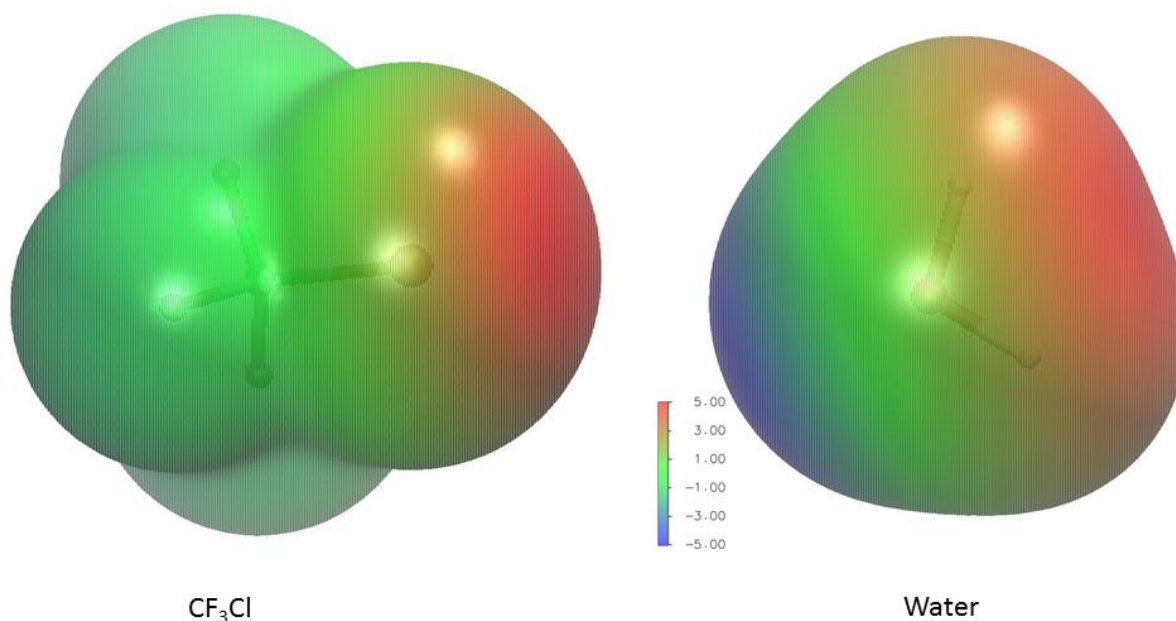
Figure 5. The changes in the MP2/aug-cc-pVTZ molecular electrostatic potential at the 0.001 electrons Bohr^{-3} isodensity surfaces caused by the self-consistent mutual polarization calculations. The colour scale is the same for the two molecules.

Conclusions

We have outlined and demonstrated model calculations for calculating the mutual polarization of bonding partners in a σ-hole bonded complex, $F_3CCl:OH_2$. These calculations are easy to perform and can be used to visualise the polarization effects that are often neglected when analysing non-covalent interactions. This is an important function because of the very close resemblance between polarization and intermolecular charge transfer, which is often invoked as a major effect in such interactions based on comparisons of the dimer electron density with the sum of those of the unpolarized monomers. In particular, Figures 1, 2 and 3 show that this procedure can easily lead to false conclusions.

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