Phosphorus and iron, vital nutrients for all organisms, control the primary productivity of many ocean regions, and aerosol deposition constitutes a major source of these nutrients to many ocean regions. However, the factors controlling the solubility, and therefore bioavailability of iron and phosphorus remain unclear. Synchrotron-based techniques provide a powerful and surprisingly underutilized approach to explore atmospheric aerosol chemistry. Using X-ray fluorescence microscopy and near edge X-ray fluorescence spectroscopy, a variety of chemical properties including the oxidation state, chemical speciation, and mineralogy of the element of interest can be obtained for both individual aerosol particles and bulk aerosol samples. When used in conjunction with ancillary measurements, such as solubility and pH, synchrotron-based techniques provide evidence of underlying chemical transformation occurring during atmospheric transport. In a study of the Mediterranean Sea, aerosol phosphorus was investigated in European and North African air masses. European aerosols deliver on average 3.5 times more soluble phosphorus than North African aerosols and furthermore are dominated by organic phosphorus compounds. The ultimate source of organic phosphorus is a mystery, but preliminary evidence suggests that aerosolized bacteria may be a likely source. In a study of Saharan dust plumes, aerosols were collected at three sites to characterize iron at different stages of atmospheric transport. Iron(III) oxides were a component of aerosols at all sampling sites and dominated the aerosol iron in Mediterranean samples. In Atlantic samples, iron(II & III) sulfate, iron(III) phosphate, and iron(II) silicates were also contributors to aerosol composition. With increased atmospheric transport time, iron(II) sulfates are found to become more abundant, aerosol iron oxidation state became more reduced, and aerosol acidity increased. Acidic reactions and photo-reduction likely influence the form of iron minerals and oxidation state in Saharan dust aerosols. These reactions contribute to increases in aerosol iron solubility, which increases its bioavailability and potential impacts on marine production.