IRSN
INSTITUT
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Impact on marine environment of radioactive releases resulting from the Fukushima-Daiichi nuclear accident

4th April 2011

Measurements taken over several days in the sea water in the vicinity of the power station have revealed severe contamination of the marine environment by various radionuclides released as a result of the accident at the Fukushima-Daiichi nuclear power station. As a general rule, the radioactive pollution of the sea is caused partly by the direct release of contaminated water from the power station, and partly by conveyance via rivers of the radioactive pollutants deposited on the ground following atmospheric release, and subsequent rainwater run-off, and partly finally by the fallout in the ocean of a proportion of the radionuclides from the atmospheric plume, which the winds carried over the sea during a large fraction of the accident sequence. Some of these radionuclides are soluble; and will be carried over very long distances by the marine currents and dissipated throughout the ocean water masses. Others will tend to be more or less bound to suspended particles in the water, causing sedimentary contamination by deposition on the ocean floor. The short –lived radioactive elements, such as iodine 131 (131I), will only be detectable for a few months (the radioactivity of iodine 131 reduces by a factor of 1000 every ten half-lives[1], i.e. every 80 days). Others, such as ruthenium 106 (106Ru) and caesium 134 (134Cs) will persist in the marine environment for several years. Caesium 137 (137Cs) has a long radioactive half-life (30 years): it will undoubtedly justify careful long-term monitoring, in Japanese coastal areas where it is liable to be present in sediments. The same would apply to plutonium if that is found in the marine effluents, but this has not yet been established.

According to the persistence of these radionuclides and their different concentrations, certain flora or animal species could be contaminated to significant levels, justifying the establishment of a radiological monitoring programme for sea food coming from the most severely affected Japanese coastal areas.

1. ORIGINS OF THE CONTAMINATION OF THE MARINE ENVIRONMENT

Since several days, radioactive pollution was observed in the marine environment, at varying distances from the Fukushima-Daiichi power station. The main radionuclides regularly found in the sea water are (T = radioactive half-life): iodine 131 (T = 8 days), caesium 137 (T = 30 years), caesium 134 (T = 2.1 years), caesium 136 (T = 13.1 days), tellurium 132 / iodine 132 (T = 78 hours). Others have also been detected occasionally at lower concentrations: tellurium 129m / tellurium 129 (T = 33.6 days), barium 140 / lanthanum 140 (T = 12.7 days), ruthenium 105 (T = 4.4 hours), ruthenium 106 (T = 368 days), molybdenum 99 / technetium 99m (T = 65.9 hours), cobalt 58 (t = 70.9 days).

This radioactive pollution stems from three possible sources: liquid radioactive effluents escaping from the site of the accident, atmospheric fallout on the surface of the sea and conveyance of radioactive pollution by rainout of contaminated soils.

[1] The radioactive half-life is the period after which the radioactivity of a radionuclide reduces by half.

1.1. Release of liquid effluents directly into the sea in the vicinity of the damaged reactors

The high concentrations recorded in the sea water in the immediate vicinity of the Fukushima-Daiichi power station, indicate that there are one or more sources of radioactive liquid effluents escaping from the nuclear power station. They probably consist of the water used to cool the damaged reactors, part of which may have washed over surfaces contaminated by radioactive deposits formed during the atmospheric release. It is equally possible that part of the water present in the damaged reactors (in particular reactor No. 2 of which the bottom part is damaged) could have leaked out of the containment building, and subsequently run into the sea. It is not currently possible to quantify the magnitude of such liquid release into the sea, nor its duration. The impact of these liquid effluents was observed from 21st March in the vicinity of the power station (1484 Bq/L of 137Cs, 5066 Bq/L of 131I). The concentrations in the sea water subsequently increased between 25th and 28th March (up to 12,000 Bq/L of 137Cs, 74,000 Bq/L of 131I). A further increase was recorded on 29th and 30th March (up to 47,000 Bq/L of 137Cs, 180,000 Bq/L of 131I). As a comparison, prior to the accident at Fukushima, the concentration levels of caesium 137 in the sea water off the Japanese coast was a few mBq/L (1 to 3 mBq/L) and iodine 131 was not detected.

This coastal radioactive pollution spread southwards between 25th and 28th March, with an increase in the concentrations of iodine 131 and caesium 137 of the order of a factor of 10 at Iwasawa (about 20 kilometres to the south of the damaged power station) from 28th March and especially on 29th March. These concentrations are likely to continue to increase at that location.

This spread of the pollution along the coast results largely from the tide which generates alternating sea currents parallel to the coast. This pollution is undoubtedly also spreading to the north of the Fukushima-Daiichi power station.

1.2. Atmospheric fallout onto the surface of the sea

Since 12th March, atmospheric releases caused by the explosions and depressurisations of the containment buildings at the Fukushima-Daiichi power station have spread over the sea. Part of the radionuclides contained in the plume may have fallen onto the surface of the sea, quickly causing a diffuse pollution of the surface water at tens of kilometres from the source. This radioactive fallout is currently continuing, but to a much lesser extent than during the first days following the accident.

The concentrations recorded some 30 km offshore are most probably due to such fallout. They vary between 2 to 27 Bq/L for caesium 137 and between 3 and 57 Bq/L for iodine 131.

The values measured on 25th March tend to indicate a reduction in such concentrations. This may be the result, either of mixing with the deeper water (dilution effect), or of the renewal of surface water by sea currents. The first hypothesis is the most likely.

1.3. Conveyance of radioactive pollution by rainout of contaminated ground

The radioactive fallout deposited on land at the moment of dispersion of the atmospheric release of the Fukushima-Daiichi power station may be partly washed off by rainwater and subsequently carried by runoff directly to the sea, or via water courses flowing into the sea. The contaminated land surfaces thus drained may represent several thousand km². The measurements available do not enable any distinction to be made between these diffused radionuclides and those stemming from other sources of radioactive pollution.

2. DISPERSION IN THE SEA OF RADIOACTIVE POLLUTANTS

2.1. Topography of the sea bed and sea currents off the Japanese coast

The Fukushima power station is located on the east coast of the island of Honshu, 200 km north-east of Tokyo. The coast runs north-south, facing the Pacific Ocean. The depth increases steadily offshore, reaching some 200 m at 50 km from the coast; it then increases suddenly to 5000 m beyond about 100 km (figure 1).

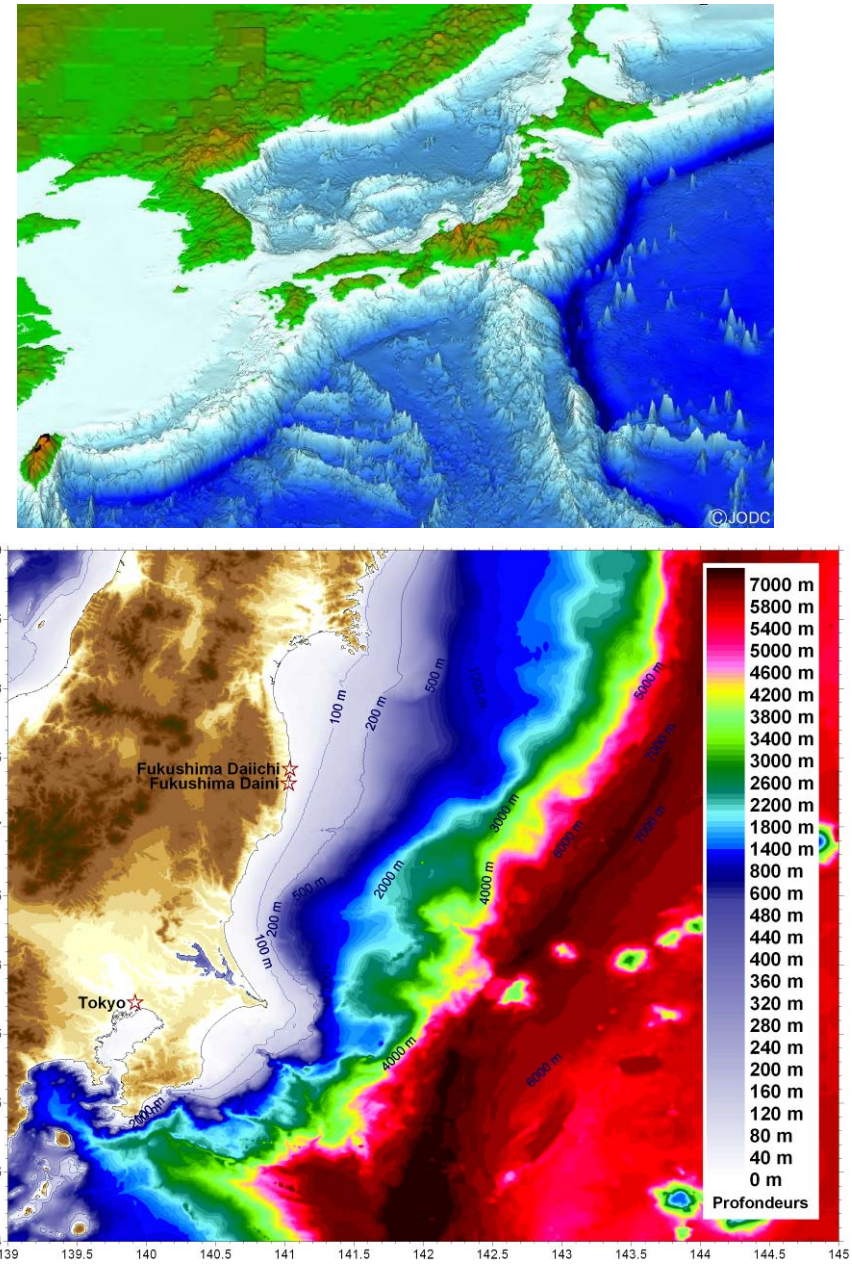

Figure 1 Topography of Japan and bathymetry off the east coast

In the zone currently affected by radioactive pollution, the currents are generated by the tide, the wind and the general circulation of the Pacific. In the short term, the effect of the tide is predominant; the tide move the water masses in an alternating motion, north and south along the coast, at speeds of the order of one meter per second and a periodicity of 12 hours. The wind influences the circulation of surface water.

The overall circulation on a larger scale results from the interaction between the Kuroshio ocean current which comes from the south, running along the Japanese coast and the Hoyashio current, which is not as strong, and which flows from the north (figures 2 and 3). The strength and extent of the Kuroshio current are comparable to those of the Gulf Stream. The coastal waters in the vicinity of the Fukushima-Daiichi power station are within the zone of interaction of the two currents, generating low strength and variable rotary currents. These currents will determine the mid-term dispersion of the radioactive pollution.

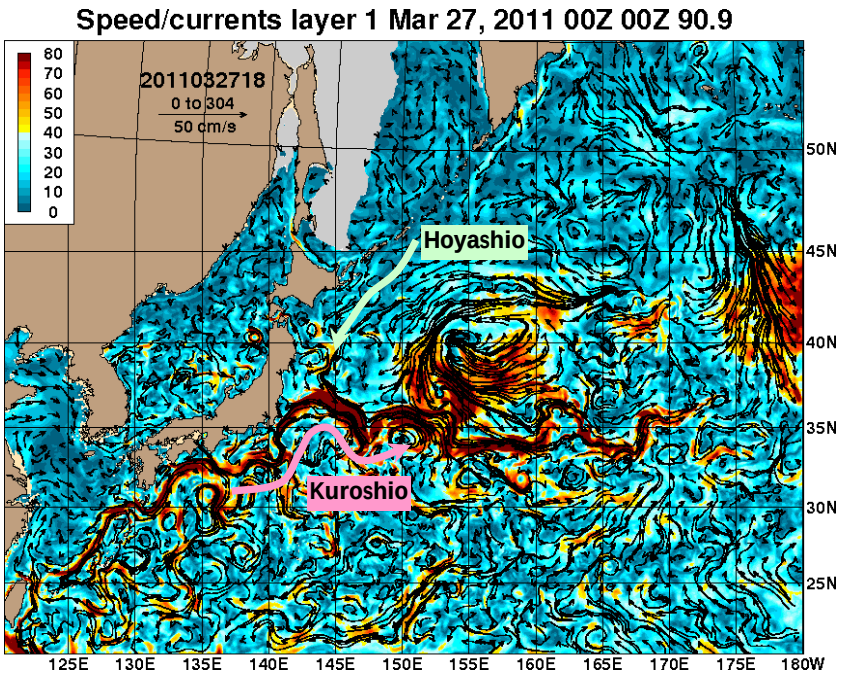

Figure 2 *Surface currents in the north-west of the Pacific (http://www.hycom.org/)*

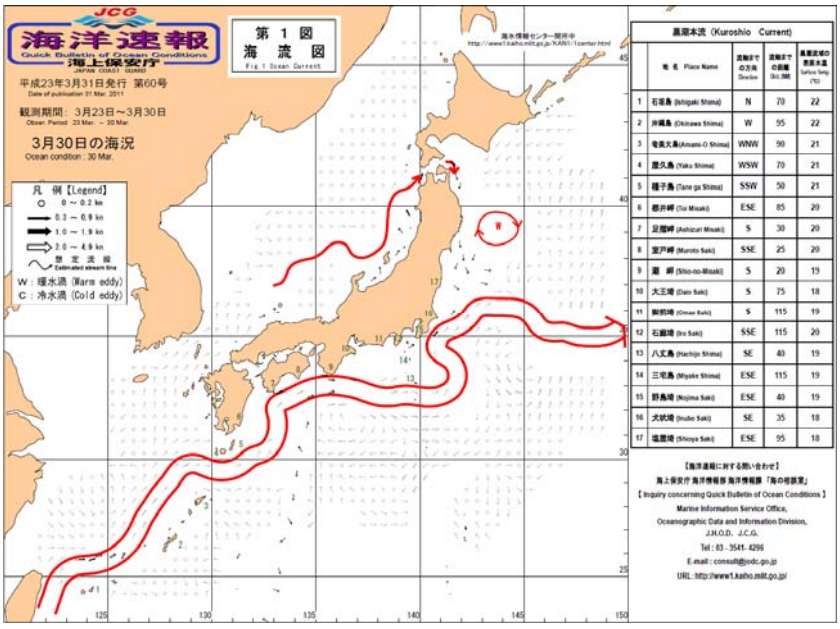

Figure 3 *Observation of the surface currents in the north-west Pacific. The Kuroshio current (in red) flows from south-west to east*
(http://www1.kaiho.mlit.go.jp/KANKYO/KAIYO/qboc/2011cal/cu0/qboc2011060cu0.html)

2.2. Immediate or short term dispersion (a few days)

The concentrations in 131I and 137Cs are representative of other radionuclides measured in the sea; the maps provided in figures 4 to 13 show the results of measurements made in sea water for these two radionuclides.

The great depth of the sea off the coast and the weak currents result in stratification of the water masses. A layer at the surface, some 20 to 50 metres deep near the coast mixes the radionuclides throughout its entire thickness. This layer may be up to 100 metres thick far offshore (source: Mercator-Ocean). It is separated from the deeper layers by a density gradient which limits mixing. The dispersion of soluble radionuclides occurs primarily at the surface. Radioactive particles may migrate to the bottom by sedimentation.

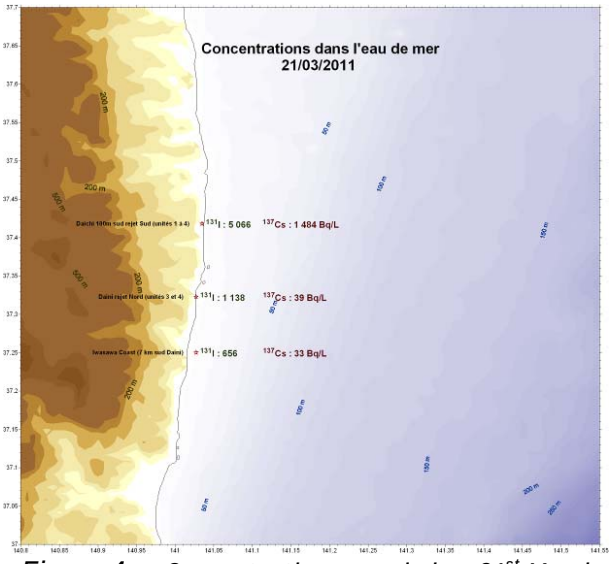

Figure 4 Concentration recorded on 21st March

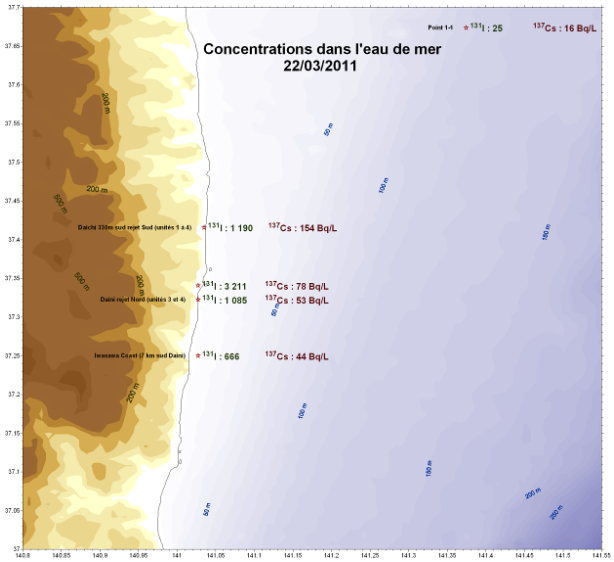

Figure 5 Concentration recorded on 22nd March

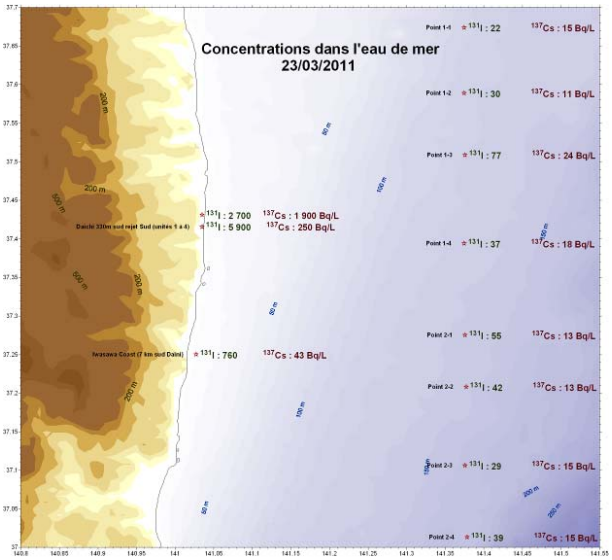

Figure 6 Concentration recorded on 23rd March

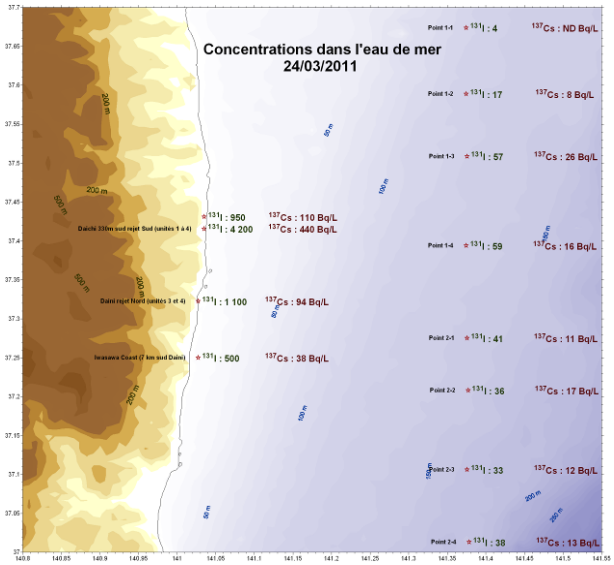

Figure 7 Concentration recorded on 24th March

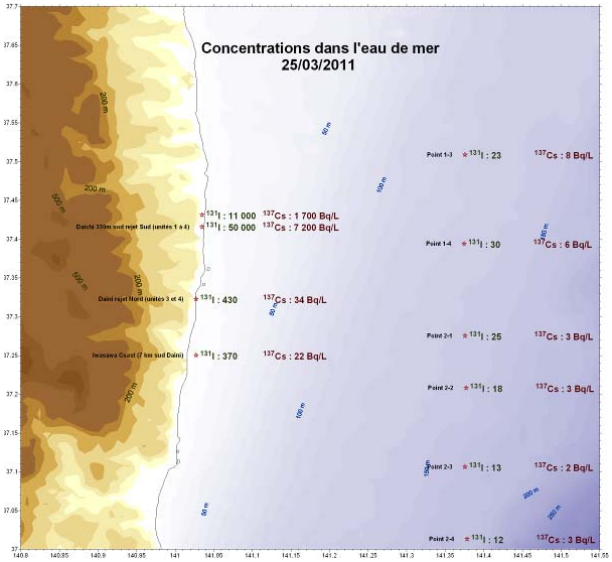

Figure 8 Concentration recorded on 25th March

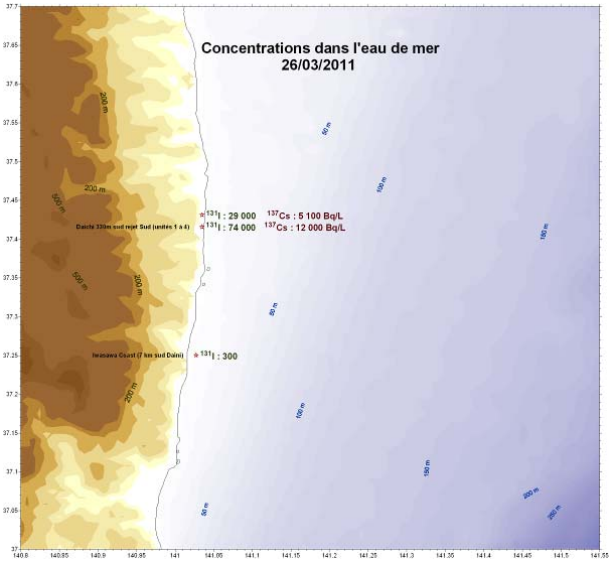

Figure 9 Concentration recorded on 26th March

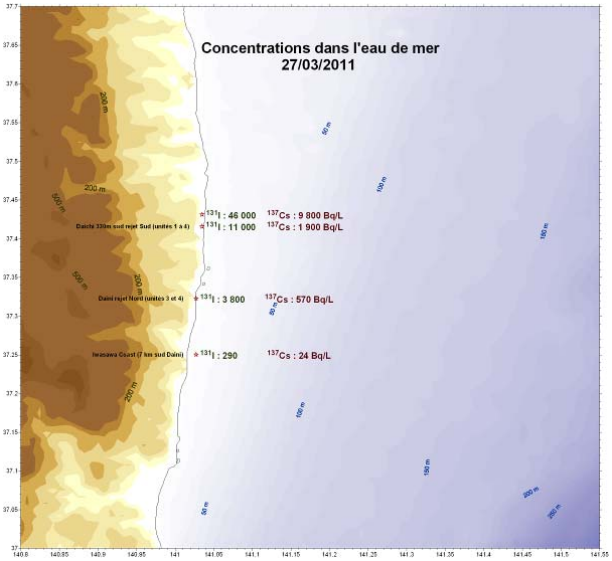

Figure 10 Concentration recorded on 27th March

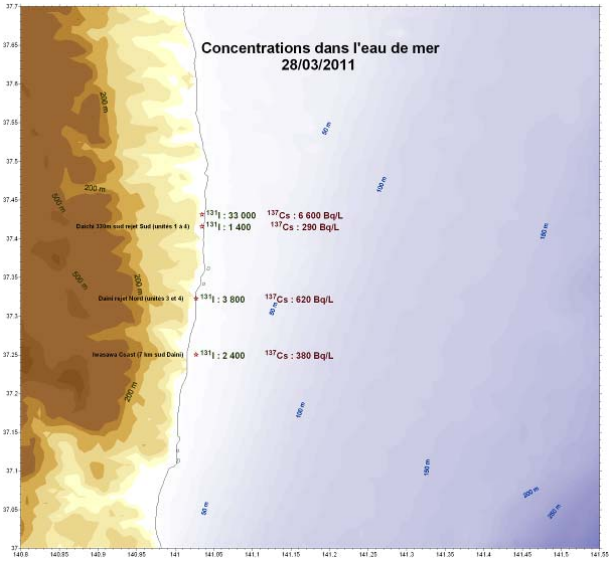

Figure 11 Concentration recorded on 28th March

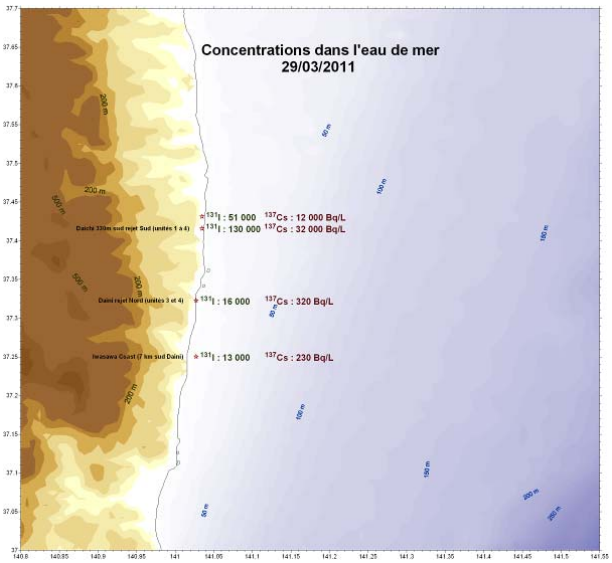

Figure 12 Concentration recorded on 29th March

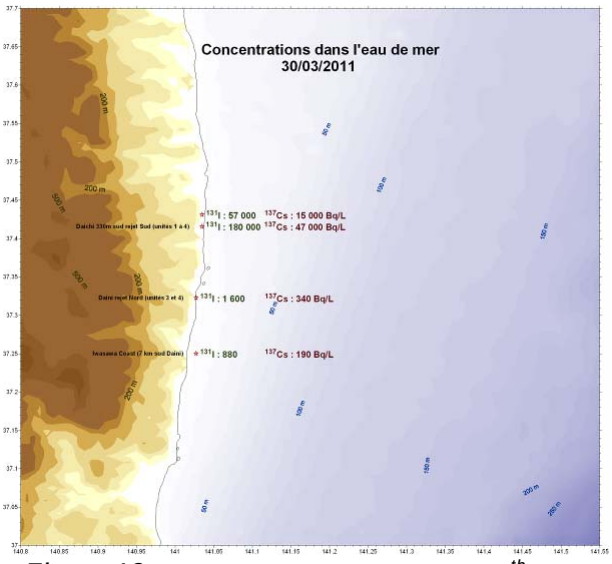

Figure 13 Concentration recorded on 30th March

Simulations have been performed of the dispersion in the sea of this radioactive pollution for the period between the 14th March and 5th April SIROCCO (CNRS and Toulouse University - http://sirocco.omp.obs-mip.fr/outils/Symphonie/Produits/Japan/SymphoniePreviJapan.htm).

They indicate the zones affected in the short term by the dispersion of radionuclides. The concentrations are provided indicatively (figures 14 and 15) as at present, there are no reliable data on the quantity of effluents released by the Fukushima-Daiichi power station nor on the radioactive fallout on the surface of the sea. These simulations do however enable evaluation of the effect of dilution on the radioactive pollution, as it spreads.

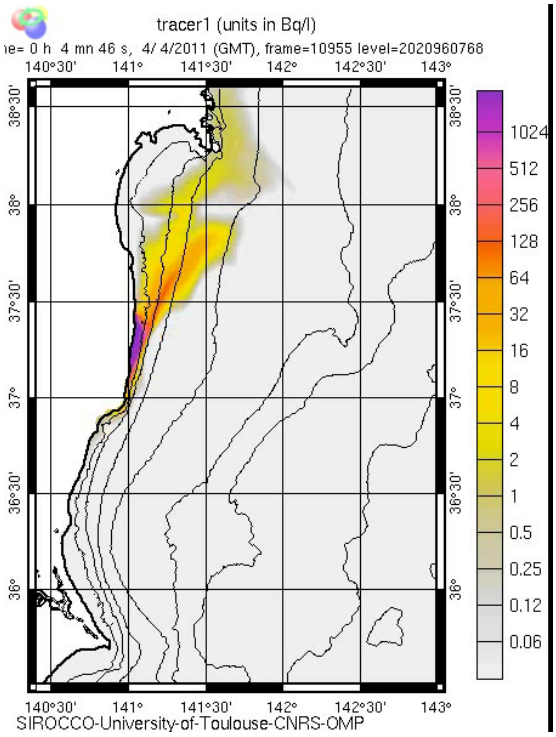

Figure 14 Simulation of the dispersion in sea water of the liquid effluents on 4th April

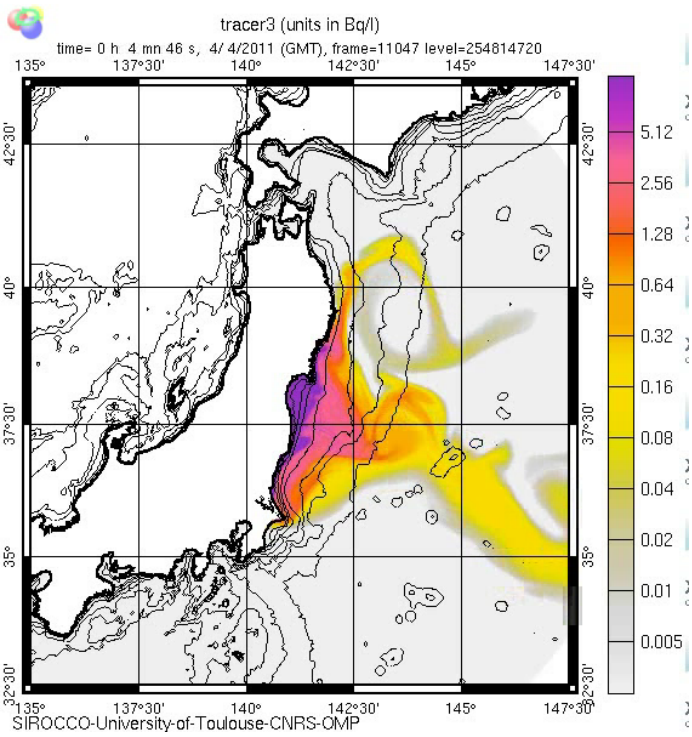

Figure 15 Simulation of the dispersion in sea water of the atmospheric fallout on 4th April

2.3. Mid-term dispersion (weeks, months)

The swirling structures present to the east of Fukushima are unstable. They mix the surface waters between the latitudes of 35°30'N and 38°30'N (figure 15). It is to be expected that the coastal zones located between those latitudes to be impacted by the dispersion of radioactive pollution. The long term migration of the surface waters will be southwards but will not extend beyond the latitude of Tokyo. The Kuroshio current will then carry the plume towards the centre of the Pacific.

A simulation of this migration of the radioactive pollution has been produced by Mercator-Ocean (figure 16). According to that simulation, the radionuclides dissolved in sea water in the vicinity of the Fukushima-Daiichi power station (the green spot on the map in figure 16) should drift for 90 days along the red trace shown on the map. The simulation shows that the coastal currents carry the polluted waters up to the Kuroshio current (the thick white swathe) and disperse to the north of that current. The diffusion is relatively turbulent but the dissolved radionuclides are contained by the Kuroshio current.

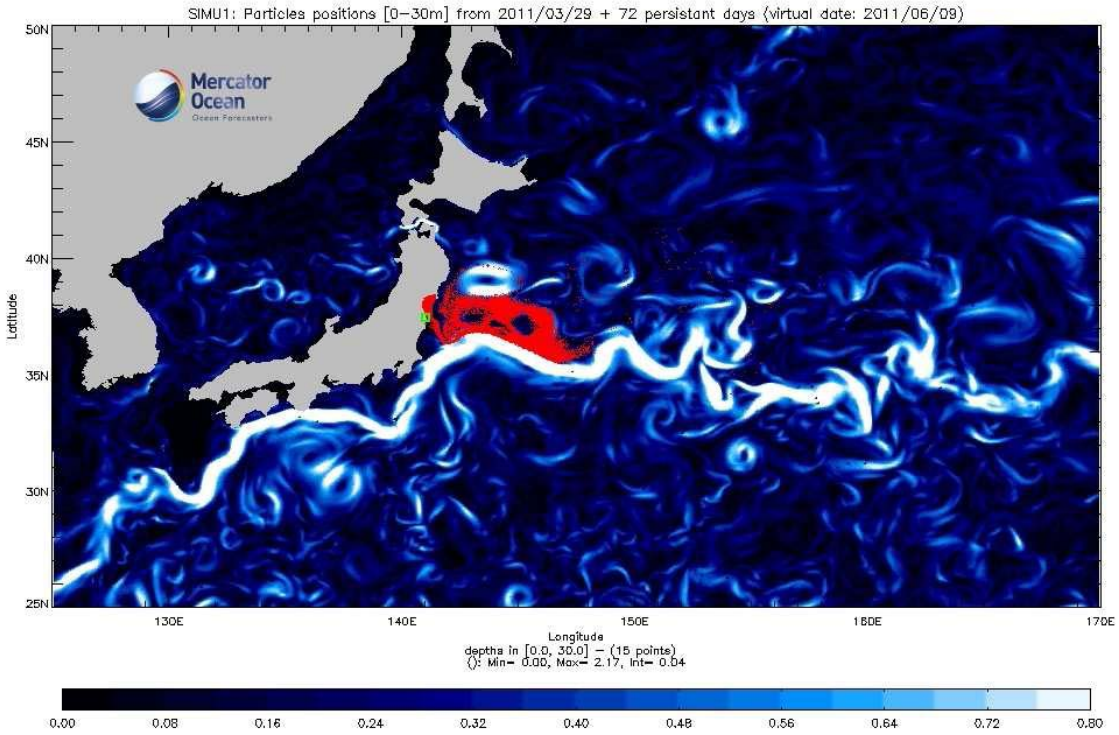

Figure 16 Simulation of the migration of radioactive pollution (Mercator-Ocean)

When the different sources of release into the sea are better evaluated, the marine dispersion simulations should provide a better estimate of the medium term changes in radionuclide concentrations.

2.4. Long term and large scale future of the radioactive pollutants

- **Residence times in the surface waters**

The short radioactive half-life radionuclides (less than a few tens of days) should cease to be detectable after a few months and should not therefore have any large scale long term impact. Others, such as ruthenium 106 and caesium 134 will persist in the marine environment for several years and will finally disappear by radioactive decay. The persistence time of caesium 137 in the surface waters of the Pacific Ocean varies between 11 and 30 years according to the region (10 years for the medium latitudes and 30 for the equatorial zone). For plutonium isotopes, assuming that these are present in the liquid effluents, the persistence time would be 5 to 17 years (the shortest times are again observed in the medium latitudes). These persistence times are dependent upon the respective affinity of the radionuclides for the particles in suspension in the surface waters, which are likely to settle and to carry the radionuclides to the seabed.

- **Transit times**

The transit times between the North-West Pacific and the equatorial zone is estimated to be about 10 to 15 years. Part of the North Pacific Ocean waters flow towards the Indian Ocean via the Indonesian seas and are then carried towards the south of the Atlantic Ocean. These transfer times have been estimated to be about 30 to 40 years.

Until recently, scientists considered that there was no exchange between the north Pacific and the south Pacific, due to the major barrier formed by the equatorial system of currents. Measurements

of traces of caesium 137 (fallout from atmospheric nuclear tests conducted in the northern hemisphere) in the Tasmanian Sea have shown that this barrier is not completely watertight and that exchanges are possible between the north and the south, in the western part of the Pacific.

3. IMPACT OF RADIOACTIVE POLLUTION ON LIVING SPECIES

In the short term, all the species in the marine trophic chains in coastal areas close to the Fukushima-Daiichi power station are likely to be impacted by the radioactive pollution of the sea water. Up to now, it is difficult to quantify the magnitude of such impact, which may be highly variable according to:

- the magnitude of the continuing release of radioactive liquids from the nuclear plant;
- atmospheric fallout onto the surface of the sea;
- the quantity of radionuclides brought by the watershed draining the contaminated zones;
- the renewal of water masses along the coast, etc.

Particular attention should be focussed on aquacultural installations (seaweed farms, molluscs and fisheries) located on the coast close to the nuclear plant, even if it is probable that such installations have been severely damaged by the tsunami on 11th March.

Iodine has a strong affinity for brown seaweed which is a major crop in Japan. There is therefore a risk of contamination of this type of seaweed by radioactive iodines, in particular iodine 131. However, in view of the short radioactive half-life of that radionuclide, the risk will only be significant for a few months.

In the longer term, it is the coastal zone subjected to contamination with radionuclides by rainout from the contaminated water basins which could be impacted by persistent radioactive pollution. Phenomena which put radionuclides initially bound to sediments back into seawater could also contribute to maintain significant concentration levels of certain radionuclides in the water and in certain living species.

Accumulation phenomena in living species could lead to higher concentrations than those measured in the water by a factor of 10 to several thousand, according to the radionuclide and the species considered (weight ratio of the concentrations in the species and in sea water). The accumulation capacity is dependent on the metabolism of each species. In the case of caesium, the concentration factors vary from 50 for molluscs and seaweed to 400 for fish. For iodine, the concentration factors vary between 15 for fish and 10,000 for seaweed.

These accumulation phenomena are ample justification for the establishment of radiological monitoring programmes. The geographic zones of interest should be specified by predictive mapping studies, covering the vegetable and animal species entering the human food chain either directly or indirectly.