Sources, Behaviour and Environmental Impacts of Petroleum Hydrocarbons Released into the Marine Environment

Kenneth Lee

Behaviour and Environmental Impacts of Crude Oil Released into Aqueous Environments

Chapters

1. Introduction – context; spills in Canada
2. Chemical Composition, Properties and Behaviour of Spilled Oil
3. Effect of the Environment on the Fate and Behaviour of Oil
4. Oil Toxicity and Ecological Effects
5. Modelling of Oil Spills in Water
6. Review of Oil Spill Response Options
7. Prevention and Response Decision Making
8. Risks from Oil Spills
9. Summary and Recommendations
10. References
11. Appendices

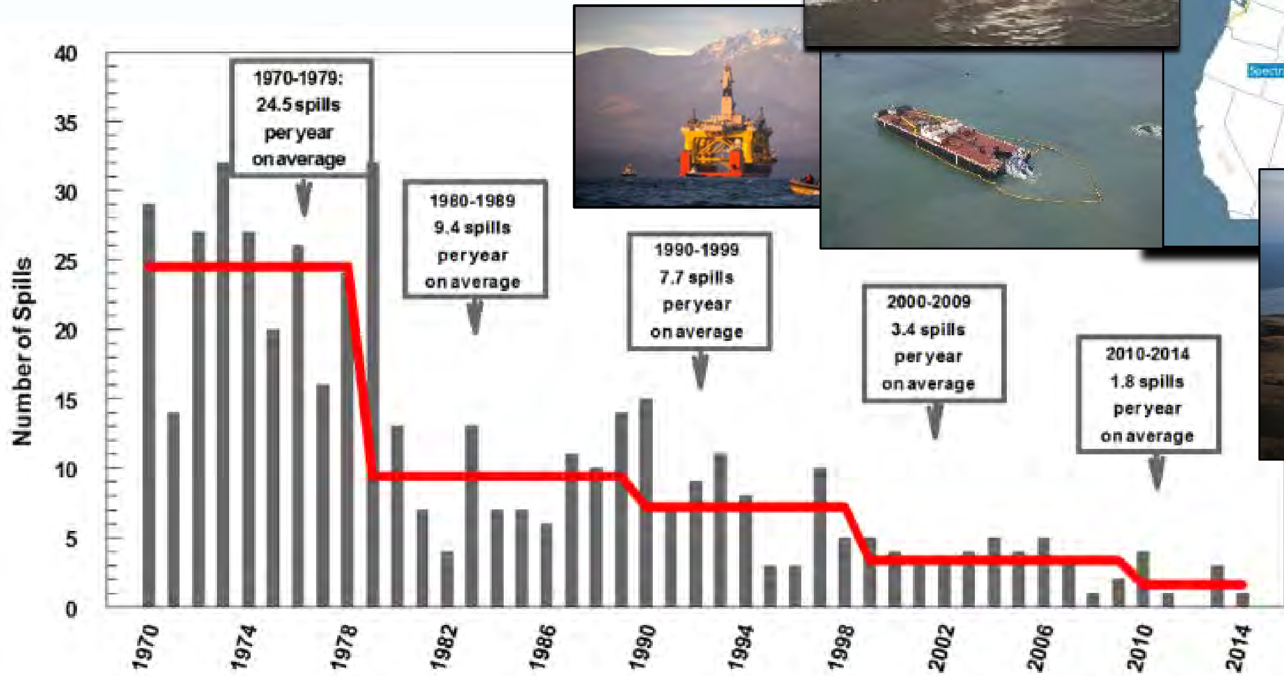
RSC SRC

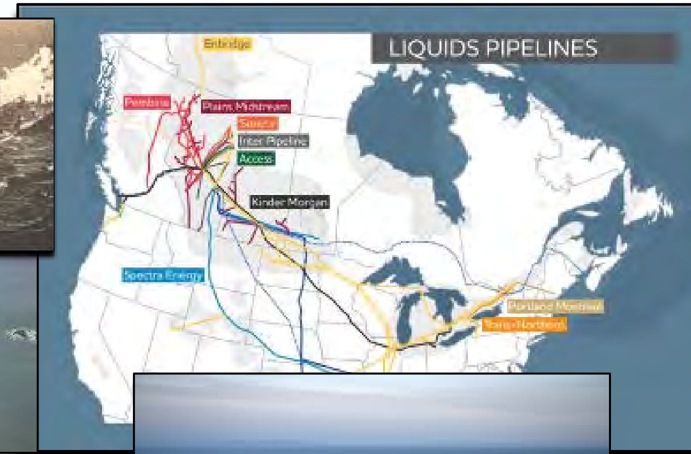
canadian energy pipeline association | association canadienne de pipelines d'énergie

CAPP CANADIAN ASSOCIATION OF PETROLEUM PRODUCERS

CSIRO

Oil Spill Risks

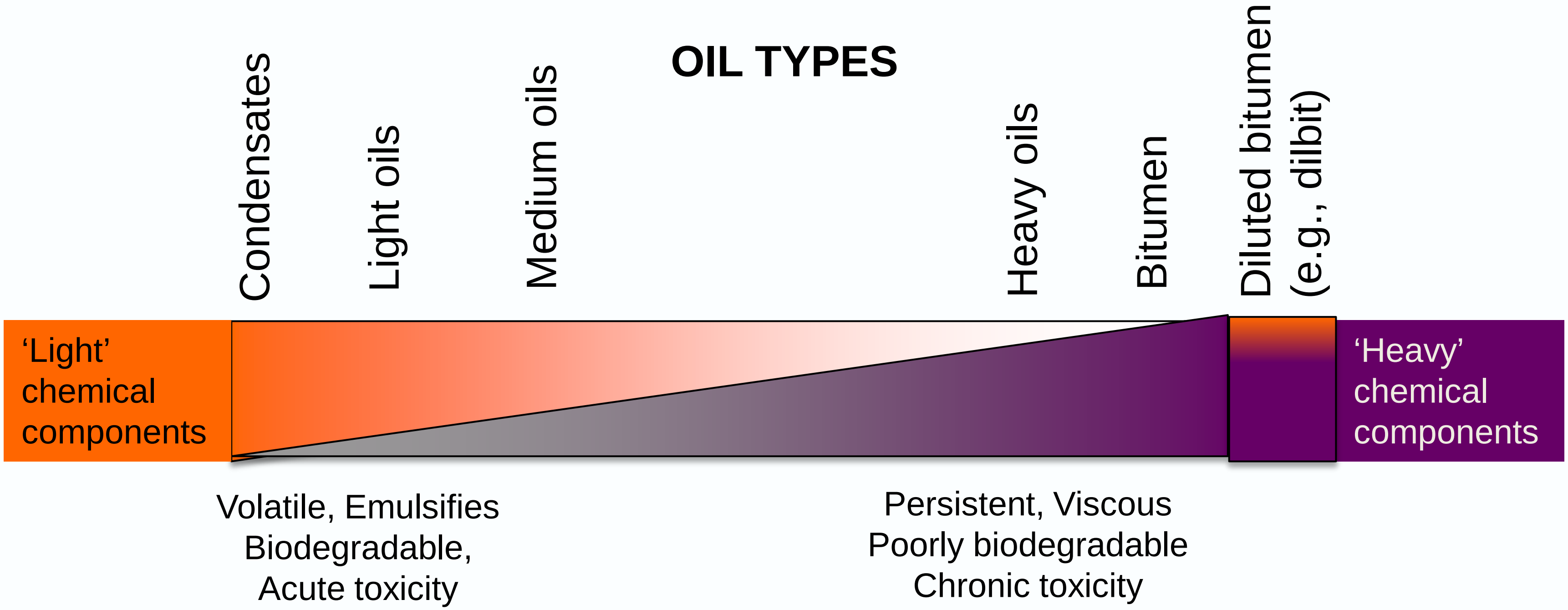




Large oil tanker spills (>700 tonnes) occurring worldwide from 1970 to 2014 *(ITOPF, 2014)*

- **Canada produces some three million barrels of oil every day, importing hundreds of thousands more, and all of it travels somewhere - accidents happen**
- **Growing concerns: spill risks in the Arctic and/or pipeline ruptures, rail and roadside accidents**

RELATIONSHIP OF OIL COMPOSITION TO OIL TYPE AND PROPERTIES

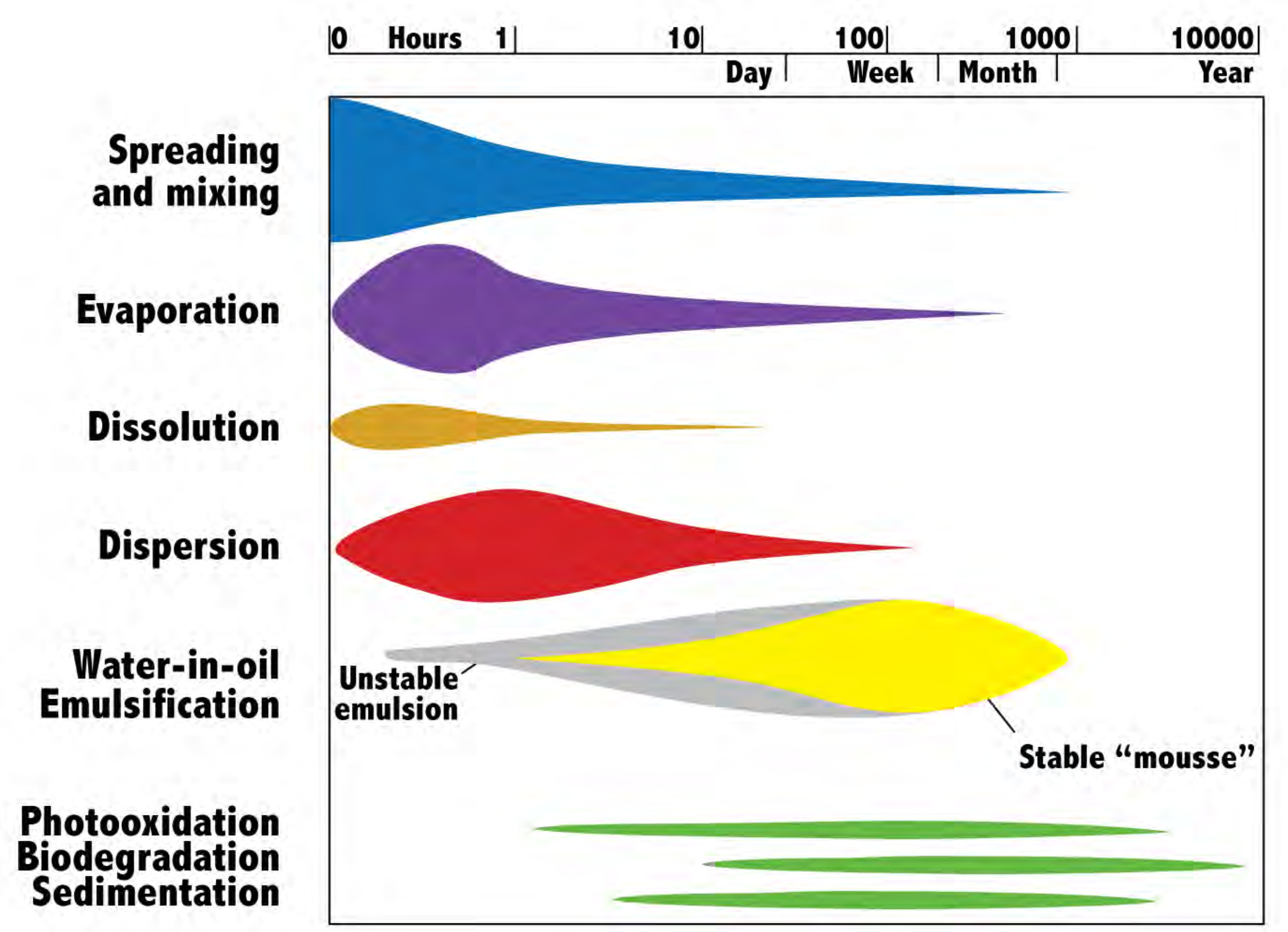


GENERALIZED OIL PROPERTIES

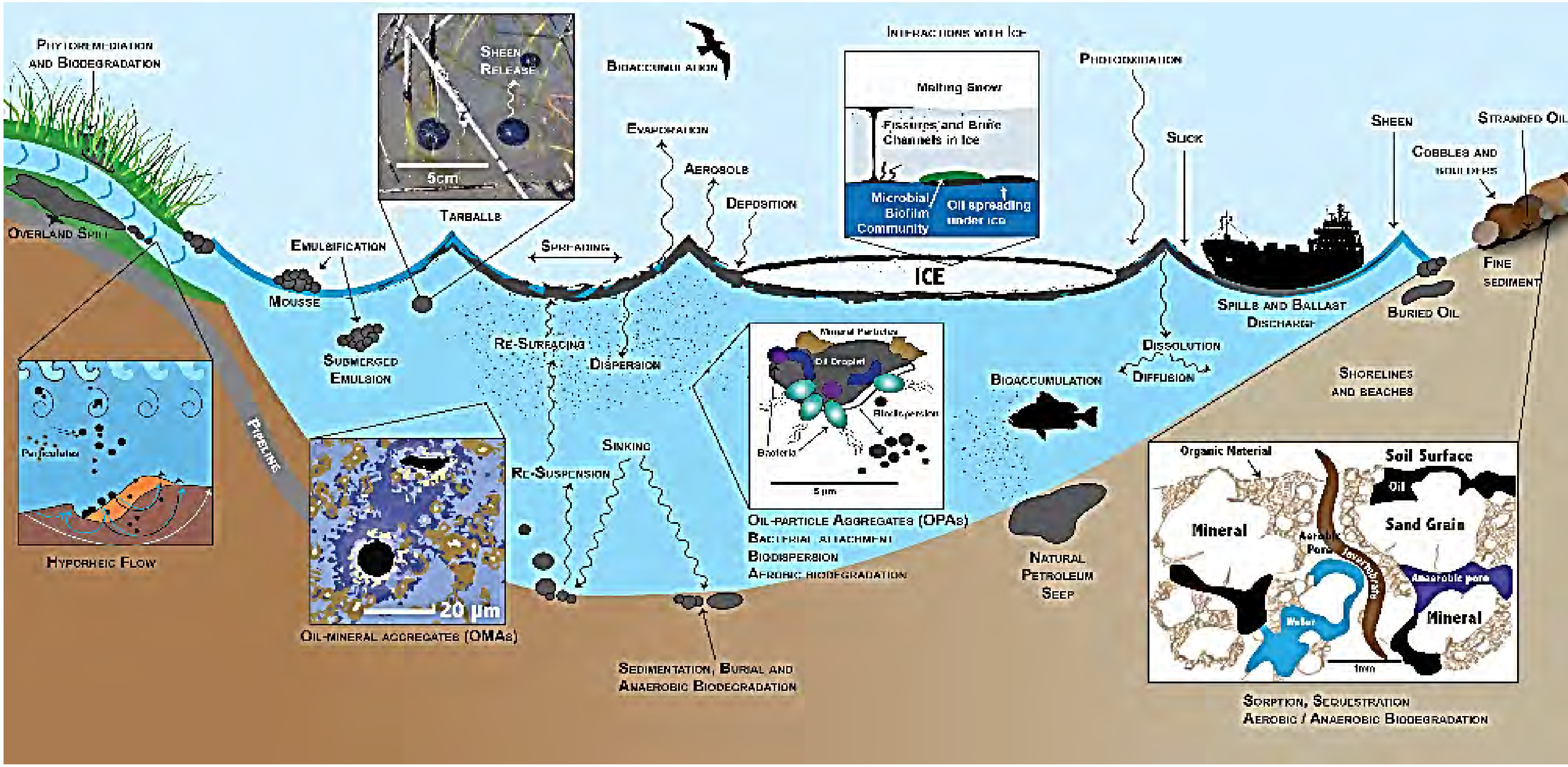
Crude and refined oils are very complex mixtures (1000s of chemicals)

- The structures of many components are unknown, but their proportions dictate oil properties and environmental fate, behaviour & effects
- Very difficult to predict fate & effects from chemistry alone; the whole is greater than the sum of the parts, which change with weathering

Sequence of Weathering Processes for a Medium Conventional Oil Spilled on Water



Fate and Behaviour of Oil Spilled in the Aquatic Environment



Each oil spill is unique due to:

- **Variety and complexity of environmental processes (physical, chemical and biological)**
- **Different fates and different timescales (immediate to decades or centuries)**
- **Differences in the type of oil (e.g. dilbit) and type of environment and prevailing conditions**

Case Studies: Understanding the Significance of Site-Specific Factors

***Arrow Spill**: Heavy fuel oil on cobble beaches; fate & persistence; 'set asides'*

***Exxon Valdez Spill**: Clean-up impacts; species diversity; diversity of impacts (e.g., fish recruitment)*

***Deepwater Horizon**: Deep-water oil plumes; effects on fitness of fish; dispersant interactions*

***Pine River Pipeline Spill**: sour crude; oil movement downstream; remote area; clean-up impacts*

***Wabamun Lake Spill**: Closed system; sinking oil; clean-up impacts; multiple stressors; ecosystem services*

***Kalamazoo River**: Fate & behaviour of dilbit; sediment contamination*

Conclusions from Case Studies

- ***Delayed response*** was a critical factor affecting the consequences of spills
- ***It's always a combination of factors, not just oil type, which determine consequences*** - oil type, response time, environmental characteristics, and clean-up effects
- The ***lack of pre-spill baseline data*** seriously limits the ability to predict or monitor long-term effects
- ***Validation of oil spill response techniques is hampered by inadequate methods*** for measuring the effectiveness of response measures
- ***Effects of oil spill cleanup on aquatic ecosystems can be significant***
- ***The presence of long-term stresses from other sources*** *(natural and human-related)* ***may tax the capacity of ecosystems to be resilient*** to shocks of oil spills
- ***Post-spill monitoring must be conducted*** according to standardized protocols

1. Understanding of Environmental Impacts from Crude Oil Spills in High-risk and Poorly Understood Areas

Arctic

- Complex interactions among physical, chemical and biological ***factors unique to Arctic conditions*** in the presence of different types of spilled crude oil
- ***Evaluate risks*** associated with the transport of petroleum hydrocarbons in the Arctic (i.e., ships and pipelines)

Freshwater

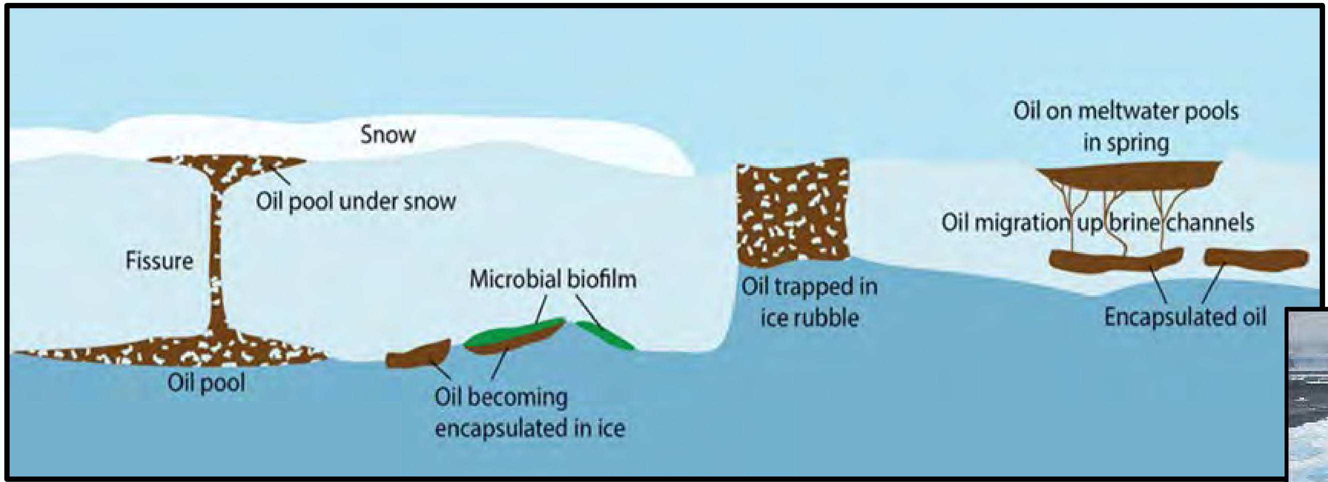
- Fate and effects of oil spilled in **freshwater ecosystems**

Marine

- Assess the risks of ***deep sea blowouts*** (e.g., subsurface ***oil plumes, residual oil*** in sediments) and the effectiveness of available and emerging **response strategies**

Potential risks to Arctic and freshwater environments

- Under similar test conditions, there is ***little difference in oil toxicity between freshwater & marine species and between temperate & Arctic species***
- Data from temperate species can provide a first approximation of risks to Arctic species
- Impacts of oil spills in Arctic and freshwater ecosystems are driven more by factors that influence the **exposure of organisms to oil** than by differences in sensitivity to oil



2. Improved Understanding of Effects of Oil Spills on Aquatic Organisms, Communities and Ecosystems

- Develop improved ***methods to detect and track spilled oil*** within different compartments of freshwater and marine ecosystems and to **monitor and model (predict) potential effects**
- Study ***effects on aquatic species at the level of populations, communities and ecosystems***
- Understand the indirect ***effects of oil spills on ecological processes***, such as interactions within and among the levels in aquatic food chains

- Study the **resilience** and **recovery** of aquatic ecosystems affected by oil spills
- Investigate the **socioeconomic impacts** of oil spills, as a first step in implementing an ecosystem services approach to oil spill impact assessments

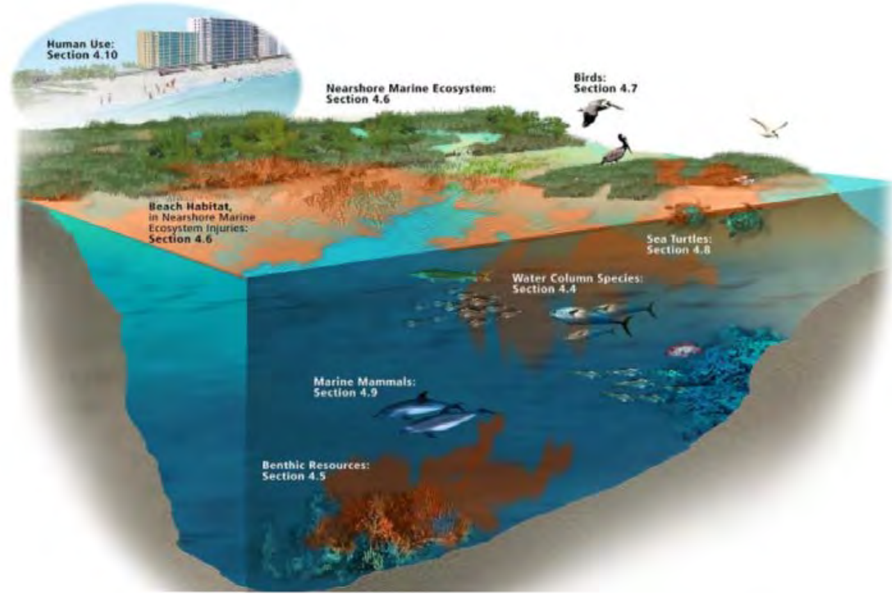
3. National Program for Baseline Research and Monitoring

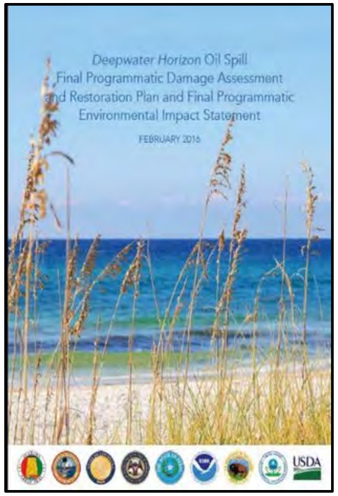
- Collect and evaluate ***baseline information from high-risk, poorly understood areas***
- ***Continue work on ecosystem sensitivity maps***, including the identification of highly-valued species and vulnerable habitats, prioritized according to recent relative risk assessments
- ***Understand the natural variability*** of population and community metrics (e.g., abundance, diversity, productivity) across physical and chemical gradients, as well as across time
- To identify and study ***interactions between other anthropogenic stressors and crude oil***
- *Develop a* ***network to provide baseline data*** *to support decision making during oil spill response operations*



NOAA Natural Resource Damage Assessment

- Determine the **amount and type of injury** to natural resources and **lost services** from time of incident through recovery of resources
- Document: Release-Pathway-Exposure-Injury-Restoration
- Develop and oversee implementation of **restoration plan**(s) to **compensate** the public for injuries and lost services
- Ensure the polluters pay for assessment and restoration
- **Engage the public** throughout the process





NERDA Toxicity Program

- **Adverse effects at sediment concentrations ~ 1 ppm (mg/kg) tPAH50 (LC_{20s})**
- **Adverse effects at water concentrations ~ 1 ppb (ug/L) for fish and ~ 13 ppb for invertebrates tPAH50 (LC_{20s})**
- **Some toxic effects conserved across species (e.g., cardiotoxic effects in fish and birds, adrenal impairment in fish, birds and mammals,other)**
- **Measured and modeled concentrations of tPAH50 in sediments and surface waters at numerous locations and times exceed these toxic concentrations**
- **Thin sheens (1 um or less) toxic to early life stages (ELS) of fish and to invertebrates**
- **UV enhanced toxicity resulted in 10x to >100x increase in toxicity under ambient UV for semi- transparent inverts, and early life stage fish**

Cardiotoxicity in Bluefin Tuna

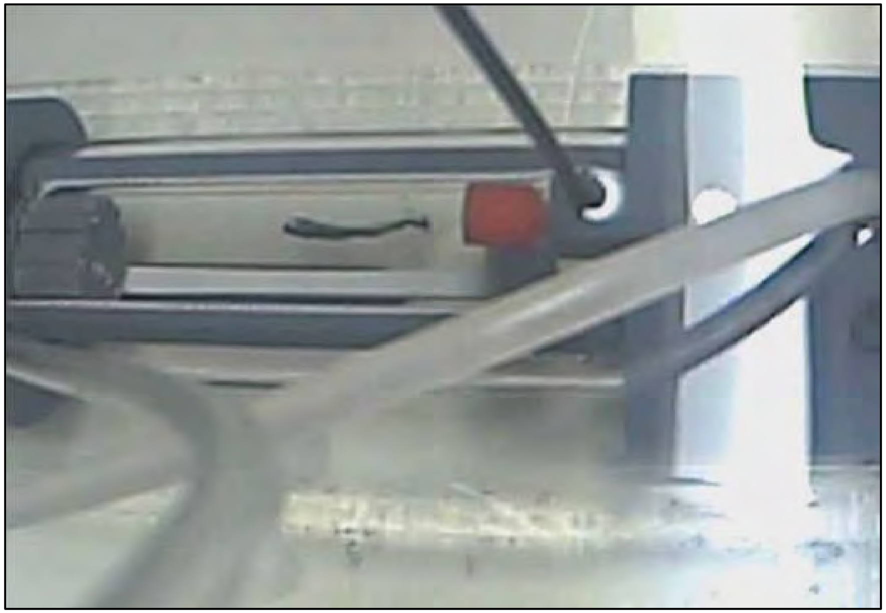
- **Impaired cardiac development (deformities)**
- **Impaired cardiac function (e.g., arrhythmia)**
- **Similar to congestive heart failure in humans**
- **Have demonstrated in pelagic fish species and standard test species**
- **20% cardiac edema to bluefin tuna at < 0.5 ppb tPAH50**

Control

Exposed

Bluefin Tuna larvae: Exposed to 9.4 PPB PAH showing extensive cardiac edema

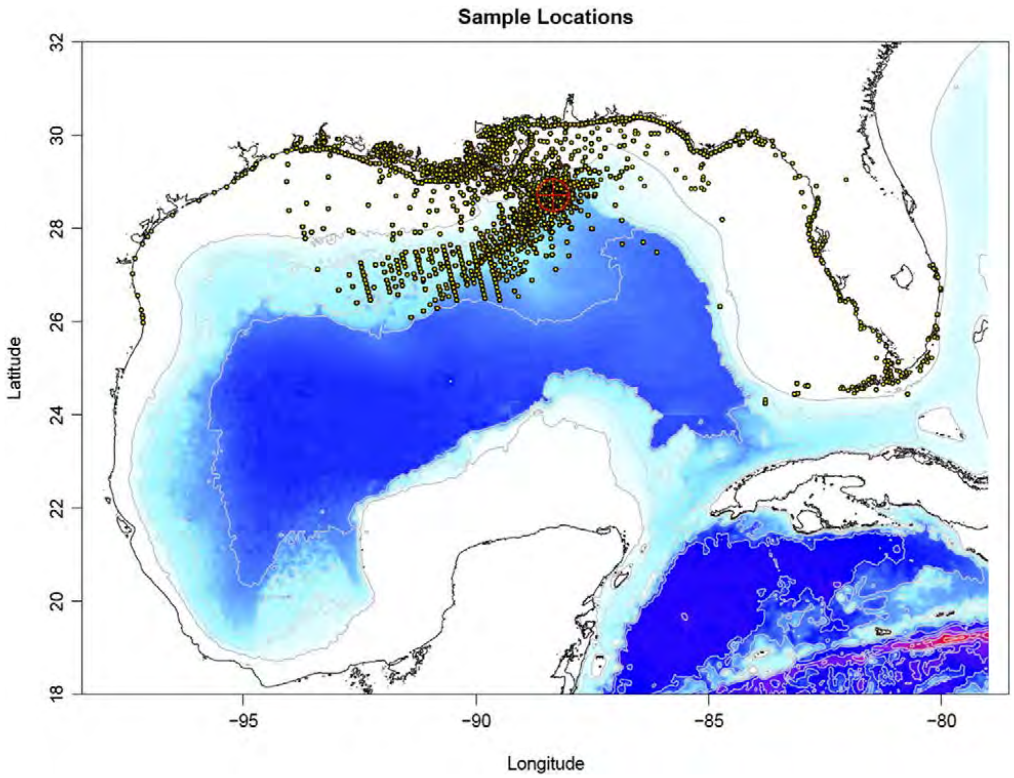
Swimming Performance and Aerobic Scope in Pelagic Fish



Acute Embryonic or Juvenile Exposure to *Deepwater Horizon* Crude Oil Impairs the Swimming Performance of Mahi-Mahi (*Coryphaena hippurus*)

Edward M. Mager, Andrew J. Esbaugh, John D. Stieglitz, Ronald Hoenig, Charlotte Bodinier, John P. Incardona, Nathaniel L. Scholz, Daniel D. Benetti, and Martin Grosell. *Environ. Sci. Technol.*, 2014, *48* (12), pp 7053–7061

Hydrocarbon Concentrations



- **Highest concentrations were collected proximal to the wellhead or in samples collected from surface slicks and dispersant use**
- **Of 13,172 water sample TPH concentrations reported, 84% were below 1 µg/L (background)**
- **Of the 16,557 water sample PAH concentrations reported, 79% were below 0.056 µg/L (the median field blank, background)**

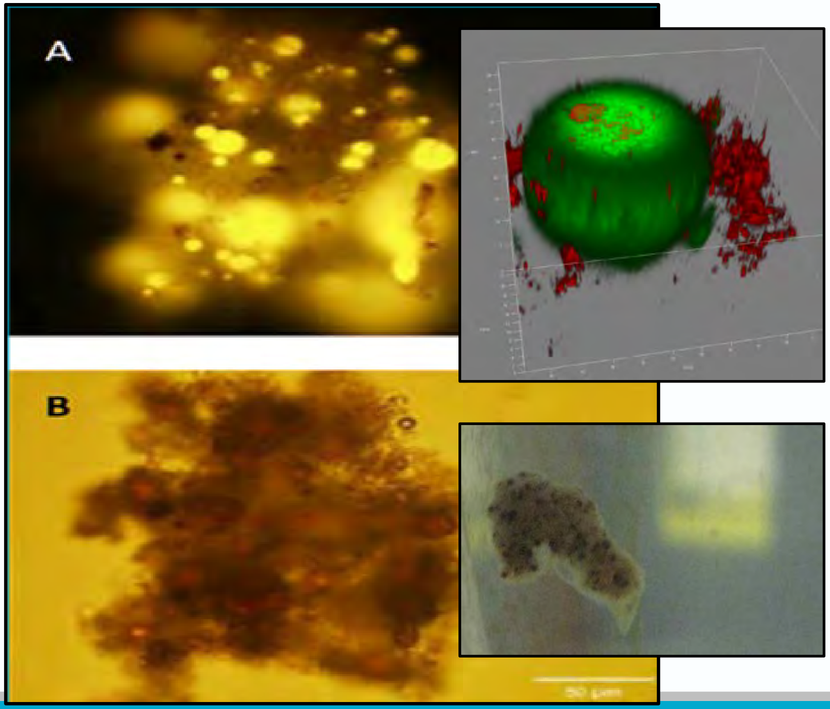
The percentage of samples below background increased rapidly after the well was capped

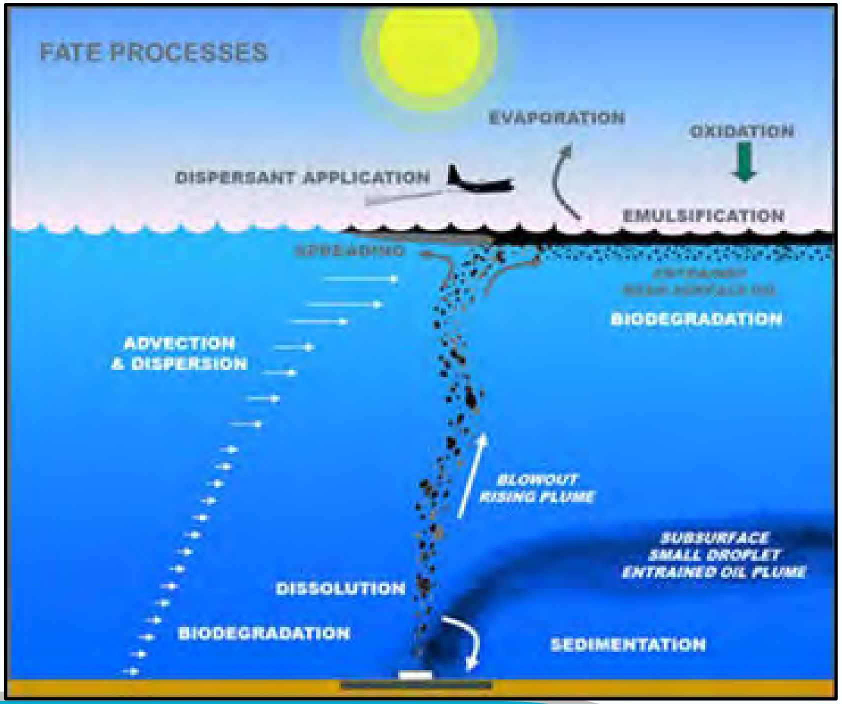
4. Controlled Field Trials to Study Spill Behaviour and Effects

- **Need regulatory permitting of controlled field experiments on oil spills** with rigorous statistical designs
- spectrum of **oil types** at a **variety of sites** representing different coastal marine and freshwater ecosystems and **conditions**
- Validate standardized methods for detailed chemical analysis of poorly-characterized oil components that will ***improve our understanding of oil weathering processe***s within the environment
- Develop and validate ***new oil spill response measures***

4. Controlled Field Trials to Study Spill Behaviour and Effects

Develop contingency funds to support research on the fate, behaviour and effects following ***"spills of opportunity"*** to provide data on the **influence of natural weathering** processes and various **spill response measures** on crude oil composition and properties and the **rate and extent of habitat recovery**





5. Improve the Efficacy of Spill Response Technologies and Strategies

To develop, refine and validate ***improved methods for contaminated-site remediation*** following oil spills

Study the ***efficacy and environmental impacts of conventional and new oil spill remediation options,*** particularly in Arctic and freshwater ecosystems

To address the long-standing remediation question "how clean is clean?"

- ***Identify endpoint benchmarks*** for treatment
- Consideration of impacts on ***ecosystem services***




Oil Spill Response Options




Natural recovery

- Natural attenuation, Evaporation, Photooxidation, Biodegradation

Physical response methods

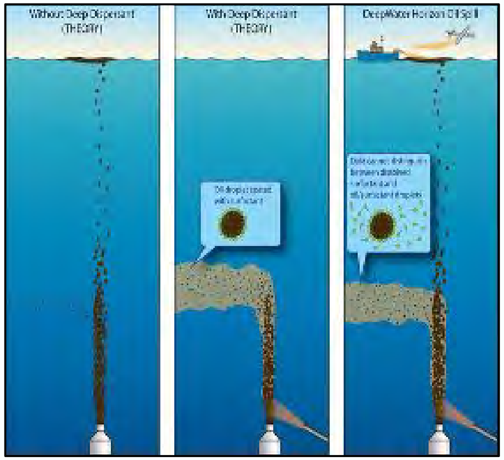
- Containment and recovery, Physical dispersion (OMA), in situ burning (ISB), etc.

Biological and chemical methods

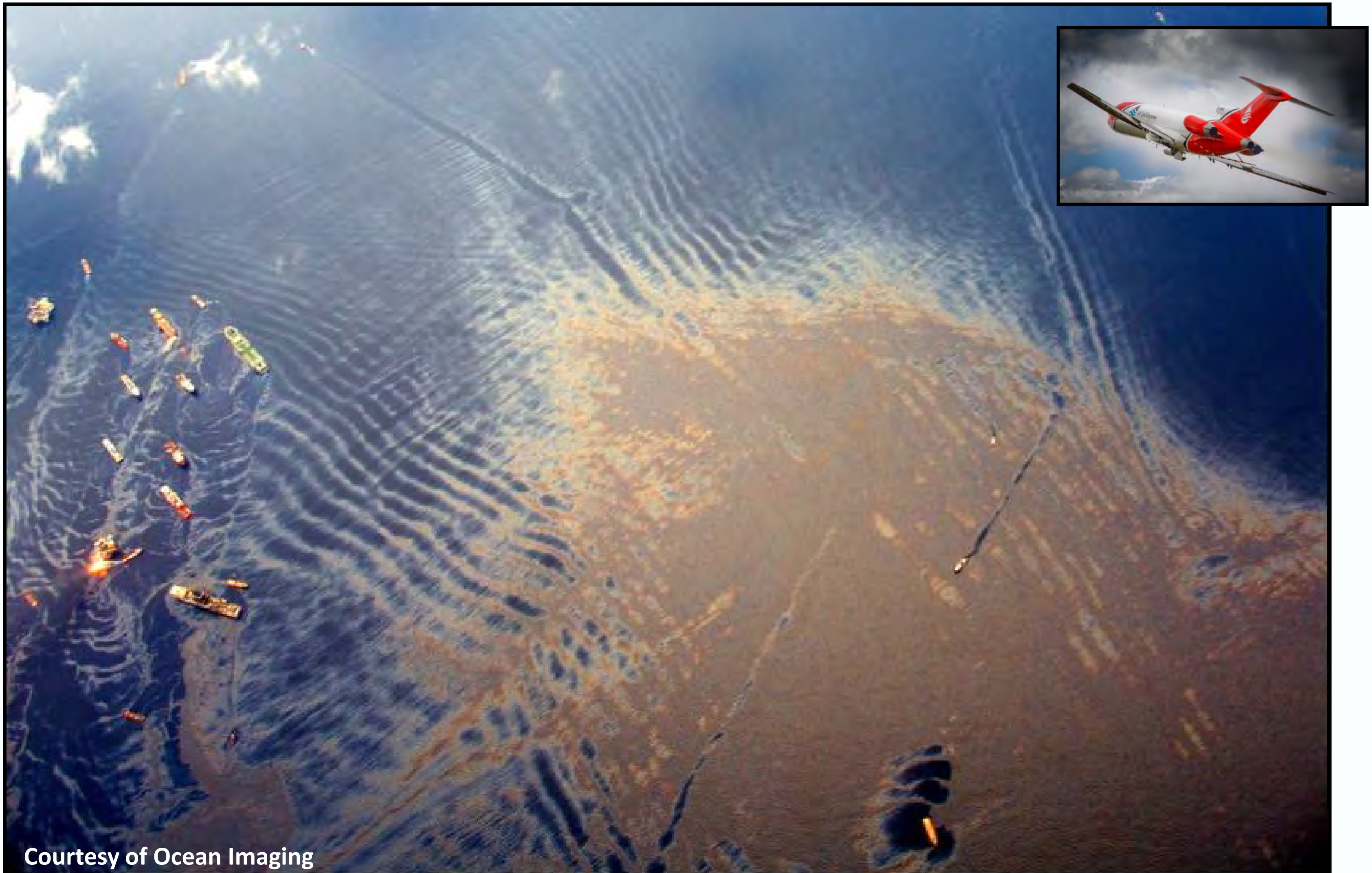
- Bioremediation, Phytoremediation, Chemical dispersion, Solidifiers, Herding agents

Chemical Dispersants

- ***Chemical dispersants facilitate oil dilution and microbial degradation***
    - Dispersion can reduce the oil exposure of surface and shoreline species but increase the exposure of algae, invertebrates and fish
    - *The potential impacts of deep water oil dispersion at well blow-outs remain controversial*
    - Dilution below “toxicity threshold limits” is the key
- ***Dispersants are moderately toxic when dissolved in water***
    - Accuracy in dispersant application to oil slicks is key to minimizing risk
    - Dispersants and oil do not cause synergistic toxicity



Encounter Rate is Key to Offshore Response



Courtesy of Ocean Imaging

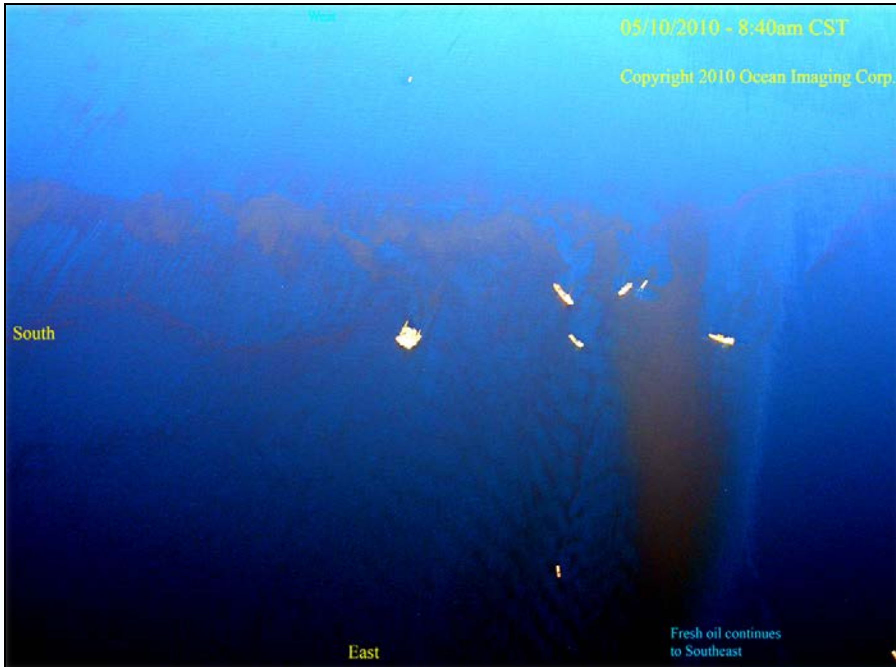
Application of Oil Dispersants

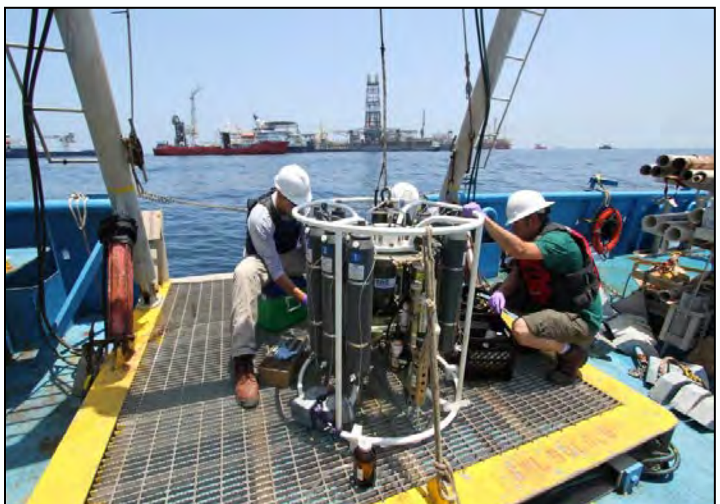
- Based on discharge rates - final estimate of 53,000 barrels per day (8,400 m^3/d) - each day the Gulf of Mexico Oil Spill would be considered a major incident

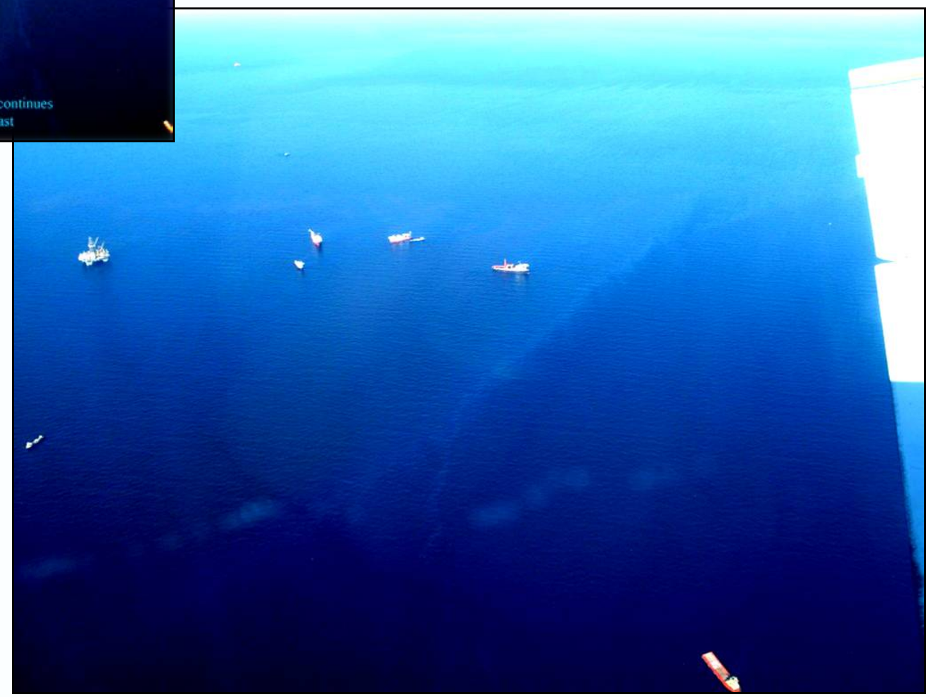
- In addition to mechanical recovery techniques (skimming and booming) and in situ burning, oil dispersants were used to prevent landfall of the oil in the Deepwater Horizon Spill

- Beginning in early May responders began injecting dispersants at the source of the release (~1500m depth) to reduce oil from reaching the surface

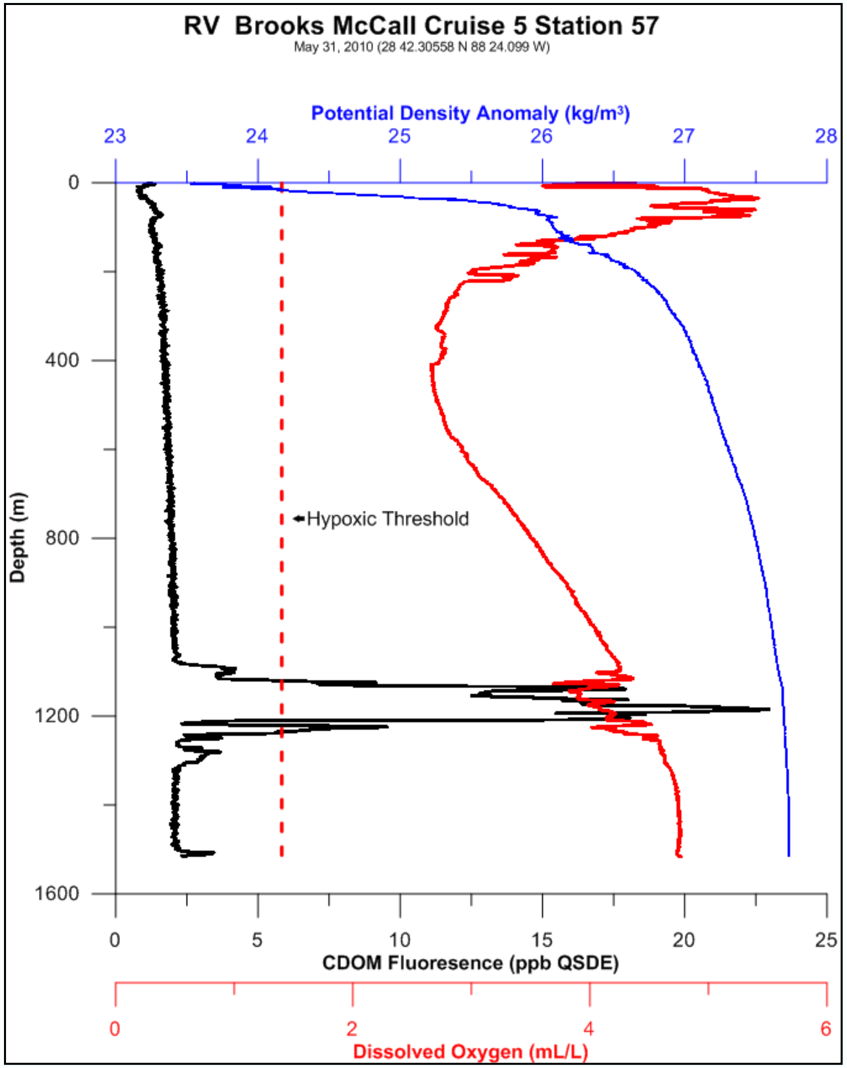
- Advantages of subsurface injection:
  - Reduced VOCs (volatile organic compounds)
  - Reduced Oil Emulsification
  - Volume of dispersant needed

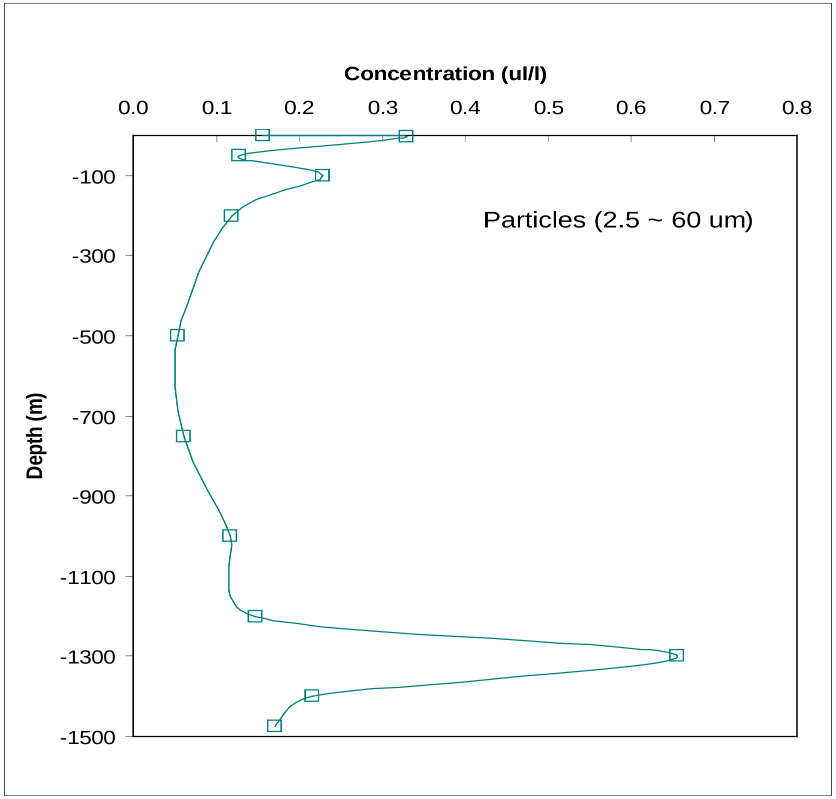

05/10/2010 - 8:40am CST
Copyright 2010 Ocean Imaging Corp.
South
East
Fresh oil continues
to Southeast





Vertical Profile - DO_2 Depression





Small particles (2.5 - 60µm) were indicative of oil droplets in the subsurface plume

Sub-lethal Impacts on Fish

Oil exposure impacted the ability of fish to face increased temperature, reduced oxygen availability or to swim against a current and these effects were further aggravated with the addition of the dispersant.

The **dispersant alone had no effect** on the ability of fish to face the challenge tests

Prof Guy Claireaux, University of Brest in France

Published in: Society for Experimental Biology (2013) Treating oil spills with chemical dispersants: Is the cure worse than the ailment?

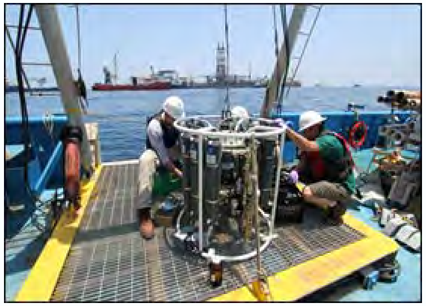
Cost / Benefit Risks

- Dispersant application represents a decision to increase the hydrocarbon load on one component of the ecosystem while reducing the load on another
- Decision involves Net Environmental Benefit Analysis (NEBA) that takes into account advantages and disadvantages of different spill response options (including no response) to arrive at a spill response decision resulting in the lowest overall environmental and socioeconomic impacts
- There are no response methods that are completely effective or risk-free

6. Improve Spill Prevention and Decision Support Systems

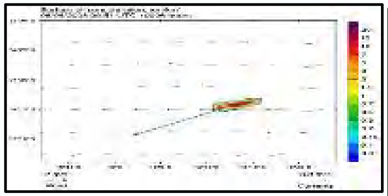
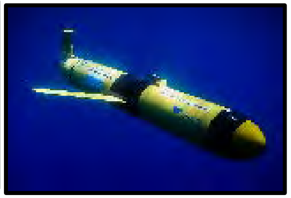
- Define parameters and ***coordinate a comprehensive national database*** to provide **data on the fate, behaviour and effects of various types of oil** spilled and the efficacy of current and emerging oil spill countermeasures over a range of environmental conditions **to support spill response decision making**

- Development of ***oil spill response decision support systems***, which can dynamically and interactively **integrate** monitoring and early warning, spill modelling, vulnerability/risk analysis, response process simulation/control, system optimization and visualization

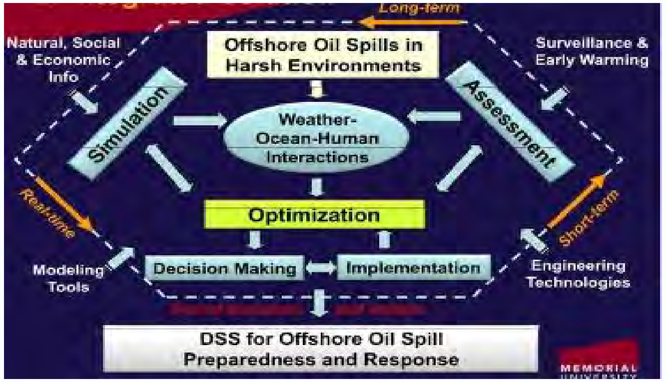


CSIRO

6. Improve Spill Prevention and Response Decision Support Systems


- ***Advance environmental forensics, remote sensing and in-situ measurement, early warning and diagnosis, and biological monitoring*** to improve spill prevention and decision making
- Develop methods for the derivation of comprehensive ***mass balances*** for spilled and recovered oil
- Develop ***modelling methods to simulate and optimize individual and collective clean-up processes*** to support response decision-making



6. Improve Spill Prevention and Decision Support Systems

Involve Indigenous peoples from all parts of Canada in the development of research protocols, in oil spill preparedness, clean-up and remediation/restoration, including long-term “spill of opportunity” investigations

- Application of ***local knowledge*** and historic conditions in preparedness planning
- Traditional use values important for ***restoration of ecosystem services***
- ***Training and employment opportunities*** regarding cleanup, restoration and monitoring
- ***Definition of benchmarks for acceptable levels of residual oil***

7. Enhancement of Oil Spill Risk Assessments in Canada

Follow-up relative risk assessments are needed to build upon the Transport Canada assessments of marine spills, focusing on high-sensitivity areas

- ***A comprehensive national database*** *with consideration of:*
  - the efficacy of oil spill countermeasures over a range of environmental conditions
  - traditional uses of resources
  - other human activities that could affect relative risk (e.g. mining)

7. Enhancement of Oil Spill Risk Assessments in Canada

Update and refine risk assessment methods:

- ***Credible spill scenarios*** relevant and comparable to actual spill incidents
- Analyses of ***seasonal differences*** in fate, transport and effects of oil (particularly for spills in winter)
- Use ***species sensitivity distributions (SSDs) and acute and chronic aquatic organism sensitivities*** for measured concentrations of total petroleum hydrocarbons and total polycyclic aromatic hydrocarbons to support risk assessments of oil spills
- ***Extend models of chronic toxicity*** to a wide array of species and environmental and life history variables
- ***Include socioeconomic impacts***, including but not limited to human health and community well-being

The Final Word

- Research should take into account Canada's unique aquatic environments and their indigenous species – focus should be placed on high-risk sites

- The Panel recommends ***coordinated multi-disciplinary research programs*** among government, industry, universities and Indigenous people to provide data towards ***a common national database network to support*** **science-based decisions** in the event of future oil spills to **ensure the protection** of our aquatic environments and their living resources