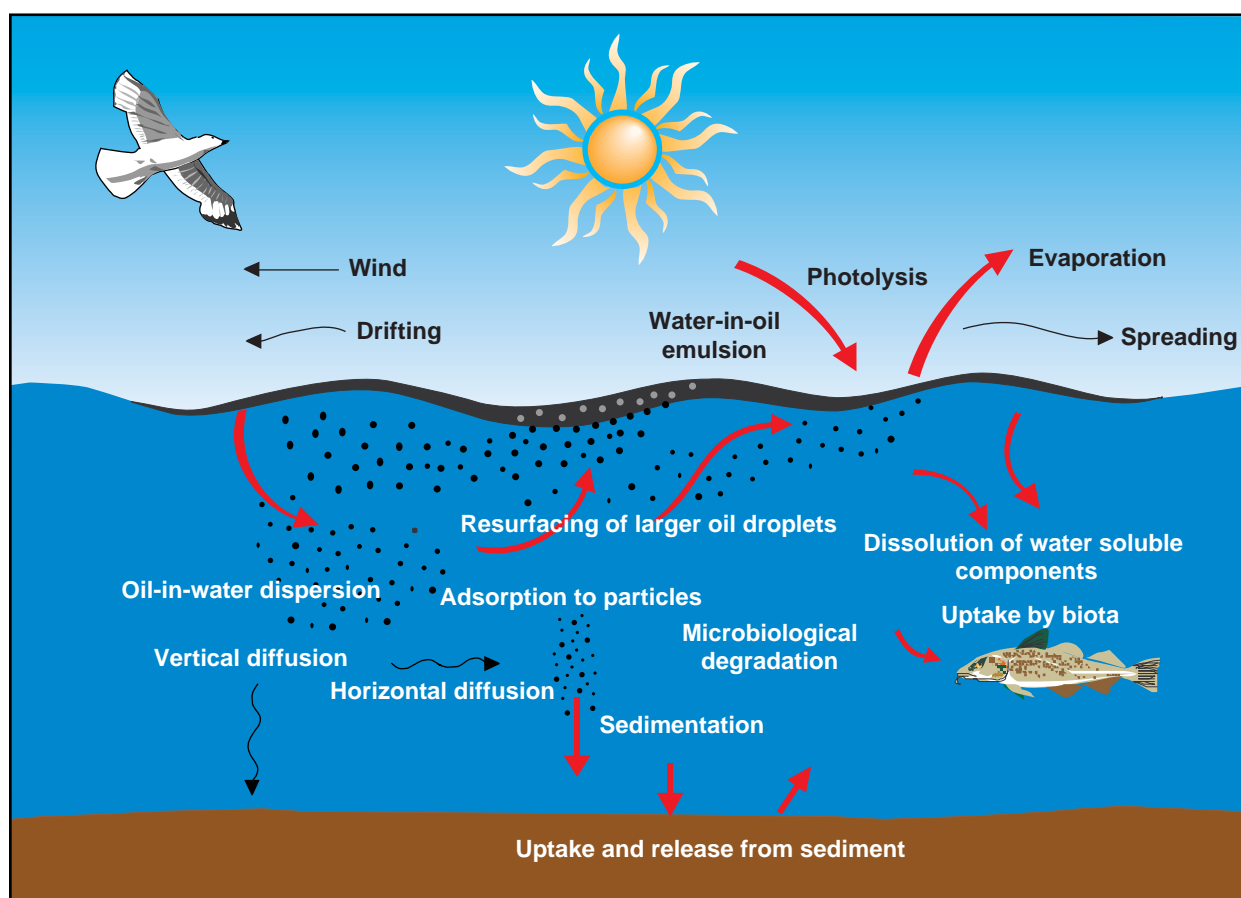# SINTEF Oil Weathering Model
User's Manual

Version 3.0

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2 September, 2004

SINTEF

Table of contents   Page

4

1. Installation

The **SINTEF Oil Weathering Model (OWM)** is delivered on a single CD-ROM, containing the model computation engine, user interface and oil type database. It requires Microsoft Windows NT. Install the **OWM** from Setup.exe from the CD-ROM, and follow the installation instructions.

2. Running the SINTEF OWM under Microsoft Windows

The SINTEF Oil Weathering Model may be started from Microsoft Windows by double clicking either the icon installed on the desktop by the setup program, or the executable file C:\OWModel\OWModel.exe.

3. Getting started: a simple scenario

When the model is started using the procedure described above, the main window appears (Figure 3.1). The main window contains a menu bar at the top, and dialog controls for a short description of the scenario, oil type and weather conditions.
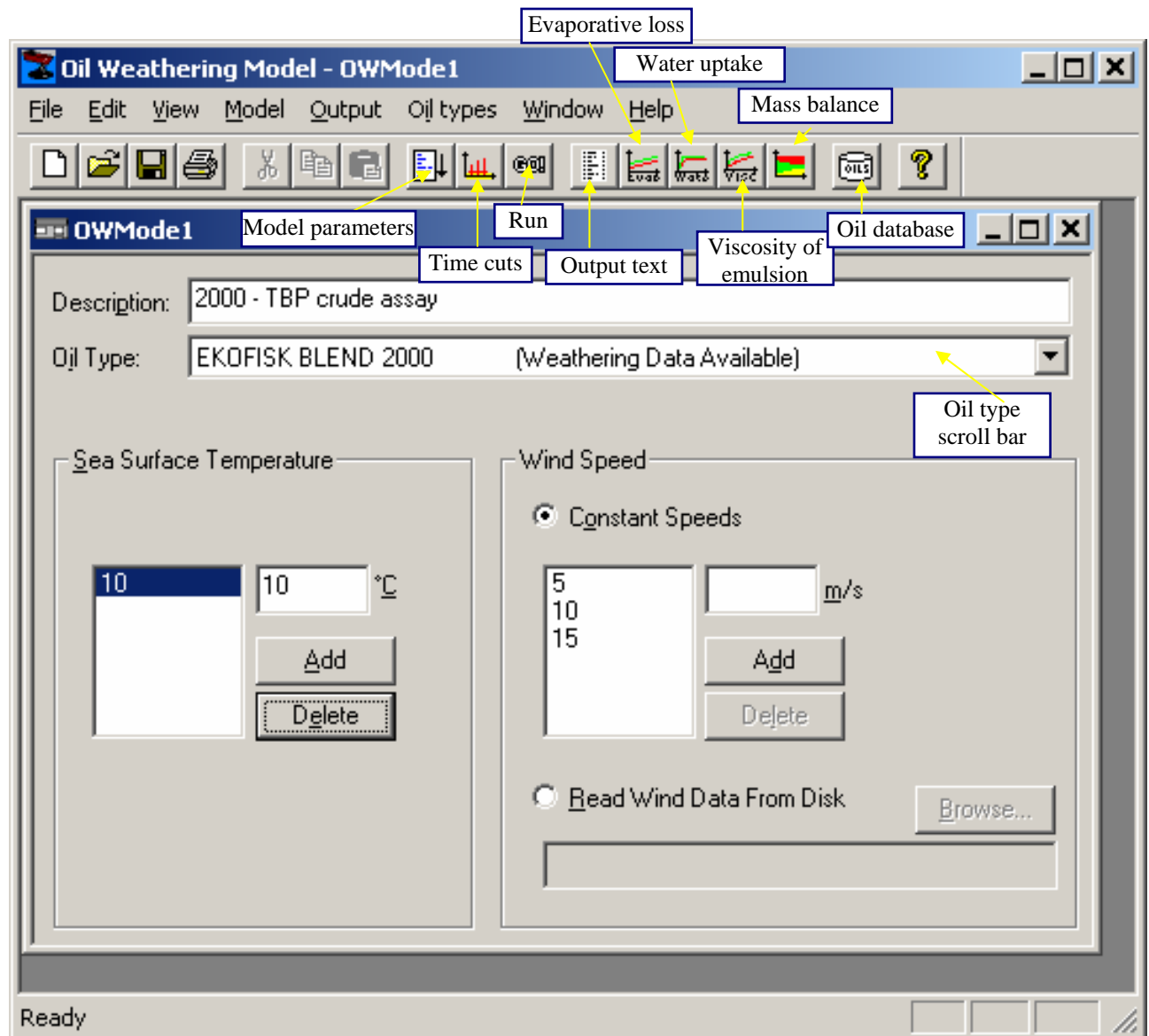

Figure 3.1.   The main window of the SINTEF Oil Weathering Model.

To run a scenario, first select an oil from the list in the *Oil Type dropdown-list*. If there is a description available for this oil in the database, it will appear in the *Description field* in the top of the dialog. If no description appears, or you want to change the description, you can type a description yourself (for example "Test case").

The model gives some default weather conditions, but one has also the opportunity to use the *Add* and *Remove* buttons to alter the sea surface temperatures and winds speeds that are required in a specific case. For example, a sea surface temperature may be added by typing the value in the blank field, and clicking the *Add* button. The specified temperature will appear in the list to the left. To remove items in either the sea surface temperature or wind speed list, highlight items by clicking, or multi-select by *<ctrl> click*, and then click on the *Delete* button. Notice that a rerun of the model computations will be necessary to see the effect of a change made in one of the lists.

In the example above, we have selected to run the model for one sea surface temperature (10 ^{o}C) and three (constant) wind speeds (5, 10 and 15 m/s). By clicking the *Go* button on the menu, we thus run 3 scenarios: 1 sea surface temperature, and 3 wind speeds for this sea temperature.To save your current scenario settings, choose *File/Save As* from the main menu.

3.1 Graphical output

Graphics displays are obtained by choosing *Output* and *Graphics* from the main menu. This brings up a menu containing the various properties calculated by the model (Figure 3.2). Click on one of them, for instance the evaporative loss, to display an x-y plot of the property as a function of time. Then go back to the main window by using the *Window menu* on top, choose one of the other properties and you can study the graphics by turn in the Window menu. Evaporative loss, water uptake, viscosity of emulsion, and mass balance are also available using buttons on the tool bar.
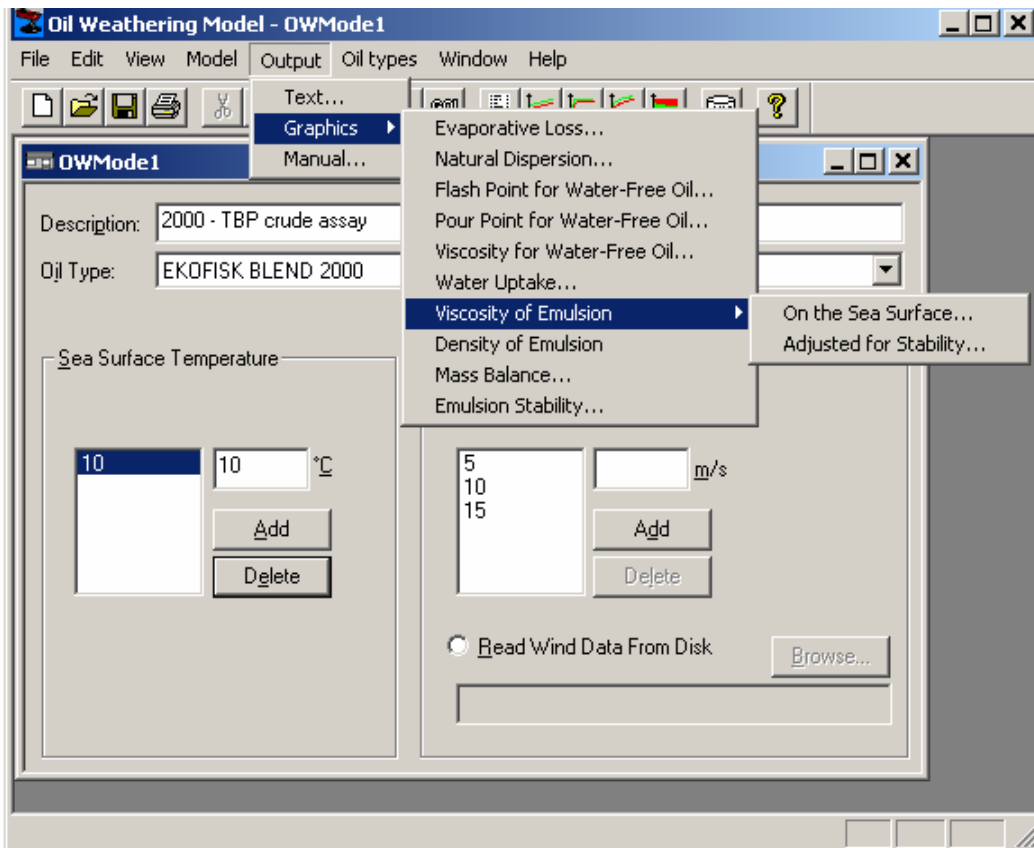

Figure 3.2   *Graphical output menu.*

Examples of the graphical output are shown in Figure 3.3 and Figure 3.4.
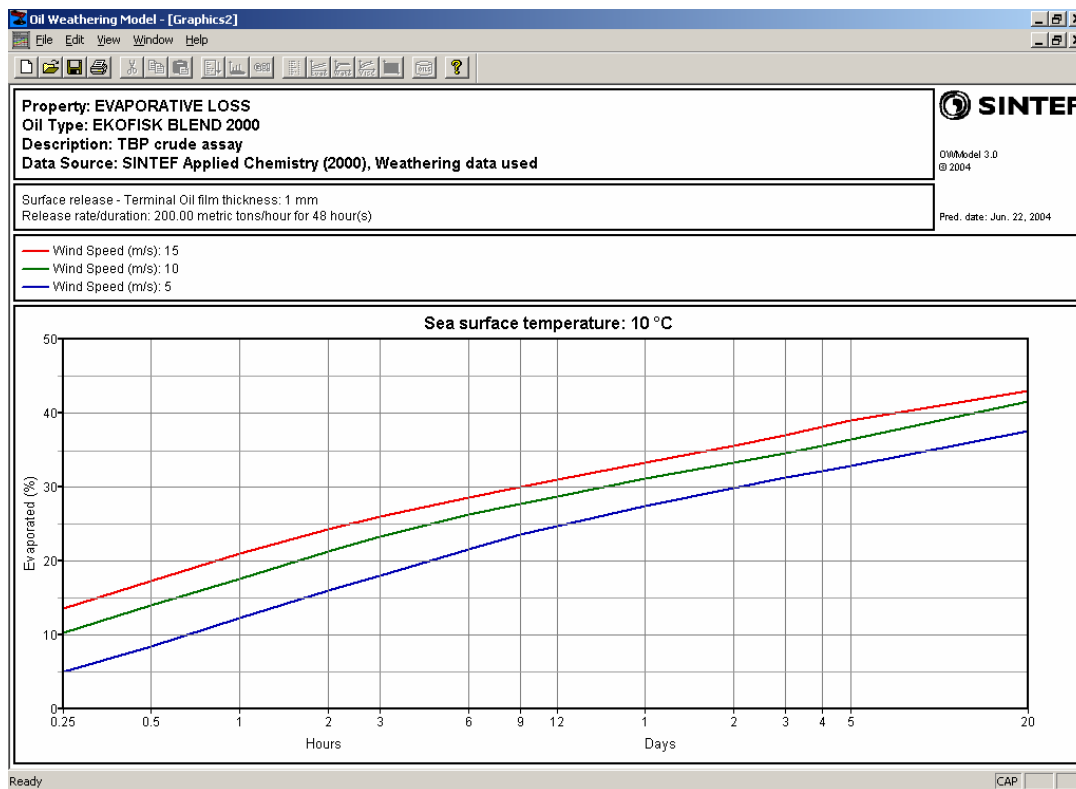

Figure 3.3   Evaporative loss, 10°C sea surface temperature and 3 wind speeds.
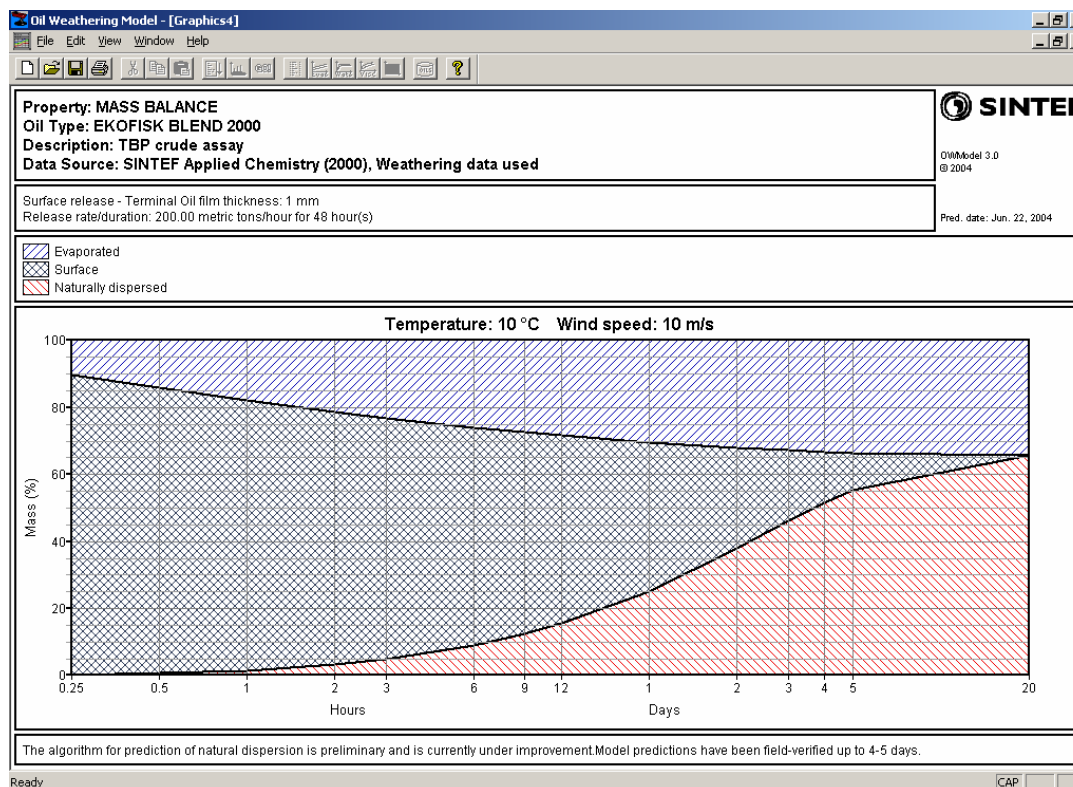
Figure 3.4   Mass balance 10°C sea surface temperature and 10 m/s wind speed.

3.2 Output textfiles (.TXT, .TX2)

The model produces a text file with a summary of input parameters, and a table with prediction results. To view this file, choose *Output* and *Text* from the main menu. As the output file shows, the model calculates several properties. These are listed in table form for the time cuts specified in the *Time Cuts form* (Section 6). You can print hardcopy of the output file by clicking the Print button. When you are finished studying the output file, click on the menu *File/Exit* to close the output window.

An example of an output text file is shown in Figure 3.5.

Figure 3.5   Output text file.

For the purpose of giving the user the possibility of making his/her own graphs of prediction results, a <scenario name>.TX2 file is generated in the same directory as the scenario file (.OWM-file); e.g. in the C:\OWModel3.0\SCENARIO directory. This file may be directly imported into Microsoft EXCEL, simply by opening it from EXCEL, and clicking *Finish* (without having to do any further specifications). By this procedure, the data table(s) "slides" directly into the actual worksheet, and the user is free to graph the fields in the preferred way.

4. Variable wind speed

In the example above, constant wind speed was used in the predictions. In an actual spill situation, however, the wind varies with time in a way that may be specified from measurements or weather forecasts. Click on the radio-button labeled *"Read Wind Data from Disk"* to enable the dropdown wind speed file list. This list works in a way similar to the scenario list. The user may either specify a new wind file in the edit box, or he may click on the *Browse* button to select an existing wind file.

A simple wind speed editor is included to create and edit wind files. Click on menu *Model/Wind Editor* to bring up the editor. The wind file editor is shown in Figure 4.1. To create a new file, it is suggested to use an existing file as a template. The first five lines in the file are header information, not used in the present version of the OWM. Each subsequent line contains a time in hours from spill start, a wind speed in meters per second, and a direction in compass degrees from which the wind comes. The wind direction thus follows meteorological convention, with 0^0 being from the north towards the south and 90^0 being from the east towards west. When one has specified the wind data for the desired period, click on the *Save As* or *Save* button to save the wind file and close the editor. Select the new wind file in the *Read Wind Data from Disk edit box*, and the model is ready to run. If you wish to re-format existing wind files for use with the SINTEF OWM, either a tab or a blank space between time, speed, and direction in each row will suffice.

Note that the OWM checks the wind file for new values at each time cut, and uses the previous wind values until a new time cut is encountered. To assure that all wind values are accounted for in a simulation, the time cuts (under the menu item Model) should match with the wind time intervals.
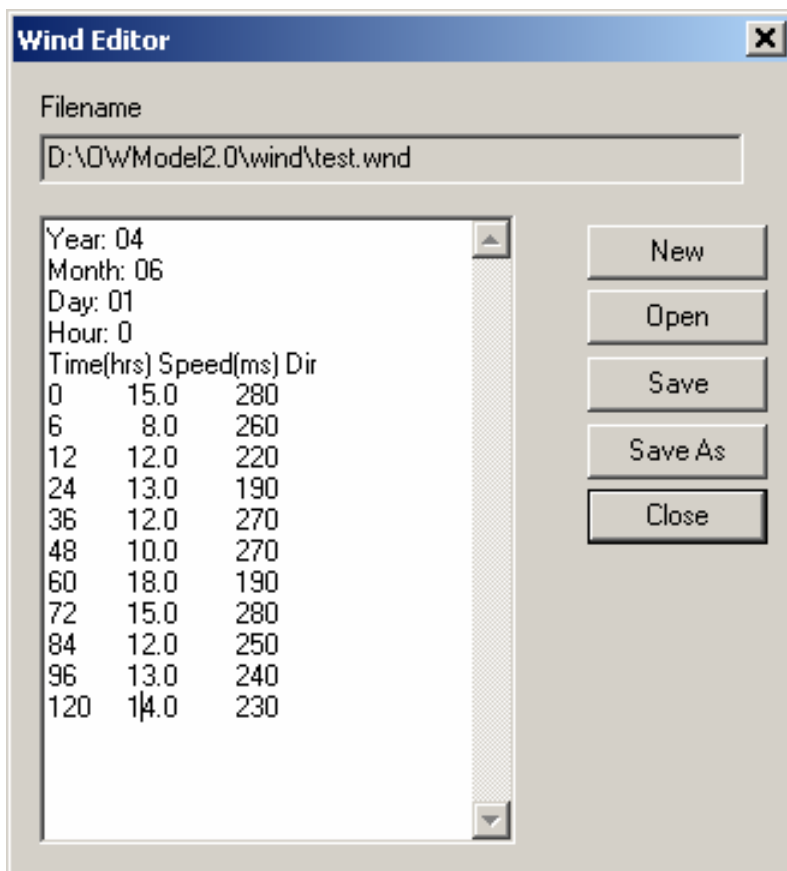
Figure 4.1   Example format for input of time-variable wind.

5. The graphics output window

Examples of the graphical output window were shown in Figure 3.3 and Figure 3.4. The menu bar of this window has several extensions in addition to the standard system menu items.
These give the user the opportunity to:

- Edit the text in the graph, *Edit/Select Caption Font* and *Select Label Font.*
- manually scale the y-axis, *View/Set Scaling*,
- put comments in the graph, *View/Edit Comments*,
- save the graph to disk, *File/Save as,*
- get hardcopies of graphs *File/Print*,
- and load an old graph from disk *File/Open*

Choosing *Edit/Select Caption Font*, brings up the window shown in Figure 5.1.
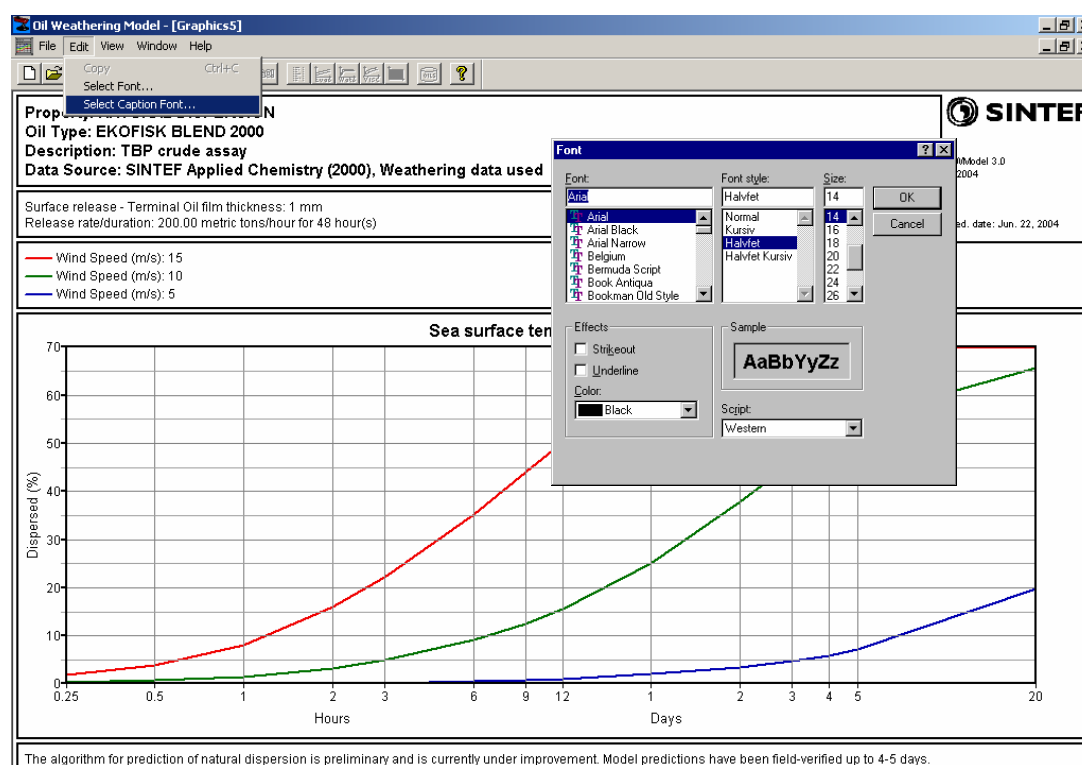
Figure 5.1   The text formatting window.

Choosing *View /Set Scaling,* brings up the window shown in Figure 5.2, where certain settings may be altered in order to customize the y-axis scale.
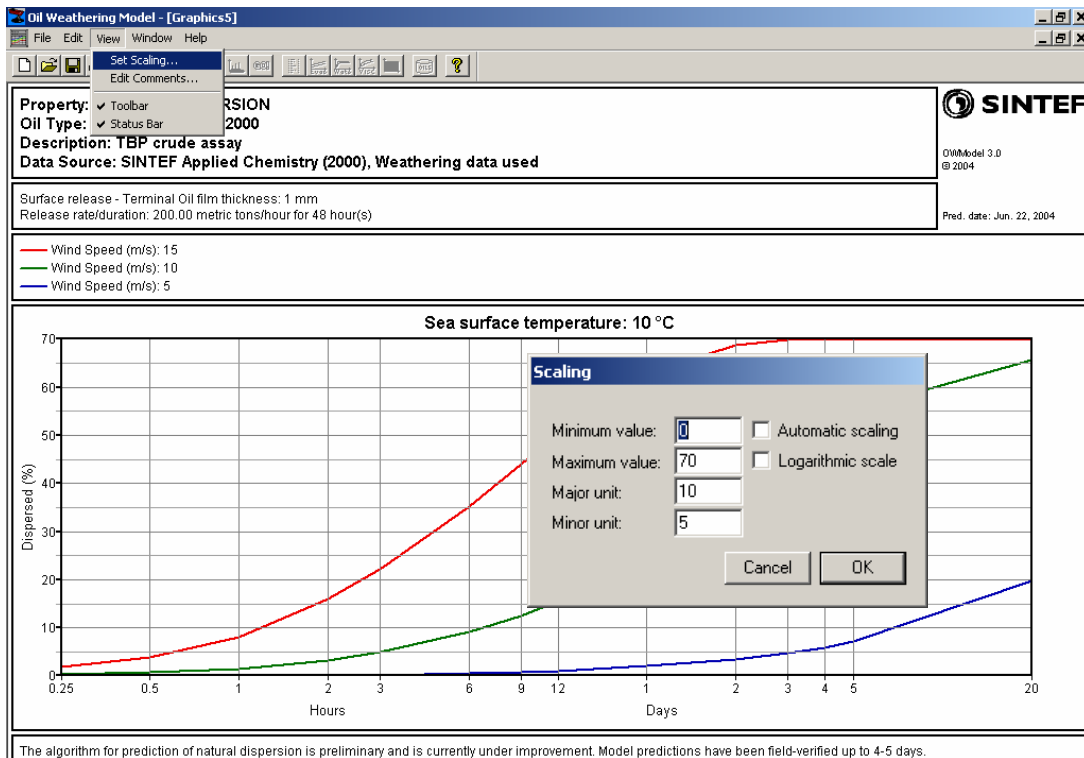
Figure 5.2   The scaling window.

Choosing *View*/*Edit Comments*... brings up the window shown in Figure 5.3.
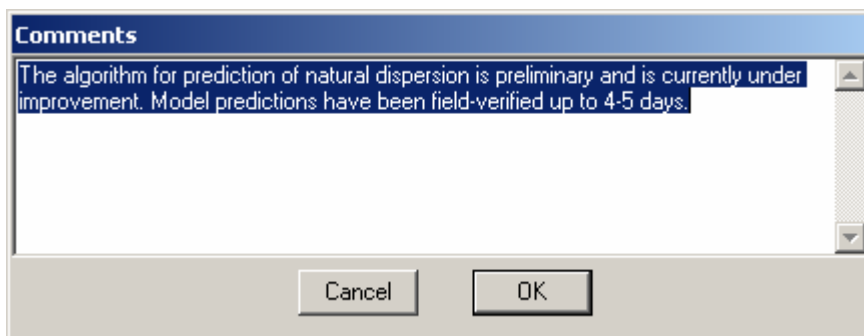
Figure 5.3   The comments editor window.

This window lets you type comments that will be displayed beneath the graph. Text will automatically wrap to the next line when a line is too long. To force a line break, type *Ctrl-Return*.

6. Changing the time window

By default, predictions are performed for the time window ranging from fifteen minutes to 5 days after the spill. The user may change this time window by selecting *Model* and *Time cuts*, in the main menu. This brings up the window shown in Figure 6.1.
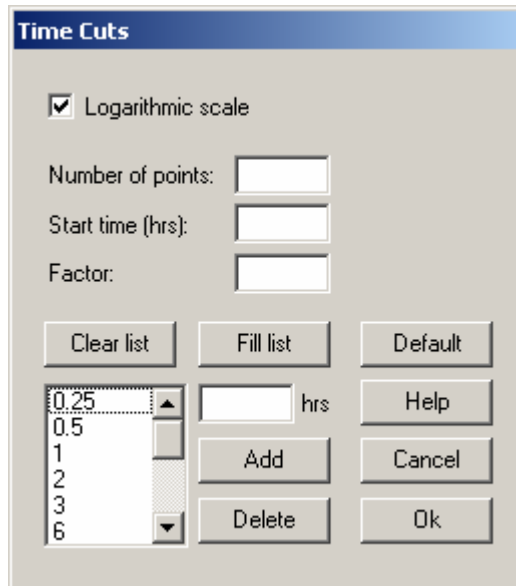
Figure 6.1   The time cuts window.

In this window the user may add and delete time cuts in the same manner as with sea temperatures and wind speeds by using the edit box and *Add* and *Delete* buttons. A utility for quickly filling the time cuts list box is also included. Here, one types the number of time cuts to use, the start time, and the step (linear scale) or factor (logarithmic scale) between succeeding time cuts into the corresponding edit controls, and then clicks on the *Fill list button*. Clicking on the *Clear list button* empties the list of time cuts. Notice that the time scale may be logarithmic or linear. The default time scale is logarithmic in order to get a higher resolution in the early stages of a spill. The maximum time for which the model can perform predictions is currently set to 480 hours (20 days).

Care should be taken when specifying the time cuts in order to obtain smooth graphs. The time cuts specify for which times the weathering state of the oil will be stored under prediction, and for which times to put numbering on the x-axis in graphs. Thus, a sufficient number of time cuts should be used to obtain a satisfactory resolution, while at the same time not making the graph crowded with numbers along the x-axis. A number of 13-20 time cuts gives visually good results. For time cuts exceeding 24 hours, the numbering along the x-axis is divided by 24 to give the time elapsed in days. Thus, the time cuts exceeding 24 hours should be chosen at an even 6, 12 or 24 hours so that the numbering along the x-axis becomes easy to interpret (1.25 or 1.5 days instead of 1.208 days and the like).

7. Changing model parameters

In addition to oil type and weather conditions, the experienced user may change a number of model parameters. By choosing *Model* and *Model Parameters* from the main menu, the window in Figure 7.1 appears.
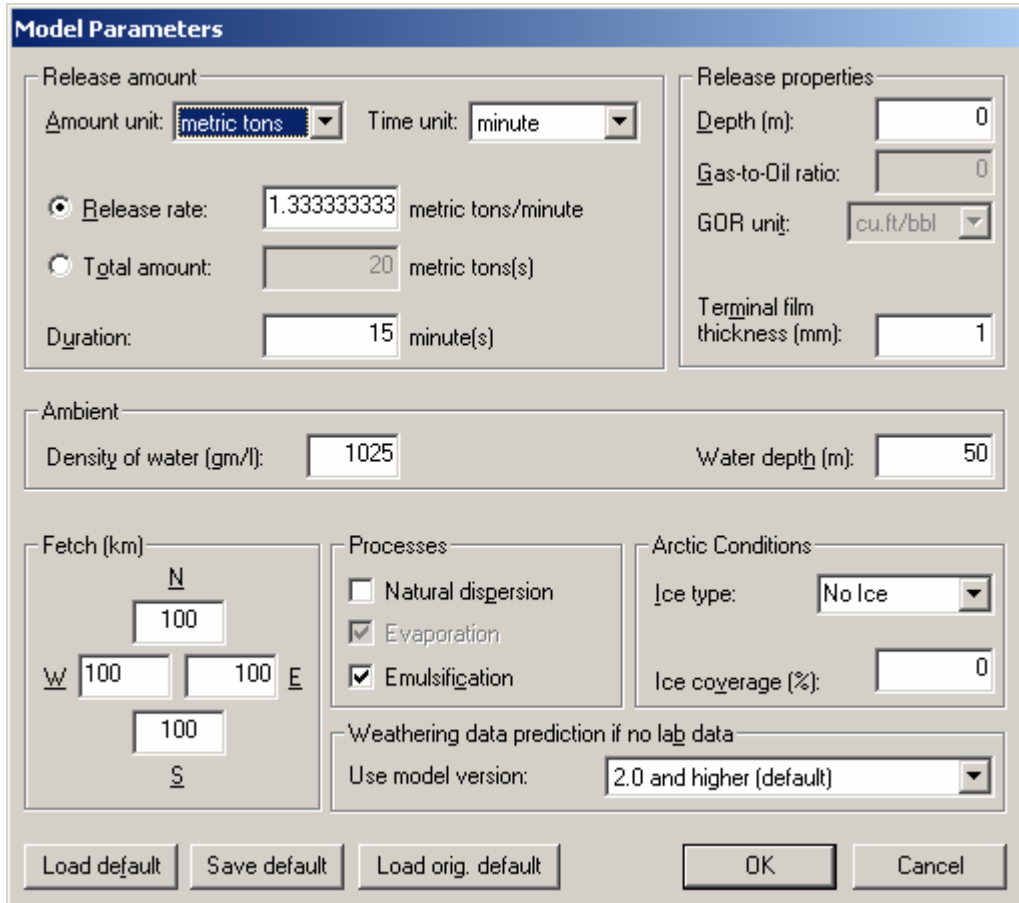
Figure 7.1   The Model Parameters window.

Terminal film thickness (default from database)
Specifies the minimum oil film thickness that the oil film will approach in the case of an oil release on the sea surface. The default value depends on the oil product selected. The value specified refers to the terminal thickness of the thick oil, not the blue sheen that appears around the edges. In the case of some petroleum products such as gasoline, the terminal thickness may equal the sheen thickness. In the case of a seabed blowout (specified by *Depth* greater than zero), the physical processes governing the film thickness forming on the sea surface are not petroleum product specific. In the latter case, the terminal film thickness is set to zero, and the respective field in the screen window is disabled.

Depth (from where the oil release occurs)
The depth of the release, in the case of an underwater release, is specified in the *Depth* field in the *Release properties section* of the screen window. By choosing a value greater than zero, the model implicitly assumes an underwater release from this depth. This also activates the *Gas-to-Oil ratio field* described below. Note that *Depth* should not be set greater than *Water depth* described below.

Gas-to-Oil ratio (GOR)
In the case of an underwater release (when the *Depth* field is set to a value greater than zero), the *Gas-to-Oil ratio (GOR) field* in the Release properties section of the screen window is activated. The GOR is a petroleum well specific value, and may vary greatly from field to field. The values may be given as a pure ratio (without denomination) or in cubic feet/bbl, specifying the volume ratio between gas and oil in an underwater leakage. The OWM 3.0 implementation assumes a regime where the dominating force regarding surfacing of the oil is gas driven (dominating the oil's inherent buoyancy). For this reason a lower limit is set for GOR; at least 10 or equivalent 56.15 cu.ft/bbl.

Release amount and duration
Amount spilled is specified in metric tons, barrels, cubic meters or liters. Duration is specified in minutes, hours, or days. The user may choose specifying either oil release *volume* and duration or oil release *rate* and duration. In the calculations, the program first calculates the rate of release in metric tons/minute, and uses this rate in all calculations.

Density of water
Specifies the density of the water in which the oil is spilled. The default value is 1025 gm/1, which is a typical value for seawater. Water density affects spreading of both fresh oil and emulsion.

Water depth
Specifies the depth of water at (and around) the spill location. The default value is 50m. This value is used by the model for calculating wave height, and needs to be changed to suit your area. Note that this value should be set greater or equal to the *Depth* of the oil release, described above.

Fetch
Specifies the distance to shore (or an ice edge) in four directions; north, south, east and west. The default value is 100 km in all directions, which corresponds to a spill in open sea. These values will influence the build-up of waves and thus the rate of natural dispersion. They need to be changed only if the spill site is very close to shore or an ice edge. Appendix D shows equations for shallow water significant wave prediction curves as functions of wind speed, fetch length, and wind duration, and depth (based on the U.S. Army Corps of Engineers <u>Shore</u> <u>Protection</u> <u>Manual</u>, 1984).

Processes: natural dispersion, evaporation and emulsification
These are on/off buttons for the three processes calculated by the model. The *Evaporation button* is always turned on (cannot be turned off), but the other two may be turned on or off to study their individual effects on the oil spilled at sea. By default, all processes except natural dispersion are turned on.

Arctic conditions
Data from a full scale field trial in the Arctic ice south of Svalbard (Spitsbergen) in the Barents Sea have been used to calibrate spreading, natural dispersion, evaporation and emulsification in the presence of ice blocks, or thick (> 0.5 m) sheet ice. The presence of sea ice reduces the spreading rate of the oil, which in turn reduces the evaporation rate (and increases the thickness). The ice also damps wave activity, which reduces both natural dispersion and emulsification.

7.1 Viewing oil database contents

The oil type database is designed to contain fresh oil properties, boiling point curve, laboratory weathering data and properties of cuts for an arbitrary number of oil types. To load and view information on a specific oil type follow these steps:

Select the oil type from the oil type drop down list in the main window.
Select *Oil types* and *Oil Properties* from the main menu (Figure 7.2).
Select the type of information you want.
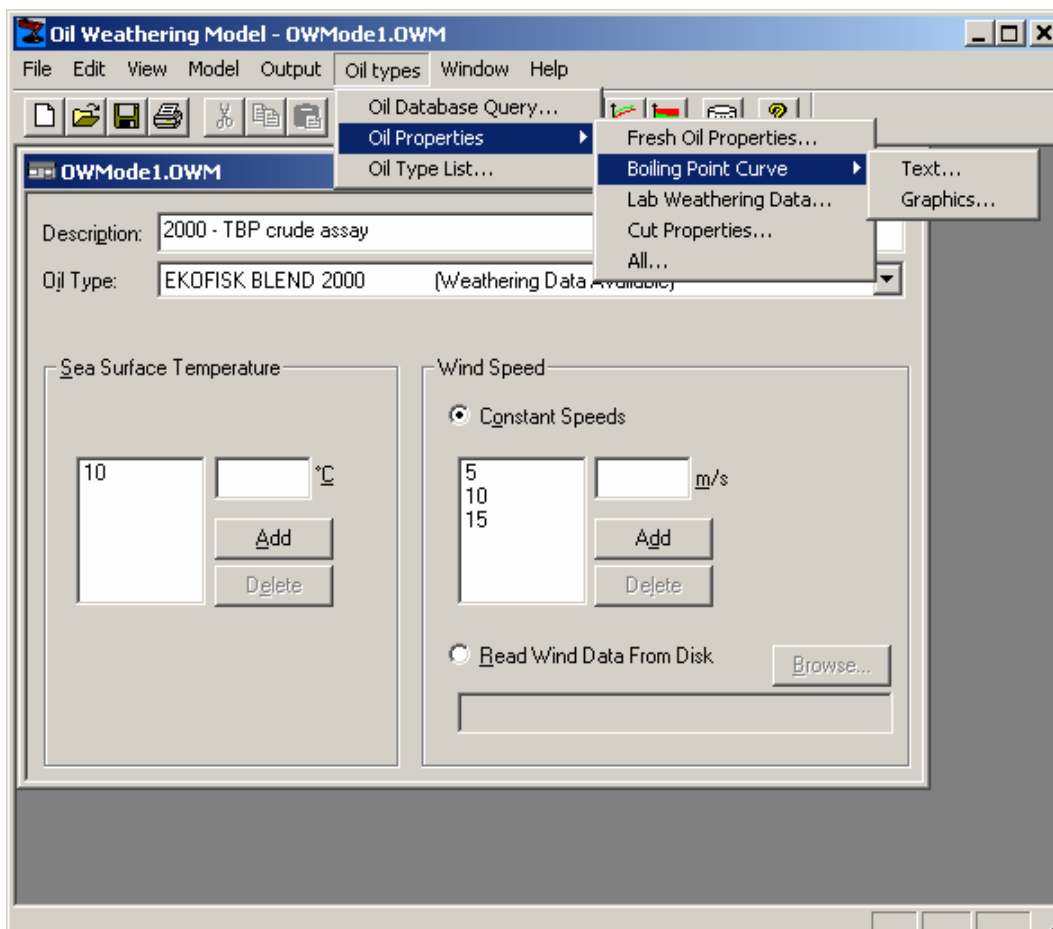
Figure 7.2   Oil properties window.

The selected information is displayed in a dedicated text editor shown in Figure 7.3, and may be altered, copied or printed. Alterations to the text are made possible so that the user may prepare printouts, for example a subset of the information. These alterations will not be stored in the database. The boiling point curve may be viewed in graphics as well by choosing the button labeled *Graphics*, in the editor window.

Laboratory weathering data presently exists for about 50 crudes and 15 refined products. However, predictions may be performed based merely on the standard crude assay for an oil type. This allows predictions to be performed for all the oil types in the oil database, but with results being less accurate for the oil types for which no laboratory weathering data exist.

```
TMP.TXT - Notepad
File  Edit  Format  Help

Product Name: EKOFISK BLEND 2000
Product Type: CRUDE
Location:     NORTH SEA
Data Source:  SINTEF Applied Chemistry
Year:         2000


Boiling point curve:
--------------------


Temp.(°C) Volume(%) Weight(%)
---------------------------
   65.0      0.82
   80.0      3.78
  100.0      8.57
  120.0     12.23
  155.0     18.83
  170.0     21.73
  190.0     25.19
  210.0     28.57
  230.0     32.13
  250.0     36.07
  275.0     40.86
  300.0     45.35
  335.0     52.32
  375.0     57.97
  400.0     61.70
  425.0     65.43
  450.0     69.16
```
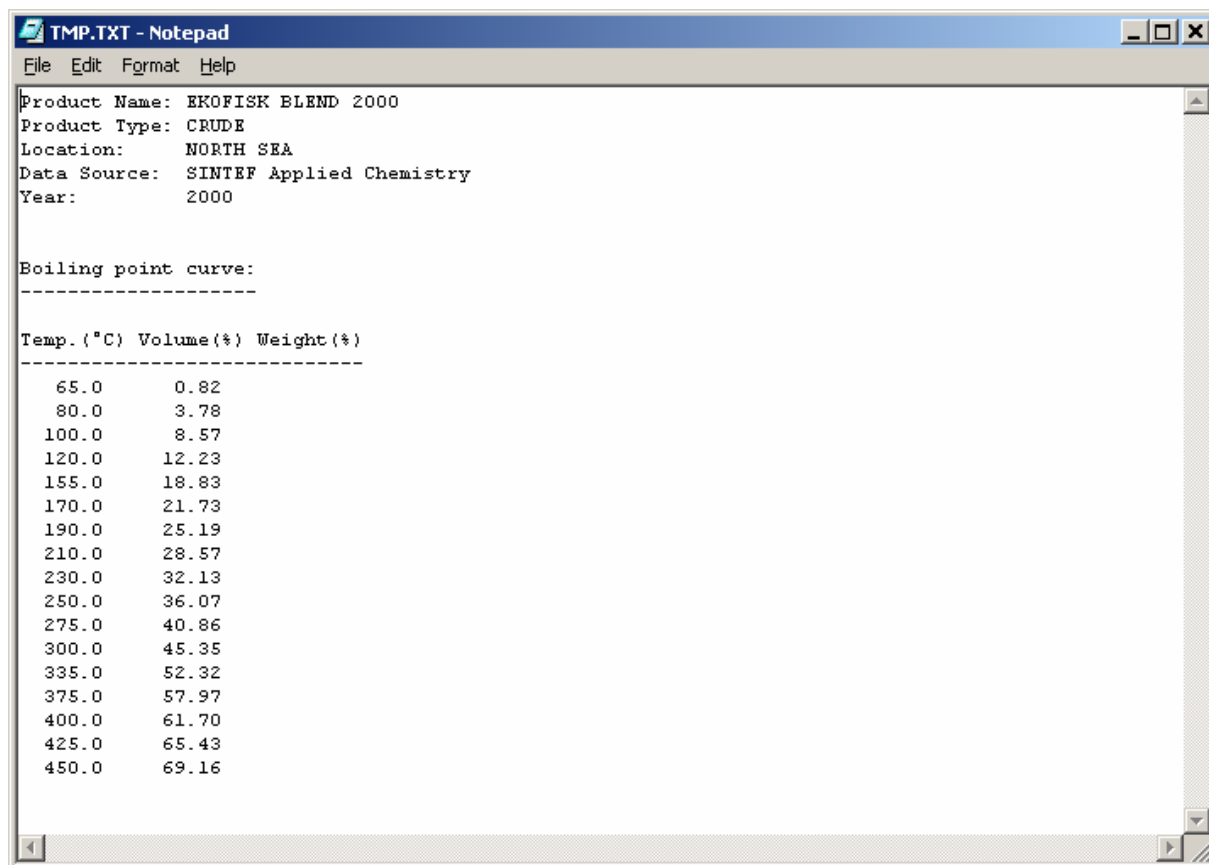
Figure 7.3   Example of information from the text editor.

7.2 Setting filters on the oil database

The oil type database contains about 200 crude oils and refined products, mostly taken from the HPI Crude Oil Assay Handbook (1987). Although these are ordered alphabetically, the list is sometimes difficult to navigate. For this reason, a database filter utility has been included. Choosing Oil types *and* Oil database query, *from the main menu, brings up the window shown in* Figure 7.4:
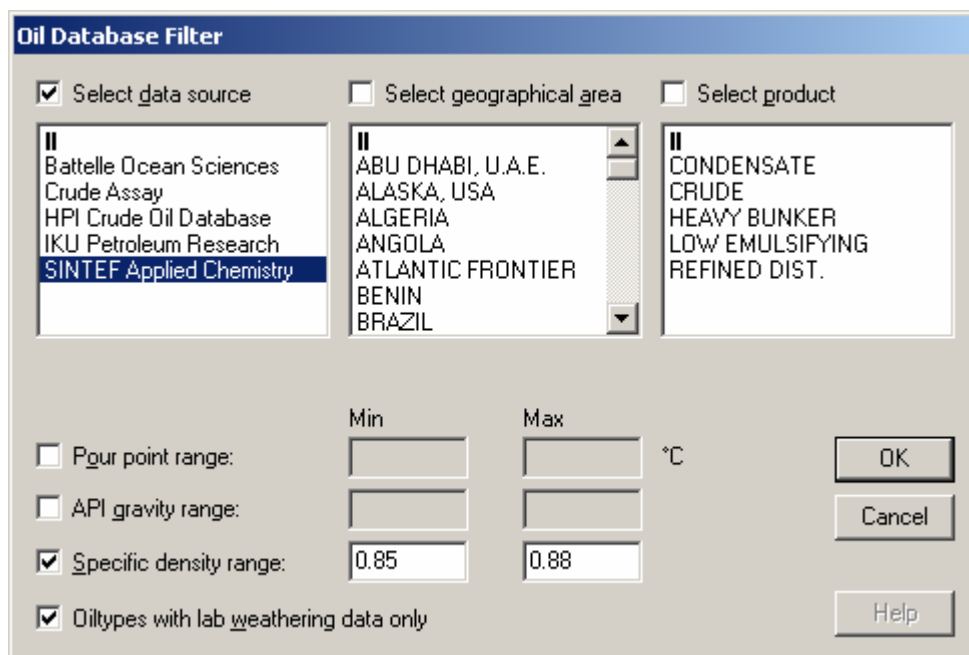
Figure 7.4   The oil database query window.

Filters may be set on seven different properties (and combinations of them):

- Data source
- Geographical area
- Product type
- Existence of weathering data (laboratory analysis results)
- Pour point range
- API gravity range
- Specific gravity range

A filtering by data source, geographical area and product type is set by clicking on a line of text in one of the list boxes. For example, if you click on Alaska, USA in the geographical area list box, only oil types from this location will be visible in the oil type dropdown list in the main window. If you also click on HPI Crude Oil Database in the data source list box, and CRUDE in the Product list box, only crude oils from Alaska and provided by the HPI Crude Oil Database will be visible in the oil type dropdown list.

The filter also gives the possibility of selecting oils within a specific pour point range and/or gravity range (either API or specific gravity). This is done, simply by putting a tick-mark in the box to the left of the according range box(es), and specifying the desired range(s) in the *Min* and *Max* fields.
If the user furthermore wants to restrict the selection of oils to those with lab weathering data, this may be done by putting a tick-mark in the box to the left of the text *"Oiltypes with lab weathering data only"*.

If the user wants to The contents of the oil type dropdown list may be sent to a printer device by selecting *Oil type* and *Oil type list* from the main menu.

8. Making graphics for standard SINTEF manuals

A special tool for making graphics for the standard SINTEF Oil Weathering Manuals is designed to quickly get printouts of all the properties predicted by the model. The window for defining characteristics of manual graphics is brought up by selecting *Output* and *Manual..* from the main menu. This window is shown in Figure 8.1
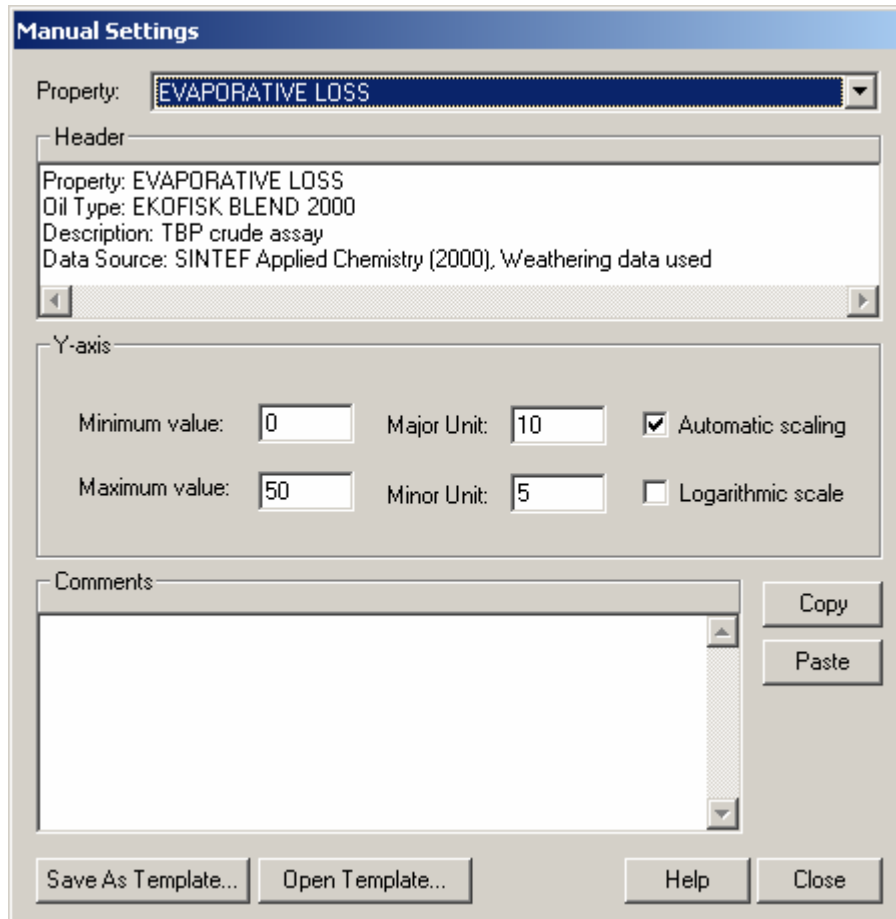
Figure 8.1   *The manual window.*

The Manual window lets the user edit the header, customize the y-axis, and add comments to the various oil properties calculated by the model.

The dropdown list at the top of the window lets the user select one of the available properties. The graph header, y-axis scaling and comments for this property will then be loaded and displayed, and the user may alter these as he pleases.

The utilities for customizing the y-axis and typing comments work as described in Section 5, but some extra facilities have been added to the comments editor. These are represented by the buttons along the right and lower edge of the comments edit box. The two upper buttons let the user copy or paste text to and from the Windows clipboard. The two lower buttons let the user save the text in the comments edit box to a text file, or load a text file into the comments edit box.

The edit box for the graph's header is similar to the comments editor, except that words don't wrap to the next line when the line is to long. Instead the text automatically scrolls to the left. However, if the lines are too long, they will be clipped when sent to the printer for hardcopies.

Although this tool is intended for creating standard SINTEF Manual graphics, which use four constant wind speeds and two sea surface temperatures, it may just as well be used for other configurations, including variable wind speed.

To print graphics, select *File* and *Print*. Then select the specific properties one wants to print. To create a graphics file (Windows Metafile format) for use in reports or other documents, select *File* and *Export to Metafile*.

9. Coupling the SINTEF oil weathering model to oil drift models

It is possible to link the SINTEF Oil Weathering Model to oil drift models through a common block that allows the programs to share information characterizing oil patches or spillets. This capability, described further in Aamo et al. (1993; Appen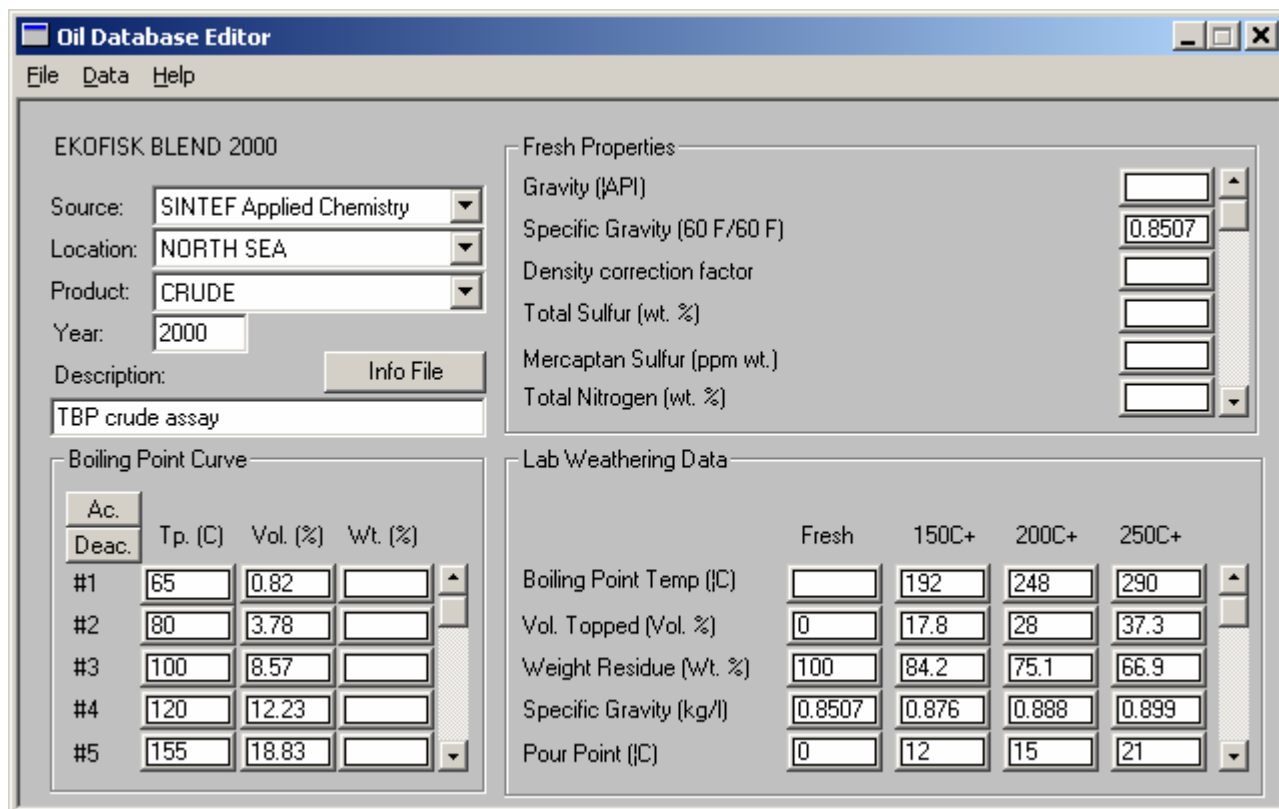dix E), requires some cooperative effort with the developers. Contact SINTEF Materials and Chemistry, Marine Environmental Technology, for further information.

10. Editing oil database

By using the oil database edit utility, OILDBED, the user may add, delete and change data on existing oil types as well as entering new oil types. The oil data base editor is started from Microsoft Windows by double clicking either the icon installed on the desktop by the setup program, or the executable file C:\OWModel\OILDBED.exe. The Main window is shown in Figure 10.1.

Figure 10.1 Main window of oil database editor.

10.1 Editing data on existing oils and create new oils in the database

To edit data on existing oils in the database, select *File/Open* and choose an oil from the list. The data for the selected oil type will appear in the main window and editing can be done. The editing is done in accordance with the description of how to add oils to the database (chapter 10.2) below. Choose *File/Save* before closing (and saving changes) of existing oils and *File/Save As* and give new oil type name before closing (and saving) the new oil type. If the user wants to filter out a selection of oils just press the *Filter* button in the *File/Open* screen window This will bring up the filtering menu for which the use is described in chapter 7.2 above.

10.2 Add oil types to database

To add oil types to the database select *File/New* and type the new oil type name. This name will appear in the oil type selection list. The main window (fig. 10.1) will appear on the screen (with

blank data fields). The Main window includes fields for entering oil type descriptions, true boiling point curves, fresh oil properties and data from weathering analysis. Use *Tab* or *left-click* with the cursor to move from one field to another. Use **period** as decimal point.

10.2.1 Fields for entering oil type description and source

Fields for entering oil type description and sources are listed below:

Source:

Select (laboratory) source from the *Source scroll menu*. If the relevant source does not appear in the list select *Data/Source* on the menu bar, add the source name and eventual extra description in the Description field, and close the source window. Fig 10.2 shows the screen window for adding new source data.
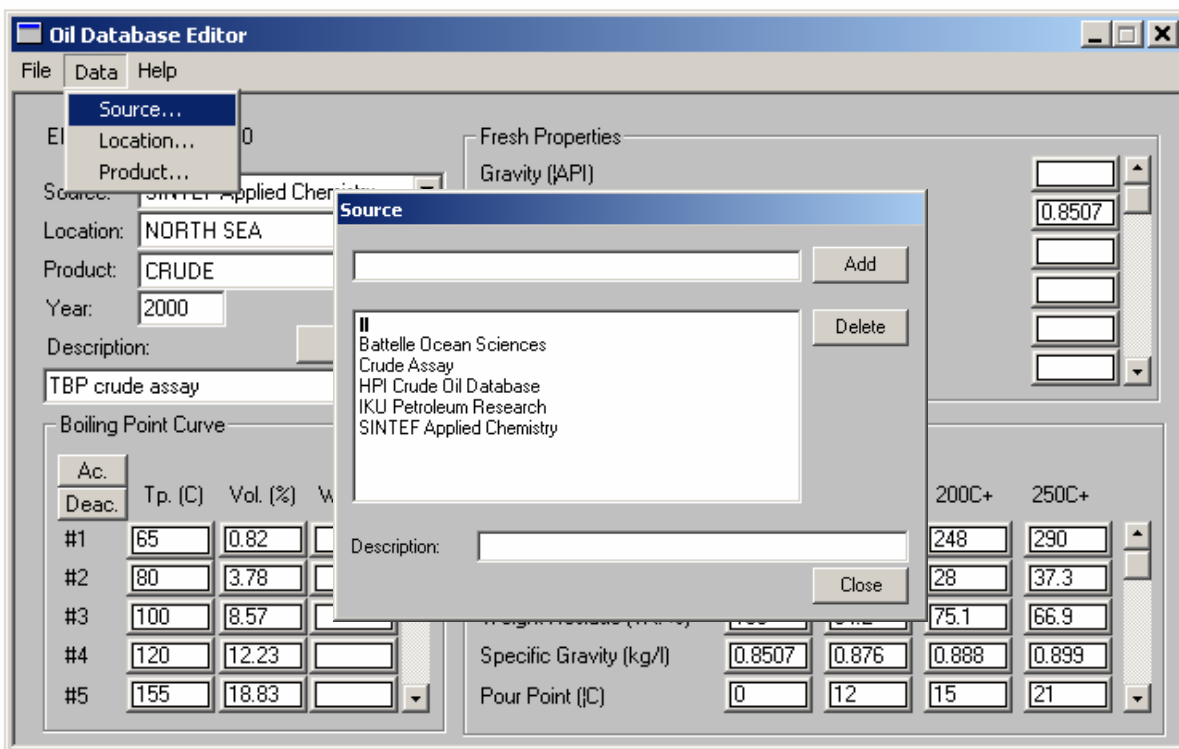
Figure 10.2   Adding new source data.

Location (region):

Select the region location from the scroll menu. If the region location does not appear in the list, select *Data/Location* on the menu bar, and add the new location similar to the procedure described for adding new source data above.

Product:

Select product (type) from the scroll menu. Selection of a product (type) will initialize the default terminal film thickness for OWM predictions using this product. If the relevant product does not appear in the list, select *Data/Product* on the menu bar, and add the new product similar to the procedure described for adding new source data above.

Year:

Enter the year the analysis has been prepared or added to the oil database.

Description:
Describe the history of the data like e.g. "data from XXX 1999 have been updated with TBP data from 2002". Descriptions, that do not fit inside the Description field, may be added using the *Info File button*, which opens a description text file for entering free textual information (e.g. oil company, date of sampling etc), to be saved together with the actual oil type.
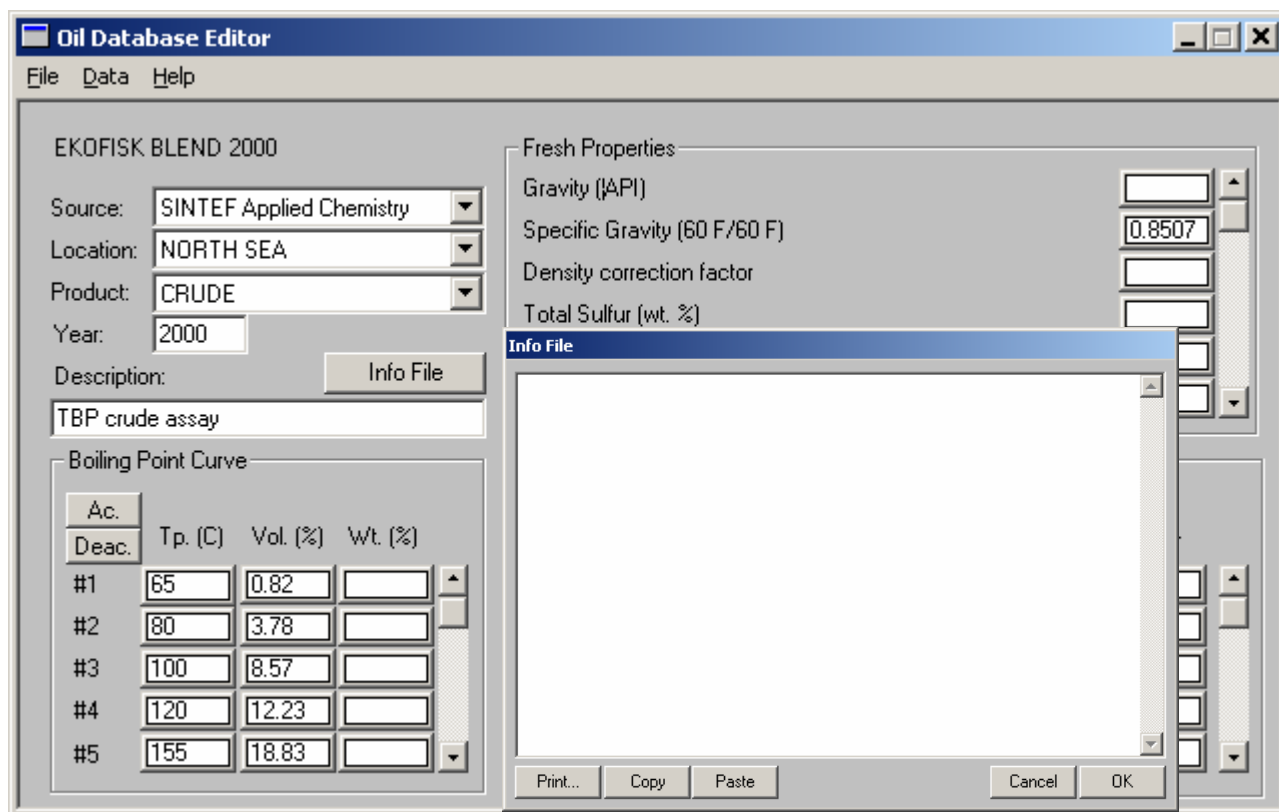
Figure 10.3   Adding extra information for the actual oil type.

11. References

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12. Index

13. Glossary

Blue sheen
The part of an oil slick that is very thin (just a few microns).

ik41961100/tegner/fig-eng/sheen.eps
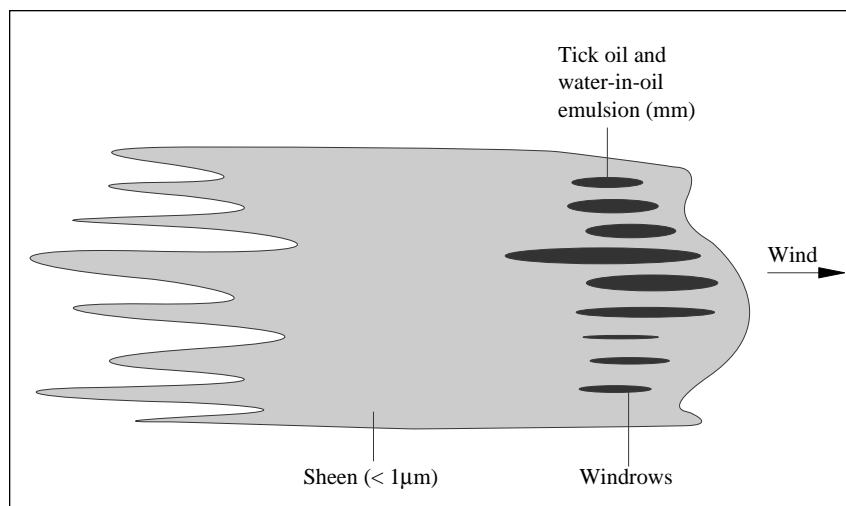
The properties predicted by the model are those of the thick part of the slick.

Emulsification
The process of mixing water-droplets into the oil, forming an emulsion.

Emulsion
Refers to a water-in-oil emulsion, where water droplets of varying sizes are mixed into the oil. This water/oil mixture has properties that are quite different from the water-free oil.

Evaporation
The process of releasing lighter fractions of the oil to the atmosphere as vapor.

Natural dispersion
The process of oil going into the water column as droplets of varying sizes. Induced primarily by breaking wave activity.

Viscosity ratio
A number giving the ratio between the viscosity of the emulsion and the viscosity of the corresponding water-free oil:

$$r = \frac{\mu}{\mu_o}$$

where
μ = viscosity of emulsion
μ_o = viscosity of water-free oil

Stability

An emulsion is considered completely stable if no water separates out after 24 hours of setting. The dehydration D of an emulsion is simply

$D = (WOR_{ref} - WOR_{24})/WOR_{ref}$

where WOR is the water-to-oil ratio in the emulsion, and the subscripts ref and 24 refer to the reference emulsion and the emulsion after 24 hours of settling, respectively. The stability S is then 1 – D, so that a stability of 1 corresponds to a completely stable emulsion (D = 0).

Appendix A: Table of the Beaufort Wind Scale

Beaufort Scale number	Description	Wind speed	
		m/s	**kts**
0	Calm	0-0.2	1.0
1	Light air	0.3-1.5	1-3
2	Light breeze	1.6-3.3	4-6
3	Gentle breeze	3.43.4	7-10
4	Moderate breeze	53-7.9	11-16
5	Fresh breeze	8-10.7	17-21
6	Strong breeze	10.8-13.8	22-27
7	Near gale	13.9-17.1	28-33
8	Gale	17.2-20.7	34-40
9	Strong gale	20.8-24.4	41-47
10	Storm	24.5-28.4	48-55
11	Violent storm	28.5-32.6	56-63
12	Hurricane	$\geq$32.7	$\geq$64

Appendix B: Step-wise instructions for running the SINTEF Oil Weathering Model

1.   Double-click on the SINTEF Oil Weathering Model icon, or on the executable file OWModel.exe. The main window of the model now appears.

2.   Type a description into the description edit field.
     Choose an oil type by clicking on the arrow at the right of the oiltype box, and then selecting from the list that appears.
     Type a sea surface temperature into the temperature edit box and click on the Add button (or select and delete one or more default values)
     Type a wind speed into the wind speed edit box, and press the Add button (or select and delete existing values).

3.   Choose "Run" from the Model menu to perform predictions.

4.   Choose "Graphics" and 'Evaporative loss' from the Output menu to view resulting graphics.

5.   Double-click on the icon in the upper-right-hand corner of the graphics window to close it.

6.   Repeat 6 and 7 for other graphs of interest.

7.   Double-click the icon in the upper-left-hand corner of the main window to close the SINTEF Oil Weathering Model.

Appendix C: Technical documentation

The model calculates four physical processes; spreading, evaporation, oil-in-water dispersion and water-in-oil emulsion formation.

C.1   Spreading of surface spills

Force balance

The force balance equations may be derived for an oil slick in a channel with a counter flow in the underlying water, i.e. corresponding to an oil slick confined by a boom (Figure C1). On this basis, a relationship is obtained between the density and volume of oil confined by the boom, and the strength of the counter current.
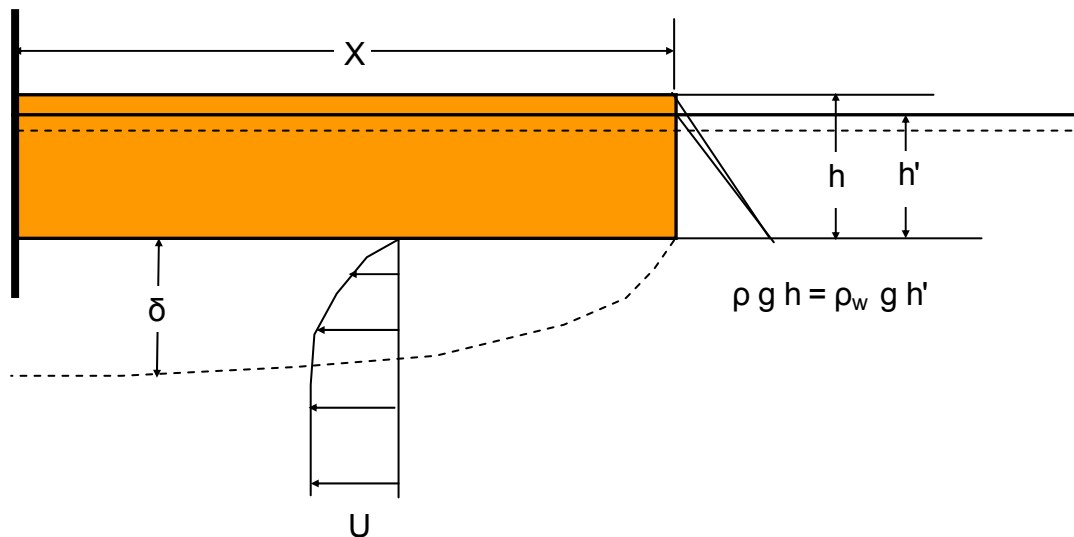
Figure C1. Idealised view of oil spreading against a counter flow in a channel.

The pressure force F_p is due to the density difference between oil and water:

$$F_p = \frac{1}{2} B h^2 \rho \, g'$$

(1)

where B (m) is the width of the channel, h (m) is the oil film thickness, ρ (kg/m^3) is the oil density, and g' (m/s^2) is the reduced gravity: $g' = g(\rho_w - \rho)/\rho_w$.

The shear force F_s is due to the friction between the oil and water in motion:

$$F_s = B X \mu_w \frac{U}{\delta}$$

(2)

where X (m) is the length of the oil layer, μ_w (Ns/m^2) is the dynamic viscosity of water, U (m/s) is the water velocity, and δ (m) is the thickness of the boundary layer in the water.

The latter may be expressed by the Blaussius formula for flow around a flat plate:

$$\delta = 3 v_w^{1/2} \sqrt{\frac{X}{U}} \tag{3}$$

where v_w (m²/s) is the kinematical viscosity of water. $v_w = \mu_w / \rho_w$.

Spreading equation

By taking into account that the confined oil volume is $V = B\,X\,h$, substituting for the boundary layer thickness, and equating the two forces, the following expression is derived for the equilibrium length of the oil layer:

$$X = \left[\frac{3}{2} \frac{V^2 \rho\, g'}{B^2} \right]^{\frac{2}{5}} \left(\rho_w \mu_w \right)^{-\frac{1}{5}} U^{-\frac{3}{5}} \tag{4}$$

If the oil is spreading on stagnant water, the velocity U may be presumed to represent the spreading velocity, i.e. $U = dX/dt$. Equation 4 will then be transformed into a separable differential equation in t with the solution:

$$X(t) = 1.3 \left(q^2 \rho\, g' \right)^{\frac{1}{4}} \left(\rho_w \mu_w \right)^{-\frac{1}{8}} t^{\frac{3}{8}} \tag{5}$$

where $q = V/B$, i.e. volume of oil per unit width of the channel.

By use of the mass conservation equation $q = X\,h$, equation 5 may alternatively be expressed in terms of the film thickness h, and be transformed into a suitable differential form which may account for changes in the oil properties with time:

$$\frac{d}{dt} X^{4/3} = 1.75 \left(h^2 \rho\, g' \right)^{\frac{2}{3}} \left(\rho_w \mu_w \right)^{-\frac{1}{3}} \tag{6}$$

This differential equation may be combined with any oil mass conservation equation relating h and X to the oil volume, i.e. any equation of the type $V = f(t, h, X)$. It should be noted that a conservation equation may also account for changes in the oil volume with time due to evaporation or emulsion formation. Excluding this for the moment, we may illustrate the concept by a few examples:

- For lateral spreading of a slick formed from a continuous surface leak with a discharge rate m (m³/s) in a steady surface current of velocity u (m/s), the oil conservation equation may be written as $q = m/u = 2\,h\,X$, where X represents the half width of the slick.

- For an instantaneous spill, the conservation equation may be written as $V = \pi X^2 h$, where V (m³) is the spilled oil volume and X represents the radius of the circular slick.

- For a continuous leak on calm water, the same equation applies, but V will be increasing with time; $V = m\,t$, where m (m³/s) is the release rate.

For a continuous leak from a point source in a steady current, the oil volume will also increase in proportion with time. In this case, gravity spreading will take place along two axis (cross-stream and downstream), but the cross-stream (lateral) component is conventionally presumed to dominate as the slick is extended downstream due to advection with the current. This assumption may be valid in cases with relatively strong currents and moderate spill rates. For weak currents and large spill rates, gravity spreading may have to be considered along both axis to get a realistic picture (see Figure C2).
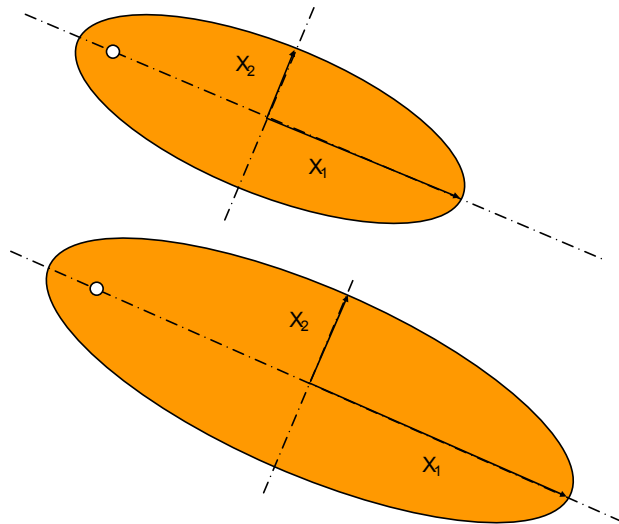
Figure C2. Spreading of an oil slick from a continuous oil leak in a steady current. The slick may be defined in terms of X_1 and X_2, representing half axis of an elliptical slick, with X_1 aligned in the downstream direction. The oil conservation equation may then be expressed as $V = m t = h \pi X_1 X_2$, where m (m³/s) is the spill rate. The progression of X_1 and X_2 may be computed by equation 6, while including an extra downstream elongation due to the current ($dX_1 = 0.5$ u dt) in the period of time when the oil is leaking.

The approach sketched in Figure C2 is in fact unifying all the "classical" Fay spreading problems, from instantaneous spills, via continuous spills on calm water to continuous spills in a steady current (Fay 1969, Fanneløp and Waldman, 1972). Figure C3 illustrates this concept for two cases. The same amounts of oil are released in both spills (2400 m³), but the duration of the release is 2 hours in the first case (a), and 24 hours in the second case (b). The oil density is 850 kg/m³ in both cases, and the surface current is presumed to be moderate (10 cm/s). The results show that the calculations for the first case approaches Fay's equation for radial spreading on calm water, while the second case approaches Fay's equation for lateral spreading of a continuous spill in a steady current.

Release 2400 m3 in 2 hours

Release 2400 m3 in 24 hours
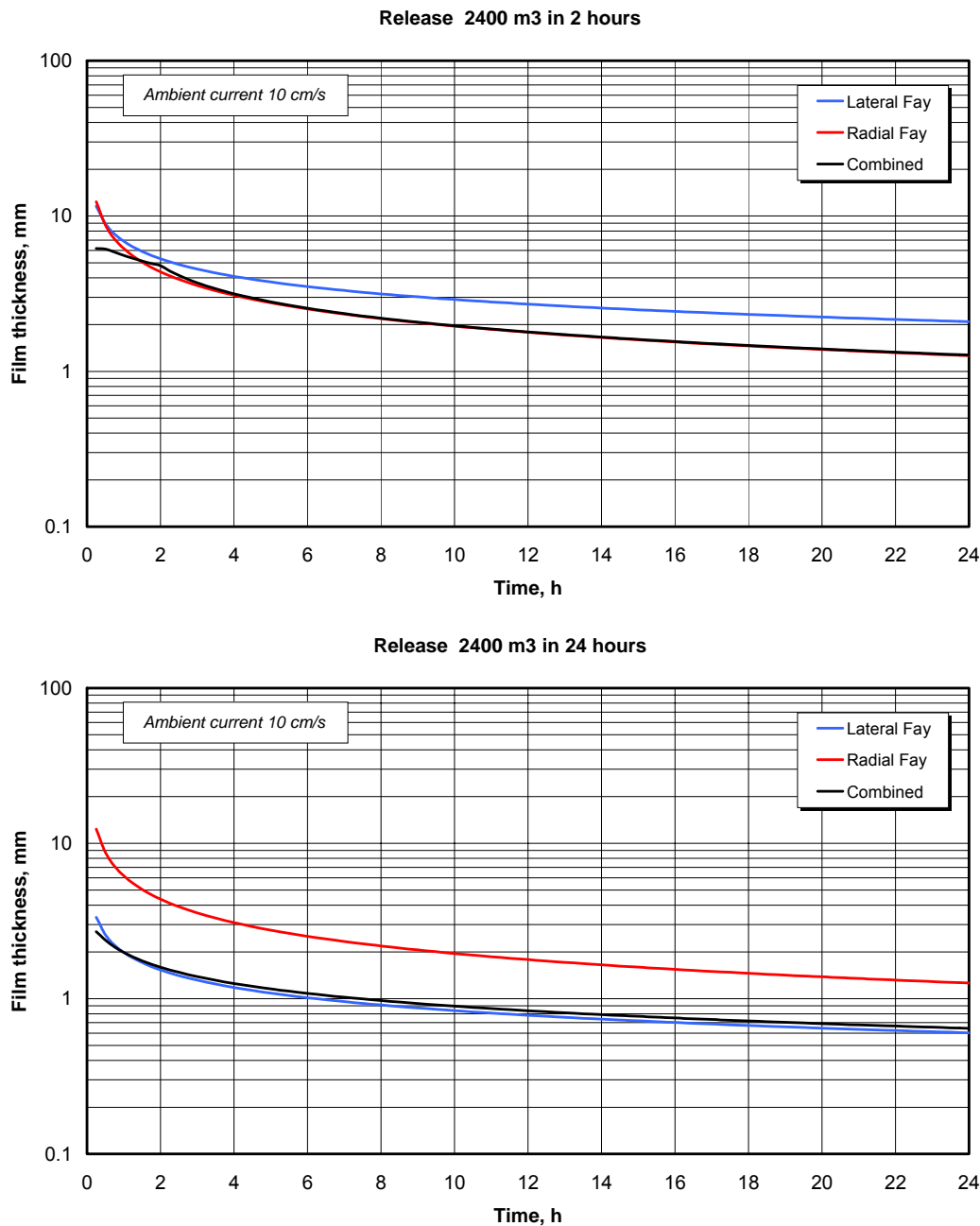
Figure C3. Gravity spreading computed with equation 6 for two cases: 2400 m³ of oil released in 2 hours (top), and 2400 m³ released in 24 hours (bottom). The calculations are made with an oil density of 850 kg/m³. The coloured lines depict the corresponding results of spreading equations for instantaneous releases ("Radial Fay"), and lateral spreading for continuous releases in a steady current ("Lateral Fay").

C.2   Surface spreading of subsea blowouts

The surface spreading of oil from a subsea blowout is governed by the generation of a rising gas bubble plume that entrains ambient water. Surfacing of the entrained water produces a radial outflow at the sea surface. The oil will be carried to the surface as fine oil droplets dispersed in the entrained water. A surface slick will form as the dispersed oil droplets settle out of the radial outflow of entrained water.

According to Fanneløp and Sjøen (1980), the surface velocity distribution in the radial outflow can be approximated by a source flow equation:

$$U(r) = \frac{S}{2\pi r} \qquad (7)$$

where S (m²/s) is the source strength.

Under such conditions – provided that all the oil comes to the surface, the oil film thickness h (m) may be estimated from the source strength and the oil spill rate m (m³/s):

$$h = m/S \qquad (8)$$

Fanneløp and Sjøen (op cit) also show that the source strength S depends on the characteristic radius b (m) and velocity w (m/s) of the surfacing plume:

$$S = k\,\pi\,b\,w \qquad (9)$$

where $k = 4.86$ is a constant.

The same authors also presented a basis for establishing the characteristic plume radius b and velocity w in terms of a non-dimensional solution to the plume equations (Figure C4).
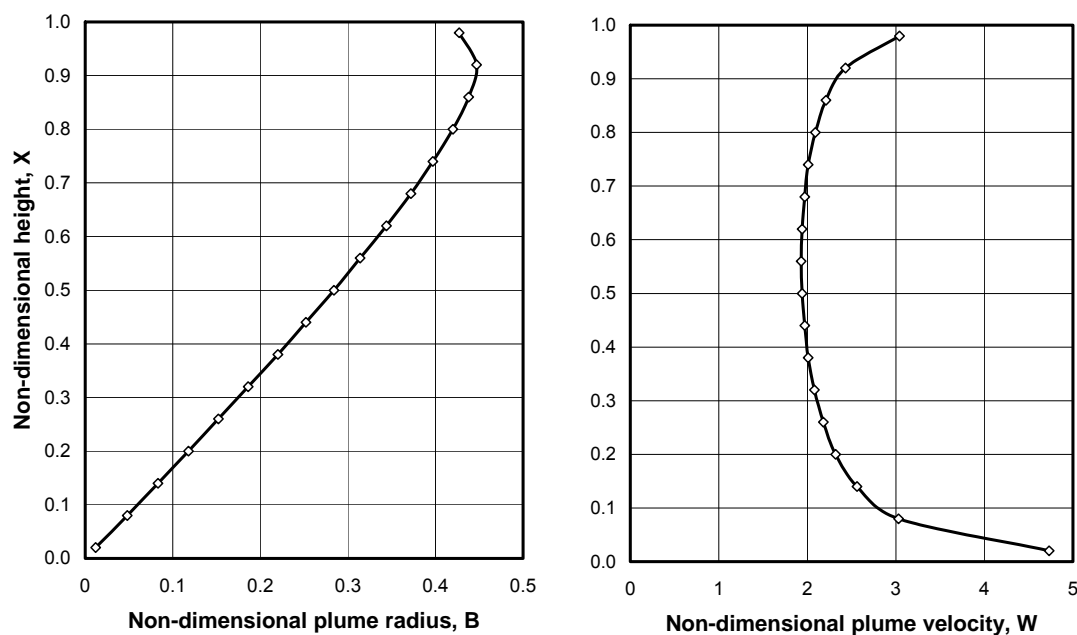
Figure C4. Non-dimensional plume radius and plume velocity computed for subsea gas blowouts (Fanneløp and Sjøen 1980). See text for definitions of the non-dimensional variables.

The non-dimensional variables are defined as follows:

$$X = z/H, \; B = b/2\alpha H, \; W = w/M,$$

$$\text{where } M = \left[\frac{\varphi_0(\lambda^2 + 1)}{2\alpha^2 H}\right]^{1/3} \qquad (10)$$

In these equations, H (m) is the pressure height, $H = H_0 + H_a$, where H_0 is the water depth and H_a is the pressure height corresponding to 1 atmosphere (10 m), $\varphi_0 = g\dot{V}_0/\pi$ (m⁴/s³) is the buoyancy flux at the exit, where $\dot{V}_0$ (m³/s) is the exit gas volume flow rate, while $\alpha = 0.1$ and $\lambda = 0.65$ are parameters related to plume dynamics.

The basic blowout specific variables in these equations are water depth H_0 and the exit gas volume flow rate $\dot{V}_0$. The latter may usually be derived from the oil discharge rate m (m³/s) and the Gas-to-Oil Ratio, GOR, representing the ratio between the released gas volume and oil volume at normal conditions (1 atmosphere and 15°C). Neglecting the minor correction due to the temperature difference, the ideal gas law gives:

$$\dot{V}_0 = m\,GOR\,H_a / H \tag{11}$$

The non-dimensional variable X at the sea surface is defined from the actual water depth, i.e. $X = H_0 / H$. The corresponding non-dimensional values B and W may then be found from the graphs shown on figure C4, or from curve-fitted functions based on the original data. The actual plume variables (*b* and *w*) may then be determined by rescaling B and W with known X and M, the latter calculated from the exit volume flux (see equation 10).

It should be noted that this approach is valid under certain conditions that in general imply that effects of cross flow and stratification can be neglected. In practice, the concept should be limited to cases with significant gas volume fluxes (GOR > 50) from moderate water depths (< 300 m).

C.3   Evaporation

The evaporative loss is computed based on a pseudo-component approach, where the composition of the fresh oil is given by it's distillation curve (Reinhart and Rose, 1982). The rate of evaporation for component *i* is given by:

$$\frac{dQ_i(t)}{dt} = -\frac{\alpha(t)Q_i(t)M(t)p_i(t)}{\rho(t)h(t)RT} \tag{12}$$

where
$Q_i(t)$ is the mass per unit area remaining of fraction *i* (kg/m²)
$\alpha(t)$ is a wind dependent mass transfer coefficient (m/s)
$M(t)$ is molar weight of liquid mixture (kg/kmol)
$p_i(t)$ is vapor pressure of fraction *i* (N/m²)
$\rho(t)$ is density of liquid mixture (kg/m³)
$h(t)$ is oil film thickness (m)
R   is universal gas constant (J/kmol K)
T   is absolute temperature (K)

The wind dependent mass transfer coefficient $\alpha(t)$ is calculated according to Amorocho and DeVries (1980):

$$\alpha(t) = C_d U(t) \tag{13}$$

where

C_d is an air/sea drag coefficient
$U(t)$ is wind speed (m/s)

The air/sea drag coefficient C_d is itself dependent on the wind speed:

$$C_d = \left(\frac{U^*}{U(t)}\right)^2 \tag{14}$$

with

$$U^* = \begin{cases} CU(t) & for \ U(t) < u_1 \\ Cu_1 + (Du_2 - Cu_1)\dfrac{U(t) - u_1}{u_2 - u_1} & for \ u_1 \leq U(t) \leq u_2 \\ DU(t) & for \ U(t) > u_2 \end{cases} \qquad (15)$$

where

C, D, u_1 and u_2 are constants (0.0323, 0.0474, 7 and 20 respectively).

C.4 Oil-in-water dispersion

The model used for prediction of entrainment of oil from the sea surface is described in Reed et al. (1992), and is based on the empirical formulation of Delvigne and Sweeney (1988):

$$Q_{di} = C^* \, D^{0.57} \, S \, F_{bw} \, d_i^{0.7} \, \Delta d \qquad (16)$$

where

Q_{di} is the entrainment rate per unit surface area of oil droplets with diameters in the range
        d_i - Δd to d_i + Δd (kg/m^{2}s)
C^* is an empirically derived entrainment coefficient
D is dissipated wave energy per unit surface area (kg/s^2)
S is fraction of sea surface covered by oil
F_{bw} is fraction of sea surface covered by breaking waves per unit time (1/s)
d_i is mean diameter of particles in size class i (m)
Δd is particle diameter interval (m)

The empirical coefficient C^* is a function of the viscosity of the oil:

$$C^* = 4450 \nu^{-0.4} \qquad (17)$$

where

ν is the kinematic viscosity (m^2/s)

The dissipated wave energy D is approximated as:

$$D = 0.0034 \rho_w g H_b^2 \qquad (18)$$

where
ρ_w is density of seawater (kg/m^3)
g   is gravitational acceleration (m/s^2)
H_b is breaking wave height (m)

The fraction F of sea surface covered by breaking waves is approximated as (Monahan and O'Muircheartaigh, 1980):

$$F = 3 \cdot 10^{-6} U(t)^{3.5} \tag{19}$$

where
U(t)   is wind speed (m/s)

The fraction covered by breaking waves per unit time F_{bw} (s^{-1}) is found by dividing F by the mean wave period:

$$F_{bw} = F / T_m \tag{20}$$

where
T_m is the mean wave period (s) computed from wind speed, water depth and fetch (Appendix D)

Currently, no rise times are calculated in the model. Resurfacing of oil is assumed to happen instantaneously for oil droplets with a diameter of more than a limiting value $d_{lim} = 370$ µm, while smaller droplets are assumed to be permanently entrained, or to resurface behind the slick, forming a blue-sheen. Droplets are divided into 10 groups between 0 and the limiting droplet size.

C.5   Water uptake and surface oil properties

The algorithms for water uptake and changes in oil properties are calibrated to laboratory weathering data. Laboratory weathering data relates the different oil properties to fraction evaporated. The following table shows an example of a lab data table for a North Sea crude.

Property	Fresh oil	150°C+ (≈ 1 hour)	200°C+ (≈ 1 day)	250°C+ (≈ 1 week)
Boiling temp. (°C)	-	197	254	305
Volume topped (%)	0	14.6	27.8	36.9
Residue (wt. %)	100	88.1	76.9	67.2
Specific gravity (kg/l)	0.853	0.883	0.895	0.913
Pour point (°C)	-6	9	12	21
Flash point (°C)	-	51.2	93.9	126
Viscosity at 13°C (cP)	15	33	67	254
Viscosity of 50% emulsion (cP)	-	880	1420	2700
Viscosity of 75% emulsion (cP)	-	5300	8600	16000
Viscosity of max water (cP)	-	-	-	-
Max. water content (%)	-	90	85	72
Halftime for water uptake (hrs)	-	0.22	0.27	0.56
Stability ratio	-	0.85	0.86	1.0

C.6 Water uptake

Water uptake W(t) is calculated as a step-wise exponential:

$$W(t + \Delta t) = W_m(t) - [W_m(t) - W(t)]0.5^{\frac{\Delta t}{t_{1/2}}} \qquad (21)$$

where

$W_m(t)$ is maximum water content (%)
$\Delta(t)$ is the time-step (s)
$t_{1/2}$ is a wind dependent half time for water uptake (s)

The $t_{1/2}$-value and $W_m(t)$-function are derived from laboratory data which relates rate of water uptake and maximum water content to fraction evaporated. From this data, a reference half time t_{ref} for a reference wind speed of 10 m/s (in the field) is found as:

$$t_{ref} = Ct_{lab} \qquad (22)$$

where

t_{lab} is an average of half time values found in the laboratory for artificially weathered oil samples (s)
C is an empirical constant (4-6)

This reference half time is used to adjust $t_{1/2}$ to other wind speeds based on data reported by Cormack (1983):

$$t_{1/2} = \left[\frac{1 + U_{ref}}{1 + U_{(t)}} \right]^2 t_{ref} \qquad (23)$$

where

t_{ref} is found from equation (22) (s)
U_{ref} is 10 (m/s)
$U_{(t)}$ is wind speed (m/s)

W_m as a function of fraction evaporated is found from lab data by assuming that maximum water content is linearly dependent on the fraction evaporated and fitting a straight line to the available data. By applying the evaporative loss found from integrating equation (12) to this line, $W_m(t)$ is found.

C.7 Surface oil properties

Four oil properties are predicted in the model. These are pour point, flash point, density and viscosity of water-free oil. These properties vary as curve fits with laboratory measured values and fraction evaporated as shown below (Johansen, 1991).

Pour point (°C):

$$P = e^{(a_p + b_p f)} - 273 \qquad (24)$$

Flash point (°C):

$$F = e^{(a_F + b_F f)} - 273 \qquad (25)$$

Density (g/l):

$$\rho_o = a_\rho + b_\rho f \qquad (26)$$

Viscosity (cP):

$$\mu_o = e^{(a_\mu + b_\mu f)} \qquad (27)$$

where

f   is fraction evaporated (-)
a_p, b_p, a_F, b_F, a_ρ, b_ρ, a_μ, b_μ are regression factors

By applying the evaporative loss found by integration of equation (12) to equations (24)-(27), the corresponding functions of time are found.

The density of emulsion $\rho(t)$ is calculated as:

$$\rho(t) = \frac{W(t)\rho_w + [100 - W(t)]\rho_o(t)}{100} \qquad (28)$$

where

W(t)   is water content (%)
ρw is density of seawater (g/l)
$\rho_o(t)$ is density of water-free oil (g/l)

The Mooney (1951) equation is used to calculate the emulsion viscosity $\mu(t)$:

$$\mu(t) = \mu_o(t) e^{\frac{aW(t)}{100 + bW(t)}} \qquad (29)$$

where

W(t) is water content (%)
a, b are empirical constants

The empirical constants, *a* and *b*, are according to Mackay (1980) $a = 2.5$ and $b = 0.654$. These are however in the model found by fitting equation (29) to lab data, with the optimal *a* between -10 and 5 and *b* between –2 and 0.9, found based on a least squares criterion.

C.8   Arctic conditions

The weathering of oil changes significantly in the presence of sea ice. The present version of the SINTEF OWM contains field-derived algorithms adjusting spreading, natural dispersion, and water uptake (emulsification) as functions of fractional sheet- or block-ice cover (Singsaas et al, 1994). Two new variables are introduced:

$I(t)$ is the percentage of ice cover [0, 100]
$G_1(t)$ is the ice modification factor for spreading.

These variables are related as follows:

$$G_1(t) = \begin{cases} 1 - \left(\dfrac{I(t)}{100}\right)^2 & 0 \leq I(t) \leq 95 \\ 0.1 & 95 < I(t) \end{cases} \tag{30}$$

G_1 is applied as a reduction factor to the spreading length computed by the spreading algorithm (6), and was chosen to obtain a reasonable fit to the Marginal Ice Zone (MIZ) evaporation data (Sørstrøm, 1993; Singsaas et al, 1994).

One major impact of ice in water is the damping of wave energy. This entails a reduction in both oil-in-water dispersion and water-in-oil emulsion rates. A proper arctic model should account for this effect directly by incorporating ice terms in the wave equation. However, no such models are currently available; an indirect empirical approach is required. Thus, in accordance with the MIZ data, we have introduced an ice parameter, $G_2(t)$, into the dispersion and emulsion formulae. This cubic factor severely reduces dispersion in ice-infested waters.

$$G_2(t) = \begin{cases} \left(1 - \dfrac{I(t)}{100}\right)^{3.5} & 0 \leq I(t) \leq 95 \\ 0 & 95 < I(t) \end{cases} \tag{31}$$

The expression for G_2, chosen to fit the MIZ water content (in the oil) data, serves as a multiplier in both the natural dispersion and emulsification equations (16) and (21) respectively.

Appendix D: US Army Corps of Engineers Shallow Water Wave Equations

Following are the governing equations used in the SINTEF Oil Weathering Model to compute wave height (H) and period (T) as functions of wind speed (U_A), depth (d), fetch (F), and gravitational acceleration (g). These equations are taken from the U.S. Army Corps of Engineers Shore Protection Manual (1984), Volume I.

$$\frac{gH}{U_A^2} = 0.283 \tanh\left[0.530\left(\frac{gd}{U_A^2}\right)^{3/4}\right] \tanh\left\{\frac{0.00565\left(\frac{gF}{U_A^2}\right)^{1/2}}{\tanh\left[0.530\left(\frac{gd}{U_A^2}\right)^{3/4}\right]}\right\}$$

$$\frac{gT}{U_A} = 7.54 \tanh\left[0.833\left(\frac{gd}{U_A^2}\right)^{3/8}\right] \tanh\left\{\frac{0.0379\left(\frac{gF}{U_A^2}\right)^{1/3}}{\tanh\left[0.833\left(\frac{gd}{U_A^2}\right)^{3/8}\right]}\right\}$$