3rd International Training School on “Convective and volcanic clouds detection, monitoring and modeling”

Modelling volcanic plumes
Computer session

Friday 20th October 2016

Preliminaries

This session will explore some of modelling of plume dynamics that were introduced in my talk. We start in Part 1 with a short investigation of pure plumes, where there are only a few parameters in the model and we can make a lot of progress analytically. We'll then look in Part 2 at a model of volcanic plumes, where there are a lot more parameters and model inputs.

In Part 1 you will adapt a short matlab/octave program that computes numerically the solutions of Morton, Taylor & Turner's (1956) model of plumes. The matlab code for Part 1 is posted on the website
www.maths.bris.ac.uk/~mw9428/VolcanicPlumes
I've assumed you have a little knowledge of matlab/octave, to run a function, produce some plots and do some analysis of the results. If you are not familiar with matlab/octave it would be good to partner with someone who is, or ask from some help.

In Part 2 you will use the PlumeRise web-tool at www.plumerise.bris.ac.uk to investigate a volcanic plume model. The web-tool is quite straightforward to use, but ask for help if you have trouble. There is a group log in:

username : volcano
password: volcano

or you can make you own account if you'd like to save your results. Note, on the group account there is some atmospheric data provided which can loaded on the web-tool. If you create you own account, the same data is available at
www.maths.bris.ac.uk/~mw9428/VolcanicPlumes

You are welcome to work at your own pace to spend more time on parts that you find most interesting. Please ask if you'd like help or to discuss some parts in more detail.

Part 1: Numerical solution of an integral model of pure plumes.

Aim: Using Matlab/Octave investigate the solutions of the integral model of pure plumes. How are the solutions affected by changes to parameters? How can we change the code to mode more practical situations by changing the boundary conditions?

The function *PurePlume.m* solves the ordinary differential equations that model a pure plume rising from a point source of buoyancy at *z=0* for specified values of the entrainment coefficient (k), the buoyancy flux from the source (F00) and the buoyancy frequency of the atmosphere (N).

Exercise 1.1

To make sure everything works ok in Matlab/Octave, run the function for k=0.1, F00=1, and N=0. The function should return with no errors. Try plotting some of the results; e.g. plot the plume radius as a function of height with

```
>> plot(soln.b,soln.z)
```

Did you get the result you expect?

Confirm that the scaling results $Q \sim z^{5/3}$, $M \sim z^{4/3}$, $w \sim z^{-1/3}$, $g' \sim z^{-5/3}$ that we anticipate from dimensional analysis are reproduced by the numerical solution.

Try changing the entrainment coefficient and the source buoyancy flux, but leave N=0. How do variations in these affect the solutions?

Exercise 1.2

Now try changing from an unstratified ambient to a stratified atmosphere. Recall that, if the buoyancy frequency *N*>0 then the atmosphere is stably stratified.

Run the solver with *N*=1. Does this solution agree with your expectation?

Try changing the source buoyancy flux and the buoyancy frequency. Can you confirm the scaling

$$H \sim N^{-3/4} {F_0}^{1/4}$$

that we anticipate from dimensional analysis? *You might find it useful to write a `wrapper' loop to vary one of the parameters.*

What effect would changing the entrainment coefficient have on the solution? Do the numerical results support?

How could you model an unstratified ambient? What does the model predict in this case?

Exercise 1.3

The point source boundary condition is convenient for theoretical analysis, but in practice it is more common to have fluid released from a given area (e.g. the vent of a volcano or the top of a chimney stack) with a specified velocity, or equivalently with specified fluxes of the mass and momentum.

Using the function PurePlume.m as a template, change the code so that the boundary conditions represent a release of fluid with specified fluxes of mass and momentum at the source. Your function should five input parameters: the entrainment coefficient k, the source buoyancy flux F0, the source mass flux Q0, the source momentum flux M0, and the buoyancy frequency of the atmosphere N.

Run the code with k=0.1, N=0 and with F0=1, Q0=0, M0=1e-8. This is the plume-like solution. *(Note we have a small non-zero momentum flux to avoid the singularity in the equations – we could do this more precisely but it would take a bit of mathematical analysis of the equations.)*

Run the code again with k=0.1, N=0 and with F0=0, Q0=0 and M0=1. This is a jet-like solution.

What is the difference between the jet-like and plume-like solutions?

Now take non-zero values for F0 and M0. This is known as a 'forced plume', as we are now giving the plume buoyancy and momentum at the source. How does this compare to the plume and jet solutions? Could you use dimensional reasoning to anticipate this behaviour?

Exercise 1.4

Using your modified code from Exercise 1.3, put k=0.1, N=0, Q0=0, M0=1 and now F0=-1.

This choice of parameter values represents a dense jet released into an unstratified ambient i.e. a fluid that is more dense than the atmosphere is ejected from the source with some momentum.

What do you expect to happen? What does the model predict?

Exercise 1.5

The final exercise with our idealized model takes us closer to the volcanic setting. We'll now apply the code developed in Exercise 1.3 to model a dense jet released into a stratified ambient.

This model captures some of the important features of volcanic plumes, where the material erupted by the volcano is usually more dense than the atmosphere, but expansion of gases in the volcanic conduit below the vent eject the material with momentum.

Investigate the predictions of this model for different choices of the source parameters (Q0, M0, F0) and the buoyancy frequency (N).

Does the erupted material ever become buoyant? *[You might want to look at the behaviour of the reduced gravity,* `soln.gr`*, which is positive if the fluid is buoyant and negative if the fluid is more dense than the ambient]*

What conclusion can we make about the applicability of this pure plume model to volcanic settings?

Part 2: A model of volcanic plumes.

Aim: Using the PlumeRise web-tool, investigate the influence of model parameters and atmospheric forcing on predictions of a model of volcanic plumes. Which parameters have most influence on the model predictions? How do changes in the meteorological conditions affect the solutions? How could a model of volcanic plumes be used to inform long-range ash dispersal models?

Go to www.plumerise.bris.ac.uk and log in to the web-tool using either the group log in (username: volcano, password: volcano) or create your own account.

There is a quick start guide to PlumeRise at
https://www.plumerise.bris.ac.uk/help/quickstart/
where you'll also find links to more extensive documentation. Take a quick look through the guide – it might be useful to have the quick start guide open as a separate tab in your browser.

When you log in to PlumeRise you'll come to the input and results screen. There is a panel with output plots and a panel with options and inputs. At the bottom of the screen is the "Run Model" button.

If you are using the group log in, then you'll first see the results and the inputs of the last run by someone in this group. It's therefore a good idea to first clear the model. To do this go to the "**Load/save parameters**" tab, and hit the "**Reset all parameters to defaults**" button. You're now ready to go!

Exercise 2.1
You'll see a default solution of a volcanic plume, rising to about 17.5 km. Notice that it is rising vertically. The "**Parameters**" tab show the inputs to the model. If you click on the "**Atmospheric model parameters**" tab you'll see that there are some parameters that describe the atmospheric structure using a Standard Atmosphere.

Try changing some of the inputs in the second column of on the "**Parameters**" tab.

The default value for the gas mass fraction is 0.03 (i.e. 97%wt of the erupted material is solid ash particles). What happens if you model an eruption that produces 5% gas (put Gas mass fraction: 0.05)? How about 10%, 20% or 90% gas? Use the coloured tabs to compare these inputs?

It seems that increasing the gas content lowers the plume height. Can you use the results to suggest why?

What happens is you decrease the gas content to 2%? Why?

Can you get an eruption with 2% gas to reach a high altitude? Try adjusting some of the other inputs?

What effect does changing the temperature have when other parameters are fixed? What is the coldest eruption that you can get to become buoyant under these conditions?

Exercise 2.2
Reset to default values by going to the "**Load/save parameters**" tab, and hitting the "**Reset all parameters to defaults**" button.

On the parameters tab, change the option from "Specific source velocity" to "**Specify source flux**" by pressing the radio button.

Now investigate the effect of changing the vent radius while leaving the source mass flux fixed at 2.0e7. Note, with the source mass flux fixed, increasing the radius will decrease the velocity. What can you say about the sensitivity of the model predictions to the choice of the vent radius?

Exercise 2.3
Reset to default values, and now lets investigate the effect of the atmosphere, using an idealized Standard Atmosphere in the "**Atmospheric model parameters**" tab.

To compare with the "reference" solution, open tab 2 [red] and in the "**Atmospheric model parameters**" tab change some settings.

Some settings you could try are:

	Polar	Mid-latitude	Tropical
Height of tropopause (km)	8	11	17
Air temp. at sea level (°C)	-10	0	20

If you are using the group log in, on the "**Load/save parameters**" tab there are some further model atmospheres (McClatchey 1972), otherwise download these from www.maths.bris.ac.uk/~mw9428/VolcanicPlumes and input them through the "**Atmospheric data**" tab (ask for help if needed).

Try loading these and investigate their effect. Note for these profiles, the humidity of the atmosphere is included. Can you notice its effect?

Exercise 2.4

Now try adding a crosswind. In the Idealized atmospheric model, the wind is described as linearly increasing up to the stratosphere and uniform within the stratosphere. Try changing the stratospheric wind speed. What effects does this have?

Investigate changing the wind speed alongside the other atmospheric parameters, and the model inputs on the "**Parameters**" tab. Which parameter has the biggest effect on the model predictions?

Exercise 2.5 – Pinatubo 1991

On 15th June 1991 there was a gigantic eruption of Mt. Pinatubo in the Philippines, the largest eruption in the last 100 years. The cloud from this eruption spread for many hundreds of kilometres, and was little affected by a nearby tropical cyclone!

Atmospheric data for the Philippines at 0600 on 15th June 1991 is provided (either on the "**Load/save parameters"** tab or online). Load this data.

The plume from Pinatubo reached over 30 km, and perhaps as climbed as high as 40 km. By adjusting the volcanological inputs to the model in the "**Parameters**" tab, can you get a plume to reach 40 km? Try using the "**Infer source flux from observed plume rise height**" option.

By mapping the deposits of the Pinatubo eruption, volcanologists estimate that the source mass flux was approximately 3×10^{8}kg/s i.e. 300000 tonnes of material erupted every second, and the eruption lasted for several hours! A really large event, but not usually large in geological history.

How does your estimate from the PlumeRise model compare with the field-mapping estimate? How sensitive is the model estimate to the parameter values?

<u>Exercise 2.6 – Eyjafjallajökull 2010</u>

On 14th April 2010, the Eyjafjallajökull volcano in Iceland began to eruption. In comparison to the eruption of Pinatubo, this eruption was tiny, but Eyjafjallajökull continued for 39 days and caused huge disruption to people in Iceland, and to air traffic in the North Atlantic and Europe.

A weather radar measured the height of the plume from Eyjafjallajökull. Figure 1b shows the record of the plume heights for the first 4 days of the eruption, when the eruption was at its most powerful.

Using the radar record of plume heights and the calibrated scaling relationship (Mastin 2009)

$$H = 0.304Q^{0.241},$$

for Q measured in kg/s and H in km above the vent, estimate the source mass flux at 1200 on 14—17 April. What is the range of values of Q during these days? From these estimates, what would you conclude about the behaviour of the volcano over these days?

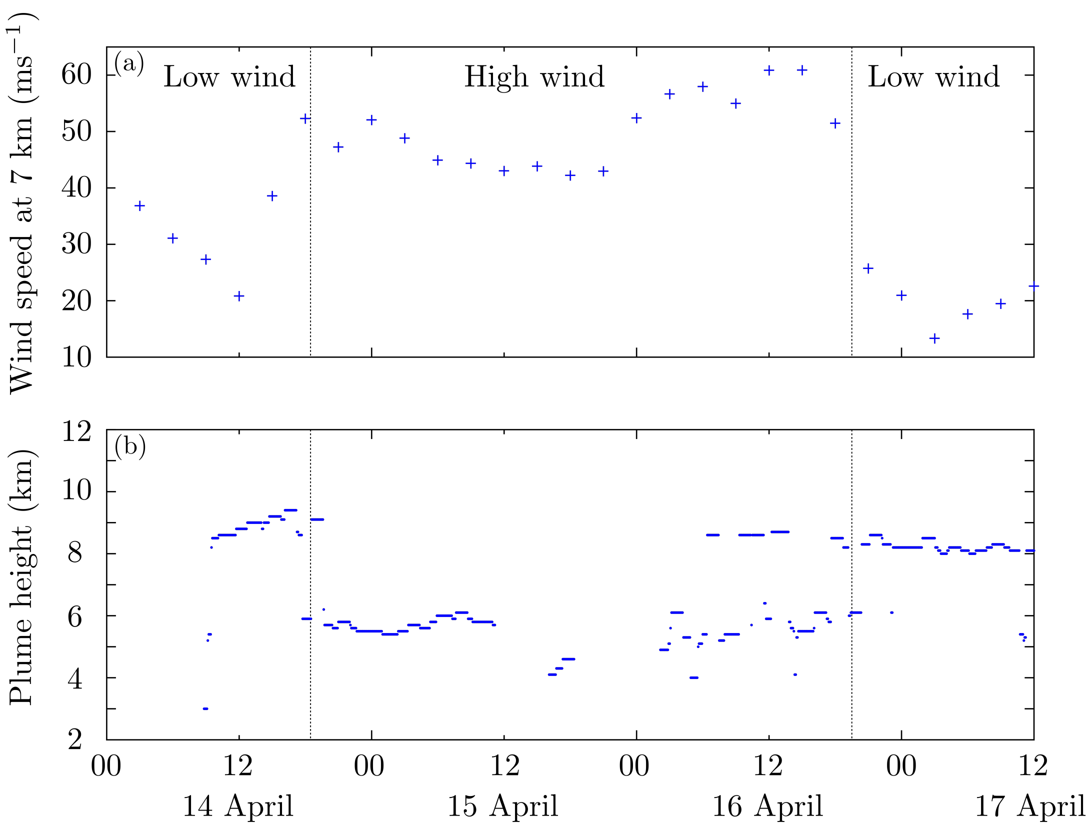

Figure 1. Plume heights and wind speed during the first explosive phase of the 2010 eruption of Eyjafjallajökull. (a) A representative wind speed, measured at 7km asl. (b) The plume height recorded by a weather radar.

The weather conditions changed during the eruption, but this is not accounted for in the scaling relationship. We can examine the effect of the changing atmospheric conditions by using the PlumeRise model.

The following source conditions can be used to model the eruption:

- Vent latitude = 63.625
- Vent longitude = -19.61
- Vent altitude = 1666 m
- Source temperature = 1000 K
- Gas mass fraction = 0.03
- Vent radius = 80 m
- Pyroclast density = 1200 kg/m^3
- No wind entrainment coef. = 0.09
- Wind entrainment coef. = 0.9

Atmospheric profiles for Iceland at 1200 on 14—17 April 2010 is provided (either on the “**Load/save parameters”** tab or online). Using this data and PlumeRise, estimate the source mass flux at these times. How does this compare with the estimates from the scaling relationship?

How could the model results be used to assist in making forecasts of ash dispersion?