# GEOB 402 - Assignment II
# HYSPLIT Modelling

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**Abstract**

Two different scenarios have been modelled using the NOAA HYSPLIT online modelling platform, which allowed for an 'incident's plume release' to be modelled for trajectory and concentration over space and time. The incidents explored compare the attacks in 2001 on the World Trade Centre as they were, versus as though an explosive nuclear device had been used. Their differences include the magnitude of the release, and the heights in the atmosphere modelled. Depending on the release height into the atmosphere we see very different forecasts as a result, both in spatial and temporal resolution. With a typical westerly flow over the eastern seaboard we see that the immediate local area is at lesser risk than may be initially assumed. Over the days following the actual attacks, it is the eastern and southern states which had the potential to be harmed by wet deposition from tropospheric contaminants. If there had been a nuclear explosion, then we see the gaseous plume become a hazard to populations across the Atlantic within only days of the release. It is therefore pertinent to remember that independent of an incidence's location, due to global nature of synoptic flow, any resulting hazard would be very difficult to avoid.

*NASA Image of September 11th smoke plume from World Trade Centre.*
*Courtesy: NASA, 2016.*

## HYSPLIT Introduction

The modelling application utilized in this assignment is a NOAA product used for the analysis and forecasting of particle trajectories and plume dispersion, named HYSPLIT. The acronym stands for 'Hybrid Single particle Lagrangian Integrated Trajectory model' and was first conceived in 1949 for calculating back-trajectories to analysis Russian nuclear weapons testing locations [Stein et al., 2015, ], [Rolph, 2015].

The model actually uses a combination of Lagrangian and Eulerian reference frames dependent whether the calculation is for particle trajectories or dispersion concentrations respectively. The model has been through a number of reconfigurations, and is officially in it's fourth generation. Now though, a number of alternative module options such as HYSPLIT-CheM (modelling of nonlinear chemistry) and HYSPLIT-Hg (tracking of atmospheric Mercury) allow for greater breadth as well as depth when it comes to transportation observations.

Meteorological data provides the framework for the model to run and although these files can be chosen by the user, the dates selected must align with data that is available to the model. The greatest geographical range and time period covered is by the NCAR global reanalysis of upper air sounding and surface observations from 1948-present. Many other modern numerical weather forecasting products (ie. GEM, WRF etc) are also available from a variety of dates dependent on when the particular model began operation.

Trajectory of a particle in the model is dependent on the advection of wind at the particle's current location in three dimensional space, and HYSPLIT uses the meteorological file provided to model particle velocity over the heights a user prescribes. The dispersion and concentration calculations are Eulerian functions whereby parameters such as vertical velocity, boundary layer height, turbulence, and available potential energy (among others) play there part in establishing the dispersion of particles from one 3D gridded box to its neighbours.

In this assignment, a number of different analysis tools were required due to factors such as:

- Sept 11th 2001 preceded the 'latest and greatest' in numerical models.
- The difference in geographical scope between the two incidents required models with different precision.
- The meteorological parameters of interest can change dependent on both the geographical scale and the altitudes used.

Meteorological files used for this assignment:

- 'EDAS 80km' for lower atmosphere fire and smoke trajectories. This is primarily due to it providing the best precision for the dates covered.
- The 'NCAR reanalysis 1948-present' was used for the high altitude radio-nucleotide tracking. This is due to the global scope that the meteorological file encompasses, as well as it covering the dates used.

## Incident Location & Context

The scenarios modelled in this assignment are taken from the attacks on the World Trade Centre, New York, on September 11th 2001. Instead of two separate dates to analyze the difference in meteorology as per the assignment outline, I have chosen (with permission) two vastly different emission scenarios, and an analysis has been made of the comparison in trajectories and concentrations due to the changing of meteorological parameters with height in the troposphere.

Both scenarios share parameters of:

- Date of occurrence: 11th September, 2001.
- Location of event: $40^o42'42"N, 72^o00'45"W$ [Wikipedia, 2016].
- A single explosive event scenario occurring at 14:00 hrs (UTC); 09:00 hrs local time. This is used for the trajectory analysis, with a 72 hour run time.
- Length of emissions for concentration analysis: 6 hours.

The scenarios differ by:
Scenario 1:

- Models a large scale building fire similar to the actual events observed.
- Amount emitted was modelled at 1000 unit masses.
- Has tracked concentrations for 72 hours, as they are seen to interact with the continental U.S.
- Is constrained to the lower half of the troposhere. Here, the main concern is the fall out of debris and heavier particulates for the 72 hours following the collapse of the World Trade Centre.

Scenario 2:

- Models a high explosive nuclear event; as if a planted device had been utilized instead of jet liner method.
- Amount modelled for emissions equalled 100,000 unit masses.
- Heights in the atmosphere focused on are 500 hPa upwards due to the larger magnitude of the scenario [Council, 2005]. The model allows only inputs of 10,000m asl as a maximum height. For the concentration analysis the plume was constrained to 8000m to 10,000m to analyze the effect's of upper level winds.
- The time for tracking for emissions and plume dispersion was reduced to 24 hours, possibly due to the meteorological file employed. A definitive conclusion to why this occurred has been difficult to ascertain, but the use of a different meteorological file was not possible due to the vast upper level transport experienced; therefore some educated extrapolation has been undertaken to forecast the possible concentration scenarios.

## Synoptic Analysis

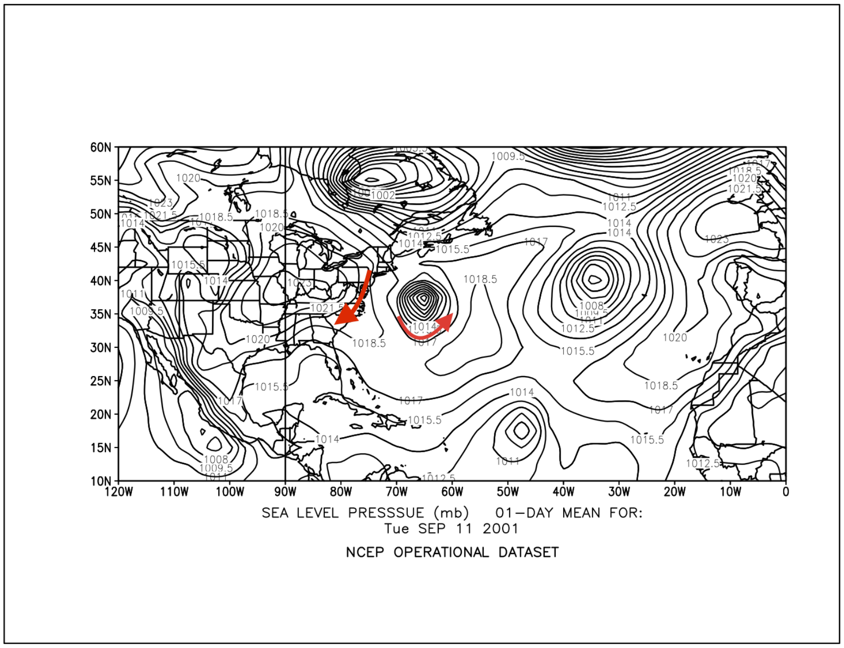



*Figure 1. Surface Synoptic patterns from 1 day average on 11th September 2011.*

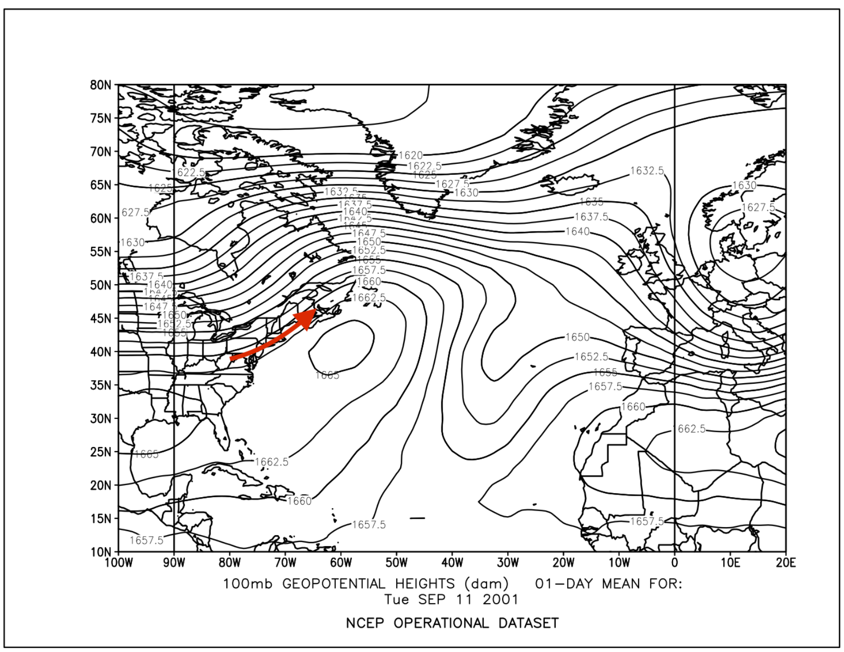



*Figure 2. 100mb Synoptic patterns from 1 day average on 11th September 2011.*

The synoptic patterns and large scale features can be seen above in Figures 1 & 2. For scenario 1 where we are concerned primarily with lower level flow, most attention is drawn to the two large scale low pressure features in the North Atlantic. If we look carefully however, much of the eastern continental U.S is under a broad area of high pressure centred around $90^oW$, and from this we would expect anticyclonic flow producing northerly to north-easterly winds over the eastern seaboard. The presence off the low pressure system just of the east coast will no doubt play a role however, and with mid-latitude cyclones typically tilting westward with height we may see its influence being felt greater above the PBL up towards the 500mb height.

For scenario 2, we are most concerned with the upper level flow and we see a strikingly different picture aloft. The lower level low pressure system off the east coast is characterized in the upper levels by higher geopotential heights, indicating we are dealing with a warm core low [Halverson, 2006]. This resultant upper level high pressure then provides anticyclonic motion to the air flow, and south-westerly winds at the 100mb height over the area of interest.

Another feature that can be seen in the 100mb map is the large gradient of heights just to the north of the added red arrow. This indicates a frontal zone, and we expect the presence of the polar Jet blowing near geostrophically along these height contours. The frontal zone is produced from the sharp temperature gradient, and these temperatures can be inferred from the geopotential heights whereby greater heights indicate a higher average temperature throughout the layer.[1] Figure 3 maps the 1-day average of geopotential heights for 11th September 2001.

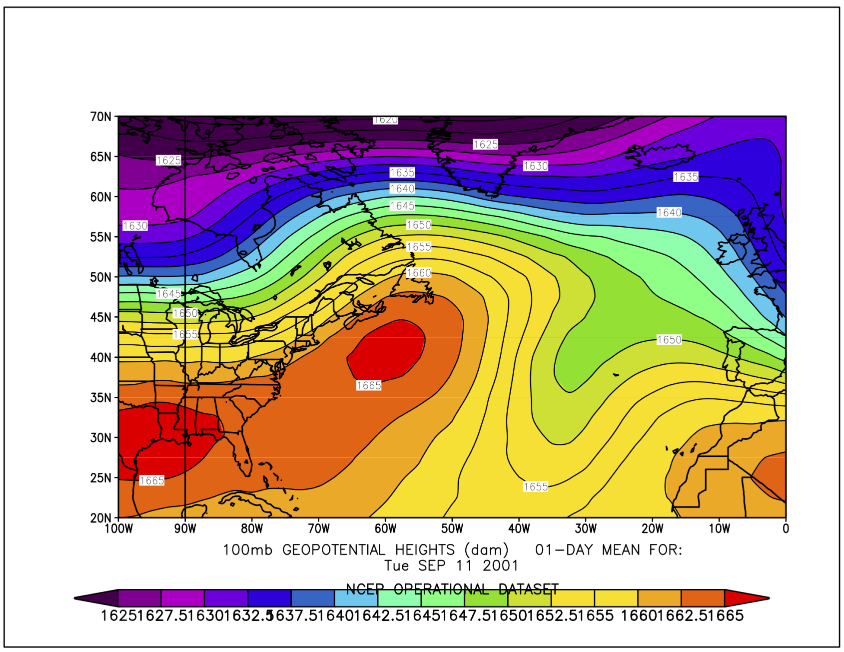



*Figure 3. 1-day average of geopotential heights. Illustrates the sharp gradient of the polar jet, and the area of upper level high pressure in the eastern-Atlantic.*

[1]The direct relationship is actually between layer thickness and average virtual temperture, yet looking at the 100mb goepotential heights is analogous to the surface-100mb layer thickness.

## Trajectory Runs

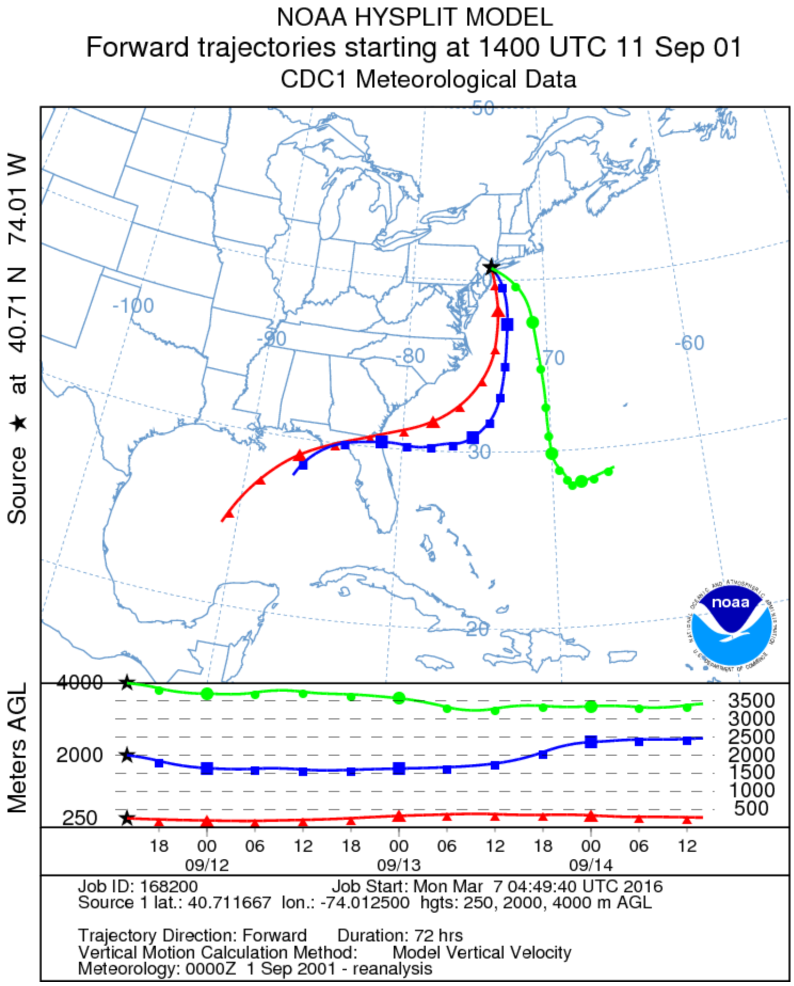



*Figure 4. 72 hour trajectory for fire debris and smoke starting 14:00 UTC, 11th Sept 2001.*

It is clear from the synoptic analysis why we see the lower level plume ejections wrapping around the east coast and heading south-west. The flow in the lower troposphere is diverging from the broad high pressure system at the surface and the trajectory run uses this flow to model the 250m and 2000m particles. In the middle of the troposphere (4000m) we see that the trajectory initially flows south, then is caught in the cyclonic flow converging in towards the low pressure centre in the Atlantic. The trajectories display counter-clockwise rotation with height, indicating 'backing' winds. Most interesting, is the crossing of inhabited continental U.S topography by the trajectory late in the 72 hours. This will be an important feature when forecasting possible exposure in the 'Forecast' section.

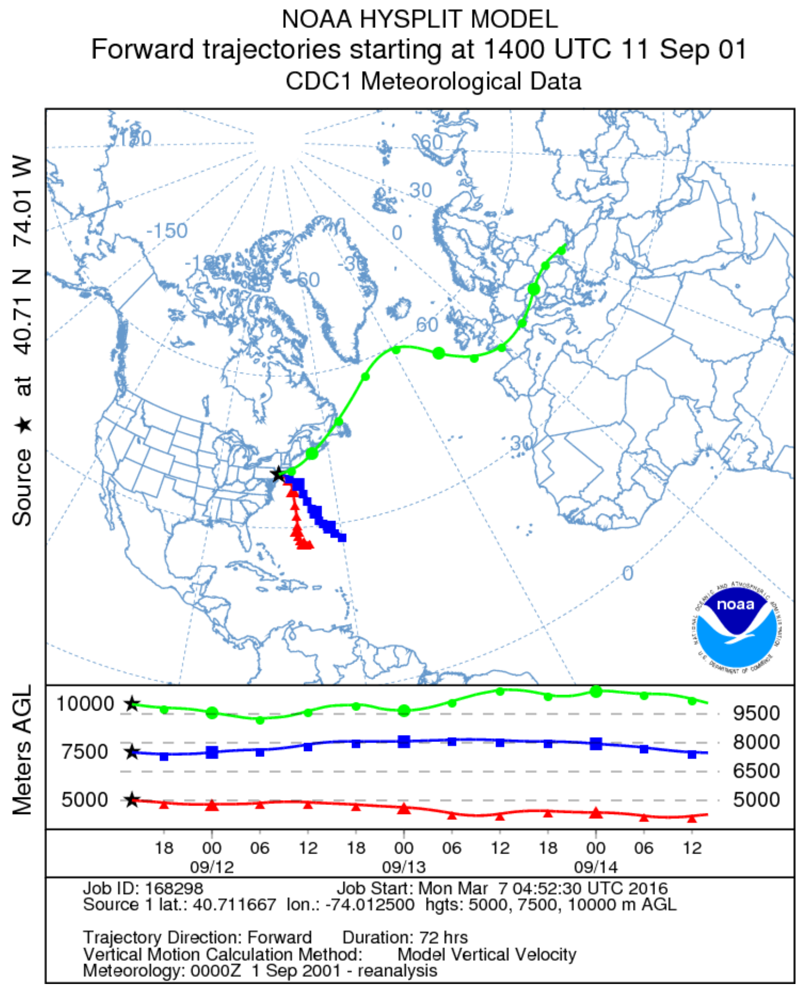



*Figure 4. 72 hour trajectory for gases associated with a Nuclear explosion, starting 14:00 UTC, 11th Sept 2001.*

In stark contrast to the first scenario, scenario 2 shows the plume trajectories in the upper troposphere for the nuclear gaseous emissions, and the vast distances possible due to the increased winds just below the tropopause. The winds are still 'backing' (counter-clockwise with height), whereby the middle troposphere flow is still flowing cyclonicly around the low pressure system, yet the upper level flow is being driven by the polar jet flowing zonally west-east.

A visual comparison indicates the distances covered to be approx 5 to 6 times larger at the 10,000m height compared to the 7500m and 5000m levels. This corresponds to the gradients seen in the 100mb chart in Figure 3, where the greater difference in geopotential heights leads to faster wind speeds. The 'bump' in the 10,000m trajectory clearly shows the upper level ridging at 100mb.

## Plume Dispersion - Scenario 1. Fire debris and Smoke:

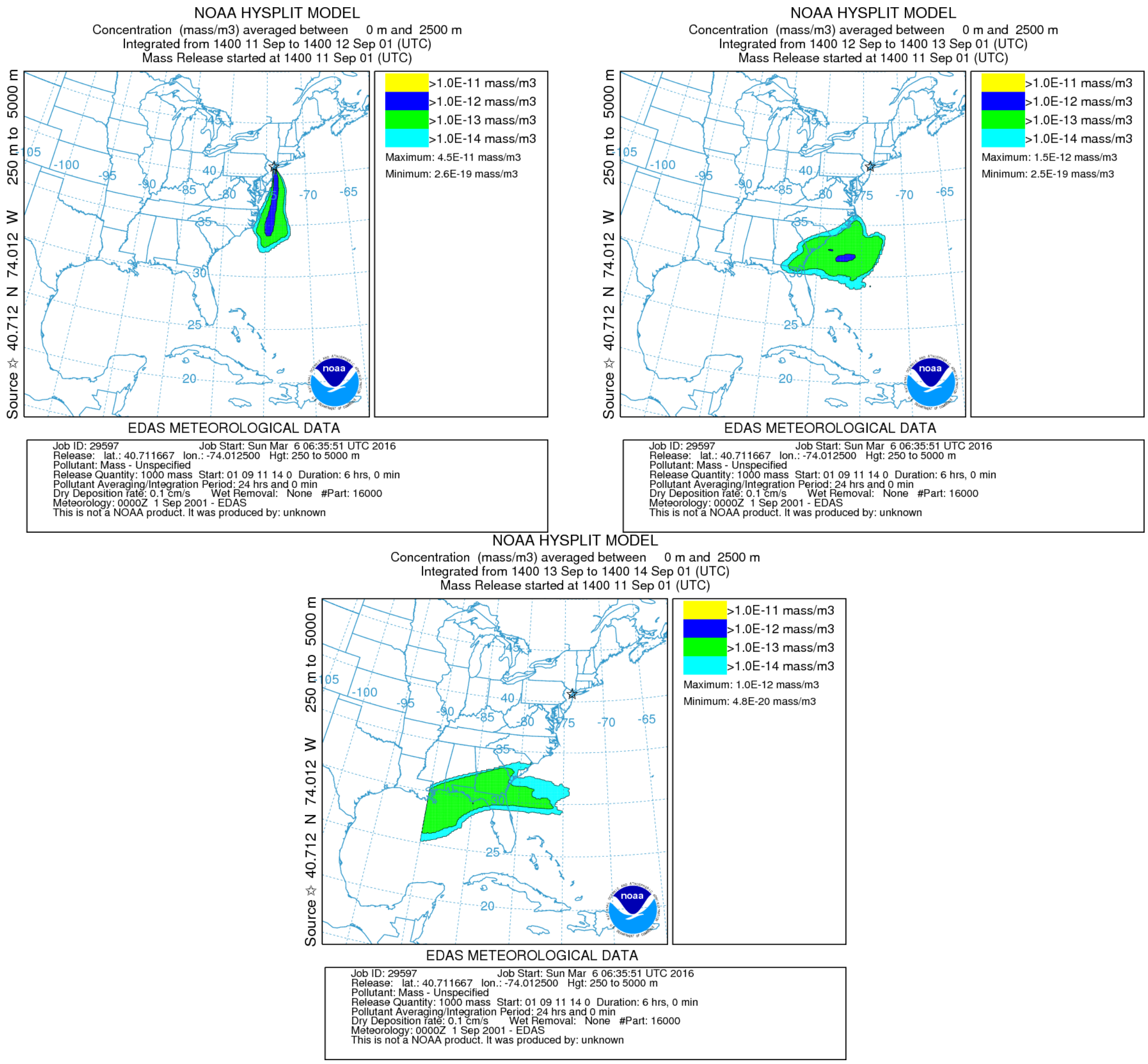



*Figure 5, 6, & 7. Fire debris and smoke plume dispersion 24hrs, 48 hrs, & 72hrs after after release.*

We can see that on the day of September 11th 2001, most of the populated area around the eastern seaboard actually escaped serious plume concentrations as the majority of the plume was blown westwards. This lines up with the trajectory run and the synoptic analysis. The largest problem would be from the fact that this anti-cyclonic flow was being produced from the broad high pressure system that then would in turn promote subsidence and a stable lower atmosphere.

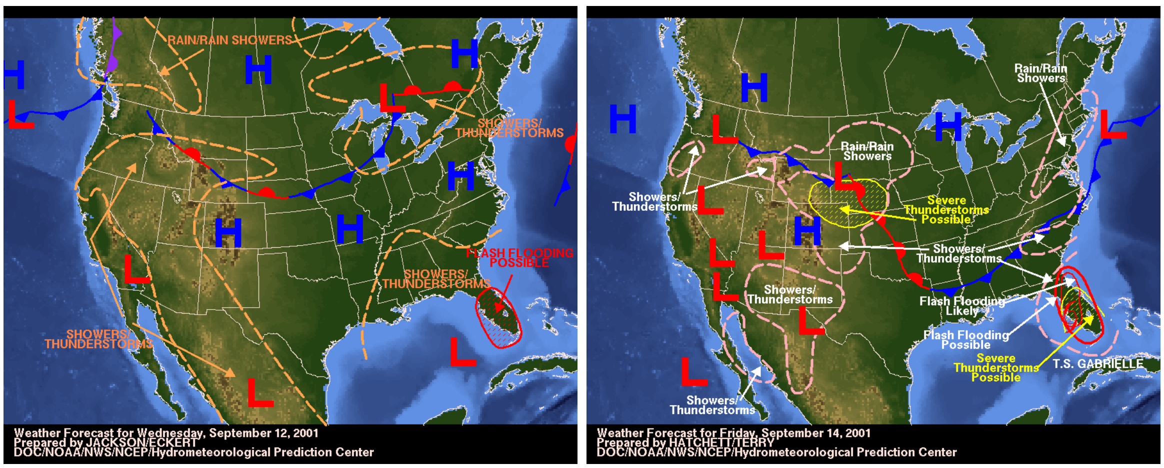
As the plume moves south-west its influence from the high pressure system is reduced and we see it interact with another low pressure system making landfall in the southern U.S.

We see for some unknown technical error the plume dispersion is cut off as it continues it's trajectory south-west. I believe this may be due to the scope of the meteorological file used in the model.

## Plume position and Forecast - Senario 1.

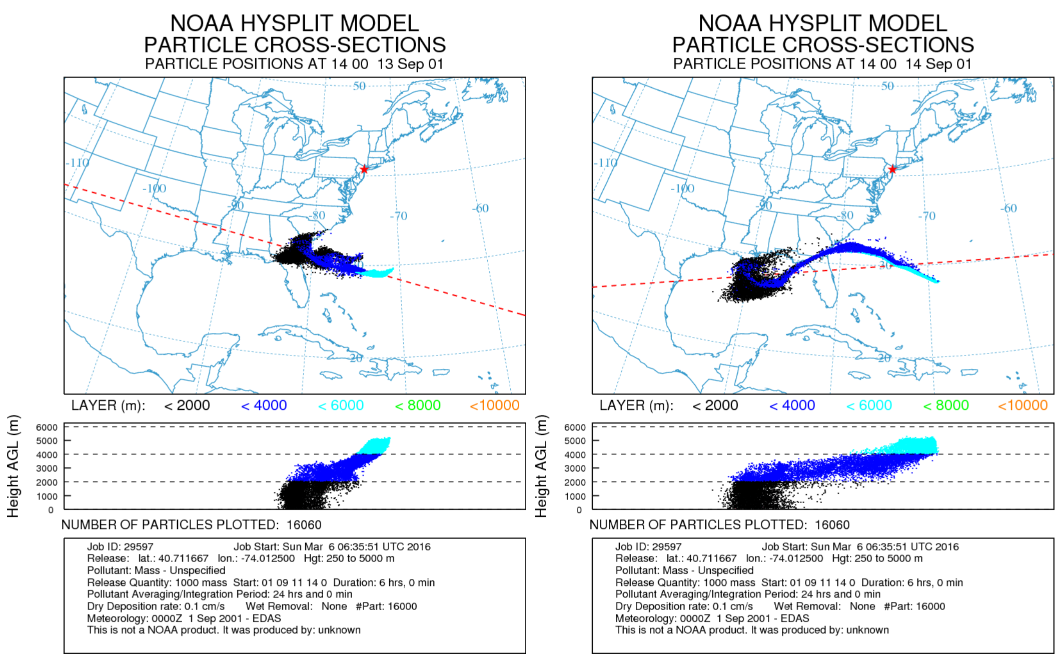
Now we must analyze the plume's potential effects on a population.

The obvious conclusion to jump to is that we need only be concerned with forecasting for populated areas on land, yet we see in the immediate 24hrs following the attack on the World Trade Centre that the plume is directed immediately over what is a busy maritime shipping and recreational boating corridor. It would be pertinent to warn maritime users of this fact via either the emergency marine radio channel, or the marine weather forecast bulletins. For further forecasting we need to look at some forecast charts and the how the particle positions corresponds with these:



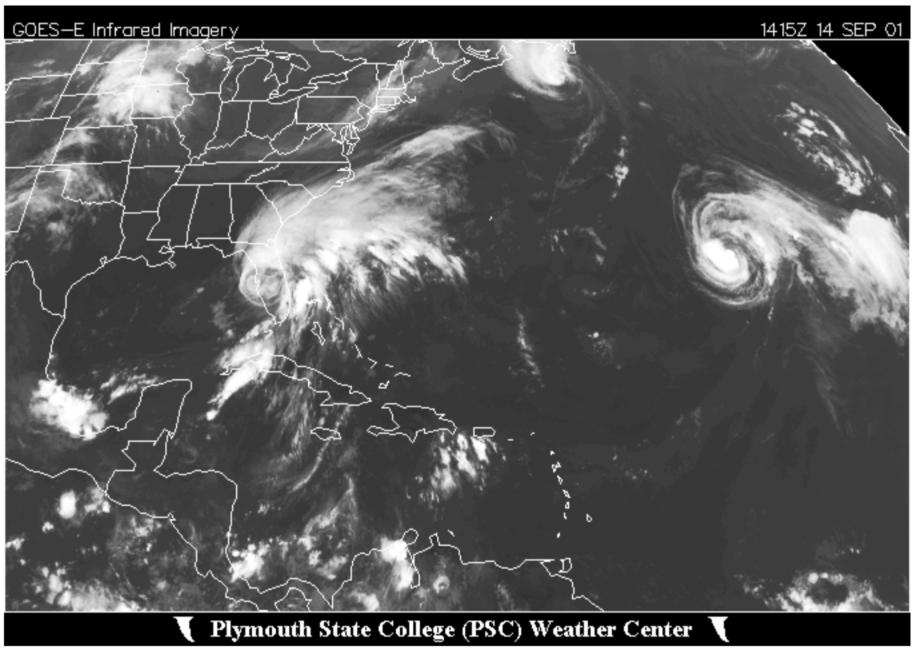

*Figures 8 & 9. Synoptic forecasts for 12th and 14th of September 2001.*

We see in the days following the 9/11 that we are forecasting plenty of active weather around the southern U.S area where the plume is expected to travel. This is made even more of a concern when we look at the particle positions:




*Figures 10 & 11. Particle positions, 48hrs and 72hrs after emission*

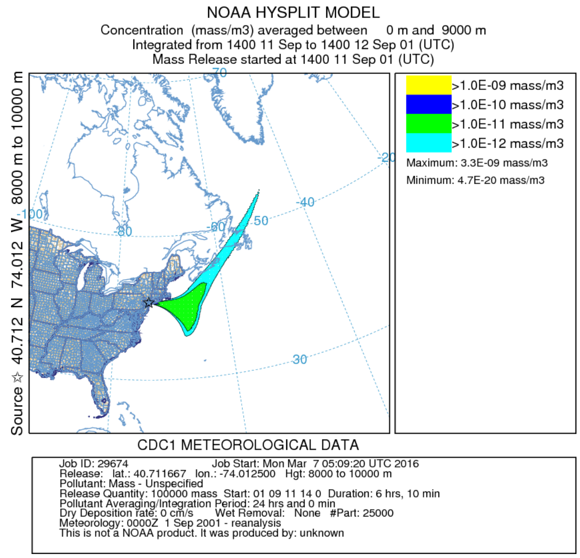
Alarmingly we see that as the reminiscence of the plume moves south there is ample opportunity for wet deposition and washout. It would be prudent to warn citizens of the possible contamination of rain-waters and some communities may even need to evaluate possible contamination to drinking water supplies. At least this mechanical removal will reduce any further spread of the plume. The landfall of tropical storm Gabrielle can be seen on the satellite image below. It is quite possible that such an energetic event would allow for tropospheric mixing that completely annihilates the dispersion model we see in Figures 10 & 11.

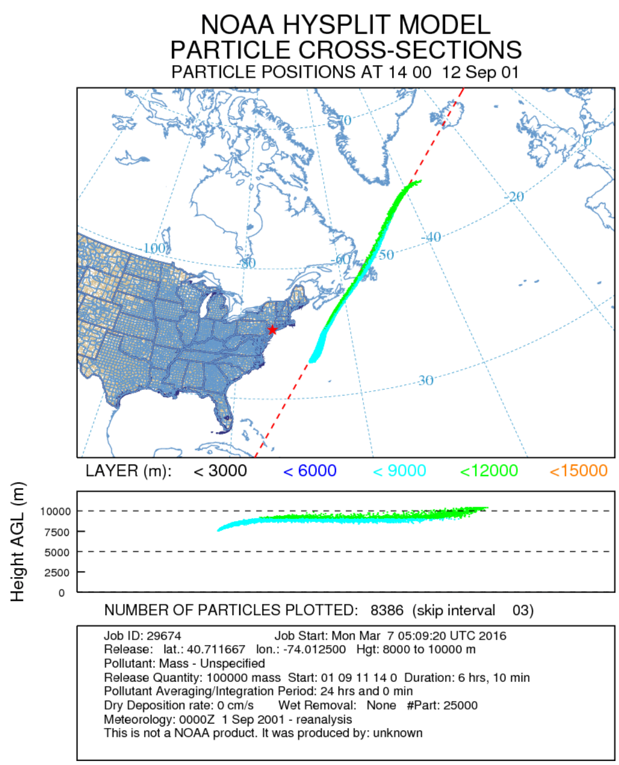



*Landfall of decaying Tropical Storm Gabrielle. Courtesy Plymouth State College, 2016.*

## Plume dispersion - Scenario 2. Gaseous Nuclear cloud:

Forecasting for the potential nuclear gas cloud / plume higher in the atmosphere is not as easy, especially as I was not able to run the plume dispersion for longer than a 24hrs period.




*Figures 12 & 13. Plume concentrations and particle position 24hrs after 'Nuclear device' scenario.*

Yet despite this we can use this 24hr dispersion run to help confirm the correlation between the synoptic analysis and the trajectory. The north-easterly flow being driven by a broad Rossby wave in the upper levels moves the plume offshore with a trajectory towards Greenland. This flow again is being driven by the anti-cyclonic rotation around the upper level high. If we can ascertain the development and direction of travel of this feature over the next few days, then we should be able to explain the rest of the trajectory run.

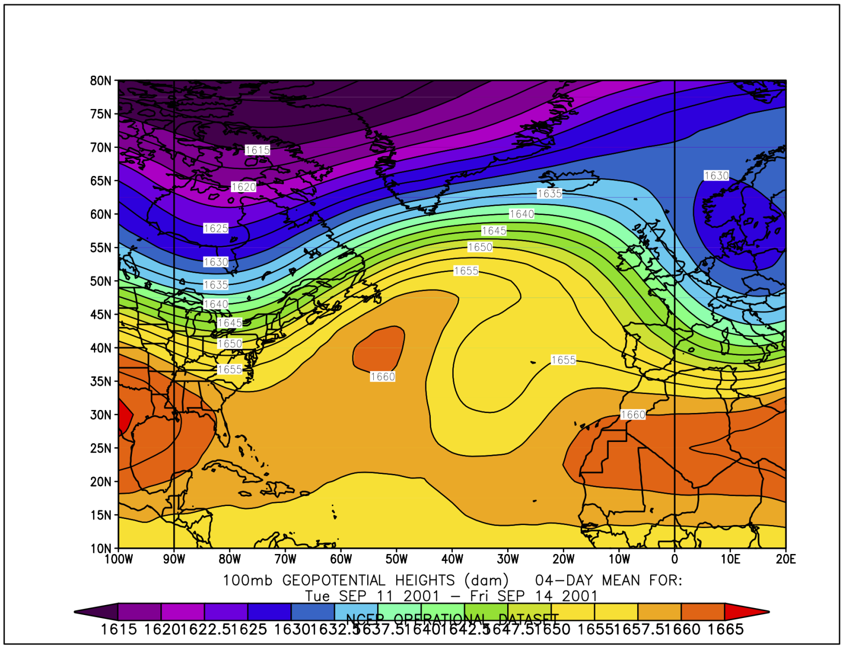



*Figure 14. 4-day averaged geopotential heights at 100mb*

Looking at the averaged synoptic pattern over the four days after the incident, we see the upper have an effect on the flow throughout the period, and the upper level Jet arc northwards then down slightly towards the United Kingdom and continental Europe. This aligns with our trajectory run again, and the persistent strong winds aloft then allow for such a distance to be covered. This is because the areas of high winds correspond to the areas of tightly packed geopotential contours from Figure 14.

What does this mean for a downstream population?

The fallout of such an event has far ranging consequences as seen by the distance of transport possible in such a short space of time. The deposition and settlement rate of any associated debris would need to be well understood before accurate forecasts could be produced, but it is obvious that prompt warning and emergency measures would need to be undertaken in locations such as the United Kingdom to avoid potential catastrophe. We could expect effects in the upper atmosphere over Western Europe to be observed within 72 hours from the time of incident.

## Discussion

This investigation has shown that with meteorology parameters alone we can estimate particle trajectory and plume dispersion similarly to how the HYSPLIT model uses met files.

The two scenarios here show that some of the greatest challengers exist in estimating the levels of the atmosphere that will be of concern. Since the meteorology that we are interested in (ie. wind speed and direction, turbulence, etc.) can be so different dependent on the height used, perhaps the safest thing to use is a blanket approach whereby all heights are used, and therefore a 'worst-case-scenario' is accounted for.

An alarming result from these comparisons of scenarios is that if we were indeed to inject the polar Jet with radioactive debris or contaminants then it would only be a mtter of one week before it would encircle the globe.

# References

[Council, 2005] Council, N. R. (2005). *Effects of Nuclear Earth-Penetrator and Other Weapons*. The National Academies Press, Washington, DC.

[Halverson, 2006] Halverson, J. B. (2006). Warm core structure of hurricane erin diagnosed from high altitude dropsondes during camex-4. *Bulletin of the American Meteorology Society*, 63:309–324.

[Rolph, 2015] Rolph, G. D. (2015). Real-time environmental applications and display system. `http://www.ready.noaa.gov`.

[Stein et al., 2015] Stein, A., Draxler, R., Rolph, G., Stunder, B., Cohen, M., , and Ngan, F. (2015). Noaa's hysplit atmospheric transport and dispersion modelling system. *Bulletin of the American Meteorology Society*, 96:2059–2077.

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