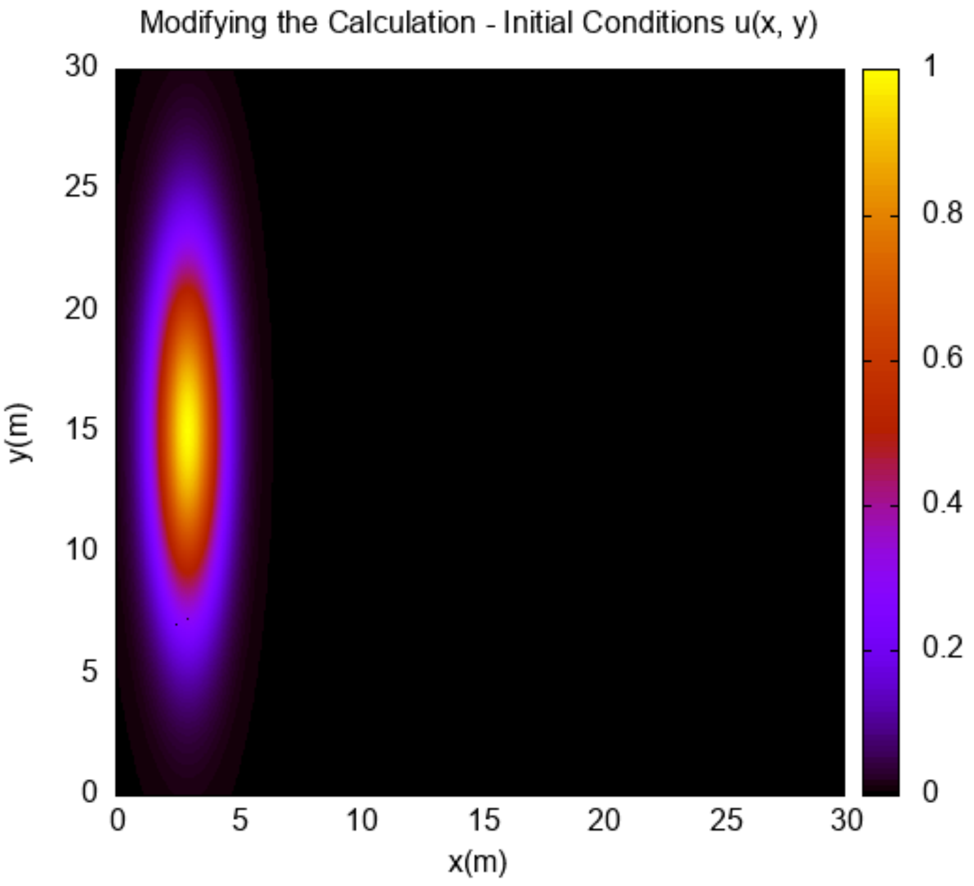
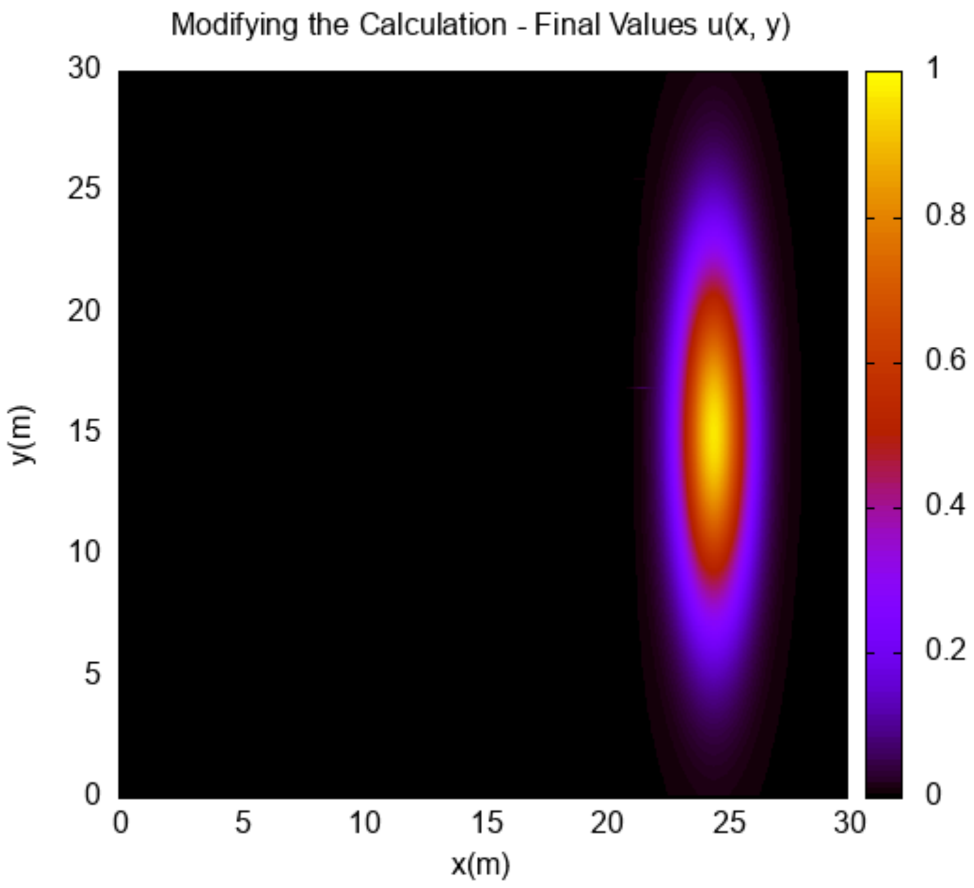
Source code can be found in the file ‘advection2D-final.c’ and is attached to the bottom of this file.

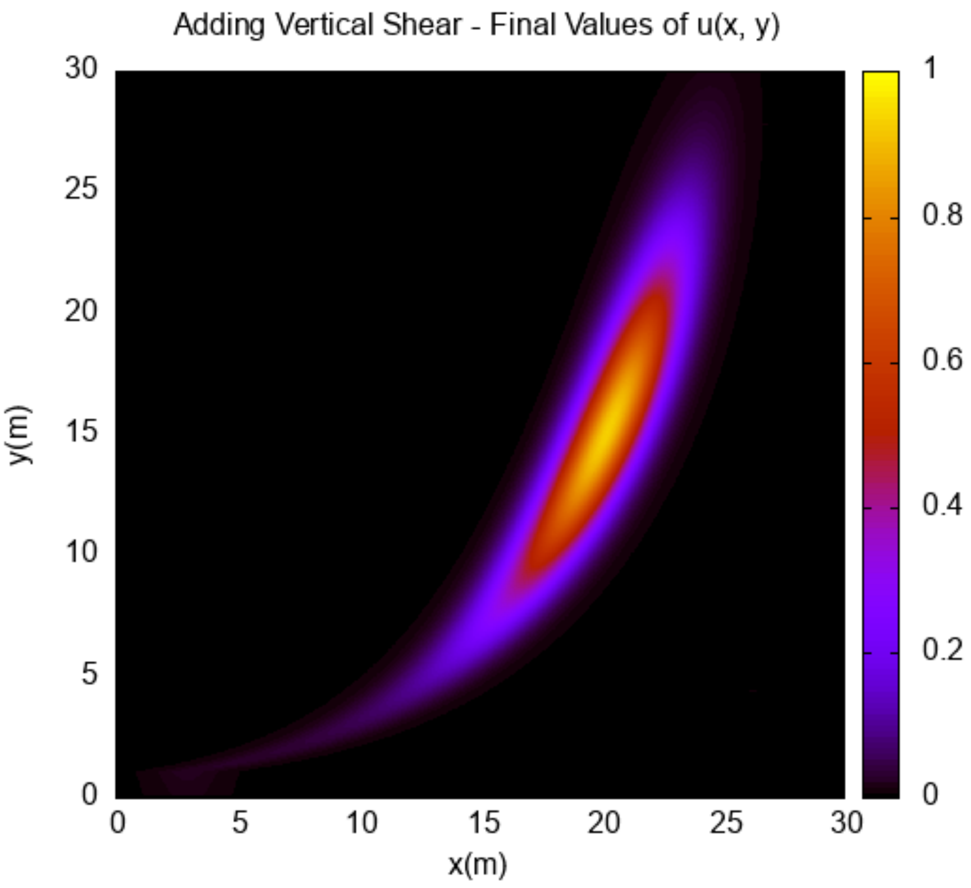
A plot of the initial conditions u(x, y) from section 2.2



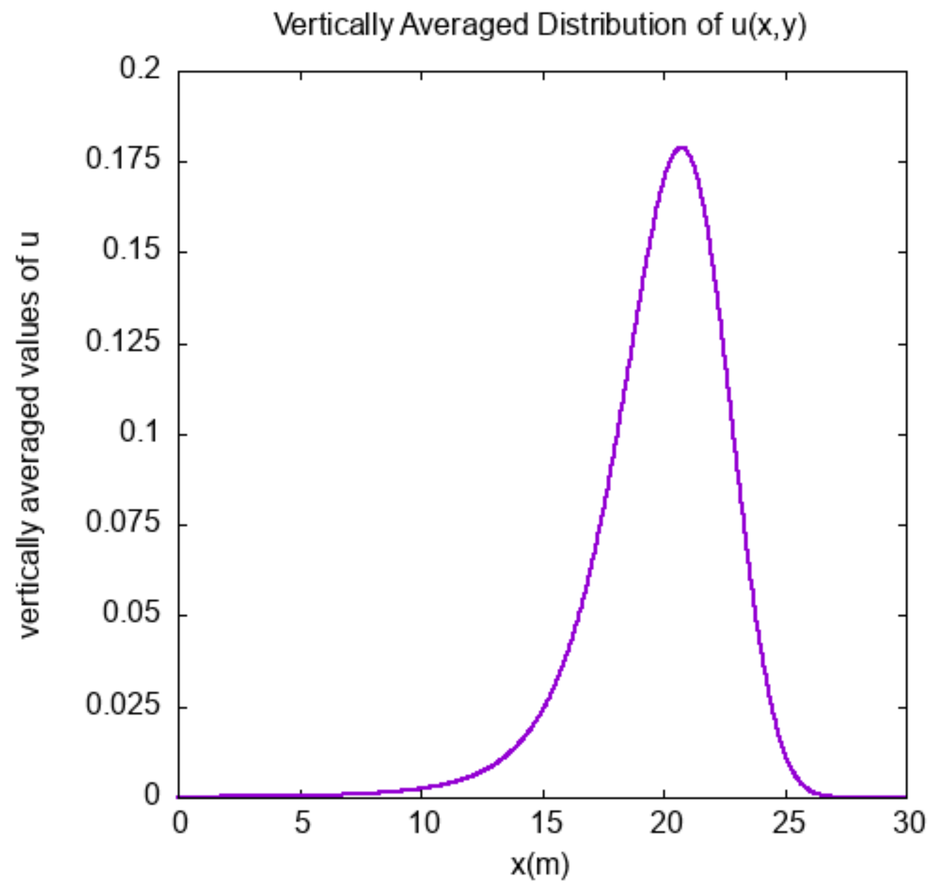
A plot of the final values of u(x, y) from section 2.2



A plot of the final values of u(x, y) from section 2.3



A plot showing the vertically averaged profile of u from section 2.4



```c
/***************************************************************************
*****
2D advection example program which advects a Gaussian u(x,y) at a fixed
velocity



Outputs: initial.dat - inital values of u(x,y)
         final.dat   - final values of u(x,y)

         The output files have three columns: x, y, u

         Compile with: gcc -o advection2D -std=c99 advection2D.c -lm

Notes: The time step is calculated using the CFL condition

***************************************************************************
*****/

/**********************************************************************
                     Include header files
***********************************************************************/

#include <stdlib.h>
#include <stdio.h>
#include <math.h>
#include <omp.h>

/**********************************************************************
                      Main function
***********************************************************************/

int main(){

  /* Grid properties */
  const int NX=1000;     // Number of x points
  const int NY=1000;     // Number of y points
  const float xmin=0.0;  // Minimum x value
  const float xmax=30.0; // Maximum x value
  const float ymin=0.0;  // Minimum y value
  const float ymax=30.0; // Maximum y value

  /* Parameters for the Gaussian initial conditions */
  const float x0=3.0;                 // Centre(x)
  const float y0=15.0;                // Centre(y)
  const float sigmax=1.0;             // Width(x)
  const float sigmay=5.0;                // Width(y)
  const float sigmax2 = sigmax * sigmax; // Width(x) squared
  const float sigmay2 = sigmay * sigmay; // Width(y) squared

  /* Boundary conditions */
  const float bval_left=0.0;    // Left boudnary value
  const float bval_right=0.0;   // Right boundary value
  const float bval_lower=0.0;   // Lower boundary
  const float bval_upper=0.0;   // Upper bounary

  /* Time stepping parameters */
  const float CFL=0.9;   // CFL number
  const int nsteps=800;  // Number of time steps

  /* Velocity */
  const float velx=1.0;  // Velocity in x direction
  const float vely=0.0;  // Velocity in y direction

  /* Arrays to store variables. These have NX+2 elements
     to allow boundary values to be stored at both ends */
  float x[NX+2];          // x-axis values
  float y[NX+2];          // y-axis values
  float u[NX+2][NY+2];    // Array of u values
  float dudt[NX+2][NY+2]; // Rate of change of u

  float x2;   // x squared (used to calculate iniital conditions)
  float y2;   // y squared (used to calculate iniital conditions)

  /* Calculate distance between points */
  float dx = (xmax-xmin) / ( (float) NX);
  float dy = (ymax-ymin) / ( (float) NY);

  /* Calculate time step using the CFL condition */
  /* The fabs function gives the absolute value in case the velocity is -ve
*/
  float dt = CFL / ( (fabs(velx) / dx) + (fabs(vely) / dy) );

  float modified_velx = 0.0; // our modified horizontal velocity
  const float ustar = 0.2;   // friction velocity
  const float k = 0.41;      // Von Karman's constant
  const float z0 = 1.0;      // roughness length

  /*** Report information about the calculation ***/
  printf("Grid spacing dx     = %g\n", dx);
  printf("Grid spacing dy     = %g\n", dy);
  printf("CFL number          = %g\n", CFL);
  printf("Time step            = %g\n", dt);
  printf("No. of time steps    = %d\n", nsteps);
  printf("End time             = %g\n", dt*(float) nsteps);
  printf("Distance advected x = %g\n", velx*dt*(float) nsteps);
  printf("Distance advected y = %g\n", vely*dt*(float) nsteps);

  /*** Place x points in the middle of the cell ***/
  /* LOOP 1 */
  // Variables scoped as shared by default
  // Each loop reads/writes to a different element of array 'x' so there is
no loop carried dependency
  #pragma omp parallel for default(shared)
  for (int i=0; i<NX+2; i++){
    x[i] = ( (float) i - 0.5) * dx;
  }

  /*** Place y points in the middle of the cell ***/
  /* LOOP 2 */
  // Variables scoped as shared by default
  // Each loop reads/writes to a different element of array 'y' so there is
no loop carried dependency
  #pragma omp parallel for default(shared)
  for (int j=0; j<NY+2; j++){
    y[j] = ( (float) j - 0.5) * dy;
  }

  /*** Set up Gaussian initial conditions ***/
  /* LOOP 3 */
  // Can write to a shared array using the unique index
  // Collapses the nested for loop into a single loop without using nested
parallelism
  // Compiler forms a single loop and then parallelises this
  #pragma omp parallel for collapse(2) default(shared)
  for (int i=0; i<NX+2; i++){
    for (int j=0; j<NY+2; j++){
      x2      = (x[i]-x0) * (x[i]-x0);
      y2      = (y[j]-y0) * (y[j]-y0);
      u[i][j] = exp( -1.0 * ( (x2/(2.0*sigmax2)) + (y2/(2.0*sigmay2)) ) );
    }
  }

  /*** Write array of initial u values out to file ***/
  FILE *initialfile;
  initialfile = fopen("initial.dat", "w");
  /* LOOP 4 */
  // Cannot be parallelised - Parallel loop iterations are not carried out
in the order specified by the loop iterator
  // The outer loop will mismatch the 'i' and 'j' indicies because they are
processsed by different threads.
  // These print statements need to happen in order so the loop iterations
must take place in order.
  // We can’t parallelise this loop.
  for (int i=0; i<NX+2; i++){
    for (int j=0; j<NY+2; j++){
      fprintf(initialfile, "%g %g %g\n", x[i], y[j], u[i][j]);
    }
  }
  fclose(initialfile);

  /*** Update solution by looping over time steps ***/
  /* LOOP 5 */
  // Cannot perfectly collapse loop due to differing inner loop depths
  // We can’t parallelise this loop.
  for (int m=0; m<nsteps; m++){

    /*** Apply boundary conditions at u[0][:] and u[NX+1][:] ***/
    /* LOOP 6 */
    // Variables scoped as shared by default
    // Can write to a shared array using the unique index
    #pragma omp parallel for default(shared)
    for (int j=0; j<NY+2; j++){
      u[0][j]    = bval_left;
      u[NX+1][j] = bval_right;
    }

    /*** Apply boundary conditions at u[:][0] and u[:][NY+1] ***/
    /* LOOP 7 */
    // Variables scoped as shared by default
    // Can write to a shared array using the unique index
    #pragma omp parallel for default(shared)
    for (int i=0; i<NX+2; i++){
      u[i][0]    = bval_lower;
      u[i][NY+1] = bval_upper;
    }

    /*** Calculate rate of change of u using leftward difference ***/
    /* Loop over points in the domain but not boundary values */
    /* LOOP 8 */
    // Variables scoped as shared by default
    // Each inner loop reads/writes to a different element of array 'duct'
so there is no loop carried dependency
```

```
  // Collapses the nested for loop into a single loop without using
nested parallelism
  // Compiler forms a single loop and then parallelises this
  #pragma omp parallel for collapse(2) default(shared)
  for (int i=1; i<NX+1; i++){
   for (int j=1; j<NY+1; j++){
    // TASK 3 - Adding Vertical Shear
    if (y[j] > 1) {
     // modified_velx = (ustar / k) * (log(y[j]) / 1.66); // close to
sqr root (e)
     // modified_velx = (ustar / k) * (log(y[j]) / sqrt(M_E)); // was
not working on remote linux
     modified_velx = (ustar / k) * (log(y[j]) / sqrt(exp(z0)));
    } else { // this else loop isn't strictly necessary but helps with
readability
      modified_velx = 0.0;
    }
    dudt[i][j] = -modified_velx * (u[i][j] - u[i-1][j]) / dx
          - vely * (u[i][j] - u[i][j-1]) / dy;
   }
  }

  /*** Update u from t to t+dt ***/
  /* Loop over points in the domain but not boundary values */
  /* LOOP 9 */
  // Variables scoped as shared by default
  // Each inner loop reads/writes to a different element of array 'u' so
there is no loop carried dependency
  // Can write to a shared array using the unique index
  // Collapses the nested for loop into a single loop without using
nested parallelism
  // Compiler forms a single loop and then parallelises this
  #pragma omp parallel for collapse(2) default(shared)
  for (int i=1; i<NX+1; i++){
   for (int j=1; j<NY+1; j++){
    u[i][j] = u[i][j] + dudt[i][j] * dt;
   }
  }

 } // time loop

 /*** Write array of final u values out to file ***/
 FILE *finalfile;
 finalfile = fopen("final.dat", "w");
 /* LOOP 10 */
```

```c
  // Cannot be parallelised - Parallel loop iterations are not carried out
in the order specified by the loop iterator
  // The outer loop will mismatch the 'i' and 'j' indicies because they are
processsed by different threads.
  // These print statements need to happen in order so the loop iterations
must take place in order.
  // We can’t parallelise this loop.
  for (int i=0; i<NX+2; i++){
    for (int j=0; j<NY+2; j++){
      fprintf(finalfile, "%g %g %g\n", x[i], y[j], u[i][j]);
    }
  }
  fclose(finalfile);

  // TASK 4 - Calculating the Vertically Averaged Distribution
  float avg[NY]; // variable store avg intensity at each value of x
  float intensity_sum; // allows us to average the value of u(x,y) for the
entire range of y values at each value of x
  /* Loop over points in the domain but not boundary values */
  for(int i=1; i<NX+1; i++){
      intensity_sum = 0.0;
    for (int j=1; j<NY+1; j++){
      intensity_sum += u[i][j]; // sum the y attribute of u(x, y) at each
value of x
    }
    avg[i] = intensity_sum / (float) NY; // average the values of intensity
in the y direction at each value of x
    // printf("%d\n", NY);
    // printf("%f\n", intensity_sum);
    // printf("%f\n\n", avg[i]);
  }

  /*** Write array of vertically averaged u values out to file ***/
  FILE *vertavgfile;
  vertavgfile = fopen("vertavg.dat", "w");
  for (int i=0; i<NX+1; i++){
    for (int j=0; j<NY+1; j++){
      fprintf(vertavgfile, "%g %g\n", x[i], avg[i]);
    }
  }
  fclose(vertavgfile);

  return 0;
}

/* End of file ******************************************************/
```

```
# This gnuplot script plots the results from the first coursework assignment.
# It is assumed that the data to be plotted are in a file called
# final.dat which contains 3 columns: x,y,u
# The plot is sent to a PNG file called final.png
# To use this file copy it to the directory/folder containing
# final.dat and run the command:
# gnuplot plot_final


# Send output to a PNG file
set terminal png  enhanced

# Set ranges and labels for axes
set xrange [0:30.0]
set yrange [0:30.0]
set xlabel "x(m)"
set ylabel "y(m)"

# Enforce an aspect ratio of 1
set size square

# Set the range of the colour scale
set cbrange [0:1]


#------ TASK 2 ------- Uncomment as appropriate
# # Set the title of the figure for task 2 initial conditions
# set title "Modifying the Calculation - Initial Conditions u(x, y)" offset 0,0.1
# # Set the name of the output file
# set output "initial-two.png"
# # Plot the data
# plot "initial.dat" with image


#------ TASK 2 ------- Uncomment as appropriate
# # Set the title of the figure for task 2 final values
# set title "Modifying the Calculation - Final Values u(x, y)" offset 0,0.1
# # Set the name of the output file
# set output "final-two.png"
# # Plot the data
# plot "final.dat" with image
```

```
#------ TASK 3 ------- Uncomment as appropriate
# Set the title of the figure for task 3 final values
set title "Adding Vertical Shear - Final Values of u(x, y)" offset 0,0.1
# Set the name of the output file
set output "final-three.png"
# Plot the data
plot "final.dat" with image


# End of file
```

```
# This gnuplot script plots the results from the first coursework
assignment.
# It is assumed that the data to be plotted are in a file called
# final.dat which contains 3 columns: x,y,u
# The plot is sent to a PNG file called final.png
# To use this file copy it to the directory/folder containing
# final.dat and run the command:
# gnuplot plot_final


# Send output to a PNG file
set terminal png  enhanced
# Set the name of the output file
set output "vertavg.png"

# Set ranges and labels for axes
set xrange [0:30.0]
set yrange [0:0.2]
set ytics 0,0.025,0.2
set xlabel "x(m)"
set ylabel "vertically averaged values of u"

# Enforce an aspect ratio of 1
set size square

# Set linestyle 1 to blue (#0060ad)
set style line 1 \
    linecolor rgb '#0060ad' \
    linetype 1 \

set title "Vertically Averaged Distribution of u(x,y)" offset 0,0.1
```

```
# Plot the data
plot 'vertavg.dat' with linespoints pt 0 lw 2 title ''

# End of file
```