PROJECT 3 - PROBLEM 1.14 in the lecture notes (p.126)
(in groups of max. 3 students) (15%)

Simulation of the sea/land breeze at the coast

In this small research project you will be concerned with a "Eulerian" numerical simulation model. You will be surprised about how close you can make a simple model correspond to observations!

The following eleven theoretical concepts or topics come up for discussion.

1. Coriolis force / acceleration
2. Inertial oscillation / inertial frequency or period
3. Geostrophic balance
4. Geostrophic wind and ageostrophic wind
5. Numerical approximations of the time derivative (Euler-forward, leap-frog, etc.)
6. Parametrisation
7. Rayleigh damping
8. Model initialisation
9. Model verification (Taylor diagram)
10. Correlation, standard deviation, root mean square (RMS) difference, biass, centred pattern RMS
11. Eulerian

The model, which is based on equations 1.110a and 1.110b in the lecture notes (repeated below), can simulate the time evolution of the horizontal wind velocity vector at the surface at one location at the coast, under influence of an imposed pressure gradient force, the Coriolis force and a frictional force. The model is called "Eulerian" because it does not describe the dynamics of one air parcel, as the "Lagrangian" model of Project 1, but instead describes the time-evolution of the horizontal wind-velocity and direction at a fixed point in space. For simplified boundary conditions and excluding the frictional term the model equations have an analytical solution, which can be used to test the accuracy of the numerical approximations of the time–derivatives in the governing differential equations.

Here, the model is used to simulate the sea/land breeze at the Dutch coast on 2 consecutive days in May. The model-performance is evaluated by comparing the output with hourly observations at the coastal measurement site of IJmuiden (west of Amsterdam) (**figure 1.35**, page 96). The quality of the simulation (or forecast) is quantified by *correlating* the simulated time series with hourly observations, by calculating the ratio of the *standard deviations* of the two time series and by the *root-mean-square difference* between the two time series (the simulation and the observations of both *u* and *v*).

The performance of the model depends on the initial conditions and on the value of certain coefficients, like the frictional damping coefficient, which can be chosen freely and can be used to optimize the performance ("tune") of the model.

The background theory is described in **section 1.17** of the lecture Notes on Atmospheric Dynamics.

A "skeleton Python script" is provided in **Box 1.9**.

A file containing the observational data, which is needed to compare the model output with reality, is provided separately.

Please study **section 1.17** and **Boxes 1.9** and **1.10**.

PROBLEM 1.14. **Simulation of the sea breeze at the coast: parametrising the effect of surface drag (PROJECT 3, in groups of up to 3 students)**.
In this research project you will use **Eulerian** numerical simulation sea breeze model, as opposed to the **Lagrangian** convection model of **PROJECT 1** (page 53). A first version of the Python code of the model is given (**Box 1.9**).

(a) The wind at IJmuiden on 7 and 8 May 1976 (48 hours) is driven by a pressure gradient perpendicular to the coast (the x-axis is perpendicular to the coast), which varies in time according to

$$\frac{\partial p}{\partial x} = A\cos(\Omega t + \varphi) + B\,. \qquad (1.109)$$

Assume that A, B and φ are constant. Find the "best values" of A, B and φ (eq. 1.109) by linearly fitting the observed *average daily cycle of the pressure gradient* at IJmuiden on 7 and 8 May 1976 (the result of the analysis in **problem 1.13**) to the analytical equation 1.109. You will be given the result of problem 1.13 if you have not done this problem.

(**b**) The model (**Box 1.9**) is based on eqs. 1.110a,b, with a "**Rayleigh-damping**" term added to represent drag of the atmosphere with the earth's surface:

$$\frac{\partial u}{\partial t} = fv - \frac{A}{\rho}\cos(\Omega t + \varphi) - \frac{B}{\rho} - \lambda u\ , \qquad (1.110a)$$

$$\frac{\partial v}{\partial t} = -fu - \lambda v\ , \qquad (1.110b)$$

Run the model assuming a state of rest at t=0. Compare the outcome with the analytical solution (1.108a,b). The accuracy of the numerical solution will depend on the time step, Δt. Find the appropriate value for Δt.

(**c**) Initialise the model using the observed values of u and v at IJmuiden at 00 UTC on 7 May 1976 (u=-9.0 m s^{-1}; v= -7.6 m s^{-1}) (https://www.knmi.nl/nederland-nu/klimatologie/uurgegevens). First assume that the Rayleigh damping coefficient, λ=0. Compare the numerical solution with the hourly observations of u and v at IJmuiden between 00 UTC on 7 May 1976 and 23 UTC on 8 May 1976, by evaluating the correlation coefficient, standard deviation, root-mean-square (RMS) difference and centred pattern RMS (**Box 1.10**). The parameter, λ, is used to "tune" the model to fit the observations as best as possible. Numerical models for weather prediction contain many of such tuning parameters! Find the "best" value of λ. Explain your criteria. Does friction reduce the rate of turning of the wind (see **figures 1.33** and **1.34**)?

(**d**) Repeat part (**c**) with the best value of λ by initialising the model with the observed values of u and v at IJmuiden at 12 UTC on 6 May 1976 (u= +3.9 m s^{-1}; v= -3.3 m s^{-1}) and again compare the outcome with the hourly observations of u and v at IJmuiden between 00 UTC on 7 May 1976 and 23 UTC on 8 May 1976 (+12 hour to +59 hour forecast). What do you conclude?

(**e**) Try a different representation of surface drag, which depends on the square of the velocity as,

$$\frac{\partial u}{\partial t} = \ldots - C_D|\vec{v}|u\ ,$$

where C_D is the drag-coefficient and $|\vec{v}|$ is the absolute value of the wind velocity vector. Does this parametrisation work better than the linear Rayleigh damping?