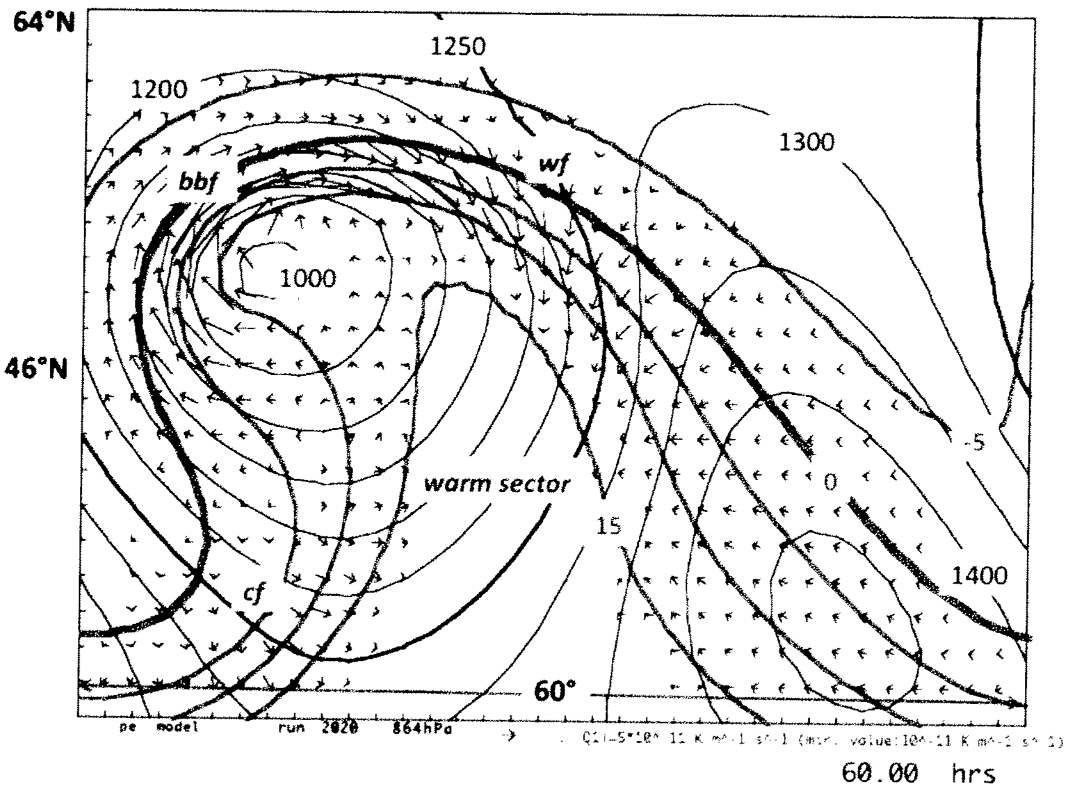
Exam: Dynamical Meteorology
Date: 11 November, 2011, 09:30-12:30

In this exam all symbols have their normal definitions.
Answers may be given in either English or Dutch.

Problem 1 (1.5 points)
Q-vector



Potential temperature, isobaric height and the ***Q*-vector** at the 864 hPa-isobaric level in a simulation of the life-cycle of a mid-latitude cyclone with a numerical model of the atmospheric circulation, which neglects frictional and diabatic effects. Thin solid **dark blue** lines are isopleths of the isobaric height (contour interval is 50 m, thick line corresponds to 1250 m). Thick light blue lines are isopleths of potential temperature (contour interval is 5 K, thick line corresponds to 0°C). Q-vectors (arrows) are shown only if the absolute value exceeds 10^{-11} K m^{-1} s^{-1}. The vertical axis corresponds to latitude. The horizontal axis corresponds to longitude. The boundary conditions at the western and eastern boundary are periodic.

The frontogenetical function is defined as follows.

$$\frac{d\left(\vec{\nabla}_h\theta\right)^2}{dt} = 2\vec{\nabla}_h\theta\cdot\frac{d\vec{\nabla}_h\theta}{dt} \equiv 2\vec{Q}\cdot\vec{\nabla}_h\theta.$$

Here $\vec{\nabla}_h\theta$ is the horizontal gradient of the potential temperature $\vec{Q}$ is referred to as the "Q-vector". Is the cold front (*cf*) (see the figure above) undergoing frontogenesis or frontolysis? Is the warm front (*wf*) undergoing frontogenesis or frontolysis? What is happening to the back-bent front (*bbf*)? What information do you need to compute the two components of the "Q-vector"?

1

Problem 2 (2 points)

Stability of geostrophic balance

Suppose that air in the atmosphere flows in west-east (zonal) direction and that, associated with this flow pattern, the meridional (y-) component of the pressure gradient force and the meridional component of the Coriolis force are in exact balance. This implies that the y-component of the equation of motion is,

$$fu_g = -\theta \frac{\partial \Pi}{\partial y},$$

where , u_g is the geostrophic wind, f is the Coriolis parameter, θ is the potential temperature and Π is the Exner function. In this hypothetical state there is no pressure gradient in the zonal (x-) direction. The horizontal motion is governed by the following two components of the equation of motion.

$$\frac{du}{dt} = fv; \qquad \frac{dv}{dt} = -\theta \frac{\partial \Pi}{\partial y} - fu.$$

The geostrophic wind at a point $y=y_0+\delta y$ can, therefore, be approximated by

$$u_g(y_0 + \delta y) \cong u_g(y_0) + \frac{\partial u_g}{\partial y}(y_0)\delta y \ .$$

The shear of the geostrophic wind,

$$\frac{\partial u_g}{\partial y} = 10^{-4} \text{ s}^{-1}.$$

Let us now consider an air parcel with a fixed mass which is located at $y= y_0= -1000$ km (i.e in the southern hemisphere), moving with the geostrophic velocity at that latitude. By an unspecified external force in the y-direction this air parcel is brought to a new position: $y=y_0+\delta y$ in the southern hemisphere without disturbing the pressure distribution. Will this air parcel spontaneously return to its original position $y=y_0$? Give a proof of your answer.

Problem 3 (2 points)

Potential temperature equation

Show that

$$\frac{d\theta}{dt} = \frac{J}{\Pi}$$

from

$$Jdt = c_v dT + p d\alpha \qquad (1)$$

($\alpha \equiv 1/\rho$) and

$$p\alpha = RT. \qquad (2)$$

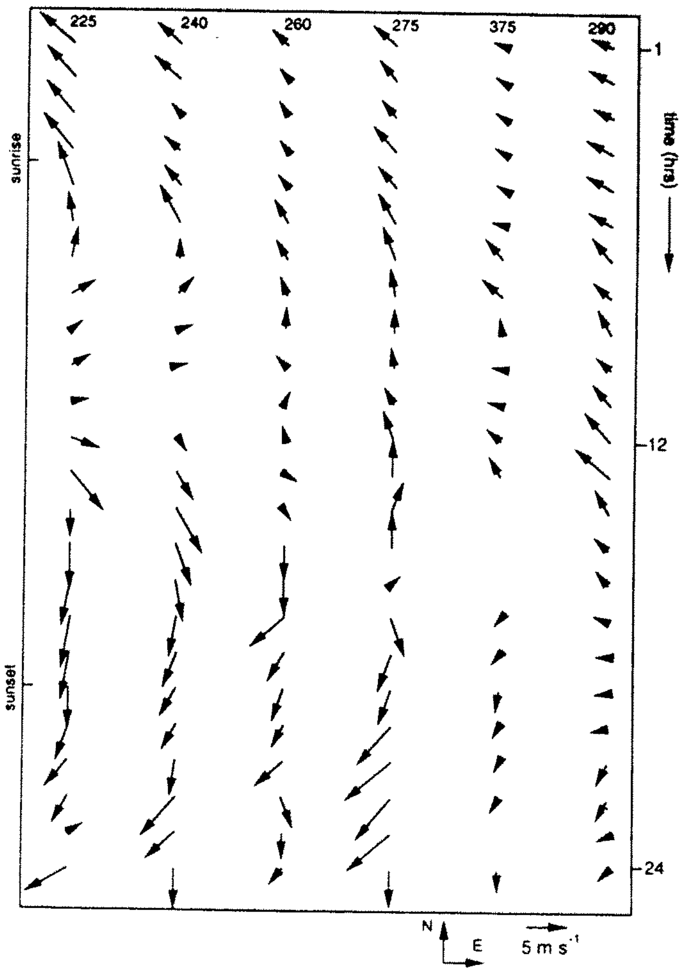
and

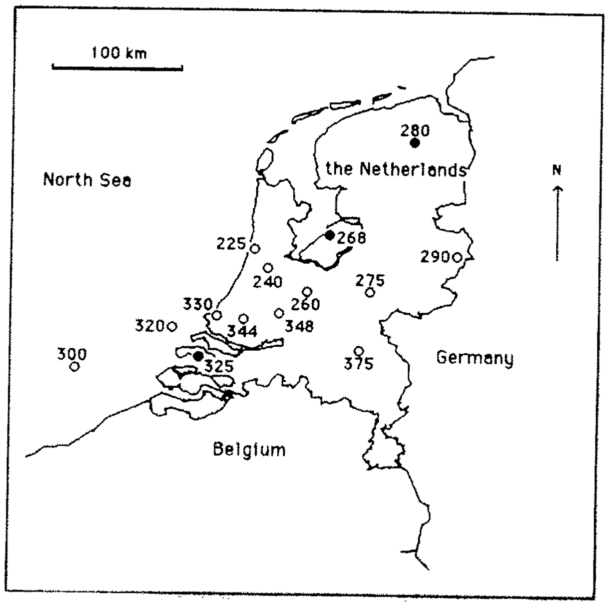
$$\theta = T\left(\frac{p_{ref}}{p}\right)^{\kappa} = \frac{c_p T}{\Pi} \qquad (3)$$

($\kappa \equiv R/c_p$). Furthermore: $R = c_p - c_v$. What physical law does equation (1) represent? What physical process does the symbol, J, represent?

Problem 4 (2 points)

Daily wind fluctuations





The figure on the left (above) shows hourly wind vectors at 10 m above the Earth's surface as a function of time on the very sunny of May 8, 1976, at six stations in the Netherlands. The station on the left (225) is closest to the coast, while the station on the right (290) is furthest from the coast (see the figure on the right for the exact location of the stations). Give an interpretation of these wind observations.

Problem 5 (2.5 points)

Multiple choice

(i) Which group of four constituents of the atmosphere is well mixed?

(a) Nitrogen, oxygen, carbon dioxide and argon

(b) Nitrogen, oxygen, carbon dioxide and water vapour

(c) Nitrogen, oxygen, carbon dioxide and ozone

(ii) The mixing ratio by volume of carbon dioxide in dry air is defined as

(a) the number of carbon dioxide molecules per unit volume divided by the number of dry air molecules per unit volume

(b) the density of carbon dioxide in air divided by the density of dry air

(c) the volume occupied by carbon dioxide in an air sample divided by the total volume of the air sample

(iii) The Clausius-Clapeyron equation is an equation of state

(a) for a heterogeneous system consisting of a substance in more than one phase

(b) for a heterogeneous system consisting of water vapour, liquid water and ice

(c) for a heterogeneous system consisting of water vapour and liquid water

(iv) If the density of water vapour in the atmosphere decreases exponentially with increasing height, z (with constant scale height, H_v), then the fraction of the total mass of water vapour that is located below $z = H_v$ is

(a) equal to 2/3

(b) more than 2/3

(c) more than 63%

(v) If the geostrophic wind veers (turns clockwise) with increasing height,

(a) this indicates cold air advection

(b) this indicates warm air advection

(c) this indicates upward motion