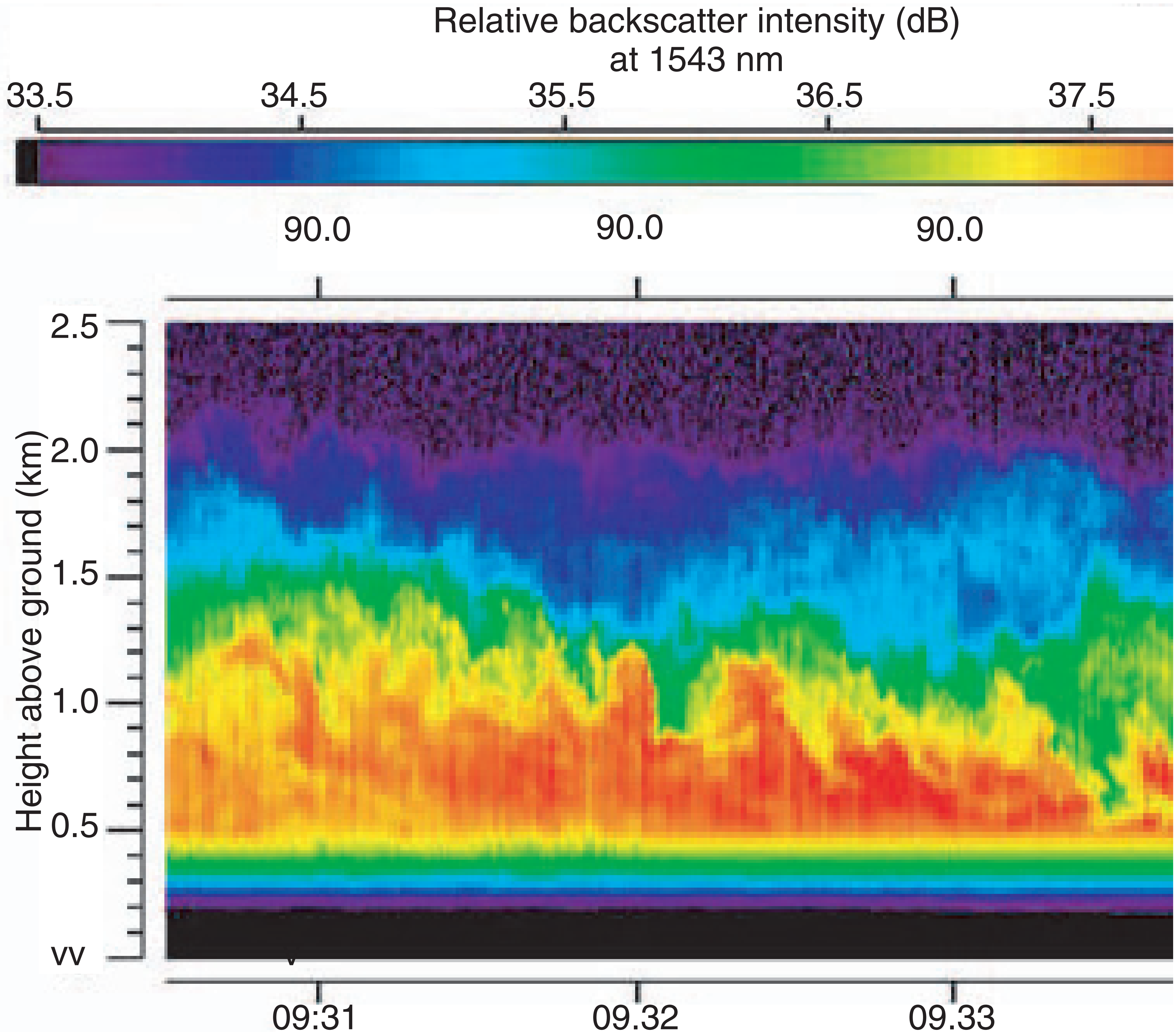
The Atmospheric Boundary Layer

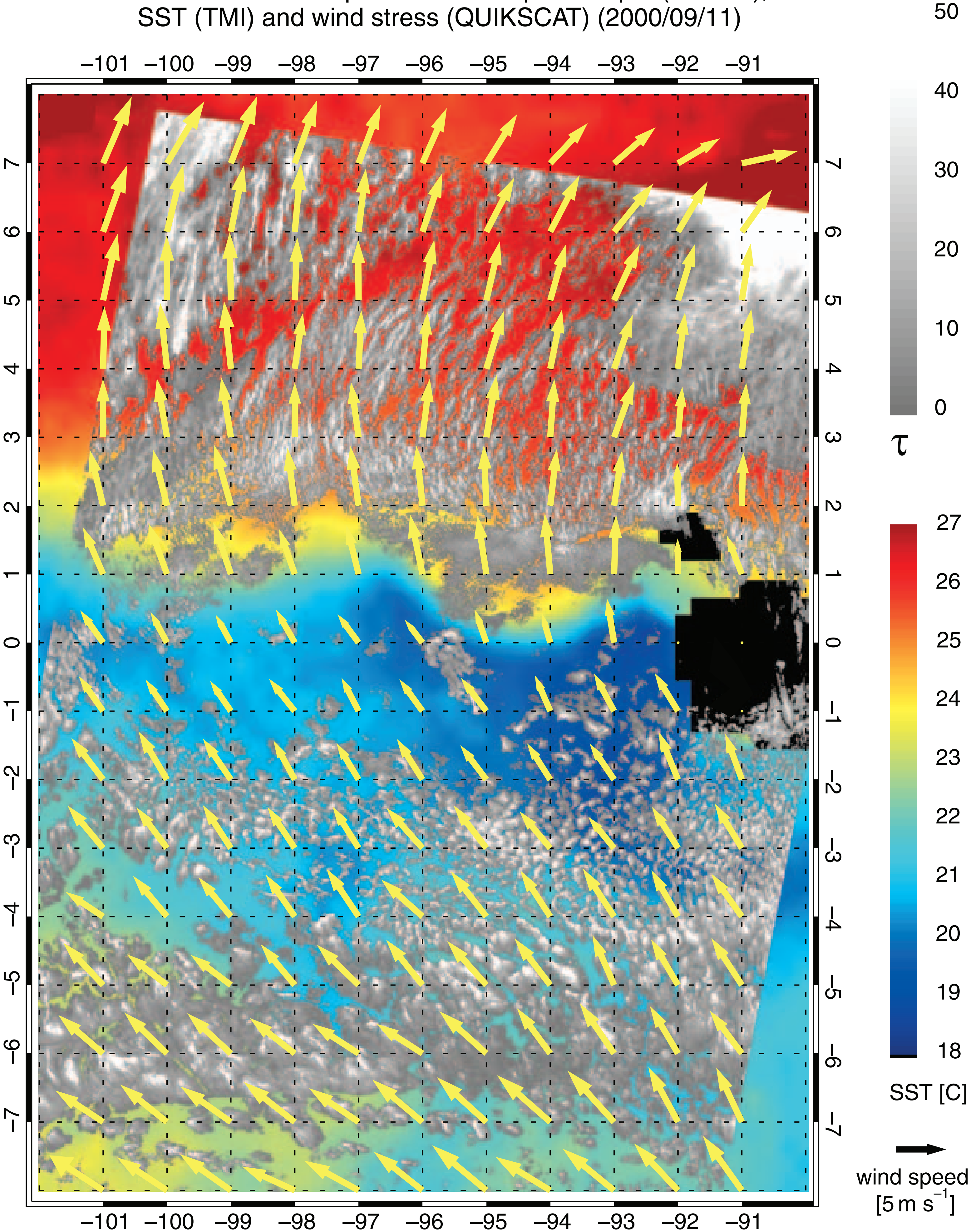
- Turbulence (9.1)
- The Surface Energy Balance (9.2)
- Vertical Structure (9.3)
- Evolution (9.4)
- Special Effects (9.5)
- ***The Boundary Layer in Context (9.6)***

- *Advances will continue to be made in boundary layer meteorology due to*
  - advances in *measurement* capabilities, both *in situ* and remote
  - increased *computational* capabilities of research numerical models
  - increases in resolution of *NWP* models
  - needs of *wind power* generation, *urban* meteorology, *wildfire* science, etc



Relative backscatter intensity (dB)
at 1543 nm
33.5
34.5
35.5
36.5
37.5
90.0
90.0
90.0
2.5
2.0
1.5
1.0
0.5
vv
Height above ground (km)
09:31
09.32
09.33

East Pacific cross-equatorial cloud optical depth (MODIS), SST (TMI) and wind stress (QUIKSCAT) (2000/09/11)



Boundary Layer Winds

For the special case of horizontallly homogeneous turbulence above the viscous sublayer (?), molecular viscosity and horizontal turbulent momentum flux divergence terms can be neglected. The mean flow momentum equations (5.9) and (5.10) become

$$\frac{\overline{D}\,\overline{u}}{Dt} = -\frac{1}{\rho_0}\frac{\partial \overline{p}}{\partial x} + f\overline{v} - \frac{\partial \overline{u'w'}}{\partial z} \tag{5.16}$$

and

$$\frac{\overline{D}\,\overline{v}}{Dt} = -\frac{1}{\rho_0}\frac{\partial \overline{p}}{\partial y} - f\overline{u} - -\frac{\partial \overline{v'w'}}{\partial z}. \tag{5.17}$$

In the boundary layer the turbulent terms must be included, and the resulting approximation is

$$f(\overline{v} - \overline{v}_g) - \frac{\partial \overline{u'w'}}{\partial z} = 0, \tag{5.18}$$

$$-f(\overline{u} - \overline{u}_g) - \frac{\partial \overline{v'w'}}{\partial z} = 0 \tag{5.19}$$

a three-way balance between the Coriolis force, the pressure gradient force, and the turbulent momentum flux divergence. Here

$$\mathbf{V}_g \equiv \mathbf{k} \times \frac{1}{\rho f}\nabla p \tag{2.23}$$

is used to express the pressure gradient force in terms of geostrophic velocity.

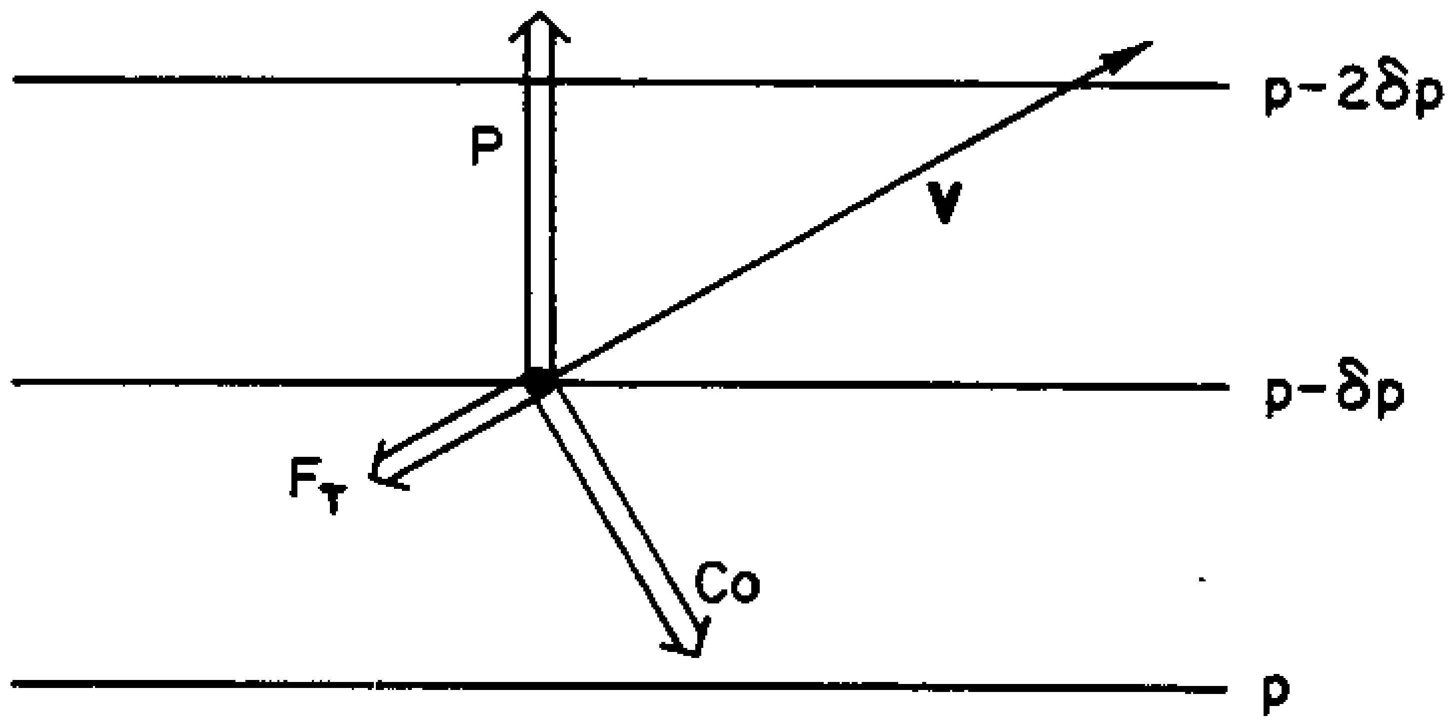


Fig. 5.3 Balance of forces in the well-mixed planetary boundary layer: P designates the pressure gradient force, Co the Coriolis force, and F_{T} the turbulent drag.

Boundary Layer Winds

5.3.1 Well–Mixed Boundary Layer

If a convective boundary layer is topped by a stable layer, turbulent mixing can lead to the formation of a well–mixed (ML) layer. Such boundary layers are common over land during the day when surface heating is strong and over oceans when the air near the sea surface is colder than the surface water temperature.

Observations also indicate that the surface momentum flux can be represented by a *bulk aerodynamic formula* where

$$(\overline{u'w'})_s = -C_d\,|\overline{V}|\,\overline{u}$$

and

$$(\overline{v'w'})_s = -C_d\,|\overline{V}|\,\overline{v}.$$

C_d is a nondimensional *drag coefficient*, $|\overline{V}| = (\overline{u}^2 + \overline{v}^2)^{1/2}$, and the subscript s denotes surface values (taken at standard anemometer height). Observations show that $C_d \sim 1.5 \times 10^{-5}$ over oceans, and is several times as large over land.

Boundary Layer Winds

Using this representation for surface momentum flux, (5.18) and (5.19) can be integrated from the surface to the top of the boundary layer where $z = h$ to give

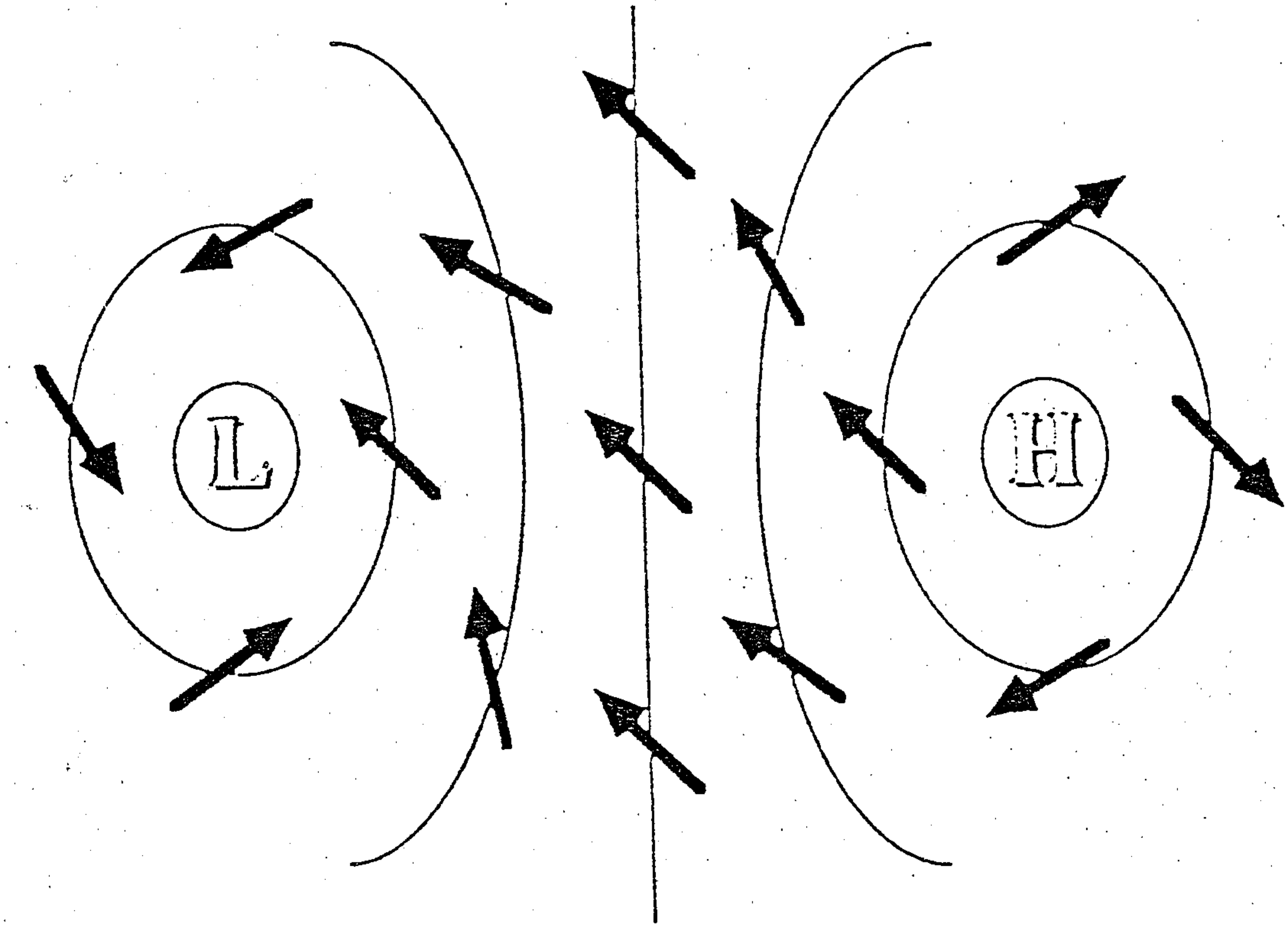
$$f(\overline{v} - \overline{v}_g) = -\frac{(\overline{u'w'})_s}{h} = \frac{C_d\,|\overline{V}|\,\overline{u}}{h}, \tag{5.20}$$

$$-f(\overline{u} - \overline{u}_g) = -\frac{(\overline{v'w'})_s}{h} = \frac{C_d\,|\overline{V}|\,\overline{v}}{h}. \tag{5.21}$$

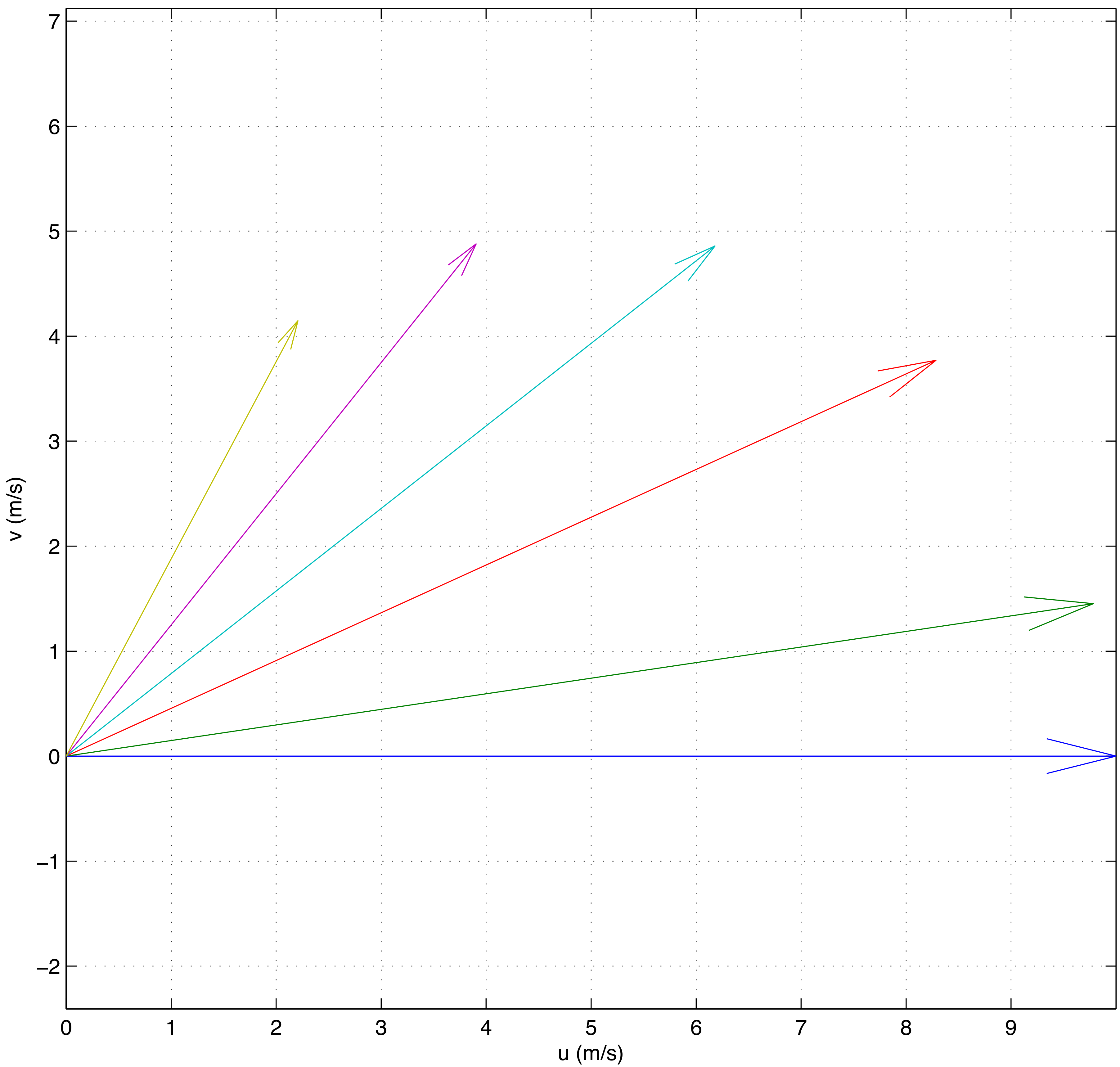
By choosing the axes such that $\overline{v}_g = 0$, (5.20) and (5.21) are written

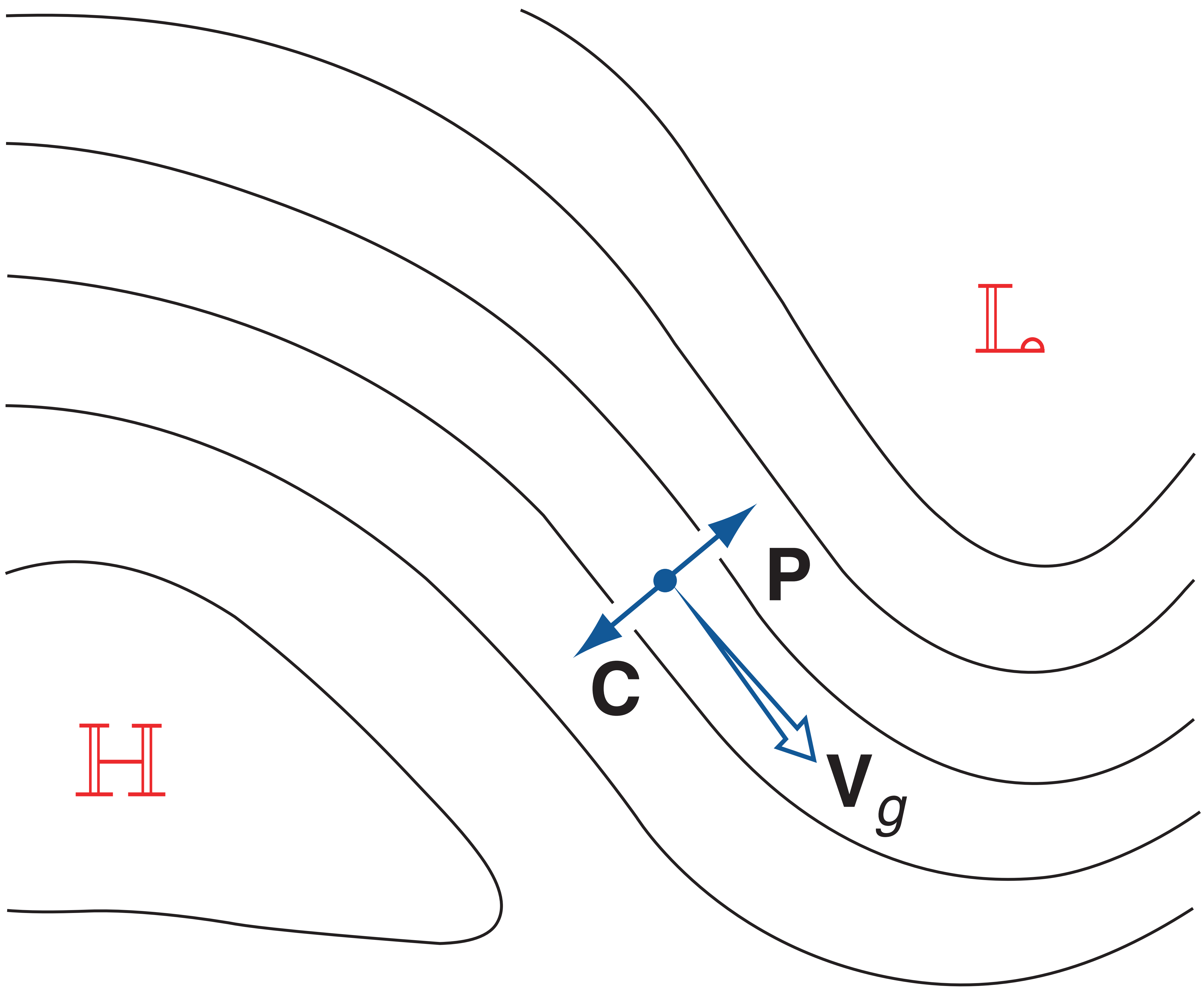
$$\overline{v} = \kappa_s|\overline{\mathbf{V}}|\overline{u}, \qquad \overline{u} = \overline{u}_g - \kappa_s|\overline{\mathbf{V}}|\overline{v} \tag{5.22}$$

where $\kappa_s \equiv C_d/(fh)$. You have already seen this wind behavior in your Synoptic Meteorology class; near the surface winds tend to spiral *into* lower pressure centres, *out of* high pressure centres. In the mixed layer wind speed is less than geostrophic speed, and there is a component of motion directed toward lower pressure (that is, to the left of the geostrophic wind in the Northern Hemisphere and to the right of the geostrophic wind in the Southern Hemisphere) whose magnitude depends on κ_s. If we plug in typical values for $\overline{u}_g$ and κ_s into (5.22), $|\overline{\mathbf{V}}|$ will be less than the magnitude of the geostrophic wind.

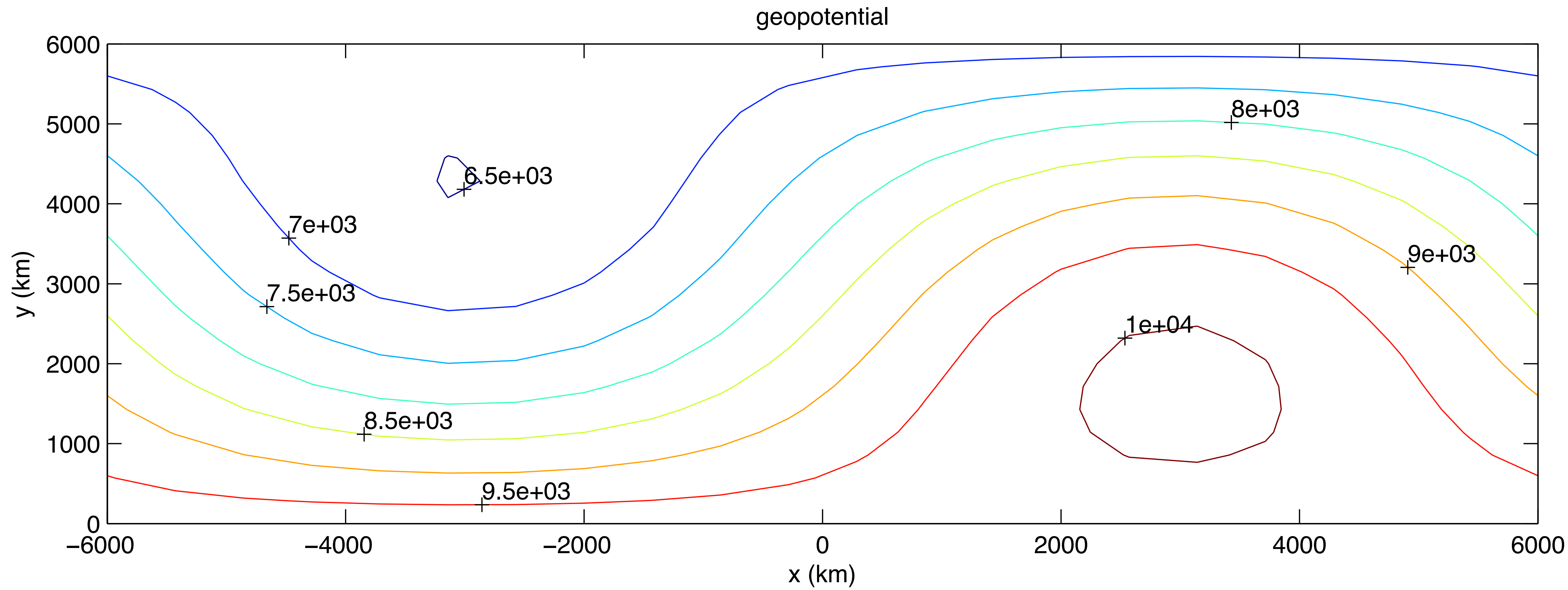

L
H

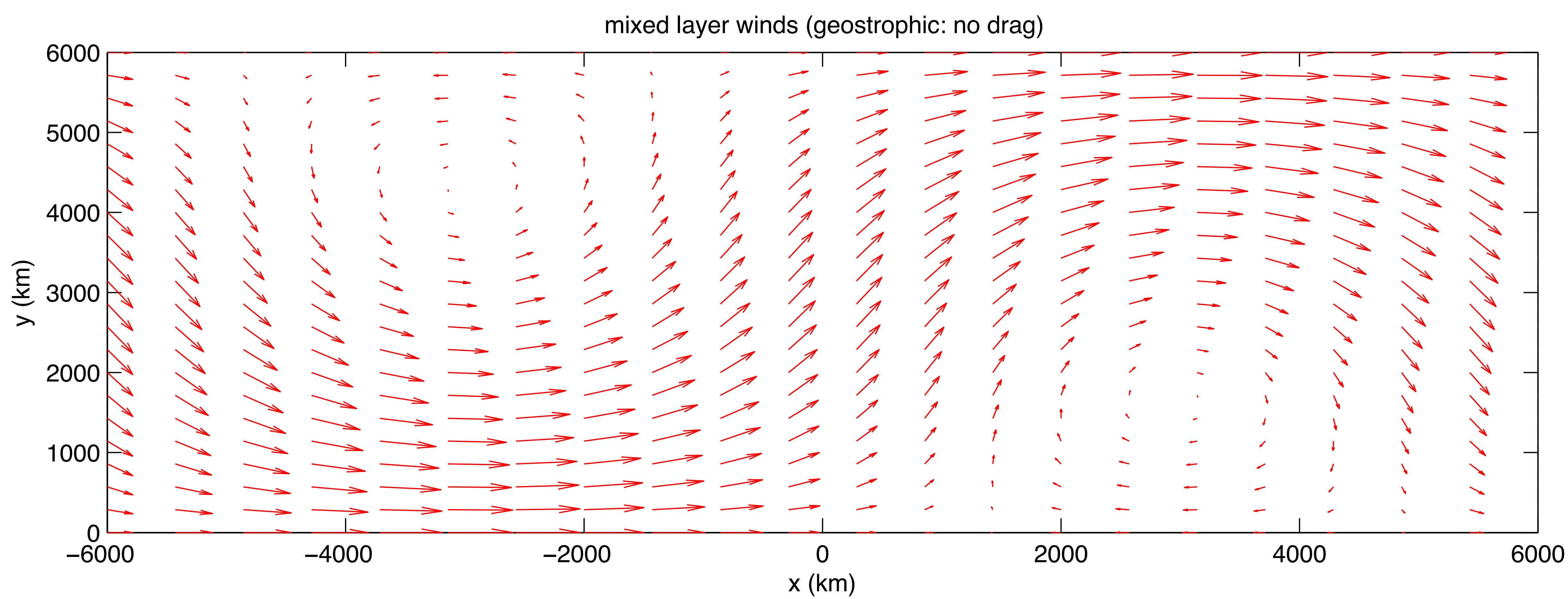
Use the mixed layer expressions for $\bar{u}$ and $\bar{v}$ to calculate $\bar{u}$, $\bar{v}$, $|\bar{\mathbf{V}}|$, and the cross-isobar angle of $\bar{\mathbf{V}}$ for $\bar{u}_g = 10$ m/s and $\kappa_s = 0$, 0.015, 0.05, 0.1, 0.2, and 0.4 s/m.



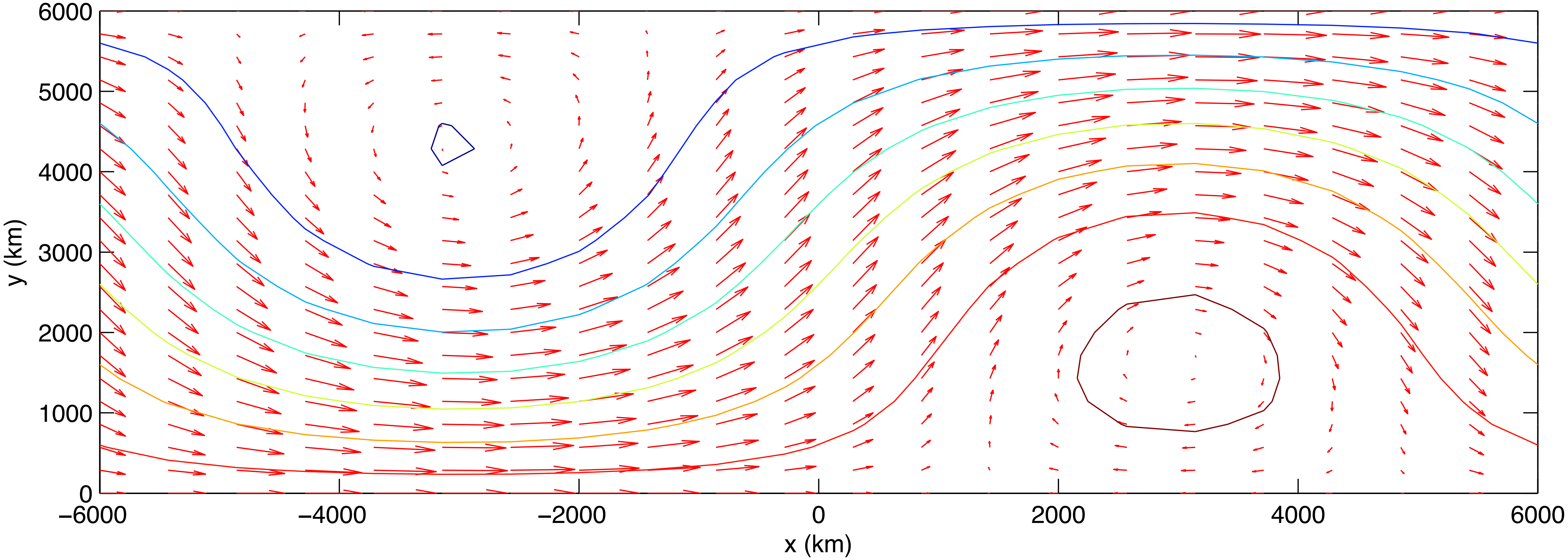


L
P
C
H
V_g


geopotential
6.5e+03
7e+03
7.5e+03
8e+03
8.5e+03
9e+03
9.5e+03
1e+04
y (km)
x (km)
0
1000
2000
3000
4000
5000
6000
−6000
−4000
−2000
0
2000
4000
6000


mixed layer winds (geostrophic: no drag)
y (km)
x (km)
0
1000
2000
3000
4000
5000
6000
−6000
−4000
−2000
0
2000
4000
6000

mixed layer winds (geostrophic: no drag) and geopotential



mixed layer winds (with drag) and geopotential